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Haze, public health and mitigation measures in China: A review of the current evidence for further policy response

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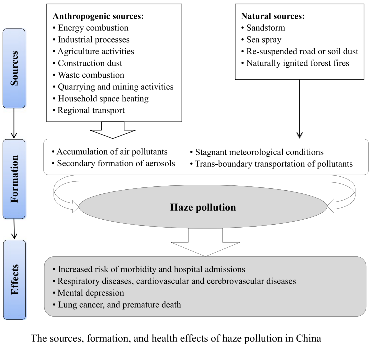
HIGHLIGHTS

- The relationship between haze pollution and public health in China was reviewed for the first time.
- The sources and formation of haze episode were described.
- The existing mitigation measures and challenges faced China were summarized.
- The potential policy options and future research directions were discussed.
- Individual prevention measures during haze events from the public aspects were further suggested.

GRAPHICAL ABSTRACT



The sources, formation, and health effects of haze pollution in China.

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ABSTRACT

With rapid economic development, China has been plagued by choking air pollution in recent years, and the frequent occurrence of haze episodes has caused widespread public concern. The purpose of this study is to describe the sources and formation of haze, summarize the mitigation measures in force, review the relationship between haze pollution and public health, and to discuss the challenges, potential research directions and policy options. Haze pollution has both natural and man-made causes, though it is anthropogenic sources that are the major contributors. Accumulation of air pollutants, secondary formation of aerosols, stagnant meteorological conditions, and trans-boundary transportation of pollutants are the principal causes driving the formation and evolution of haze. In China, haze includes gaseous pollutants and fine particles, of which $PM_{2.5}$ is the dominant component.

Abbreviations: BTH, Beijing-Tianjin-Hebei region; CI, confidence interval; GDP, the gross domestic product; ER, excessive risk; FYP, Five Year Plans; MEP, the Ministry of Environmental Protection; NAAQS, the national air quality standards; PM, particulate matters; $PM_{2.5}$, PM with aerodynamic diameter less than or equal to 2.5 μm; PM_{10}, PM with an aerodynamic diameter of 10 μm or less; PRD, Pearl River Delta; YRD, Yangtze River Delta.

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Haze
Public health
Mitigation measure
China

Short and long-term exposure to haze pollution are associated with a range of negative health outcomes, including respiratory diseases, cardiovascular and cerebrovascular diseases, mental health problems, lung cancer and premature death. China has paid increasing attention to the improvement of air quality, and has introduced action plans and policies to tackle pollution, but many interventions have only temporary effects. There may be fierce resistance from industry groups and some government agencies, and often it is challenging to enforce relevant control measures and laws. We discuss the potential policy options for prevention, the need for wider public dialogue and the implications for scientific research.

1. Instruction

In the past three decades, China has developed extraordinarily rapidly, driven by increases year on year in energy consumption by as much as 10% (Li and Zhang, 2014; Wang and Hao, 2012). In 2011, China passed the United States as the world's largest energy consumer, in absolute terms (He et al., 2016). With few exceptions, growth has been achieved by combustion of fossil fuels, and as a consequence air quality has been degraded in most parts of the country. According to the Asian Development Bank, fewer than 1% of the 500 largest cities in China meet the air quality standards for $PM_{2.5}$ (10 μg/m^3 for annual mean and 25 μg/m^3 for 24-hour mean) recommended by the World Health Organization, and 7 are included among the 10 most polluted cities in the world (Zhang and Crooks, 2012). Results from routine monitoring of 360 cities in 2004 revealed that more than three-quarters of the Chinese urban population is exposed to air that does not meet the national air quality standards (NAAQS) (GB3095-1996) (Shao et al., 2008). Indeed air pollution is now the fourth leading risk factor for premature deaths and morbidity in China, accounting for approximately 1.2 million premature deaths in 2010 (Lim et al., 2012; Ouyang, 2014). In 2007, the World Bank estimated that economic losses resulting from damage to health caused by air pollution may be as much as 87 billion dollars per year in China (Lu et al., 2013).

The most conspicuous manifestation of choking air pollution in China is the increasing occurrence of "haze episodes" which have drawn widespread public concern (Ouyang, 2014; Qiu, 2014; The Lancet, 2014). A haze event is defined by the China Meteorological Administration as a pollution phenomenon which cuts atmospheric visibility to <10 km due to complex materials that are suspended in the atmosphere, such as the solid or liquid particulates, dust, smoke, and vapor (China Meteorological Administration, 2010; Kong et al., 2015; Wang et al., 2012). Haze occurs when particle aerosols accumulate in the air and scatter and absorb solar radiation, leading to atmospheric opacity and impaired visibility (Wang et al., 2012; Xu et al., 2013b). These events have occurred recently on an unprecedented scale, distinguished by long duration, frequent occurrence and record-breaking concentrations of air pollutants. Most severely affected are the most economically developed, highly industrialized and densely populated areas such as the Beijing-Tianjin-Hebei region (BTH), the Yangtze River Delta (YRD), and the Pearl River Delta (PRD) (Li and Zhang, 2014; Qiu, 2014; Wang et al., 2012; Wang et al., 2015; Zhang and Cao, 2015). Monitoring data indicated that 71% of the 615 meteorological stations in China reported a notable decrease in visibility from 1981 to 2005, especially after 1990, when there was a reduction in visibility of about 2.1 km per decade (Che et al., 2009; Che et al., 2007). In January 2013, a persistent and hazardous dense haze event hit China. Based on measurements of 74 major cities the daily average concentrations of $PM_{2.5}$ exceeded the updated NAAQS of 75 μg/m^3 for 69% of days in the month, with a record-breaking daily concentration of 772 μg/m^3 (Huang et al., 2014). This particular haze episodes covered about 1.4 million km^2 and affected more than 800 million people (Huang et al., 2014; Xu et al., 2013a). Together with the costs on transportation, it caused approximately 23 billion Chinese Yuan of economic losses primarily from increased visits to outpatients and emergency rooms, especially in the YRD and BTH regions (Mu and Zhang, 2013; Zhang et al., 2014a).

As "the pollution people see", haze has attracted a great deal of public attention. Haze pollution can obscure the clarity of the sky (The Lancet, 2014), cause contamination of lakes and rivers (Ren et al., 2016), affect the regional climate by altering solar and infrared radiation in the atmosphere (Quinn and Bates, 2003), and influence ecological and agricultural systems (Chameides et al., 1999; Liu and Li, 2015). Health risks linked to haze pollution have also attracted extensive scientific interest. There is growing evidence that haze not only affects mood and increases the frequency of depressive illnesses because of its contribution to frequent gray skies (Hyslop, 2009), but also is an indicator of high concentration of particulate matters (PM) and gaseous pollutants, which may lead to respiratory and cardiovascular diseases, cancers and premature death (Liu and Li, 2015; Liu et al., 2014b; Ren et al., 2016; Tie et al., 2009; Xu et al., 2013a). For example, during the 1997 smoke haze, Singapore saw a 30% jump in outpatient admission for respiratory diseases like upper respiratory tract illnesses, asthma exacerbations and rhinitis (Emmanuel, 2000). Ho et al. suggested that a severe haze in 2013 was associated with acute physical symptoms and mild psychological stress (Ho et al., 2014). However, to date, no review has specifically focused on the relationship between haze pollution and public health in China and related mitigation measures.

The purpose of the present study is to shed some light on the health risks caused by haze in China, using the framework shown in Fig. 1. First, we briefly describe the sources and formation of haze pollution, and the main health threatening air pollutants during haze event. Second, we review the effects of haze on human health, focusing on the current evidence from China. Third, we briefly summarize the measures being taken now to control haze pollution, the corresponding health benefits, and challenges faced in China when new and more radical interventions are implemented. Lastly, we come to future research directions and potential policy options. To the best of our knowledge, this is the first comprehensive account of haze and health, and we hope the findings will help improve the further development and implementation of haze pollution response policies in China.

2. Sources and formation of haze pollution

Generally, the sources of haze pollution are predominantly man-made, although sand storms, sea spray, re-suspended road or soil dust, and naturally ignited forest fires are significant natural sources (Fig. 2) (Che et al., 2007; Sun et al., 2013; Xu et al., 2015). Anthropogenic sources include fossil fuel-related energy combustion, industrial processes, agriculture activities, construction dust, waste combustion, quarrying and mining activities, and household space heating (Guo et al., 2014; Hu et al., 2015; Ren et al., 2016; Wang and Hao, 2012; Xu et al., 2015). Aerosol particles transported from the upwind region through atmospheric movement also make an important contribution to haze pollution (Liu et al., 2014a; Zhang et al., 2015a). However, there are still many challenges to quantify the specific contributions from each source as a whole at national level due to the high heterogeneity among different regions.

Haze episodes tend to occur under conditions of air pollutants accumulation (especially atmospheric fine and coarse particles) (Cheng et al., 2014; Sun et al., 2013), secondary formation of aerosols converted via gas-to-particle under favorable weather conditions (Pachauri et al., 2013; Sun et al., 2006), meteorological stagnation (Wang et al., 2014b;

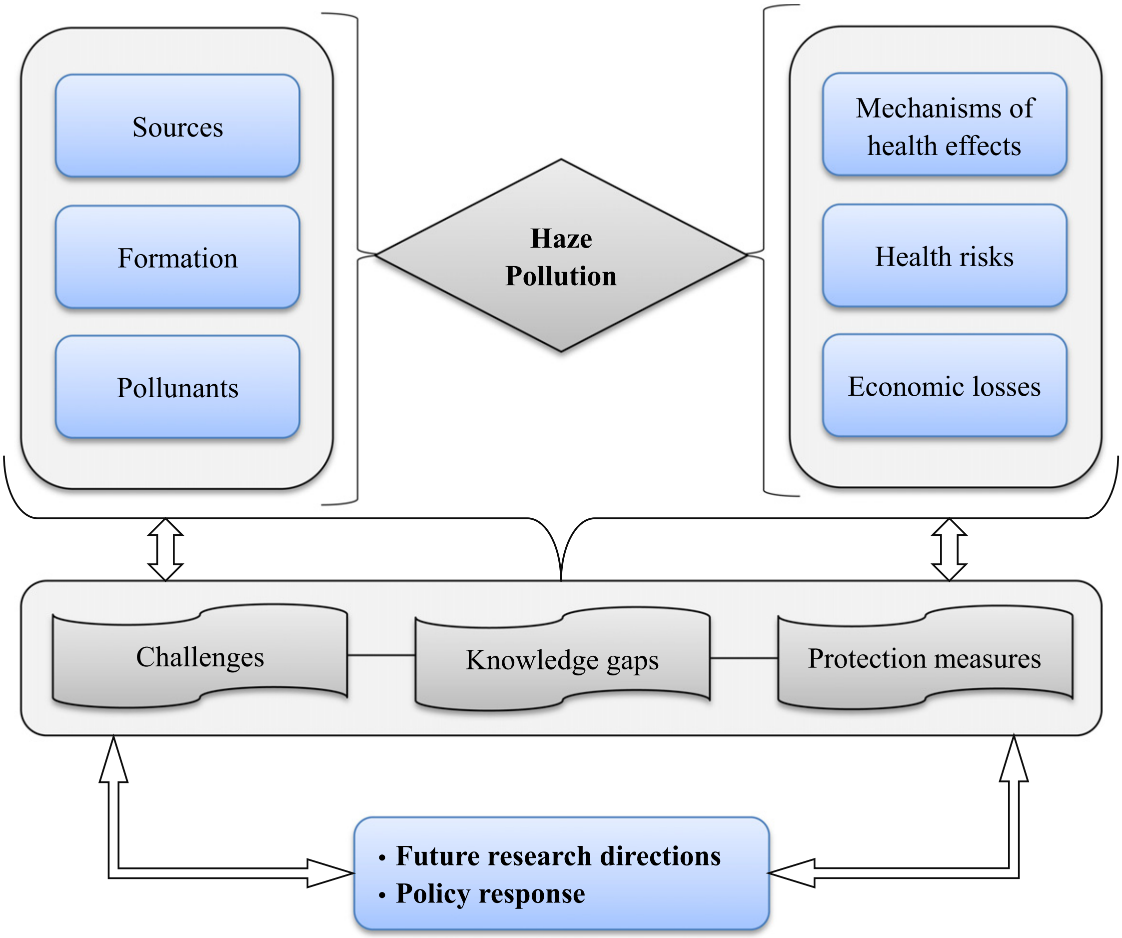

Fig. 1. Framework and focuses of the current review.

Wang et al., 2015), and regional transport of pollutants (Guo et al., 2014; Liu et al., 2014a; Sun et al., 2014a) (Fig. 2). In addition, a low boundary layer, temperature inversion, and higher relative humidity are also important factors that contribute to the formation and evolution of haze events (Yang et al., 2015; Zhang et al., 2015b).

3. Air pollutants during haze episodes

The main components of Chinese haze are gaseous pollutants and particulate matter, especially $PM_{2.5}$ (PM with aerodynamic diameter less than or equal to 2.5 μm) (Liu and Li, 2015; Liu et al., 2014a; Zhuang et al., 2014). $PM_{2.5}$ is a complex mixture with various constituents. Major components include carbonaceous species (mainly categorized into organic carbon and elemental carbon based on their thermal, chemical, and optical properties) (Liu et al., 2014a; Yin et al., 2012), water-soluble inorganic ions (e.g. SO_4^{2-}, NO_3^-, and NH_4^+) (Wang et al., 2014a; Wang et al., 2014d), chemical elements and heavy metals (e.g. Si, Pb, Zn, Ca, Al, Fe, Ni, Cr and Cu) (Hu et al., 2015; Ren et al., 2016; Yin et al., 2012), and secondary aerosols formed from gaseous precursors (e.g. sulfate, nitrate and organic aerosols) (Huang et al., 2014; Wang et al., 2014a; Xu et al., 2014; Zhuang et al., 2014). Haze episodes are usually evident from record-high $PM_{2.5}$ concentrations (typically exceed 100 μg/m^3) (Andersson et al., 2015; Kong et al., 2015; Zhang et al., 2015a), and are associated with substantial elevations in gaseous pollutants including NO_x, SO_2, ozone (O_3), NH_3 and volatile organic compounds (VOCs) (Guo et al., 2014; Huang et al., 2014; Tao et al., 2014; Zhuang et al., 2014).

4. Effects of haze on public health

There is growing epidemiological and experimental evidence that short or long-term exposure to haze pollution is associated with a number of health risks such as morbidity and mortality resulting from respiratory and cardiovascular diseases, lung cancer, and reduced life expectancy (Khoo, 2006; Lu et al., 2013).

4.1. Mechanisms of the health risks caused by haze pollution

Studies related to the health effects of haze pollution mainly focus on PM, especially $PM_{2.5}$. PM with different aerodynamic diameters tends to have different effects on human health. PM_{10} (PM with an aerodynamic diameter of 10 μm or less) mainly deposit in the primary bronchi, since large particles are not inhaled deep into the lungs (Cheng et al., 2014; Ren et al., 2016). On the other hand, $PM_{2.5}$ is penetrates into the small airways and alveoli, and finally into the blood stream (Li et al., 2013; Lu et al., 2013). The toxicological mechanisms of $PM_{2.5}$ and its subset (PM_1) are complex and may include inflammation and allergic reaction, the decrease of the resistance of lung tissues to pathogenic microorganisms, oxidative stress, dysfunction of immune system, dysfunction in coagulation or vascular endothelium, accelerated atherosclerosis, altered cardiac autonomic function, and carcinogenesis (Lu et al., 2015; Lu et al., 2013; Pan et al., 2014; Ren et al., 2016; Zhang et al., 2016) (Fig. 2). Moreover, $PM_{2.5}$ is also the carrier of toxic compounds including chemical elements, heavy metals, and monoaromatic hydrocarbons, resulting in increased toxicity and damage to chromosomes, DNA and other genetic material (Cheng et al., 2014; Hu et al., 2015; Lu et al., 2013; Ren et al., 2016; Sun et al., 2014b; Zhang et al., 2016).

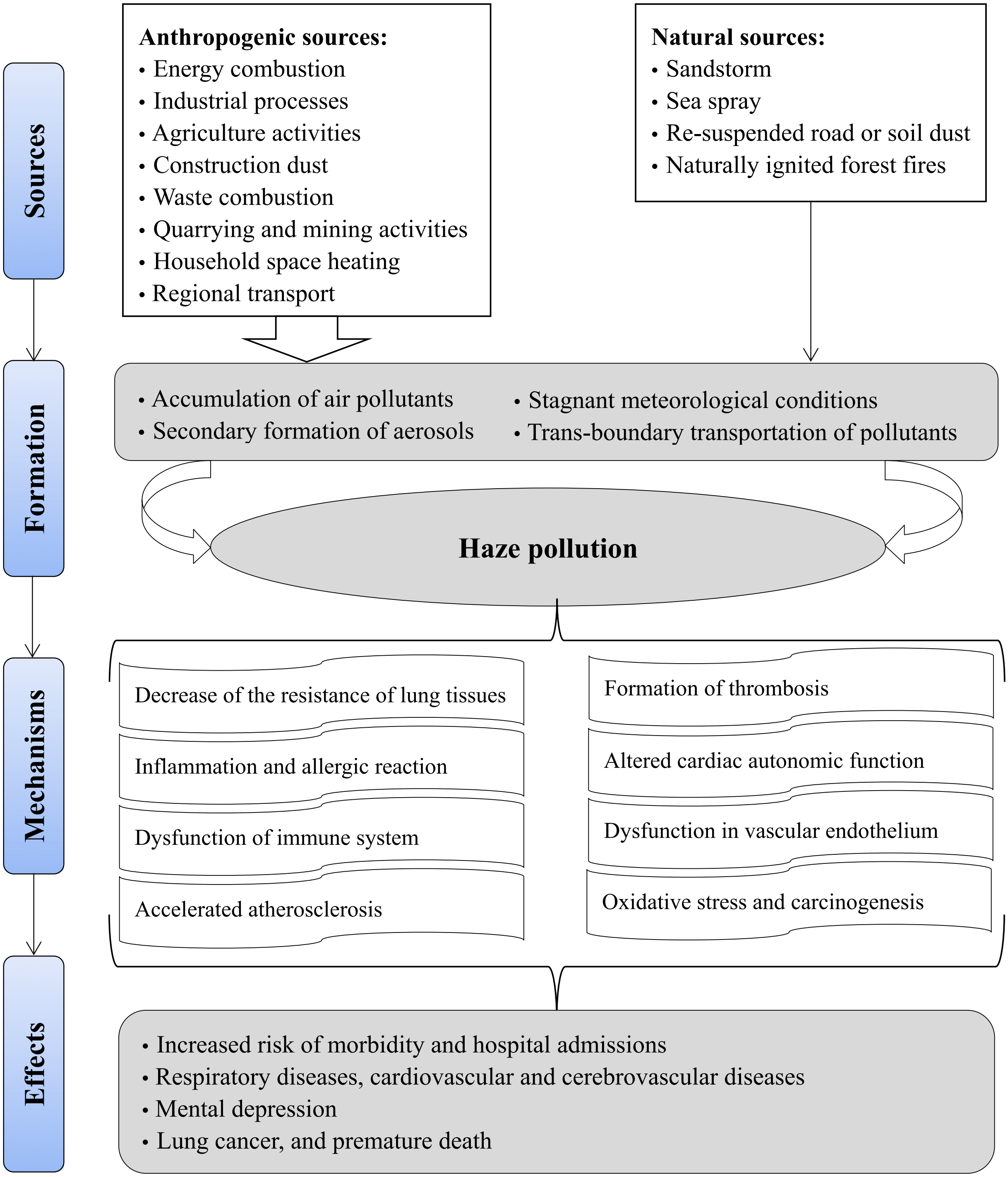

Fig. 2. The sources, formation, and health effects of haze pollution in China.

Recently, there has been increasing interest in the effects of ultrafine and nanoparticles (namely $PM_{0.1}$ and $PM_{0.05}$) on public health, especially during haze events. There are four potential mechanisms for the health effects. First, $PM_{0.1}$ and $PM_{0.05}$ can penetrate readily deep into the alveolar region of the lungs (Behera et al., 2015; Khoo, 2006). Second, these highly reactive particles with greater potential to ferry toxic compounds due to the large surface area (Betha et al., 2014; Khoo, 2006). Third, a complex mixture of organic and inorganic compounds like carbonaceous material, organic acids and metals, adheres to the surface of these submicrometer particles, especially particulate-bound trace elements (e.g. Cd, Cr, Ni, Pb, Mn and Zn). These compounds may undergo biochemical reactions in the respiratory system and generate reactive oxygen species. The reactive species induce harmful health effects due to the direct effects of oxidative stress, and may act also through the production and release of inflammatory mediators by respiratory tract epithelium (Behera et al., 2015; Betha et al., 2014; Hu et al., 2015; Li et al., 2016a). Lastly, the ultrafine particles may even pass through the blood-brain barrier and olfactory nerve, causing neurological inflammation, neuronal damage, cognitive impairment, and ischemic cerebrovascular disease (Khoo, 2006; Lu et al., 2013).

Besides PM, other gaseous pollutants, such as O_3, SO_2 and NO_x that are present during haze events may also play a role in triggering health problems, including aggravated asthma, chronic bronchitis, and premature death (Guo et al., 2014; Zhang et al., 2016). A secondary pollutant, ambient ozone is generated due to reactions between precursors (e.g. NO_x, VOCs) and solar radiation. Elevated concentrations of O_3 have been observed in many Chinese cities during haze days, especially for urban areas in Beijing, YRD and PRD (Wang and Hao, 2012; Zhang and Samet, 2015). Levels of O_3 are associated with health problems of urban populations including increased respiratory and bronchial reactivity, and ischemic cardiac disease (Lai, 2012; Zhang et al., 2016). For further information, the readers may be interested in another special review on the topic of ozone pollution in China, in which the concentrations, chemical and meteorological processes, and health impacts of ozone pollution were summarized (Wang et al., 2017).

4.2. Health effects of haze pollution

Studies of haze have provided evidence of acute adverse health effects. Analysing hospital admissions to a Beijing hospital between December 1, 2012 and January 31, 2013, Chen et al. showed that the risk ratios of emergency room visits, outpatient visits and hospital admissions were 1.16 (95% confidence interval [CI]: 1.02–1.32), 1.12 (95% CI: 1.09–1.15), and 1.69 (95% CI: 1.29–2.21), respectively, during the haze period (when concentrations of pollutants were approximately two to three times those of the "non-haze" periods) (Chen et al., 2013). A time series study in Guangzhou, 2008–2011, reported that persistent heavy haze pollution was associated with a 3.46 (95% CI: 1.67–5.27) increase in excessive risk (ER) of total hospital admissions (at 1 lag) (Zhang et al., 2014c). In January 2013, an unprecedentedly severe and long-lasting haze event occurred over eastern and northern China. Gao et al. conducted a health impacts assessment to quantify the burden of $PM_{2.5}$ during this haze episode in Beijing area. The results indicated that $PM_{2.5}$ might cause 2610 (95% CI: 950–4180) and 88,160 (95% CI: 50,360–124,660) clinic visits of ages 0–14 and age above 15, respectively (Gao et al., 2015) (Table 1).

Respiratory disease is an important adverse consequence of haze pollution. Zhang et al. estimated that a 10 $\mu g/m^3$ increase in NO_2 during haze event was associated with a statistically significant increase in respiratory admissions, especially for chronic obstructive pulmonary disease, with a 3.57 (95% CI: 1.85–5.33) increase in ER (at lag 0 day) (Zhang et al., 2014c). A study in Beijing reported similar adverse effects of haze. Emergency room and outpatient visits due to respiratory disease during the haze episode were increased by factors of 1.74 (95% CI: 1.44–2.11) and 1.16 (95% CI: 1.07–1.27), respectively (Chen et al., 2013). Zhang et al. found that the number of hazy days was positively correlated with the number of cases of respiratory diseases ($r = 0.56$) seen at Beijing Emergency Center between 2006 and 2013 (Zhang et al., 2014b). During the mentioned 2013 January haze episode, it was estimated that increased $PM_{2.5}$ concentrations in Beijing might have caused an additional 5470 (95% CI: 3800–6990) hospitalization due to respiratory disease (Gao et al., 2015). Also, it was suggested that haze pollution may increase the risk of respiratory infection, including avian influenza A (e.g. H_7N_9). For example, in Shanghai, compared with the same period the previous year, the number of patient admissions because of respiratory infection into the infectious diseases department of a hospital increased by more than 3-fold over three months (Pan et al., 2014).

Cardiovascular diseases are sensitive to haze pollution. Chen et al. found a significant increase in outpatient visits and hospital admissions due to cardiovascular disease during haze events (Chen et al., 2013), and Zhang et al. observed an 11.42 (95% CI: 4.32–18.99) increase in ER of cardiovascular hospital admissions (at lag 2 days) (Zhang et al., 2014c). Gao et al. reported 6080 (95% CI: 2720–9190) hospitalization of cardiovascular disease were associated with the 2013 January haze event (Gao et al., 2015). Another study found a positive correlation between the number of hazy days and the number of acute cardiovascular cases ($r = 0.55$) (Zhang et al., 2014b).

Premature death is another severe consequence of haze pollution. An ecological study reported findings on dust-haze and mortality in Guangzhou during 2006–2011. The authors found that the light, medium and heavy dust-haze days were associated with 3.4%, 6.8% and 10.4% increase in mortality respectively (at different lags), and these adverse effects were more pronounced for cardiovascular and respiratory mortality, during the cold season, in males and people ≥60 years (Liu et al., 2014b). Zhou et al. employed generalized additive models to investigate the relationship between haze episodes and daily mortality in BTH region in 2013. The results revealed that primarily through the adverse impacts on cardiovascular and respiratory diseases, the haze event was associated with 6.94% (95% CI: 0.20–14.58) and 19.26% (95% CI: 6.66–33.34) increase in overall mortality in Ji and Ci County, respectively (Zhou et al., 2015). A health impacts assessment of haze pollution from Gao et al. indicated that the increase in $PM_{2.5}$ concentration during 2013 January haze may correspond to 690 (95% CI: 490–890) premature deaths in Beijing (Gao et al., 2015). Premature deaths due to haze pollution were also observed or estimated by other studies performed in different regions in China (Li et al., 2013; Xie et al., 2014; Zhang et al., 2013).

Other health risks are also associated with haze pollution. In Guangzhou, Tie et al. collected 52-year (1954–2006) historical surface measurements of haze data to examine the association between the degradation of air quality and deaths due to lung cancers. The findings are not conclusive, but the increasing occurrence of air pollution events was associated with a steep rise in lung cancer deaths (Tie et al., 2009). In Beijing, there was a positive correlation ($r = 0.48$) between the number of hazy days and the number of cerebrovascular cases from Beijing Emergency Center between 2006 and 2013 (Zhang et al., 2014b). Studies also suggested that gray skies color and impaired visibility during haze events could affect mental health and add to symptoms of depression (Ho et al., 2014; The Lancet, 2014).

4.3. Economic losses of health hazards caused by haze pollution

Several studies assessed the health-related economic loss caused by haze episodes, and the findings demonstrated that haze pollution not only causes adverse effects on public health, but also brings huge economic losses. Yin et al. reported that health costs due to haze pollution in 2009 were 2.46 billion Chinese Yuan in Shanghai, taking up around 0.17% in the gross domestic product (GDP) of this city (Yin et al., 2011). Based on the available data from 20 provinces (cities), Mu and Zhang evaluated the direct economic loss of the haze event during January 2013 in China. The authors estimated that the cost due to increased demand for outpatient and emergency services caused by haze pollution was nearly twice that during non-haze periods in China, and accounted for 98% of the total haze-related economic losses (23 billion Chinese Yuan) (Mu and Zhang, 2013). A study in Beijing concluded that the adverse health effects of high-level $PM_{2.5}$ exposure during the haze occurred from January 10th to 15th, 2013 lead to about 489 (95% CI: 204–749) million Chinese Yuan economic loss, more than 90% was attributable to premature deaths, acute bronchitis and asthma (Xie et al., 2014). Another study from Beijing suggested that the haze events in January 2013 might lead to 253.8 (95% CI: 170.2–331.2) million dollars health-related economic losses, accounting for 0.08% of the total 2013 annual GDP of Beijing (Gao et al., 2015).

5. Current mitigation measures and challenges

In recent years, the frequent occurrence, long persistence, and especially the appreciable health risks and corresponding economic losses of extreme haze episodes, have triggered the Chinese government to pay more attention to reducing emissions of atmospheric pollutants, improve air quality and protect public health across the country. China has developed and implemented a series of measures, action plans and policies to tackle the serious situation, including standards, regulations, and laws that have been modified and updated, formulated and promulgated (Chai et al., 2014). A national air quality monitoring

Table 1
Summary of the studies on health effects of haze pollution in China (n = 13).

Author (year)	Study region and period	Target population	Study design and analysis method	Pollutants exposure during haze episodes	Outcomes	Effect estimate
Tie et al. (2009)	Guangzhou, 1954–2006	Lung cancer incidence	Correlation analysis for different time-lags (year)	Concentrations of atmospheric aerosol particles	Relationship between the abundance of atmospheric aerosol particles and the incidence of lung cancers	For lag (year) = 7/8, correlation coefficient = 0.97 (highest value among various lags)
Yin et al. (2011)	Shanghai 2009	Permanent residents	Proportion risk model of Poisson regression	$PM_{2.5}$ concentrations	Health hazards and health-related economic losses	10,513 premature deaths; together with other diseases and health hazards, leading to total 2.46 billion Chinese yuan economic losses
Mu and Zhang (2013)	20 provinces/cities in China; January 2013	Outpatient and emergency visits	Comparative analysis	Haze periods versus non-haze events	Increased in outpatient and emergency accounts	10%–150% increased in outpatient and emergency visits, together with transportation, leading to economic cost is 23 billion Chinese Yuan
Li et al. (2013)	Beijing, Shanghai, Guangzhou and Xi'an; January 2013	Permanent residents	Proportion risk model of Poisson regression	$PM_{2.5}$ concentrations	Premature death risk (number of premature death)	725 (95% CI: 457–977), 296 (95% CI: 96–502), 310 (95% CI: 189–434), and 85 (95% CI: 21–141) premature death for the four study cities, respectively
Zhang et al. (2013)	12 cities of BTH region; January 2013	Urban population in the 12 cities	Exposure-response analysis	$PM_{2.5}$ concentrations	Excess deaths caused by short-term $PM_{2.5}$ exposure	2725 excess death: 846 duo to respiratory disease, and 1878 due to circulatory disease
Chen et al. (2013)	Beijing, December 2012, and January 2013	Hospital visits from local permanent residents	Comparative analysis (rate ratios, RR)	Various air pollutants, including PM_{10}, $PM_{2.5}$, SO_2, and NO_2	1) Emergency room visits 2) Outpatient visits 3) Hospital admissions	RR = 1.16 (95% CI: 1.02–1.32) RR = 1.12 (95% CI: 1.09–1.15) RR = 1.69 (95% CI: 1.29–2.21)
Xie et al. (2014)	Beijing, January 2013	Permanent residents	Poisson regression model, and environmental valuation method	$PM_{2.5}$ concentrations	Health risks and impaired values	201 premature deaths, together with other diseases, leading to 489 (95% CI: 204–749) million Chinese Yuan health-related economic losses
Pan et al. (2014)	Shanghai, 2013	Patients with respiratory infection	Comparative analysis (increase on patient admissions)	hazy weather conditions (increased $PM_{2.5}$)	The number of patient admissions due to respiratory infection	Increased by more than 3-fold over three months compared with previous year
Zhang et al. (2014a, 2014b)	Guangzhou, 2008–2011	Permanent residents	Generalized additive model	Increase in total air pollutant emissions, and NO_2 during haze episodes	Daily hospital admissions (increase in excessive risk, ER)	1) For total pollutant emissions 3.46 (95% CI: 1.67–5.27) for total hospital admissions; 11.42 (95% CI: 4.32–18.99) for cardiovascular illnesses 2) For increase in NO_2 0.73 (95% CI: 0.11–1.35) for total hospital admissions; 1.94 (95% CI: 0.50–3.40) for respiratory illnesses
Liu et al. (2014a, 2014b)	Guangzhou, 2006–2011	Population from two districts of Guangzhou (YueXiu and LiWan)	Distributed lag linear model	Defined light, medium and heavy haze days according to visibility	Cumulative Excess Risk (CER) of haze on mortality for lag 0–6 days, compared to none haze days	1) Light: 3.4% (95% CI: 1.1–5.7) 2) Medium: 6.8% (95% CI: 2.3–11.6) 3) Heavy: 10.4% (95% CI: 3.4–17.9)
Gao et al. (2015)	Beijing, December 2012 to January 2013	Permanent residents	Weather Research and Forecasting-Chemistry (WRFChem) model	Simulated and interpolated $PM_{2.5}$ concentrations	Health impacts and health-related economic losses	690 (95% CI: 490–890) premature deaths; 45,350 (95% CI: 21,640–57,860) acute bronchitis; 23,720 (95% CI: 17,090–29,710) asthma cases; leading to 253.8 (95% CI: 170.2–331.2) million US$ losses
Zhang et al. (2015a, 2015b)	Beijing, 2006–2013	Cases of cardiovascular, cerebrovascular, and respiratory diseases in Beijing Emergency Center	Univariate linear regression analysis	Number of hazy days	Relationships between the number of hazy days and the number of cases of the above types of diseases	1) Cardiovascular diseases: $r = 0.55$, $P < 0.01$; 2) Cerebrovascular diseases: $r = 0.48$, $P < 0.01$; 3) Respiratory diseases: $r = 0.56$, $P < 0.01$
Zhou et al. (2015)	Beijing, Tianjin and Hebei Province; 2013	Mortality classified by causes of death from the studied regions	Generalized additive models	Haze episodes	Associations between smog episodes and daily mortality for each district/county	1) For Ji County, 6.94% (95% CI: 0.20–14.58) increase in overall mortality; 2) For Ci County, 19.26% (95% CI: 6.66–33.34) increase in overall mortality

system was set up (Li and Zhang, 2014; Wang and Hao, 2012) accompanied by: implementation of clean production processes (Zhang et al., 2016); controls on coal consumption (Xu et al., 2013a); installations of flue gas desulfurization in coal-fired power plants (Li et al., 2016b); promotion of clean vehicles; and increase in the use of renewable energy (Fang et al., 2009). Table 2 shows representative steps taken by the Chinese government to reduce emissions, improve air quality and protect public health. Similar targets have been or will be further announced in the 13th Five Year Plans (FYP).

Health benefits from reductions in the emissions of air pollutants, resulting from deliberate mitigation policies and measures, have been reported around China. Based on models of alternative strategies for coal-fired power generation and industrial coal use in Shanghai, Li et al. reported that the health benefit-to-cost ratio is in the range of 1–5 for the power-sector and 2–15 for the industrial-sector, meaning that there appear to be considerable net benefits (Li et al., 2004). He el al. attempted to quantify the co-benefits of improving energy efficiency in China, and the modeling results indicated that with respect to the baseline in 2001, if aggressive energy policies are implemented, more than 100 billion dollars due to health gains, can be achieved around the year 2030 (He et al., 2010). Hasanbeigi et al. quantified the health co-benefits of energy-efficiency measures at 16 cement plants in Shandong Province in 2008, and their findings revealed that the health-related economic benefits of PM_{10} and SO_2 emission reductions were up to 3,056,065 and 272,457 US$, respectively, which meant that the measures as a whole would be cost effective (Hasanbeigi et al., 2013). With the goal of reducing coal burning emissions and related environmental impacts, Shanxi province has mounted several initiatives since 2000. A study estimated that from 2001 to 2010 in Taiyuan, Shanxi Province, there were 2810 premature deaths prevented because of air quality improvement, and the disability-adjusted life years decreased by 56.92% from 52,937 (7274 million Yuan) in 2001 to 22,807 (3442 million Yuan) in 2010 (Tang et al., 2014). In summary, there is strong evidence that mitigation of air pollution brings considerable health benefits, and these findings support action in China to regulate and enforce tighter controls on air pollution.

Table 2
Main efforts from the Chinese government to improve air quality and protect public health.

Date	Mitigation measures/action plans
2006	The government incorporated stringent goals of air quality improvement into the 11th FYP (2006–2010), such as a 20% reduction in energy intensity and a 10% drop in SO_2 emissions in 2010 respect to 2005 levels
2010	The China State Council issued the "*Guiding Opinions on Pushing Forward the Joint Prevention and Control of Air Pollution to Improve Regional Air Quality*" to formulate a framework of standards, regulations and policies, and to establish a regional level joint prevention and control system, to continuously and significantly reduce the total amount of air pollutants, and ensure air quality meet the standards by 2015
2011	In the 12th FYP (2010–2015), Chinese Government committed to spend 3.4 trillion on environmental protection, and announced targets to reduce energy and CO_2 intensity by 16% and 17%, NO_x and SO_2 emissions by 10% and 8%, respectively, in 2015 from the 2010 levels. In 2011, MEP released "*Emission Standard of Air Pollutants for Thermal Power Plants*" (GB 13223-2011) to further strengthen the nationwide pollution controls and guarantee the achievements of the targets
2011	In order to ensure cities improve and maintain air quality at or better than the *Grade II National Ambient Air Quality Standard* (GB3095–1996) effectively throughout metropolitan areas, MEP issued the action of "*Joint Prevention and Control of Air Pollution*", which will first be implemented in BTH, YRD and PRD during the 12th FYP
2012	MEP published the updated revision of "*the National Ambient Air Quality Standards*" (NAAQS) (GB3095-2012), and $PM_{2.5}$ is included into the NAAQS for the first time
2013	An extended national air quality monitoring network with 946 monitoring stations in 190 cities is put into operation, which release real-time air quality information ($PM_{2.5}$, PM_{10}, O_3, SO_2, CO, and NO_2) to the public
2013	Chinese government released the "*Atmospheric Pollution Prevention and Control Action Plan*", and the "*National Action Plan on Air Pollution and Prevention Control* (2013–2017)", with the aims that to reduce $PM_{2.5}$ by up to 25%, 20%, 15%, and 10% in the BTH, YRD, PRD, and all other cities, respectively, and control the yearly $PM_{2.5}$ level in Beijing at 60 $\mu g/m^3$, by 2017 relative to their 2012 baseline annual average levels, which is backed by US$ 277 billion in investments
2013	Chinese government unveiled a plan and vowed to improve air quality by cutting coal use, closing huge polluters, shifting energy generation and promoting cleaner production. The plan aims to cut the concentration of inhalable PM by at least 10% nationwide in major cities by 2017
2014	The Legislative Affairs Office of China's State Council released the first draft of the highly anticipated revisions to the national Air Pollution Prevention and Control Law, which has been passed by the State Council on November 26, 2014
2016	According to the newest 13th FYP, Chinese government put high emphasis on atmospheric pollutants reduction (especially for PM), air quality improvement, and comprehensive atmospheric environmental management, especially for the three key regions (BTH, YRD, and PRD)

Although it is may be decades before there is substantial country-wide reduction in air pollution, China's efforts so far have made a difference and have achieved health benefits, at least in some regions. That severe pollution episodes can be avoided was demonstrated during the 2008 Olympics and the 2014 Asia-Pacific Economic Cooperation meeting held in Beijing, when closing heavy polluters, reducing car use and stopping construction works around the Beijing region led to appreciable short-term improvement in air quality (Chung et al., 2015; Li et al., 2016b; Rich et al., 2012). But measures such as these can only be temporary because of the evident adverse economic and social implications. There is growing agreement that China must switch from a traditional model of economic development, whatever the environmental and health costs, to one that is much more sustainable. However, due to vested interests, fierce resistance from industry groups and some government agencies is foreseeable (Fang et al., 2009; Qiu, 2014). Another problem in China is not the lack of necessary regulations, but the deficiencies faced in enforcing laws that are already in place (Zhang and Samet, 2015). The key challenge faced in China is how to bring in sustainable mitigation measures and apply them continuously, while advancing economic prosperity.

6. Future policy options to protect public health

We suggest there are seven key issues that should be highlighted in the fight against unprecedented haze pollution in China. First is recognition that it is impossible for the action of one or two government departments alone to curb haze (Li and Zhang, 2014). Strengthening the coordination and cooperation among key ministries involving air pollution controls is crucial to improve air quality and protect public health. This applies especially to the Ministry of Environmental Protection (MEP), the National Development and Reform Commission and, the National Health and Family Planning Committee (Pan et al., 2014; Qiu, 2014). The MEP is "under-resourced" and often powerless to act against many polluters. MEP is often ignored or fines are paid but polluting practices continue, so granting MEP more power and resources has been suggested (Qiu, 2014). Second, since there is substantial movement of air pollutants from area to area, measures in a single city are unlikely to solve the haze pollution (Guo et al., 2014; Wang et al., 2014c). Therefore, comprehensive actions of regional joint prevention and control must be further strengthened. These could better address the haze both locally and regionally, and achieve air quality improvement with greater efficiency (Chai et al., 2014; Wang and Hao, 2012). Third, in order to deal with haze pollution efficiently and cost-effectively, some argue there is a need for comprehensive emission control plans including PM, NO_x, O_3, CO and SO_2, as well as VOCs and possibly CO_2 (Dong et al., 2015; Wang and Hao, 2012). Since China is now facing severe air pollution and multiple health risks due to both primary and secondary pollutants, the traditional problem-oriented one-issue-at-a-time strategy may not be sufficient (Liu et al., 2015; Wang and Hao, 2012). Fourth, international contributions to knowledge transfer, technology innovation and financial support can play a role in increasing the motivation and confidence of the Chinese government in the battle with haze pollution

(Wang and Hao, 2012; Wang et al., 2011). Fifth, timely establishment and update of systemic and scientific ambient air quality standards are necessary (Wang and Hao, 2012). Sixth, in light of the relative high daily average level of air pollution in China, although haze episodes have attracted wide public and government concerns, this does not meaning that the "usual" air pollution days should be ignored, since long-term exposure to less extreme pollution may still be harmful. Lastly, it is imperative to develop a thorough performance appraisal system to understand the effectiveness and cost–benefits of air pollution prevention and control measures. A system of this kind will assist the design and revision of response policy to improve air quality in future (Wang et al., 2014c).

Governmental and political issues aside, in order to provide better evidence-based haze prevention and control strategies, there are scientific questions to be resolved. Firstly, haze pollution in China is complicated and discrepant in sources, formation mechanism and composition, which means that the health effects include strong regional characteristics, varying between urban and rural areas, and these variations have not been assessed quantitatively (Li et al., 2016b; Lu et al., 2013; Qiu, 2014). Secondly, research priorities should go beyond investigating health risks caused by traditional air pollutants (e.g. SO_2, CO, PM_{10}), to include the potential interactive and synergistic effects between $PM_{2.5}$ and other air pollutants (e.g. O_3, NO_2) and meteorological factors (e.g. temperature, humidity) on public health, the independent health effects of NO_x, VOCs and O_3 during haze episodes, the sources of specific ambient pollutants contributed to haze pollution, and the protective role of air purifiers and masks (Gao et al., 2015; Lu et al., 2013; The Lancet, 2014; Wang et al., 2017). In addition, further efforts are needed to improve the national air quality monitoring network and to promote the transparency and sharing of air pollution information (Qiu, 2014).

To date, air pollution policy discourse is mainly dominated by state leaders and experts in China, whereas the public has not played an active citizen role. This weak air pollution citizenship may discourage voluntary efforts including technical assistance and financial contributions, since the public may be the strongest ally in the fight against air pollution (Qiu, 2014; Wang and Hao, 2012). However, the situation has been changing for the better, with some encouraging steps taken to in improve public participation. For instance, on September 9, 2014, China's State Council announced the first draft of the revised version of the national Air Pollution Prevention and Control Law, and openly solicited ideas and comments from the public. Releasing the draft at such an early stage of the law-making process for public comments is rare in China, and is an encouraging development for both public participation and governmental transparency (Zhang and Samet, 2015).

Given that air pollution levels are unlikely to be reduced substantially in the near term, individual protection measures to reduce exposure are also necessary. Publicity campaigns framed in the context of air pollution should be carried out to increase public awareness of the health risks and the corresponding personal prevention and protection measures. For some susceptible individuals such as the elderly, pregnant women and children this may include advice to stay indoors and avoid outdoor physical activities during haze episodes (Cai and He, 2016; Zhang et al., 2016). It may be helpful to wear appropriate face masks if one does have to go out during haze events (Langrish et al., 2012; Ren et al., 2016; Zhang et al., 2016). Besides, keeping doors and windows shut, turning on air-conditioners, and using air humidifiers or purifiers (if budget allows) were also suggested by recent studies to improve air quality when people stay indoors during haze episodes (Li et al., 2016b; Ouyang, 2014; Ren et al., 2016; Zhang et al., 2016).

7. Summary

We describe the sources and formation of haze episodes in China, the associated health effects, current mitigation measures and challenges for response, future research directions and potential policy options. According to our knowledge, this is the first comprehensive review of the health effects of haze pollution in China, and we hope this paper will provide evidence for the further development and implementation of haze pollution policies in China.

Adherence to the principles of environmental sustainability and health are vital, future development needs to recognize that the quality of the environment and the wellbeing of China's population should not be subordinated to the objectives of economic development. China should apply continuous efforts to control air pollution, especially extreme events like haze, and to ensure the public benefits from economic growth and achieves national promises of good health. After all, haze pollution respects no boundaries and the adverse health effects touch all populations, in urban regions and rural areas also.

Conflicts of interest

The authors all declare they have no actual or potential competing financial interests.

Authors' contributions

JHG and QYL conceptualized, designed and initiated the study. JHG and QYL drafted the initial manuscript. LX, JL, JY, JL, and LNC involved in the development of methodology and discussion of article structure, AW, SV, SK, PW, LPL, XBL and HXW reviewed and revised the manuscript. All authors read and approved the final manuscript as submitted.

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