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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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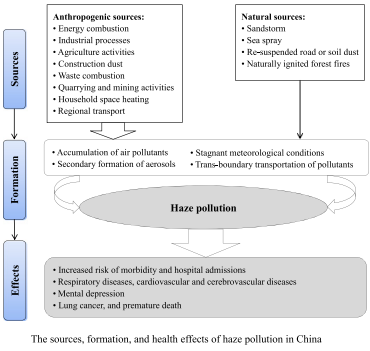
HIGHLIGHTS

- 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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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;

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