ARTICLE IN PRESS

STOTEN-21263; No of Pages 18

Science of the Total Environment xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Formation, features and controlling strategies of severe haze-fog pollutions in China

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HIGHLIGHTS

- The effect of the haze and fog events on air quality, climate change and health risk in China are reviewed.
- Factors contributing to formation of fog-haze events in China are reviewed.
- Advances in the studies of haze and fog pollutions in China are reviewed.
- Future directions of haze pollutions in China are suggested.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 26 July 2016
Received in revised form 5 October 2016
Accepted 26 October 2016
Available online xxxx

Dr. J Jay Gan

Keywords:
Fog-haze pollution
Fine particles
Health
China

ABSTRACT

With rapid industrialization and urbanization, China is facing a great challenge with regard to severe fog-haze pollutions, which were characterized by high fine particulate concentration level and visibility impairment. The control strategies for atmosphere pollutions in China were not only cutting-edge topics of atmospheric research, but also an urgent issue to be addressed by the Chinese government and the public. Focused on the core scientific issues of the haze and fog pollution, this paper reviews the main studies conducted in China, especially after 2010, including formation mechanisms, evolution features, and factors contributing to the fog-haze pollutions. Present policy and control strategies were synoptically discussed. The major challenges ahead will be stated and recommendations for future research directions are proposed at the end of this Review.

1. Introduction

Rapid industrialization and urbanization in developing countries has led to an increase in air pollution, along a similar trajectory to that previously experienced by the developed nations (Huang et al., 2014; Wang et al., 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2014h;

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http://dx.doi.org/10.1016/j.scitotenv.2016.10.201

Please cite this article as: Fu, H., Chen, J., Formation, features and controlling strategies of severe haze-fog pollutions in China, Sci Total Environ (2016), http://dx.doi.org/10.1016/j.scitotenv.2016.10.201

Zhang et al., 2015a; Kulmala, 2015; Guo et al., 2014; Tian et al., 2016). As the world's first largest developing country, China has experienced severe haze-fog (HF) pollution, which was defined as a phenomenon in which a visibility of less than 10 km results from dense accumulation of fine aerosol particles (Tao et al., 2012; Xu et al., 2016; Wang et al., 2013a, 2013b). The most prominent feature of this extreme HF pollution is its long lasting, extensive coverage, and high particle concentration (Huang et al., 2014; Chen et al., 2015; Sun et al., 2016a). More serious HF episodes occurs in China after 2013 because of high levels of atmospheric pollutant emissions and adverse meteorological conditions, especially in city-clusters such as the Yangtze River Delta area, the Beijing-Tianjin-Hebei Province region, the Pearl River Delta area, and Sichuan Basin (Li et al., 2016a, 2016b; Zhang et al., 2015b; Fu et al., 2014; Wang et al., 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2014h; Bi et al., 2014; Wang et al., 2015a, 2015b, 2015c, 2015d, 2015e, 2015f). The first three regions are rapidly developing economic areas with high pollutant emission levels. Under calm meteorological conditions, a haze forms readily. The geography of Sichuan Basin does not favor the diffusion of pollutants and the higher relative humidity (RH) in this region, which can favor the formation of hazes (Yang et al., 2015; Zhang et al., 2015c; Wang et al., 2015a, 2015b, 2015c, 2015d, 2015e, 2015f).

Fine particulate matter ($PM_{2.5}$) represents a major environmental problem during HF episodes: degrading visibility, negatively affecting ecosystems and human health, and directly and indirectly impacting weather and climate (Wang et al., 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2014h; Shen et al., 2015; Chen et al., 2015; Bi et al., 2014; Zhang et al., 2015d). The increased aerosol particles on the haze days reduce visibility, thus delaying traffic. It has been well documented that $PM_{2.5}$ are the most effective factor for visibility impairment (Zhang et al., 2015d; Lin et al., 2012; Yang et al., 2012). The visibility reduction is obvious in some Chinese mega cities and even throughout suburbs in recent years (Han et al., 2016a, 2016b; Zhang et al., 2015d; Zhang et al., 2015e; Tao et al., 2014a, 2014b). Over the past 25 years, there has been a significant decrease in horizontal visibility (2.1 km per decade from 1990 to 2005), and it has speculated that increased aerosol loadings were responsible for the observed decreases in horizontal visibility (Che et al., 2007). By scattering and absorbing solar radiation, haze layer can greatly cool the surface of the Earth while heating the atmosphere, which in turn affects convections and stability in the low troposphere (Xu et al., 2016; Tao et al., 2014a, 2014b; Zhang et al., 2015b; Zhang et al., 2015c). Heavy loading of aerosols alter cloud properties and their lifetimes over polluted regions, and weaken monsoons (Tao et al., 2012). In addition to these climate effects, haze particles near the surface can cause serious health problems, from respiratory illnesses to heart disease, premature death, and cancer. Especially, airborne metals can also impose long-term burdens on biogeochemical cycling in ecosystems (Duan and Tan, 2013; Li et al., 2016a, 2016b). It has been documented that the number of pediatric patients with pneumonia has increased dramatically in China in recent years (Chen et al., 2015; Xie et al., 2014; Wang and Mauzerall, 2006). An estimated 2.5 million people in china die each year from the health effects of indoor and outdoor air pollution (Kulmala, 2015). Moreover, an early study using satellite remote sensing has shown that haze particles have a negative effect on agricultural productivity (Chameides et al., 1999). Sulfate and nitrate aerosols can increase soil acidity through acid deposition, which has a negative impact on the ecosystem (Zhao et al., 2009).

Acute particulate pollution has also attracted great scientific interest (Wang et al., 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2014h; Huang et al., 2014; Shen et al., 2015; Tie et al., 2015; Wen et al., 2015). Extensive studies have been conducted to investigate the characteristics and formation mechanisms of haze pollution in China (Wang et al., 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2014h; Fu et al., 2008; Quan et al., 2015; Behera et al., 2015; Yang et al., 2015; Andersson et al., 2015; Yu et al., 2016). High emission intensity, adverse meteorological conditions, and the formation of substantial amounts of secondary aerosols are generally regarded as the principal factors underlying the formation of HF episodes (Sun et al., 2016b; Sun et al., 2013a; Sun et al., 2013b; Huang et al., 2014; Wang et al., 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2014h; Han et al., 2014). It is well known that emissions of aerosols and their precursors released by human activities in China are higher by far than those in Europe and North America today and will continue to increase in the future (Akimoto, 2003; Ohara et al., 2007; Zhang et al., 2012; Zhang et al., 2009). Carbonaceous aerosols account for a large fraction of $PM_{2.5}$ particles (~20–90%) and are considered to be a vital constituent controlling the formation and evolution of haze episodes. China is generally thought to be responsible for about 25% of global black carbon (Wang et al., 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2014h; Cao et al., 2012). Extremely high concentrations of carbonaceous aerosols (~100 μg C/m^3) have been recorded during typical haze days (Liu et al., 2014; Zhang et al., 2008b). In particular, Chinese NO_x emissions showed a marked increase of 280% over 1980 levels, and growth in emissions since 2000 has been extremely high (Ohara et al., 2007). In addition to the effects of human activities, the increased number of haze days may be associated with adverse meteorological conditions, including weak surface winds, low mixing layers, thick temperature inversion layer, or anomalous winds in the lower troposphere that transport large amounts of water vapor and pollutants (Tao et al., 2014a, 2014b; Wang et al., 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2014h; Ye et al., 2016; Han et al., 2016a, 2016b). Under such weather conditions, large amounts of secondary aerosols can be generated, of which will be further accumulated formation of HF pollutions (Huang et al., 2014; Gao et al., 2015a, 2015b, 2015c; Tian et al., 2015). Field-measurements have revealed the formations of stronger zonal circulations in the mid-troposphere and weaker winds on the surface when the heavy haze occurs (Wu et al., 2008; Chen et al., 2015). The declining Arctic Sea ice has been proven to intensify haze pollution in eastern China (Wang et al., 2015a, 2015b, 2015c, 2015d, 2015e, 2015f).

In response to the extremely severe and persistent haze pollution during January 2013, the Chinese State Council announced its aim to reduce concentrations of $PM_{2.5}$ by up to 25 percent relative to 2012 levels by 2017 (Wang et al., 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2014h; Zhang et al., 2015b). To achieve this goal, the Chinese government promoted 10 prevention measures and countermeasures for aerosol pollution control called *Atmospheric Pollution Prevention and Control of the Ten Measures of China* (http://www.gov.cn/gzdt/2013-09/16/content_2489162.htm). The government also released the Second Atmospheric Pollution Control Special Plan (Zhang et al., 2015e; Yang et al., 2015). All of these have gained increasing attention among researchers to reduce emissions caused by aerosols with an emphasis on coal combustion, industrial manufacturing processes, and vehicle fuel quality (Guo et al., 2014; Chen et al., 2015; Zhang et al., 2015f). With strictly controlling, emissions were also reduced by approximately 35% in Beijing and its vicinity in November 2014 and August 2015, thereby producing "the Asia Pacific Economic Cooperation (APEC) blue" and "Military Parade blue". However, the air pollution control remains a great challenge because urban air is a complex cocktail of chemicals whose poorly understood interactions and feedbacks may exacerbate health problems (Kulmala, 2015; Chen et al., 2015). The long-term chemical characterization of aerosols in China is thus essential to assess the effect of aerosols in the atmosphere and climate, and the results can be used to evaluate and improve existing haze-fog forecasting systems (Sun et al., 2015a; Zhang et al., 2015g).

The review is organized as follows. In Sections 2, we briefly reviewed the long-term change characteristics of HF pollutions, and introduced two typical of HF events occurred in January and December 2013, respectively. The effect of the HF events on air quality, climate change and health risk is described in Section 3. Section 4 summarized factors contributing to formation of fog-haze events. Advances in the studies of haze and fog pollutions were presented in Section 5. Section 6 contained present policy, controlled strategies. Challenges and future direction were stated.

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