JOURNAL OF ENVIRONMENTAL SCIENCES 46 (2016) 134–146

Available online at www.sciencedirect.com

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JES JOURNAL OF ENVIRONMENTAL SCIENCES www.jesc.ac.cn

Spatial and temporal variation of haze in China from 1961 to 2012

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ARTICLE INFO

Article history:
Received 29 May 2015
Revised 27 November 2015
Accepted 28 November 2015
Available online 8 April 2016

Keywords:
China
Haze
Spatial distribution
Interannual trend
Meteorological factors
Anthropogenic activities

ABSTRACT

The purpose of this study is to analyze the climatic characteristics and long-term spatial and temporal variations of haze occurrence in China. The impact factors of haze trends are also discussed. Meteorological data from 1961 to 2012 and daily PM_{10} concentrations from 2003 to 2012 were employed in this study. The results indicate that the annual-average hazy days at all stations have been increasing rapidly from 4 days in 1961 to 18 days in 2012. The maximum number of haze days occur in winter (41.1%) while the minimum occur in summer (10.4%). During 1961-2012, the high occurrence areas of haze shifted from central to south and east regions of China. The Beijing-Tianjin-Hebei (Jing-Jin-Ji) region, Shanxi, Shaanxi, and Henan Province are the high occurrence areas for haze, while the Yangtze River Delta (YRD) and the Pearl River Delta (PRD) have become regions with high haze occurrences in the last 25 years. Temperature and pressure are positively correlated with the number of haze days. However, wind, relative humidity, precipitation, and sunshine duration are negatively correlated with the number of haze days. The key meteorological factors affecting the formation and dissipation of haze vary for high and low altitudes, and are closely related to anthropogenic activities. In recent years, anthropogenic activities have played a more important role in haze occurrences compared with meteorological factors.

Introduction

With the rapid expansion of China's economy and urbanization, the emissions of primary gaseous pollutants and particles, as well as the secondary particles formed by photochemical reaction, have gradually increased (Hao et al., 2010). These can scatter and absorb the incident light and therefore lead to atmosphere opacity and horizontal visibility degradation, and deteriorated air quality (Liu et al., 2013; Oh et al., 2015), which results in haze occurrence. Haze is an atmospheric phenomenon where dust, smoke and other dry particles in the atmosphere obscure the clarity of the sky and reduce the visibility to less than 10 km (CMA, 2010, 2003). The formation of haze is known to be closely related to meteorological factors and environmental pollution (Zhao et al., 2013; Huang et al., 2014), which has caused a number of

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http://dx.doi.org/10.1016/j.jes.2015.12.033

social and economic issues, such as human health problems, traffic jams from visibility reduction, and deterioration of plant growth (Panyacosit, 2000; Harrison and Yin, 2000; Al-Saadi et al.,2005; Lee et al., 2013; Friedlander 1977). Haze has become a major environmental issue to be resolved in China (Wang et al., 2014; Zhang et al., 2012).

Study of the spatial and temporal trends, causes, and human impacts of haze started early in developed countries. Sloane (1983, 1984) examined the effect of meteorology on visibility trends and the extraction of valid air-quality related conclusions from these data. Long term studies of haziness within the United States were also carried out by Husar et al., (1981) and Schichtel et al., (2001). It was shown that haze days increased at first in the 1950s-70s and then declined after the 1980s. Doyle and Dorling (2002) constructed trends from 1950 to 1997 in the United Kingdom using four different statistical methods. These haze occurrences mainly arose due to high incidence of fossil fuel burning for domestic heating purposes. Others tried to illustrate the haze formation and evolution mechanism by using satellite, lidar, upper as well as lower atmosphere composition data and model results (Hand et al., 2012; Tsai et al., 2007; Oanh et al., 2006; Al-Saadi et al., 2005; Malm et al., 2004; Ramanathan and Ramana 2003).

In China, haze has drawn wide attention since 2002 (Wu, 2012). During the past two decades, Chinese scientists have carried out many experiments to explain the formation and evolution mechanism of haze. Wu et al. (2010) and Gao (2008) have analyzed and discussed the historical trends of haze. The result showed a marked increase in annual-average haze days took place for years before 2006 in China. Several studies have focused on the trends of important regions, including the Yangtze River Delta (YRD) (Deng et al., 2012; Niu et al., 2010; Tong et al., 2007), the Pearl River Delta (PRD) (Wu et al., 2006, 2007a, 2007b; Fan and Sun, 2009; Qian et al., 2006; Liu et al., 2004), and the Beijing-Tianjin-Hebei (Jing-Jin-Ji) region (Fu et al., 2014; Wang et al., 2013 ; Fan and Li, 2008). Some studies have focused on severe haze events, for which visibility is equal to or less than 5 km (QX/T 113-2010), which have occurred frequently in many Chinese cities over recent decades (Liu et al., 2013; Wu et al., 2009; Fu et al., 2008; Wu, 2005). Meanwhile, some studies using single surface meteorological factors (such as visibility, relative humidity or wind speed) have discussed their relationship with haze (Ding and Liu, 2014; Chen et al., 2012; Wu et al., 2008; Sun, 1985). Other researchers have tended to study the correlation between haze and air pollutant components (including particulate matter (PM) concentrations and gaseous pollutants) accompanying a heavy haze event (Zheng et al., 2014; Zhao et al., 2013; Wang and Hao, 2012; Sun et al., 2006). In fact, most studies have focused on comparatively fragmented regions. Very limited research has analyzed haze climate characteristics and the long-term trend of haze in the whole of China. At the same time, haze phenomena have resulted from the comprehensive effects of natural and anthropogenic factors, such as geographic factors (altitude), meteorological factors, and man-made pollution. In addition, these comprehensive effects of haze formation could be potentially related to the environmental capacity (limiting the size of anthropogenic emissions). However, there is lack of combined-effect analysis on this important issue.

The purpose of this study is to analyze the climatic characteristics and long-term spatial and temporal variations of haze occurrence in China from 1961 to 2012. Our manuscript is divided into 4 parts. First, this paper describes the temporal variations of haze. The long-term trend of haze (from 1961 to 2012) in China is analyzed. Monthly trends and seasonal trends using the data of hazy days, precipitation and Air Pollution Index (API) of PM_{10} are also discussed. Second, in order to describe the phenomenon more clearly, this paper discusses research on the spatial distribution of haze during 6 periods by interannual comparison. Third, to better understand the impact of meteorological parameters on haze occurrence, the correlations between haze and 6 meteorological factors (pressure, temperature, wind speed, relative humidity, precipitation, and sunshine duration) at different altitudes are described. Finally, this paper attempts to explain the causes of the haze trend based on meteorological factors and anthropogenic activities.

1. Data and methods

1.1. Data

The location and altitude information for 1701 meteorological stations and 83 PM stations is shown in Fig. 1. In this paper, if a station's altitude is lower than 1000 m (blue areas in Fig. 1), we defined this station as a 'low altitude' station, otherwise the station is categorized as a 'high altitude' station (Hu 2009).

1.1.1. Meteorological data

Drawing from surface meteorological observations, various types of meteorological data have been recorded since 1951, but the standard surface observation criteria were established and followed starting in 1954 (CMA, 1954). Meanwhile, the number of observation stations has increased from approximately 400 stations in 1954 to about 2400 stations in 2012. Thus, some selection of stations was needed. Selection criteria included the following: (1) a month was considered to have sufficiently complete data if there were seven or fewer missing days within that month; (2) a year was considered to have sufficiently complete data if all months were complete according to (1). While the selected stations in 1961-2012 do not cover all areas equally, their coverage is sufficient for the purposes of this study. Based on surface observations in China, a total of 1701 meteorological stations with successive identifiers and available data were selected during the period 1961-2012 in this work (CMA, 2010; Powell and Keim, 2014). The geographical location of the stations is shown in Fig. 1.

In this study, the hourly data used included 1701 meteorological observation stations covering air temperature, air pressure, precipitation, wind speed and direction, relative humidity, visibility, and altitude at surface stations. The daily data also used these stations covering sunshine duration, fog, haze, dust and all other weather phenomena. All data were recorded from 1701 meteorological stations over a 52-year period from January 1st 1961 to December 31th 2012 in China by the National Meteorological Information Center (NMIC).

Among these data, wind speed and direction were observed at 10 m off the ground, while air temperature and