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Long-term atmospheric visibility trends in megacities of China, India and the United States

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ABSTRACT

Millions of premature deaths worldwide every year mostly in China and India are contributed by the poor air quality. The atmospheric visibility is a proven indicator of the ambient air quality. In this study, nine megacities were selected, including Beijing, Shanghai and Guangzhou from China, Chicago, Los Angeles (LA) and New York City (NYC) from the United States, and Mumbai, Chennai and Jaipur from India. The data of visibility, aerosol optical depth (AOD), and meteorological factors from 1973 to 2015 were collected. The temporal variations of annual and monthly percentages of bad days (visibility < 5 km) and good days (visibility > 15 km) were evaluated. Visibility of Chicago, LA and NYC gradually improved during the past 43 years and has reached a very good level (good day percentages: 75–88%; bad day percentages: 0 – 4%). Conversely, visibility in Mumbai, Chennai and Jaipur continued deteriorating and suffered an extremely poor visibility situation in recent years (good day percentages: 0; bad day percentages: 6–100%). Likewise, visibility in Beijing, Shanghai and Guangzhou has experienced the worsening period during the industrial development from 1970s and turned better after the 1990s. A strong seasonal pattern of bad day percentages of each year were observed in most cities, especially in the winter, which is caused by the fossil fuel combustion for heating, relatively high relative humidity, and other unfavorable meteorological conditions. The low visibility events occurred more frequently in days with low wind speeds and specific wind directions, further explaining the seasonal patterns of visibility. With population growth from the period of 2000–2010 to the period of 2011–2015, AOD and bad day percentages both increased in Mumbai, Chennai, Jaipur and Beijing while others were relatively stable. This study demonstrated that the macro-control of pollution emissions could effectively reduce air deterioration. The relationships among visibility variation, meteorological, pollutant and population factors provide valuable scientific support for public health researches, air quality managements (monitoring and forecasting), and clean energy initiatives.

1. Introduction

The atmospheric visibility is defined as the maximum horizontal distance, at which the threshold of a target object can be recognized against the background by human eyes (Deng et al., 2012; Horvath, 1981). High visibility (> 100 km) can be observed in unpolluted circumstances with clear weather while low visibility would be often attributed to heavy air pollution and bad meteorological conditions (Deng et al., 2012; Zhao et al., 2011). The visibility could decrease due to the scattering and absorption of visible light by particles and gases in the atmosphere (Watson and Chow, 2006; Hyslop, 2009), and the patterns of air pollution are exactly massive emissions of particle and gas pollutants into the air. Furthermore, it is known that the emission of particulate pollutants can cause visibility impairment, which makes the visibility an important proxy for the particulate matter pollution (Clancy et al., 2002; Kim et al., 2006). Although visibility can be impacted by specific meteorological phenomena such as high wind speeds, rainfall and fog events, the long-term influence of meteorological conditions is relatively stable (Zhao et al., 2011). Therefore, the long-term trend of visibility can indicate the variation of air pollution status (Chen and Xie, 2013; Fu et al., 2014).

Due to rapid industrial developments and economic growth, human beings have paid great environmental costs for serious air pollution issues, which could heavily damage public health (Zhang et al., 2010).

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The United States, China and India are three of the most populated countries in the world with vast territories. They all have been experiencing significant industrial developing processes. In the past decades, because of the industrial revolution and significant environmental improvement, atmospheric visibility of the U.S. cites decreased before 1970s and then increased, which has the most serious sulfur and organics pollution in the mid-eastern and western urban regions (Davis, 1991; Malm, 1992; Malm and Molenar, 1984; Malm et al., 1994; Schichtel et al., 2001). As a result of population and economic explosions in Indian cities, the associated air pollution cause significant declines of visibility over a hundred years (Dani et al., 2012; De et al., 2005; Jaswal et al., 2013; Tiwari et al., 2011). In the most populated areas of China such as the North China Plain and the Pearl River Delta, evident visibility falling on account of air pollution attracted a large number of researchers investigating the visibility trends and relationships with meteorological factors and other pollutants (Deng et al., 2012, 2008; Fu et al., 2014; Gao et al., 2011; Zhang et al., 2010; Zhao et al., 2011). Hence, the understanding of the mechanism of visibility variations plays a key role in air pollution emergency response and regional air quality management.

In this study, three megacities from the three countries including China, the U.S. and India were chosen. These nine cities are Beijing, Shanghai, Guangzhou, New York City (NYC), Chicago, Los Angeles (LA), Mumbai, Chennai and Jaipur (Fig. 1). These cities are the most economically developed, populated and represent different geographic and meteorological conditions of each country. From 1973 to 2015, the annual visibility variations were investigated. Relationships between visibility and meteorological factors (relative humidity, wind speed and wind direction), social economic parameters and the aerosol optical depth (AOD) were discussed. Studying the long-term trends of visibility in populated cities with the consideration of impacts of human activities is valuable for smart urban planning.

2. Data and methodology

Beijing, Shanghai, Guangzhou, Chicago, NYC, LA, Mumbai, Chennai and Jaipur were chosen as the representative cities from China, the U.S. and India, respectively (Fig. 1), which were selected from ten most populated cities of each country. With complete time series of datasets from 1973 to 2015, the top three populated cites were determined. Visibility and other meteorological parameters including the wind speed, wind direction, air temperature and dew-point temperature of these nine cities with at least 3 h intervals from 1973 to 2015 were collected from the National Climate Data Center (NCDC) (Data source: http://www1.ncdc.noaa.gov/pub/data/noaa/). The units of visibility datasets are miles, which was converted into kilometers. Although the NCDC is highly authoritative that provides global weather and climate data, there are non-negligible uncertainties of original datasets caused by various factors such as the conversion of observation methods. Hence a series of processes were performed to obtain data, which could accurately reflect relationships between visibility and air pollution.

To minimize the influences caused by meteorological factors, low visibility observations due to specific weather conditions such as mist, precipitation and fog were removed, which generally have high relative humidity (RH) and could not represent status of air pollution (Che et al., 2007; Chen and Xie, 2013). With RH changing, the diameter and refractive index will change because hydrophilic aerosols absorb water vapor. It is defined as the aerosol hygroscopicity, which reflected as the variation of visibility in the horizontal direction (Liu et al., 2012; Tang, 1996). Therefore, visibility data with RH < 90% in the range from 9:00 a.m. to 6:00 p.m. (local time) were chosen for screening, cleaning and further long-term trend analysis (Section 3.1). RH was calculated through the equation (Linsley et al., 1988):

$$RH = 100 \times \left(\frac{112 - 0.1T + T_d}{112 + 0.9T}\right)^8$$

where T (°C) represents the air temperature and T_d represents (°C) the dew point temperature. In addition, the SYNOP (Surface Synoptic Observations) and METAR (Meteorological Terminal Air Report) standards of visibility observation were mixed together in original datasets. METAR data are encoded by automated airport weather stations and SYNOP data are encoded by both manned and automated weather stations. These two types of records have different observation standards, that the upper limit of METAR is 10 miles while observations of SYNOP could reach 30 miles or higher (many observations with values of 100 miles were recorded) (Li et al., 2016). Moreover, the time resolution of SYNOP is 3 h and METAR is 1 h or half an hour. To compensate the influences caused by METAR records, only monitoring

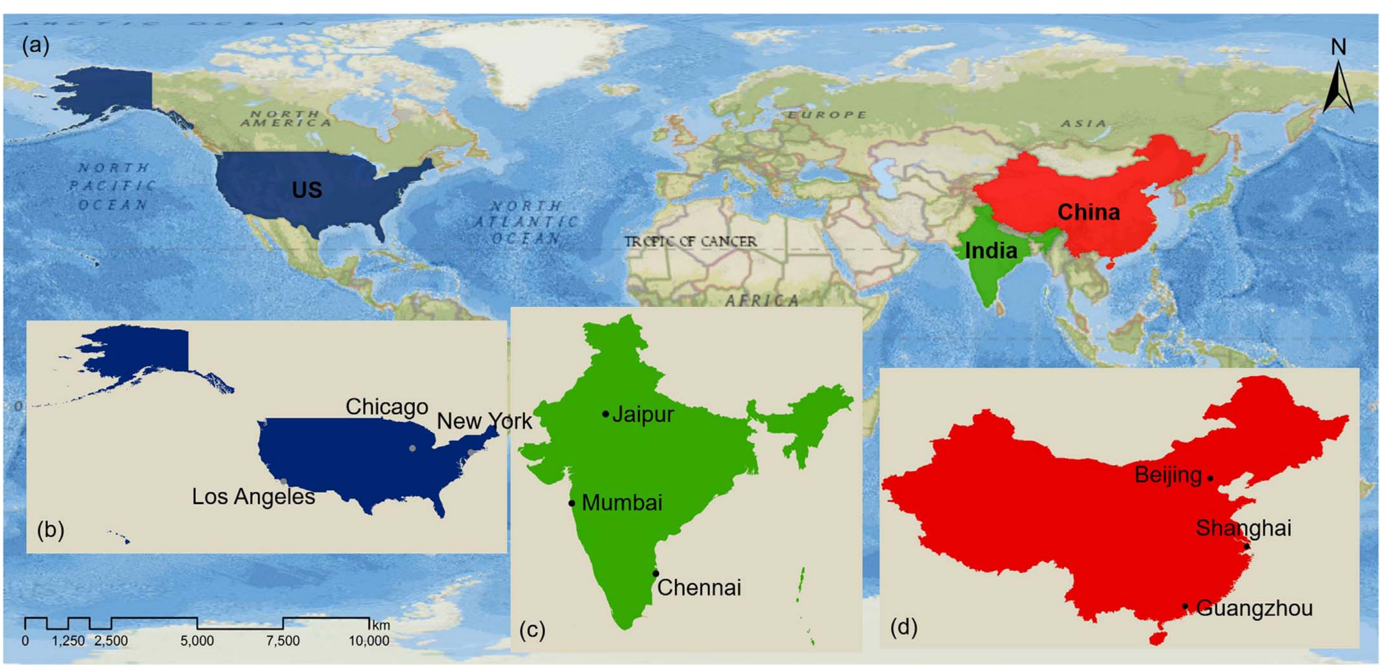

Fig. 1. **(a)** Locations of China, the United States and India on the world map; **(b)** Locations of Chicago, Los Angeles and New York City in the US; **(c)** Locations of Mumbai, Chennai and Jaipur in India; **(d)** Locations of Beijing, Shanghai and Guangzhou in China.