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Effects of human activities and climate change on the reduction of visibility in Beijing over the past 36 years

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ABSTRACT

Both climate change and intensive human activities are thought to have contributed to the impairment of atmospheric visibility in Beijing. But the detailed processes involved and relative roles of human activities and climate change have not been quantified. Optical extinction of aerosols, the inverse of meteorological visibility is especially sensitive to fine particles $< 1.0\,\mu m$. These submicron particles are considered more hazardous than larger ones in terms of cardiovascular and respiratory diseases. Here we used the aerosol optical extinction (inverse of visibility) as the indicator of submicron particles pollution to estimate its inter-annual variability from 1980 to 2015. Our results indicated that optical extinction experienced two different periods: a weakly increasing stage (1980–2005) and a rapidly increasing stage (2005–2015). We attributed the variations of optical extinction to the joint effects of human activities and climate change. Over the past 36 years, human activities played a leading role in the increase of optical extinction, with a positive contribution of $0.077\,km^{-1}/10\,y$. While under the effects of climate change, optical extinction firstly decreased by $0.035\,km^{-1}/10\,y$ until 2005 and then increased by $0.087\,km^{-1}/10\,y$. Detailed analysis revealed that the abrupt change (around 2005) of optical extinction resulted from the trend reversals of climate change. We found since 2005 the decreasing trend by $0.58\,m\cdot s^{-1}/10\,y$ in wind speed, the growing trend at 8.69%/10 y in relative humidity and the declining trend by 2.72 hPa/10 y in atmospheric pressure have caused the rapid increase of optical extinction. In brief, the higher load of fine particles $< 1.0\,\mu m$ in Beijing in recent decades could be associated with both human activities and climate change. Particularly after 2005, the adverse climate change aggravated the situation of submicron particles pollution.

1. Introduction

Is there a landmark you can observe clearly on some days and not on others? Well, it is related to atmospheric visibility where you live. Visibility usually refers to the clarity or transparency of the atmosphere, which is defined as horizontal distance at which an observer can just see a black object viewed against the sky background (Koschmieder, 1926). At polluted sites, atmospheric visibility can be impacted by air aerosols through their scattering and absorption of solar radiation. Optical extinction of aerosols, the inverse of atmospheric visibility, is especially sensitive to fine particles $< 1.0\,\mu m$, because these particles are close to the wavelength of visible solar radiation and are the most effective at reducing atmospheric visibility (Nicole Pauly, 2009; Watson, 2011). The World Health Organizations (WHO) has announced that fine particles are more hazardous to human health than larger ones in cardiovascular and respiratory diseases (Englert, 2004). For this reason, visibility has been a major concern in pollution studies and climatology at local, regional, continental and global scales (Li et al., 2017; Wang et al., 2009; Wang et al., 2012; Zhao et al., 2011). The inverse of optical extinction, meteorological visibility, which has been routinely observed at weather station and globally available from the early 20th century (Vautard et al., 2009; Wang et al., 2012), provides a proxy of the optical concentrations of $PM_{1.0}$. Many studies on meteorological visibility has been used successfully to quantify inter-annual variability of air aerosols over the past decades (Field et al., 2009; Li et al., 2015; Liu et al., 2015; Wang et al., 2009; Wang et al., 2012).

In the past several decades, clear sky visibility has decreased over land globally (Fu et al., 2013; Hua et al., 2015; Sabetghadam et al., 2012; Wang et al., 2009; Wang et al., 2012; Zhao et al., 2011). It has been reported that since 1973 visibility has decreased substantially over

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South and East Asia, South America, Australia and Africa (Wang et al., 2009). The long-term changing assessment of optical extinction of aerosols over the Northern Hemisphere by Wang et al. (2012) also indicated there was a decreasing trend in visibility from 1992 to 2011. China, as the largest developing country, is deemed as one of the most significant emitters of aerosols and their precursor gases (Streets et al., 2003). Visibility impairment has been reported in some mega cities and even some medium and small cities in recent decades (Chang et al., 2009; Liang et al., 2017; Wu et al., 2012).

The studies mentioned above mainly focused on the spatial distribution and changing trend of visibility, which indicated visibility reduction has become a trend across the globe. However, when comparing the mass concentration of aerosols ($PM_{2.5}$ and PM_{10}) with the optical extinction of aerosols over the Northern Hemisphere for a long period, Wang et al. (2012) found the contrasting trends. That is to say though the mass concentration of aerosols has decreased, the optical extinction of aerosols has increased abnormally. This conclusion can be verified by a certain city, such as Beijing (Chang et al., 2009; Kong et al., 2017; Tian et al., 2014; Zhao et al., 2011). Considering the optical extinction of aerosols is especially sensitive to particles $< 1.0\,\mu m$, we think it could be the increasing fine aerosols (such as $PM_{1.0}$) that led to the increase of optical extinction. A previous study also confirmed that the optical extinction was generally well correlated with the $PM_{1.0}$ mass concentrations (Xu et al., 2016). Therefore, we should pay more attention to those fine particles with sizes of a few microns or less because they are more hazardous than larger ones (Sánchez-Soberón et al., 2015). In view of the close relationships between the optical extinction and fine particles $< 1.0\,\mu m$, optical extinction can be regarded as the indictor of $PM_{1.0}$ mass concentrations.

Beijing is regarded as the political, economic and cultural center of China, but the city is facing the challenge of the deterioration of visibility due to the growing intensity of human activities (Chang et al., 2009; Zhao et al., 2011). To maintain the good impression of the city in people's mind, the government has adopted a series of control measures, including adjusting industrial structure, using clean energy, limiting the number of private cars and establishing the joint prevention and control work with neighboring provinces (Hu et al., 2013; Liang et al., 2018; Pope et al., 2017; Zhang et al., 2010). However, the effect was not obvious. The most mentioned event is the record that in January 2013, the atmospheric visibility of Beijing was extremely low and the $PM_{2.5}$ concentrations reached up to $996\,\mu g/m^3$ (Li et al., 2017; Uno et al., 2014; Zheng et al., 2015). So it appears that meteorological conditions may be another critical factor that contributes to such serious pollution, besides the impact of human activities. Hence, both anthropogenic and meteorological factors are responsible for the impairment of visibility in Beijing. However, it is unclear how much the visibility reduction is caused by human activities and how much is caused by climate change.

In summary, optical extinction of aerosols is well associated with the mass concentrations of fine particles $< 1.0\,\mu m$. Over the past decades, the increase of submicron particles mass concentrations in Beijing has contributed to the visibility reduction. We should attribute the pollution of submicron particles to the combined effects of human activities and climate change, rather than single factor. However, we cannot directly analyze the submicron particles pollution, because the long-term observational data for $PM_{1.0}$ is unavailable. In this study, we considered the optical extinction measurement as the indicator of submicron particles to estimate its inter-annual variability and driving factors from 1980 to 2015. While quantifying the relative roles of human activities and climate change, we used the linear regression model to separate their individual effects on optical extinction. The aim of this paper is to figure out how human activities and climate change influence the changing trend of submicron particles pollution through the optical extinction data.

2. Methodology and materials

2.1. Study region

Beijing (39°54′N, 116°25′E), the capital of the People's Republic of China, is located in the North China Plain. The city is influenced by a sub-humid warm temperate continental monsoon climate, and experiences a hot and humid summer, and a cold and dry winter. In recent decades, Beijing has witnessed tremendous changes due to the rapid economic development and urban sprawl under the reform and opening-up policy (W. Chen et al., 2016; Wang et al., 2007; Y. J. Zhang et al., 2015). Nevertheless, the achievements on economic development was at the cost of negative environmental consequences. Chang et al. (2009) illustrated a downward trend of visibility from 1973 to 2007, using the visibility data in Beijing from National Climate Data Center. The government had adopted a series of measures to reduce the emissions of air pollutants and improve air quality (Hu et al., 2013; Zhang et al., 2010), but the effect was unsatisfactory. In recent years, Beijing has experienced the extremely severe and persistent haze pollution in autumn and winter (Wang et al., 2016; Yang et al., 2015). These results indicated visibility reduction in Beijing is governed by anthropogenic and meteorological factors.

2.2. Data sources and preparation

Daily atmospheric visibility and meteorological data, including wind speed (WS), temperature (TEM), air pressure (PRES), and indicators for the occurrence during the day of fog, rain, snow and tornado were obtained from Global Summary of the Day from the National Climate Data Center of the U.S. Department of Commerce (available at: https://www.ncdc.noaa.gov/). Visibility in the daytime is measured using a barely distinguished black object silhouetted against the horizontal skyline. Additionally, relative humidity (RH) data were obtained from the China National Meteorological Information Center (available at: http://www.cma.gov.cn/). Both visibility and other meteorological data have been recorded in Beijing airport from 1980 to 2015. Daily data were obtained by mathematically averaging a minimum of four synoptic observations per day. Our results were based on annual averaged data, which were calculated from the daily meteorological observations.

To investigate the impact of climate change on atmospheric visibility, the observed days under the extreme meteorological conditions, such as rain and fog resulted in very low visibility, were eliminated (Chang et al., 2009; Gao et al., 2011). Furthermore, visibility data with relative humidity above 90% were also screened out because high humid environment contributed to hygroscopic particle increasing by five or more times in the scattering cross section (Malm and Day, 2001).

Human activities data including the gross domestic product (GDP), vehicle holdings (VH), total population (TP) and energy consumption (EC) were collected from Beijing Municipal Bureau of Statistics (available at: http://www.bjstats.gov.cn/). Further correlation with aerosol optical extinction would be analyzed to understand the influence of human activities in Beijing over the past 36 year of 1980–2015.

2.3. Statistical analysis

The presence of aerosols and hydrometeors in atmosphere is able to cause visibility impairment. Eliminating the influence of hydrometeors on visibility allows an estimation of the near-surface optical extinction coefficient of aerosols (Husar et al., 2000). In this paper, we used relative humidity to correct optical extinction for obtaining dry extinction coefficients, which can better reflect the concentration levels of fine aerosols (those $< 1.0\,\mu m$) (Deng et al., 2012). The *RH* corrected extinction coefficient, which is called dry extinction coefficient, was estimated by the following formula (Eq. (1)) (Husar and Holloway, 1984):