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Regionalization based on spatial and seasonal variation in ground-level ozone concentrations across China☆

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ABSTRACT

Owing to the vast territory of China and strong regional characteristic of ozone pollution, it's desirable for policy makers to have a targeted and prioritized regulation and ozone pollution control strategy in China based on scientific evidences. It's important to assess its current pollution status as well as spatial and temporal variation patterns across China. Recent advances of national monitoring networks provide an opportunity to insight the actions of ozone pollution. Here, we present rotated empirical orthogonal function (REOF) analysis that was used on studying the spatiotemporal characteristics of daily ozone concentrations. Based on results of REOF analysis in pollution seasons for 3 years' observations, twelve regions with clear patterns were identified in China. The patterns of temporal variation of ozone in each region were separated well and different from each other, reflecting local meteorological, photochemical or pollution features. A rising trend in annual averaged Eight-hour Average Ozone Concentrations (O_3-8 hr) from 2014 to 2016 was observed for all regions, except for the Tibetan Plateau. The mean values of annual and 90 percentile concentrations for all 338 cities were 82.6 ± 14.6 and 133.9 ± 25.8 μg/m^3, respectively, in 2015. The regionalization results of ozone were found to be influenced greatly by terrain features, indicating significant terrain and landform effects on ozone spatial correlations. Among 12 regions, North China Plain, Huanghuai Plain, Central Yangtze River Plain, Pearl River Delta and Sichuan Basin were realized as priority regions for mitigation strategies, due to their higher ozone concentrations and dense population.

Introduction

Increased ground-level ozone concentrations are the cause of major environmental concern. Ground-level ozone has been considered the most phytotoxic air pollutant due to its significant damage to the plants and rising trend of concentrations at regional scale (The Royal Society, 2008). Urbanization, industrialization, high-speed propulsion, and atmospheric emissions of a large numbers of active substances, are causing many parts of China to face severe ozone concentrations in summer and autumn, linked to photochemical reactions (Tang et al., 2006; Zhang et al., 1998; Shao et al., 2006; Streets et al., 2007). Such

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problems have become regional and more complex over time (Zhang et al., 1998), with severe episodes occurring more frequently. In some cities, ozone has levels higher than the national standard around 20% of the time; while in other areas, ozone maximum hourly concentrations exceed the European alarm level (240 ppb) for heavy pollution (Chen et al., 2013; Yang et al., 2012; Huang et al., 2011, 2013; Zhang et al., 2004, 2009). The ground-level ozone associated with some other pollutants, which can induce severe diseases. In animal and human studies, repeated exposures in ozone have been shown to lead to airway inflammation and affect lung function (Aris et al., 1993; Coleridge et al., 1993). Published studies have indicated that air ozone concentrations in an average of 40 ppb have significantly reduced the yield of major food crops (including wheat, rice, soybean, potato) by about 10% compared with ozone-free air (Feng and Kobayashi, 2009). It can be deduced that human health and food security are being or has already been threatened by ozone concentration and the damage will continue in the future.

China is the third largest country in the world with a land area of 9.6 million square kilometers and a north–south cross-latitude of nearly 50°. The meteorological condition is complex and varied, and the terrain is high in the west and low in the east. Therefore, the impacting factors on ozone generating, such as radiation or humidity, were very different across the country. Since 1999, the pollution status, temporal variation pattern, and health effects of ozone have been investigated in several metropolitans in China (Wang and Li, 2014; Wei and Zheng, 2006; Yin et al., 2015; Zhang et al., 2013; Su et al., 2011; Chen and Wang, 2015; Liang et al., 2014; Y.Y. Chen et al., 2010; R.J. Chen et al., 2010). However, these studies are then limited to spatial range, and there is no information on the characteristics of the national ozone pollution distribution. Administrative measures implemented by the Ministry of Environmental Protection (MEP) to respond to ozone pollution were initiated in 2013. As a result, a real-time on line ground ozone observation system was established, that monitoring makes it possible to conduct a detailed studies on the spatiotemporal characteristics of ozone pollution in China for the first time. Given the significant regional contribution to local ozone pollution (Wang and Li, 1998), regional-scale pollution prevention measures should be adopted to effectively control air pollution by Chinese government. The MEP has identified several key prevention and control areas for ozone pollution, which are based on their level of economic development and pollution. They are Beijing–Tianjin–Hebei region, Yangtze River Delta, Pearl River Delta and Chengdu-Chongqing region. However, the spatiotemporal variability of ozone levels was not considered, when identifying these regions. Several studies (Zhang et al., 2012; Duan et al., 2008) have attempted to build air pollution divisions of China, based on the spatiotemporal characteristics of visibility or the air pollution index (API), by empirical orthogonal function (EOF) analysis. However, such studies have a limited scope, and have not dealt with the regionalization of datasets for one specific air pollutant, such as ozone in China.

The objectives of this work were to find the spatiotemporal characteristics of ozone pollution on a national scale, and help developing regionally prevention strategies. The method of rotated empirical orthogonal function (REOF), which has been widely used in meteorological science, was applied in this study. This method could decompose the time series of spatial variables into several orthogonal modes and corresponding time coefficients. The spatial distributions of modes reflect the spatial correlations between variables, which gives insights for regionalization of cities. The time coefficients of each mode represent the temporal variation pattern of ozone for those cities. The results of this study will improve the current understanding of the spatial distributions, seasonal trends, and regional situation of ozone within China. This helps policy makers to develop targeted prevention and control measures based on ozone pollution characteristics over different regions.

1. Methods

1.1. Datasets

Datasets include ozone monitoring data, topographic data and meteorological data. The ozone monitoring datasets were provided by the China National Environmental Monitoring Center (CNEMC). We used ozone daily maximum 8-hour sliding average (O_3-8 hr) concentration as ozone concentration to record from 161 cities in 2014, and 338 cities in 2015 and 2016, yielding more than 242,000 individual data points. Value of a city is average of the concentrations measured at all urban sites of this city. Ozone monitoring data was collected by continuous automated equipment, the measure principles were Ultraviolet photometer or Differential Optical Absorption Spectroscopy. All the equipment used had passed the applicability test of the CNEMC.

Topographic data were obtained from Global 30 Arc-Second Elevation dataset, which is supplied by United States Geological Survey. The spatial resolution for topographic data was 0.0833° × 0.0833° (1 km resolution).

Daily meteorological parameters records including temperature, relative humidity, wind speed, atmosphere pressure and Sunshine duration were from China Meteorological Agency.

1.2. Computational method

To explore the spatiotemporal variations in ozone across China, data from these 338 cities were geographically grouped into seven divisions, namely North China (Beijing, Tianjin, Shanxi, Hebei, Inner Mongolia), Northeast China (Heilongjiang, Jilin, Liaoning), Northwest China (Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang), East China (Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Shandong, Fujian), Central China (Henan, Hubei, Hunan), South China (Guangdong, Guangxi, Hainan), and Southwest China (Sichuan, Guizhou, Yunnan, Chongqing, Tibet). Regional ozone concentrations for each division were calculated as means of ozone concentrations for all cities located in that division.

To study the spatiotemporal variation of ozone, the REOF analysis was used to investigate any significant spatial correlations among different cities. This method has been successfully used for regionalization of precipitation and visibility in China (Zhang et al., 2012; Y.Y. Chen et al., 2010; R.J. Chen et al., 2010; Chen et al., 2011; Yang and Xu, 1994), but has seldom been used to undertake regionalization of O_3. By REOF analysis, several main orthogonal temporal variation