Science of the Total Environment 635 (2018) 576–585

Contents lists available at ScienceDirect

Science of the Total Environment

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

Air stagnation and its impact on air quality during winter in Sichuan and Chongqing, southwestern China

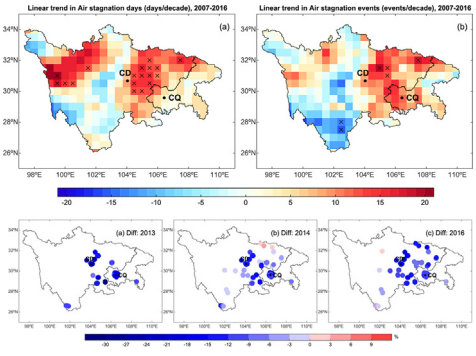
Tingting Liao [a], Ke Gui [b], Wanting Jiang [a], Shigong Wang [a], Bihan Wang [a], Zhaoliang Zeng [d], Huizheng Che [b], Yaqiang Wang [b], Yang Sun [c,*]

[a] Plateau Atmospheric and Environment Key Laboratory of Sichuan Province, College of Atmosphere Sciences, Chengdu University of Information Technology, Chengdu 610225, China
[b] Key Laboratory for Atmospheric Chemistry, Chinese Academy of Meteorological Sciences, CMA, Beijing 100081, China
[c] Huainan Academy of Atmospheric Sciences, Institute of Atmospheric Physics, Chinese Academy of Science, Beijing 100029, China
[d] Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan 430079, China

HIGHLIGHTS

- Air stagnation days occurred frequently in Sichuan-Chongqing region in winter.
- Air stagnation events impacts strongly on the air quality in Sichuan Basin.
- Frequency of air stagnation events in recent 10 years increased slightly.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 February 2018
Received in revised form 8 April 2018
Accepted 9 April 2018
Available online 24 April 2018

Editor: Jianmin Chen

Keywords:
Sichuan Basin
Air stagnation events
$PM_{2.5}$
Winter

ABSTRACT

The Sichuan and Chongqing regions suffer from severe haze weather in winter due to the unfavourable atmospheric diffusion conditions. Reanalysis and precipitation datasets were applied in this study to calculate and distinguish air stagnation events using a developed criterion, and the impacts of the occurrence of air stagnation events on air quality were analysed in combination with the $PM_{2.5}$ concentration data for the winters of 2013–2016. The highest occurrence frequency of air stagnation events was observed in 2013, and the lowest, 2015. The meteorological conditions during winter in the Sichuan Basin were inclined to form unfavourable atmospheric diffusion conditions, and the occurrence frequency of air stagnation days was up to 76.6% on average during the four winters. The effects of air stagnation events on air quality were most obvious in the western and southern Sichuan Basin. The mean concentrations of $PM_{2.5}$ during air stagnation days were higher by 41.9% than those during non-air stagnation days. The $PM_{2.5}$ concentrations were adjusted using the favourable atmospheric diffusion conditions in 2015 as a baseline to quantify the $PM_{2.5}$ contribution to the improvement of air quality in the other years, which revealed that the level of $PM_{2.5}$ in the Sichuan and Chongqing regions was declining at a rate of approximately 10.7% overall during the winters of 2013–2016, implying that the air pollutant reduction measures have been highly effective. Furthermore, the occurrence frequency of air stagnation days and events were increased in recent ten years of 2007–2016, with linear slopes of 0.61 yr^{-1} and 0.26 yr^{-1}, respectively. The study revealed that the government might face a greater challenge in improving the air quality over winter and should pay more attention to reduction of pollutant emission in areas of Chengdu, Chongqing and cities in the south of the Sichuan Basin.

* Corresponding author.
E-mail address: suny@mail.iap.ac.cn. (Y. Sun).

https://doi.org/10.1016/j.scitotenv.2018.04.122
0048-9697/

1. Introduction

With the rapid development of industrialization and urbanization in recent decades, severe urban air pollution has become a major environmental and social problem in China due to the increased emission of pollutants, arousing considerable attention (Chan and Yao, 2008; Che et al., 2014, 2009; Huang et al., 2014; Zhang et al., 2012a, 2012b; Fang et al., 2009). A high loading of $PM_{2.5}$ (fine particles with a diameter <2.5 μm) concentration not only contributes to sharp visibility degradation by directly scattering and absorbing solar radiation (Charlson et al., 1992; Li et al., 2016a) but also has an adverse effect on economic activities by causing ground, sea and air traffic hazards and disruptions (Sheehan et al., 2014; Zhang and Cao, 2015; Zhang et al., 2014; Cai et al., 2017). In addition, numerous studies have shown that these fine particles ($PM_{2.5}$) contain substantial toxic substances that can induce serious health effects on respiratory, cardiovascular and nervous systems (Pope et al., 2002; Künzli et al., 2005; Bai et al., 2007; Cohen et al., 2017). It is worth noting that ambient $PM_{2.5}$ exposure led to approximately 1.1 million deaths in 2015 in China, according to the Global Burden of Diseases Study 2015 (GBD 2015) (Cohen et al., 2017)

Presently, numerous studies have been carried out to reveal the formation mechanisms of haze and its long-term trends for three key atmospheric pollution regions in China: the Beijing-Tianjin-Hebei (BTH), the Pearl River Delta (PRD), and the Yangtze River Delta (YRD) (Mu and Zhang, 2014; Wang and Chen, 2016; Chen and Wang, 2015; Zhang et al., 2014; Gao et al., 2011; Che et al., 2014; Sun et al., 2017; Gui et al., 2016). These studies determined that high pollutant emissions and unfavourable and stagnant weather conditions are two key factors in causing frequent severe winter haze events in China. Secondary aerosol formation by atmospheric chemical reactions also contributes to severe haze events (Huang et al., 2014). Further, the formation of severe winter haze events in northern China has been closely linked with climate change, including decreased relative humidity (Ding and Liu, 2014), reduced East Asian winter monsoons (Li et al., 2016b), and declined Arctic sea ice (Wang et al., 2015; Zou et al., 2017). However, little research has been reported regarding the formation and persistence of haze in southwestern China, including the Sichuan-Chongqing region. Sichuan-Chongqing is considered to be one of the four regions with the most severely polluted air in China (Zhang et al., 2012a, 2012b; Wang et al., 2013a; Ning et al., 2017). In the winter of 2013, multiple continuous severe haze events occurred in Chengdu, and the maximum daily $PM_{2.5}$ average near Chengdu reached 427 μg m^{-3}, as observed by Liao et al. (2017). As a result of the complex topographic and unfavourable local meteorological conditions (i.e., low wind speed, low precipitation, high relatively humidity and strong temperature inversion), the formation mechanisms of continuous heavy pollution weather in the Sichuan-Chongqing region during winter is completely different from that in other regions in China (Tao et al., 2014; Liao et al., 2017).

The total emissions of nitrogen oxides in the Sichuan-Chongqing region reached 0.99×10^6, 0.94×10^6, 0.85×10^6, and 0.67×10^6 tons in 2013, 2014, 2015, and 2016, respectively; 1.36×10^6, 1.32×10^6, 1.21×10^6, and 0.78×10^6 tons of sulfur dioxide, respectively; and 0.49×10^6, 0.65×10^6, 0.62×10^6 and 0.37×10^6 tons of soot or dust, respectively, according to the website of the National Bureau of Statistics of China (http://data.stats.gov.cn/). Although the total emissions in the Sichuan-Chongqing region have shown a significant declining trend, the observation of the ground $PM_{2.5}$ concentration has not shown a corresponding decline during the most recent winter, which might have been related to different atmospheric diffusion conditions during different periods. It is generally known that the meteorological background can affect the accumulation, dispersion and transport of air pollutants over brief time periods (Wang et al., 2016; Huang et al., 2017). Some favourable meteorological conditions are beneficial to the improvement of air quality. Recently, a study demonstrated that Sichuan basin experienced frequent air stagnation conditions approximately half of the whole year (>47% in winter) (Wang et al., 2018). However, there have been fewer studies on the impact of atmospheric diffusion conditions with a focus on recent years over the Sichuan-Chongqing region. Understanding how meteorological conditions affect the formation and diffusion of haze weather in recent years is very important for the development and improvement of additional policy controls in the future. Accordingly, our aim in the current study is to explore the distributions of the winter $PM_{2.5}$ concentration level and its relationship with meteorological conditions in the Sichuan-Chongqing region during 2013–2016 and to quantitatively evaluate the improvement of air quality that can be attributed to the change in atmospheric diffusion conditions and the trends in winter air stagnation days or events from 2007 to 2016 based on a newly defined air stagnation method (Wang et al., 2018).

2. Materials and methods

2.1. Study area

The Sichuan-Chongqing region is located in southwestern China, covering Sichuan Province and the Chongqing Municipality. There are 22 cities in the region, including the 2 megacities of Chengdu and Chongqing, which are the regional centers of southwestern China, the 17 prefecture-level cities of Mianyang (MY), Deyang (DY), Leshan (LS), Yaan (YA), Meishan (MS), Ziyang (ZY), Luzhou (LZ), Yibin (YB), Zigong (ZG), Neijiang (NJ), Nanchong (NC), Bazhong (BZ), Suining (SN), Guangyuan (GY), Guangan (GA), Dazhou (DZ), and Panzhihua (PZH), and the 3 autonomous prefectures of Aba Zhou (ABZ), Ganzi Zhou (GZZ) and Liangshan Zhou (LSZ). Sichuan-Chongqing is recognized as one of the regions with the most complex terrain in the world, and it could be divided into three parts, as the Sichuan Basin (SB), Western Sichuan Plateau (WSP) and Panxi Plateau (PXP), due to the large difference in terrain (Fig. 1). The average altitude of the SB is only 500 m, with a high population density and fairly developed economy. The terrain rises abruptly to the west of the SB with an altitude over 4000 m as one part of the Tibetan Plateau, named the WSP. The PXP is one part of the Yungui Plateau with an altitude between 1500 and 2000 m. The climate characteristics are fairly different from each other due to the different terrain and altitude characteristics.

High level of $PM_{2.5}$ has aroused unprecedented public concern in the Sichuan-Chongqing region, and the government has enacted many policies of emission reduction with an enormous financial input and at a large economic cost. However, the air quality is greatly affected by both pollutant emissions and meteorological conditions in this region (Zhang et al., 2014; Tao et al., 2015; Chen and Wang, 2015); thus, it is not scientific enough to determine whether the emission reduction measurements are effective by evaluating only the pollutant concentrations. Instead, we should consider atmospheric diffusion conditions to quantify the improvement of air quality in the study area.

2.2. Data

The $PM_{2.5}$ mass concentration data from 113 monitoring stations (95 stations in Sichuan Province and 18 stations in Chongqing city) between December 2013 and February 2017 have been continuously collected by the Chinese Ministry of Environmental Protection (CMEP, http://113.108.142.147:20035/emcpublish/). The 113 stations cover all of the contiguous Sichuan and Chongqing regions well. These data enable us to study the changes in the characteristics of $PM_{2.5}$ for different regions and the linkage between the air pollution level and weather conditions. Because the observation network is developing and improving constantly, the duration of available data is different for each station during different periods. Thus, subsets of a total of 57, 104, 104 and 98 stations were selected for 2013, 2014, 2015 and 2016, respectively. Furthermore, these 113 monitoring sites were divided into 22 cities (Table 1) in terms of their geographical characteristics (see Fig. 1) to compare air-quality