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Brief Communication

China's Complex Urban Air Pollution: An Improved Understanding with Ground Operational Measurements

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ABSTRACT

Complex urban air quality has long been assessed by a single (or major) contaminant, for example, fine particulate matter (PM2.5), but scant attention has been given to multicontaminant air pollution, especially in countries with severe air pollution, for example, China. We thus proposed an improved method for quantifying both single- and multicontaminant air pollution. Our approach uses China's major cities as an example because they have an operational national urban air quality monitoring network. We found that our proposed method could remove the duplicated consideration under both single- and multicontaminant conditions, thus proving to be an improved and more accurate way to understand complex urban air pollution conditions. Our method involved monitoring 3 contaminants (PM2.5, PM10, and SO_2) in cities in Shanxi, Shandong, Henan, and Hebei Provinces and 2 contaminants (PM2.5 and PM10) in the cities between the Yellow River and the Yangtze River, and these pollutants were the major contributors to multicontaminant air pollution. We argue that both the research community and the government should pay increased attention to multicontaminant air pollution beyond the current single major pollutant–based air pollution method when building a sustainable city. *Integr Environ Assess Manag* 2020;16:306–313. © 2020 SETAC

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INTRODUCTION

Urban air pollution has changed over time because air contaminants are closely correlated with changing technologies. Air pollution cannot be fully contained until nonpolluting resources and energy sources are widely or completely used in cities and nearby regions (Fenger 2009). However, to date, this has been very hard to achieve in human history. Air pollutants have been gradually recognized with the development of modern technology since the nineteenth century (Brimblecombe 1987; Han 2018).

Modern technology since the first industrial revolution in the 1840s has clearly shown changes in pollutants from sulfur dioxide (SO_2) and total suspended particles (TSPs) to nitrogen oxide (NO_x) and particulate matter (PM_x). The first industrial revolution caused a drastic increase in the consumption of coal and led to the emissions of large amounts of sulfur dioxide (SO_2) and TSPs (e.g., Stradling and Thorsheim 1999). The second great change was during the petroleum age beginning in the 1900s, when gasoline consumption and combustion engines released new pollutants, such as NO_x (e.g., McNeill 2001). Rapid economic development after World Wars I and II led to new air pollution problems, as countries in Europe, North America, and Asia increased fossil fuel burning and chemical industry growth (e.g., Fenger 2009). The SO_2, NO_2, TSPs, PM_x, and emissions increased during this period, including some notable atmospheric environmental pollution incidents, for example, London (United Kingdom) smog, Los Angeles (California) chemical fog, and Beijing (China) haze. These events prompted the public and the government to realize the negative public health and environmental impacts of urban air pollution (Gong et al. 2012; Huang 2014).

Although high-income countries have a long history of trade-offs between development and air pollution, that history can be clearly classified into key periods during which certain pollutants were emitted. In contrast, in mid- and low-income countries, for example, most Asian and African countries, many pollutants have been emitted on a relatively short time scale due to rapid development (Gong et al. 2012; Bai et al. 2014; Han, Zhou, Li et al. 2018). This caused the emissions of many different pollutants at the same time. China is a typical country where coal-fired industries and automobile usage have increased simultaneously (Han et al. 2014; Han 2018; Ouyang et al. 2019).

In the past decade, much attention has been given to PM2.5 pollution, and very limited previous work has examined China's multicontaminant air pollution, due to a lack of both accurate methods and time scales (Han, Zhou,

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Pickett et al. 2018). Due to this very limited and initial understanding, the objectives of the present research were to build an improved method for quantifying multicontaminant air pollution based on the World Health Organization's Air Quality Guideline (WHO 2005) and to apply the improved method in China from 2014 to 2017. We hope this method will advance the scientific understanding of multicontaminant air pollution and increase the awareness of the general public.

MATERIALS AND METHODS

Air pollutant records

Daily air quality records for 190 cities in 2014 and 366 cities during 2015 to 2017 from China's national urban air quality monitoring network under the ambient air quality standard of GB3095-2012 (MEE 2016) were adapted in the present work. The air quality records, available at China's National Urban Air Quality Real-time Publishing Platform (http://106.37.208.233:20035/), include pollutants of fine particulate matter with diameters not more than 2.5 μm (PM2.5) and diameters between 2.5 and 10 μm (PM10), including SO_2, NO_2, ozone (O_3), and carbon monoxide (CO). In the present work, daily PM2.5, PM10, SO_2, NO_2, and O_3 records were used because no daily CO standard was provided in WHO's AQG.

Quantification of single- and multicontaminant urban air pollution

The daily limit of WHO's AQG was used in the present work for each contaminant (Table 1). When all 5 contaminants exceed the limits, the day will be set as a day with 5-contaminant air pollution. Similarly, when 4, 3, 2, or single contaminants exceed their limits, the day will be recognized as a day with 4-, 3-, 2-, or single-contaminant air pollution, respectively. Different from our previous work (Han, Zhou, Pickett et al. 2018), the multicontaminant conditions were not considered twice in this approach. For instance, once a day was recognized as a day with 5-contaminant air pollution, and it was not further considered as a day with 4-, 3-, 2-, and/or single-contaminant air pollution. Thus, each day in a year was recognized as a day with unique single or multicontaminant air pollution.

Table 1. Daily limits of WHO's AQG for ambient air quality

Contaminant	Daily limit μg/m^3	Mean
PM2.5	25	24 h
PM10	50	24 h
NO_2	200	1 h
SO_2	20	24 h
O_3	100	8 h

AQG = air quality guideline; PM = particulate matter; WHO = World Health Organization.

Changes in single- and multicontaminant urban air pollution

Although only 4 y of urban air quality records were available, the changes among the years are an important output, given China's intense urban air pollution prevention activities. Because only 190 city records were available in 2014, the change analysis was conducted for all 366 cities during 2015 to 2017. The 5 types of changes were defined from the variations in percent of days in a year between 2015 and 2016 and between 2016 and 2017: 0 means no change, 1 means increases occurred both between 2015 and 2016 and between 2016 and 2017, 2 means decreases occurred both between 2015 and 2016 and between 2016 and 2017, 3 means increases occurred between 2015 and 2016 but decreases occurred between 2016 and 2017, and 4 means decreases occurred between 2015 and 2016 but increases occurred between 2016 and 2017.

RESULTS

Three contaminants, which were mainly found in cities in Shanxi, Shandong, Henan, and Hebei Provinces, and 2 contaminants, which were mainly found in cities between the Yellow River and the Yangtze River, were the major contributors to the multicontaminant urban air pollution in China. The 3 major contaminants were PM2.5, PM10, and SO_2, and PM2.5 and PM10 were the 2 major contaminants in urban air pollution. The detailed results follow.

Single- and multicontaminant air pollution in China

Single-contaminant air pollution occurred on less than 25% of the days in a year with an increasing trend; however, multicontaminant air pollution occurred on more than 75% of the days in a year with a decreasing trend during 2014 to 2017 (Figure 1A). Generally, 3 contaminants occurred on 28% to 54% of the days in a year, and 2 contaminants occurred on 24% to 32% of the days in a year, representing major portions of a year from 2014 to 2017. Four-contaminant air pollution occurred on only 2% to 5% of the days in a year, whereas 5-contaminant air pollution occurred on 1% of the days in a year during 2014 to 2017. The number of multicontaminant air pollution detections in a year mainly decreased, except for 2-contaminant air pollution from 2014 to 2017. In contrast, the percentage of days with single contaminants and no air pollution exceeding the WHO's AQG increased from 8% to 13% and from 10% to 25%, respectively.

The primary 4-contaminant combination was PM2.5, PM10, SO_2, and O_3, which was found to impact 5% of the days in 2014 but 2% of days in 2017 (Figure 1B). The primary 3-contaminant combination was PM2.5, PM10, and SO_2, which affected 51% of the days in 2014 but 21% of the days in 2017 (Figure 1C). In contrast to the 4- and 3-contaminant air pollution, the 2-contaminant pollution primarily contained PM2.5 and PM10 with an increased occurrence from 20% of the days in 2014 to 29% of the days in 2017 in the major Chinese cities (Figure 1D). Single-contaminant air pollution consisting of PM2.5 represented the majority of the pollution. Although O_3 and PM10 were found to have an

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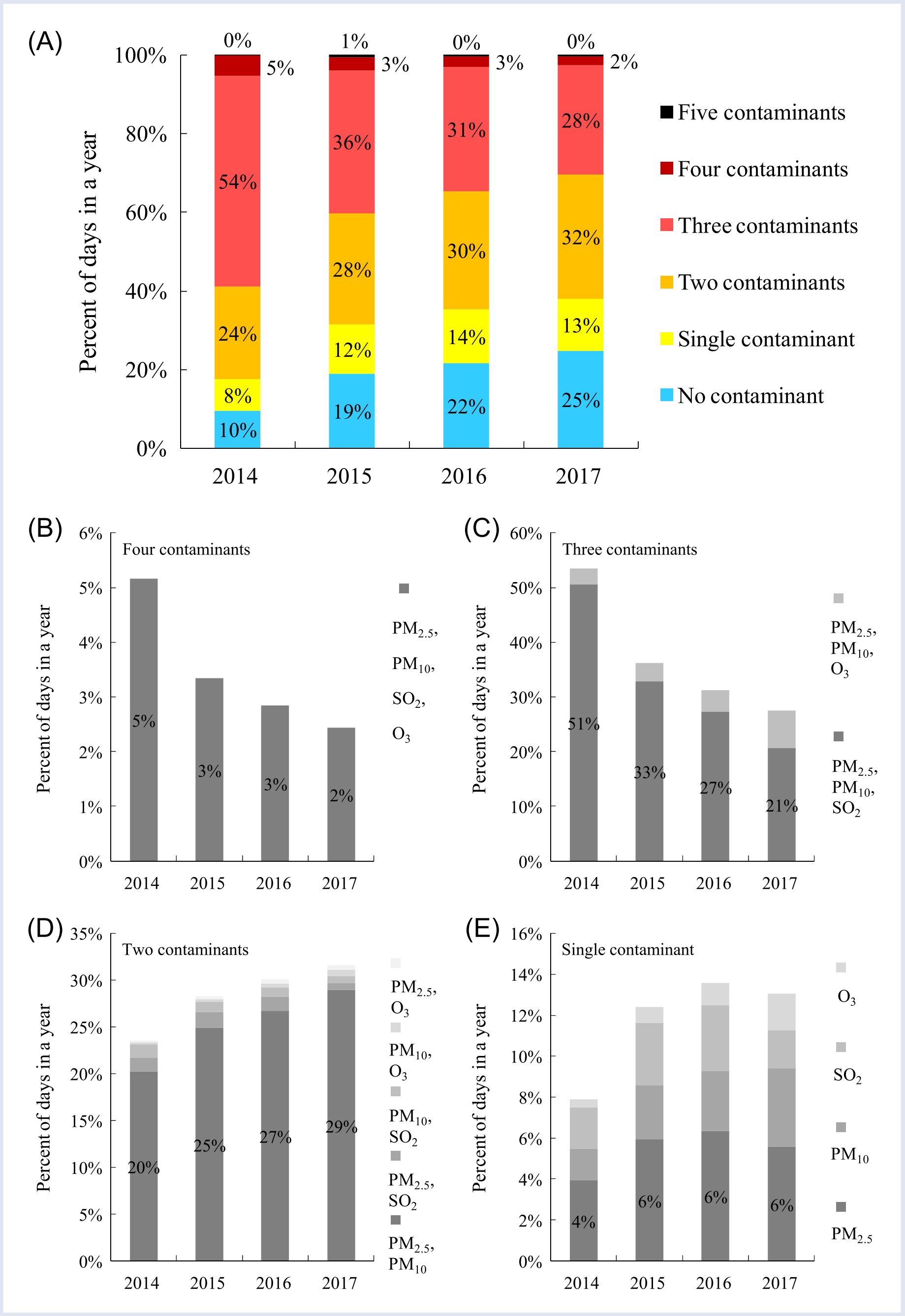

Figure 1. A general view of China's major cities' complex air pollution in a year. Note: 190 cities were analyzed in 2014, and 366 cities were analyzed in 2015, 2016, and 2017. PM = particulate matter.

increasing trend, SO_2 and PM2.5 were found to have an increasing and then decreasing trend (Figure 1E).

During 2015 to 2017, most of the cities were affected by air pollution, mainly multicontaminant air pollution; however, single-contaminant air pollution generally occurred less than 20% of the days per year in most cities (Figure 2). Cities with more than 80% of the days per year with urban air pollution or urban multicontaminant air pollution occurring were mostly found to the north of the Yangtze River, whereas the cities to the south of the Yangtze River had relatively fewer pollution days, especially multicontaminant pollution days (Figures 2A to C). A total of 173 of 366 cities showed a decrease in the number of days with air pollution, and 78 and 87 cities were found to have an increase-and-decrease and decrease and increase in the number of days with air pollution, respectively. Only 25 cities were found to have an increased number of days with air pollution; these cities were mainly found in Shanxi and Hebei Provinces (Figure 2D). Such a change in the total days affected by pollution was highly attributed to the changes in the days with multicontaminant air pollution because these days had similar change patterns (Figure 2E). A total of 86 cities were

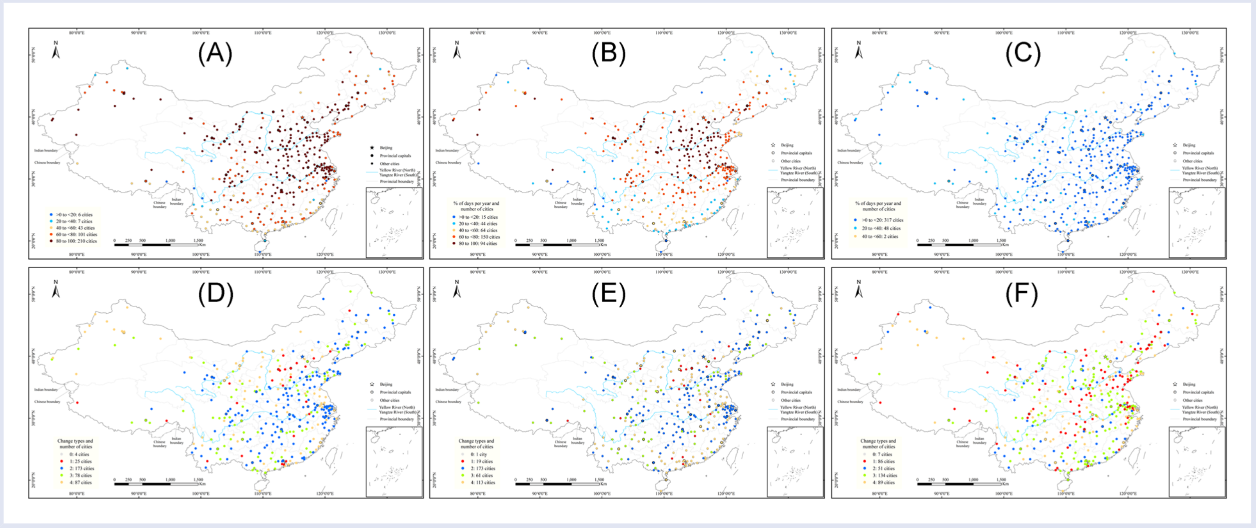

Figure 2. Spatial pattern of urban multicontaminant and/or single-contaminant air pollution in China: Percent of days per year and numbers of cities with single- and multicontaminant air pollution (**A**), multicontaminant air pollution (**B**), and single-contaminant air pollution (**C**); change types and number of cities with single- and multicontaminant air pollution (**D**); multicontaminant air pollution (**E**); and single-contaminant air pollution (**F**).

found to have an increasing number of days in a year with single-contaminant air pollution. These cities were highly concentrated in Shandong Province (Figure 2F).

Mean pattern and changes in each type of multicontaminant air pollution

Five-contaminant air pollution occurred in 280 cities, with less than 20% of the days per year being affected. These cities were mainly along the east coast and were less frequent in the central and western regions of China (Figure 3A). Of these 280 cities, only 14 cities showed a decrease in the number of days with pollution, and 3 cities had an increase–decrease in the number of days with pollution from 2015 to 2017 (Figure 3B).

Only 1 city, Dongying in Shandong Province, had 4-contaminant air pollution (PM2.5, PM10, SO_2, and O_3) occur on 20% to 40% of the days per year; thus, 307 cities had 4-contaminant air pollution (PM2.5, PM10, SO_2, and O_3) occur on less than 20% of the days per year (Figure 4A). Only 25 cities had an increase in the days per year with 4-contaminant air pollution (PM2.5, PM10, SO_2, and O_3), but 99 cities had a decrease in the days per year with 4-contaminant air pollution (PM2.5, PM10, SO_2, and O_3) (Figure 4B).

Only 1 city, Hetian, in the Xinjiang Uygur Autonomous Region, was found to have more than 80% of the days per year with 3-contaminant air pollution; no other city was observed to have more than 80% of the days per year affected by 3-contaminant pollution of PM2.5, PM10, and SO_2 (Figure 5A). Furthermore, cities with 60% to 80% and 40% to 60% of the days per year affected by 3-contaminant air pollution (PM2.5, PM10, and SO_2) were mainly observed in Shanxi, Shandong, Hebei, and Henan Provinces. A total of 239 cities had fewer than 40% of the days per year affected by 3-contaminant air pollution, and 268 cities were affected by the 3-contaminant pollution with PM2.5, PM10, and SO_2 (Figure 5B).

Most cities, 299 and 292 out of the 366 cities, were found to have less than 40% of the days per year with 2-contaminant air pollution and 2-contaminant PM2.5 and PM10 (Figure 6A,B). In addition, cities with more than 40%

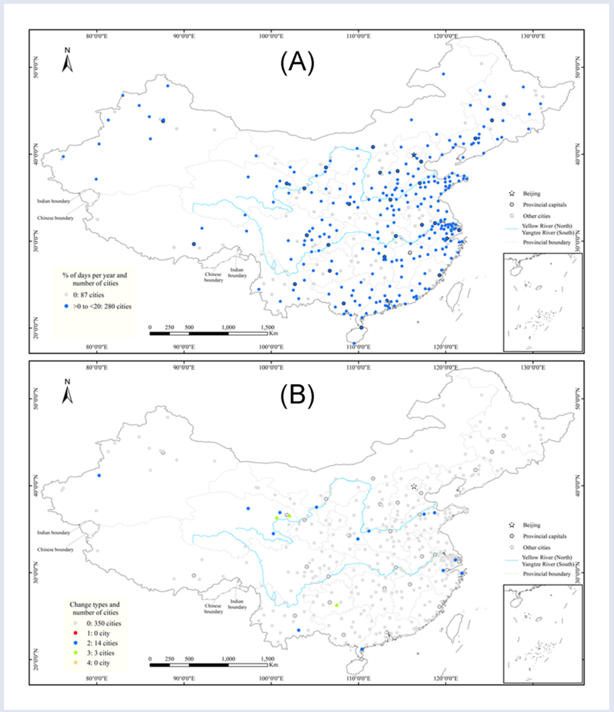

Figure 3. Spatial and temporal patterns in urban 5-contaminant air pollution in China: Percent of days per year and numbers of cities with 5-contaminant air pollution (**A**), and change types and number of cities with 5-contaminant air pollution (**B**).

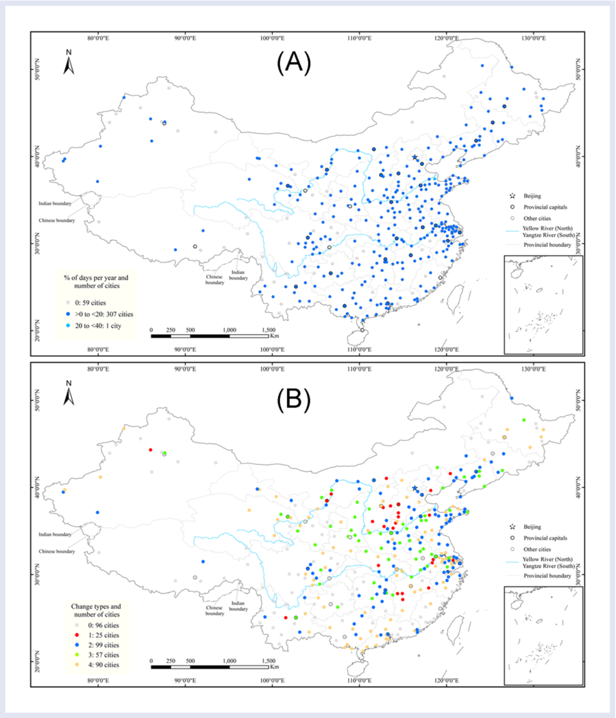

Figure 4. Spatial and temporal patterns in urban 4-contaminant air pollution in China: Percent of days per year and numbers of cities with all types of 4-contaminant air pollution and with the 4 contaminants PM2.5, PM10, SO_2, and O_3, which are the same as those shown in (**A**); change types and numbers of cities with all types of 4-contaminant air pollution and with the 4 contaminants PM2.5, PM10, SO_2, and O_3, which are the same as those shown in (**B**). PM = particulate matter.

of the days per year with 2-contaminant air pollution (PM2.5 and PM10) mainly occurred between the Yellow River and Yangtze River. Nearly one-third of the cities, 114 and 120 out of the 366 cities, had an increase in the days with 2-contaminant air pollution (PM2.5 and PM10) (Figure 6C,D). In addition, those cities were mainly located in the eastern region of China.

DISCUSSION

Determining multicontaminant urban air pollution is a new method of quantifying real urban air quality, given that previous research has mainly focused on the quantification of a single pollutant (Han, Zhou, Pickett et al. 2018). The former way to quantify multicontaminant air pollution was to use one of the major contaminants, for example, NO_2, SO_2, PM2.5, or PM10, which would drive the major potential impact to public health, or to consider overlapping pollution conditions; for instance, if a city was impacted by 4-contaminant air pollution, it would also have 3-, 2- and single-contaminant air pollution (e.g., Han, Zhou, Pickett et al. 2018). The major process for understanding urban air quality was to build a simple air quality index or air pollution index by considering some major contaminants at the same time or using only the maximum of a certain subindex. For example, the Canadian air quality health index considers a combination of 3 pollutants, O_3, NO_2, and PM2.5 (Abelsohn and Stieb 2011), whereas mainland China, India, the United Kingdom, and the United States utilize the maximum of certain pollutant subindexes (CPCB 2009; COMEPA 2011; MEPoC 2012; USEPA 2015). These methods provide a

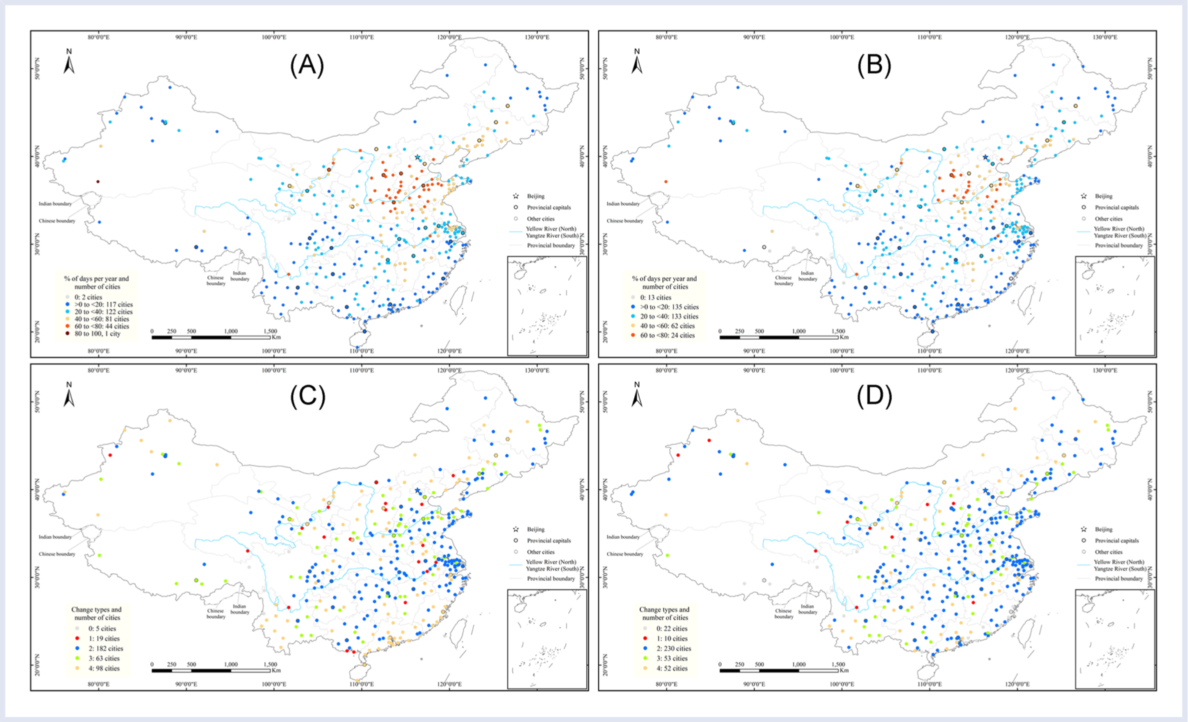

Figure 5. Spatial and temporal patterns in urban 3-contaminant air pollution in China: Percent of days per year and numbers of cities with all types of 3-contaminant air pollution (**A**) and with the 3 contaminants PM2.5, PM10, and SO_2 (**B**); change types and numbers of cities with all types of 3-contaminant air pollution (**C**) and with the 3 contaminant PM2.5, PM10, and SO_2 (**D**). PM = particulate matter.

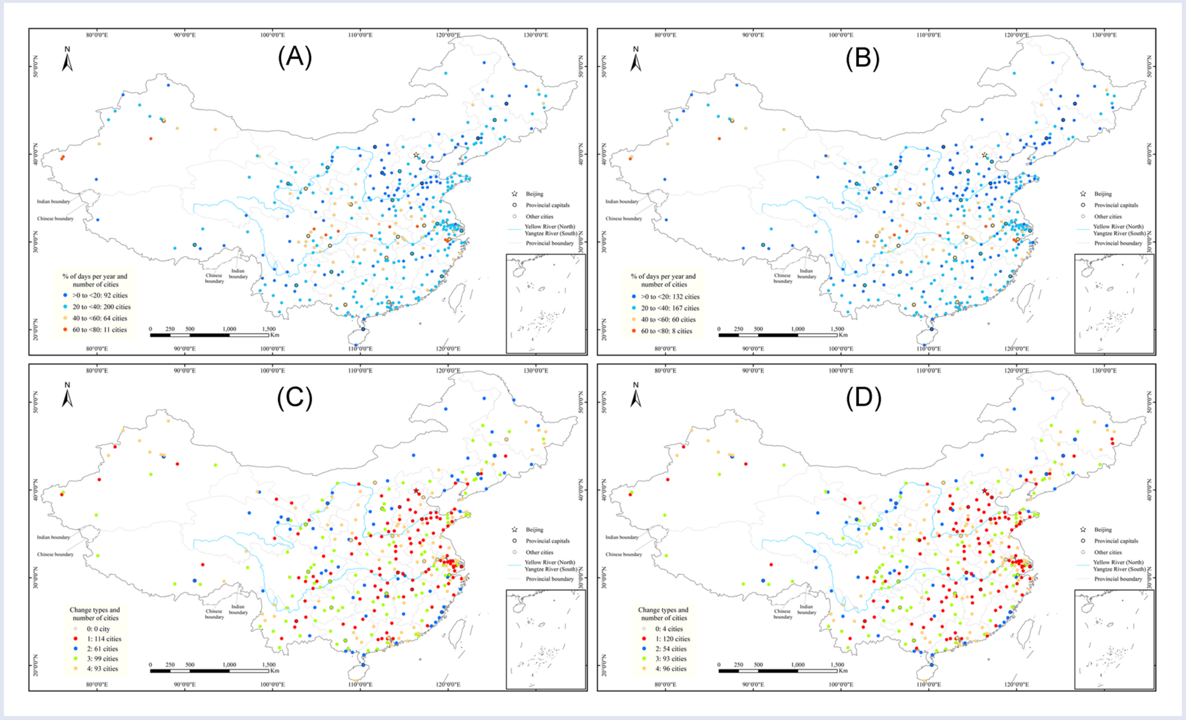

Figure 6. Spatial and temporal patterns in urban 2-contaminant air pollution in China: Percent of days per year and numbers of cities with 2-contaminant air pollution (**A**) and with the 2 contaminants PM2.5 and PM10 (**B**); change types and numbers of cities with 2-contaminant air pollution (**C**) and with the 2 contaminants PM2.5 and PM10 (**D**). PM = particulate matter.

general understanding of the major air pollution conditions, but these methods ignore the additional pollutants that may, together with the major air pollutants, result in enhanced public health threats. Today, most low- and mid-income countries follow already established operational urban air quality monitoring networks for tracking the dynamics of severe urban air pollution (Baldauf et al. 2001; Zhang et al. 2018). This is a particularly important practice in understanding air quality, and it is based on easing urban air pollution. By considering the rapid development that induces the overlap of pollution stages, the current conventional method would not encompass many complex conditions and potentially undermine the health impact. Therefore, we argue that by using our improved method to quantify the condition of multicontaminant air pollution, this additional information would provide a better understanding of complex urban air pollution.

The primary high-income countries such as the United States and countries in Europe have already experienced rapid urbanization or economic development overall and heavy air pollution periods. Other low- and mid-income countries such as India are still facing severe air pollution without substantial pollution prevention actions. Presently, China is paying close attention to combating urban and regional air pollution, whereas China was mainly concerned with Asian dust before 2010 (Yang et al. 2013; Fan et al. 2016) and then with PM2.5 (e.g., Huang 2014; Han et al. 2015; Peng et al. 2016). Asian dust was the major concern in China, especially in northern China; however, the dust was eased due to both climatic and ecological conservation in the first decade of this century (Kurosaki et al. 2011; Mao et al. 2011). Since 2008, and especially after 2012, the daily PM2.5 concentration at the US Embassy and Consulates in Beijing, China, greatly increased concern about urban air pollution by PM2.5 of both the public and authorities (Huang 2014). As many previous studies on PM2.5 pollution have indicated, China is one of the most typical areas to study the rapid efforts to address PM2.5 (Han, Zhou, Li 2018). Here, we suggest that researchers pay attention to the trade-off between rapid development, in terms of urbanization and industrialization, and air pollution, in terms of both single- and multicontaminant air pollution. Thus, a strategy can be developed to improve air quality by considering more than just a single major pollutant, for example, PM2.5 (Han, Zhou, Li, Qian et al. 2018). Such consideration would provide important examples, both negative and positive, to the other low- and mid-income countries that are experiencing rapid development. China's "Belt and Road" effort was well accepted by many low- and mid-income countries who prefer to follow China's way in terms of economic development and environmental conservation.

In terms of decreasing multicontaminant air pollution in major Chinese cities, the following concerns should be highlighted by both the research community and the authorities. First, zoning policies for urban and regional air pollution should consider both single- and multicontaminant pollution because this kind of regulation is not fully utilized in China. For example, a 3-contaminant critical zone is recognized in cities in Shanxi, Shandong, Henan, and Hebei Provinces, and a 2-contaminant critical zone is recognized in areas between the Yellow River and the Yangtze River. We also suggest that further work involve conducting an analysis between social economic factors and multicontaminant air pollution to explain the reason for this distribution. Second, carrying out research on potential health impact estimations for both single- and multicontaminant air pollution should be considered, especially the impact of those primary combinations of PM2.5, PM10, and SO_2, as well as other future potential combinations such as PM2.5, PM10, and O_3. Such considerations would go beyond current methods, and the combination of different pollutant concentrations would be important for further investigating examples of China's major cities. Third, further promotion of urban-friendly methods by considering and applying the concept of low-impact development to address air quality degradation should be implemented.

CONCLUSIONS

Complex urban air pollution has long been assessed by a major single contaminant, but scant attention has been given to multicontaminant pollution, especially in countries with severe air pollution, for example, China. We thus proposed an improved methodology for quantifying multicontaminant air pollution in major Chinese cities based on existing data from China's operational urban air quality monitoring network. The conclusions follow.

The proposed improved method for determining days with single- or multicontaminant air pollution was based on WHO's AQG. The method removes the duplicated consideration of single- or multicontaminant conditions, thus providing an improved and accurate way of understanding daily urban air pollution conditions. By applying the method, 3-contaminant air pollution, mainly in cities in Shanxi, Shandong, Henan, and Hebei Provinces, and 2-contaminant air pollution, mainly in cities between the Yellow River and the Yangtze River, were the major combinations of multicontaminant urban air pollution in China. Additionally, PM2.5, PM10, and SO_2 were the 3 contaminants, and PM2.5 and PM10 were the 2 major contaminants of urban air pollution.

In conclusion, we argue that the research community could conduct complex multicontaminant air pollution research and that the government should pay attention to multicontaminant air pollution beyond the current single major pollutant–based air pollution when building a sustainable city.

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Data Availability Statement—Data can be obtained by request to author Lijian Han (ljhan@rcees.ac.cn).

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