

Mapping of Ambient Ozone Pollution in China and the Assessment of Its Health Impact on Socio-Economy

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Abstract

China recently established an hourly updating air quality monitoring network covering over 1400 sites, and put strict control over several regions under heavy air pollution. In recent years, ground-level ozone pollution has become more and more severe, especially during summer time. This research takes the advantage of abundant ozone datasets collected from China Environmental Monitoring Center and plots ozone distribution maps at a 10 km resolution. Spatial and temporal features of ozone distribution and its impact on the public health are examined from 2014 to 2017. Results show that ozone pollution has obvious seasonal changes in its distribution across China. Ozone pollution occurs most frequently from April to September in a year. Comparing June data in 2014, 2015, and 2016, the national ozone related death toll within the month fluctuates, with the lowest number happening in 2015 and the highest in 2016. The estimated death toll in 2015 was 12 773.4 and 15 455.7 in 2016 respectively. The health burden has also exhibited a distinctive regional feature. High attributable premature mortality concentrates in regions where high population density exists. Beijing, Tianjin, Shandong, Jiangsu, Shanghai, Guangdong are among the most polluted areas. Increasing trends are witnessed across the nation. In addition, there are newly developed high ozone concentration centers in the inner part of mainland China. While researches and air pollution policies in recent years focus on dealing with PM pollution in China, we urge the environmental scientists pay more attention to the yearly increasing concentration of ozone pollution and the potential risks that might be brought about in China.

1. Introduction

In recent summers, ground-level ozone has become the primary air pollutant in many major cities in China. Researchers found that short-term exposure to ground-level ozone could lead to a series of hazardous health effects, including increased mortality, increased rates of respiratory hospital admissions, lung inflammation and asthma¹⁻⁴. Compared with the regulation procedure for particulate matter pm2.5 and pm10, it is much more difficult to control ozone pollution, due to its complex approaches of generation and relatively short life cycle.

China is experiencing severe and complex ambient air pollution as a result of industrialization. It ranks as one of the most polluted countries in the world⁵. The Global Burden of Disease (GBD) reported that outdoor air pollution in China caused 1.2 million premature deaths and 25 million disability adjusted life years (DALY) losses in 2010⁶. Air quality management is an issue that requires our immediate attention.

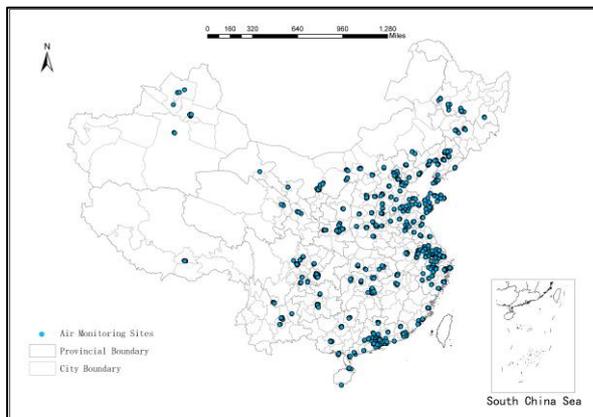


Fig. 1 (A). Monitoring sites in 2014.

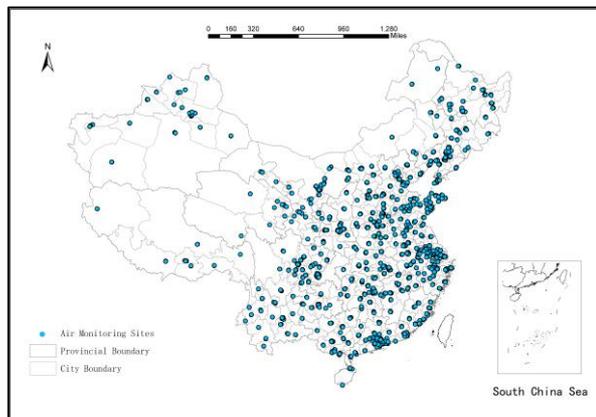


Fig. 1 (B). Monitoring sites since 2015.

In addition to particulate matter, ozone pollution in China has grown rapidly over the past two decades⁷ with a strong seasonal-appearing feature. In 2012, China adopted the Ambient Air Quality Standard⁸ and began developing a national air quality reporting system. By the end of 2014, the system covered 947 sites (Fig. 1 (A)). Now this number has increased up to 1,497, indicating that China has now gradually developed a monitoring network for air quality (Fig. 1 (B)).

However, little research has been done in analyzing spatial distribution or assessing health impact of ozone pollution based on the mapping of ozone pollution in China. Unlike particulate matter which has long-term effect on humankind^{9,10}, ozone pollution causes tissue damage as a result of short-term exposure¹¹. In addition, general health data is more achievable than daily mortality and morbidity data. Due to the scarcity of monitoring data in previous years, publications are mostly regional researches located in cities where abundant air quality monitoring sites exist¹². Although there are researches focusing on mapping ozone or its precursors¹³, and some even cover eastern China¹⁴, they either apply remote sensing retrieval to satellite data with low spatial resolution¹⁵ or limit themselves to regional mapping.¹⁴ However, comprehensive data has been collected as it has been over three years since China fully established the 1,497-sites air quality monitoring network. A rather extensive spatial and temporal coverage for ozone concentration has been established. It is time that we start bringing ozone pollution under control at this transitioning period when particulate matter pollutants are greatly reduced and ozone pollution level rockets as a partial result.

As is demanded by the Chinese government, China is trying to broaden its air quality management from understanding the scope of problems to targeting interventions. However, little research has touched the specific area of ozone pollution. Aimed to push forward the research on ambient ozone pollution, we use daily published ozone concentration data in conjunction with the fine scale of population data to develop the identification of spatial and temporal trends of ozone pollution. On top of that, we try to assess the health impact of the ozone pollution in terms of its loss on China's socio-economy. Insights into the current air pollution problem and possible suggestions for future policies are explored based on the observed spatial distributions and temporal trends.

2. Methods and data

The present study area covers mainland China. Due to the fact that there is no national-controlled monitoring site in Taiwan, it is not covered within this research. We choose year 2010 as our base year to assess the real GDP loss caused by ozone pollution during 2014 to 2017. Therefore, health and economy data for 2010 are matched in order to perform a rigorous calculation. According to the report from National Bureau of Statistics of China, the total population in 2010 was 1 340.91 million.

GIS is the main tool used to process ozone data achieved from 947 sites in 2014 and 1,497 sites since 2015 to derive pollution maps in China. Together with the 1 Km Grid Population Dataset of China¹⁶ and health data collected from China Statistical Yearbook, we attempt to measure the socio-economy impact of ambient ozone pollution at a 10 km resolution.

2.1 Data source

2.1.1 Air pollution and meteorological data

While there are several ozone pollution indexes in China, we focus on outdoor daily maximum 8-hour average ozone concentration (MDA8) as the indicator for ozone pollution assessment, as recommended by WHO in *Air Quality Guidelines*¹⁷. We obtained the hourly published air quality data from May 13, 2014 to June 3, 2017, originally collected from the official website of China Environmental Monitoring Center (<http://106.37.208.233:20035>). The daily average concentrations of maximum 8-hour average ozone are calculated for each monitoring stations.

We first identify the locations of all 1,497 sites (946 in 2014) on the map of China. The daily ambient ozone concentration data is then put into the system and matched with those sites. Finally, we apply spatial interpolation to derive the estimated ambient ozone distribution in China.

Seasonal variations of ozone distribution are calculated in order to display ozone pollution features on a long time scale. In consideration of the period that our monitoring data covers, we divide each year into four seasons. The first season includes January, February, and March; the second includes April, May, and

June; the third lasts from July to September; and the last season covers October, November, and December.

In order to assess the short-term effect of ambient ozone pollution on humankind on a short time scale, we pick June as our sample month for each year to compare the daily health impact that ozone pollution has on citizens across years, assuming that daily relationship between ozone and the environment is constant for the same Day of Year (DOY) in each year. Maps for each day in June of year 2014, 2015, and 2016 are plotted.

2.1.2 Health data

Regarding outcomes, we select total all-cause mortality as examined health endpoint, since there are abundant regional researches on short-term exposure-response relationship in China. However, the daily mortality data is inaccessible to the public. We could only use the general mortality data. The annual cause-specific baseline mortality rates are taken from China Statistical Yearbook, compiled by National Bureau of Statistics of China. Daily total non-accidental deaths are identified based on the International Classification of Diseases, Revision 10 (ICD-10).

According to WHO's publication in 2006¹⁷, the background ozone concentration level is about 70 $\mu\text{g}/\text{m}^3$.

2.2 Health impact assessment

Because daily mortality is very low, they were usually assumed to follow an over-dispersed Poisson distribution. Thus, a quasi-Poisson regression can be used to evaluate the adverse health effects. The formulas are shown below¹⁸:

1. The correlation between ozone and its health effects:

$$\text{RR} = \frac{\exp(\alpha + \beta C)}{\exp(\alpha + \beta C_0)} = \exp(\beta (C - C_0)) \quad (1)$$

where RR represents the estimated percentage of effect of ozone per $\mu\text{g}/\text{m}^3 \times (1 / 100) \times$ change in ozone; α is the constant term; β is the coefficient for ozone; C is the input ozone concentration; and C_0 is the standard background ozone concentration level, the unit is $\mu\text{g}/\text{m}^3$.

The value of β appears to be essential in estimating the exposure-response relation between ozone and its health impact. The ideal value of relative risk per unit of excess exposure for total mortality outcome for the whole population of China should be the results of aggregated regional cohort studies, presented in form of a grid pattern that could be matched with our population and pollution distribution grid. However, till 2015, there were only 8 time-series studies analyzing relative risks of short-term exposure to ozone, covering merely several metropolitans in China. Under this circumstance, the combined results from the meta-analysis in Zhang's research¹⁹ which includes the eight studies and examines mortality risk of acute exposure to ozone seem to be our most suitable choice. In terms of estimated mortality burdens attributed to ozone pollution, they conclude that with per 10 $\mu\text{g}/\text{m}^3$ increase, there is an increase of 0.48% in premature deaths. Therefore, the value of β in this research is 0.0048 (95% CI: 0.38, 0.58).

Here bias could be induced, as there are only eight researches on short-term exposure-response analysis on ozone pollution identified in Shang's research. However, the result of their research still falls in the reasonable range of estimated global excess mortality rate attribute to ozone exposure. *In Air Quality Guideline*¹⁷, WHO concludes that the total excess mortality risk rate caused by ozone pollution is around 0.3% ~ 0.5%.

2. Formula for estimating change in daily morbidity and mortality caused by ozone:

$$P_{di} = (f_{pi} - f_{ti}) \times P_e \quad (2)$$

where variable i represents the kind of health endpoint; P_{di} is the amount of the occurrence of health endpoint as a result of ozone pollution; f_{pi} is the occurrence rate of non-accidental mortality or

morbidity; f_{ti} is the standard background occurrence of non-accidental mortality or morbidity; P_e is the population exposed to ozone pollution.

Since $f_{pi} = f_{ti} \times \exp(\Delta C_i \times \beta_i / 100)$, formula (2) could be converted into the following:

$$P_{di} = \frac{RR_i - 1}{RR_i} \times f_{pi} \times P_e \quad (3)$$

According to the availability of data, we pick daily mortality number as the studied health endpoints.

2.5 Health economic evaluation (HEV)

The formula for calculating economic impact of ambient ozone pollution is shown below:

$$EC = P_{di} \times T \times HC \quad (4)$$

where EC represents the total economic burden added to the society; T is the average years of potential life lost in year 2010; and HC is the average GDP of 2010.

3. Results

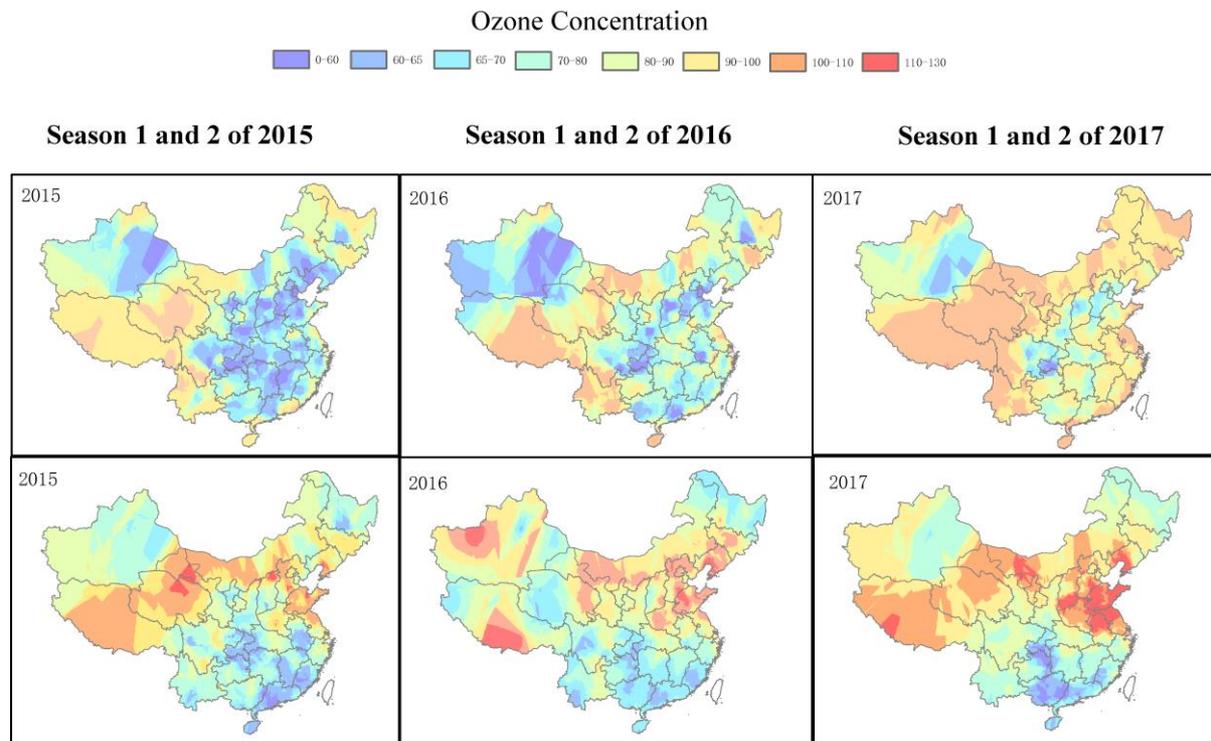


Fig. 2. Spatial distributions of ambient ozone during January to March and April to June, from 2015 to 2017 (10 km resolution). Grey lines are the provincial boundaries.

3.1 Spatial and Temporal Trends

Using ground-level monitoring data, we have derived spatial distribution maps of ambient ozone concentrations at 10 km resolution across China from 2014 – 2017, and have observed significant temporal variations and ozone related mortality burden. To visualize seasonal changes in ozone distribution, we divide each year into four seasons and plot the ozone concentration maps. In addition, health impacts brought by ozone pollution are also displayed on the maps to show the spatial differences.

The maps exhibit strong spatial and temporal variations of ambient ozone level. During season 2 and 3, which last from April to September, many areas experience significantly stronger average ozone concentrations than that from October to March. However, robust year-on-year increases in the area of high-concentration centers are observed in all four seasonal periods. According to the average ozone level

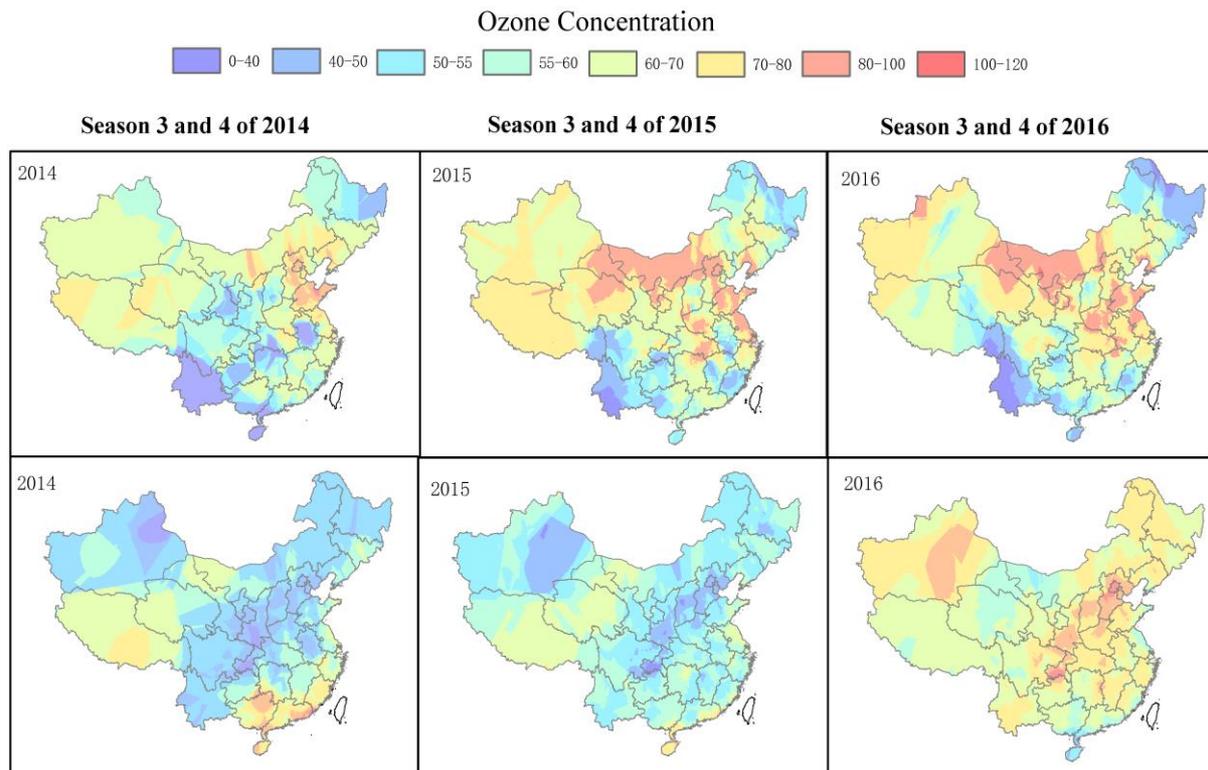


Fig. 3. Spatial distributions of ambient ozone during July to September and October to December, from 2014 to 2016 (10 km resolution). Grey lines are the provincial boundaries.

of the fourth season in 2014 and 2015, only parts of Guangdong, Guangxi, and Hainan were exposed to ozone pollution, which was slightly over the average background ozone concentration level according to WHO's report. However, the estimated area over-exposed to ozone has expanded tremendously in 2016 in comparison to previous years. Not only were the regions mentioned above, but also Sichuan, Chongqing, Shanxi, Xi'an, and the Beijing-Tianjin Metropolitan Region were above the risk level. Similar to season 4, the national situation during season 1 has become worse. The east coast tends to suffer more and more from the fast growing ozone pollution level. Statistics show that a total of 10.65 % of the population are under ozone level higher than $70\mu\text{g}/\text{m}^3$ in 2017 season 1.

3.2 Major High-risk Regions

Though a majority of area in China has transferred from a non-ozone-pollution region to one with potential risks, the average level of ozone concentration during winter is still significantly lower than that in summer. Our maps show that especially during April to June, the high-concentration zones have constantly expanded while their centers generally remain the same. In contrast to those centers in season 1 and 4, the highly polluted regions gather at the east and the northeast China. Liaoning, Beijing-Tianjin Metropolitan area, Shandong, Jiangsu, Anhui, Henan, Shanxi have an averaged ozone concentration level above $110\mu\text{g}/\text{m}^3$. Surprisingly, Guangdong and Guangxi are among the least polluted provinces nationwide at this time. Our calculation gives a fine estimation that over 400 million people are exposed to ozone pollution over $100\mu\text{g}/\text{m}^3$ during April to June in 2017, accounting for about 32.63 % of the national population. In addition, increases in ozone concentration level in Xinjiang and Xizang are observed in this research, which will be discussed later. We also attempt to assess the impact ozone pollution has posed on China's socio-economy in terms of total excess premature deaths and the economic loss (Fig.4). The maps of mortality distribution exhibited strong spatial gradients and noticeable growth throughout the examined time period. As expected, cities on the east coast bear the densest deaths attributed to short-term ozone exposure. Premature deaths in Beijing-Tianjin metropolitan area, Shandong, Jiangsu, Shanghai and Guangdong, contribute a large proportion of the total mortality burden. Moreover, we have found that there is a newly developed center of ozone pollution in Shanxi Province. There is a high mortality occurring center near Xi'an, capital of Shaanxi Province. The center is visible in June 2014 and expanded quickly around the city.

In June 2016, premature deaths in Shaanxi Province almost doubled the number in 2014, with a total of over 709 and 400 respectively.

3.3 Health Impact of Ozone Pollution

Generally, the estimated total excess mortality attributed to ozone pollution is around 14 105.7 (95% CI: 11, 232-17, 008) in June 2014, 12 773.4 (95% CI: 10, 168-15, 402) in June 2015, and 15 455.7 (95% CI: 12, 333-18, 678) in June 2016, leading to a total economic loss of 740.4 million RMB, 670.5 million RMB and 811.3 million RMB in terms of real GDP (base year 2010), respectively. Total excess premature deaths in June fluctuated from 2014 to 2016, with the highest number in June 2016, and the lowest in 2015. During the 30 days in June 2016 only, there were over 15 000 excess premature deaths related to ozone exposure. The growth rate is about 9.57 % comparing to that in 2014. Though in terms of the maximum and the minimum ozone concentration level, there are not significant year-on-year variations, the result for June 2015 was rather different from what we expected. We observed a rather sharp decrease in total excess premature mortality in 2015 compared to that in 2014.

4. Discussion

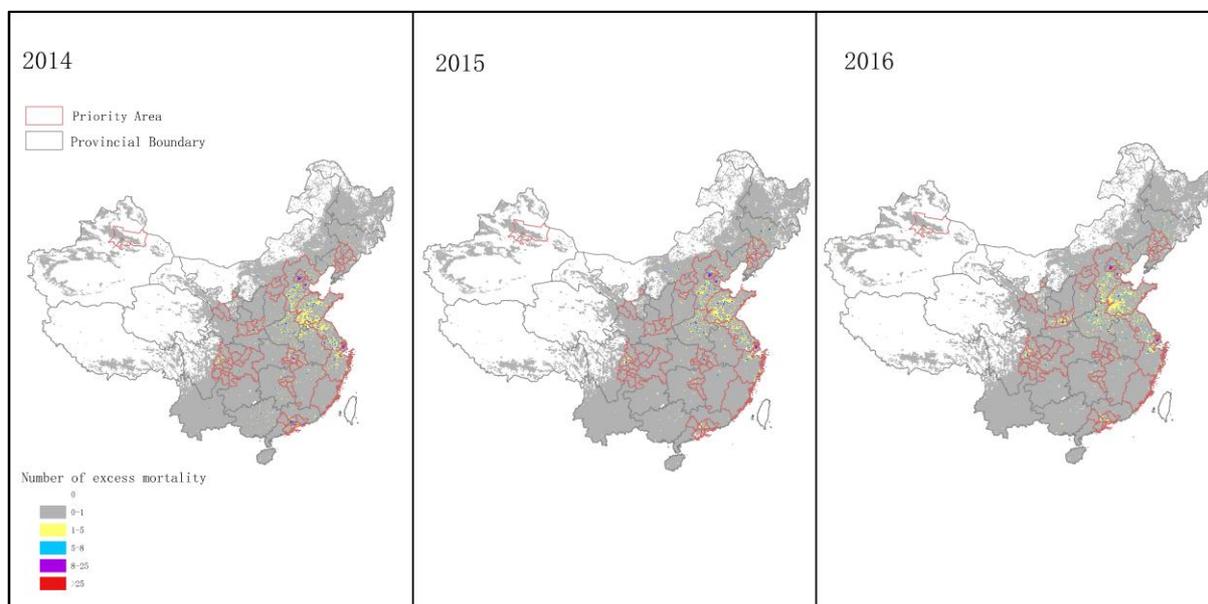


Fig. 4. The aggregation 31 days of total excess mortality caused attributed to short-term exposure to ground-level ozone pollution in June of 2014, 2015, and 2016. Grey lines are the provincial boundaries. Red lines are the boundaries of the 13 air pollution control priority areas.

According to our research results, high ozone pollutions mainly concentrate in areas where high population density, industry plants and heavy air pollution are located. In terms of general spatial distribution characteristics, ambient ozone pollution centers are located along the coastal areas. There is a recent trend of expansion to inner parts of mainland China. Therefore, ozone pollution has potential risks on a considerable amount of Chinese citizens. On the other hand, implications to future ozone-pollution related policies can be drawn.

4.1 Significance of this Research

There are some important differences and breakthroughs within this research in comparison to previous air quality studies in China. In comparison to Robert's research¹⁴, our research is no longer limited to regional mapping and has a finer spatial resolution. Moreover, we focus especially on the hourly published data from monitoring sites, and cover the scale of the whole nation. According to our knowledge, this study takes a historical step into the area of mapping ambient ozone pollution in China and the related health risk assessment. This is the first research studying both the spatial distribution of ozone and the temporal change of the distribution pattern in China. Our seasonal average maps exhibit the sharp

differences of ozone distribution between warm and cold seasons. This is also the first time to assess short-term exposure-response relationship between ozone pollution and excess premature mortality burden on the national scale. Socio-economy damage is estimated at a fine resolution.

Our findings on spatial characteristics of health burdens have important implications for ozone pollution control policies in China. Spatial-differentiation strategy adopted by China's Ministry of Environmental Protection (CMEP) requires that strict controls being performed over regions where severe air quality problem occurs. The 12th five-year plan has determined 13 priority areas where air pollution levels are highly attended to^{20, 21}. We overlay the ozone mortality map with the 13 region map to examine if high excess deaths happen within these places (Fig. 4.). Although the 13 regions cover most of the high-risk ozone areas, parts of Henan and Shaanxi where high excess premature mortality rates occur are still left aside. As ozone pollution is considered to be highly related to its precursors that are emitted during fuel burning²², we expect differentiated and stricter emission control strategies being made in existing priority areas and those potential high-risk areas that are not yet on the list. During October to March, the average ozone concentrations across the nation are lower than those during April to September (Fig 2., Fig. 3), indicating that we may need to put much emphasis on ozone control during summer. However, this does not mean that ozone pollution is not a problem to be worried about in the rest of the year. Our graphs have shown that there is a noticeable trend that ozone pollution is rising in all four seasons.

4.2 Implications to Future Policies

Additionally, the Shandong, Jiangsu, Henan, Hebei joint area appears to be frequently polluted by ozone. Because of the multiplying combination effect of ozone and its precursors^{23, 24}, and their remarkable ability to travel along distances²⁵, joint efforts from several provincial governments may be a useful strategy in order to largely reduce the ozone pollution.

It is also worthy to notice that there seems to have a growing tendency that the western part of China becomes over-exposed to ambient ozone pollution. However, taking into consideration of the number and location of air quality monitoring sites in the western part of China, counter-arguments could be drawn that the data from a few sites is covering a large region. We have also noticed that the relatively scarce data from Xinjiang, Tibet, Gansu, and Inner Mongolia may bring some bias and deviations to our mapping. We still believe that valuable projections into the future expansion of ozone pollution are embedded within the maps. Under the circumstances that mapping methods for all three years and locations of the air quality monitoring sites in 2015 and 2016 remain the same, we can still observe that the western part of China are experiencing severer ozone pollution recently. Even though the air monitoring sites are not abundant as those in along the east coast, our result can serve as a prediction into the sites-lacking areas and as well into the future.

4.3 Limitations

While informative implications for future policies has been drawn, our research has some limitations that need to be mentioned. The first one is the fact that parts of our air quality data are missing. Since there is no officially published history data for air quality, we had to use the data provided by other researchers, who can only record the available hourly published air monitoring data from the official website. To address this problem, we extended the validation to monthly addition and seasonal level, and picked June of 2014, 2015, and 2016 as specifically examined time periods to assess daily mortality burden, since the data is relatively complete. Therefore, missing monitoring data is a minor parameter in this research. The second limitation is the spatial resolution of our maps. A total of 947 sites were established in 2014 and this number increased to 1497 in 2015, much more than we had in previous decades. Their distribution pattern is still too coarse for this country covering 9.6 million square kilometers of land. Also, it is questionable whether the locations of air quality monitoring sites are scientifically appropriate. For example, the nine sites in Nanjing gather at the downtown area, where population and vehicle densities are high (Fig. 5.). Though the distribution of these sites in Nanjing can provide a fine coverage of population, it is very hard to define the concentration level of any kind of pollutants in the suburban areas of Nanjing. On the other hand, the temporal trends assessment is also affected by this issue. We have observed a fluctuation of total excess premature deaths burden during 2014 to 2016. In year 2015, slightly fewer premature deaths were attributed to ozone pollution in comparison to the previous year, which may reflect the intersection of locations of monitoring sites, weather, and the variations in the match of ozone pollution

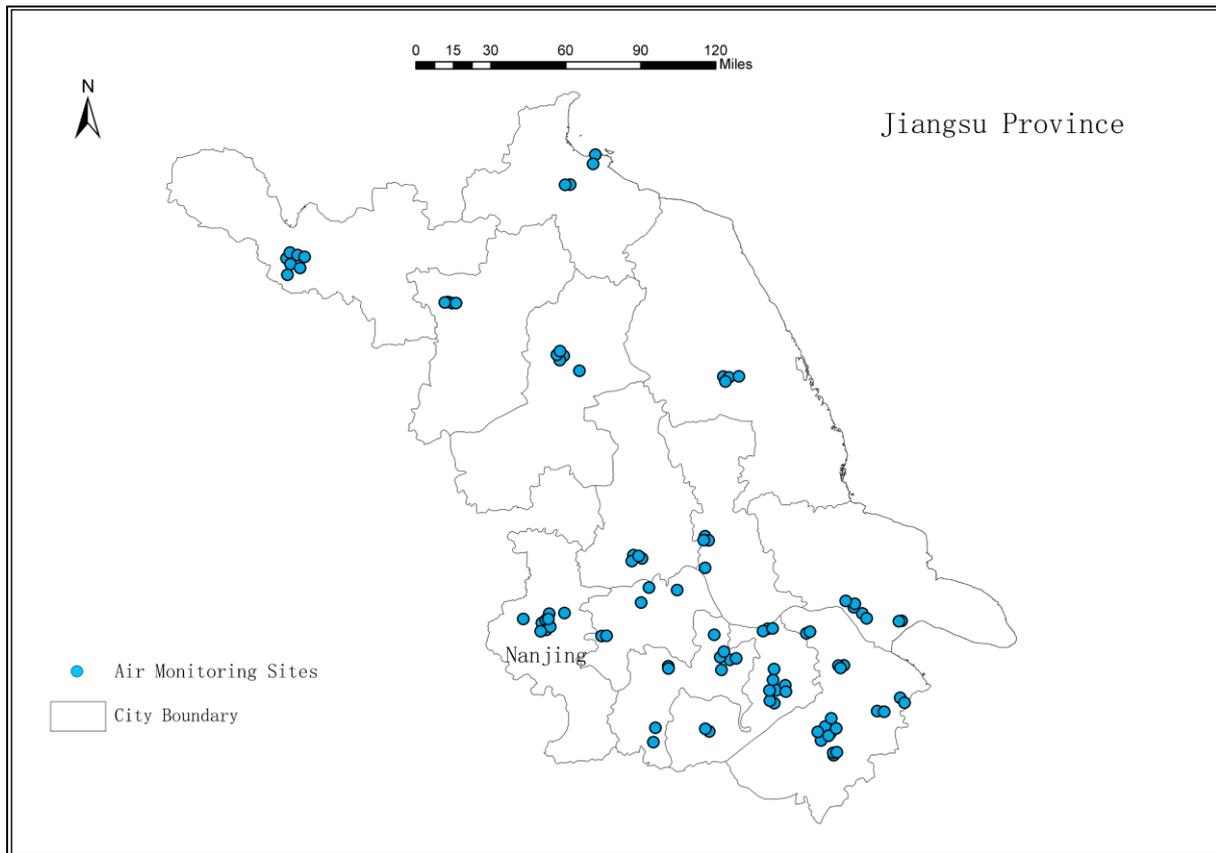


Fig. 5. The distribution of air quality monitoring sites in Jiangsu Province.

and population distribution. This issue is averaged as we apply our research on a national scale, but we still expect more town-level and county-level air monitoring networks to be built up in the near future.

Another limitation is about the value of coefficient rate between short-term ozone exposure and daily excess mortality burden. Since there are only a few short-term exposure-response studies on ozone pollution in China, and China's coefficient is estimated to be rather different from the research results based in the U. S. and in Europe, we choose results from the meta-analysis report of Shang's. The coefficient value is highly generalized, though carefully calculated. Moreover, all eight researches conducted are based in metropolitan cities while none touched the rural area, where large proportion of Chinese population still exists. Although the result of Shang's falls within the estimated global range of relative risks of ozone's, we hereon urge biology researchers to focus on exposure-response rate of short-term exposure to ambient ozone and to put much effort into building up a detailed pattern of exposure-response variations throughout China, because more areas are now exposed to ozone pollution.

5. Conclusion

The present study provides an estimation of ozone's spatial distribution and temporal trends from 2014 to 2017 in China at a 10 km resolution. To our knowledge, this is the first study to plot the ozone pollution over the whole China and the first to quantify the socio-economy impact brought up by that. Though there are some limitations, it can serve as a base analysis for all environmental researchers about the current issue of ozone pollution. At the same time, we urge environmental researchers to pay attention to this burning issue and to build up a research chain similar to that of particulate matter so that we can have a detailed track of ambient ozone pollution situation and strive to solve the problem as soon as possible.

6. Acknowledgement

This research is funded by Henry Luce Foundation, through Joint Luce-China Program jointly held by Occidental College and Nanjing University. The contents of this paper are solely the responsibility of the authors and do not necessarily represent official views of the sponsor.

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