HOW MANY PEOPLE DIED DUE TO PM2.5 AND WHERE THE MORTALITY RISKS INCREASED? A CASE STUDY IN BEIJING

Yuenan Li[a,b], *Zhuo Chen*[a], *Jonathan Li*[a]

[a]Department of Geography and Environment Management, University of Waterloo, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada – (y745li@uwaterloo.ca; z338chen@uwaterloo.ca; junli@uwaterloo.ca)
[b]Location Analysis, Canada Post Corporation, 2701 Riverside Drive, Ottawa, K1V 2E4, Canada)

ABSTRACT

This study used MODIS 3 KM Aerosol Optical Depth (AOD) products, ground-level PM2.5 measurements in Beijing and the Public Health knowledge to estimate the number of death attributed to the long-term exposure to a harmful level of PM2.5 concentrations. The study results demonstrated that 2015 population-weighted averaged PM2.5 in Beijing was 70.46 μg/m^3, 369.73% exceeding the China's yearly standard. Additionally, it was estimated that in 2015, 4172 non-accidental deaths in Beijing may attribute to the long-term exposure of excessive PM2.5 concentrations.

Index Terms— PM2.5, Public Health, Remote Sensing, Mortality, AOD,

1. INTRODUCTION

Fine particulate matter with a diameter less than 2.5 μm (PM2.5) has harmful impacts on public health. According to the Health Effects of Particulate Matter reported by the World Health Organization (WHO, 2013), in 2010, 3.1 million deaths are attributed to PM2.5 globally. However, threats of PM2.5 to human beings varies in different regions. Therefore, local governments and health organizations have released relevant reference showing the local deaths' number or the mortality attributed to long-term and short-term exposure to PM2.5. The *Air Quality in Europe* Report indicated that in 2012, the premature deaths attributable to PM2.5 was 59,500 in Germany, 44,600 in Poland, 37,800 in the UK and 403,000 in the whole Europe (European Environment Agency, 2015). However, in China, this kind of information is usually difficult to acquire not only from hospitals but also from government agencies. Therefore, scholars have attempted to estimate the mortality and relevant disease attributable to PM2.5 pollutants (Li et al., 2015; Zheng et al., 2015; Apte et al., 2015).

Mortality consists of accidental mortality and non-accidental mortality. In this study, we only discuss the non-accidental mortality attributed by PM2.5. In the public health field, the mortality rate can be derived by the relative risk (RR), excessive risk (ER) and attributable fraction (AF). RR is the risk or bad outcome of a group exposed to a treatment (such as PM2.5) compared with another group without this treatment (Irwig et al., 2008). ER is also known as excess relative risk (Fry et al., 2013). AF can assess the proportion of the disease (or mortality) attributed to a certain risk (such as PM2.5) in a population (Steenland et al., 2006). The relationship between ER and RR are ca be described as Eq. (1) (Fry et al., 2013):

$$ER(\%) = (RR-1)*100\% \qquad (1)$$

The relationship between AF and RR can be described by Eq. (2) (Anenberg et al., 2009):

$$AF = (RR-1)/RR \qquad (2)$$

The complaints on PM2.5 pollutants have pushed the governments and health organizations to issue yearly and daily standards towards PM2.5 concentrations. The latest version of China's Ambient Air Quality Standards was released in 2012, in which the daily and yearly standards were set as 35 μg/m^3 and 15 μg/m^3 respectively.

To monitor ground-level PM2.5 concentrations, the Chinese government spent significant expense in building more than 1500 in-situ stations (12 stations in Beijing). However, each station can only represent a limited area around that station, which leaves the vast rural land out of monitoring. This also becomes a limitation of those mortality-PM2.5 studies without utilizing geographic information system (GIS) and remote sensing (RS) techniques. GIS and RS techniques can be used as complementary tools to benefit spatial air quality and public health study.

With the development of RS technology, previous studies have shown the correlation between satellite-derived AOD and ground-level PM2.5 concentrations by various models, such as the multiple linear regression model and the geographically weighted regression (GWR) model (Chu et al., 2003). AOD is a parameter of the extinction of electromagnetic radiation at a given wavelength (Chudnovsky et al., 2014).

In 2016, our research group estimated the annual PM2.5 concentrations in the Beijing-Tianjin-Hebei region, China via combining MODIS AOD product, ground-level PM2.5 measurements and the GWR model (Li et al., 2016). Based on our previous research, this study addressed the non-accidental deaths' number attributed to the PM2.5 concentration exceeding China's national yearly standard. Additionally, this study also represented where the mortality risk increased spatially in Beijing.

2. STUDY AREA AND DATASET

Beijing with a land area of 16,801 KM^2, is the capital city of China. The huge population (12.66 million), local heavy industries and vehicle emissions have resulted in severe air pollution. The study period of this project is from September 2014 to August 2015. Figure 1 shows the study area.

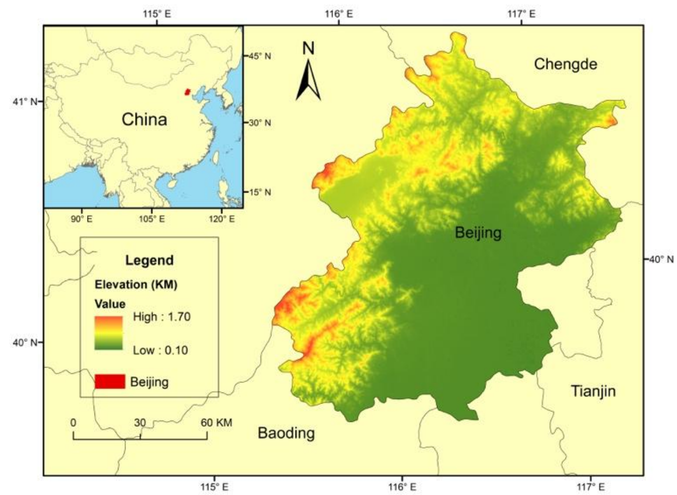


Figure 1. The study Area

Table 1. Data used in this project

Date Type	Data	Acquired Time	Spatial Resolutio n
Ground-level PM2.5	PM2.5 (μg/m^3)	14:00	N/A
RS Data	Aqua MODIS AOD (dimensionless)	14:00	3 KM
Population	Population (person)	2010	1 KM
ER	ER	2011	N/A
Non-accidental Mortality	Non-accidental Mortality	2015	N/A

Table 1 shows the detail information of the spatial and non-spatial datasets involved in this study. The ground-level PM2.5 hourly monitoring data was acquired from the Chinese Ministry of Environmental Protection. Meanwhile, the 3KM AOD product was obtained from Aqua MODIS product datasets. In addition, the 2010 population data was provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC).

Cao et al. (2011) estimated that in China, 10 μg/m^3 increase of PM2.5 was corresponded with 0.90% increment in total non-accidental mortality, which was adopted as the ER in this study. According to the China Statistical Yearbook (2016) and the National Disease and Cause Death Database, 2015 non-accidental mortality was 0.64%, which was used as the non-accidental mortality baseline in this research.

3. METHODOLOGY

This project firstly utilized the GWR model to estimate 2015 PM2.5 spatial concentrations in Beijing. Then the estimated PM2.5 concentrations were used as the input for mortality estimation model. The GWR model can be expressed as Eq. (3):

$$PM_{2.5s}{=}a_{0,s}{+}a_{1,s}AOD_s{+}a_{2,s}V_{2,s}{+}a_{3,s}V_{3,s}\ldots\ldots\ a_{n,s}V_{n,s} \qquad (3)$$

where $PM_{2.5s}$ is PM2.5 concentration at location s; $a_{0,s}$ is the intercept at location s; $V_{2,s}$ to $V_{n,s}$ are values of variables 2 to n at location s; $a_{2,s}$ to $a_{3,s}$ are slopes of corresponding variables.

After the model was built, a 10-fold cross validation (CV) was conducted. For more details in GWR model building and 10-fold CV conduction, please refer to our previous study (Li et al., 2016).

In this study, the mortality estimation model is built based on Eq. (1) and the Eq. (2) in Section 1. The number of the excessive death in each cell can be determined by Eq. (4):

$$\Delta Total\ non{-}accidental\ Mortality_{pm2.5}\,(i,j) = pop\,(i,j) * Total\ non{-}accidental\ Mortality\ Baseline * AF_{PM2.5} * \Delta PM_{2.5}(i,j) \qquad (4)$$

where $\Delta Total\ non{-}accidental\ Mortality_{pm2.5}$ is the total non-accidental excessive deaths at location (i,j) attributed to those PM2.5 concentrations higher than Chinese national yearly standard (15μg/m^3); $pop\ (i,j)$ is the population at location (i,j); total non-accidental mortality baseline was 0.647% as introduced in the Section 2; $AF_{PM2.5}$ is the attributed fraction of PM2.5 derived from Eq. (2); $\Delta PM_{2.5}(i,j)$ is the difference between the estimated PM2.5 and the national yearly standard at location (i,j).

4. RESULTS

The statistical results are shown in Table 2. Comparing the Akaike Information Criterion (AIC) of the GWR model and the Global Regression Model (GRM), it can be found the GWR model's AIC was lower, indicating the GWR model's performance in PM2.5 estimation was better. At the same time, the 10-fold CV's results demonstrated that the GWR model was not overestimated. When conducting the autocorrelation analysis, the Moran's I value of both the GWR model and 10-fold CV are near 0, which indicate the use of GWR model is rational. The estimated 2015 annual averaged PM2.5 concentrations are mapped in Figure 2 (a). The estimated PM2.5 concentrations ranged from 10.00 to 86 (μg/m^3). The high value concentrated in the southeastern Beijing. The spatial averaged PM2.5 was 59.27 (μg/m^3), while the population-weighted averaged PM2.5 was 70.46 (μg/m^3), 396.73% higher than the China's national yearly standard (See Table 3). The population-weighted averaged PM2.5 was assessed in this study was because it could better demonstrate how severe of the air pollution citizens were exposure to.

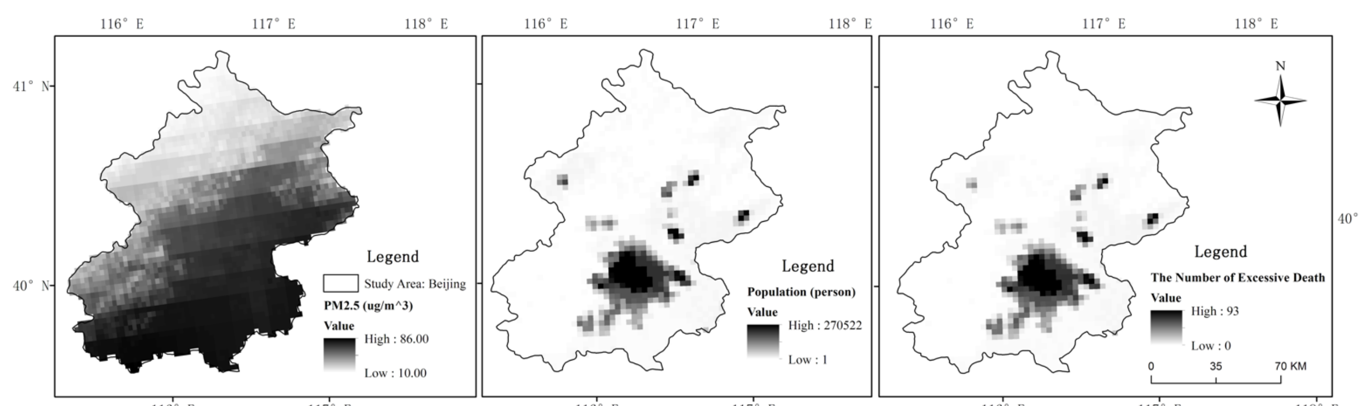
After the PM2.5 concentrations were derived, the excessive non-accidental death's number was estimated, which was also mapped in Figure 2 (c). It was estimated that 4172 people may die non-accidentally in Beijing during the study period attributed to the long-term (1 year) exposure to the PM2.5 concentrations higher than the Chinese National level (See Table 3). The mortality risks increased in the urban area in the Southern Beijing, which is consistent with the Beijing's total population distribution (Figure 2 (c) and (b)). All this information illustrated the PM2.5 concentrations have not yet had a significant effect in mortality risks' spatial distribution. However, it does not mean the harmful effect of PM2.5 on human health can be ignored by local governments or urban planner. China recently released the Two-children Policy instead of the One-child Policy. It can be predicted that in the near future, Beijing or even China will still face the problems coming with the population growth and urban expansion. In this situation, 4172, the number of the excessive death estimated in this paper, is expected to increase along with the growing population.

Table.2 Summary of the GWR model, 10-fold CV and the Global Regression Model (GWR)

Model	N	AIC	Local R^2	RMSE (μg/m^3)	MAPE (%)	Moran's I
GWR	12	522.63	0.88-0.93	2.81	3.32	-0.03
GWR 10-Fold CV	12	N/A	0.87-0.94	5.01	5.48	0.16
GRM	12	537.29	0.91	3.59	5.24	N/A

Table 3. Spatial Statistic Results

Spatial Statistic Item	Value
Population	12,659,132
Population-weighted Averaged PM2.5	70.46 (μg/m^3)
Spatial Averaged PM2.5	59.27 (μg/m^3)
The sum of 2015 Beijing Non-accidental Death attributable to excessive PM2.5 concentrations	4,172



(a) the estimated 2015 annual averaged PM2.5 Concentrations

(b) 2010 population distribution

(c) the estimated number of the excessive death attributed to the long-term exposure to PM2.5 exceeding 15 μg/m^3.

Figure 2. Estimated 2015 annual averaged PM2.5 concentrations in Beijing (a), 2010 Beijing population distribution (b), and the estimated number of the excessive death attributed to the long-term exposure to PM2.5 exceeding 15 μg/m3 (c)

5. CONCLUSION

This project combined RS datasets, GIS analyzing techniques and public health knowledge to estimate the number of death attributable to long-term exposure to PM2.5 exceeding China's national standards. The study results indicated that in 2015, more than 4,000 residences' non-accidental death in Beijing might be caused by the excessive PM2.5 concentrations. As a conclusion, this study demonstrated the RS and GIS tools' possibility in public health study. Meanwhile, the study results provide a reference for local governments and health organizations in decision making, and it can also be used as data support in urban planning. Additionally, the research methods in this study can be adopted in other regional, national or even global scale's study.

However, the limitations of this study should be addressed in the future research. Firstly, the acquired time of data sources is different (See Table.1), which affected the accuracy. In terms of the accuracy, the estimated mortality was not able to be validated with true value in this study due to the lack of true value in China. This is actually why we did this research: most Chinese citizens are unaware of the risks due to the lack of data or reference in China, but we are providing such a scientific reference. At the last, PM2.5 concentrations should be estimated at a smaller spatial scale to consider the influences from neighbor regions.

7. ACKNOWLEDGEMENTS

We would acknowledge the MODIS teams for providing the AOD products. We also acknowledge Dr. Jianjun Wang from the Third Institute of Oceanography, State Oceanic Administration of China for providing us the ground-level PM2.5 data. In addition, we appreciate RESDC for providing the population data. Special thanks go to Dr. Rebecca K. Saari from University of Waterloo for her advice from the perspective of public health.

8. REFERENCES

[1] Anenberg, S. C., West, J. J., Fiore, A. M., Jaffe, D. A., Prather, M. J., Bergmann, D., ... & Hess, P. Intercontinental impacts of ozone pollution on human mortality. *Environmental science & technology*, *43*(17), 6482-6487. (2009).

[2] Apte, J. S., Marshall, J. D., Cohen, A. J., & Brauer, M. Addressing global mortality from ambient PM2. 5. *Environmental science & technology*, 49(13), 8057-8066. (2015).

[3] European Environment Agency. Air Quality in Europe. (2015).

[4] Cao, J., Yang, C., Li, J., Chen, R., Chen, B., Gu, D., & Kan, H. Association between long-term exposure to outdoor air pollution and mortality in China: a cohort study. *Journal of Hazardous Materials*, *186*(2), 1594-1600. (2011).

[5] China Statistical Yearbook. National Bureau of Statistics of China: http://www.stats.gov.cn/tjsj/ndsj/2016/indexeh.htm. Retrieved at Jan 07, 2017.

[6] Chu, D. A., Kaufman, Y. J., Zibordi, G., Chern, J. D., Mao, J., Li, C., & Holben, B. N. Global monitoring of air pollution over land from the Earth Observing System-Terra Moderate Resolution Imaging Spectroradiometer (MODIS). *Journal of Geophysical Research: Atmospheres*, *108*(D21). (2003).

[7] Chudnovsky, A. A., Koutrakis, P., Kloog, I., Melly, S., Nordio, F., Lyapustin, A., ...& Schwartz, J. Fine particulate matter predictions using high resolution Aerosol Optical Depth (AOD) retrievals. Atmospheric Environment,89, 189-198. (2014).

[8] Fry, J. S., Lee, P. N., Forey, B. A., & Coombs, K. J. How rapidly does the excess risk of lung cancer decline following quitting smoking? A quantitative review using the negative exponential model. *Regulatory Toxicology and Pharmacology*, *67*(1), 13-26. (2013).

[9] Irwig, L., Irwig, J., Trevena, L., & Sweet, M. Relative risk, relative and absolute risk reduction, number needed to treat and confidence intervals. (2008).

[10] Li, Y., Ma, Z., Zheng, C., & Shang, Y. Ambient temperature enhanced acute cardiovascular-respiratory mortality effects of PM2. 5 in Beijing, China. *International journal of biometeorology,* 59(12), 1761-1770. (2015).

[11] Li, Y., Wang, J., Chen, C., Chen, Y., & Li, J. Estimating PM2.5 in the Beijing-Tianjin-Hebei Region Using MODIS AOD Product from 2014 to 2015. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 721-727. (2016).

[12] Steenland, K., & Armstrong, B. An overview of methods for calculating the burden of disease due to specific risk factors. *Epidemiology*, *17*(5), 512-519. (2006).

[13] WHO. Health Effects of Particulate Matter. (2013).

[14] Zheng, S., Pozzer, A., Cao, C. X., & Lelieveld, J. Long-term (2001–2012) concentrations of fine particulate matter (PM2.5) and the impact on human health in Beijing, *China. Atmospheric Chemistry and Physics,* 15(10), 5715-5725. (2015).