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The January 2013 Beijing “Airpocalypse” and its Acute Effects on Emergency and Outpatient Visits at a Beijing Hospital

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Abstract

Severe air pollution episodes in Europe and the USA in the early- to mid-twentieth century caused large health impacts, spurring national legislation. Similarly severe episodes currently affect developing regions, as exemplified by a particularly extreme episode in January 2013 in Beijing, China. We investigated associations between this episode and medical visits at a Beijing hospital. We obtained fine particulate matter (PM_{2.5}) measurements from the US State Department’s Embassy monitor and daily counts of all-cause, cardiovascular, and respiratory emergency visits, and outpatient visits from a nearby hospital in the Liufang Nanli community. We analyzed whether risks increased during this episode (with daily PM_{2.5} 350 µg/m³) using generalized linear modeling, controlling for potential confounders. The episode brought exceptionally high PM_{2.5} (peak daily average, 569 µg/m³). Risk increased during the episode for all-cause (relative risk 1.29 [95% CI 1.13, 1.46]), cardiovascular (1.55 [0.90, 2.68]) and respiratory (1.33 [1.10, 1.62]) emergency medical visits, and respiratory outpatient visits (1.16 [1.00, 1.33]). Relative risks of all-cause (0.95 [0.82, 1.10]) and cardiovascular (0.83 [0.67, 1.02]) outpatient visits were not statistically significant. Results were robust to modeling choices and episode definitions. This episode was extraordinarily severe, with maximum daily PM_{2.5} concentration nearly 22-fold above the World Health Organization guideline. During the episode, risk increased for all-cause, cardiovascular, and respiratory emergency medical visits, and respiratory outpatient visits, consistent with previous US-based research. However, no association was found for all-cause or cardiovascular outpatient visits. China-based studies like this one provide critical evidence in developing efforts regarding air pollution remediation in China.

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Introduction

Fine particulate matter (aerodynamic diameter $\leq 2.5 \mu\text{m}$, $\text{PM}_{2.5}$) levels in Chinese cities are record-breaking (Ji et al. 2014), in part because rapid urbanization and industrialization have brought an influx of population and increased motor vehicle use (Hao and Wang 2005). In northern China, coal burning for home heating drives concentrations even higher mid-November through mid-March, and this coal burning has been implicated in a variety of haze events over the past two decades (He et al. 2001; Ji et al. 2014; Kan et al. 2003; Liang et al. 2015; Wang et al. 2014b; Zheng et al. 2005), with vehicle emissions also playing an important role in some episodes (Hao and Wang 2005; Wang 2014b). Severe episodes have grounded planes (Armstrong and Ke 2013; Associated Press 2013; Ji et al. 2014), prevented outdoor activities (Ji et al. 2014), restricted school activities (Armstrong and Ke 2013; Ma 2013), and affected road travel (Armstrong and Ke 2013). From January 11, 2013, to January 13, 2013, Beijing, China, experienced an exceptionally severe episode of high air pollution concentrations. Unlike another severe air pollution event that occurred later in January 2013, which was associated with a slow, progressing increase in $\text{PM}_{2.5}$ over four days, during the January 11–13 2013 episode air pollution levels rapidly rose to dangerously high levels as high emissions from both industrial and local anthropogenic sources combined with conditions of stratospheric warming following a period of particularly cold weather and stagnant atmospheric conditions (Ji et al. 2014; Wang et al. 2014b). Compared to suburban and rural China, air pollution episodes in major urban centers of Northern China, such as Beijing, are often associated with a particularly notable increase in secondary organic-rich particles (Huang et al. 2014). This January 2013 episode was characterized by a rapid conversion of primary to secondary aerosols, as the combustion of fossil fuels and vehicle emissions led to particularly high levels of nitrous oxide, converting sulfur dioxide to secondary sulphate aerosols (Ji et al. 2014; Wang et al. 2014b), creating conditions so severe the period was called an “Airpocalypse” (Voorhees 2014).

Air pollution as severe as that experienced during this episode is likely to cause major health impacts. During severe episodes in Donora, Pennsylvania, and the Meuse Valley, Belgium, in the mid 20th century, daily mortality increased 5- and 10-fold, respectively (Anderson 2009; Firket 1936; Schrenk et al. 1950), while the 1952 “London Fog” increased risks for hospital admissions (Davis et al. 2002), sickness claims (Greater London Authority 2002), and pneumonia (Davis et al. 2002). Data for $\text{PM}_{2.5}$, a component of air pollution accepted to have severe health impacts, has only recently become publicly available in China (Chen et al. 2013a), and therefore there is only a limited body of literature assessing the health impact of $\text{PM}_{2.5}$ in China, with most previous research instead focused on other air pollutants. For example, Chen et al. (2012) assessed the risk of mortality from PM_{10} exposure in 16 Chinese cities and found that for every $10 \mu\text{g}/\text{m}^3$ increase in PM_{10} there was a statistically significant increase in all-cause, cardiovascular, and respiratory mortality (0.35% (0.18, 0.52), 0.44% (0.23, 0.64), and 0.56% (0.31, 0.81) respectively). However, a few studies have investigated the health impacts of $\text{PM}_{2.5}$ in Beijing, and these provide evidence that lowering air pollution levels may have benefits for overall respiratory, cardiovascular, and fetal health in the Beijing population. For example, the 2008 Beijing Olympics provided a unique opportunity for researchers to evaluate the health effects of a temporary, substantial decrease

in air pollution, including PM_{2.5}. Studies that compared the reduced-pollution 2008 Beijing Olympic period to pre- and post-Olympic periods found an overall decrease in respiratory inflammatory biomarkers (Huang et al. 2012; Zhang et al. 2012), cardiovascular/thrombotic inflammatory biomarkers (Rich et al. 2012; Zhang et al. 2012), and an increase in average birth weights (Rich et al. 2015). Further, a study of the January 2013 air pollution episode at a different Beijing hospital than that considered in our analysis found statistically significant increases in all-cause emergency visits (relative risk: 1.16 [95% confidence interval (CI): 1.02, 1.32]), respiratory emergency visits (1.74 [1.44, 2.11]), all-cause outpatient visits (1.12 [1.09, 1.15]), cardiovascular outpatient visits (1.16 [1.06, 1.28]), respiratory outpatient visits (1.16 [1.07, 1.27]), all-cause hospital admissions (1.69 [1.29, 2.21]), and cardiovascular hospital admissions (2.27 [1.12, 4.62]) (Chen et al. 2013a).

While US- and Europe-based research has extensively studied health effects of PM_{2.5} exposures (Anderson 2009; Atkinson et al. 2014; Brook et al. 2004; Metzger et al. 2004; Peng et al. 2009; Pope 2006), these studies covered much lower concentrations than those common in China, and extrapolation to higher concentrations may not be appropriate (Burnett et al. 2014; Ezzati et al. 2004). Further, both the population susceptibility and the air pollution mixture, including the chemical structure of PM_{2.5}, could differ in China from those in Western countries; this, therefore, makes it critical to conduct China-based studies of associations between air pollution exposure and human health. Here, we investigate the association between Beijing's 2013 "Airlpocalypse" and medical visits at a Beijing hospital, to add to the growing understanding of health effects of PM_{2.5} within China.

Methods

Data

We obtained PM_{2.5} concentration data collected at the US Embassy in Beijing, China, and published on Twitter through @Beijingair (Beijing Air 2008) (Fig 1). Hourly concentrations were measured using MetOne BAM 1020 and Ecotech EC9810 monitors (Beijing Air 2008). We aggregated hourly values to create 24-hour daily averages, calculated from midnight to midnight. Values for the day were considered missing if >25% of hourly measurements were missing. We obtained emergency and outpatient visit data from a hospital in the Liufang Nanli community, 2.66 kilometers from the US Embassy (Fig 1). Unlike larger Beijing hospitals, this hospital rarely operates at capacity, making it a useful study location as total daily counts of medical visits are rarely capped by capacity limitations. Data included daily counts for all-cause (ICD-10: A00-Z99), respiratory (J00-J99), and cardiovascular (I00-I99) emergency and outpatient visits. Daily weather measurements (temperature and dew point temperature) are from the United States' National Climatic Data Center's online database. Our full dataset covers February 17, 2009, to February 28, 2013.

Statistical methods

Here, we defined the air pollution episode as the series of two or more consecutive days in mid-January 2013 with 24-hour daily average PM_{2.5} measurements $\geq 350 \mu\text{g}/\text{m}^3$. Using these criteria, we defined the air pollution episode as January 11, 2013, to January 13, 2013 for our main analysis. However, since other studies defined this episode with different dates

(Chen et al. 2013a; Ji et al. 2014; Wang et al. 2014a; Wang et al. 2014b), we also performed a sensitivity analysis to determine if results were consistent across these different identified dates for this episode.

For our primary analysis (labeled as “Main” in Results), we modeled the association between daily morbidity and this episode using an overdispersed Poisson generalized linear model:

$$\log(E(Y_t)) = \alpha + \beta(E_t) + \gamma C_t$$

where Y_t is the count on day t of a particular health outcome, E_t is a binary indicator variable of whether day t was in the episode ($E_t = 1$) or not ($E_t = 0$), and C_t is a matrix of covariates and potential confounders for day t , including: day of the week (modeled as a factor), holiday (indicator), last two weeks of each year (indicator), long-term and seasonal trends (natural cubic spline with 6 degrees of freedom / year), same-day mean temperature (spline with 4 degrees of freedom), and a severe influenza epidemic that occurred from October 1, 2009, to December 23, 2009 (Xi et al. 2010) (spline with additional knots during the epidemic). We included the indicator for each year’s last two weeks because patients at this hospital tend to make additional visits then to use healthcare benefits that expire at year’s end. Holiday dates were specific to China (e.g., Lunar New Year).

In addition to our primary analysis, we fit five other models to help ensure that our results were robust to modeling choices. In particular, we did so to help identify any evidence of potential residual confounding, including from seasonal factors and from a severe influenza epidemic during the study period, in results generated from the main model fit for our primary analysis. First, we fit a model (which we refer to as the *eliminated weeks* model in the Results) that was identical to the main model, except that all days a week before and a week after the air pollution episode period were eliminated prior to fitting the model. The risk of a health event during the episode period was then compared to the risk on all the remaining days beside this period of days immediately adjacent to the episode. Second, we fit a model (*influenza days removed* model) that was identical to the main model, except with all days during the influenza epidemic (October 1, 2009, to December 23, 2009 (Xi et al. 2010)) removed from analysis. Third, we fit a model (*no influenza spline* model) that was identical to the main model, except the additional spline to model the influenza epidemic was excluded from the C_t variable in the model equation above. Fourth, we fit a generalized linear model, modeled with an overdispersed Poisson distribution, with analysis limited to study days in January (*January-only* model). In this model, we included controls for day of the week and year (both modeled as factors), but not a seasonal covariate or control for the influenza epidemic, since the model was only fit to January days. Fifth, we performed a matched analysis restricted to episode days and control days, with matching on year, month, and day of week (i.e., only specific days from January 2013), using a case-crossover model fit using a generalized linear model (*case-crossover* model) (Armstrong et al. 2014).

Finally, an earlier study by Chen and coauthors (2013a) estimated health risks during this episode at another Beijing hospital, using both a different definition of the air pollution

episode and different methods for assessing the risk of health outcomes during this episode. To aid comparability with results from the Chen et al. (2013a) study, we included an analysis where we applied both the Chen et al. (2013a) study's methodology and their episode definition to our data. Using the Chen et al. (2013a) methodology and episode period, for this part of our analysis we estimated relative risks by comparing average daily health outcome counts during a "Smog Period" of January 10–17, 2013, to reference periods of December 27–30, 2012 ("Pre-smog Period"), and January 21–24, 2013 ("Post-smog Period") (Chen et al. 2013a). Relative risks were calculated for each health outcome by taking the mean count for the health outcome during the Smog period divided by the mean counts during the Pre-smog and Post-smog periods (Chen et al. 2013a).

Results

Our dataset included over two million medical visits (Table 1). Outpatient visits for cardiovascular and respiratory causes occurred at similar rates (~250/day), while cardiovascular emergency visits (~4/day) were much less common than respiratory emergency visits (~50/day) at the study hospital. Year-round, 87% of study days exceeded the WHO PM_{2.5} guideline (25 µg/m³) (WHO 2016) (Table 2), with highest concentrations in winter (Table 2).

Under our primary episode definition, we identified the episode as January 11–13, 2013 (Fig 2). During the episode, daily PM_{2.5} concentrations reached 569 µg/m³, nearly 8 times the Grade II Chinese standard (75 µg/m³) (Olivares 2014). Risk was elevated during the episode compared to other study days, after adjustment for potential confounders, for all emergency visit outcomes considered—all-cause (relative risk: 1.29 [95% confidence interval (CI): 1.13, 1.46]), cardiovascular (1.55 [0.90, 2.68]), and respiratory (1.33 [1.10, 1.62]) (Fig 3; Table 3). Risk was also elevated for respiratory outpatient visits (1.16 [1.00, 1.33]). There was a modest decrease in risk during the episode in outpatient visits for all-cause (0.95 [0.82, 1.10]) and cardiovascular (0.83 [0.67, 1.02]) outcomes.

Results were relatively consistent when using episode definitions from other studies to identify days in the episode (Chen et al. 2013a; Ji et al. 2014; Wang et al. 2014a; Wang et al. 2014b) (Fig 4). Under all definitions, risk was elevated during the episode for all-cause, cardiovascular, and respiratory emergency visits, as well as for respiratory outpatient visits, and no association was observed with all-cause and cardiovascular outpatient visits. Point estimates were typically slightly closer to null for longer episode definitions, which included days with less severe PM_{2.5} (Fig 4). Results were also similar across sensitivity analyses for model form (Table 3).

As sensitivity analysis, we applied Chen et al.'s (2013a) statistical methodology and episode definition using our health data from a different hospital. When applying Chen et al.'s (2013a) approach to our health data, we found similar relative risk estimates for all-cause and cardiovascular emergency visits (Table 4), but a lower risk in our study population for respiratory emergency visits than Chen et al. (2013a) found for their study population. There were also differences in results for outpatient visits, for which we found reduced risks during

the episode in our study population, while Chen et al. (2013a) found an increased risk at their study hospital.

Discussion

Beijing's January 2013 "Airpocalypse" was extraordinarily severe, with the maximum daily PM_{2.5} concentration exceeding the WHO guideline nearly 22-fold. By comparison, during London's 1952 "Great Fog", peak concentrations of total suspended matter (TSM) were estimated (albeit with data limitations) to have reached a maximum daily average of 1,620 µg/m³ (Bell and Davis 2001). Using approximate conversion ratios to estimate TSM concentrations based on PM_{2.5} concentrations (Ezzati et al. 2004), the Beijing episode may have approached 2,000 µg/m³ TSM. While a limited comparison, given differences in measurement instruments and the broad approximations required for conversion, the comparison nevertheless highlights this episode's severity in comparison to a well-studied historical episode.

We found that during the Beijing episode, risk increased for all-cause, cardiovascular, and respiratory emergency medical visits and respiratory outpatient visits at our study hospital. Though the confidence intervals were wide, there was a modest decrease in risk for all cause and cardiovascular outpatient visits which are of uncertain significance. Our results for respiratory outcomes are consistent with previous US-based research, which found increased respiratory medical visits associated with PM_{2.5} exposure (Peel et al. 2005). Although previous US-based research also linked elevated PM_{2.5} to increased risk of cardiovascular medical visits (Metzger et al. 2004), we did not find a similar association for this episode at our study hospital. This observation could result in part from a differing healthcare system in China, where those with severe cardiovascular events would more likely go to a larger hospital than the hospital considered in this study. Further, this episode's severity may have convinced some to remain indoors, leading to avoided hospital visits for less severe complaints. This phenomenon may also explain the lack of an observed association for all-cause outpatient visits.

When we used this study's data to compare with an earlier study of this episode's impacts at another Beijing hospital (Chen et al. 2013a), results were similar for emergency visits but varied for outpatient visits (Table 4). The variation likely is not attributable to differences in exposure near the hospitals, as this episode was characterized by similar PM_{2.5} concentrations across Beijing (Ji et al. 2014). Differences may result from variation in the hospitals: in particular, our study hospital is near a cardiovascular specialty hospital, and so may receive fewer cardiovascular emergencies. Further, Chen et al.'s (2013a) method may be inappropriate for our study's hospital, since at our hospital part of the control period under this method is poorly representative of expected medical visit patterns during the case period. At our study hospital, outpatient visits tend to be higher at the end of December than in neighboring weeks, as patients make extra visits to use expiring healthcare benefits. This increased rate of outpatient visits during the end-of-December control period would dampen the estimated episode effect at our hospital when using the Chen et al. (2013a) methodology.

This study provides an in-depth analysis of a severe air pollution episode that occurred in Beijing, China, using PM_{2.5} measurements from the United States Embassy (Beijing Air 2008) and health data from a local Beijing hospital, helping to expand our understanding of the potential health risks associated with exposure to extremely high PM_{2.5} concentrations in Beijing. Since both health outcome rates and air pollution patterns can follow strong seasonal patterns, the potential for seasonal confounding is a key concern in air pollution epidemiology. A key strength of this study is the use of a number of alternative modeling approaches as a sensitivity analysis to confirm that observed associations were not a relic of residual seasonal confounding, including analyses that were limited to only days in the same season as the episode (*January-only model* and *Case-crossover model*). This study does, however, have a number of limitations. The most significant is its use of data from a single hospital, which limits the generalizability of estimated associations to the broader Beijing population and also resulted in low statistical power to identify associations, particularly for cardiovascular emergency visits. However, our results contribute evidence to the growing literature on the potential health impacts of short-term episodes of severe air pollution in Beijing, particularly in helping clarify which observed health risks during this episode were similar between our study hospital and another hospital studied previously, versus which outcomes showed strong heterogeneity in episode-related risks across these two study sites. Finally, the episode may have changed behavior, including causing some people to stay inside during the episode. In this case, the percent of the study population exposed to the severe air pollution would be lower during the episode than during days outside the episode used as comparisons in the models. Measurement error under this scenario would likely bias results towards the null, which would result in our estimates of the association between the episode and health risks being conservative.

Severe air pollution episodes in the United States and Europe informed policies to protect human health, including the United States' and United Kingdom's Clean Air Acts (Anderson 2009; Greater London Authority 2002; Snyder 1994). China-based studies are critical as China continues developing air pollution policies. China has recently taken important steps to reduce dangerous air pollution concentrations (Chen et al. 2013b). Short-term efforts reduced air pollution for major events, including the 2008 Olympics and 2014 Asia-Pacific Economic Cooperation Summit (Huang et al. 2015), and China has begun issuing red alerts during severe air pollution (BBC 2015). China is also developing long-term remediation measures, seeking to reduce PM_{2.5} by 25% by 2017 (Ministry of Environmental Protection 2013), and the Chinese government has expanded its air pollution monitoring systems (Chen et al. 2013b). China-based studies like this one provide important evidence in these developing efforts.

References

- Anderson HR (2009) Air pollution and mortality: a history. *Atmos Environ* 43(1):142–152. doi: 10.1016/j.atmosenv.2008.09.026
- Armstrong BG, Gasparrini A, Tobias A (2014) Conditional Poisson models: a flexible alternative to conditional logistic case cross-over analysis. *BMC Med Res Methodol* 14(1):122. doi: 10.1186/1471-2288-14-122 [PubMed: 25417555]

- Armstrong P, Ke F (2013) Beijing announces emergency measures amid fog of pollution. CNN. <http://www.cnn.com/2013/10/23/world/asia/china-beijing-smog-emergency-measures/>. Accessed 15 December 2015
- Associated Press in Beijing (2013) China's air pollution again at danger levels. The Guardian. <http://www.theguardian.com/world/2013/jan/29/china-air-pollution-danger>. Accessed 15 December 2015
- Atkinson RW, Kang S, Anderson HR, Mills IC, Walton HA (2014) Epidemiological time series studies of PM_{2.5} and daily mortality and hospital admissions: a systematic review and meta-analysis. *Thorax* 69(7): 660–665. doi: 10.1136/thoraxjnl-2013-204492 [PubMed: 24706041]
- Beijing air (@BeijingAir) (2008). <http://twitter.com/beijingair>
- Bell ML, Davis DL (2001) Reassessment of the lethal London fog of 1952: novel indicators of acute and chronic consequences of acute exposure to air pollution. *Environ Health Persp* 109(Suppl 3): 389–394.
- British Broadcasting Company (BBC) (2015) China smog sparks red alerts in 10 cities. British Broadcasting Company <http://www.bbc.com/news/world-asia-china-35173709>. Accessed 02 March 2016
- Brook RD, Franklin B, Cascio W et al. (2004) Air pollution and cardiovascular disease: a statement for healthcare professionals from the expert panel on population and prevention science of the American Heart Association. *Circulation* 109(21):2655–2671. doi: 10.1161/01.CIR.0000128587.30041.C8 [PubMed: 15173049]
- Burnett RT, Pope CA III, Ezzati M et al. (2014) An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ Health Persp* 122(4): 397–403. doi: 10.1289/ehp.1307049
- Chen R, Kan H, Chen B et al. (2012) Association of particulate air pollution with daily mortality the China air pollution and health effects study. *Am J Epidemiol* 175(11):1173–1181. doi: 10.1093/aje/kwr425
- Chen R, Zhao Z, Kan H (2013a) Heavy smog and hospital visits in Beijing, China. *Am J Resp Crit Care* 188(9):1170–1171. doi: 10.1164/rccm.201304-0678LE
- Chen Z, Wang JN, Ma GX, Zhang YS (2013b) China tackles the health effects of air pollution. *Lancet* 382(9909):1959–1960. doi: 10.1016/S0140-6736(13)62064-4 [PubMed: 24332069]
- Davis DL, Bell ML, Fletcher T (2002) A look back at the London smog of 1952 and the half century since. *Environ Health Persp* 110(12): A734–A735.
- Ezzati M, Lopez AD, Rodgers A, Murray CJ (2004) Comparative quantification of health risks Global and regional burden of disease attributable to selected major risk factors. Geneva: World Health Organization 1987–97.
- Firket J (1936) Fog along the Meuse valley. *T Faraday Soc* 32:1192–1196.
- Greater London Authority (2002) Years on: the struggle for air quality in London since the great smog of December 1952. Greater London Authority, London.
- Hao J, Wang L (2005) Improving urban air quality in China: Beijing case study. *J Air Waste Manag Assoc* 55(9): 1298–1305. doi: 10.1080/10473289.2005.10464726 [PubMed: 16259425]
- He K, Yang F, Ma Y et al. (2001) The characteristics of PM_{2.5} in Beijing, China. *Atmos Environ* 35(29): 4959–4970. doi: 10.1016/S1352-2310(01)00301-6
- Huang K, Zhang X, Lin Y (2015) The “APEC Blue” phenomenon: regional emission control effects observed from space. *Atmos Res* 164:65–75. doi: 10.1016/j.atmosres.2015.04.018
- Huang RJ, Zhang Y, Bozzetti C, Ho KF, Cao JJ, Han Y, Daellenbach KR, Slowik JG, Platt SM, Canonaco F, Zotter P, Wolf R, Pieber SM, Bruns EA, et al. (2014) High secondary aerosol contribution to particulate pollution during haze events in China. *Nature* 514: 218–222. doi: 10.1038/nature13774 [PubMed: 25231863]
- Huang W, Wang G, Lu S, Kipen H, Wang Y, Hu M, Lin W, Rich D, Ohman-Strickland P, Diehl SR, Zhu P, Tong J, Gong J, Zhu T, Zhang J (2012) Inflammatory and oxidative stress response of healthy young adults to changes in air quality during the Beijing Olympics. *Am J Respir Crit Care Med* 186(11): 1150–1159. doi: 10.1164/rccm.201205-0850OC [PubMed: 22936356]
- Ji D, Li L, Wang Y et al. (2014) The heaviest particulate air-pollution episodes occurred in northern China in January, 2013: insights gained from observation. *Atmos Environ* 92:546–556. doi: 10.1016/j.atmosenv.2014.04.048

- Kan H, Jia J, Chen B (2003) Acute stroke mortality and air pollution: new evidence from Shanghai, China. *J Occup Health* 45(5):321–323. doi: 10.1539/joh.45.321 [PubMed: 14646274]
- Liang X, Zou T, Guo B et al. (2015) Assessing Beijing's PM_{2.5} pollution: severity, weather impact, APEC and winter heating. *Proc R Soc A* 471:20150257. doi: 10.1098/rspa.2015.0257
- Ma W (2013) Beijing pollution hits highs. *The Wall Street Journal*. <http://www.wsj.com/articles/SB10001424127887324235104578239142337079994>. Accessed 15 December 2015
- Metzger KB, Tolbert PE, Klein M et al. (2004) Ambient air pollution and cardiovascular emergency department visits. *Epidemiology* 15(1):46–56. doi: 10.1097/01.EDE.0000101748.28283.97 [PubMed: 14712146]
- Ministry of Environmental Protection (2013) Atmospheric pollution prevention and control action plan. http://english.mep.gov.cn/News_service/infocus/201309/t20130924_260707.htm. Accessed 15 December 2015
- Olivares E (2014) China: air quality standards. *TransportPolicy.net*. http://transportpolicy.net/index.php?title=China:_Air_Quality_Standards. Accessed 02 March 2016
- Peel JL, Tolbert PE, Klein M et al. (2005) Ambient air pollution and respiratory emergency department visits. *Epidemiology* 16(2):164–174. doi: 10.1097/01.ede.0000152905.42113.db [PubMed: 15703530]
- Peng RD, Bell ML, Geyh AS et al. (2009) Emergency admissions for cardiovascular and respiratory diseases and the chemical composition of fine particle air pollution. *Environ Health Persp* 117(6): 957–963. doi: 10.1289/ehp.0800185
- Pope III CA, Dockery DW (2006) Health effects of fine particulate air pollution: lines that connect. *J Air Waste Manag Assoc* 56(6): 709–742. doi: 10.1080/10473289.2006.10464485 [PubMed: 16805397]
- Rich DQ, Kipen HM, Wang G, Wang Y, Zhu P, Ohman-Strickland P, Hu M, Philipp C, Diehl SR, Lu S, Tong J, Gong J, Thomas D, Zhu T, Zhang J (2012) Association between changes in air pollution levels during the Beijing Olympics and biomarkers of inflammation and thrombosis in healthy young adults. *JAMA* 307(19): 2068–2078 [PubMed: 22665106]
- Rich DQ, Liu K, Zhang J, Thurston SW, Stevens TP, Pan Y, Kane C, Weinberger B, Ohman-Strickland P, Woodruff TJ, Duan X, Assibey-Mensah V, Zhang J (2015) Differences in birth weight associated with the 2008 Beijing Olympics air pollution reduction: results from a natural experiment. *Environ Health Persp* 123(9): 880–887. doi: 10.1289/ehp.1408795
- Schrenk HH, Heimann H, Clayton GD, Gafafer WM, Wexler H (1950) Air pollution in Donora, PA. epidemiology of the unusual smog episode of October 1948. Preliminary Report. *JAMA* 143(3): 323. doi: 10.1001/jama.1950.02910380107025
- Snyder LP (1994) The death-dealing smog over Donora, Pennsylvania: industrial air pollution, public health policy, and the politics of expertise, 1948–1949. *Environ Hist Rev* 18(1):117–139. doi: 10.2307/3984747
- Voorhees AS, Wang J, Wang C, Zhao B, Wang S, Kan H (2014) Public health benefits of reducing air pollution in Shanghai: a proof-of-concept methodology with application to BenMAP. *Sci Total Environ* 485:396–405. doi: 10.1016/j.scitotenv.2014.03.113 [PubMed: 24742548]
- Wang H, Tan SC, Wang Y et al. (2014a) A multisource observation study of the severe prolonged regional haze episode over eastern China in January 2013. *Atmos Environ* 89:807–815. doi: 10.1016/j.atmosenv.2014.03.004
- Wang Y, Yao L, Wang L et al. (2014b) Mechanism for the formation of the January 2013 heavy haze pollution episode over central and eastern China. *Sci China Earth Sci* 57(1):14–25. doi: 10.1007/s11430-013-4773-4
- World Health Organization (WHO) (2006) Air quality guidelines: global update 2005: particulate matter, ozone, nitrogen dioxide, and sulfur dioxide. World Health Organization http://apps.who.int/iris/bitstream/10665/69477/1/WHO_SDE_PHE_OEH_06.02_eng.pdf. Accessed 15 December 2015
- Xi X, Xu Y, Jiang L, Li A, Duan J, Du B (2010) Hospitalized adult patients with 2009 influenza A (H1N1) in Beijing, China: risk factors for hospital mortality. *BMC Infect Dis* 10(1):1–8. doi: 10.1186/1471-2334-10-256 [PubMed: 20044936]

- Zhang J, Zhu T, Wang G, Huang W, Rich D, Zhu P, Wang Y, Lu S, Ohman-Strickland P, Diehl S, Hu M, Tong J, Gong J, Thomas D (2012) Cardiorespiratory biomarker responses in healthy young adults to drastic air quality changes surrounding the 2008 Beijing Olympics. *Res Rep Health Eff Inst* 174: 5–174.
- Zheng M, Salmon LG, Schauer JJ et al. (2005) Seasonal trends in PM_{2.5} source contributions in Beijing, China. *Atmos Environ* 39(22): 3967–3976. doi: 10.1016/j.atmosenv.2005.03.036

Fig. 1. Locations of the study hospital and air pollution monitor. Locations are marked by black triangles and include the study hospital in the Liufang Nanli community and the US Embassy in Beijing, which is the source of the daily air pollution measurements tweeted by @Beijingair (screenshot of Twitter feed shown).

Fig. 2.

PM_{2.5} concentrations in Beijing, China, in January 2013. The solid black line shows daily average PM_{2.5} as measured at the US Embassy's monitor. Horizontal grey dashed lines show the U.S. PM_{2.5} standard (35 µg/m³) and WHO PM_{2.5} guideline (25 µg/m³). Other horizontal grey dashed lines show a PM_{2.5} concentration of 350 µg/m³, the threshold to identify episode days for our primary definition, and average PM_{2.5} concentration in Beijing over the study. The bold solid horizontal lines above the graph show episode dates as defined by different studies. Asterisks indicate atmospheric science, rather than epidemiologic, studies.

Fig. 3. Relative risks of health outcomes during the January 2013 episode compared to all other study days, controlling for confounders. For each outcome, central point estimates (dot) and 95% confidence intervals (horizontal lines) are shown.

Fig. 4. Sensitivity of results to different definitions of episode dates. Points show central estimates of relative risks while horizontal lines show 95% confidence intervals.

Table 1

Summary statistics for medical visits to the study hospital in the Liufang Nanli community of Beijing, February 17, 2009, to February 28, 2013, the January control days, case-crossover control days, and study episode, January 11, 2013, to January 13, 2013.

Outcome	Total over study period ^a	Mean daily count across full study period, February 17, 2009–February 28, 2013 (standard deviation)	Mean daily count for episode (January 11, 2013–January 13, 2013) days (SD)	Mean daily count across full study period, February 17, 2009–February 28, 2013, excluding the episode (January 11, 2013–January 13, 2013) (SD)	Mean daily count for control days used for January-only model (SD)	Mean daily count for control days used for case-crossover model (SD)
All Cause Emergency	200,098	151 (28.0)	207 (15.0)	151 (27.9)	152 (30.9)	164 (23.1)
Cardiovascular Emergency	5,459	4 (2.4)	6 (2.1)	4 (2.4)	4 (2.3)	3 (1.9)
Respiratory Emergency	68,492	52 (16.9)	81 (4.7)	52 (16.9)	59 (16.9)	62 (14.0)
All Cause Outpatient	1,892,748	1,427 (544.0)	1,329 (573.1)	1,428 (544.1)	1,294 (525.5)	1,459 (515.1)
Cardiovascular Outpatient	342,403	258 (129.1)	214 (155.2)	258 (129.1)	235 (121.9)	276 (130.5)
Respiratory Outpatient	300,421	227 (71.7)	336 (41.6)	226 (71.6)	249 (73.3)	301 (68.0)

^aTotal health outcome counts are the sum of all daily counts across the study period.

Table 2

Mean and interquartile ranges (IQR) for PM_{2.5} in Beijing, China, from February 17, 2009, to February 28, 2013.

Season ^a	Percent of days above:		
	Mean PM _{2.5} (µg/m ³) (Interquartile range)	US standard (35 µg/m ³)	WHO guideline (25 µg/m ³)
Overall	101 (43, 136)	80%	87%
Spring	83 (39, 113)	76%	84%
Summer	102 (64, 138)	89%	94%
Fall	109 (41, 154)	79%	87%
Winter	110 (38, 147)	77%	85%

^aMean and IQR PM_{2.5} measurements are provided across all study dates (Overall) and seasonally (Spring: March-May; Summer: June-August; Fall: September-November; Winter: December-February)

Relative risk (95% confidence intervals) for each health outcome comparing risk during the air pollution episode to all other days in the data set based on different models for sensitivity analysis.

Table 3

Model	Emergency Visits			Outpatient Visits		
	All-Cause	Cardiovascular	Respiratory	All-Cause	Cardiovascular	Respiratory
Main	1.29 (1.13, 1.46)	1.55 (0.90, 2.68)	1.33 (1.10, 1.62)	0.95 (0.82, 1.10)	0.83 (0.67, 1.02)	1.16 (1.00, 1.33)
Eliminated Weeks	1.37 (1.21, 1.55)	1.69 (0.97, 2.95)	1.46 (1.20, 1.77)	0.95 (0.82, 1.10)	0.82 (0.66, 1.01)	1.20 (1.04, 1.39)
Influenza Days Removed	1.29 (1.13, 1.46)	1.55 (0.90, 2.70)	1.33 (1.10, 1.61)	0.95 (0.82, 1.10)	0.83 (0.67, 1.02)	1.16 (1.00, 1.34)
No Influenza Spline	1.29 (1.12, 1.49)	1.57 (0.91, 2.72)	1.33 (1.07, 1.66)	0.95 (0.81, 1.10)	0.83 (0.66, 1.02)	1.16 (1.00, 1.35)
January-Only	1.22 (1.01, 1.47)	1.50 (0.81, 2.77)	1.28 (0.97, 1.69)	0.97 (0.69, 1.36)	0.84 (0.53, 1.31)	1.12 (0.92, 1.37)
Case-crossover	1.27 (1.15, 1.39)	1.76 (0.97, 3.20)	1.31 (1.13, 1.52)	0.91 (0.88, 0.94)	0.78 (0.71, 0.85)	1.12 (1.04, 1.20)

Table 4

Relative risks (95% confidence intervals) for health outcomes during the episode (January 10–17, 2013) compared to pre- and post-episode reference periods, based on applying the methodology and episode definition from Chen et al. (2013a) to data from our study population.

	Effect estimates from Chen et al. 2013 ^a	Effect estimates using our study data (different hospital) and Chen et al. 2013 methods ^b
All Cause Emergency	1.16 (1.02, 1.32)	1.12 (1.04, 1.20)
Cardiovascular Emergency	1.34 (0.98, 1.83)	1.34 (0.83, 2.17)
Respiratory Emergency	1.74 (1.44, 2.10)	1.12 (1.00, 1.25)
All Cause Outpatient	1.12 (1.09, 1.15)	0.81 (0.79, 0.83)
Cardiovascular Outpatient	1.16 (1.06, 1.27)	0.73 (0.69, 0.77)
Respiratory Outpatient	1.16 (1.07, 1.26)	0.94 (0.89, 0.99)

^aEffect estimates are shown as presented in the Chen et al. 2013a study, which used data from a different hospital in Beijing than the one used in this study.

^bEffect estimates using our health data from a hospital in the Liufang Nanli community of Beijing, using both Chen et al.'s (2013a) episode period definition and methodology for assessing the risk of a health event during the pollution episode compared to two reference periods (see Methods section).