ENVIRONMENTAL HEALTH

RESEARCH   **Open Access**

PM$_{2.5}$ in Beijing – temporal pattern and its association with influenza

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Abstract

Background: Air pollution in Beijing, especially PM$_{2.5}$, has received increasing attention in the past years. Despite Beijing being one of the most polluted cities in the world, there has still been a lack of quantitative research regarding the health impact of PM$_{2.5}$ on the impact of diseases in Beijing. In this study, we aimed to characterize temporal pattern of PM$_{2.5}$ and its potential association with human influenza in Beijing.

Methods: Based on the data collected on hourly ambient PM$_{2.5}$ from year 2008 to 2013 and on monthly human influenza cases from 2008 and 2011, we investigated temporal patterns of PM$_{2.5}$ over the five-year period and utilized the wavelet approach to exploring the potential association between PM$_{2.5}$ and influenza.

Results: Our results found that ambient PM$_{2.5}$ pollution was severe in Beijing with PM$_{2.5}$ concentrations being significantly higher than the standards of the World Health Organization, the US EPA, and the Chinese EPA in the majority of days during the study period. Furthermore, PM$_{2.5}$ concentrations in the winter heating seasons were higher than those in non-heating seasons despite high variations. We also found significant association between ambient PM$_{2.5}$ peak and human influenza case increase with a delayed effect (e.g. delayed effect of PM$_{2.5}$ on influenza).

Conclusions: Ambient PM$_{2.5}$ concentrations were significantly associated with human influenza cases in Beijing, which have important implications for public health and environmental actions.

Keywords: Air pollution, PM$_{2.5}$, Temporal pattern, Association, Influenza, Beijing

Introduction

Air pollution has long been held as one of the foremost threats to human health, especially in metropolitan areas throughout the world [1-4]. In China, rapid urbanization has been recognized as a cause of increased amounts of air pollution, especially in the capital city of Beijing [5]. Some reports indicated that air pollution in Beijing to be worsening every year, especially for PM$_{2.5}$, with concentrations vastly exceeding China's urban hourly standard of 75 μg/m^3 [6-9]. The numbers of migrants and automobiles in Beijing are set to continue as the Chinese government looks to urbanization to grow its economy, and thus PM$_{2.5}$ pollution is becoming ever important to study as detrimental to the health of the residents, especially those living in big metropolitan areas globally [10] (Table 1).

PM$_{2.5}$, particles with an aerodynamic diameter of less than 2.5 μm, has some important chemical and physical characteristics, varying from place to place [11]. Many chemical constituents, such as sulfates, nitrates, ammonium, inorganic ions, organic elemental carbon, particle-bound water, polycyclic aromatic hydrocarbons (PAH), and among other, can be part of the composition of PM$_{2.5}$ [12]. In Beijing, carbonaceous aerosols and major ions (sulfate, nitrate and ammonium) constituted more than 69% of PM$_{2.5}$ with the major sources coming from dust, secondary sulfate and nitrate, coal combustion, and diesel and gasoline exhaust [8]. Exposure to PM$_{2.5}$ has already been linked to many health issues, such as arrhythmia [13], and systemic vascular dysfunction [14], among others. For the millions living and moving to Beijing, daily inhalation of polluted air could become a major health issue, with the government already advising citizens to stay inside on high concentration days [15]. Therefore, the potential risk for increased mortality rates merits increased research in PM$_{2.5}$ pollution itself, but

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Table 1 Characteristics of PM$_{2.5}$ measurements and days exceeding the standards by the SEPA, EPA, and the WHO from 2008 to 2013

Year	Measurements (days)	Range (lowest, highest)	Annual mean	Days[1] (%)	Days[2] (%)	Days[3] (%)
2008	212	(5.8 235.38)	84.74 (50.31)	105 (49.53)	174 (82.08)	194 (91.51)
2009	263	(13.94, 482.25)	104.65(70.41)	165 (62.74)	227 (86.31)	239 (90.87)
2010	320	(9.0, 441.5)	104.89 (76.38)	186 (58.13)	267 (83.44)	286 (89.38)
2011	333	(10.38, 492.75)	98.30 (79.65)	170 (51.05)	257 (77.18)	279 (83.78)
2012	329	(2.92, 428.54)	91.74 (68.85)	169 (51.37)	246 (74.77)	278 (84.50)
2013	289	(10.5, 568.57)	103.04 (83.77)	149 (51.56)	242 (83.74)	262 (90.66)

Days[1] – days with 24-hr average exceeding the SEPA standard; days[2] – days with 24-hr average exceeding the EPA standard; days[3] – days with 24-hr average exceeding the WHO standard.

despite PM$_{2.5}$ pollution becoming a prevalent problem, the public, especially the ordinary residents in China lack of access to the quality and quantity of air quality data. Occasionally, the data come in small intervals, with one study only obtaining access to 37 days [16]. Unfortunately, small sample sizes do not allow for thorough understanding of the problem at hand. Moreover, air pollution has become a long-term problem as well; many health effects are chronic due to long-term exposure. As such, it becomes important to analyze longer trends of air pollution in order to establish a clearer understanding of what the future might bring.

In addition to these health effects associated with PM$_{2.5}$ exposure, there is increasing concern over its association with infectious diseases, some of which have caused major global health issues. Of particular note is influenza, which is a major global health problem, especially in China [17,18]. Geographic variations in influenza in China are prevalent throughout the nation, creating complex problems regarding vaccination programs [19]. Special strains of influenza outbreaks in China have presented challenges of adequately addressing influenza health crises [20]. Influenza complications can lead to severe respiratory diseases, a health issue that has also been linked with PM$_{2.5}$ exposure [21]. Though ostensibly different health issues, exposure to PM$_{2.5}$ can potentially exacerbate flu symptoms, yet no study has explored the relationship between PM$_{2.5}$ exposure and influenza cases. To address this, we studied the measurements collected from Embassy of the United States in Beijing, ranging from 2008 to 2013, obtaining detailed information regarding PM$_{2.5}$ concentrations on an hourly basis, and influenza case data from Beijing in an attempt to establish such a relationship, which may contribute to the future changes in environmental regulation and public health policies.

Materials and methods
Sources of data
Hourly measurements of PM$_{2.5}$ from April 2008 to October 2013 were collected from an air quality monitoring site at the US Embassy in Beijing. The Embassy used two US EPA approved air quality monitors [MetOne BAM 1020] to measure PM$_{2.5}$ particulates at hourly intervals in the Chaoyang district, where the Embassy compound is located (39.953°N 116.459°E). We chose the Embassy's air pollution data because it recorded detailed measurements of PM$_{2.5}$ over a long period of time, despite originating from only one source. Other sources of PM$_{2.5}$ data include Chinese government agencies, but their released data are sporadic (short-term and discontinuous), limiting proper characterization of PM$_{2.5}$ [16]. The hourly measurements (C_{hr}) were converted to daily average $\left(\tilde{C}_{daily} = \sum_1^{24} C_{hr}/24 \right)$ and monthly average $\left(\tilde{C}_{monthly} \right)$ for subsequent analyses described below. From December 2008 to February 2009, the Embassy air quality monitor had malfunctions, leading to missing measurements for this three-month period. In addition to describing characteristics of PM$_{2.5}$ concentrations over the five-year period, we were also interested in potential relationships between air quality and health impacts, specifically respiratory infections. In this study, we explored the association between PM$_{2.5}$ concentrations and human influenza in urban area of Beijing. In China, influenza has been on the list of Class C notifiable diseases as part of China's national infectious diseases surveillance (now called National Infectious Diseases Reporting Systems, or NIDR) since 1970 and individual cases were reported by hospitals and clinics required by law [20]. At participating surveillance hospitals, each influenza-like case (defined as the one with body temperature ≥38°C and cough or sore throat) is recruited, sample (nasal or throat swab) is taken and sent for laboratory confirmation. Sample handling and processing follow national standard protocol by Ministry of Health [22]. Both influenza-like case and confirmed case information are then reported to the NIDR system [22]. Nevertheless, under-reporting does exist, as elaborated further in discussion section. In this study, reported influenza case data from January 2008 to December 2011 for all 17 districts in Beijing were retrieved from the National Infectious Disease Reporting

system (NIDR). The reported cases from the NIDR system were aggregated for each district at the monthly interval. Since the US Embassy is located in Chaoyang district, reflecting a typical downtown setting of Beijing, we assume that the $PM_{2.5}$ measurements from the US Embassy were likely representative of downtown environment. To explore the possible association between the $PM_{2.5}$ and human influenza, we aggregated human influenza cases for the following eight districts which include and/or surround downtown areas: Haidian, Dongcheng, Xicheng, Chaoyang, Fengtai, Shijingshan, Chongwen, and Xuanwu districts. The aggregated data and $PM_{2.5}$ measurements were then explored using the Wavelet analysis described below.

Descriptive and wavelet analyses

Descriptive statistical analyses were performed to characterize the following aspects of air quality in Beijing: daily and monthly averages, minimum and maximum concentrations of $PM_{2.5}$, peak days/seasons of $PM_{2.5}$, days of exceeding the standard for $PM_{2.5}$ by the World Health Organization [23], the US EPA and the Chinese EPA [6],, monthly variations in $PM_{2.5}$ concentrations by overlaying the six years' monthly averages.

   Like many environmental and epidemiological time-series data, the $PM_{2.5}$ and influenza time-series data are subject to non-stationary properties which are usually complex [24]. To account for these factors, we used wavelet analysis to characterize the temporal patterns of monthly $PM_{2.5}$ concentrations, following the general approach described by Cazelles *et al* [24]. Wavelet analysis was used to decompose a time-series from a time domain to time-frequency (or time-period) domain and detect localized intermittent periods of a time-series [25]. Following the general approach described by Grinsted *et al.* [26] we used cross wavelet coherence approach to explore the possible association between the two time-series, $PM_{2.5}$ concentrations and human influenza cases. The cross wavelet angle was used to assess the phase difference between components of the two time series (for technical details, please refer to (Grinsted *et al.*, 2004)). A Matlab package for performing cross wavelet coherence analysis was downloaded for the analysis (http://noc.ac.uk/using-science/cross-wavelet-wavelet-coherence).

Results

Descriptive analysis

The $PM_{2.5}$ measurements covered a span of five years, from 2008 to 2013, encompassing 43,255 hourly measurements. Figure 1 shows the hourly measurements of $PM_{2.5}$ over the five-year period and indicates that, for the most part, $PM_{2.5}$ concentrations way exceed the US EPA and Chinese standards of 35 μg/m^3. Figure 1 also

shows the monthly average, 97.5 and 2.5 percentiles of monthly measurements, superimposed with the 35 μg/m^3 line showing the US EPA and the Chinese National standard. Clearly, all monthly averages exceeded the standard (Figure 1). Overall, the $PM_{2.5}$ concentrations were lowest in 2008 and then increased in the following years (Figure 1). We counted days for each month with daily average over the standard for the whole study period and Figure 2 shows the distribution of days with the daily $PM_{2.5}$ exceeding the national standard (Figure 2). Only 328 days out of 1746 days met the standard and the remaining 1418 days (the number of days exceeding the 35 μg/m^3 standard was 81.21%) exceeding the standard with the range between more than 35 μg/m^3 to 550 μg/m^3 (Figure 2). Note that there was a three-month period during which the measurements were missing due to malfunctions of the equipment. Figure 3 shows monthly averages over a span of 12 months superimposed for each year from 2008-13, in order to identify potential season trends. From April to June, the monthly averages are similar for every year, but besides that period there is quite a bit of variation. There are clear within- and between-year variations in monthly averages of $PM_{2.5}$ – overall, the months with lowest concentrations were clustered between April and May, and highest months were concentrated between October and December with the highest variations in January (Figure 3). The heating season in Beijing, which starts in mid-November and ends in mid-March, is shaded in blue. Generally, $PM_{2.5}$ concentrations tend to rise during this period (Figure 3).

Wavelet analysis

To explore the evolution of the oscillating characteristics of the time-series of $PM_{2.5}$ at the monthly interval over the five-year period in Beijing, we used the wavelet approach. Transient dynamic relationships were observed as shown in Figure 4 – the monthly $PM_{2.5}$ over the study period was dominated by a slightly greater than 1-year mode, particularly after 2009. During the 2008 and 2009, weak dominant modes (1-1.3 years) were observed (Figure 4).

   We also use the cross wavelet approach to explore the potential relationship between $PM_{2.5}$ concentrations and human influenza. Figure 5 shows the time profiles of $PM_{2.5}$ concentrations and human influenza reported in urban areas of Beijing from 2008 to 2011 (Figure 5). Interestingly, the wavelet coherence analysis shows that there is clearly significant correlation between the two quantities from December 2008 to June 2010 period and downward phase angle (close to 90°, equivalent to 1-2 months), suggesting that there was a delay in the occurrence of influenza following $PM_{2.5}$ (Figure 5).
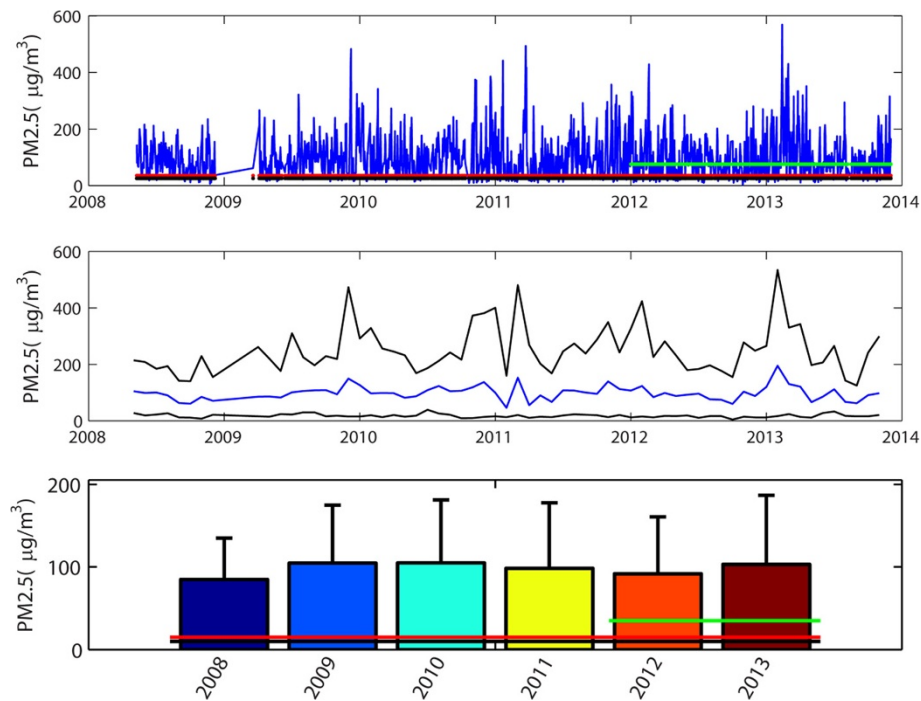
Figure 1 PM$_{2.5}$ concentrations (µg/m^3) from 2008 to 2013 in Beijing. Top-24-hour averages of PM$_{2.5}$ measurements superimposed with standards by the WHO (25 µg/m^3 for the 24-hour average, black line), the USEPA (35 µg/m^3 for the 24-hour average, redline), and the Chinese State Environmental Protection Administration (SEPA, 75 µg/m^3, implemented from 2012, green line; the 75 µg/m^3 standard, or Class II standard, was developed specific for residential, commercial, industrial, and heavy-traffic areas) (ref, Cao et al. *Chinese and US air quality standard evolution paper*). Middle - Monthly variations in average, 97.5 and 2.5 percentiles of PM$_{2.5}$ from 2008 to 2013 in Beijing. Bottom – Annual averages of PM$_{2.5}$ concentrations from 2008 to 2013, superimposed with the standards by the WHO (10 µg/m^3 for the annual average, black line), the US EPA (15 µg/m^3 for the annual average, redline, the EPA standard was reduced to 12 µg/m^3 after 2013), and the SEPA (35 µg/m^3, implemented from 2012).

Discussion

Many studies, in particular epidemiological studies, have demonstrated strong evidence for the association between particulate air pollution (from both PM$_{10}$ and PM$_{2.5}$) and human illness, in particular cardiovascular and respiratory disease. Both short- and long-term exposures to ambient particulate matters have implications for different health impacts [13,27-31]. In China, much attention on air pollution has been focused on PM$_{10}$, and the studies about PM$_{2.5}$ exposure on health impact in China have just started. In this study, we report a five-year period of PM$_{2.5}$ measurements from an urban site of Beijing and its possible association with human influenza. To our knowledge, this is the first study reporting comprehensive measurements of PM$_{2.5}$ related to influenza in Beijing, China.

Although the present study only used data from one monitoring site in Beijing, it certainly reflects the unacceptably high air pollution occurring in one of the most populated cities in the world. From the monitoring records, on average, more than 81% of days each year, people live in the environment with polluted air exceeding US EPA and Chinese health standards. PM$_{2.5}$ has

increasingly been shown to be more harmful to human health than bigger particles since the smaller particles have more potential to be deposited in the alveoli and even penetrate the blood-gas barrier [32]. However, China has only been recently releasing PM$_{2.5}$ concentrations to the public in major cities. We all recognize that significant efforts have been made, but record-breaking pollution levels were recorded in the winter of 2013 in Beijing, China [33]. This indicates that more comprehensive efforts still are needed so that the air quality improvements during the Beijing Olympic Games in 2008 could be sustainable [34,35].

Air pollution has been implicated in respiratory illness infections [36]. Moreover, many reports are related to indoor air pollution (e.g. combustion) which has been related to acute lower respiratory infections [37-40] and this has been a concern in many developing countries. There are not many studies related to ambient air pollution and infections, although there are reports on association between air pollution and pneumococcal disease related to respiratory viruses [41]. In this study, we chose to explore the potential linkage between exposure to PM$_{2.5}$ and human influenza, given the consideration
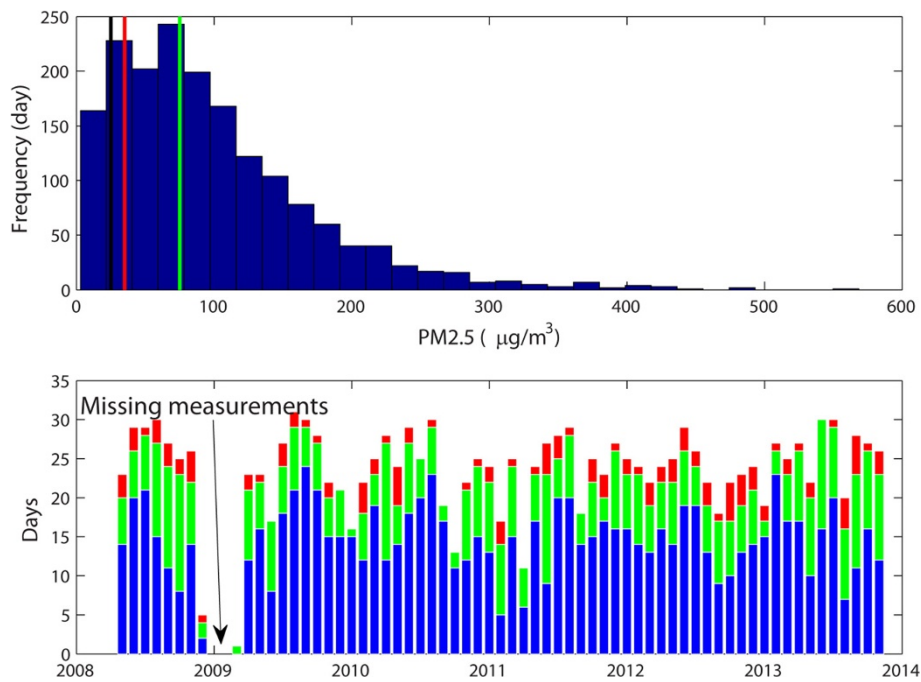
Figure 2 Distribution of PM$_{2.5}$ concentrations and days with 24-hr averages exceeding the standards. Top – frequency distribution of days with varying 24-hr average concentrations for the whole study period; black line – the WHO standard (25 μg/m^3), redline – the EPA standard (35 μg/m^3), green – the SEPA standard (75 μg/m^3). Bottom – distribution of days each month with the 24-hr averages exceeding the standards by the WHO (red), the EPA (green) and SEPA (blue). The gap between December 2008 and February 2009 was due to missing measurements.
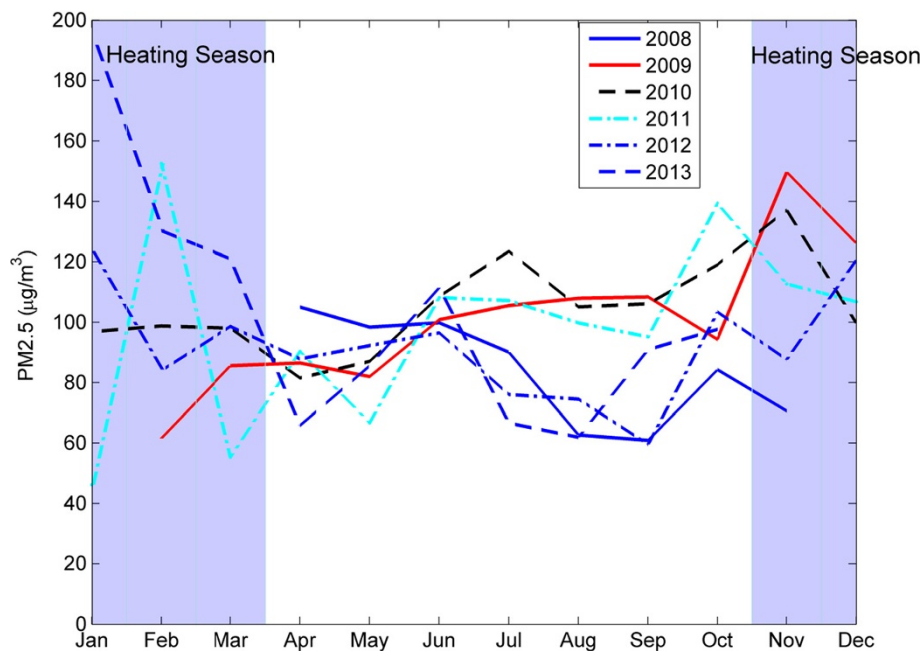

Figure 3 Monthly variations in PM$_{2.5}$ in Beijing for each year between 2008 and 2013. The light blue shaded area covers from the mid-November to mid-March, typically winter season in Beijing during which centralized heating is provided. Overall, the PM$_{2.5}$ concentrations are higher in the winter season. During 2008, the year of the Beijing Olympics, the Chinese government imposed regulatory controls on emissions, which may be a mechanistic explanation for why concentrations in 2008 are generally lower in each month than concentrations in other years.
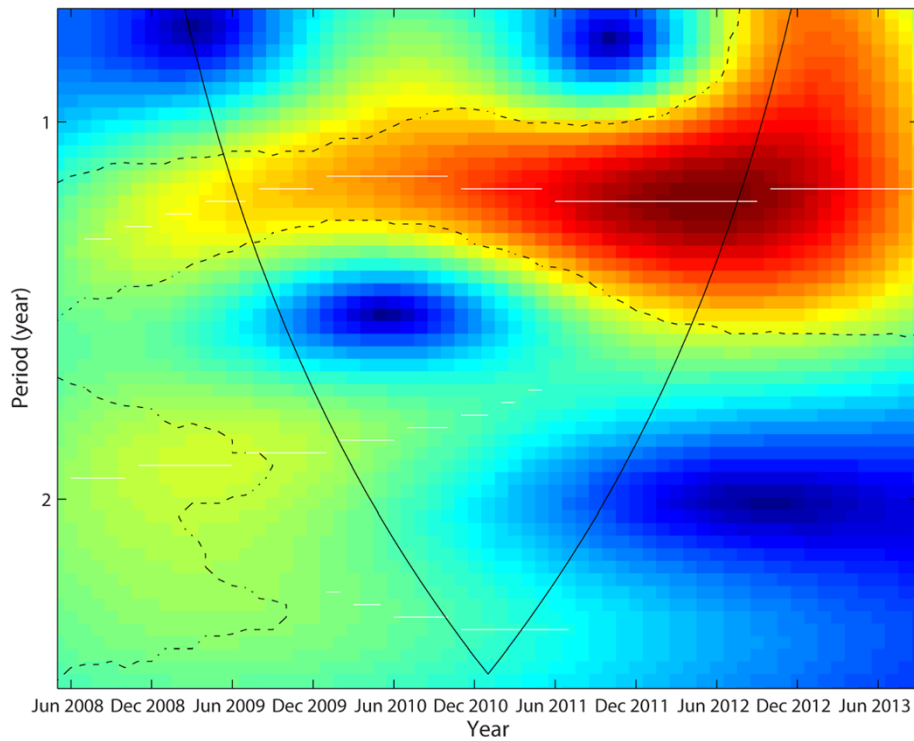
Figure 4 Wavelet power spectrum analysis of monthly PM$_{2.5}$ concentrations from year 2008 to 2013 in Beijing. The color code for power values from dark blue (low value) to dark red (high value). The dotted white lines show the maxima of the undulations of the wavelet power spectrum and the dotted-dashed show the α = 5% significant levels and the cone of influence which indicates the region not influenced by edge (following the algorithm/software by Cazelle et al. 2007).
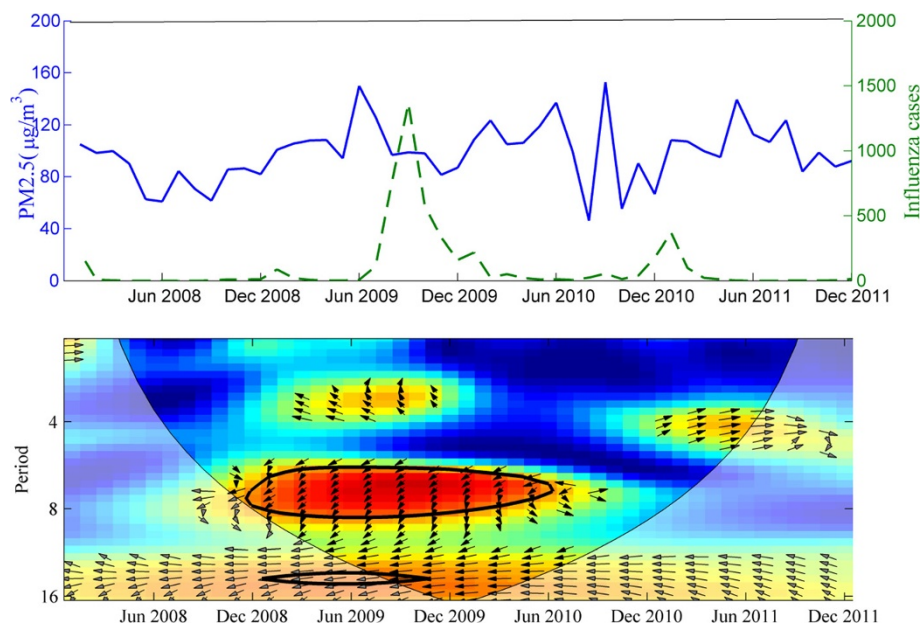
Figure 5 The association between monthly PM$_{2.5}$ (μg/m^3) and reported influenza cases (in five urban districts) from 2008 to 2011 in Beijing. Top – monthly PM$_{2.5}$ and reported influenza cases. Bottom: Wavelet coherence between the standardized PM$_{2.5}$ measurements and reported influenza cases in Beijing. The 5% significance level against red noise is shown as a thick contour. The relative phase relationship is shown as arrows, suggesting that PM$_{2.5}$ leads influenza by about 90° pointing down, equivalent to 1-2 months delay in occurrence.

of nature of the disease, biological plausibility, and availability of the influenza data. Using three-year's data, our study suggested that human influenza cases were correlated to $PM_{2.5}$ concentrations in Beijing and the finding is in general agreement with other studies [42]. This seems to have a time lag while peaks of $PM_{2.5}$ levels were followed by peaks of influenza in 2009 and 2010. Interestingly, the peak of $PM_{2.5}$ levels were not obvious in 2008, so was relatively moderate for influenza cases during the same year, which further strengthens the correlation between $PM_{2.5}$ exposure and influenza occurrence. The underlying possible mechanisms related to this are complex. There are some reports about ambient air pollution on respiratory infections in humans [43,44] and it is likely that air pollution exposure causes host defense disorders, including both innate and cell-mediated immune responses against bacterial and viral infections [45,46]. Various experimental studies have suggested that the deposition of particulates on epithelial cells that line the airways activates inflammatory signaling cascades [47,48]. In addition, high $PM_{2.5}$ levels could precipitate inflammatory and tissue remodeling changes in the lungs [49].

The study is also subject to some limitations. First, we only used one measurement source from the US Embassy, limiting spatial representativeness of the present work. Second, our data suffer from under-reporting of influenza cases; however, the under-reporting tends to occur in consistent pattern throughout the country and we believe that the relative pattern (e.g. seasonal variations in influenza) still holds. Third, the observational time periods of five years for $PM_{2.5}$ levels and three years for influenza cases are relatively short, especially when a definite, strong correlation is concluded. Fourth, one kind of infectious disease, such as influenza in our study, may not be ideal, and more similar respiratory infectious diseases should be included in the future to demonstrate strong and broad correlation between $PM_{2.5}$ and infectious diseases. Nevertheless, this study demonstrates a temporal correlation between $PM_{2.5}$ pollution and influenza peak occurrence in Beijing, which provides significant impact on both environmental policy-making and public health preparedness.

In conclusion, despite the limitations, our study has indicated severity of $PM_{2.5}$ pollution in urban Beijing and health implications associated with human influenza. Further studies are in urgent need to understand the mechanisms underlying the potential association as well as public health and environmental policy implications.

Abbreviations
$PM_{2.5}$: Fine particulate matters; US: The United States of America; US EPA: United States Environmental Protection Agency.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
YL, LF, KZ, HK and QS have made substantial contributions to conception and design, acquisition of data, and analysis and interpretation of data; YL, LF, HP, HK, JRB and QS have been involved in drafting the manuscript critically for important intellectual content. All authors read and approved the final manuscript.

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