LETTER

Estimating the mortality burden attributable to temperature and PM$_{2.5}$ from the perspective of atmospheric flow

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Abstract

The flow of the Earth’s atmosphere not only largely determines its temperature status, but also profoundly affects aerosol concentrations. Therefore, exploring how to evaluate the synthetical effects of temperature and aerosol pollution on human health is an important topic. Regarding the atmosphere as a whole, we quantified the mortality burden attributable to short-term exposure to abnormal temperatures and PM$_{2.5}$ in Beijing from the perspective of atmospheric flow. We first divided the atmospheric stability into three levels (including disturbed, normal, and stable conditions) according to the variations in meteorological conditions and PM$_{2.5}$ concentrations across the stable weather index levels. We then applied a generalized additive model to separately evaluate the short-term effects of temperature and PM$_{2.5}$ on mortality under each level of atmospheric stability. We further estimate the associated mortality burden using two indicators, namely attributable fraction and attributable number of deaths. Abnormal temperatures were responsible for most of the mortality burden. Cold temperatures accounted for a substantially higher mortality burden than hot temperatures. The synthetical mortality effects of temperature and PM$_{2.5}$ varied for different atmospheric stabilities. A stable atmosphere poses the strongest synthetical effects of temperature and PM$_{2.5}$, while a normal atmosphere provides comparatively beneficial conditions for human health. Our results indicated that the synthetical health impacts of temperature and PM$_{2.5}$ driven by atmospheric flow need to be considered in the further promulgation of public health policies and air pollution abatement strategies, particularly in the context of climate change.

1. Introduction

Extensive epidemiological studies have demonstrated the adverse effects of abnormal ambient temperatures [1–3] and PM$_{2.5}$ [4–7] on human health. These evidences are almost exclusively based on the separate estimations of the effects of temperature and PM$_{2.5}$; thus, it is unclear whether and to what extent there is a discrepancy between the magnitude of the health effects of these two factors. More importantly, the flow of the Earth’s atmosphere not only largely determines its cold and hot status, but also profoundly affects aerosol concentrations. Hence, humans suffer from the synchronous impacts of abnormal temperatures and aerosol pollution. As such, considering the atmosphere as a whole is pivotal to reaching a comprehensive understanding of the health effects of changes in temperature and PM$_{2.5}$. This is particularly important in the context of climate change, which significantly affects the occurrence of extreme temperature events [8] and air pollution [9].

As a result of urbanization and industrialization, the frequent occurrence of haze episodes caused by
PM$_{2.5}$ pollution has become a severe air pollution issue negatively affecting many countries worldwide, particularly those with middle- and low-income economies. Despite large pollutant emissions being the primary cause, conducive weather conditions are favorable for the development and maintenance of haze events [10–12]. Meteorological conditions can influence the evolution of haze episodes by dynamic and thermodynamic effects of various factors, including temperature, wind speed, relative humidity, pressure, and the mixing layer height, thus, affecting the intensity, frequency and duration of extreme events, which have substantial impacts on human health, such as heat waves, cold spells, and severe haze episodes.

As a comprehensive meteorological condition index, the stable weather index (SWI) has been developed to quantitatively describe the stability and mobility of the atmosphere [13]. Low SWI values signify severe fluctuations in the atmosphere, which are favorable for the dispersion of pollutants, whereas high SWI values signify stable weather conditions conducive for haze formation. The SWI has been widely applied by the National Meteorological Center of the China Meteorological Administration to predict the meteorological potential and the evolution of air pollution, and to quantitatively estimate the impacts of meteorological conditions on the air pollution process and reductions in PM$_{2.5}$ concentration resulting from emission reduction measures. Yet, it can be extended to a medium for synthesizing the health effects of temperature and PM$_{2.5}$ because variations in the SWI reflect the associated variations in both PM$_{2.5}$ concentrations and weather conditions.

Moreover, to mitigate PM$_{2.5}$ pollution and protect public health, the Chinese government launched the Air Pollution Prevention and Control Action Plan (referred to as the APPCAP henceforth) in September 2013, which has led to substantial declines in PM$_{2.5}$ concentrations nationwide and, subsequently, to significant health benefits associated with reduced PM$_{2.5}$ exposure [14–18]. However, studies on the changes in the comprehensive health effects related to temperature and PM$_{2.5}$ are limited. Such evaluation has practical implications for the formulation of further pollution control strategies and for developing comprehensive public health policies.

Herein, considering the atmosphere as a whole, we quantified the mortality burden attributable to the short-term exposure to abnormal temperatures and PM$_{2.5}$ in Beijing, a megacity located between the mid- and high-latitudes in East Asia and characterized by monsoon transitions. We first divided the atmospheric stability into three levels (including disturbed, normal, and stable conditions) according to the variations in meteorological conditions and PM$_{2.5}$ concentrations across SWI levels. We then applied a generalized additive model (GAM) to separately evaluate the effects of temperature and PM$_{2.5}$ on mortality under each level of atmospheric stability. We used this as a base to further estimate the associated mortality burden using two indicators, namely attributable fraction and attributable number of deaths. Our results offer additional insights into the adverse health effects of temperature and PM$_{2.5}$ from the perspective of atmospheric flow and have beneficial implications for the planning of public health policies.

2. Materials and methods

2.1. Data collection

2.1.1. Environmental data

We obtained daily average data on PM$_{2.5}$ from 1 March 2009 to 31 December 2016 from the US Embassy station in the Chaoyang District. The maximum 8 h average data on ozone (O$_3$) was derived from the Bao Lian station in the Haidian District. We collected daily data on meteorological elements, including mean temperature, pressure, wind speed, and relative humidity over the same period from the Beijing Meteorological Observation Center. The geographic locations of monitoring stations in this study are shown in figure S1 (available online at https://stacks.iop.org/ERL/15/124059/mmedia).

In addition, we derived the SWI data from the National Meteorological Center of the China Meteorological Administration. The SWI was calculated using the meteorological data obtained from the National Centers for Environmental Prediction reanalysis data ($1^\circ \times 1^\circ$). The subindex of any meteorological parameter is adopted to determine its impact degree on stable weather, which is defined as the ratio of the probability of haze weather occurring under different segments of this parameter to the climatological probability. The subindex of any parameter was segmentally calculated according to specific division methods, which are described in supplementary note 1. The leading ten parameters (in the order of descending rank) were ultimately proved to be significant indicators for stable weather, including 2 m relative humidity, 10 m wind speed, the potential temperature differences at 850 hPa and 925 hPa, the vertical velocity at 925 hPa, relative humidity at 925 hPa, 24 h pressure variation, 24 h temperature variation at 850 hPa, the relative humidity differences at 700 hPa and 1000 hPa, meridional wind at 500 hPa and sea level pressure. The SWI was calculated by summing the subindices of the ten meteorological elements. The detailed calculation method of the SWI is provided in supplementary note 1.

2.1.2. Mortality data

We derived daily mortality data for all urban residents in Beijing from the Chinese Center for Disease Control and Prevention. Causes of deaths were coded according to the International Classification of Disease, 10th Revision. We collected mortality data for two primary specific causes: deaths due to respiratory
2.2. Statistical analysis

2.2.1. Estimation of exposure-response association

We utilized a GAM that allows for over-dispersed death counts to separately evaluate the short-term effects of PM$_{2.5}$ or temperatures on daily mortality. The underlying nonlinear effects of confounding factors can be controlled for by nonparametric smoothing functions in the GAM. Several common covariates were incorporated to establish the core models: (a) spline function with 7 degrees of freedom (df) to control for the long-term trend in mortality; (b) spline function with 3 df for relative humidity and O$_3$ to control for their potential effects; (c) an indicator variable for day-of-week. Moreover, when estimating the mortality effects of PM$_{2.5}$, a spline function with 3 df for mean temperature was additionally included in the main model to control for the effects of temperature; when estimating the mortality effects of temperature, a spline function with 3 df for PM$_{2.5}$ was additionally included in the main model to control for the effects of PM$_{2.5}$.

Growing epidemiological evidence indicates that abnormal ambient temperatures could increase the risk of death from a wide range of diseases, and J-, V-, and U-shaped associations between temperature and mortality have been reported [19, 20]. The minimum mortality results from the optimum temperature, termed as the minimum mortality temperature (MMT) [21]. Mortality risks increase with mean temperatures above and below the MMT. Previous studies reported that MMTs in different regions approximately corresponded to the 75th percentile of the temperature distribution [22–24], equivalent to 24.1 °C in this study. Thus, mean temperatures were stratified as cold (<24.1 °C) and hot (>24.1 °C) with the threshold of 24.1 °C. We separately estimated the mortality effects of hot and cold temperatures.

In addition, the short-term effects of ambient temperatures and PM$_{2.5}$ exhibit different lag patterns. Specifically, the mortality effects of cold temperatures last for more than 14 d [25, 26], whereas the effects of hot temperatures may be acute after exposure [27]. Significant associations were found between mortality and PM$_{2.5}$ on lag0 and lag1 [28]. Thus, we incorporated different lag periods in the model, with lag periods extending to 15 d (lag0 to lag14) for cold temperatures and 4 d (lag0 to lag3) for hot temperatures and PM$_{2.5}$, respectively. We selected the maximum estimations of different exposure factors across the lag periods to conduct the further analyses. Additionally, to test the robustness of our results, we performed sensitivity analyses by altering the df value from 5 to 8 for calendar time and to 3, 5, 7, and 9 for relative humidity.

The excess risk (ER%) was used to estimate the proportional increase in the daily mortality per 10 µg m$^{-3}$ increase in PM$_{2.5}$ concentrations and per 1 °C change (per 1 °C decrease in cold temperatures and per 1 °C increase in hot temperatures) in temperature. The above analyses were conducted using the ‘mgcv’ package in the R software (Version R 3.6.0). All statistical tests were two-sided and $P < 0.05$ was defined as statistically significant.

2.2.2. Estimation of mortality burden

We calculated the attributable fraction and attributable number of deaths to quantitatively evaluate the mortality burden associated with short-term exposure to abnormal temperatures and PM$_{2.5}$. The equations are given as follows [29–31]:

$$ AF = \sum \{ \text{baseline mortality} \times [1 - 1/\exp(\beta \times \Delta Y)] \} / \text{total mortality} $$

(1)

$$ AN = \sum \{ \text{baseline mortality} \times [1 - 1/\exp(\beta \times \Delta Y)] \} $$

(2)

where AF and AN are the attributable fraction and attributable number of deaths; baseline mortality are the death counts at a specific day; $\beta$ is the exposure-response relation coefficient of the mortality effects of temperatures and PM$_{2.5}$ derived from the GAM; when the mortality burden attributable to abnormal temperatures is calculated, $\Delta Y$ is the mean temperature difference between the actual observation and the threshold level at which the minimum adverse health effects appear (24.1 °C). When the mortality burden attributable to PM$_{2.5}$ is calculated, $\Delta Y$ is the concentration difference between the actual observation and the threshold level at which no adverse health effects occur. It has been reported by the World Health Organization (WHO) that there is little evidence for a threshold for airborne particulate matter below which no harmful health effects could be anticipated [32]. Therefore, 0 µg m$^{-3}$ was selected as the PM$_{2.5}$ threshold concentration.

We estimated the mortality burden related to abnormal temperatures and PM$_{2.5}$ for respiratory and circulatory disease at overall and daily mean levels. Furthermore, we analyzed changes in the mortality burden before the APPCAP implementation (from 2010 to 2013) and after (from 2014 to 2016). The yearly mortality burden from 2010 to 2016 was also estimated. The reason for why the mortality burden in 2009 was not estimated was that missing data in 2009 could not be included in the final estimation. We divided SWI values into 11 levels, and data of 0 < SWI ≤ 5 and SWI > 14 were separately merged.
into a group due to the small sample size. The frequency distribution of daily SWI was skewed to the left with a peak in the range of 12–13 (figure 1(a)). The daily SWI was positively correlated with daily PM$_{2.5}$ concentrations (Pearson correlation coefficient $= 0.54$, $P < 0.001$). Concentrations of PM$_{2.5}$ increased with increments in SWI, signifying that higher SWI values corresponded to more favorable weather conditions for haze formation (figure 1(b)). Further, we selected two heavily polluted months from the study period, February and October in 2014, when the daily average PM$_{2.5}$ concentrations were $174.7 \, \mu g \, m^{-3}$ and $150.8 \, \mu g \, m^{-3}$, respectively. There were only 3 d during February, 2014 and 2 d during October, 2014 with 24 h average PM$_{2.5}$ concentrations lower than the air quality guideline ($25 \, \mu g \, m^{-3}$) proposed by the WHO [32]. Additionally, there were 20 d during February, 2014 and 19 d during October, 2014 exceeded the second grade ($75 \, \mu g \, m^{-3}$) of the Ambient Air Quality Standard (GB3095-2012) proposed by the Chinese government [33]. The variations in mean temperatures exhibited an inverse V-shape with a peak at the SWI range of 9 and 13, daily average PM$_{2.5}$ concentrations progressively increased, whereas wind speed and diurnal pressure range gradually decreased. The division basis was amplified as follows. Overall, as SWI levels increased, relative humidity and PM$_{2.5}$ concentrations progressively increased, whereas wind speed and diurnal pressure range gradually decreased. The variations in mean temperatures exhibited an inverse V-shape with a peak at the SWI range of 12–13. Specifically, when SWI values were equal or lower than 9, the positive values of the diurnal pressure range indicated increments in pressure resulting from the disturbance by cold air masses; the atmospheric stability was defined as being in a stable condition at SWI > 13. Consequently, the atmospheric stability was defined as being in a normal condition at 9 < SWI ≤ 13. The division of atmospheric stability into three conditions, including disturbed conditions at SWI ≤ 9, normal conditions at 9 < SWI ≤ 13 and stable conditions at SWI > 13. The division was determined based on the variations in the daily average values of 21.2 and 97.8, respectively. Analogously, V-shaped patterns could be observed for the relationships between SWI levels and daily average deaths, with the minimum value at 12 < SWI ≤ 13 for circulatory disease and 13 < SWI ≤ 14 for respiratory disease (figure 2(b)).

### 3.3. Variations in daily average deaths by SWI level

From 1 March 2009 to 31 December 2016, there were 60 698 deaths from respiratory disease and 280 135 deaths from circulatory disease in Beijing, with daily average values of 21.2 and 97.8, respectively. Furthermore, disturbances could be observed for the relationships between SWI levels and daily average deaths, with the minimum value at 12 < SWI ≤ 13 for circulatory disease and 13 < SWI ≤ 14 for respiratory disease (figure 2(b)).

### 3.4. Mortality effects of temperature and PM$_{2.5}$

The effect estimates of the identical exposure factor varied apparently for different atmospheric stabilities, which were overall statistically significant with the exception of the association between PM$_{2.5}$ and respiratory mortality under stable conditions (table 1). For the effects of ambient temperature, the magnitudes of hot temperatures were generally larger than those of cold temperatures under any atmospheric stability condition. For the effects of PM$_{2.5}$, we observed the strongest mortality effects under the disturbed conditions. Additionally, in sensitivity analyses, there were no significant changes in the effect estimates when altering the df value for calendar time (table S2) and relative humidity (table S3), indicating the robustness of the estimates obtained from the core model.

### 3.5. Mortality burden attributable to temperature and PM$_{2.5}$

Overall, the mortality burden was mainly attributable to cold temperatures, followed by PM$_{2.5}$, while hot temperatures had the least effect (figures 3(a) and (b)). For respiratory disease, a total of 14 423 (95% CI: 11 508–17 223) deaths were associated with abnormal temperatures and PM$_{2.5}$, corresponding to an attributable fraction of 23.76% (95% CI: 18.96–28.38). Among this fraction, there were 9 985 (95% CI: 9 030–10 902) cold-related deaths, 1130 (95% CI: 478–1734) heat-related deaths, and 3308 (95% CI: 2000–4587) PM$_{2.5}$-related deaths, with estimated fractions of 16.45% (95% CI: 14.88–17.96), 1.86% (95% CI: 0.79–2.86), and 5.45% (95% CI: 3.30–7.56) for cold, hot, and PM$_{2.5}$, respectively (figure 3(a) and table 2). For circulatory disease, a total of 49 148 (95% CI: 42 649–55 505) deaths were associated with abnormal temperatures and PM$_{2.5}$, equivalent to an attributable fraction of 17.54% (95% CI: 15.22–19.81). Among this fraction, there were 35 259 (95% CI: 33 051–37 423) cold-related deaths, 3190 (95% CI: 1782–4551) heat-related deaths, and 10 699 (95% CI: 7 816–13 530) PM$_{2.5}$-related deaths,
with estimated fractions of 12.59% (95% CI: 11.80–13.36), 1.14% (95% CI: 0.64–1.62), and 3.82% (95% CI: 2.79–4.83) for cold, hot, and PM$_{2.5}$, respectively (figure 3(b) and table 2). The results stratified by atmospheric stability condition showed that the fewest deaths occurred under stable conditions, mainly because stable weather accounted for the fewest days in the study period.

The magnitude of the mortality burden induced by the identical exposure factor varied with atmospheric stability conditions; this could be reflected by variations in the daily average attributable deaths (figures 3(c) and (d)). The number of cold-related daily average deaths under normal conditions was lower than that under disturbed and stable conditions. Analogous patterns could also be found for heat-related deaths, where a pronounced increase in heat-related deaths was observed under stable conditions. Daily average circulatory deaths associated with PM$_{2.5}$ progressively increased with consecutive increases in atmospheric stability levels, while there were comparatively less daily average respiratory deaths under stable than under disturbed and normal conditions. Aggregating the overall mortality
Table 1. Estimated excess risks (ER%) and the 95% confidence intervals of respiratory and circulatory mortality associated with a 1 °C change in abnormal temperatures (a 1 °C decrease in cold temperatures and a 1 °C increase in hot temperatures) and a 10 µg m$^{-3}$ increase in PM$_{2.5}$ concentrations under different atmospheric stabilities.

| Disease     | Atmospheric stability | Exposure to cold | Exposure to hot | Exposure to PM$_{2.5}$ |
|-------------|-----------------------|------------------|----------------|------------------------|
| Respiratory | Disturbed             | 1.84 (1.65–2.03) | 2.63 (0.33–4.98) | 1.34 (0.87–1.82) |
|             | Normal                | 1.66 (1.50–1.82) | 1.88 (0.68–3.10) | 0.56 (0.39–0.74) |
|             | Stable                | 1.72 (1.37–2.07) | 6.06 (3.20–9.00) | 0.30 (–0.02–0.61) |
| Circulatory | Disturbed             | 1.20 (1.11–1.29) | 1.89 (0.85–2.93) | 0.65 (0.43–0.87) |
|             | Normal                | 1.29 (1.22–1.36) | 1.39 (0.83–1.95) | 0.34 (0.26–0.42) |
|             | Stable                | 1.47 (1.30–1.63) | 2.37 (1.18–3.57) | 0.50 (0.35–0.64) |

Table 2. Mortality burden attributable to abnormal temperatures (cold and hot) and PM$_{2.5}$ from 1 March 2009 to 31 December 2016 in Beijing, China.

| Disease     | Mortality burden (95% CI) |
|-------------|---------------------------|
|             | Cold-related | Hot-related | PM$_{2.5}$-related |
| Respiratory | AN (person)  | 9985 (9030–10 902) | 1130 (478–1734) | 3308 (2000–4587) |
|             | AF (%)        | 16.45% (14.88–17.96) | 1.86% (0.79–2.86) | 5.45% (3.30–7.56) |
| Circulatory | AN (person)  | 35 259 (33 051–37 423) | 3190 (1782–4551) | 10 699 (7816–13 530) |
|             | AF (%)        | 12.59% (11.80–13.36) | 1.14% (0.64–1.62) | 3.82% (2.79–4.83) |

AN, attributable number of deaths; AF, attributable fraction of deaths.

Effects of temperature and PM$_{2.5}$, individuals suffer from the strongest effects under stable conditions and the weakest effects under normal conditions.

Moreover, we analyzed variations in the daily average deaths attributable to abnormal temperatures and PM$_{2.5}$ across SWI levels (figure 4). We also delineated variations in exposure factors by SWI level (figure S2) to better understand the varied curves of the associations between SWI and daily average deaths. Under cold conditions, daily mean temperatures were associated with SWI in a reversed V-shape, having the peak at 12 < SWI ≤ 13. In contrast, daily average deaths were associated with SWI in a V-shape, having the bottom at 12 < SWI ≤ 13. As such, increases in daily average cold-related deaths were associated with decreases in daily mean temperatures. However, under hot conditions, the curves of the associations between daily mean temperatures and SWI levels were generally in agreement with those between daily average deaths and SWI levels, indicating that increases in daily average hot-related deaths were related to increases in daily mean temperatures. With regard to the effects of PM$_{2.5}$ as SWI levels increased, both daily average PM$_{2.5}$ concentrations and daily average deaths generally increased. However, daily average deaths did not increase monotonically with an increase in SWI levels, especially for respiratory disease. The results indicated a non-linear association between mortality and PM$_{2.5}$ concentrations.

3.6. Comparison of mortality burden before and after emission reduction

Compared with the level before emission reduction (from 2010 to 2013), the total mortality burden attributable to abnormal temperatures and PM$_{2.5}$ significantly declined after emission reduction (from 2014 to 2016), from 24.91% (95% CI: 19.99–29.65) to 22.88% (95% CI: 18.28–27.29) (P < 0.001) for respiratory disease and from 18.30% (95% CI: 15.92–20.63) to 16.95% (95% CI: 14.74–19.12) (P < 0.001) for circulatory disease (figure 5). However, there was some discrepancy in the trends of different exposure factors. Specifically, the estimated fractions due to PM$_{2.5}$ declined for both mortality outcomes and the differences were statistically significant (P < 0.001). Identical attenuation patterns could also be observed for the cold-related mortality burden, despite the fact that the difference was not statistically significant for respiratory disease (P = 0.223 for respiratory disease and P < 0.001 for circulatory disease). In contrast, variations in the hot-related mortality burden were slight and contrary, decreasing for respiratory disease (P = 0.645), while increasing for circulatory disease (P = 0.014). Additionally, we analyzed the trends...
in the yearly mortality burden from 2010 to 2016 (figure S3). The variations in the estimated fractions exhibited downward trends for cold temperatures and PM$_{2.5}$ and slightly upward trends for hot temperatures.

4. Discussion

This study provides a quantitative estimation of the mortality burden attributable to short-term exposure to abnormal temperatures and PM$_{2.5}$ in Beijing considering the atmosphere as a whole. During 1 March 2009 to 31 December 2016, a total of 14 423 (95% CI: 11 508–17 223) deaths from respiratory disease and 49 148 (95% CI: 42 649–55 505) deaths from circulatory disease were associated with temperature and PM$_{2.5}$, with attributable fractions of 23.76% (95% CI: 18.96–28.38) and 17.54% (95% CI: 15.22–19.81), respectively. Cold temperatures were responsible for the highest mortality burden, followed by PM$_{2.5}$, whereas hot temperatures had the least effect. Our findings improve our understanding of the adverse health impacts related to abnormal temperatures and PM$_{2.5}$ from the perspective of atmospheric flow.

We observed different trends in meteorological parameters and PM$_{2.5}$ concentrations by SWI level, upon which we divided the atmospheric stability into three levels, including disturbed, normal, and stable conditions (visually described in figure S4). Disturbed conditions were conducive to pollutant dispersion, characterized by cold air masses, strong winds, a low relative humidity, and high planetary boundary layer. In contrast, under stable conditions, weak winds, a high relative humidity, and low planetary boundary layer created favorable conditions for the formation and accumulation of pollutants, consequently leading to high PM$_{2.5}$ concentrations; at the same time, solar radiation could be effectively attenuated by the combined effects of extremely high PM$_{2.5}$ levels, abundant moisture and higher cloud cover, leading to a near-ground temperature
reduction, which reinforced temperature inversions and boosted near-ground moisture accumulation \[35\]. Consequently, the already worsening meteorological conditions were further exacerbated. These feedback effects of cumulative PM\(_{2.5}\) pollution on meteorological conditions could partially explain the phenomenon of mean temperature reductions under stable conditions. The meteorological conditions and PM\(_{2.5}\) level under normal conditions were intermediate between those under disturbed and stable conditions.

Because SWI values contain dual information about meteorological conditions and PM\(_{2.5}\) concentrations, we were able to adapt this index as a bridge to synthetically evaluate the short-term effects of temperature and PM\(_{2.5}\) on mortality. We found that, compared to the mortality burden induced by PM\(_{2.5}\) and hot temperatures, cold-related deaths accounted for the largest proportion in Beijing, indicating that the local government needs to strengthen the associated public health protection policies against the adverse impacts of cold temperatures. It has been reported that cold temperatures made appreciably larger contributions to the mortality burden than hot temperatures in many regions \[20\]. A few studies also estimated the mortality burden attributable to short-term exposure to PM\(_{2.5}\) in China \[36, 37\]. However, discrepancies in the study areas, study periods, and included mortality outcomes restricted the comparability of these results, making it difficult to analyze the differences in the magnitude of the temperature-related and PM\(_{2.5}\)-related mortality burden in a certain region. Even so, the proportions of cold-related and heat-related deaths in our study were broadly comparable with other studies in China \[26, 38, 39\].

Our findings suggest that in addition to the separate estimation of the adverse health effects of temperature and particulate matter pollution, more attention should be directed toward a comprehensive effect assessment of those exposure factors due to their significant implications for policy making and public health protection. Additionally, it should be noted that the currently low mortality burden attributable to hot temperatures was mainly related to the small proportion of hot weather. However, under the context of climate change, the frequency, intensity and duration of heat waves are projected to rise, increasing the influence of hot temperatures which could lead to far greater influence on mortality burden in future \[40\].

![Figure 4. Daily average deaths by respiratory disease and circulatory disease attributable to abnormal temperatures (cold and hot) and PM\(_{2.5}\) across SWI levels. Error bars denote 95% confidence intervals.](image-url)
The different distributions of the meteorological conditions and PM$_{2.5}$ concentrations under different atmospheric stabilities resulted in a discrepancy between the mortality effects with an identical exposure factor under different atmospheric stabilities. This finding could provide more information for the government to formulate more comprehensive public health policies under different weather conditions. Under disturbed conditions, despite the fact that the favorable meteorological conditions for pollutant dispersion lowered PM$_{2.5}$ concentrations, the number of daily average PM$_{2.5}$-related deaths was still high, especially for respiratory disease. The association between PM$_{2.5}$ concentrations and mortality, exhibiting a positive slope at low PM$_{2.5}$ levels and a leveling-off at high PM$_{2.5}$ levels, has been found in many Chinese cities, which may be related to the ‘harvesting effect’ of particulate matter and the adopted protective behaviors by the public during heavy polluted periods [28, 41]. More obviously, the high number of daily average cold-related deaths under disturbed conditions indicate a huge threat of cold temperatures on human health. Under stable conditions, the worsening meteorological conditions led to high PM$_{2.5}$ concentrations, against which the conventional consensus was to take timely interventions to attenuate the hazardous impacts of PM$_{2.5}$. However, the adverse effects of hot and cold temperatures cannot not be disregarded, manifested by the high daily average levels of cold- and heat-related deaths. Thus, the strongest comprehensive adverse effects of temperature and PM$_{2.5}$ under a stable atmosphere put forward more rigorous challenges for combined interventions against those exposure factors. In contrast, under normal conditions, the overall number of daily average deaths induced by abnormal temperatures and PM$_{2.5}$ was smallest, indicating that a normal atmospheric stability provided relatively more beneficial conditions for human health than disturbed and stable conditions.

Moreover, we evaluated changes in the mortality burden before and after the APPCAP implementation. Different from existing studies, which merely focused on the changes in PM$_{2.5}$-related mortality, we made this comparison from a more comprehensive perspective. Consistent with existing studies [42–44], we observed significant reductions in the PM$_{2.5}$-related mortality burden after the implementation of the APPCAP. Moreover, the cold-related mortality burden was pronouncedly decreased. Compared with the levels during 2010–2013, we found an increased frequency of normal conditions, a decreased frequency of extreme cold temperatures, and remarkable reductions in PM$_{2.5}$ concentrations (figure S5) during 2014–2016. These changes may combinedly explain the reduction in the PM$_{2.5}$-related and cold-related mortality burden. However, with regard to changes in the heat-related mortality burden, our results show contrary trends for respiratory and circulatory disease, not completely consistent with the increased frequency of extreme hot temperatures after the APPCAP implementation (figure S5). Due to the less frequent occurrence of hot days and the further stratification by atmospheric stability in this study, our estimations of heat-related effects suffered from some uncertainties with wide confidence intervals.

Figure 5. Comparison of mortality burden attributable to abnormal temperatures (cold and hot) and PM$_{2.5}$ before and after emission reduction. Green and red represent periods before (from 2010 to 2013) and after (from 2014 to 2016) emission reduction, respectively. Error bars denote 95% confidence intervals.
Therefore, changes in the hot-related mortality burden after the APPCAP implementation still need further investigation.

Our results show an increase in the frequency of normal conditions and decreases in the frequency of disturbed and stable conditions after the APPCAP implementation, which is in agreement with existing findings that favorable meteorological conditions positively contribute to PM\(_{2.5}\) reductions in the years directly after the APPCAP implementation in Beijing [45–47]. However, in the long run, the occurrence of stable weather condition has been projected to increase under future climate change conditions in China [48, 49]. Due to the pronounced mortality effects of abnormal temperatures and PM\(_{2.5}\) under stable conditions, such increase may aggravate the mortality burden posed by temperature and PM\(_{2.5}\) assuming no change in other influencing factors. Therefore, to protect public health, the Chinese government needs to further implement emission control policies to mitigate the health hazards induced by PM\(_{2.5}\). More importantly, comprehensive strategies are required to simultaneously take the adverse impacts of abnormal temperatures into account in the context of climate change.

Our study, which considered the atmosphere as whole based on the rationale that atmospheric flow reflects variations in ambient temperature and has an influence on aerosol concentrations, presented a novel perspective from which to quantify the mortality burden attributable to abnormal temperatures and PM\(_{2.5}\). As the SWI characterizes the mobility and stability of the atmosphere, we adapted it as a medium with which to conduct an entire study, thus expanding the scope of its application from pure meteorology to the health effect assessments of meteorology and air pollution. Although the study was conducted in one city and caution should be exercised before extrapolating the findings to others, the research approach used in this study can be readily generalized to evaluate the synthetical health effects of temperature and aerosol pollution worldwide. As such, it could offer one basis on which to make decisions that could benefit air quality improvements and public health protection. Such a tool has a significant implication given the backdrop of climate change, under which substantial changes in weather conditions and aerosol pollution are expected to occur in the future.

Some limitations of this study should also be acknowledged. First, we did not control for the potential confounding effects of some socioeconomic factors (including income level, health status of individuals, education level and individual smoking level) on mortality. Therefore, the estimated mortality risks attributable to PM\(_{2.5}\) and temperature should be interpreted cautiously. Second, our findings are based on the short-term mortality effects of temperatures and PM\(_{2.5}\). However, many studies indicate that the chronic effects of PM\(_{2.5}\) are far more substantial than acute effects [50, 51]. Thus, further investigations remain to be done with regard to the mortality impacts of temperature and PM\(_{2.5}\) in the long-term. Third, we only compared changes in the effects of temperature and PM\(_{2.5}\) before and after the national pollution control policy in the recent years, which restricts our capacity to provide more information on the future trend. We intend to conduct future projections on health effects of atmospheric flow under different pollution control policy scenarios.

### 5. Conclusion

In summary, as atmospheric flow drove the changes in both meteorological conditions and aerosol pollution, we estimated the mortality burden attributable to short-term exposure to abnormal temperatures and PM\(_{2.5}\) in Beijing from the perspective of atmospheric flow. Abnormal temperatures were responsible for most of the mortality burden. Here, cold temperatures accounted for a substantially higher mortality burden than hot temperatures. The mortality effects of temperature and PM\(_{2.5}\) varied for different atmospheric stability conditions. A stable atmosphere poses the strongest synthetical effects of temperature and PM\(_{2.5}\), followed by a disturbed atmosphere, while a normal atmosphere provides comparatively beneficial conditions for human health. Despite the significant health benefits in the recent years after the national clear air policy was enacted, the Chinese government needs to develop comprehensive public health strategies, which simultaneously consider the negative impacts of air pollution and abnormal temperatures in the context of climate change.

### Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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