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Risk of illness-related school absenteeism for elementary students with exposure to $PM_{2.5}$ and O_3

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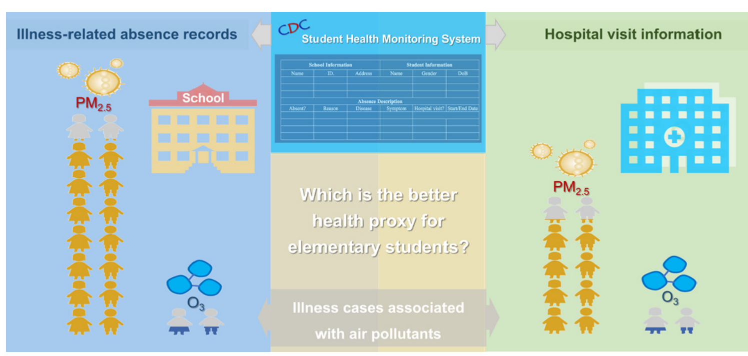
HIGHLIGHTS

- Up to 43 % absentees selected home nursing without going to a hospital.
- Using hospital visit record undervalued 18–42 % pollution-related illness cases.
- $PM_{2.5}$ exposure was related to increased illness-related absence for all subgroups.
- O_3 exposure was associated with high absence risk for the less unhealthy group.

GRAPHICAL ABSTRACT



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ABSTRACT

Air pollution addresses short-term health effects on morbidity, especially for children. Assessing the impacts of air pollution on elementary students is critical for developing preparedness response strategies for this sensitive group. In the 2016–17 academic year, up to 687,748 groups of illness-related absence records and the information on whether the absentee had gone to a hospital or not were collected from 2564 elementary schools across Jiangsu Province China. We explored the associations between air pollution and illness-related records using a time-stratified case-crossover analysis with distributed lag non-linear design. An increase of 10 $\mu g/m^3$ in the current-day concentration of $PM_{2.5}$ and O_3 was positively associated with illness-related absenteeism overall. The excess risk of absenteeism was 4.52 % (95%CI 4.37–4.67 %) for $PM_{2.5}$ and 0.25 % (95%CI 0.01–0.36 %) for O_3. The risk associated with O_3 was boosted for the frequent absentees who tended to have basic diseases or were more vulnerable to infectious diseases. Students in 43.1 % illness-related absenteeism, mainly due to highly infectious diseases, only received home nursing without going to a hospital. The increase in the number of illness cases associated with $PM_{2.5}$ and O_3 estimated based on the illness-related absence data was 41.5 % and 18.6 % higher than that evaluated based on hospital visit records. Such underestimations persisted in sensitivity analyses and persisted in subgroups classified by gender or grade. Together, the performance of illness-related absence records far outweighed that of hospital visit data regarding the thorough

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evaluation of air pollution-related illness cases for elementary students. Improvement in air quality and home health care education are warranted as well for the health benefits of children.

1. Introduction

Exposure to ambient air pollution is among the leading risk factors and contributed to around 6.67 million deaths, according to the Global Burden of Diseases, Injuries, and Risk Factors Study 2019 (GBD 2019 Risk Factors Collaborators 2020, 2020). Growing scientific evidence has documented the widespread negative impacts associated with air pollutant exposure (Chowdhury et al., 2022; Vicedo-Cabrera et al., 2020). Among the commonly reported list of air pollutants, fine particulate matter ($PM_{2.5}$) and ozone (O_3) attract the most attention, partially due to the severe $PM_{2.5}$ pollution and aggravated O_3 pollution status in China (Meng et al., 2022; Wei et al., 2021).

For children, the undeveloped lung function, immature immune system, high activity rate, and resultant high breathing rate jointly make them more vulnerable to air pollution (Nhung et al., 2018). Compared with other age groups, the estimated risk of hospital admission for asthma in Texas associated with ozone exposure was the highest for children aged 5–14 years (Zu et al., 2017). A longitudinal study involving 4602 children observed statistically significant decreases in bronchitic symptoms in children when the ambient $PM_{2.5}$ and ozone concentrations reduced in California (Berhane et al., 2016). The unfavorable situation is exacerbated among children in China, a major developing country suffering from dramatic epidemiological transitions (Guan et al., 2017). Many shreds of evidence have documented the adverse health effects of air pollutants in children from China (Cui et al., 2020; Zhang et al., 2019a). The adverse health effects in children caused by air pollution, unfortunately, may further drive the increase in school absences and even an increase in hospital visits (Pope et al., 1995).

A handful of studies have investigated the influence of air pollutants on illness-related school absenteeism (Adar et al., 2015; Mendoza et al., 2020); however, results from these studies are inconsistent. A study in South Korea detected the adverse effects of PM_{10} and O_3 on illness-related absenteeism (Park et al., 2002). In Japan, there was evidence of a positive association between absence due to sickness and $PM_{2.5}$, but no evidence was observed for photochemical oxidants (Watanabe et al., 2021). When it comes to the US, the increase in illness-related absenteeism associated with O_3 was far larger than with PM_{10} (Gilliland et al., 2001). Findings focusing on the particular matters in the US also differ between studies. Some revealed a strong impact (Adar et al., 2015; Gilliland et al., 2003), while others only identified a relatively weaker influence (Mendoza et al., 2020). The inconsistency from existing studies might be partially due to (1) absence records of thousands, or even hundreds of elementary students from a limited number of schools/communities are not representative enough, (2) air pollutant concentrations generated directly from fixed-site monitoring measurements or simply interpolated data could hardly reflect the accurate individual exposure levels, and (3) some researches used all absence records instead of focusing only on those related to illness. Solid evidence regarding the relationship between air pollution and illness-related school absenteeism is still scarce.

With a few studies using school absenteeism as the proxy for children's health, none of them examined the performance of absence records via comparison with other proxies. Hospital visit record is among the most populated indexes used to evaluate exposure-response relationships for a large-scale population (Wei et al., 2019a). The possibility exists that absent students may select home nursing instead of seeking treatments in hospitals after requesting absences (Zhang et al., 2018). We hypothesize that ignoring this group and considering those visiting a hospital only could result in an underestimation of air pollutant-related illness cases. However, the difficulty exists in the paired collection of both school absence and hospital visit records. Thus, it remains unclear to what extent the illness cases associated with air pollutant exposures would be underestimated when evaluated based on the hospital visit data compared based on the illness-related school absence records.

In this study, we collected around 0.7 million illness-related absence records and paired information on whether the absentee had visited a hospital or not from >2500 elementary schools across Jiangsu Province in the academic year 2016–17. With a case-crossover design, we conducted a pioneering comparison between illness-related absence and hospital visit records to check with which proxy could we fully address the health effects of air pollutants in children. Our objectives are to compare the illness cases related to exposures to $PM_{2.5}$ and O_3 estimated based on the two proxies, determine the type of health outcome to use, and thoroughly estimate the health impact of air pollution in elementary students in China.

2. Methods

2.1. Illness-related absence data

In this study, we collected school absenteeism records from the Student Health Monitoring System arranged by the Jiangsu Provincial Center for Disease Control and Prevention (JS CDC). In the Student Health Monitoring System, daily illness and absence information were collected by school healthcare teachers with the help of the headteachers of each class. The healthcare teachers had been trained ahead and filled absence reports via the online monitoring system every day if it was a school day, following specific instructions. CDC staff also randomly checked the reports to ensure their quality. More information about the records is in the supplementary material.

Via the system, we extracted records marked as illness-related from 1,071,813 absence records collected in 2564 elementary schools across Jiangsu Province during the 2016–17 academic year (September 2016–June 2017) (Fig. 1). The dataset contained information including the beginning and end dates of absence, demographic information (city, district/county, school, grade, class, birthday, and sex), visiting a hospital or not, diagnosed disease, and corresponding medical symptom(s). Each group of information represented one illness-related absence case. The group "hospital visit" includes all cases if a student went to the hospital for further treatment. Those receiving home health care only were in the group "home nursing". Including the group "others", there were 21 types of medical symptoms recorded in total. There was one type of disease at most but multiple types of medical symptoms recorded for one absence. We went through records with five more medical symptoms one by one and removed those that could hardly appear for the given disease (e.g., reported eye disease and the symptom of runny nose simultaneously) to avoid messy reports. We further excluded cases with twenty more students absent in the same class in one day (the typical class size is around 40) (Fig. S1). In those cases, we suspected that many students requested an absence in case of getting infected. We also screened out records with no specific information of neither disease nor medical symptom in that they were more likely to be from inaccurate reports. The data extraction was carried out separately by two researchers and checked by a third researcher to avoid human error. Diseases were coded according to the *International Statistical Classification of Diseases and Related Health Problems, 10th Revision*. There were 16 types of diseases identified. Asthma was not separately recorded in the monitoring system or included in the 16 diseases. We further grouped cold, tracheitis/pneumonia, and tuberculosis as "respiratory disease", grouped diseases characterized by rash, mumps, and hand-foot-mouth disease as "highly infectious disease" (Table 1).

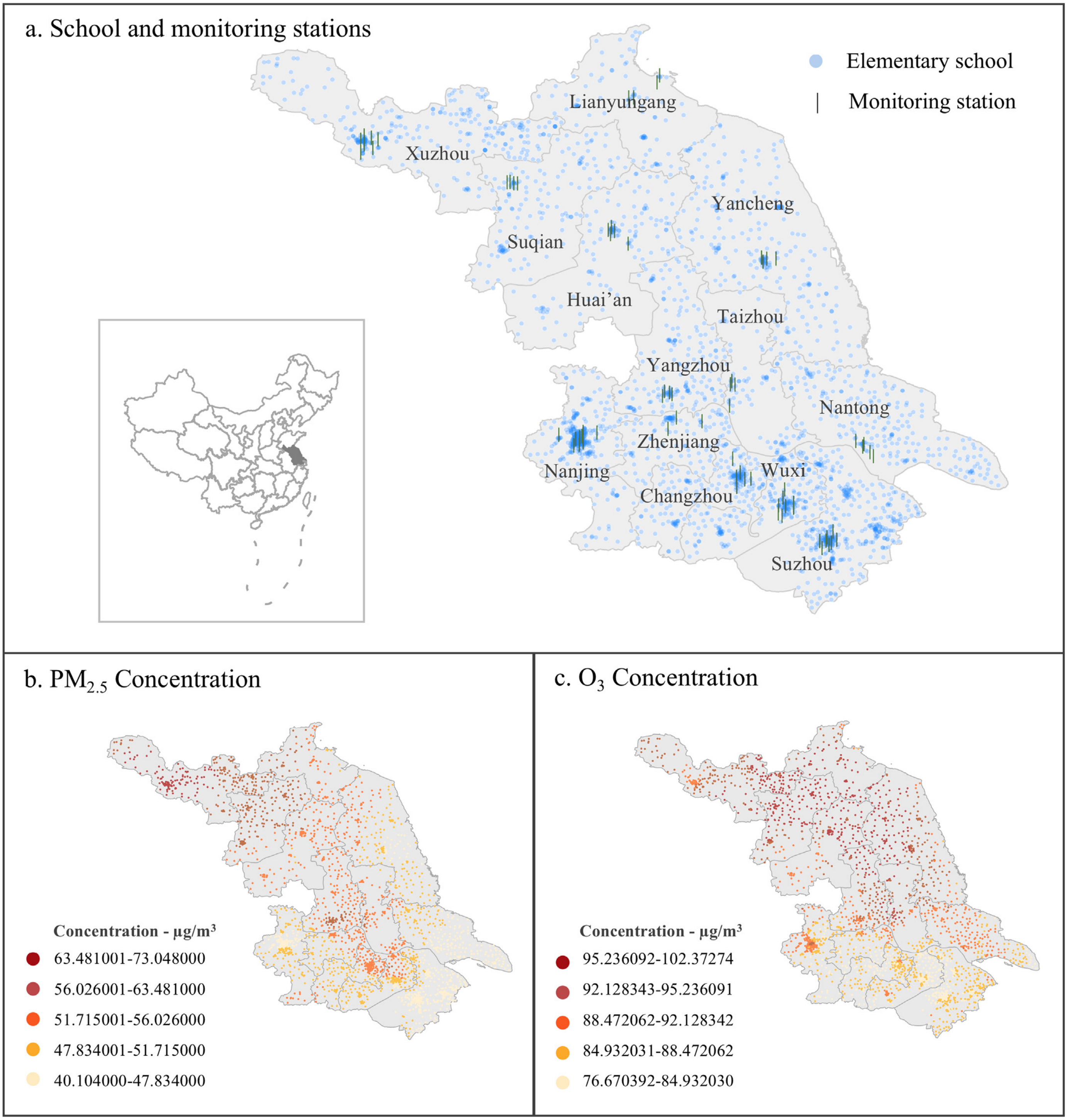


Fig. 1. Distribution of the studied elementary schools, routine air quality monitoring stations (a), and the $PM_{2.5}$ (b) and MDA O_3 (c) concentrations for elementary schools in Jiangsu Province in the academic year 2016–17 (MDA O_3, maximum daily 8-hr ozone).

2.2. Exposure assessment

We obtained daily $PM_{2.5}$ concentrations of each school from the ChinaHighAirPollutants (CHAP, https://weijing-rs.github.io/product.html) dataset developed by Wei et al. (2019a) and Wei et al. (2021). The $PM_{2.5}$ concentrations were estimated based on a proposed Space-Time Extra-Trees (STET) model. Some of the $PM_{2.5}$ concentrations were missing, and we used the interpolated concentrations to fill the missing values. We derived exposure to maximum daily 8-h ozone averages (MDA8 O_3) from a random forest (RF) model developed by Meng et al. (2022). Both $PM_{2.5}$ and O_3 concentrations were of 1-km resolution. The Root Mean Square Error (RMSE) was ~10.0–18.4 μg/m^3 for the STET model and 20.9 μg/m^3 for the RF model when calibrated with data from the national monitoring network (Wei et al., 2019a; Meng et al., 2022). Hourly concentrations of NO_2 and SO_2 from 72 monitoring stations in Jiangsu Province were collected from the National Urban Air Quality Real-time Publishing Platform and rounded to daily averages for two-pollutant analyses. Missing values from <1 % of the studied days were substituted by concentration averages of the previous and followed two days. Daily relative humidity (RH) and temperature data from 22 meteorological monitoring stations were

Table 1
Number and percentage of enrolled diseases associated with illness-related absenteeism records.

	All records[a]		Hospital visit[a]		>5 times[a]	
	Count	Percentage	Count	Percentage	Count	Percentage
Respiratory disease	**484,440**	**70.4 %**	**282,391**	**72.1 %**	**24,191**	**51.3 %**
Cold	466,573	67.8 %	268,708	68.6 %	21,802	46.2 %
Tracheitis/pneumonia	17,838	2.6 %	13,666	3.5 %	2389	5.1 %
Tuberculosis	29	0.0 %	17	0.0 %	0	0.0 %
Highly infectious	**52,794**	**7.7 %**	**22,512**	**5.7 %**	**8665**	**18.4 %**
HFMD[b]	5958	0.9 %	2899	0.7 %	1202	2.5 %
Measles	458	0.1 %	253	0.1 %	46	0.1 %
Mumps	3477	0.5 %	1742	0.4 %	451	1.0 %
Rubella	943	0.1 %	604	0.2 %	84	0.2 %
Scarlet fever	1524	0.2 %	893	0.2 %	175	0.4 %
Varicella	40,434	5.9 %	16,121	4.1 %	6707	14.2 %
Others	**150,514**	**21.9 %**	**86,739**	**22.1 %**	**14,330**	**30.4 %**
Cardiac disease	802	0.1 %	469	0.1 %	393	0.8 %
Eye disease	4047	0.6 %	2938	0.8 %	332	0.7 %
Gastrointestinal	62,492	9.1 %	37,119	9.5 %	3256	6.9 %
Hepatitis	70	0.0 %	57	0.0 %	0	0.0 %
Neurasthenia	217	0.0 %	83	0.0 %	86	0.2 %
Tooth disease	2750	0.4 %	2202	0.6 %	119	0.3 %
Urinary disease	586	0.1 %	476	0.1 %	114	0.2 %
Other infectious	1762	0.3 %	843	0.2 %	260	0.6 %
Other	77,788	11.3 %	42,552	10.9 %	9770	20.7 %
Subtotal	**687,748**	**100.0 %**	**391,642**	**100.0 %**	**47,186**	**100.0 %**

[a] All records, all absent elementary students; Hospital visits, absent students who also went to hospital; >5 times, students requesting illness-related absences of >5 times during the study period.
[b] HFMD, hand-foot-mouth disease

obtained from the National Meteorological Data Center. There were no missing metrological data. We retrieved the NO_2, SO_2, and meteorology estimates of each enrolled elementary school using the ordinary Kriging interpolation by fitting the semivariogram with a spherical variogram model (Biswas et al., 2019). The RMSE from the kriging interpolation NO_2 and SO_2 was 15.6 μg/m^3 and 8.2 μg/m^3, respectively. For temperature and RH, the RMSE was 1.3 °C and 7.3 %, respectively. We estimated the pollution and meteorological levels of each enrolled elementary school by matching the three nearest grid points and using the averages to represent the exposures of students in that school.

2.3. Statistical analysis

We applied a time-stratified case-crossover design with a conditional logistic regression model. Case-crossover design is a well-developed method widely applied in assessing acute outcomes from environmental exposures (Gasparrini et al., 2015; Peralta et al., 2020). In such a design, each enrolled subject serves as his or her own control by comparing the subject's exposure in "case" and paired "control" days. There was only one record for each absence case on the first day of the absence. We set this day as the "case" day. The case and control were matched by day of the week in the same calendar month of the same year. This self-matching helped control for the effects of the day of the week and seasonality (Carracedo-Martinez et al., 2010). We deleted a match if it was a public holiday. To investigate lag-cumulative effects, we introduced the distributed lag nonlinear model for each pollutant via a cross-basis matrix. We implemented a linear function to examine the relationship between air pollutants and illness-related absenteeism and a natural cubic spline for the lag-response with two internal knots equally placed in the log scale. The lag was set to seven days. We controlled for the current day's RH and temperature. We applied a nature cubic spline smooth function with 3 degrees of freedom (df) for RH and 6 df for temperature. The df values were determined via the Akaike Information Criterion method. A dichotomous variable was added to represent whether a day was the first day after a public holiday to account for the holiday effect. We estimated the exposure-response relationship for illness-related absence associated with every 10 μg/m^3 increase in air pollutants. The percent change in odds of illness-related absence [defined as (odds ratio − 1) ∗ 100 (%)] and its 95 % confidence intervals (95 % CI) were estimated to represent this relationship.

Effect modification of air pollutants on all illness-related absenteeism was exanimated with stratification analyses by sex, grade, season, and disease. Related results could be checked in the supplementary file. Specifically, we also separated students asking for >5 absences to those having fewer absences to distinguish effects on normal elementary school students from those potentially having basic disease(s).

We also calculated the changes in the number of illness cases with the following function:

$$absence.case = percent_i * N_i$$

Here, $percent_i$ is the percent change for one student due to air pollutant *i*, while N_i is the number of illness cases associated with air pollutant *i* during the study period in Jiangsu Province.

We compared the excess illness cases attributable to $PM_{2.5}$ and O_3 for all absentees and for those grouped in "hospital visit" to examine the health impacts of air pollutants in elementary students and to check to which extent the air pollution-related illness cases could be potentially undervalued in previous researches using hospital visits as health outcomes.

We conducted a 2-sample test based on the point estimates and standard errors to assess the statistically significant differences in estimated effects within subgroups of the same category following Di et al. (2017). In the 2-sample test, the between-group difference is smaller when the *p*-value is closer to 1.

2.4. Sensitivity analysis

Sensitivity analyses were conducted by (1) focusing on the pollutant pairs with low collinearity of variance inflation factor (VIF) < 5 and carrying out two-pollutant models, the second pollutant was added into the model with a cross-basis matrix using the same settlement as introduced above; (2) examining meteorological effects by using the temperature of current and previous two days, or adding a strata cross-basis spline for temperature and/or for RH, (3) converting the lag-response analysis from 3 to 6 days (from lag03 to lag06).

The interpolation was performed with package "gstat" and model analyses were conducted with the packages "dlnm" and "survival" using R (version 3.6.1). A two-sided *p*-value of <0.05 was considered statistically significant for all enrolled analyses.

3. Results

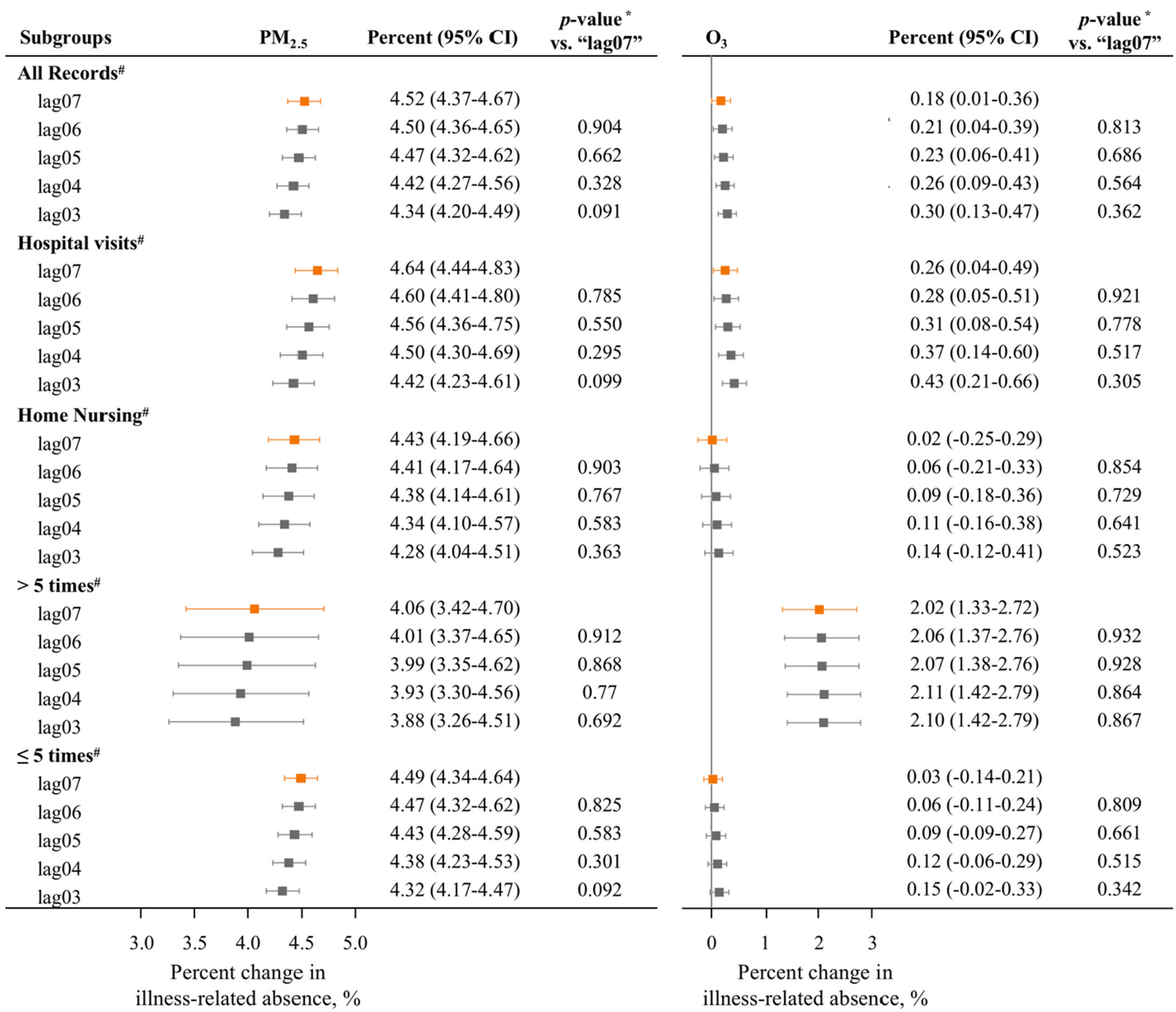
3.1. Exposure status and absenteeism records

Average pollution levels (±SD) were 52 ± 32 μg/m^3 for daily $PM_{2.5}$ and 107 ± 51 μg/m^3 for maximum daily 8-h O_3, respectively (Table S1, Fig. S1). Concentrations of all pollutants but O_3 were positively correlated (Fig. S2, Fig. S3).

After excluding the suspicious reports, there were 687,748 illness-related absence records left for further analyses, accounting for 64.2 % of the total absences recorded. The mean age of students having illness-related absence was 9.1 (Standard deviation, SD 3.4) years, and 309,864 (45.1 %) were girls. Cold (466,573 [67.8 %]) was the most reported cause, followed by gastrointestinal disease (62,492 [9.1 %]), varicella (40,434 [5.9 %]), and tracheitis/pneumonia (17,838 [2.6 %]). The records of grouped highly infectious diseases reached 52,796 (7.7 %) (Table 1). A total of 391,642 (56.9 %) records were for students seeking treatments in hospitals after requesting absences, and 22,569 (5.8 %) of these records were from absentees visiting a hospital due to highly infectious diseases. Among those choosing home nursing, 28,836 (10.7 %) of them were associated with highly infectious diseases (Table S2). Around 47,186 (6.9 %) records were from frequent absentees with illness-related absences >5 times during the study period. Up to 8665 (18.4 %) of them were absent due to highly infectious diseases. Diseases including cardiac disease, neurasthenia, and urinary disorder also showed notable growth in proportion (Table 1).

3.2. Relationship between air pollution and illness-related absenteeism

With a default lag of 7 days, a significant increase in illness-related absenteeism was detected to be associated with exposure to $PM_{2.5}$



- * p-value for statistically significant effect estimate (at 5% level) compared with the reference group "lag07";
- # All records, all absent elementary students; Hospital visits, absent students who also went to hospital; Home nursing, students choosing home nursing after requesting absences; ≤ 5 times and > 5 times, students requesting illness-related absences of ≤ or > 5 times during the study period.)

Fig. 2. Percent change (and 95 % CI) in illness-related absenteeism associated with per 10 μg/m^3 increase in air pollutant concentrations with different lag cumulative days.

(4.52 %; 95%CI, 4.37 %–4.67 %) and O_3 (0.18 %; 95%CI, 0.01 %–0.36 %) (Fig. 2). The pooled exposure-response curve showed a monotonic upward trend for the two pollutants (Fig. S4). For students also going to a hospital during the absence, the percent change in illness-related absenteeism associated with $PM_{2.5}$ slightly increased to 4.64 % (95%CI, 4.44–4.83 %) while that related to O_3 remarkably increased to 0.26 % (95%CI, 0.04–0.49 %) (Fig. 2). The percentage increase in absence attenuated for $PM_{2.5}$ (4.43 %; 95%CI, 4.19 %–4.66 %) and was insignificant for O_3 for those chose home nursing.

For all absentees requesting a sick leave, controlling with NO_2 and SO_2 drove notably decreased risk related to $PM_{2.5}$ (p-value <0.001) while adjusting with O_3 barely made a difference in the two-pollutant models. In comparison, the adjustment for NO_2 and SO_2 increased the risk associated with O_3, even though the increase was not always significant (p-value range, 0.008–0.706) (Table 2). However, the risk associated with O_3 disappeared after adjustment for $PM_{2.5}$. The trend was similar for those also going to a hospital and for frequent absentees. The only difference was that, the risk of illness-related absence remained significant for O_3 (1.70 %; 95%CI, 1.01 %–2.40 %) after controlling for $PM_{2.5}$.

Risk related to $PM_{2.5}$ gradually increased when changing the length of cumulative days. For O_3, the associated risk continuously attenuated as the cumulative period was prolonged. However, the influence of changing the length of cumulative period were almost negligible (Fig. 2). Effects of $PM_{2.5}$ and O_3 on illness-related absenteeism in all absentees and in those visiting the hospital persisted with a variation in meteorological parameters in the models (Table S3).

Regarding students that were absent >5 times within the academic year, a significant surge in risk was identified from O_3 (2.02 %; 95%CI, 1.33 %–2.72 %) (p-value <0.001) (Fig. 2). In comparison, the risk from $PM_{2.5}$ dropped to 4.06 % (95%CI, 4.44 %–4.83 %) for these students. Persistent effects of $PM_{2.5}$ were detected on different subgroups divided by gender or grade. For all absentees, the risk associated with $PM_{2.5}$ was 4.62 % (95%CI, 4.40 %–4.84 %) for girls and attenuated for boys (4.39 %; 95% CI, 4.19 %–4.60 %); meanwhile, the risk associated with O_3 was slightly higher for boys. For students in different grades, the effect of $PM_{2.5}$ was the strongest for students in the higher grades, followed by those in middle and lower grades while there was no consistent trend for O_3 (Table S4). The between-group differences were statistically insignificant either the risk was estimated based on all illness-related absence records or based on hospital visit information (Table S4).

3.3. Estimations of illness-related cases based on two indexes

Based on all illness-related absenteeism records, the estimated associated increase in illness cases was 31,061 (30,038– 32,085) for $PM_{2.5}$ and 1270 (87– 2454) for O_3 (Fig. 3, Table S7).

After restricting analysis on those looking for further treatment in hospitals, the calculated cases dropped 41.5 % and 18.6 % for $PM_{2.5}$ and O_3, respectively. Similar drops in illness cases were detected in sensitivity analyses (Table S8, S9). The switch to using illness cases based on hospital visit records then resulted in an underestimation of around 12,898 and 236 illness cases possibly related to $PM_{2.5}$ and O_3 exposure in the academic year 2016–17 in Jiangsu Province alone. With 5.22 million elementary students in Jiangsu Province and 100.9 million of them across China, we further estimated that such a switch might lead to 249,312 and 4562 fewer illness cases nationwide. Besides, when switching the health proxy, we consistently observed the drops in illness cases in boys and girls, and in students from lower, middle, and higher grades (Table S10).

4. Discussion

This is the first study we know of to compare the estimated health impacts of air pollutants in children based on both illness-related absence and corresponding hospital visit records. Up to one-third of the records were not illness-related, verifying the importance of excluding absences due to other reasons when using absenteeism to indicate adverse health effects of air pollutants (Park et al., 2002). With ~0.7 million illness-related records, this study is still the largest investigation of associations between air pollutants and illness-related school absenteeism reported to date. We collected absence records in the academic year 2016–17 from over 2500 elementary schools across Jiangsu Province and found significant associations between exposure to ambient $PM_{2.5}$ and O_3 with elevated illness-related absenteeism.

Compared with air pollutant-related illness cases estimated based on illness-related absence records, the illness cases estimated based on hospital visits dramatically dropped. Even though the exposure to $PM_{2.5}$ and O_3 both drove an increase in the percent risk of illness-related absence, the evaluated number of illness cases was notably distinguished when using the two health proxies. Emergency department visits (Johnston et al., 2020), hospital admissions (Wei et al., 2019b), and hospital outpatient records (Chai et al., 2019) are prevalent indexes used to indicate health outcomes in large-scale epidemiological studies. However, compared with the

Table 2
Percent change (and 95 % CI) in illness-related absenteeism associated with per 10 μg/m^3 increase in air pollutant concentrations in two-pollutant models.

Refer pollutant	Adjusting for	All records[a]		Hospital visits[a]		>5 times[a]	
		Percent 95%CI	p-Values*	Percent 95%CI	p-Values*	Percent 95%CI	p-Values*
$PM_{2.5}$		4.52 4.37–4.67		4.64 4.44–4.83		4.49 4.34–4.64	
	O_3	4.47 4.23–4.70	0.689	4.69 4.49–4.88	0.719	3.99 3.35–4.64	0.881
	NO_2	2.25 2.05–2.46	0.000	2.50 2.22–2.77	0.000	2.56 1.69–3.43	0.005
	SO_2	3.13 2.90–3.36	0.000	3.49 3.19–3.79	0.000	2.62 1.68–3.57	0.011
O_3		0.18 0.01–0.36		0.26 0.04–0.49		2.02 1.33–2.72	
	$PM_{2.5}$	−0.20 −0.37 ~ −0.03	0.002	−0.17 −0.40– 0.06	0.008	1.70 1.01–2.40	0.516
	NO_2	0.51 0.34–0.69	0.008	0.54 0.31–0.77	0.091	2.33 1.63–3.03	0.531
	SO_2	0.34 0.17–0.51	0.214	0.33 0.10–0.56	0.706	2.20 1.51–2.90	0.715

[a] All records, all absent elementary students; Hospital visits, absent students who also went to hospital; > 5 times, students requesting illness-related absences of >5 times during the study period.

* p-value for statistically significant effect estimate (at 5 % level) of results generated from two-pollutant models compared with those from one-pollutant models.

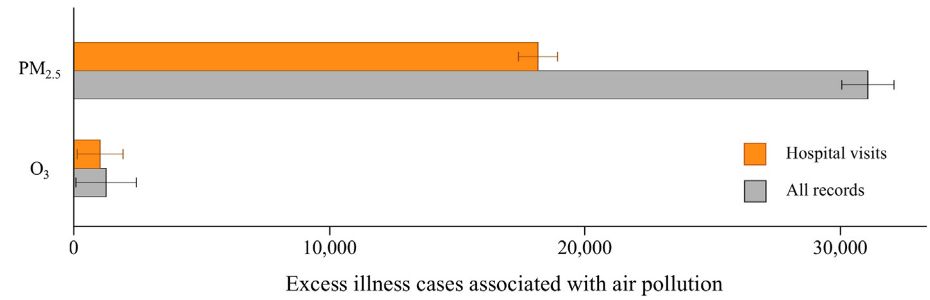


Fig. 3. Changes in the number of illness cases evaluated based on all illness-related absenteeism records (All records) and absence records where absentees also going to a hospital (Hospital visits).

potential resultant illness cases estimated based on hospital visit records, we found the extension in disadvantages of air pollutant exposure for children evaluated based on school illness-related absence records. Except for physical discomfort, children's sick leaves, whether they selected home nursing or going to a hospital, are associated with reduced academic performance and even influence their future employment (Berman et al., 2018; Larose et al., 2021). The undervalued illness cases could further translate to an underestimation of elevated work absence and diminished productivity for the caregivers (Mendoza et al., 2020). Overall, compared with hospital outpatient information, illness-related absence records offer an opportunity for a more thorough investigation of the exposure-response relationships. This result backs up the value of using illness-related absence records in research for public health purposes for the first time.

Among absentees selecting home nursing instead of going to a hospital, a considerable proportion of them requested absences due to infectious diseases. With the promulgated two-child policy in 2016 and the followed three-child policy in 2021 in China, the possibility exists that more families would foster more than one child. The question of how to provide more professional suggestions for home health care, therefore, deserves more attention in the hope of taking better care of this large group and providing preventions for their sibling(s), if any. Improvement in home health care education might be more important for those with economic disadvantages.

We further confirmed the reported positive associations between illness-related absence and $PM_{2.5}$, and the detected association coefficients were generally smaller than previous estimates in more developed countries/areas (Park et al., 2002). The excess illness-related absences attributable to $PM_{2.5}$ in our study was 4.52 %. This is slightly higher than the risk for students in Guangzhou City, China (Chen et al., 2018), the estimations in this study were conducted based on air pollutant measurements from the closest national monitoring stations. In comparison, after switching to ultralow-sulfur diesel, the $PM_{2.5}$ concentration declined by 10 μg/m^3 over a 40-min bus trip, and the resultant decrease in absenteeism reached 8 % in Washington, USA (Adar et al., 2015). For elementary students from California, school absences related to respiratory diseases could be doubled or even quadrupled due to the indoor particles (Wenten et al., 2005). In Japan, the related school absence surged by >20 % with the same 10 μg/m^3 increase in daily $PM_{2.5}$ concentration (Watanabe et al., 2021). Liu and Salvo (2018) suggest that students in China usually face tougher air pollution situations, their lower risk of illness-related absence may be due to the adaptation after long-term exposure to elevated pollutant levels and the developed defensive actions (Liu and Salvo, 2018). The high content of crustal materials in $PM_{2.5}$ in China may make the particles less toxic and contribute to the attenuated risk of illness-related absenteeism (Yang et al., 2011).

We also provide novel insight into the associations between O_3 and illness-related absenteeism for elementary students, especially those in relatively non-healthy status. O_3 is a powerful oxidizing agent (Wang et al., 2019a). In previous research, some suggested O_3 as a strong predictor of illness-related absence (Chen et al., 2018; Gilliland et al., 2001), while the others observed no effects of O_3 on absenteeism (Rondeau et al., 2005; Watanabe et al., 2021). The series of studies conducted in Greek carried out personal O_3 measurements but found no correlation between school absenteeism and O_3 exposure (Samoli et al., 2017; Karakatsani et al., 2017). These studies examined the associations between daily or weekly averages of O_3 concentration and all-cause absenteeism instead of illness-related absence. The associations between health outcomes and different metrics (e.g., daily vs. MDA8 O_3 averages) could be vastly different (Sun et al., 2018). In our study, the risk from O_3 in multiple subgroups further implies that O_3 is a force to be reckoned with. The effect of O_3 exposure was far more notable when restricting the analysis to students frequently requesting illness-related absences. The frequent absentees tend to experience basic diseases such as cardiac disease or be more vulnerable to contagious diseases, indicating their relatively unfavorable health conditions. Considerable consistency existed across studies that the less healthy people tend to be more susceptible to air pollutants (Li et al., 2014; Sinharay et al., 2018). The underlying mechanisms of the impact of O_3 exposure were to be determined but still somewhat plausible in terms of its immunological or inflammatory damages as a powerful oxidizing agent (Wang et al., 2019a).

The association between $PM_{2.5}$ exposure and illness-related absenteeism was stable and the risk of absenteeism due to O_3 exposure also deserves more attention. In the two-pollutant models, the effects of $PM_{2.5}$ were always robust. However, the impacts of O_3 boosted after controlling with NO_2 and SO_2 but disappeared when adjusting for $PM_{2.5}$. The O_3-related risk was only robust for the less healthy group. The high temperature and strong sunshine radiation lead to peaked O_3 concentrations in Jiangsu Province in summer (Shu et al., 2020), while the relatively more static meteorological conditions and bulk contribution of air mass from northwest China jointly promote severe $PM_{2.5}$ pollution in Jiangsu in winter (Sun et al., 2019; Wang et al., 2019b). Even though the $PM_{2.5}$ and O_3 pollution peaked in different seasons, we were still not able to disentangle the independence of O_3 exposure since it was tightly correlated with other pollutants. Instead, we speculate that the confounding by NO_2 and SO_2 could considerably contribute to the risk of illness-related absenteeism promoted by O_3. The annual $PM_{2.5}$ average in Jiangsu Province was 66 μg/m^3 in 2014 and decreased to 49 μg/m^3 by 2017 and the annual O_3 has increased from 154 μg/m^3 to 177 μg/m^3 during this period. With the rising O_3 pollution level, which would be further exacerbated due to the process of global climate change (Zhang et al., 2019b), it may also be possible that O_3 will become the culprit pollutant.

Limitations exist for our study. First, with only one academic year enrolled, our results may not be generalizable to seasonal effects. However, given its large sample size, this study still successfully provided a better understanding of the correlations between air pollution and students' absenteeism. Secondly, the modeled ambient pollutant concentration may not be representative enough of students' exposure without accounting for influential factors such as local emissions, ventilation of microenvironments, and the time-activity pattern difference among individuals. More accurate personal exposure modeling could help refine the exposure-risk evaluation. Thirdly, with illness-related school absenteeism being the health proxy, we could not estimate the health effects during Spring Festival or summer vacation when air pollutant concentrations may peak, especially ozone. Fourthly, there might be inaccurate descriptions of disease or symptom reported by the absentees and/or their parents. We had tried to reduce the influence of such a description by conducting comprehensive data cleaning procedures. We were also not able to completely distinguish the genuine illness-related absences from absences due to worries of becoming sick or identify whether the choice of home nursing was related to the severity of the illness or the economic condition. The addition of environmental emergency event records and students' socioeconomic information would help toss up between different situations in future studies. Finally, there was no disease classification for asthma in the Student Health Monitoring System and we were unable to identify the specific effects for asthma children.

5. Conclusion

The study suggests that exposure to $PM_{2.5}$ and O_3 is responsible for students' illness-related absenteeism. O_3 alone is especially hazardous to frequent absentees in non-healthy status. The study also demonstrates a great potential for underestimation in illness cases associated with air pollution if only hospital visits are examined compared with when considering the illness-related absences. While illness-related school absenteeism warrants comprehensive pollution control policies, a large number of sick students only received home nursing, highlighting the need for additional context-specific home health care education.

CRediT authorship contribution statement

Hong Sun: Conceptualization, Project administration, Investigation, Resources, Methodology, Writing - Review & Editing, Funding acquisition; Lei Huang: Conceptualization, Supervision, Project administration, Resources, Writing - Review & Editing, Funding acquisition; Ting Zhang: Conceptualization, Methodology, Validation, Formal analysis, Data Curation, Visualization, Writing - Original Draft, Writing - Review & Editing, Funding acquisition; Yangyang Wu: Investigation, Validation, Formal analysis; Yuming Guo and Beizhan Yan: Methodology, Writing - Review & Editing; Jing Wei, Hongliang Zhang and Xia Meng: Resources Can Zhang: Investigation, Validation.

Dr. H. Sun would handle correspondence at all stages of refereeing and publication, also post-publication.

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Ethical approval

Not required.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Adar, S.D., D'Souza, J., Sheppard, L., Kaufman, J.D., Hallstrand, T.S., Davey, M.E., et al., 2015. Adopting clean fuels and technologies on school buses. Pollution and health impacts in children. Am. J. Respir. Crit. Care Med. 191, 1413–1421.

Berhane, K., Chang, C.C., McConnell, R., Gauderman, W.J., Avol, E., Rapappaport, E., et al., 2016. Association of changes in air quality with bronchitic symptoms in children in California, 1993–2012. JAMA 315, 1491–1501.

Berman, J.D., McCormack, M.C., Koehler, K.A., Connolly, F., Clemons-Erby, D., Davis, M.F., et al., 2018. School environmental conditions and links to academic performance and absenteeism in urban, mid-Atlantic public schools. Int. J. Hyg. Environ. Health 221, 800–808.

Biswas, S., Wu, M., Melles, S.J., Kwon, T.J., 2019. Use of topography, weather zones, and semivariogram parameters to optimize road weather information system station density across large spatial scales. Transp. Res. Rec. 2673.

Carracedo-Martinez, E., Taracido, M., Tobias, A., Saez, M., Figueiras, A., 2010. Case-crossover analysis of air pollution health effects: a systematic review of methodology and application. Environ. Health Perspect. 118, 1173–1182.

Chai, G., He, H., Sha, Y., Zhai, G., Zong, S., 2019. Effect of PM2.5 on daily outpatient visits for respiratory diseases in Lanzhou, China. Sci. Total Environ. 649, 1563–1572.

Chen, S., Guo, C., Huang, X., 2018. Air pollution, student health, and school absences: evidence from China. J. Environ. Eco Manag. 92, 465–497.

Chowdhury, S., Pozzer, A., Haines, A., Klingmuller, K., Munzel, T., Paasonen, P., et al., 2022. Global health burden of ambient PM2.5 and the contribution of anthropogenic black carbon and organic aerosols. Environ. Int. 159 (107020).

Cui, X., Li, Z., Teng, Y., Barkjohn, K.K., Norris, C.L., Fang, L., et al., 2020. Association between bedroom particulate matter filtration and changes in airway pathophysiology in children with asthma. JAMA Pediatr. 174, 533–542.

Di, Q., Dai, L., Wang, Y., Zanobetti, A., Choirat, C., Schwartz, J.D., et al., 2017. Association of short-term exposure to air pollution with mortality in older adults. JAMA 318, 2446–2456.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., et al., 2015. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet 386, 369–375.

GBD 2019 Risk Factors Collaborators 2020, 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the global burden of disease study 2019. The Lancet 396, 1223–1249.

Gilliland, F.D., Berhane, K., Rappaport, E.B., Thomas, D.C., Avol, E., Gauderman, W.J., et al., 2001. The effects of ambient air pollution on school absenteeism due to respiratory illness. Epidemiol 12, 43–54.

Gilliland, F.D., Berhane, K., Islam, T.M.W., Rappaport, E., Avol, E.W.J.G., McConnell, R., 2003. Environmental tobacco smoke and absenteeism related to respiratory illness in schoolchildren. Am. J. Epidemiol. 157, 861–869.

Guan, W.-J., Zheng, X.-Y., Zhong, N.-S., 2017. Industrial pollutant emission and the major smog in China: from debates to action. Lancet Planet. Health 1, e57.

Johnston, F.H., Borchers-Arriagada, N., Morgan, G.G., Jalaludin, B., Palmer, A.J., Williamson, G.J., et al., 2020. Unprecedented health costs of smoke-related PM2.5 from the 2019–20 australian megafires. Nat. Sustain. 4, 42–47.

Karakatsani, A., Samoli, E., Rodopoulou, S., Dimakopoulou, K., Papakosta, D., Spyratos, D., et al., 2017. Weekly personal ozone exposure and respiratory health in a panel of Greek schoolchildren. Environ. Health Perspect. 125, 077016.

Larose, M.P., Haeck, C., Ouellet-Morin, I., Barker, E.D., Cote, S.M., 2021. Childcare attendance and academic achievement at age 16 years. JAMA Pediatr.

Li, S., Baker, P.J., Jalaludin, B.B., Marks, G.B., Denison, L.S., Williams, G.M., 2014. Ambient temperature and lung function in children with asthma in Australia. Eur. Respir. J. 43, 1059–1066.

Liu, H., Salvo, A., 2018. Severe air pollution and child absences when schools and parents respond. J. Environ. Eco Manag. 92, 300–330.

Mendoza, D.L., Pirozzi, C.S., Crosman, E.T., Liou, T.G., Zhang, Y., Cleeves, J.J., et al., 2020. Impact of low-level fine particulate matter and ozone exposure on absences in k-12 students and economic consequences. Environ. Res. Lett. 15.

Meng, X., Wang, W., Shi, S., Zhu, S., Wang, P., Chen, R., et al., 2022. Evaluating the spatiotemporal ozone characteristics with high-resolution predictions in mainland China, 2013–2019. Environ. Pollut. 299, 118865.

Nhung, N.T.T., Schindler, C., Dien, T.M., Probst-Hensch, N., Perez, L., Kunzli, N., 2018. Acute effects of ambient air pollution on lower respiratory infections in Hanoi children: an eight-year time series study. Environ. Int. 110, 139–148.

Park, H., Lee, B., Ha, E.H., Lee, J.T., Kim, H., Hong, Y.C., 2002. Association of air pollution with school absenteeism due to illness. Arch Pediatr Adolesc Med 156, 1235–1239.

Peralta, A.A., Link, M.S., Schwartz, J., Luttmann-Gibson, H., Dockery, D.W., Blomberg, A., et al., 2020. Exposure to air pollution and particle radioactivity with the risk of ventricular arrhythmias. Circulation 142, 858–867.

Pope III, C.A., Bates, D.V., Raizenne, M.E., 1995. Health effects of particulate air pollution: time for reassessment? Environ. Health Perspect. 103, 472–480.

Rondeau, V., Berhane, K., Thomas, D.C., 2005. A three-level model for binary time-series data: the effects of air pollution on school absences in the southern California children's health study. Stat. Med. 24, 1103–1115.

Samoli, E., Dimakopoulou, K., Evangelopoulos, D., Rodopoulou, S., Karakatsani, A., Veneti, L., et al., 2017. Is daily exposure to ozone associated with respiratory morbidity and lung function in a representative sample of schoolchildren? Results from a panel study in Greece. J. Expo. Sci. Environ. Epidemiol. 27, 346–351.

Shu, L., Wang, T., Han, H., Xie, M., Chen, P., Li, M., et al., 2020. Summertime ozone pollution in the Yangtze River Delta of eastern China during 2013–2017: synoptic impacts and source apportionment. Environ. Pollut. 257, 113631.

Sinharay, R., Gong, J., Barratt, B., Ohman-Strickland, P., Ernst, S., Kelly, F.J., et al., 2018. Respiratory and cardiovascular responses to walking down a traffic-polluted road compared with walking in a traffic-free area in participants aged 60 years and older with chronic lung or heart disease and age-matched healthy controls: a randomised, crossover study. Lancet 391, 339–349.

Sun, Q., Wang, W., Chen, C., Ban, J., Xu, D., Zhu, P., et al., 2018. Acute effect of multiple ozone metrics on mortality by season in 34 chinese counties in 2013–2015. J. Intern. Med. 283, 481–488.

Sun, X., Luo, X.S., Xu, J., Zhao, Z., Chen, Y., Wu, L., et al., 2019. Spatio-temporal variations and factors of a provincial PM2.5 pollution in eastern China during 2013–2017 by geostatistics. Sci. Rep. 9:3613.

Vicedo-Cabrera, A.M., Sera, F., Liu, C., Armstrong, B., Milojevic, A., Guo, Y., et al., 2020. Short term association between ozone and mortality: global two stage time series study in 406 locations in 20 countries. BMJ 368, m108.

Wang, M., Aaron, C.P., Madrigano, J., Hoffman, E.A., Angelini, E., Yang, J., et al., 2019a. Association between long-term exposure to ambient air pollution and change in quantitatively assessed emphysema and lung function. JAMA 322, 546–556.

Wang, D., Jiang, B., Lin, W., Gu, F., 2019b. Effects of aerosol-radiation feedback and topography during an air pollution event over the North China Plain during December 2017. Atmos. Pollut. Res. 10, 587–596.

Watanabe, M., Noma, H., Kurai, J., Kato, K., Sano, H., 2021. Association with ambient air pollutants and school absence due to sickness in schoolchildren: a case-crossover study in a provincial town of Japan. Int. J. Environ. Res. Publ. Health 18.

Wei, J., Li, Z., Cribb, M., Huang, W., Xue, W., Sun, L., et al., 2019a. Improved 1 km resolution PM2.5 estimates across China using enhanced space–time extremely randomized trees. Atmos. Chem. Phys. 20, 3273–3289.

Wei, Y., Wang, Y., Di, Q., Choirat, C., Wang, Y., Koutrakis, P., et al., 2019b. Short term exposure to fine particulate matter and hospital admission risks and costs in the medicare population: time stratified, case crossover study. BMJ 367, l6258.

Wei, J., Li, Z.Q., Lyapustin, A., Sun, L., Peng, Y.R., Xue, W.H., et al., 2021. Reconstructing 1-km-resolution high-quality PM2.5 data records from 2000 to 2018 in China: spatiotemporal variations and policy implications. Remote Sens. Environ. 252.

Wenten, M., Berhane, K., Rappaport, E.B., Avol, E., Tsai, W.W., Gauderman, W.J., et al., 2005. Tnf-308 modifies the effect of second-hand smoke on respiratory illness-related school absences. Am. J. Respir. Crit. Care Med. 172, 1563–1568.

Yang, F., Tan, J., Zhao, Q., Du, Z., He, K., Ma, Y., et al., 2011. Characteristics of PM2.5 speciation in representative megacities and across China. Atmos. Chem. Phys. 11, 5207–5219.

Zhang, Y., Cui, L., Xu, D., He, M.Z., Zhou, J., Han, L., et al., 2018. The association of ambient PM2.5 with school absence and symptoms in schoolchildren: a panel study. Pediatr. Res. 84, 28–33.

Zhang, C., Guo, Y., Xiao, X., Bloom, M.S., Qian, Z., Rolling, C.A., et al., 2019a. Association of breastfeeding and air pollution exposure with lung function in Chinese children. JAMA Netw. Open 2, e194186.

Zhang, J.J., Wei, Y., Fang, Z., 2019b. Ozone pollution: a major health hazard worldwide. Front. Immunol. 10, 2518.

Zu, K., Liu, X., Shi, L., Tao, G., Loftus, C.T., Lange, S., et al., 2017. Concentration-response of short-term ozone exposure and hospital admissions for asthma in Texas. Environ. Int. 104, 139–145.