Ambient temperature and lung function in children with asthma in Australia

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ABSTRACT The association between ambient temperature and lung function in children with asthma is still uncertain.

A panel of 270 children (aged 7–12 years) with asthma was recruited from six Australian cities. They performed three successive forced expiratory manoeuvres twice daily for 4 weeks. The highest peak expiratory flow rate (PEF) and forced expiratory volume in 1 s (FEV₁) were stored for each session. During the same period, data were obtained daily on ambient temperature, relative humidity and air pollution. Mixed models were used to examine the effects of temperature on lung function, controlling for individual characteristics and environmental factors.

Ambient temperature was negatively related to both morning and evening PEF and FEV₁ for 0–3 days lag. In general, the effects of temperature were stronger in males than in females for evening PEF, while the effects were stronger in females for evening FEV₁. Children with asthma living in southern cities were more sensitive to high temperature than those in the northernmost city.

Higher ambient temperature is associated with lower lung function in children with asthma. Preventive health policies will be required to protect children with asthma from increasingly frequent high temperatures.

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Introduction

Asthma is the most prevalent chronic disease among children and is of great public health concern. The prevalence of asthma among children in Australia is one of the highest in the world, affecting 16% of Australian children [1]. It is the leading cause of burden of disease in children aged 0–14 years in Australia, accounting for 17.9% of the total burden in males and 18.6% in females [2].

Genetic factors [3] and environmental factors (e.g. air pollution) [4] and their interaction [5] are all important in the aetiology and manifestations of asthma. Ambient temperature is a possible trigger for symptoms and disease exacerbation in people with asthma. It is widely accepted that average global ambient temperature is increasing and the frequency and intensity of high temperatures are increasing [6]. Many epidemiological studies have reported associations between changes in ambient temperature and increased risk of respiratory mortality [7] and morbidity [8], especially for vulnerable subgroups of the population, including children. A study conducted in London (UK) reported that a decrease in ambient temperature was associated with decline in lung function in patients with chronic obstructive pulmonary disease [9]. However, few studies have investigated whether ambient temperature has short-term impacts on lung function in children with asthma in Australia.

The Australian Child Health and Air Pollution Study (ACHAPS) examined both the cumulative and short-term effects of environmental factors (e.g. ambient air pollution and temperature) on lung health in a representative national urban sample of children with asthma in Australia. Using data collected for the ACHAPS panel study, this analysis investigates the prospective day-to-day association between urban ambient temperature and lung function in a panel of primary school children with a history of asthma across Australia.

Methods

Study sites

This study was conducted in six major Australian cities: Brisbane, Perth, Sydney, Adelaide, Canberra and Melbourne (the locations of the cities are shown in online supplementary fig. S1). A minimum of two air monitoring stations, with a history of ≥ 5 years of monitoring, were selected per city. Air monitoring stations were located so as to measure background concentrations of air pollutants, rather than point sources of air pollutants. The study period for each location is described in online supplementary table S1.

Data on ambient temperature, air pollution and relative humidity

Daily ambient levels of temperature and air pollution for 2007–2008 were obtained for each of the selected air monitoring stations. The measurements of interest for this panel study included daily 24-h averages, maximum and minimum temperatures, average ozone of the previous 8 h for each hour of the day (8-h moving average) and daily 24-h average nitrogen dioxide.

We collected daily 24-h average relative humidity from Weather Underground (www.wunderground.com) for each city, as the data were incomplete at the monitoring stations.

Study subjects

Schools within 3 km of selected air monitoring stations were identified. All children in school years 3–5 (aged 7–12 years) attending schools that had agreed to participate were then invited to participate in the cross-sectional study. In this part of the study, conducted in 2007–2008, parents completed a baseline questionnaire about the children's lung health and potential environmental factors related to asthma. Children with doctor-diagnosed asthma and symptoms of asthma within the preceding year, that is, with current asthma, and who lived within a 3-km radius of the corresponding air monitoring station were invited to take part in the panel study. A panel of 270 primary school children with a history of asthma formed the sample for this study. Each child provided data over 4 weeks. The study was conducted in Melbourne, Brisbane, Adelaide, Perth and Canberra during 2007 and in Sydney during 2008.

Lung function measurement

Each participant was provided with an electronic peak flow meter (Mini Wright Digital, Clement Clarke, Harlow, UK) and asked to perform three successive forced expiratory manoeuvres, before taking any inhaled medication, twice daily for 4 weeks. The highest peak expiratory flow rate (PEF) and forced expiratory volume in 1 s (FEV₁) from these three successive measurements were automatically stored in the device with a date and time stamp. The children also recorded in a diary any symptoms of asthma and medications taken every morning and evening.

FIGURE 1 Relationship between daily maximum temperature (95% CI) and a–d) peak expiratory flow (PEF) and e–h) forced expiratory volume in 1 s (FEV₁) on the current (lag 0) and previous (lag 1) days, with three degrees of freedom natural cubic spline for daily maximum temperature.

Statistical analyses

A generalised additive mixed model (GAMM) was used to examine the effects of ambient temperature (daily 24-h average, maximum and minimum) on PEF and FEV₁ (morning and evening values). Children's morning and evening PEF and FEV₁ were used as dependent variables. As both the morning and evening

PEF and FEV₁ were normally distributed, Gaussian distribution was used in the analyses. A natural cubic spline with three degrees of freedom for ambient temperatures was used to detect nonlinearity of effects. Preliminary results (plots and model comparisons) suggested that associations could be modelled using a linear function without major loss of precision (fig. 1 is an example), therefore, a linear function was used in the final analyses.

Because children's sex, age, standing height and weight affect lung function, such factors were controlled for by inclusion in all models. In the basic models, ambient temperature, children's sex, age, standing height and weight were specified as fixed effects, while subject was included as a random effect, thus controlling for the effects of season and location. Because air pollution, relative humidity, city characteristics and medication use are potential confounders for the association between temperature and lung function, we introduced 3-day mean concentration of ozone, 3-day mean concentration of nitrogen dioxide, 3-day mean of relative humidity, city and category of medication use into the regression models as fixed effects. We controlled only for ozone and nitrogen dioxide, because ozone is strongly correlated with temperature and a previous study found that nitrogen dioxide had a significant effect on children's lung function in Australia (www.scew.gov.au/resource/australian-child-health-and-air-pollution-study-achaps-final-report).

As previous studies showed that effects of ambient temperature appeared not only on the same day, but also on several following days [10, 11], the lagged effects of ambient temperature for up to 3 days on children's PEF and FEV₁ were also examined.

The same model was used to assess the effects of ambient temperature on children's lung function stratified by sex. To describe whether children have adapted to their local climate, we also examined the effects of temperature (moving average lag 0–3 days) on lung function in five cities separately (Brisbane, Perth, Sydney, Adelaide and Melbourne). The number of participants was insufficient to fit GAMM in Canberra.

In general, children's lung function was more sensitive to daily maximum temperature than daily 24-h average and minimum temperatures. The maximum temperature gave the highest effect estimates and best model fits (results not shown). Therefore, we used daily maximum temperature as the exposure metric in this study.

A number of sensitivity analyses were conducted to check the robustness of our findings and included controlling for respiratory symptoms as a categorical variable; removing ozone, nitrogen dioxide, relative humidity and medication use from the models one at a time to check for changes in the effect estimates; controlling for other air pollutants, for example, particles with a 50% cut-off aerodynamic diameter of 2.5 µm (PM_{2.5}) and sulfur dioxide; and including time and time squared in the models to control for learning effects.

All statistical analyses were performed using R software (The R Project for Statistical Computing, www.r-project.org). The “mgcv” package was used to conduct GAMM. In all analyses, the first 3 days of lung function recordings were excluded to minimise any learning effects. Final results are presented as the estimated changes in lung function associated with a 5°C increase in ambient temperature, with the 95% confidence interval. A p-value of <0.05 was declared as statistically significant.

Ethics statement

The study protocol was approved by the Universities of Queensland and Sydney, Departments of Education in the Australian Capital Territory, New South Wales, Queensland, South Australia, Victoria, and Western Australia. Ethics approval was also obtained from the Catholic Education Office of Victoria to perform the study at selected Victorian Catholic primary schools. All subjects and parents or guardians gave written informed consent before participation in the study.

Results

270 primary school children with asthma were recruited, 46% of whom were female. The children ranged in age from 7 to 12 years and had mean $\pm$ SD standing height and weight of 141 ± 9.47 cm and 38.0 ± 10.6 kg, respectively. As expected, evening PEF and FEV₁ values were slightly higher than morning values (table 1). 14 children took asthma medication every day and 127 children took no medication during the study period (online supplementary fig. S2). Individual characteristics were similar in the six cities, but exposure levels varied by city (online supplementary table S2). All PEF and FEV₁ values were positively correlated (online supplementary table S3).

Table 2 presents the summary statistics for different metrics of ambient temperature, 8-h moving average ozone, daily 24-h average nitrogen dioxide and relative humidity during the panel study period. Mean observed daily 24-h average, maximum and minimum ambient temperatures were 15°C, 20°C and 10°C, respectively. The mean values for 8-h moving average ozone, daily 24-h average nitrogen dioxide and relative humidity were 25.3 ppb, $9.89 \mu\text{g}\cdot\text{m}^{-3}$ and 71.0%, respectively. Minimum, daily 24-h average and

maximum temperatures and 8-h moving average ozone were positively correlated (online supplementary table S4), but they were negatively correlated with daily 24-h average nitrogen dioxide and relative humidity (online supplementary table S4).

Table 3 shows the associations between daily maximum temperature and morning and evening PEF and FEV₁ in asthmatic children from Australia. For all participants, daily maximum temperature was negatively associated with both morning and evening PEF and FEV₁ with a lag of 1, 2 or 3 days. In females, there was no significant association between daily maximum temperature and evening PEF at any lags. In general, the effects of daily maximum temperature on evening FEV₁ were stronger in females than in males, while the effects were stronger in males for evening PEF.

Table 4 shows the effects of daily maximum temperature (moving average lag 0–3 days) on PEF and FEV₁ in five cities in Australia. The effects of temperature on children's lung function varied by city. In general, such effects were greater in southern cities (Perth, Sydney, Adelaide and Melbourne) than in the relatively northern city (Brisbane). Melbourne had the highest effects of temperature on lung function. For example, for evening FEV₁, a 5°C increase in daily maximum temperature (moving average lag 0–3 days) was associated with a decline (95% CI) of 90.1 mL (30.1–150 mL) in Melbourne and 6.86 mL (71.2–84.9 mL) in Brisbane.

When children's respiratory symptoms were included in the models as a categorical variable, the results were similar to our main findings (online supplementary table S5). In other sensitivity analyses, the effect estimates were unchanged when ozone, nitrogen dioxide, relative humidity and medication use were removed from the models (results not shown). The results were also very similar to the main findings when other air pollutants (PM_{2.5} and sulfur dioxide) were controlled for or when time and time squared were added to control for any learning effects (results not shown).

Discussion

The principal findings of this study are that ambient temperature had adverse effects on the lung function of children with asthma and that the effects were apparent even when temperature was lagged by up to 3 days. Increases in ambient temperature were consistently associated with decrements in both PEF and FEV₁ in both males and females. The effects of temperature on children's lung function were higher in southern Australian cities than those in the northernmost city.

Previous studies have found that reduced lung function is associated with mortality and morbidity from cardiovascular and respiratory diseases [12, 13]. There is also evidence that lung function is a good predictor of human health [14]. The finding that increased ambient temperature is associated with a reduction in lung function in children with asthma may have long-term implications for morbidity and mortality.

The results of this study are consistent with previous studies on ambient temperature and human lung function. MANN *et al.* [15] found that in summer, increases in ambient temperature were associated with reduced PEF and increased frequency of respiratory tract infection. An American cohort study reported that warmer temperatures were associated with lower FEV₁ in cystic fibrosis patients [16]. HALES *et al.* [17] found that warmer temperatures were associated with increased prevalence of asthma in adults.

There are very few studies examining the possible mechanisms for the association between temperature increases and their adverse effects on lung function. A possible explanation is that high temperatures are associated with higher levels of allergen exposure, which is a potential environmental trigger of asthma [17]. Higher temperatures are also associated with airway drying, which may trigger bronchoconstriction [18]. Our results suggest that further studies are needed to assess the possible mechanisms for the associations between temperature and lung function.

This study found that the effects of ambient temperature on lung function appeared on the days following exposure (lag effects). This is consistent with observations from many studies that have reported that effects of ambient temperature on mortality and morbidity last several days. The relationships were often observed to be acute and short-term, with the strongest effects recorded in the first 1–3 days following exposure [10, 11]. Understanding this lagged effect is very important when developing preventive health and risk management policies for high temperature days.

This study revealed that males exhibited greater susceptibility to high temperature than females for evening PEF, while females were more sensitive to high temperature than males for evening FEV₁. However, these differences might be explained by chance, as they were not statistically significant (interaction test results not shown). So far, no consistent results have been reported in the literature regarding differential temperature risks by sex. Some studies found that males were sensitive to high temperatures while females were more vulnerable to lower temperatures [19], whereas others have found no differences between the

TABLE 1 Selected demographics and outcomes summary of study participants (270 primary school children with asthma) in Australia

	All	Female	Male
Subjects n	270	123	147
Age years	10.0 ± 1.20 (7.50–12.8)	10.1 ± 1.20 (7.50–12.3)	9.97 ± 1.18 (7.79–12.8)
Standing height cm	141 ± 9.47 (117–170)	142 ± 9.85 (117–170)	140 ± 9.02 (121–169)
Weight kg	38.0 ± 10.6 (21.0–84.0)	39.0 ± 10.9 (21.0–78.0)	37.3 ± 10.2 (22.0–84.0)
Morning PEF L·min⁻¹	257 ± 64.5 (70.0–545)	262 ± 68.2 (70.0–515)	253 ± 61.1 (70.0–545)
Evening PEF L·min⁻¹	266 ± 64.2 (65.0–605)	270 ± 65.2 (65.0–520)	262 ± 63.2 (70.0–605)
Morning FEV₁ L	1.81 ± 0.47 (0.60–4.35)	1.73 ± 0.46 (0.60–3.40)	1.87 ± 0.47 (0.60–4.35)
Evening FEV₁ L	1.84 ± 0.48 (0.65–4.45)	1.76 ± 0.47 (0.65–3.45)	1.90 ± 0.49 (0.70–4.45)

Data are presented as mean ± sd (range), unless otherwise stated. PEF: peak expiratory flow; FEV₁: forced expiratory volume in 1 s.

sensitivity of males and females to cold or hot weather [20, 21]. Further detailed studies are needed to explore these sex differences.

We found that the effects of ambient temperature on children's lung function varied in different Australian cities. Children with asthma living in southern cities were more vulnerable to high temperatures than those in the northernmost city. Melbourne should pay more attention to the effects of high temperature on children's lung function. Our results are consistent with the fact that mortality reaches its minimum at higher temperatures in hotter regions than in colder places [22, 23]. It may be that people acclimatise to their local climate through physiological adaptation to slowly increasing temperatures [24]. Previous studies have found that local conditions, such as social, economic and demographic factors and characteristics of infrastructure may modify the effects of ambient temperatures on human health [25]. Intensity of urban heat islands, social isolation, access to air conditioning and housing characteristics are also modifiers of the temperature–health relationship [26]. However, when socioeconomic indexes for areas of Australia were included in the models, effects were unchanged (results not shown).

The finding that high temperature has a significant impact on the lung function of children with asthma may have clinically important implications. In particular, in population terms, even a small decline in average lung function may have important impacts at the extreme ends of the distribution [27]. Meanwhile, asthma is the most common chronic disease among children in Australia. The most recent data suggest that one in six Australian children have diagnosed asthma [1]. Therefore, a large group of children are susceptible to adverse effects of ambient temperature.

To the best of our knowledge, this is the first panel study to examine the short-term effects of ambient temperature on lung function in schoolchildren with asthma. It employed an Australian national sample with a relatively large sample size (n=270) to examine the effects of ambient temperature on both PEF and FEV₁. Morning and evening lung function were measured twice daily for 4 weeks, which contributed to the reliability of this study, along with the use of different metrics of ambient temperature, examination of lag effects and assessment of the effects by sex and location. We controlled for other pollutants as potential confounders of temperature effects, because a number of studies have reported that air pollution is a risk

TABLE 2 Descriptive statistics for selected daily exposure measurements during the study period (4 weeks in 2007–2008) in Australia

Exposures	Mean ± sd	Median	IQR	Range
24-h average temperature °C	15.1 ± 4.66	15.1	11.8–17.6	4.27–31.0
Maximum temperature °C	20.0 ± 5.76	19.4	15.4–23.5	9.50–39.9
Minimum temperature °C	10.5 ± 4.35	10.5	7.30–13.6	0.10–24.1
8-h moving average ozone[#] ppb	25.3 ± 8.63	24.6	19.9–30.0	0.88–65.9
24-h average nitrogen dioxide µg·m⁻³	9.89 ± 6.27	8.91	5.26–13.2	0.05–35.4
Relative humidity %	71.0 ± 13.1	73.0	63.0–80.0	32.0–94.1

IQR: interquartile range. [#]: average ozone of the previous 8 h for each hour of the day.

TABLE 3 Mixed model estimates of changes in lung function with every 5°C increase in daily maximum temperature at different lags among 270 children with asthma in Australia

	Lag [#]	All	Female	Male
Morning PEF L·min⁻¹	0	-2.42 [-4.19--0.65]**	-3.48 [-6.08--0.88]**	-1.38 [-3.80--1.04]
	1	-2.80 [-4.55--1.05]**	-2.42 [-4.98--0.14]	-3.08 [-5.48--0.68]*
	2	-3.00 [-4.74--1.26]**	-2.59 [-5.12--0.05]*	-3.27 [-5.67--0.87]**
	3	-1.59 [-3.29--0.11]	-1.62 [-4.09--0.85]	-1.46 [-3.80--0.88]
Evening PEF L·min⁻¹	0	-0.85 [-2.70--1.00]	-0.26 [-2.89--2.36]	-1.31 [-3.93--1.31]
	1	-1.04 [-2.86--0.78]	1.15 [-1.43--3.74]	-2.88 [-5.45--0.32]*
	2	-1.45 [-3.22--0.32]	-0.52 [-3.01--1.97]	-2.14 [-4.66--0.38]
	3	-2.33 [-4.09--0.56]**	-0.27 [-2.74--2.19]	-4.14 [-6.66--1.61]**
Morning FEV₁ mL	0	-9.39 [-24.7--5.88]	-16.0 [-36.8--4.80]	-2.97 [-25.0--19.1]
	1	-18.1 [-33.0--3.16]*	-7.06 [-27.4--13.3]	-26.6 [-48.2--5.01]*
	2	-26.9 [-41.6--12.1]**	-24.4 [-44.4--4.34]*	-29.1 [-50.5--7.73]**
	3	-19.0 [-33.6--4.33]*	-30.3 [-50.4--10.3]**	-8.83 [-29.9--12.2]
Evening FEV₁ mL	0	-4.40 [-22.6--13.8]	-14.1 [-38.6--10.5]	2.29 [-24.3--28.9]
	1	-27.8 [-45.7--9.99]**	-37.8 [-61.8--13.7]**	-19.0 [-45.1--7.18]
	2	-39.7 [-57.6--21.9]**	-64.9 [-88.8--40.9]**	-16.7 [-43.0--9.56]
	3	-38.5 [-56.2--20.7]**	-48.0 [-71.5--24.5]**	-29.0 [-55.5--2.46]*

Data are presented as coefficient (95% CI). All models controlled for children's sex, age, standing height, weight, 3-day mean concentration of ozone, 3-day mean concentration of nitrogen dioxide, 3-day mean of relative humidity, city and medication use as fixed effects. PEF: peak expiratory flow; FEV₁: forced expiratory volume in 1 s. [#]: lag exposure of temperature [0: exposure of current day's temperature; 1: exposure of temperature on the previous day; 2: exposure of temperature 2 days previously; 3: exposure of temperature 3 days previously]. *: p<0.05; **: p<0.01.

factor for decreased lung function and it may induce childhood asthma [28]. The findings may have implications for promoting capacity building for preventing health problems related to temperature increase.

A limitation of this study was that it only included urban children and, therefore, we cannot generalise the results to children who live in rural areas. In addition, the information on ambient temperature, relative humidity and air pollution was from fixed monitoring sites rather than individual exposures, which may lead to measurement errors in exposures. The estimated effects might be overestimated if exposure levels at the given monitoring site are in the lower range of population exposure. However, temperature measurements at fixed monitoring sites have been shown to be as good at estimating city-wide associations between temperature and mortality as spatially resolved temperatures [29], because temperatures show little spatial variation within cities. We used the current day's maximum temperature as the principal exposure to assess effects on morning lung function, which may lead to measurement errors. However, because daily 24-h average, maximum and minimum temperatures are very strongly correlated (online supplementary table S4) and daily maximum temperature was the best predictor in this study, maximum temperature was the most appropriate exposure. The study lacked data on effects during summer, as measurements were performed only during school terms. We have used a nonlinear function to examine whether the effects of temperature on

TABLE 4 Mixed model estimates of changes in lung function with every 5°C increase in maximum temperature (moving average lag 0–3 days) among children with asthma in five cities in Australia

	Morning PEF L·min ⁻¹	Evening PEF L·min ⁻¹	Morning FEV ₁ mL	Evening FEV ₁ mL
Brisbane	-1.48 [-4.94--1.98]	-3.98 [-15.3--7.33]	-21.5 [-96.8--53.9]	-6.86 [-84.9--71.2]
Perth	-9.68 [-19.9--0.52]	1.12 [-17.9--20.1]	-48.0 [-181--86.0]	-39.3 [-276--198]
Sydney	-11.4 [-18.2--4.54]**	-6.56 [-14.1--0.93]	-73.5 [-139--8.17]*	-9.84 [-91.4--71.8]
Adelaide	-14.2 [-29.8--1.32]	0.28 [-5.10--5.65]	-9.75 [-63.6--44.1]	-8.88 [-58.6--40.9]
Melbourne	-9.20 [-14.6--3.85]**	-5.18 [-10.4--0.06]	-69.2 [-121--17.2]**	-90.1 [-150--30.1]**

Data are presented as coefficient (95% CI). All models controlled for children's sex, age, standing height, weight, 3-day mean concentration of ozone, 3-day mean concentration of nitrogen dioxide, 3-day mean of relative humidity and medication use as fixed effects. Cities are ordered by latitude (north to south from Brisbane to Melbourne). PEF: peak expiratory flow; FEV₁: forced expiratory volume in 1 s. *: p<0.05; **: p<0.01.

lung function were nonlinear, but a consistent linear relationship was found for both PEF and FEV₁. We have not examined or controlled for the effects of aeroallergens, such as pollens, in this study, as we didn't measure these factors in the study period.

Conclusions

This study suggests that increased ambient temperature adversely affected both PEF and FEV₁ in Australian schoolchildren with asthma. The effects lasted for several days. For evening PEF, males were more sensitive to ambient temperature than females, while females were more vulnerable than males for evening FEV₁. The results indicate that the increasing frequency of high temperatures might be a risk to the health of children with asthma.

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