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Association between weather, air quality and asthma-related emergency department visits: a retrospective time-series study in Singapore

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ABSTRACT

Objectives To evaluate the association between asthma-related emergency department (ED) visits and weather, air quality, monsoons, haze and cultural festivals in Singapore.

Design Retrospective cohort study.

Setting A public healthcare cluster that covers 20% of the nation's adult asthma population.

Participants 2617 adult patients accounting for 5337 asthma ED visits between 2016 and 2024.

Primary and secondary outcome measures Temperature, rainfall, wet bulb temperature (WBT), wind speed and Pollution Standards Index (PSI) were correlated with asthma ED counts at 0–7 day lags. Associations between ED visits and monsoons, transboundary haze and cultural festivals were evaluated using one-way analysis of variance. Weekly seasonal ARIMA models with exogenous regressors were fitted, incorporating PSI as a covariate and adjusting for demographic, clinical and socioeconomic factors.

Results Asthma ED visits were positively correlated with PSI (lag 0: r=0.142; 95% CI 0.107 to 0.178) and inversely correlated with rainfall (lag 3: r=−0.062; 95% CI −0.099 to −0.026) and WBT (lag 1: r=−0.067; 95% CI −0.104 to −0.031). Wind speed (lag 2: r=−0.049; 95% CI −0.086 to −0.013) and ambient temperature (lag 6: r=−0.045; 95% CI −0.081 to −0.008) showed weaker inverse associations. Mean PSI was higher during haze (82.67 vs 51.46, p<0.001) and festival periods (53.42 vs 51.57, p=0.001). Mean ED visits fell across successive haze events (2.60 in 2016, 2.36 in 2019, 1.46 in 2023) but peaked during the Northeast monsoons despite lower PSI, indicating weather influences beyond ambient pollution.

Conclusions PSI–ED association peaked on the same day of exposure but was no longer significant after adjusting for demographic and clinical factors. Pollution-linked festivals, transboundary haze and the Northeast monsoon were associated with increased asthma ED visits

STRENGTHS AND LIMITATIONS OF THIS STUDY

⇒ Novel real-world study examining region-specific events such as cultural festivals, haze periods and monsoon seasons.
⇒ Long follow-up period using a large data set from the largest public healthcare system in Singapore.
⇒ Absence of indoor air quality measurements may have led to exposure misclassification.
⇒ Data from other healthcare clusters and on broader aspects of asthma control were unavailable.

BACKGROUND

Fluctuations in weather and air quality can significantly affect asthma control.[1] A recent systematic review showed increased asthma events during extreme weather changes such as heat waves, hurricanes and floods.[2] An understanding of how acute asthma care worsens with these events is helpful in guiding the formulation of actionable public health strategies and improving health system preparedness. However, most of the available evidence originated from temperate countries with seasonal variations, where poor air quality and extreme weather events (eg, thunderstorms and floods) are associated with asthma exacerbations.[2 3] Less is known about these associations in tropical countries including those in Southeast Asia (SEA).

Singapore is a tropical country that experiences high temperatures, humidity and abundant rainfall throughout most of the year. Its climate is shaped by regional monsoons and transboundary haze events instead of the four seasons found in more temperate climates.[4 5] Its multicultural society celebrates several cultural festivals with practices such as incense burning, joss-paper combustion and oil-lamp lighting, which may contribute to ambient air pollution.[6] To fill the gap and clarify any associations between acute asthma care, weather and air quality in a tropical setting, we examined the temporal patterns and associations between individual weather variables, monsoons, transboundary haze and cultural festivals with asthma ED visits in Singapore. Our findings will help to inform public health strategies in the region.

METHODS

We performed a retrospective observational study on patients with asthma seen across the public healthcare continuum. This included primary care in 10 community polyclinics, secondary care in respiratory specialist clinics and tertiary care in a large hospital in Singapore between 2016 and 2024. This healthcare cluster covers about 20% of Singapore's adult population.[7] Patient records were retrieved from the SingHealth Chronic Obstructive Pulmonary Disease (COPD) and Asthma Data Mart (SCDM), an integrated real-world data database.[8] There were no missing data for the variables included in this analysis, as these clinical and demographic variables were routinely captured and extracted directly from the electronic medical record system.

Inclusion criteria were adults aged 18 years and above with physician-diagnosed asthma who had at least one ED visit coded for asthma (International Classification of Diseases (ICD)−10 code J45.9) within the study period. No exclusion criteria were applied, as all identified cases were eligible for analysis. No independent validation against the global initiative for asthma (GINA) diagnostic criteria or spirometry results was performed; diagnoses were based on clinician-entered ICD coding.

Data on weather (temperature, rainfall, wet bulb temperature (WBT), wind speed) and Pollution Standards Index (PSI) were retrieved from public databases under the National Environment Agency and Singapore Meteorological Service.[9] To address any missing weather data, we imputed the national mean from the remaining stations (Supplemental Materials, Missing Data Handling). PSI, as defined by the US Environmental Protection Agency and adopted by Singapore's National Environment Agency, integrates six pollutants (PM2.5, PM10, SO2, NO2, O3 and CO) into a single air-quality score ranging from 0 to 500, with higher values indicating poorer air quality.[10] PSI was chosen due to the data completeness compared with other individual air quality measures.[11]

Effect of individual weather and PSI variables on asthma ED visits

Analyses were conducted at daily, weekly and monthly scales. Pearson correlations assessed linear associations, with lagged effects (lags 0–7) to capture delayed associations between environmental exposure and asthma ED visits.[12] Extreme weather periods were defined by the fifth and 95th percentiles of each meteorological variable. Asthma-ED visit frequencies across low, normal and high strata were compared with the Kruskal-Wallis test, followed by Dunn's pairwise comparisons with Bonferroni adjustment.

Stratified and interaction SARIMAX analysis of PSI on asthma ED visits

To account for seasonality and serial autocorrelation in ED visits, we fitted weekly seasonal ARIMA models with exogenous regressors (SARIMAX). A baseline SARIMAX (2,1,2)(1,0,1,52) model was applied to the full data set, incorporating PSI as a time-varying covariate and adjusting for subgroup proportions (age≥65 years, male sex, GINA steps 2–5, allergic rhinitis, COPD and Singapore Housing Index (SHI) quartiles 2–4, where SHI is a socioeconomic proxy based on housing type and transaction prices.[13] An extended specification added PSI interaction terms with these subgroup covariates to assess effect modification. Convergence diagnostics, Ljung–Box Q tests and inspection of autocorrelation and partial autocorrelation functions confirmed that model residuals approximated white noise after inclusion of the 52 week seasonal term.

Effect of monsoons, haze and festival periods on asthma ED visits

Differences in ED visits frequency across monsoon seasons were analysed with one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) post-hoc test. Mean asthma ED visit rates during transboundary haze events and festival periods were compared with all other days using independent t-tests. Details on the festival periods can be found in Supplemental Materials (online supplemental table S1).

For the remaining univariate comparisons, we used the χ^2 test for categorical variables and the Mann-Whitney U test for non-parametric data. All analyses were performed in Python (V.3.10). Details on how statistical assumptions were evaluated prior to each analysis are provided in the Supplemental Materials (Additional Statistical Analyses, Evaluating Statistical Method Assumptions). We also performed extensive sensitivity and robustness analyses across multiple model specifications, including alternative imputation strategies, subsampling and leave-1 year-out validation (Supplemental Materials, Additional Statistical Analyses, Modelling Variable Uncertainty).

Patient and public involvement

Patients and members of the public were not involved in the design, conduct, reporting or dissemination of this study, as it was based on a retrospective analysis of our Asthma Data Mart and environmental data available from public databases. However, we plan to develop a lay summary of the findings and share these with relevant patient groups and organisations as part of our dissemination activities.

RESULTS

We reviewed 2617 patients who accounted for 5337 asthma ED visits (table 1). ED visits demonstrated a gradual decline from 2016 to 2024. A significant decline in ED visits was observed during the COVID-19 pandemic compared with the prepandemic period (figure 1). PSI

Table 1 Clinical characteristics of the study population

Variable		Number of patients (%)
Total number of patients with at least one ED visit	2617	
Mean age, years (±SD)	51.90±18.87	
Race	Chinese	1095 (41.8)
	Malay	651 (24.9)
	Indian	626 (23.9)
	Others	245 (9.4)
Sex	Male	1018 (38.9)
	Female	1599 (61.1)
Mean ESHI* (±SD)	3.75±0.62	
Comorbidities	Allergic rhinitis	504 (19.3)
	Anxiety disorder	56 (2.1)
	Atopic dermatitis	12 (0.5)
	COPD	261 (10.0)
	Depression	39 (1.5)
	GERD	302 (11.5)
	Heart failure	183 (7.0)
	Hypertension	1017 (38.9)
	Obstructive sleep apnoea	141 (5.4)
GINA step at first visit†	1	982 (37.5)
	2	418 (16.0)
	3	439 (16.8)
	4	716 (27.4)
	5	62 (2.4)
Number of ED visits	2016	804
	2017	803
	2018	786
	2019	798
	2020	393
	2021	436
	2022	574
	2023	586

*ESHI (Environmental, Social and Health Index) was available for 1160 patients.
†GINA (global initiative for asthma) steps were based on 2016 criteria.
COPD, chronic obstructive pulmonary disease; ED, emergency department; GERD, gastroesophageal reflux disease.

spikes were observed during August and November in 2016, 2019 and 2023, coinciding with the transboundary haze periods. Weather trends were consistent, with drier and warmer conditions in the second half of each year (figure 1).

Asthma ED visits were positively correlated with PSI and inversely correlated with rainfall and WBT (figure 2). Daily asthma ED visits showed the strongest same-day correlation with PSI (lag 0: r=0.142, 95% CI 0.107 to 0.178). Rainfall showed its strongest inverse association 3 days later (lag 3: r=−0.062, 95% CI −0.099 to −0.026), and WBT remained consistently negative, strongest at lag 1 (r=−0.067, 95 CI −0.104 to −0.031). Wind speed reached its greatest inverse correlation at lag 2 (r=−0.049, 95% CI −0.086 to −0.013), while ambient temperature showed only weak negative correlations at lags 5–6 (figure 3, online supplemental table S2).

In fully adjusted SARIMAX models, PSI was not significantly associated with ED visits, and no effect modification was observed across subgroups, age, sex, GINA step, allergic rhinitis, COPD or SHI quartile (table 2, online supplemental figure S1). When comparing the extreme weather conditions, the extremes of PSI (high), WBT (low) and wind speed (low) had significantly higher ED visits than the rest (figure 4, online supplemental table S3).

Transboundary haze, festival periods and monsoons

PSI levels were significantly elevated during both transboundary haze periods (mean PSI: 82.67 vs 51.46 during non-haze periods) and cultural festival periods (53.42 vs 51.57 during non-festival periods) (tables 3 and 4).

Festival periods had almost twice as many mean asthma ED visits per day as non-festival periods (2.74 vs 1.59) (table 3). All six types of festivals showed higher ED visits compared with those during non-festival periods, while only the Chinese Festivals of Qingming, Hungry Ghost and Mid-autumn Festivals (which involved extensive outdoor incense burning) had greater PSI (online supplemental tables S4 and S5).

Mean daily visits declined across successive haze events, from 2.60 (in 2016) to 2.36 (in 2019), and further to 1.46 (in 2023), dropping below the non-haze average of 1.78 (table 4). The cooler and drier Northeast monsoon was significantly associated with increased ED visits, despite lower PSI levels (table 5).

DISCUSSION

We demonstrated that even in a tropical country with ostensibly stable weather, a significant rise in asthma ED visits can coincide with shifts in weather during the Northeast monsoons, worsened air quality from haze and uniquely, pollution-linked festivals. This finding contrasts with the well-studied effects of seasonal fluctuations in asthma ED visits in temperate countries.[2 3] The decline in ED visits during the COVID-19 pandemic has also been reported in other local studies and was postulated to be related to public health measures such as mask-wearing and social distancing.[14 15]

Individual associations between weather, PSI and ED visits

We found that higher PSI values were consistently associated with more asthma ED visits, consistent with other epidemiologic studies with similar risk ratios (RR 1.011 in Shanghai; RR 1.01–1.07 in Texas).[16 17] However, the

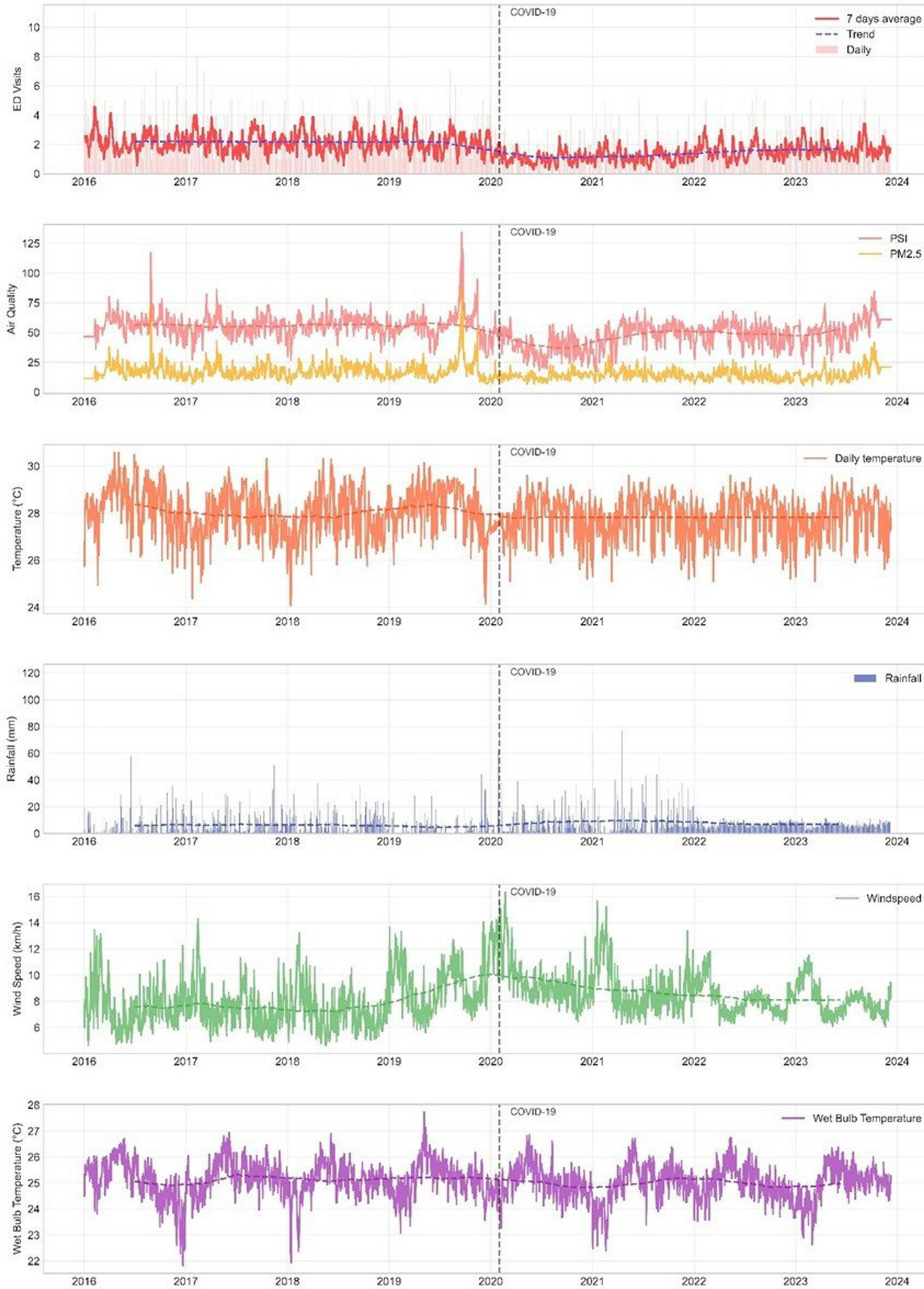

Figure 1 Daily trends of ED visits, air quality, temperature, rainfall, wind speed and wet bulb temperature between 2016 and 2024. Seasonal variations can be observed: cooler, drier weather during Northeast monsoon (December to March) and warmer, wetter weather during Southwest monsoon (June to September). A notable decrease in ED visits was observed after 2020, corresponding to the onset of the COVID-19 pandemic and isolation measures. ED, emergency department; PSI, Pollution Standards Index.

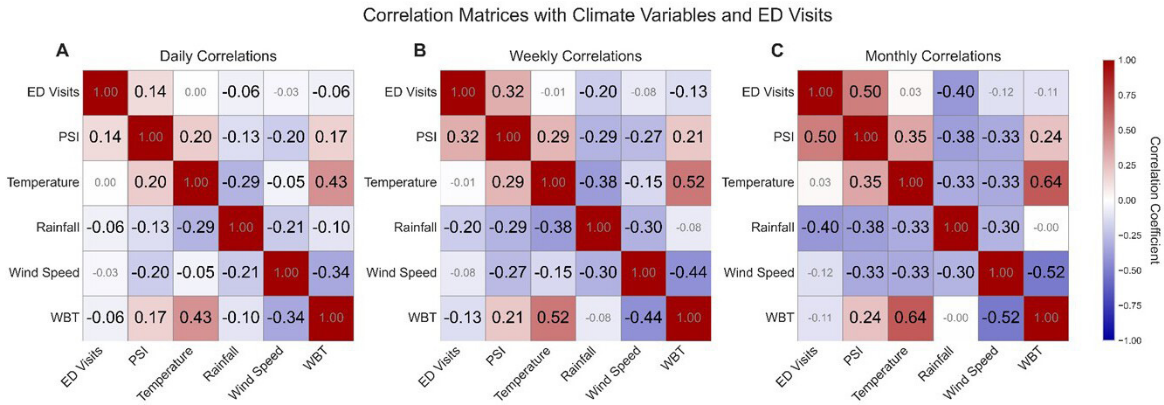

Figure 2 Correlation matrices between ED visits and weather variables at daily (A), weekly (B) and monthly (C) levels. Enlarged fonts indicate statistically significant correlations (p<0.05). ED visit was positively correlated with PSI and negatively correlated with rainfall and WBT. The strongest PSI–ED correlation was seen with the monthly values. Linearity assessment for Pearson correlations was shown in online supplemental figure S3. ED, emergency department; PSI, pollution standards index; WBT, wet-bulb temperature.

significant PSI–ED correlation was not observed in the adjusted SARIMAX model, which may reflect underlying contributions from patient demographic and clinical factors.

Lower rainfall and humidity were associated with higher risks of asthma ED visits, possibly due to increased airway hyper-responsiveness triggered by cold and dry air.[18–20] A recent meta-analysis demonstrated a weak but statistically significant inverse association between precipitation (rainfall) and asthma risk (OR 0.9991, 95% CI 0.9987 to 0.9995).[21] The authors postulated that higher rainfall may reduce asthma risk through enhanced clearance of airborne pollutants and allergens, as well as by delaying health-seeking behaviours. However, when analyses were stratified by geographic region, no statistically significant association was observed in low-latitude countries, where

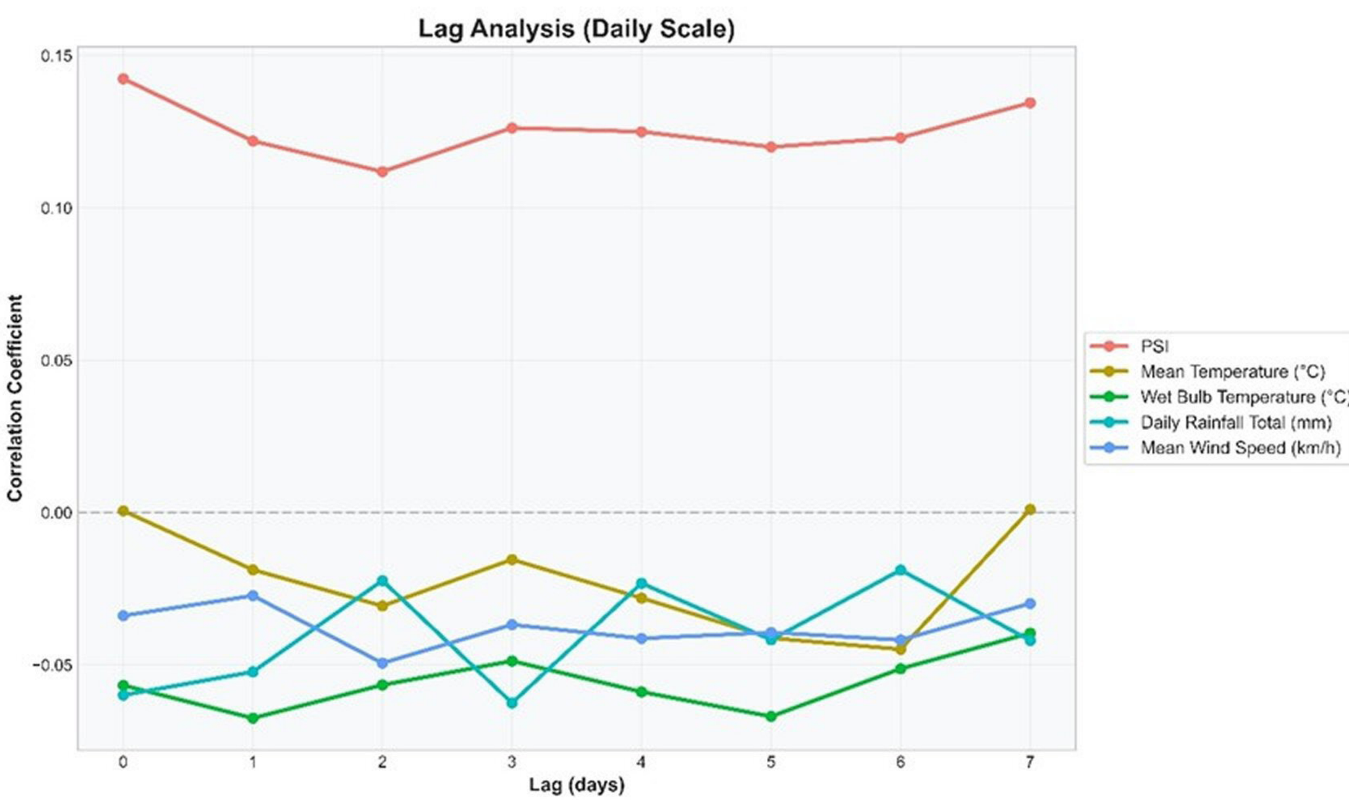

Figure 3 Time-lag correlations between emergency department (ED) visits, air quality and weather variables (lags 0–7 days). Daily asthma ED visits showed the strongest same-day correlation with PSI. Rainfall had its peak inverse association 3 days later and WBT remained consistently negative, highest at lag 1. Wind speed reached its greatest inverse correlation at lag 2, while ambient temperature showed only weak negative correlations at lags 5–6. The actual values are summarised in online supplemental table S2. PSI, Pollution Standards Index.

Table 2 Stratified SARIMAX associations between PSI and weekly asthma ED visits

Stratification variable	Group	β (log-count)	95% CI	IRR	95% CI	P value
Age	<65 y (ref)	0.015	–0.064 to 0.093	1.02	0.94 to 1.10	0.712
	≥65 y	0.077	–2.257 to 2.411	1.08	0.10 to 11.14	0.788
Gender	Female (ref)	0.015	–0.064 to 0.093	1.02	0.94 to 1.10	0.712
	Male	–0.807	–3.022 to 1.408	0.45	0.05 to 4.09	0.387
GINA step	1 (ref)	0.015	–0.064 to 0.093	1.02	0.94 to 1.10	0.712
	2	0.074	–2.309 to 2.458	1.08	0.10 to 11.68	0.798
	3	0.242	–2.264 to 2.748	1.27	0.10 to 15.61	0.684
	4	–0.669	–3.409 to 2.072	0.51	0.03 to 7.94	0.644
	5	–0.586	–3.595 to 2.423	0.56	0.03 to 11.28	0.735
Allergic rhinitis	Absent (ref)	0.015	–0.064 to 0.093	1.02	0.94 to 1.10	0.712
	Present	0.015	–2.143 to 2.173	1.02	0.12 to 8.79	0.816
COPD	Absent (ref)	0.015	–0.064 to 0.093	1.02	0.94 to 1.10	0.712
	Present	–0.435	–3.269 to 2.399	0.65	0.04 to 11.02	0.810
SHI quartile	Q1 (most-deprived, ref)	0.015	–0.064 to 0.093	1.02	0.94 to 1.10	0.712
	Q2	0.284	–2.273 to 2.841	1.33	0.10 to 17.13	0.663
	Q3	0.352	–2.246 to 2.950	1.42	0.11 to 19.11	0.624
	Q4 (least-deprived)	–0.222	–2.755 to 2.311	0.80	0.06 to 10.08	0.942

β=log-count coefficient for PSI; IRR=incidence rate ratio per one-unit increase in PSI. SARIMAX model residual diagnostics were shown in online supplemental figure S4.
COPD, chronic obstructive pulmonary disease; ED, emergency department; GINA, global initiative for asthma; IRR, incidence rate ratio; PSI, Pollution Standards Index; SARIMAX, seasonal ARIMA models with exogenous regressors; SHI, Environmental, Social and Health Index.

rainfall and humidity levels are chronically high.[21] Further studies in SEA are warranted to validate these findings.

Temperature showed no significant correlation with ED visits, likely due to Singapore's narrow temperature range (26.4°C–29.4°C) (online supplemental table S6).[9] In contrast, settings with wider temperature fluctuations, such as Shenzhen, China (3.5°C–32.4°C), reported increased risk of ED visits during heat waves (90th percentile: RR 1.17) and cold waves (10th percentile: RR 1.06).[22] Wind speed was also non-significant, similar to the mixed findings in the literature.[18 23] While high wind speed may affect allergen-driven asthma via aeroallergen dispersion, more work integrating trends in allergen exposure is needed to elucidate the allergen-mediated effects of wind speed on asthma exacerbations.

Monsoons and haze

Every year in SEA, the Northeast monsoon winds bring in cool, dry air from Central Asia, while the Southwest monsoon winds bring in warm, humid air from the Indian Ocean. We found that asthma ED visits peaked during the cool, dry Northeast monsoon, despite air quality being better than during other periods. A similar pattern has been documented in South Korea, where the cooler, drier, windier non-fog days generated more exacerbations than fog-laden, polluted days.[23] Possible explanations include reduced outdoor exposure during visible haze and the irritant or infection-promoting effects of cool, dry air.[20 23]

In 2016, 2019 and 2023, the Southwest monsoon winds carried smoke from regional peatland fires, contributing up to 50%–85% of regional pollutants with spikes seen in August and November.[24] Prior to our study, the 1997 haze in Singapore saw a 20% increase in asthma ED presentations.[5] We observed more asthma ED visits during the haze periods of 2016 and 2019 compared with non-haze periods, but not for the 2023 haze. The apparent decline in mean daily asthma ED visits across the successive episodes may indirectly reflect the effect of haze advisories and adaptive behaviours, though further studies are needed to confirm this.[25] The effects of haze transcend beyond asthma ED visits or hospitalisations. A study in Malaysia saw a 19% rise in mortality from respiratory disease during the haze periods between 2000 and 2007. Beyond asthma, haze in SEA has been associated with an 8%–11% rise in myocardial infarction.[26]

Festival-related air pollution

Singapore's multiethnic calendar features several religious festivals that can inevitably generate outdoor and indoor pollution. We found that during Qingming, Hungry Ghost and Mid-Autumn festivals, where incense burning is prevalent, asthma ED visits nearly doubled even though PSI increased only marginally from 51.57 to 53.40. This suggests that other pollutants released during burning, such as volatile organic compounds and methane, might have contributed to the rise in ED visits.[27]

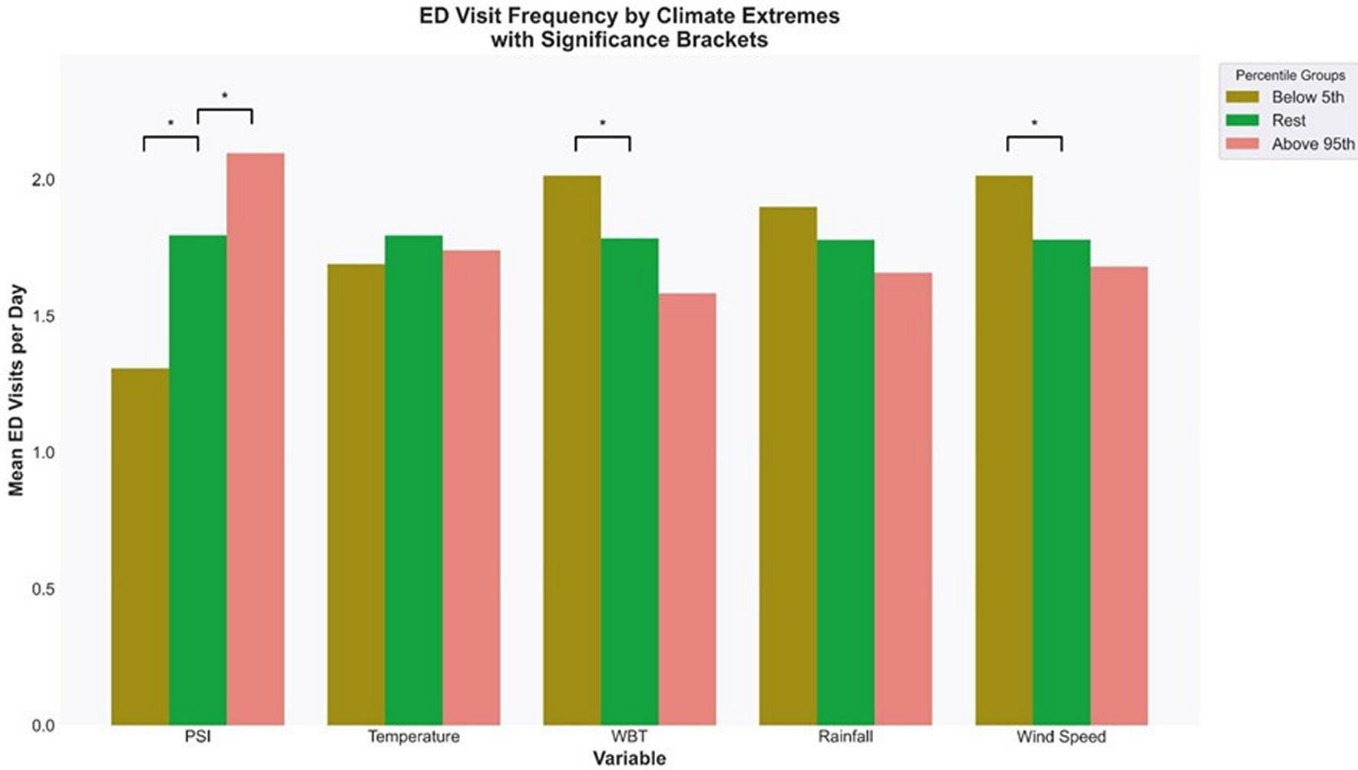

Figure 4 Comparison of mean daily ED visit across extreme weather conditions and the rest of the study period, represented as olive brown (fifth percentile), green (5–95th percentiles) and pink (95th percentile). Asterixis represents statistically significant relationships. ED visits were significantly greater during periods of high PSI, low WBT and low wind speed. ED, emergency department; PSI, Pollution Standards Index; WBT, wet bulb temperature.

Another potential contributor to the worsened air quality during these festivals could be the increased traffic emissions; in Taiwan, both heavier motor-vehicle traffic and incense burning contributed to a 9.8%–18.6% spike in ambient pollutants during the Tomb-Sweeping Day.[28] By contrast, the Hindu festival of Thaipusam showed increased ED visits despite a lower mean PSI than those during the non-festival periods. This might be related to factors beyond ambient PSI, such as worsened indoor air quality from burning candles and aromatic oils, which are responsible for substantial amounts of particulate matter above 1000 µg/m.3[29 30] Additionally, increased social mixing might have promoted the transmission of respiratory viral infections, contributing to more asthma exacerbations.[31]

Table 3 Weather variables and ED visits during the various festivals (2016–2023)

Variable, mean±SD	Festival	Non-festival	P value
ED visits	2.74±1.66	1.59±1.31	<0.005
PSI	53.42±11.33	51.57±11.34	<0.005
Temperature (°C)	28.03±0.87	27.95±0.97	0.060
WBT (°C)	24.91±0.64	25.12±0.72	<0.005
Rainfall (mm/day)	6.41±9.30	7.00±8.72	0.197
Wind speed (km/hour)	8.60±1.84	8.20±1.78	<0.005

Refer to online supplemental table S1 for the specific periods for each year, and subgroup analysis of each festival (online supplemental tables S4 and S5).
*Festival category includes Chinese New Year, Qingming, Hungry Ghost festival, mid-Autumn festival, Thaipusam, Deepavali.
ED, emergency department; PSI, Pollution Standards Index; WBT, wet bulb temperature.

Limitations

This study has several limitations. First, meteorological coverage was incomplete with missing data from two of the 13 weather stations. To address this, we imputed the national mean from the remaining stations, which may have attenuated true local variability. However, bootstrap resampling demonstrated consistent correlation patterns, and sensitivity analyses showed results were robust to missing-data imputation and subsampling (online supplemental tables S8, S9 and figure S2). Our clinical data were confined to one of the three public health clusters, potentially limiting the generalisability of our findings. Second, our air-quality analyses were limited to outdoor PSI measurements. Using PSI instead of the Air Quality Index (AQI) and PM2.5 may have underestimated fine-particle pollution, and omitting indoor pollutants, especially during the COVID-19 pandemic, could have led to exposure misclassification.[32] Third, we captured only asthma ED visits, missing milder events and patient symptoms, which may be affected earlier by environmental changes.

Table 4 Weather variables and ED visits during the haze periods (2016–2023)

Variable, mean±SD	Haze*	Non-haze	P value	2016 haze	2019 haze	2023 haze	Welch -ANOVA p value	Significant post-hoc differences
ED visits	2.10±1.28	1.78±1.45	0.125	2.60±1.95	2.36±1.05	1.46±1.20	0.097	2019>non-haze
PSI	82.67±19.91	51.46±10.58	<0.005	93.52±26.10	85.68±22.06	73.42±7.17	<0.005	2016, 2019, 2023>non-haze
Temperature (°C)	28.45±0.78	27.95±0.95	<0.005	28.99±0.70	28.22±0.88	28.64±0.47	<0.005	2016, 2019, 2023>non-haze
WBT (°C)	25.15±0.43	25.08±0.72	0.350	25.14±0.60	24.94±0.35	25.51±0.21	<0.005	2016>non-haze
Rainfall (mm/day)	4.59±6.88	6.93±8.84	0.039	2.62±2.30	4.29±9.17	5.84±1.23	<0.005	Non-haze>2016
Wind speed (km/hour)	8.40±1.57	8.27±1.80	0.597	7.43±1.28	9.27±1.56	7.31±0.44	<0.005	2019>2016, 2023

*Transboundary haze periods refer to: 26–30 August 2016, 14 September to 5 October 2019 and 7–19 October 2023.
ANOVA, analysis of variance; ED, emergency department; PSI, Pollution Standards Index; WBT, wet bulb temperature.

Excluding children further limited insight into paediatric asthma, a group highly sensitive to weather and pollution.

10% of patients had a concurrent COPD diagnosis, which may have partly influenced their exacerbations. We did not exclude these patients, as asthma-COPD overlap is common in clinical practice and both conditions share similar air pollution-related triggers.[33 34] Diagnostic overlap may remain, but exclusion would have reduced the real-world representativeness of our findings. Finally, we lacked data on key asthma triggers such as aeroallergens, respiratory viruses and indoor pollution, which limited our ability to separate their effects from outdoor pollution.[35] We also could not account for protective measures like asthma action plans, pre-emptive medication escalation and reinforcement of medication adherence.

Implications for policy, practice and research

Our findings can be used to develop effective adaptation strategies against avoidable asthma ED visits.[36] Real-time alert systems in anticipation of known triggers, such as transboundary haze, Northeast monsoons and cultural festivals, could prompt timely measures such as mask wearing and crowd avoidance, practices already proven effective during the COVID-19 pandemic.[37] Pre-emptive escalation of maintenance inhalers and reminders to enforce medication adherence can also be implemented ahead of these events, particularly for susceptible cohorts such as children and the socioeconomically disadvantaged.[18]

Finally, our findings create an opportunity for policymakers and religious leaders to collaborate and reduce

Table 5 Weather variables and ED visits during monsoons (2016–2023)

Variable, mean±SD	Northeast monsoon (NEM)	Inter-monsoon I (IM1)	Southwest monsoon (SWM)	Inter-monsoon II (IM2)	ANOVA p value	Significant post-hoc differences (Tukey's HSD)
ED visits	1.91±1.50	1.74±1.45	1.77±1.45	1.61±1.30	0.002	NEM>IM2
PSI	48.85±9.65	53.36±10.54	53.14±12.52	53.80±11.63	<0.005	IM1, IM2, SWM>NEM
Temperature (°C)	27.50±0.87	28.31±0.87	28.31±0.88	27.80±0.91	<0.005	IM1<NEM, SWM, IM2; NEM>IM2, SWM
WBT (°C)	24.63±0.70	25.73±0.52	25.25±0.55	24.98±0.53	<0.005	IM1<NEM, SWM, IM2; NEM>SWM, IM2
Rainfall (mm/day)	6.31±9.86	7.92±8.35	6.22±8.34	8.37±7.79	<0.005	NEM, SWM>IM1; NEM, SWM>IM2
Wind speed (km/hour)	9.45±2.06	7.25±1.23	8.06±1.31	7.41±1.16	<0.005	NEM, SWM>IM1; NEM, SWM>IM2; NEM>SWM

Monsoon periods are defined as follows: Northeast monsoon (December–March), inter-monsoon I (April–May), Southwest monsoon (June–September) and inter-monsoon II (October–November). The detailed post-hoc analysis can be found under online supplemental table S7. Assumption checks are summarised in online supplemental table S10 and figure S5.
ANOVA, analysis of variance; ED, emergency department; HSD, honestly significant difference; PSI, Pollution Standards Index; WBT, wet bulb temperature.

asthma ED visits during these festivals. Interventions for high-emission rituals include designating specific areas for incense burning, downscaling mass rituals and encouraging cleaner alternatives like electronic incense sticks or candles. For low-emission rituals, include crowd management and mask-wearing. Moving forward, we need to establish asthma registries that integrate electronic health records with real-time weather and air quality data. These registries would provide the statistical power and generalisability needed to validate and refine our findings.

CONCLUSION

Air quality and weather are important determinants of asthma ED visits, even in a tropical country like Singapore. The PSI–ED association peaked on the same day of exposure but was no longer significant after adjusting for demographic and clinical factors. Pollution-linked festivals, transboundary haze and the Northeast monsoon were associated with increased asthma ED visits.

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