City-Specific Air Quality Warnings for Improved Asthma Self-Management

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Introduction: This study presents a framework for identifying "high-risk" days for asthma attacks associated with elevated concentrations of criteria pollutants using local information to warn citizens on days when the concentrations differ from Environmental Protection Agency Air Quality Index (AQI) warnings. Studies that consider the unique mixture of pollutants and the health data specific to a city provide additional information for asthma self-management. This framework is applied to air pollution and asthma data to identify supplemental warning days in Houston, Texas.

Methods: A four-step framework was established to identify days with pollutant levels that pose meaningful increased risk for asthma attacks compared with baseline. Historical associations between 18,542 ambulance-treated asthma attacks and air pollutant concentrations in Houston, Texas (2004−2016; analyzed in 2018), were analyzed using a case-crossover study design with conditional logistic regression. Days with historically high associations between pollution and asthma attacks were identified as supplemental warning days.

Results: Days with 8-hour maximum ozone >66.6 parts per billion for the 3 previous days and same-day 24-hour nitrogen dioxide >19.3 parts per billion pose an RR of 15% above baseline; concentrations above these levels pose an increased risk of 15% (RR=1.15, 95% CI=1.14, 1.16) and 30% (RR=1.30, 95% CI=1.29, 1.32), respectively. These warnings add an additional 12% days per year over the AQI warnings.

Conclusions: Houston uses this framework to identify supplemental air quality warnings to improve asthma self-management. Supplemental days reflect risk lower than the National Ambient Air Quality Standards and consecutive poor air quality days, differing from the AQI.
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INTRODUCTION

The link between exposure to air pollution and asthma attacks is well established but complex, thus making asthma management difficult.[1−13] Triggers can differ by pollutant, mixtures of pollutants, and duration of individual exposure to pollutants.[8,12] Ambient air quality is unique to each city and influenced by meteorology, geography, vegetation, and activities taking place in the city. Studies have shown the impact of local differences in air quality on asthma.[14−18]

The most widespread method to warn for potentially hazardous levels of air pollution is the U.S. Environmental Protection Agency (EPA) Air Quality Index (AQI), a tool that provides local information on air quality to the public and recommends how to protect human health.[19] This system maps concentrations of criteria pollutants to an indexed number and a corresponding air quality

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category (good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, or hazardous). As people with asthma are considered a sensitive group, knowing when air quality is unhealthy for sensitive groups or worse is important information for asthma self-management. The AQI does not address local pollutant mixtures or exposures longer than a day.

City-specific characterizations of air quality can address both and, therefore, can supplement AQI warnings. Although AQI warnings remain the most common type of alert, the City of Houston developed supplemental warning days to enhance public health protection. This supplemental information aids public officials, healthcare providers, and affected residents in efforts to reduce asthma exacerbation from poor air quality.[20−22]

Case-crossover with conditional logistic regression is frequently used to analyze associations between air pollution and acute health effects. This method has been used previously to demonstrate local associations between factors such as ozone (O_3), particulate matter ≤2.5 microns, sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and temperature with negative health effects using pollution lagging structures.[11,23−26]

These methods, however, have not been used previously to inform public health warnings. Case-crossover designs are useful when exposure to the factors is not constant. In case-crossover, a health event (case) serves as its own reference, and individuals act as their own control. Airborne pollution concentrations are used in proxy for personal exposure. Ambient air pollution concentrations when individuals experience an adverse health effect are compared with reference concentrations on different days. Conditional logistic regression is used to approximate the association between pollution and increased RR of the health event while controlling for confounding factors.[26] These estimated increases in the risk of observing an adverse health event can be used to establish additional pollution concentration−based warnings.

This work aims to increase the accuracy of how Houston identifies and communicates the link between air quality and asthma risk. Raun et al.[11] found an association between ambient air pollution and emergency medical service ambulance-treated asthma attacks in Houston using case-crossover analysis with conditional logistic regression. This previous work indicated that people with asthma in Houston were at an increased risk from exposure to consecutive days of O_3 and NO_2 at levels lower than the National Ambient Air Quality Standards, but it did not identify city-specific concentration warning levels. Houston uses the framework presented in this study to define city-specific concentration levels. Days with high asthma risk were defined by pollution

levels with risk 15% above the established historical baseline. These warnings augment the EPA warnings. They are issued on days when the EPA does not signal an air quality warning for sensitive subpopulations. This study provides a methodology to identify supplemental warning days, currently used by the City of Houston to supplement those issued by EPA.

METHODS

Study Sample
The analysis assessed the relationship between ambulance-treated asthma attacks and the air pollutants CO, NO_2, particulate matter ≤2.5 microns, O_3, and SO_2. These pollutants are measured in Houston with a fixed site monitoring network and are known to exacerbate asthma.[1−5] The statistical metric evaluated was the daily average with the exception of O_3, which was the 8-hour maximum, in agreement with National Ambient Air Quality Standards criteria pollutant standards. Hourly pollution data were obtained from the Texas Commission on Environmental Quality's online database.[27] These data were collected using EPA federal reference methods and validated by the Texas Commission on Environmental Quality. Data related to ambulance-treated asthma attacks were obtained from the Houston Fire Department emergency medical service call database where the working assessment was asthma treated with nebulized albuterol. There were 18,587 ambulance-treated asthma attacks in Houston during the study period (January 4, 2004−June 15, 2016). The data were analyzed in 2018.

Measures
The analysis was conducted in four steps. First, conditional logistic regression with case-crossover analysis of ambulance-treated asthma attacks was conducted for each pollutant to identify pollutants and lags with a statistically significant association, controlling for apparent temperature. This analysis was conducted in single- and double-pollutant combinations at the following daily pollutant time lags: 0, 1, 2, 3, 0−2, 1−2, and 1−3. The lagging structure was used to identify the effects of previous pollution on asthma outcomes and was informed by previous research.[11] Each pollution variable's lag value was divided by its IQR to reduce the influence of differently scaled concentrations of pollution. Pollutants and lags with no significant association with ambulance-treated asthma attacks were not evaluated further.

In the second step, significant pollutants and lags were further evaluated to identify the concentration level associated with a risk of ≥15% above the baseline risk. The baseline was defined as days with low to no risk of pollution-triggered asthma attacks. Because previous research indicated that high levels of 8-hour maximum O_3 with a lag of 0−2 and daily average NO_2 pose a risk, low levels of these pollutants and their lags were defined as reference baseline days (i.e., below the median).[11] This analysis was conducted using case-crossover with conditional logistic regression and compared high concentration day bins with reference day bins. The high concentration bin limit was initiated at the median, and the concentration was increased by 5% until the risk above baseline was 15%. If the increase in risk above baseline did not reach 15%, the pollutant and lag were dropped from further analysis.

In the third step, the high concentration bins for pollutants with an increased risk above baseline of ≥15% were further evaluated to quantify whether the RR associated with the bin was also ≥15% using case-crossover with conditional logistic regression. The pollutant and lag were dropped from the analysis if the risk within the upper bin was <15%.

The fourth step of the methodology to identify supplemental air pollution warning days was to evaluate the following: (1) if the supplemental warning days differ from EPA AQI warning days and (2) if the percentage of the time warnings that occur is sufficiently low to avoid over-warning. This evaluation is important to strike a balance between providing extra information to Houstonians without desensitizing the public by over-warning.

In the fourth step, potential warning days were identified between 2010 and 2015. These days were compared with days when EPA AQI warnings were issued as "unhealthy for sensitive groups" or more severe to determine the extent of overlap. Supplemental warning days for the same period were then evaluated by month and year to assess the potential for over-warning. Supplemental warning days are those that do not coincide with EPA AQI warning days and whose frequency of occurrence does not exceed 20%. The AQI may differ from the proposed warnings because it does not address local pollutant mixtures or exposures longer than 1 day.

Statistical Analysis

Statistical analysis was conducted in SAS, version 9.4; R, version 3.5.1; and RStudio, version 1.1.456 (2009−2018). Rice University IRB approved all data-collecting procedures for human subjects.

RESULTS

There were 18,587 ambulance-treated asthma attacks in Houston during the study period (2004−2016) at an annual average for the years 2004−2015 of 1,491 asthma attacks (SD=174 asthma attacks). Of these calls, 24% of patients were aged ≤18 years, 19% were aged ≥60 years, and 54% were female. The ethnic breakdown was 70% African American, 14% Caucasian, 13% Hispanic, and 3% other. In comparison, the ethnic breakdown for the general population of Houston is 20% African American, 61% Caucasian, 39% Hispanic, and 19% other.[28]

Table 1 shows the apparent temperature and the means, SDs, and percentiles of each pollutant. Correlations between daily pollutant concentrations indicated that NO_2 and CO were the most highly correlated of the pollutants (Pearson correlation, $r=0.74$), followed by NO_2 and SO_2 ($r=0.53$) and SO_2 and CO ($r=0.41$), each with p-values <0.0001. Correlation coefficients between other pollutant pairs were <0.25 in magnitude.

The results of the first three steps of the analysis to identify the supplemental warning days are summarized in Table 2. SO_2 was not significant and was excluded from further analyses.

The significant pollutants and lags were then evaluated to identify the concentration level associated with a risk of ≥15% above a reference group of baseline risk (Step 2). The reference group of baseline risk was defined as days when the concentration is below the median of same-day NO_2 (NO_2 lag 0) and O_3 from same-day through the previous 2 days (O_3 lag 0−2). These thresholds demonstrated no association between air pollution and asthma attacks. The median for same-day NO_2 was 11.7 parts per billion (ppb) and the median for O_3 lag 0−2 was 41.9 ppb. Pollutants and lags that posed a 15% increased significant risk above baseline (Table 2) were CO lag 0 (504.8 ppb), lag 1 (417.3 ppb), and lag 1−2 (403.4 ppb); NO_2 lag 0 (19.3 ppb); and O_3 lag 0 (58.8 ppb), lag 2 (79.0 ppb), and lag 1−3 (66.6 ppb).

Only the concentration limits associated with same-day NO_2 and O_3 from the previous 3 days (O_3 lag 1−3) exceeded 15% risk over baseline. At a concentration of 19.3 ppb (85th percentile), same-day NO_2 posed an increased risk of asthma attacks of 30% (RR=1.30, 95% CI=1.29, 1.32), and at an average concentration of 66.6 ppb (95th percentile), O_3 from the previous 3 days posed an increased risk of asthma attacks of 15% (RR=1.15, 95% CI=1.14, 1.16). These two concentration cut offs serve as the basis for the proposed supplemental warning day concentration limits in Houston.

The retrospective analysis conducted as part of Step 4 indicated supplemental warning days that would have occurred, based on the two concentration limits described above, resulting in warnings 16% of days between 2010

Table 1. Statistics of Daily Pollution and Apparent Temperature, January 4, 2004 to June 15, 2016

Variable	Monitors	% missing[a]	Mean (SD)	Percentile 5%	25%	50%	75%	95%	IQR
CO daily mean (ppb)	8	0.11	1,017.5 (5.3)	1,009.5	1,014.1	1,016.9	1,020.4	102.3	6.2
NO_2 daily average (ppb)	10	0.09	12.7 (6.0)	4.8	8.1	11.7	16.5	23.9	8.4
$PM_{2.5}$ daily mean ($\mu g/m^3$)	4	0.11	11.8 (4.9)	5.5	8.4	10.9	14.3	21.4	5.9
SO_2 daily mean (ppb)	7	0.00	1.3 (1.5)	−0.3	0.2	0.8	2.1	4.0	1.9
O_3 8-hour max (ppb)	13	0.00	44.6 (18.1)	20.6	31.6	41.3	54.3	79.0	22.6
Apparent temperature (°F)	15	0.09	73.4 (17.5)	42.2	59.7	76.0	88.7	96.0	29.0

[a]% Missing: percentage of time when hourly data were unavailable at any monitor.
CO, carbon monoxide; NO_2, nitrogen dioxide; O_3, ozone; $PM_{2.5}$, particulate matter ≤2.5 microns; ppb, parts per billion; SO_2, sulfur dioxide.

Table 2. Identification of Supplemental Warning Days Using EMS-Treated Asthma Attack Data

Pollutant and lag[f]	Step 1[a]: Significant RR of increased asthma attack		Step 2[b]: Concentration limit at 15% above baseline,[d] concentration (ppb)	Step 3[c]: RR above concentration limit[e]	
	RR per IQR	n		RR	n
CO lag 0	1.03 (1.01, 1.05)	18,520	504.8	1.01 (1.01, 1.01)	1,047
CO lag 1	1.02 (1.00, 1.04)	18,511	417.3	1.01 (1.01, 1.01)	2,005
CO lag 0−2	1.04 (1.01, 1.06)	18,520	–	—	—
CO 1−2	1.02 (1.00, 1.05)	18,517	403.4	1.01 (1.01, 1.01)	7,962
CO 1−3	1.03 (1.00, 1.05)	18,517	–	—	—
NO_2 0	1.06 (1.03, 1.09)	18,524	19.3	1.30 (1.29, 1.32)[e]	3,167
NO_2 lag 1	1.04 (1.01, 1.07)	18,515	–	—	—
NO_2 lag 0−2	1.05 (1.02, 1.09)	18,524	–	—	—
NO_2 lag 1−2	1.03 (1.00, 1.06)	18,520	–	—	—
$PM_{2.5}$ lag 2	1.02 (1.00, 1.05)	18,479	–	—	—
$PM_{2.5}$ lag 3	1.03 (1.01, 1.05)	18,479	–	—	—
$PM_{2.5}$ lag 1−3	1.03 (1.00, 1.06)	18,491	–	—	—
O_3 lag 0	1.03 (1.01, 1.06)	18,524	58.8	1.08 (1.08, 1.09)	3,616
O_3 lag 1	1.03 (1.01, 1.06)	18,524	–	—	—
O_3 lag 2	1.03 (1.00, 1.05)	18,524	79.0	1.12 (1.11, 1.13)	3,485
O_3 lag 0−2	1.05 (1.02, 1.08)	18,524	–	—	—
O_3 lag 1−2	1.04 (1.01, 1.07)	18,524	–	—	—
O_3 lag 1−3	1.04 (1.01, 1.07)	18,524	66.6	1.15 (1.14, 1.16)[e]	1,808

Note: EMS data: January 4, 2004 through June 15, 2016.
[a]Step 1: identify pollutants /lags posing a significant risk for EMS-treated asthma attacks.
[b]Step 2: identify concentration levels of pollutants/lags in Step 1 associated with 15% above baseline.
[c]Step 3: identify RR associated above concentration limit in Step 2 posing a risk of 15% or greater.
[d]Baseline is defined as days with low to no risk of pollution triggered asthma attacks: baseline=below 41.9 ppb for O_3 0−2 and below 11.7 ppb for NO_2 lag0; pollutants/lags marked as "−" are <15% above baseline.
[e]RR above concentration limit exceeds 15%; days above this limit are potential warning days.
[f]Daily pollutant average for CO, NO_2, and $PM_{2.5}$; 8-hour maximum for O_3.
CO, carbon monoxide; EMS, emergency medical services; NO_2, nitrogen dioxide; O_3, ozone; $PM_{2.5}$, particulate matter ≤2.5 microns; ppb, parts per billion.

and 2015. Comparatively, EPA's AQI warning was issued on 9% of days in the same period. There was a 4% overlap with the proposed supplementary warning days (Figure 1) and EPA's AQI warning. In other words, supplementary
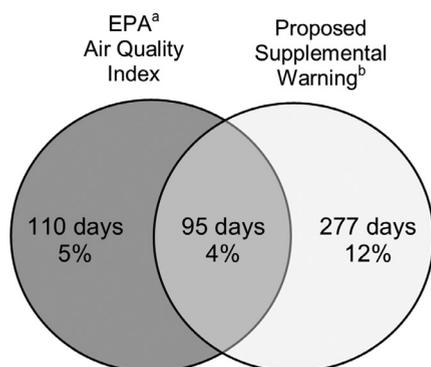

Figure 1. Venn diagram of retrospective overlap between EPA AQI warning days and proposed supplemental warning days.
Note: n=2,191 days (2010 to 2015)
[a]Published EPA Air Quality Index warning of Unhealthy or greater.
[b]Proposed supplemental warning days.
AQI, Air Quality Index; EPA, Environmental Protection Agency.

warnings would have added an additional 12% warning frequency to the current AQI warning system. The retrospective analysis indicated a range of supplemental warning occurrence between 6% and 24% by year during 2010 and 2015 (Figure 2). Monthly analysis of 2010 through 2015 indicated warnings would have occurred between a range of 5% and 29% of the month. Warnings triggered by NO_2 occurred most commonly in the cooler months between October and March, whereas warnings triggered by O_3 occurred most commonly in the warmer months between April and September. In Figure 2, the black segment indicates the percentage of days when both O_3 and NO_2 would have triggered a warning on the same day. The maximum occurrence of warning by both pollutants occurred in October at a frequency of 3.2%. Because air quality improved over the entire study period, only the second half was used to evaluate potential warning frequency.

DISCUSSION

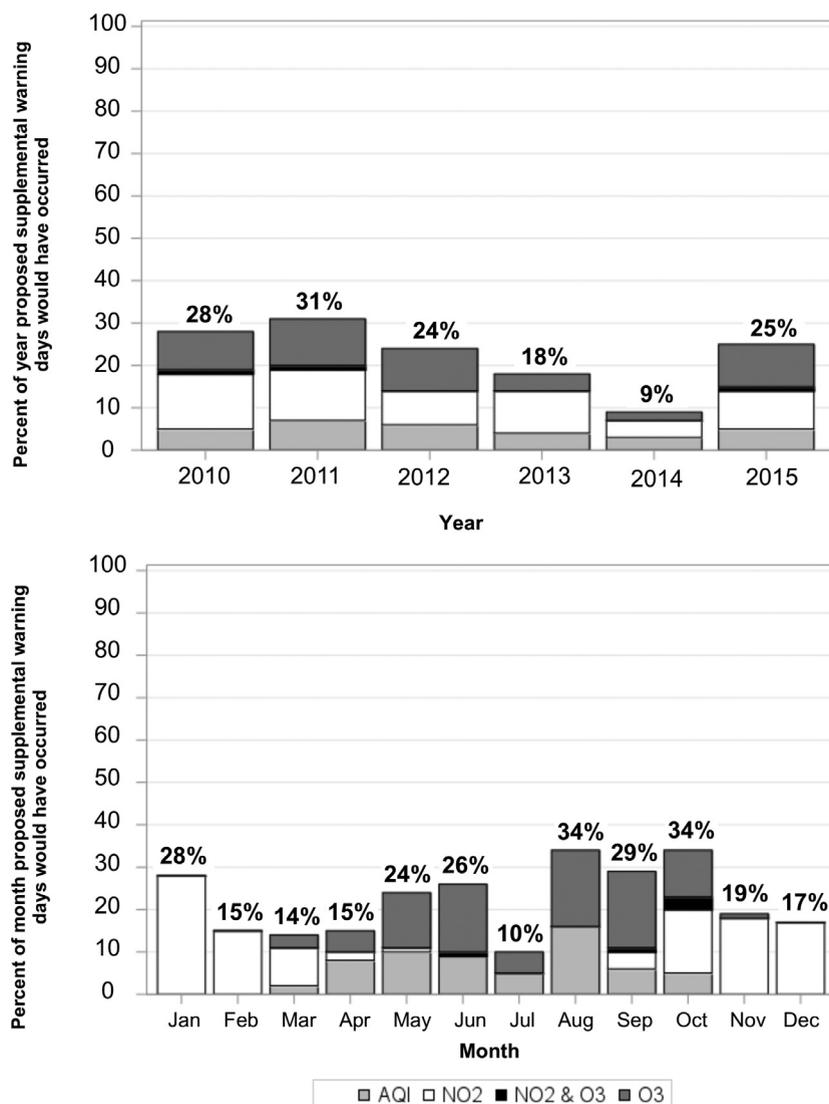Asthma attacks are a serious concern in Houston. There are approximately 1,500 ambulance-treated attacks a

Figure 2. Stacked bar charts of percent of supplemental warnings by pollutant between 2010 and 2015.
Note: When ozone is >66.6 ppb, NO_2 is >19.3 ppb or AQI is >100.
AQI, Air Quality Index; NO_2, nitrogen dioxide; ppb, parts per billion.

year in this metropolitan area, for a medical emergency that is almost always preventable. The City of Houston was spurred to action by previous research showing an association between air pollution and asthma attacks in Houston. A framework was developed to identify days when air pollution concentrations historically posed high risk for asthma attacks in the city, and the Houston Health Department began warning the community on days when concentrations may exceed these levels. These warnings are intended to supplement the EPA AQI warnings by providing additional information to the community to enhance asthma self-management.

The warning days identified by this methodology are days when, historically, NO_2 or lagged elevated O_3 concentrations posed a statistically significant increased risk

of an ambulance-treated asthma attack for Houstonians. These pollutants may not be the only trigger of the attacks but may serve as a proxy for the conditions that create the increased risk. The criteria pollutants analyzed in the study are themselves correlated, and therefore, their distinct impact cannot be distinguished (e.g., daily average NO_2 and CO are correlated, $r=0.73$). In addition, Houston's complex mixture of hazardous air pollutants emitted from the large industrial complex, including one of the largest ports in the U.S., likely plays a role in the high-risk days.[20,29] Finally, the role of aeroallergens in the increased risk is unknown because data are not available on a consistent enough basis to be included in the framework models.[11] However, seasonal and meteorological conditions that cause pollutant mixtures to be

elevated may be correlated with days with elevated aero-allergens in Houston, therefore, also represented by proxy.[11] The intent of the framework is to identify days posing a high risk rather than pinpoint the exact causes of the risk.

The identified warning days indicate risk of about 30% when the daily average NO_2 is expected to exceed 19.3 ppb. The EPA AQI warnings for NO_2 are for daily 1-hour maximum NO_2 and currently do not accommodate the daily average statistical metric. The daily maximum and the daily average are highly correlated, but prediction of the maximum is much more difficult for use in warnings (r=0.898, p<0.0001). Retrospective comparison indicates the EPA AQI warning for daily maximum occurred 9% of the time in the second half of the study period, whereas a supplemental warning day for Houston would have occurred 12% of the time not covered by the AQI.

The supplemental warning days identified for Houston based on increased risk of consecutive levels of O_3 are also not accommodated in the EPA AQI at this time. The EPA AQI warning is issued based on the daily 8-hour maximum O_3 concentration, whereas this research indicates Houstonians also have an increased risk for exposure prolonged over more than 1 day of about 15%. A warning to Houstonians is issued on a day when the previous 3 days' average 8-hour maximum concentration exceeds 66.6 ppb. The issued warnings remind people with asthma to be self-aware and prepared on these days that have historically posed a problem. The warning, posted on the Houston Health Department webpage at 5:00AM on warning days, is, "Asthma Air Aware Day Warning. The Houston Health Department is notifying you that today is a Houston Asthma Air Aware Day. Houston Asthma Air Aware Days occur when outdoor air conditions are similar to days when Houstonians historically experience a high number of asthma problems. Houstonians with asthma should be mindful of today's potential risk."

The concentration limits identified in this study show risk on days when AQI warnings were not issued, adding an average of 46 warning days per year between 2010 and 2015 (277 days in 6 years); these additional 12% of days warned would be particularly meaningful for people with asthma.

Careful attention was paid to the frequency of warning. The frequency was chosen as a balance between increasing the number of warnings to provide extra information compared with providing too many warnings and having the public fatigued by over-warning. The methodology chosen to search for the warning day concentration level in Step 2 represents the best practices identified during in-depth exploratory analysis. Use of classification and regression tree analysis was explored as a method to define natural breaks for the upper concentration risk bins as an alternative to Step 2. This method was abandoned because it yielded low concentration limits resulting in over-warning (e.g., warnings would have occurred 43% of days between 2010 and 2015). Although the 6-year average between 2010 and 2015 sits at 16% warning, the trend from 2010 through 2014 was generally decreasing. With further analysis of the proposed warning concentration limits, it is possible that the warning frequency would decrease even further.

Limitations

A limitation of this study is the use of ambulance-treated asthma exacerbations over emergency department visits. The study uses ambulance data because they are maintained by the city, and records are readily available on a real-time basis for ongoing analysis. There is no central location for data pertaining to emergency department visits for asthma attacks. The use of ambulance data likely underestimates the number of asthma exacerbations associated with pollution. Another limitation of this study is that aeroallergen data were not complete enough to include in the analysis. However, the intent is to identify days that historically pose an increased health risk to Houstonians, rather than pinpoint the trigger. Risk posed by aeroallergens may be represented by proxy through correlated pollutants and meteorological conditions. Analysis with aeroallergen data will be included when and if sufficient data are available.

Another limitation is warning at 15% risk above baseline or on average 46 additional days a year. There is limited research published on the awareness of and compliance with air pollution advisories, and none, to the authors' knowledge, of how much warning of poor air quality is too much. Future work will include follow-up with the community regarding usefulness of the warnings, at which time the 15% above baseline limit will be adjusted, as needed.

CONCLUSIONS

This study provides a city-specific approach to examine exposures that may pose a risk for people with asthma. Houston has developed messaging and a warning system that can be used to make personal health decisions based on local, data-driven risk factors. This study furthers the understanding of how local data on city-specific air quality can help better target air quality warnings for sensitive subpopulations and provides a framework that the Houston Health Department uses to supplement EPA AQI warnings.

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SUPPLEMENTAL MATERIAL

Supplemental materials associated with this article can be found in the online version at https://doi.org/10.1016/j.amepre.2019.03.022.

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