FINAL REPORT:

Development of an Indicator to Identify the Association between Air Pollution and Health Effects in Mexico City

NYU | Marron Institute
of Urban Management

CDMX
CIUDAD DE MÉXICO | SEDEMA

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1. Introduction

In October 2017, NYU's Marron Institute of Urban Management delivered a preliminary report to SEDEMA outlining the development of an indicator tool intended to improve air pollution risk communication in Mexico City. The primary objective was to provide a quantitative means for improved risk communication via a health-based indicator that is both simple in construction and easy to use. This indicator has now been fully developed, the process and utilization of which is outlined here.

In the preliminary report, exploratory work examining missing data, imputation, monitor selection, health endpoint definitions, inclusion criteria, and data trends was presented. This data preparation was applied to meteorological variables, pollution data, and health data. As outlined there, and presented in complete form in the current report, the resulting health-based indicator is effective at both high and low pollutant concentrations, placing an important emphasis on individuals susceptible to health risks at lower levels. The tool has been developed from pollution data and health records in Mexico City, and considered lagged health effects in its risk assessment. Unique from other air pollution indices, our tool provides a single indicator value directly associated with health risk, making it simple to interpret and intuitive to the general public. Indicator values are based on respiratory morbidity events (e.g., asthma attacks), outcomes which are more applicable to the areas of greatest concern to the general public from a day-to-day perspective as compared to other health endpoints (i.e., risk of cardiovascular mortality).

This final work product includes calculated weighting factors for individual pollutants and the corresponding equations necessary to calculate and scale the health-based indicator values in Mexico City. With a commitment to good science and the delivery of a quality work product, this index tool has been tested and refined into order to meet the three key measures of success outlined in our preliminary report:

> ***Standard 1.*** *The index needs to be predictive of respiratory morbidity among two groups: children and adults. Pollutants affect age groups to different extents; a successful index must be suitable for both groups.*
>
> ***Standard 2.*** *The index must include at least three ambient air pollutants; indices that rely too heavily on a single pollutant are unable to accurately capture the overall health risk to a population that is exposed to many different pollutants on any given day.*
>
> ***Standard 3.*** *The index should result in a [generally] normal distribution to allow for effective risk communication. This will allow the resulting risk communication tool to be most effective, particularly at relatively lower levels of pollution. A skewed index, in contrast, creates communication challenges.*

2. Methods for Exposure Assessment

The intent of the exposure assessment was to provide pollution estimates that, after controlling for other relevant variables, could be used to evaluate the health impacts of air pollution in the most generalized way possible in order to avoid results that are highly specific to model specifications. This conceptual goal was more specifically carried out in the exposure assessment by estimating the daily, city-wide, average pollution exposures experienced by the population in Mexico City that could be used directly in Poisson, time-series models to assess population-level health associations.

Hourly and daily pollution monitoring data was obtained for all available monitors from 2010-2015 from SEDEMA. The individual pollution variables were aggregated into daily exposure variables at health relevant averaging times (24-hour average for $PM_{2.5}$, 8-hour maximum average for O_3, 1-hour maximum for NO_2). All missing monitoring data as was inputted using methods previously described in the preliminary report. In brief, missing values were inputted with multivariate imputation by chained equations (MICE) using predictive mean matching to input non-normally distributed pollution data. All imputations were completed using R.[1]

Several groupings of air pollution monitors were considered as part of the exposure assessment process to account for the potential spatial heterogeneity of ambient air pollutants that can exist within the urban extent of large metropolitan areas. Various combinations of approximately 3 to 11 monitors were used in each grouping. The resulting pollution estimates were then compared prior to selection of a final grouping for use in the health analysis. The specific monitors included in the groupings used in the primary health analysis are shown in Table 1.

$PM_{2.5}$ Monitor Grouping: CAM, COY, MER, SAG, SJA, TLA, UIZ

O_3 Monitor Grouping: COY, FAC, IZT, MER, PED, TAH, TLA, SAG, UIZ, XAL

NO_2 Monitor Grouping: IZT, MER, PED, SUR, UIZ

Table 1. Monitors included in determining average city-wide pollution concentrations in Mexico City from 2010-2015, by pollutant. Monitors included in the grouping had missing data inputted prior to averaging. Monitors are listed in alphabetically order and ordering does not imply any additional information.

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[1] R Development Core Team. 2016. R: a language and environment for statistical computing R Foundation for Statistical Computing. Vienna, Austria.

	Monitoring Frequency per Seasonal Period			
$PM_{2.5}$ Station ID	1	2	3	4
ACO	31.1	24.8	18.2	12.9
AJM	11.8	12.0	13.7	12.6
CAM	**83.5**	**84.0**	**69.5**	**80.2**
CCA	13.8	13.2	19.7	27.7
COY	94.5	87.7	90.0	89.2
HGM	45.8	51.7	46.0	44.6
MER	**93.2**	**90.8**	**79.5**	**92.3**
MGH	13.7	13.1	14.0	13.1
NEZ	52.0	42.5	64.0	69.4
PED	48.5	50.3	64.0	59.8
PER	39.5	40.2	24.8	28.2
SAG	**85.8**	**81.8**	**86.3**	**80.0**
SFE	44.9	46.5	49.5	35.1
SJA	**91.5**	**90.8**	**77.1**	**73.5**
TLA	**80.3**	**85.8**	**71.8**	**94.3**
UAX	46.5	53.5	55.7	51.1
UIZ	**90.8**	**90.5**	**93.1**	**94.8**
XAL	39.8	50.2	51.7	55.2

Table 2. Frequency of monitoring days by season for $PM_{2.5}$ monitors in the Mexico City Metropolitan Area, from 2010-2015. Frequencies represent the number of valid monitoring days prior to data inputation. Monitors in bold correspond to the monitors used in the primary health analysis for $PM_{2.5}$. A monitoring threshold of 70% per season was used as the cut-point criteria for consideration in the primary health model.

Monitors used in the primary health analysis were selected in part due to a low number of missing monitoring days by season and spatial representation of the metropolitan area. A frequency cut-point of 70% of days with valid monitoring data per season, prior to data imputation, was used as a screening criteria for inclusion into final groupings used in the health analysis. An example of the frequency of monitoring days per season is shown in Table 2 for $PM_{2.5}$ from 2010-2015.

Average monthly pollution values were similar across all monitor groupings considered for each pollutant. More importantly, the daily correlations of pollution values between monitor groupings were very high for all pollutants. As a representative example, monthly pollution averages across monitor groupings for O_3 (which demonstrated the highest levels of spatial heterogeneity of the considered pollutants) is shown in Figure 1. Despite having some noticeable variation in average monthly pollution levels between monitor groupings for O_3, the daily correlations show almost perfect agreement between groups as shown in Table 3. In addition to the observation that daily pollution values were highly correlated across monitor groupings, additional sensitivity analysis using non-selected monitor groupings as alternative exposure assessment estimates in the health analysis were also performed; no difference in the health outcomes evaluated in this study were observed regardless of the monitor groupings selected.

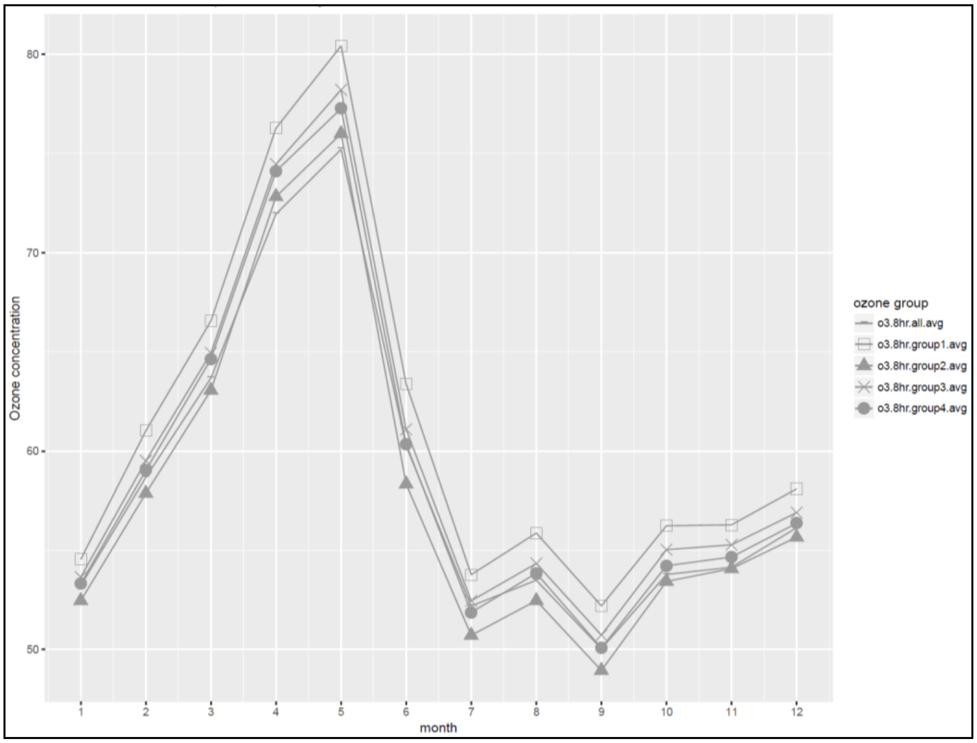

Figure 1. Monthly average ozone concentrations by monitor grouping in Mexico City from 2010-2015. Despite differences in monthly average ozone concentrations observed between monitor groups, these differences remain stable throughout the year.

Despite the insensitivity of the health results based on pollution monitor grouping, this finding does not indicate that the monitored pollution values from central site monitors are a perfect representation of the absolute concentration of individual-level pollution exposures. Exposure misclassification both in terms of spatial mismatch and temporal exposure periods results in population-level exposure estimates that will be an imprecise measurement of individual-level exposure. As a result, the indicator coefficients developed in this study are well suited for use with either central site monitors or with modeled pollution data using the averaging times specified in the health models; use of this index with real-time, personal air pollution monitors has not been validated in this study.

Ozone (8-hour)	**Group 1**	**Group 2**	**Group 3**	**Group 4***
Group 1	1.00			
Group 2	0.96	1.00		
Group 3	0.99	0.99	1.00	
Group 4*	0.99	0.99	1.00	1.00

Table 3. Correlations between monitor groups for daily ozone values, from 2010-2015. The asterisk indicates that Grouping 4 was used in the primary health analysis. Groups had various combinations of 3 to 11 monitors combined to estimate daily, city-wide pollution exposures. Sensitivity analysis using other groupings did not modify the results of the health analysis.

Meteorological variables were also used in the analysis to control for the effects of temperature and relative humidity which have been shown to be associated with both respiratory health outcomes and daily pollution concentrations. A similar approach to the one used for air pollutants was used to impute missing values and to assess which monitoring stations should be used to generate a daily, city-wide variable for temperature and relative humidity. While there is some same-day variation of these weather variables across the metropolitan area, the correlation between monitor sites was very high (average r^2 value of 0.97). As a result, and after consideration of multiple groupings, the MER station was used as a surrogate for daily temperature and relative humidity due to it having the fewest number of missing monitoring days. The daily 24-hour average temperature and relative humidity was used in the primary analysis, although sensitivity analysis using maximum temperatures and maximum relative humidity values did not change the results of the health analysis.

3. Health Data

The primary health outcome of interest for daily air pollution risk communication in this study is respiratory morbidity. Not only is respiratory morbidity the health outcome that is most relevant to the widest range of age categories (from children to the oldest adults)[2,3] it is also the health

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[2] Gauderman W, Urman R, Avol E, Berhane K, McConnell R, Rappaport E, et al. 2015. Association of improved air quality with lung development in children. N Engl J Med.

[3] Lepeule J, Litonjua A, Coull B, Koutrakis P, Sparrow D, Vokonas P, et al. 2014. Long-term effects of traffic particles on lung function decline in the elderly. Am J Respir Crit Care Med.

outcome that is most likely to drive individual behavior modification decisions.[4,5,6,7,8] It has also been recently demonstrated that it is the only health outcome to be improved through awareness and utilization of a health-based air quality index in Canada, even though that index was designed based on short-term mortality risk. Examining ten years' worth of data from Toronto, this study found that only asthma-related emergency department visits showed significant reductions in correlation with air quality alerts; the six other cardiovascular and respiratory-related health endpoints, including mortality, revealed no association to index communication.[9]

In this study we focused primarily on respiratory emergency department (ED) visits as a surrogate for overall population-level respiratory morbidity. Health data was available for the years 2010-2015 in the metropolitan area of Mexico City. There were 610,982 respiratory ED visits reported from a total of 40 facilities during the study period. Approximately 80% of the total ED visits came from a smaller subset of 17 facilities.

Respiratory ED visits were defined in this study as upper respiratory infections (ICD-10 codes J00-J06), asthma (J45-J46), COPD (J44), pneumonia (J12-J18), acute lower respiratory infections (J20-J22), chronic lower respiratory disease (J40-J42, J47), and other respiratory illness (J30-J39). Daily respiratory ED counts were calculated for age groups 2-17 years, 18+ years, and a combined category of all ages. Descriptive statistics by age group and year are shown in Table 4.

Respiratory ED visits, rather than respiratory hospital admissions, was used as our primary measure of population-level morbidity due to the nearly 20 times greater number of events per day. A sensitivity analysis, which combined daily respiratory hospital admissions with respiratory ED visits, did not modify the results of the health study.

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[4] McDermott M, Srivastava R, Croskell S. 2006. Awareness of and compliance with air pollution advisories: a comparison of parents of asthmatics with other parents. The Journal of asthma : official journal of the Association for the Care of Asthma 43:235-239.

[5] Neidell M. 2010. Air quality warnings and outdoor activities: evidence from Southern California using a regression discontinuity design. Journal of epidemiology and community health 64:921-926.

[6] Ward A, Beatty T. 2016. Who Responds to Air Quality Alerts? Environ Resource Econ 65:487-511.

[7] Wells EM, Dearborn DG, Jackson LW. 2012. Activity change in response to bad air quality, National Health and Nutrition Examination Survey, 2007-2010. PloS one 7:e50526.

[8] Wen XJ, Balluz L, Mokdad A. 2009. Association between media alerts of air quality index and change of outdoor activity among adult asthma in six states, BRFSS, 2005. Journal of community health 34:40-46.

[9] Chen H, Li Q, Kaufman JS, Wang J, Copes R, Su Y, et al. 2018. Effect of air quality alerts on human health: a regression discontinuity analysis in Toronto, Canada. Lancet Planet Health 2:19-26.

	All Ages		**2-17 years**		**18+ years**	
Year	Total ED Visits	Counts/day	Total ED Visits	Counts/day	Total ED Visits	Counts/day
2010	103,013	282.2	72,325	198.2	12,779	35.0
2011	94,094	257.8	65,890	180.5	11,796	32.3
2012	110,777	302.7	77,243	211.0	15,094	41.2
2013	109,762	300.7	75,944	208.1	15,087	41.3
2014	111,138	304.5	74,355	203.7	20,147	55.2
2015	82,198	229.0	53,756	149.7	15,187	42.3
	610,982	**279.5**	**419,513**	**191.9**	**90,090**	**41.2**

Table 4. Descriptive statistics of respiratory ED visits in Mexico City from 2010-2015, by year and age group. The total ages 2-17 years and 18+ years does not add up to the total for all ages because of the ED visits that occur in infants ages 0-1. Respiratory ED visits are defined as acute upper respiratory infections, asthma, COPD, pneumonia, lower respiratory infections and other respiratory illness.

4. Methods for Health Analysis

Poisson, generalized linear models were used to assess the associations of individual air pollutants with respiratory ED visits in Mexico City. Quasi-likelihood estimators were used in order to account for over-dispersion of the data. Model selection, including the number of degrees of freedom used for natural splines, was completed using Akaike information criterion (AIC) scores as well as inclusion of variables that are associated with both air pollution concentrations and the health outcomes of interest. The primary time series model for each of the individual air pollutants used non-linear terms to control for long-term and seasonal trends, day of the week, and same day and multiple day lagged meteorological variables as shown below:

> ***Daily Respiratory ER Visits*** *= pollutant concentration + day of week (6 df) + length of study period (24 df) + same day temperature (3 df) + lag days 1-3 temperature (3 df) + same day relative humidity (3 df) + lag days 1-3 relative humidity (3 df)*

Natural splines were used for all of the variables, in addition to the air pollutants, using the indicated number of degrees of freedom (df). Sensitivity analysis was also completed using alternative degrees of freedom, based on the number of degrees of freedom with the next lowest AIC values; this sensitivity analysis indicated that the health results were not substantially changed using alternative degrees of freedom.

The daily averaging time for each pollutant was the 24-hour average for $PM_{2.5}$ ($\mu g/m^3$), the 8-hour maximum for O_3 (ppb), and the maximum 1-hour concentration for NO_2 (ppb). Associations were assessed for individual lag days 0-5 as well as average lag structures using permutations within the same 6-day exposure time window. Reported relative risks and 95% confidence intervals (CI) were calculated for the inter-quartile range of the individual air pollutants. All analysis was completed using R.

5. Results of the Health Analysis

The study period was divided into even and odd years *a priori* in order to have independent health data available for the creation and validation of the health-based air quality indicator. The coefficients corresponding to the associations of individual pollutants and respiratory health outcomes were assessed on odd study years 2011, 2013, and 2015, while the health-based air quality indicators were validated using even study years 2010, 2012, and 2014.

Significant associations between increased air pollution exposures and increased counts of daily respiratory ER visits were commonly observed among multiple pollutants, age ranges, and lag days. A complete listing of relative risks by lag structure and age group can be seen for all three pollutants in Table 5. The coefficients and standard errors used to calculate these relative risks are found in Table 6 for the same age groups, lag structures, and pollutants.

Figure 2 shows the relative risk of respiratory ED visits for an inter-quartile increase of $PM_{2.5}$ concentrations. Significant associations are observed across multiple individual lag days for both children (ages 2-17 years) and adults (ages 18+ years) with maximum relative risks observed around lag days 2 and 3 in both age groups. The average of lag days 0-3 captures this window and indicates a relative risk of 1.03 (95% CI: 1.01-1.04) for an inter-quartile increase in pollutant concentrations among individuals of all ages. This effect is slightly more pronounced in adults than children but effect sizes are highly similar on a per unit basis.

Exposures to increased levels of ambient O_3 was also observed to be significantly associated with respiratory ED visits in Mexico City during the study period. Figure 3 shows the relative risks for children, adults, and all ages for inter-quartile increases in O_3. Unlike what was observed for $PM_{2.5}$, the peak impact of O_3 appears to occur primarily on lag day 1 among adults and lag days 1 and 2 among children. A four-day moving average of lag days 0-3 captures this window and indicates a relative risk of 1.03 (95% CI: 1.01-1.05) among individuals of all ages. Unlike the effects of $PM_{2.5}$, which were observed to be similar among children and adults, the effect size among adults is more than twice as great as among children for inter-quartile increases in ambient O_3.

		PM$_{2.5}$		**O$_3$**		**NO$_2$**	
Age	*Lag Days*	*Risk Ratio (95% CI)*	*IQR (μg/m^3)*	*Risk Ratio (95% CI)*	*IQR (ppb)*	*Risk Ratio (95% CI)*	*IQR (ppb)*
2-17 years	Lag 0-3	1.03 (1.01, 1.04)	10.69	1.02 (1.00, 1.04)	19.23	1.01 (1.00, 1.03)	15.20
	Lag 0	1.00 (0.99, 1.01)	13.00	1.01 (0.99, 1.03)	22.20	1.00 (0.99, 1.02)	19.80
	Lag 1	1.02 (1.00, 1.03)	13.00	1.02 (1.01, 1.04)	22.25	1.01 (1.00, 1.03)	19.80
	Lag 2	1.02 (1.01, 1.04)	13.03	1.02 (1.01, 1.04)	22.30	1.01 (0.99, 1.02)	19.70
	Lag 3	1.02 (1.01, 1.03)	13.05	1.00 (0.99, 1.02)	22.30	1.01 (0.99, 1.02)	19.70
	Lag 4	1.01 (1.00, 1.03)	13.10	1.00 (0.99, 1.02)	22.30	1.01 (1.00, 1.02)	19.70
	Lag 5	1.01 (1.00, 1.02)	13.15	1.00 (0.98, 1.01)	22.30	1.00 (0.99, 1.01)	19.70
18+ years	Lag 0-3	1.04 (1.01, 1.06)	10.69	1.06 (1.03, 1.09)	19.23	1.00 (0.98, 1.03)	15.20
	Lag 0	1.01 (0.99, 1.03)	13.00	1.04 (1.02, 1.07)	22.20	1.01 (0.99, 1.03)	19.80
	Lag 1	1.01 (0.99, 1.03)	13.00	1.05 (1.02, 1.07)	22.25	1.00 (0.98, 1.02)	19.80
	Lag 2	1.02 (1.00, 1.04)	13.03	1.03 (1.01, 1.06)	22.30	1.01 (0.99, 1.03)	19.70
	Lag 3	1.04 (1.02, 1.06)	13.05	1.02 (1.00, 1.04)	22.30	1.00 (0.98, 1.02)	19.70
	Lag 4	1.02 (1.00, 1.04)	13.10	1.02 (1.00, 1.04)	22.30	1.01 (0.99, 1.03)	19.70
	Lag 5	1.02 (.99, 1.04)	13.15	1.01 (0.99, 1.04)	22.30	1.00 (0.98, 1.02)	19.70
All ages	Lag 0-3	1.03 (1.01, 1.04)	10.69	1.03 (1.01, 1.05)	19.23	1.01 (0.99, 1.02)	15.20
	Lag 0	1.00 (0.99, 1.01)	13.00	1.02 (1.00, 1.03)	22.20	1.00 (0.99, 1.01)	19.80
	Lag 1	1.02 (1.01, 1.03)	13.00	1.03 (1.01, 1.04)	22.25	1.01 (1.00, 1.02)	19.80
	Lag 2	1.02 (1.01, 1.04)	13.03	1.02 (1.01, 1.04)	22.30	1.01 (0.99, 1.02)	19.70
	Lag 3	1.02 (1.01, 1.03)	13.05	1.01 (0.99, 1.02)	22.30	1.00 (0.99, 1.01)	19.70
	Lag 4	1.01 (1.00, 1.02)	13.10	1.00 (0.99, 1.02)	22.30	1.01 (0.99, 1.02)	19.70
	Lag 5	1.01 (1.00, 1.02)	13.15	1.00 (0.99, 1.01)	22.30	1.00 (0.99, 1.01)	19.70

Table 5. Risk ratios (per inter-quartile range, or IQR) of respiratory emergency department visits in Mexico City associated with key pollutants, by age group and lag structure. Significant positive associations for population-level respiratory health risk is most consistently observed for PM$_{2.5}$ and O$_3$. Average lag structures were able to capture effects that were observed to occur over multiple days following exposure.

		$PM_{2.5}$		**O_3**		**NO_2**	
Age	*Lag Days*	*Coefficient*	*Standard Error*	*Coefficient*	*Standard Error*	*Coefficient*	*Standard Error*
2-17 years	Lag 0-3	0.002473	0.000801	0.001231	0.000502	0.000834	0.000527
	Lag 0	-0.000050	0.000557	0.000433	0.000372	0.000130	0.000354
	Lag 1	0.001403	0.000549	0.000993	0.000367	0.000607	0.000350
	Lag 2	0.001817	0.000539	0.001043	0.000369	0.000357	0.000347
	Lag 3	0.001511	0.000539	0.000157	0.000360	0.000347	0.000339
	Lag 4	0.000931	0.000538	0.000062	0.000338	0.000481	0.000332
	Lag 5	0.000682	0.000534	-0.000057	0.000325	0.000059	0.000326
18+ years	Lag 0-3	0.003535	0.001185	0.002854	0.000749	0.000272	0.000790
	Lag 0	0.000804	0.000803	0.001777	0.000557	0.000297	0.000528
	Lag 1	0.001062	0.000800	0.002070	0.000549	-0.000070	0.000526
	Lag 2	0.001726	0.000788	0.001437	0.000553	0.000305	0.000521
	Lag 3	0.002776	0.000784	0.000863	0.000541	-0.000055	0.000509
	Lag 4	0.001666	0.000779	0.000974	0.000505	0.000474	0.000498
	Lag 5	0.001137	0.000775	0.000605	0.000487	0.000072	0.000489
All ages	Lag 0-3	0.002586	0.000711	0.001593	0.000447	0.000524	0.000470
	Lag 0	0.000176	0.000494	0.000808	0.000332	0.000106	0.000315
	Lag 1	0.001338	0.000487	0.001304	0.000326	0.000434	0.000312
	Lag 2	0.001808	0.000478	0.001066	0.000328	0.000304	0.000309
	Lag 3	0.001518	0.000478	0.000235	0.000321	0.000071	0.000303
	Lag 4	0.000803	0.000477	0.000174	0.000301	0.000280	0.000296
	Lag 5	0.000648	0.000474	-0.000031	0.000290	-0.000109	0.000291

Table 6. Coefficients and standard errors of respiratory emergency department visits in Mexico City associated with key pollutants, by age group and lag structure. Coefficients for lag days 0-3 for $PM_{2.5}$, O_3, and NO_2, for individuals of all ages, was used in the creation of the final validated air pollution indicator.

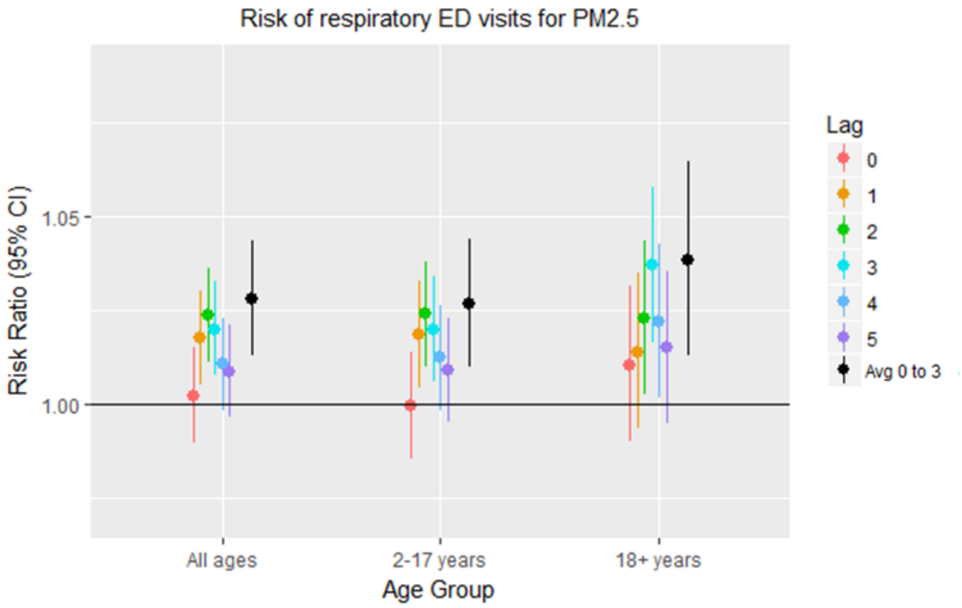

Figure 2. Relative risk of respiratory ED visits in Mexico City corresponding to an inter-quartile increase in $PM_{2.5}$ concentration, by lag structure and age group. $PM_{2.5}$ was consistently associated with significant increases in population-level respiratory morbidity among both children and adults over multiple lag days.

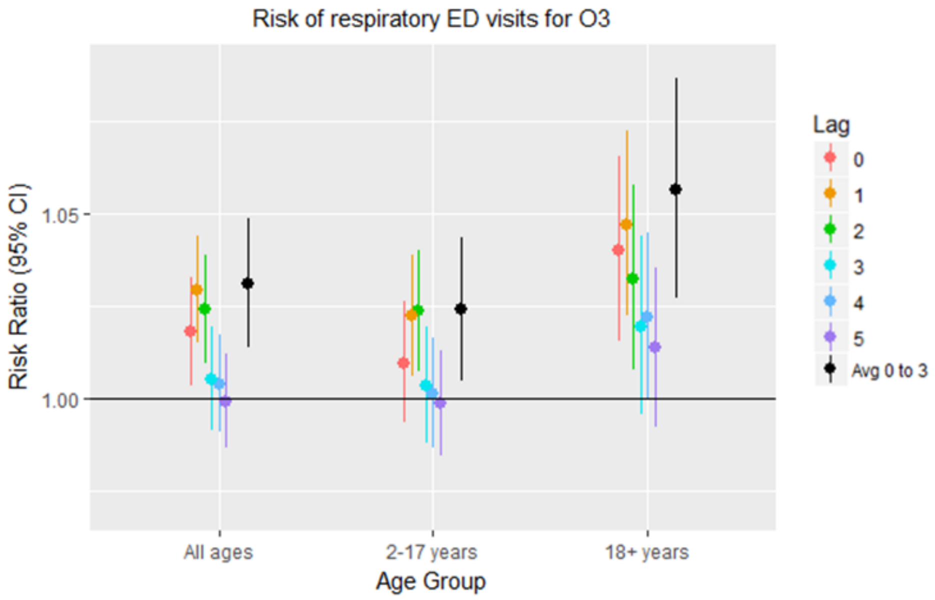

Figure 3. Relative risk of respiratory ED visits in Mexico City corresponding to one inter-quartile increase in O_3 concentration, by lag structure and age group. Significant, positive associations with O_3 were consistently observed for population-level respiratory risks among children and adults in Mexico City. Multi-day lag structures were better able to account for health risks as compared to individual days.

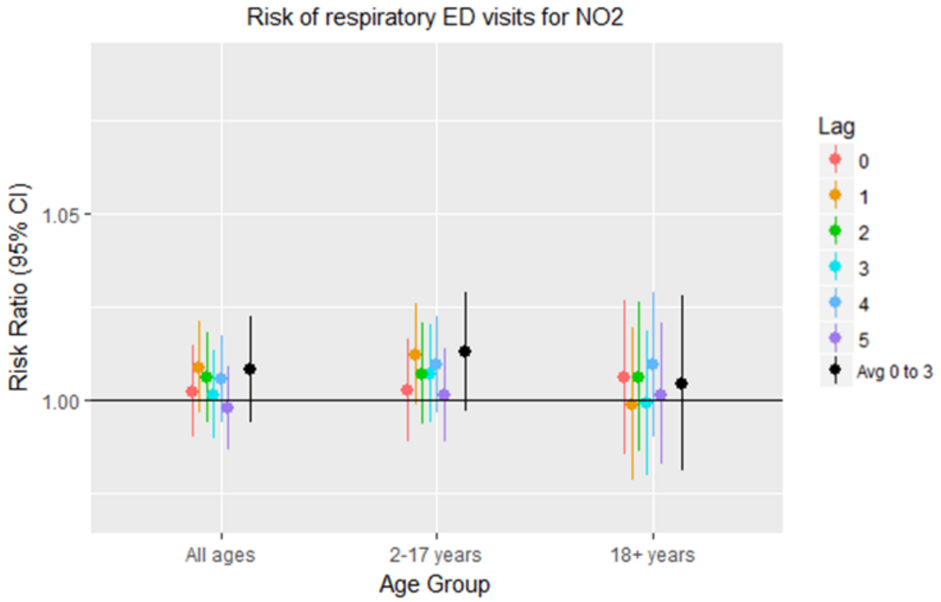

Figure 4. Relative risk of respiratory ED visits in Mexico City corresponding to one inter-quartile increase in NO_2 concentration, by lag structure and age group. Associations of NO_2 with population-level health risks is not as consistent as observed for $PM_{2.5}$ and O_3. Significant associations were observed among children, but not adults, for individual lag days. Average effects at lag days 0-3 show positive, but not significant, associations among children.

As shown in Figure 4, associations of respiratory ED visits were not as consistent for NO_2 as they were for $PM_{2.5}$ and O_3. In fact, none of the individual lag days were significantly associated with increased respiratory morbidity risk among adults during the study period. Among children there were significant or nearly significant positive associations for NO_2 and respiratory ED visits at lag days 1 and 4, although non-significant positive associations were observed on other lag days. In order to maintain consistency with the other pollutants, a four day moving average of lag days 0-3 was also considered which showed nearly significant associations among children but not adults. Specific coefficients and standard errors can be seen by age group and lag day in Table 6. Not only were the associations less likely to be significant for NO_2 as compared to $PM_{2.5}$ and O_3, but the effect size is also approximately one third of the other pollutants among individuals of all ages.

The inability to detect a stronger NO_2 effect, especially among adults, is likely due to increased exposure misclassification when using central site monitors in estimating population level health effects. Given the much higher NO_2 concentrations near major roads and experienced during commute times, the central site measurements of NO_2 are likely not accounting for the true exposures of affected populations. Despite this limitation, the coefficient for NO_2 associations with population-level respiratory morbidity was used in the creation of an air pollution indicator absent more precise exposure estimates for NO_2.

6. Creation and Validation of Multi-Pollutant Air Pollution Indicators

Unlike other health-based risk communication indices for air pollution that exist (e.g., Air Quality Health Index in Canada[10,11]) this indicator is built specifically to consider the respiratory morbidity risks of air pollution rather than mortality risks. Additionally, this indicator is designed to consider the multi-day effects that have been consistently observed to be associated with air pollution exposures rather than a same-day, rolling hourly exposure to air pollution.[12] This indicator is also agnostic towards existing regulatory limits or recommended standards which are considered in some air quality indices (e.g., AQI in the US and the health-based index in Hong Kong).[13,14] Rather, this indicator is built to specifically consider observable population-level health risks and is created using coefficients specifically developed for Mexico City. It is possible that a generic health-based index using coefficients derived from a variety of locales could be developed, but this approach was not tested in this study.

As outlined in the introduction, the goal of the creation of a health-based air pollution indicator is to easily and accurately communicate the daily health risks of outdoor air pollution exposures. The indicator must take into account the effects of multiple pollutants at both high and relatively low concentrations. The indicator must also be able to represent risks that occur across broad age ranges in order to be meaningful for the general population. Beyond these general goals, there was no pre-determined combination of pollutants that we stipulated to be included in the generation of the final indicator model.

Instead, several variations of a health-based air pollution indicator was created using the results of the time-series analysis of the individual pollutants. These variations also included using coefficients from multi-pollutant coefficients that were obtained by including two or more pollutants in our generalized linear models at the same time. Despite the convenience of having a model that "controls" for multiple pollutants, the interpretation of these two-, three- or four-

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[10] Stieb DM, Burnett RT, Smith-Doiron M, Brion O, Shin HH, Economou V. 2008. A new multipollutant, no-threshold air quality health index based on short-term associations observed in daily time-series analyses. Journal of the Air & Waste Management Association (1995) 58:435-450.

[11] Canada EaCC. 2015. Air quality health index categories and health messages. Available: http://www.ec.gc.ca/cas-aqhi/default.asp?lang=En&n=79A8041B-1.

[12] Samet JM, Zeger SL, Dominici F, Curriero F, Coursac I, Dockery DW, et al. 2000. The National Morbidity, Mortality, and Air Pollution Study. Part II: Morbidity and mortality from air pollution in the United States. Res Rep Health Eff Inst 94:5-70; discussion 71-79.

[13] Cheng W-L, Chen Y-S, Zhang J, Lyons TJ, Pai J-L, Chang S-H. 2007. Comparison of the Revised Air Quality Index with the PSI and AQI indices. Science of The Total Environment 382:191-198.

[14] Wang X-K, Lu W-Z. 2006. Seasonal variation of air pollution index: Hong Kong case study. Chemosphere 63:1261-1272.

pollutant models are not always clear. At their best these models can be used to demonstrate that significant associations remain even when including other pollutants. However, the precise magnitude of these associations should be treated carefully when using more than one pollutant at a time due to ambiguity in the interpretation of coefficients from multi-pollutant models. Given that daily concentrations of the individual pollutants vary independently across time, and the challenge of multi-pollutant models to generate coefficients that capture the absolute magnitude of impact from each pollutant, it was not surprising that ultimately it was an indicator that was constructed of coefficients from individual pollutant models that performed the best in our validation.

Combinations of different indicators constructed using only two pollutants were considered in addition to a four-pollutant indicator that included the effects from SO_2. The outdoor concentrations of SO_2 were not significantly associated with population-level respiratory morbidity among any age group (results not shown in this report). But in order to test the possibility that it may serve as an indicator of modified ambient air pollution risks when considering the entire composition of the ambient air, it was included in a test indicator. However, we did not see any additional improvement during validation when including SO_2, so it was not included in the final model.

Ultimately we selected an indicator that included $PM_{2.5}$, O_3, and NO_2 using coefficients from individual pollutant models. The effects of the individual pollutants were represented as being additive in nature in the final indicator. Daily indicator values were estimated using lag days 0-3 coefficients for each pollutant (see Table 6). These calculated daily values were then used to estimate population-level respiratory morbidity using a similar model to that described for the individual pollutants as a way to validate the effectiveness of the indicator to represent population-level health risks. The equation is as follows:

> ***Daily Respiratory ER Visits*** *= daily indicator value + day of week (6 df) + length of study period (24 df) + same day temperature (3 df) + lag days 1-3 temperature (3 df) + same day relative humidity (3 df) + lag days 1-3 relative humidity (3 df)*

Effects were estimated at individual lag days 0-5 as well as at permutations of average lag structures over the same time period using inter-quartile increases of indicator values. Particular attention was given to a wide range of lag days (6 day average of lag days 0-5) given the wide range of adverse effects that were observed among the underlying pollutants.

The results of the validation of the indicator constructed using daily concentrations of $PM_{2.5}$, O_3, and NO_2 are shown in Figure 5. Significant associations were observed at a 6-day moving average of lag days 0-5, with similar effect sizes for both children and adults. The relative risks and 95% CI are shown by age group in Table 7. The coefficients used to derive these risk ratios are shown in Table 8.

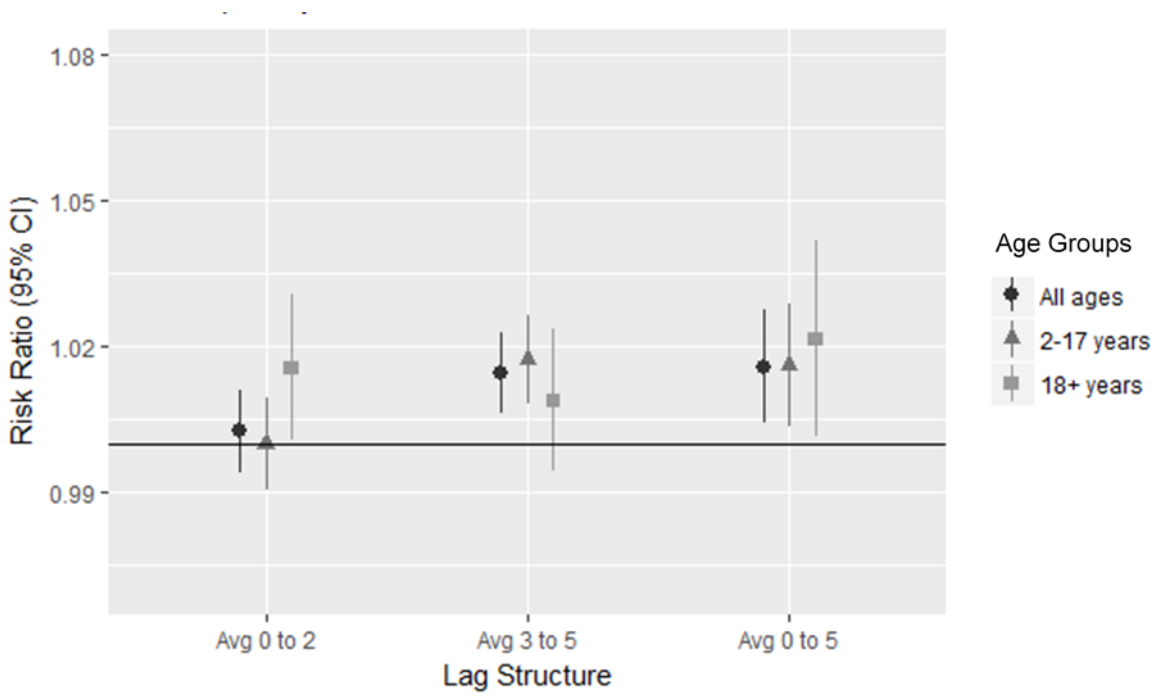


Figure 5. Relative risk of respiratory ED visits in Mexico City corresponding to one inter-quartile increase in health-based indicator values, by lag structure and age group. The primary exposure window of interest is the 6-day average of lag days 0-5. The indicator values are significantly associated with population-level respiratory risk for both children and adults over the multi-day window of health impacts observed for the underlying individual pollutants. Examples of lag days 0-2 and lag days 3-5 represent the extreme differences in results observed between age groups. Other lag structures (i.e., lag days 1-3) are significantly associated with health risks in both populations at similar levels of relative risk.

	Health-based Indicator Values		
Age	*Risk Ratio (95% CI)*		
	Lag 0-2	*Lag 3-5*	*Lag 0-5*
2-17 years	1.00 (0.99, 1.01)	1.02 (1.01, 1.03)	1.02 (1.00, 1.03)
18+ years	1.02 (1.00, 1.03)	1.01 (0.99, 1.02)	1.02 (1.00, 1.04)
All ages	1.00 (0.99, 1.01)	1.01 (1.01, 1.02)	1.02 (1.00, 1.03)

Table 7. Risk ratios for respiratory emergency department visits in Mexico City associated with air pollution indicator values, by age group and lag structure. The primary exposure period of interest of the 6-day average observed at lag days 0-5. Significant associations were observed for both children and adults for the critical time period at which health effects were observed across the range of individual pollutants evaluated in this study.

	Health-based Indicator Values					
Age	*Lag 0-2*		*Lag 3-5*		*Lag 0-5*	
	Coefficient	*Standard Error*	*Coefficient*	*Standard Error*	*Coefficient*	*Standard Error*
2-17 years	-0.000157	0.004791	0.016971	0.004609	0.015984	0.006370
18+ years	0.015301	0.007577	0.008744	0.007388	0.021203	0.010035
All ages	0.002471	0.004353	0.014237	0.004194	0.015671	0.005779

Table 8. Coefficients and standard errors for respiratory ED visits in Mexico City associated with health-based indicator values, by age group and lag structure. These coefficients were used to validate the indicator values. However, they are not used in the calculation of indicator values. Those coefficients are found in Table 6.

It is interesting to note the differences in the timing in regards to when significant effects are occurring between the two age groups. The most extreme examples were selected for presentation in Figure 5 and shown in more detail in Table 7. At the population-level, adults showed significant associations with adverse respiratory health outcomes more immediately following exposure (i.e., lag days 0-2) but not at later lag periods (i.e., lag days 3-5).

The opposite was true for children, who continued to experience adverse health impacts of exposure to elevated levels of air pollution 3-5 days following exposures. However, the lack of positive associations among children at lag days 0-2 should be interpreted with caution given that the non-significant association is driven entirely by a lack of effect observed at lag day 0, a finding that was also consistently observed in the individual pollutant results. These curated values were specifically selected to show the most dramatic differences in effects observed by age group. Other groupings of lag days (e.g., lag days 1-3, etc.) show significant associations for population-level health risks among both children and adults with similar magnitudes of relative risks (t-statistic for children at lag days 1-3 = 2.55, t-statistic for adults = 2.49).

The standards of success outlined in the preliminary report and restated in the introduction of this final report were all accomplished in the creation and validation of a health-based air pollution indicator for Mexico City. Specifically, the indicator is comprised of three pollutants which allows for a more accurate representation of the complex air mixtures that exist throughout the year in Mexico City. It is significantly associated with population-level respiratory health risks in both children and adults. This is critical given the differences in exposure profiles and health outcomes associated with air pollution that are observed between children and adults. And finally, applying the validated indicator values to the entire study period (2010-2015), and scaled to the maximum observed excess risk over the same time period, resulted in a normal distribution of indicator values which allows for improved risk communication opportunities when disseminating indicator values to the general public.

7. Calculating Daily Air Pollution Indicator Values

A two-day online training and teleconference was held in December 2018 with staff at SEDEMA and NYU researchers to provide step by step guidance in the interpretation of study results and the calculation of daily air pollution indicator values. This training also included sample runs using air pollution data from 2017. Through completion of the training, and through feedback and revision to sample data from 2017, the staff members at SEDEMA were able to accurately calculate and interpret the daily indicator values representing the population-level respiratory health risks from multiple pollutants in Mexico City.

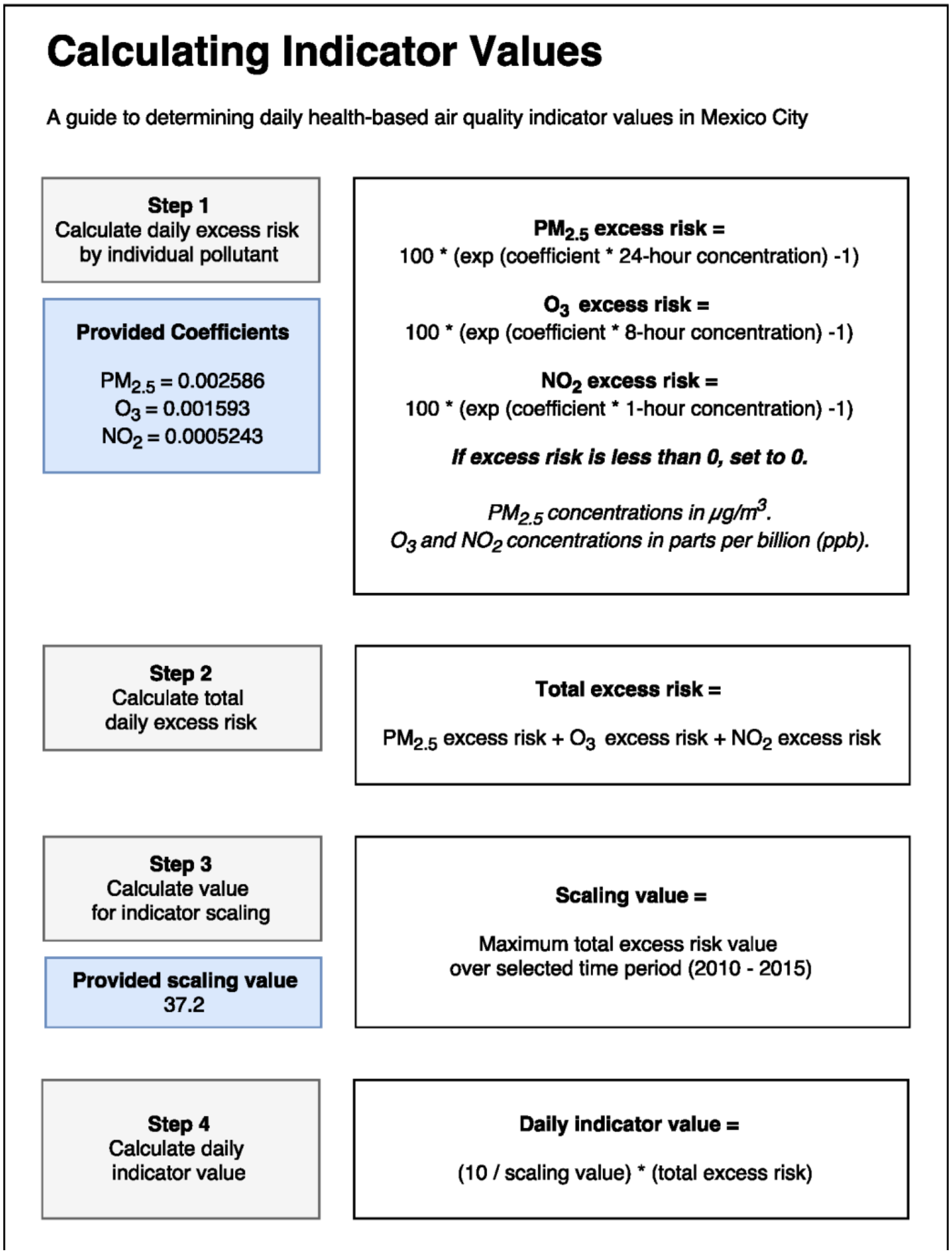
A summary of the procedure to calculate daily indicator values in shown in the flow chart illustrated in Figure 6. Of particular note are the identification of the averaging time for each pollutant that are to be used for each pollutant along with the accompanying coefficients derived from the time-series analysis.

The precise values of these coefficients are less important than the ratio of the coefficient values which indicate the increased importance of $PM_{2.5}$ and O_3 when computing the indicator values as compared to NO_2. These coefficients were derived from the lag 0-3 associations among individuals of all ages but use of slightly different coefficients using different age groupings or lag structures would not alter the validation of the created indicator.

It is important to note that it is possible that the calculation of excess risk from an individual pollutant may be negative on a given day. In these circumstances it is essential that this value is changed to zero when calculating the combined daily excess risk as shown in Step 1 of the flow chart illustrated in Figure 6. Failure to do so will result in indicator values that will not accurately reflect population-level risks.

As described during the remote training, and as identified is Step 3 of the flow chart, an initial scaling value corresponding to the maximum excess risk observed during the study period has been provided. This value can be changed in accordance with priorities and preferences of local staff but once selected should not be modified. This value, in conjunction with the desired maximum index value, will determine how the indicator values are scaled for communication purposes. It does not change the ability of the indicator to represent health risks. It is possible that the daily excess risk may be greater than the selected scaling value. When this happens the calculated indicator value will be greater than the maximum index values which can be easily planned for during formulation of how the indicator is communicated to the public.

Rudimentary sample R code has been provided in Appendix A to show the same process as the flow chart in coding language. This code is for demonstration purposes only and does not replace the need for creating a data analysis process to calculate daily indicator values.



Calculating Indicator Values

A guide to determining daily health-based air quality indicator values in Mexico City

Step 1
Calculate daily excess risk by individual pollutant

Provided Coefficients

$PM_{2.5}$ = 0.002586
O_3 = 0.001593
NO_2 = 0.0005243

$PM_{2.5}$ excess risk =
100 * (exp (coefficient * 24-hour concentration) -1)

O_3 excess risk =
100 * (exp (coefficient * 8-hour concentration) -1)

NO_2 excess risk =
100 * (exp (coefficient * 1-hour concentration) -1)

If excess risk is less than 0, set to 0.

$PM_{2.5}$ concentrations in $\mu g/m^3$.
O_3 and NO_2 concentrations in parts per billion (ppb).

Step 2
Calculate total daily excess risk

Total excess risk =

$PM_{2.5}$ excess risk + O_3 excess risk + NO_2 excess risk

Step 3
Calculate value for indicator scaling

Provided scaling value
37.2

Scaling value =

Maximum total excess risk value over selected time period (2010 - 2015)

Step 4
Calculate daily indicator value

Daily indicator value =

(10 / scaling value) * (total excess risk)

Figure 6. A Guide to Calculating a Daily Air Pollution Indicator in Mexico City. Coefficients provided correspond to lag days 0-3 associations for the individual pollutants and respiratory ED visits for all ages of individuals. The provided scaling value corresponds to the maximum daily indicator value observed from 2010-2015. This value can be modified as desired in order to re-scale indicator values. Similarly, step 4 shows the creation of daily index values that range from 0 to 10. Alternative ranges of values can be used if a maximum value of 10 is not desired. It is possible that maximum excess risk will be greater than the scaling value provided, resulting in an indicator value greater than the maximum value selected.

8. Suggestions for Communication of Daily Air Pollution Indicator Values

As discussed in the preliminary report, there are several important aspects to consider when planning to utilize the multi-pollutant indicator for risk communication purposes. While the completion of these essential remaining steps is outside the specific scope of this project, there are some recommendations that may improve the effectiveness of how the air pollution indicator is applied towards reducing respiratory morbidity in Mexico City.

Unlike existing risk communication approaches, this indicator is able to provide individuals with reliable information not just on high pollution days but also on days typically described as having good or moderate levels of air pollution. Susceptible individuals already experience adverse health risks at these lower concentrations[15,16,17] but previously have not had access to the information that could inform daily behavior modification decisions.

It is not recommended that this indicator replace existing mechanisms that trigger required actions based on categories of outdoor pollution levels. These existing mechanisms are well-suited to both reduce continued emissions of pollutants and provided broad-based guidance for reductions in exposures. Instead, this indicator should be a health-focused supplement, for use by individuals to inform behavior modification decisions, in addition to the effective regulatory actions are already in place.

It is also recommended that communication of health-based air pollution indicator values avoid the use of strict cut-points both in visual and descriptive dissemination of information. Existing communication approaches rely heavily on strict cut-points in the messaging of outdoor air pollution levels, which have little scientific basis and do not reflect the individual heterogeneity of effects that occur across healthy individuals, much less among individuals with increased susceptibility who this indicator is specifically designed to help. Rather than specifying categories of health risks using cut-points, it is preferable to instead identify categories of air pollution levels (e.g., days with relatively low, typical, or relatively high pollution levels in the context of what is commonly observed in Mexico City). It is likely that colors may add to the effectiveness of communication of the indicator in this regard and if they are used they should reflect the continuous, non-threshold scale of health risks accompanying indicator values.

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[15] Cromar KR, Gladson LA, Ghazipura M, Ewart G. 2018. Estimated excess morbidity and mortality associated with air pollution above American Thoracic Society–recommended standards, 2013–2015. Annals of the American Thoracic Society.

[16] Perlmutt L, Stieb D, Cromar K. 2017. Accuracy of quantification of risk using a single-pollutant Air Quality Index. J Expo Sci Environ Epidemiol 27:24-32.

[17] Thurston G, Ahn J, Cromar K, Shao Y, Reynolds H, Jerrett M, et al. 2016. Ambient Particulate Matter Air Pollution Exposure and Mortality in the NIH-AARP Diet and Health Cohort. Environ Health Perspect 124:484-490.

The indicator values will be most effective when communicated in a consistent manner that allows susceptible individuals to learn the level at which they might want to consider behavior modification to reduce personal exposure to outdoor air pollution. Therefore, while the choice of scaling values and maximum index values is fluid, it should not be modified once individuals begin to adapt to the new indicator values.

Many important decisions regarding the spatial and temporal resolution of the indicator values will need to be made in order to best communicate the health risks of ambient outdoor air pollution in Mexico City. It is not recommended that these values be combined with real-time, personal monitoring of air pollutants, given that it was developed based on longer pollutant averaging times measured at central site monitors.

The use of rolling rather than daily pollutant concentrations using the same averaging times as used in the study may allow for "real-time" reporting of indicator values. Even while this approach may maintain the scientific basis of the indicator values, special consideration needs to be made for what will encourage the most consistent risk communication to the general public. In considering these important issues we have recommended that the reporting of daily temperatures be used as a guide in how to best use the air pollution indicator values to communicate the health risks of air pollution. In particular this may mean emphasizing forecasted values of indicator values to allow susceptible individuals to make plans regarding their personal behaviors. It may also mean allowing the public to learn for themselves the levels at which they will start to take specific actions to reduce exposures.

In addition to working with traditional media outlets and developing web-based and mobile-based communication tools, it may be advisable to specifically train primary health care providers in the utilization and interpretation of air pollution indicator values. Previous research has shown that this is a viable mechanism for informing the public of air pollution indices. This approach may also provide an accelerated path towards targeting individuals in the population who are most susceptible, and thus most likely to benefit from this tool.

Finally, special attention should be paid to environmental justice and health literacy issues in considering how the information can be best communicated to the public. This is especially true given that socio-economic status impacts both susceptibility to the health risks of air pollution and the ways in which information is most frequently derived. Consideration of relevant environmental justice issues in communicating this indicator, and maximizing the ability of individuals all along the socio-economic spectrum to have ready access to reported air pollution indicator values, will result in the greatest mitigation of adverse public health risks associated with daily air pollution exposures.