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Use of an Index to Reflect the Aggregate Burden of Long-Term Exposure to Criteria Air Pollutants in the United States

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Air pollution control in the United States for five common pollutants—particulate matter, ground-level ozone, sulfur dioxide, nitrogen dioxide, and carbon monoxide—is based partly on the attainment of ambient air quality standards that represent a level of air pollution regarded as safe. Regulatory and health agencies often focus on whether standards for short periods are attained; the number of days that standards are exceeded is used to track progress. Efforts to explain air pollution to the public often incorporate an air quality index that represents daily concentrations of pollutants. While effects of short-term exposures have been emphasized, research shows that long-term exposures to lower concentrations of air pollutants can also result in adverse health effects. We developed an aggregate index that represents long-term exposure to these pollutants, using 1995 monitoring data for metropolitan areas obtained from the U.S. Environmental Protection Agency's Aerometric Information Retrieval System. We compared the ranking of metropolitan areas under the proposed aggregate index with the ranking of areas by the number of days that short-term standards were exceeded. The geographic areas with the highest burden of long-term exposures are not, in all cases, the same as those with the most days that exceeded a short-term standard. We believe that an aggregate index of long-term air pollution offers an informative addition to the principal approaches currently used to describe air pollution exposures; further work on an aggregate index representing long-term exposure to air pollutants is warranted. *Key words*: air pollution health effects, air pollution index, air pollution policy, criteria pollutants, cumulative exposure to air pollution, environmental indicators, long-term air pollution exposure. *Environ Health Perspect* 110(suppl 1):95–102 (2002).
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It is well established that air pollution causes adverse health effects (*1*). In the United States, five of the pollutants identified as being of greatest concern from a health perspective, known as "criteria" pollutants, are ground-level ozone, inhalable particulate matter with a diameter of ≤10 µm (PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO). Many epidemiologic studies have found adverse health effects to be associated with daily exposure to one or more of these air pollutants, including increased mortality (*2–13*), respiratory effects (*8,14–22*), exacerbation of asthma (*23–25*), and cardiovascular effects (*26–28*). For these pollutants, the U.S. Environmental Protection Agency (U.S. EPA) has adopted standards that define the maximum concentrations that are to be allowed in the air (*29*). These are known as the National Ambient Air Quality Standards (NAAQS).

The public health response to air pollution involves both regulatory actions to reduce pollution to acceptable levels and public education to inform people about its health significance. A principal means to assess the effectiveness of air pollution control programs is to look at compliance with the NAAQS. Two metrics are widely reported for both regulatory and health-planning purposes—the number of areas that fail to attain the NAAQS and the number of days that standards are exceeded in a year. For example, in its principal report on trends in air quality, the U.S. EPA reports the number of days that metropolitan areas exceed the NAAQS (*30*). The U.S. Department of Health and Human Services has incorporated tracking of daily exceedances into its national health-related objectives, known as Healthy People, and assesses air pollution in terms of the number of people who live in areas without such exceedances (*31*).

To represent the significance of air pollution to the public, the principal tool used by the U.S. EPA and by states is an air quality index that focuses on the one of five criteria pollutants that achieves the highest concentration relative to its standard on a given day (*32*). (Lead, the sixth criteria pollutant, is not included.) The index characterizes air quality as "good," "average," or "fair," and gives health warnings of increasing severity when concentrations exceed NAAQS. Such an index can help the public better understand environmental conditions and help people decide how to alter their behavior. For example, on high-pollution days, individuals may decide not to exercise outdoors to reduce their risk of respiratory symptoms or not to drive private vehicles to reduce their contribution to pollution. The categorization of air quality is based on a comparison of the pollutant with the highest concentration relative to its short-term standard. In general, days that have concentrations of pollutants below the short-term standards but above the long-term standards are reported to have good air quality. This could be true even if the long-term standards were exceeded for the year.

Although much attention has been focused on the adverse health effects associated with daily exposure to air pollutants, researchers are reporting adverse health effects that are associated with long-term exposures. Many studies have found adverse effects to be associated with long-term exposure to PM_{10} and ozone, and several studies have found effects to be associated with long-term exposure to NO_2 and SO_2. We review these studies in the following section. Because of these long-term effects, it is useful to consider an index that reflects long-term exposures to these pollutants in addition to the daily air quality index now used.

Evidence of Effects of Chronic Exposures to Criteria Air Pollutants

Several studies have considered the relationships between long-term exposures to criteria air pollutants and adverse health effects. The strength of evidence for such associations differs for the various pollutants and is much stronger for particulate matter and ground-level ozone than for the other pollutants, particularly CO.

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Particulate Matter

In three cohort analyses, researchers examined the relationship between long-term exposures to particulate matter and health effects. In the Six Cities Study, Dockery et al. (*33*) prospectively studied six cities, following more than 8,000 white adults for approximately 15 years. Using data from centrally located monitors in metropolitan areas, the researchers determined mean concentrations of particulate matter, initially measured as particles of ≤15 µm in diameter and later as PM_{10}. The study found increased mortality to be associated with exposure to higher levels of fine particulate matter in cities where annual average concentrations were 46.5–18.3 µg/m^3. These values are well below the 24-hr PM_{10} standard of 150 µg/m^3 and also below the 1-year PM_{10} standard of 50 µg/m^3. Increased mortality was also associated with exposure to higher levels of very fine particles (<2.5 µm in diameter). In a second prospective study, Pope et al. (*34*), followed 500,000 adults for 7 years; these subjects were recruited by the American Cancer Society. The investigators examined 50 metropolitan areas and found an association between median concentrations of fine particulate matter and increased mortality. Abbey and co-workers in a third study in Southern California, known as the Adventist Health Studies of Smog (*35*), have followed 6,338 nonsmoking adults since 1977. The investigators reported that mortality from all causes is associated with exposure to PM_{10} measured as the number of days with concentrations exceeding 100 µg/m^3. A positive association is also seen with PM_{10} when it was expressed as a mean concentration, although these results are not considered to have reached the level of statistical significance. These three studies were designed to ascertain and adjust for individual risk factors.

Investigators have also found increased mortality from several specific causes to be associated with long-term exposure to particulate matter. These types of mortality include cardiopulmonary mortality (*33*), respiratory mortality (*35*), and mortality in infants up to 1 year of age (*36*).

Increased morbidity is also a concern. Increased morbidity has been found to be associated with long-term exposure to particulate matter, for decreased lung function (*37,38*), increased respiratory symptoms or illness (*39–46*), increased symptoms in children with asthma (*47*), increased hospitalizations or emergency room visits for persons with asthma (*48,49*), and low birth weight (*50–52*). Investigators studying children's absences from school, lung function, and respiratory symptoms report similar results (*25,53*).

While it is not possible to definitively separate short- and long-term exposures as causes of excess mortality and morbidity, these studies provide a basis for concern about long-term effects. In a review, Pope et al. (*54*) concluded that an increase of 10 µg/m^3 of PM_{10} on average was associated with a 3% increase in mortality. These researchers point out that there is little evidence for a threshold for effects for PM_{10} and suggest that the relationship between PM_{10} concentrations and increased risk of mortality and morbidity may be linear at low doses (*54,55*). The U.S. EPA concluded, in a review of studies of particulate matter (*56*), that there was no clear evidence of a threshold of mortality or morbidity effects from exposure to PM_{10} in air.

Ozone

While peak exposures to ozone have customarily been considered a health risk, evidence of risks associated with long-term exposures is emerging. Studies of long-term exposures found decreases in lung function in humans (*42,57–59*) and changes in the respiratory tract in animals (*60*). The U.S. EPA review of animal tests and epidemiologic studies of ozone (*61*) concluded that chronic effects may be associated with long-term exposure to ozone. Increases in the prevalence of asthma (*62*), as well as exacerbation of asthma (*47,56,63*), have been found to be associated with long-term exposure to ozone. There is also some evidence of effects of ozone at levels below current air quality standards (*20,64*).

Nitrogen Dioxide

Researchers have found increased morbidity to be associated with long-term exposure to NO_2, for decreased lung function (*38,58,65,66*), increased respiratory symptoms or illness (*41,46,65,67–69*), and increased symptoms in children with asthma (*47*).

Sulfur Dioxide

Researchers have found decreased lung function (*38,58*) and increased respiratory symptoms or illness (*39,65*) to be associated with long-term exposure to SO_2.

Carbon Monoxide

Carbon monoxide is often a concern for short-term exposures, and few investigators have examined long-term exposures. Hirsch et al. (*65*) recently found an association between CO and other pollutants and respiratory symptoms in children. Ritz and Yu (*70*) found an association between 3-month average maternal exposures to CO and low birth weight. Although there is limited evidence of direct effects for long-term exposures, CO reduces the capacity of the blood to carry oxygen, thereby reducing the supply of oxygen to tissues. This could exacerbate other health conditions and could relate to long-term effects associated with exposures to other pollutants. We decided to include CO in the index while recognizing that the evidence for long-term effects is limited.

Multiple Pollutants

Whereas we have reviewed evidence of effects of individual pollutants, people are exposed to mixtures of the criteria pollutants. It is a challenge for researchers to fully separate their effects, particularly over long periods. The combined effects of several pollutants may be important to some adverse health outcomes, possibly including exacerbation of asthma (*71*). Moreover, while the effects of combinations of pollutants are not well known (*72*), evidence indicates that ozone and NO_2 may damage the lung and render it more susceptible to effects of other agents, including particulate matter (*73*).

Pollutants released into the environment may be transformed by chemical reactions in ways that convert them from one category of pollutant to another. Chemical reactions in the atmosphere convert SO_2 and nitrogen oxides, including NO_2, to forms measured as particulate matter. Ozone is also involved in these reactions (*56*). Especially in the Eastern United States, a significant percentage of acid aerosols, which can be measured as a component of PM_{10}, appears to originate as SO_2 (*74*). Moreover, NO_2 contributes to the formation of ozone.

Disparities in health status are receiving increasing attention. Differences in environmental exposures may contribute to disparities in health status. To reflect such disparities, investigators may find it more appropriate to examine the net burden of pollution rather than to focus solely on the single highest pollutant. An aggregate approach can examine the net burden.

In this article, we consider approaches that could be used to represent the net burden of long-term exposure to five criteria pollutants, not as a regulatory approach but as a way to look at trends and differences among areas. Using data from 1995, we study how an index of long-term exposure compares with the distribution of the exceedances of a daily index. We suggest that an aggregate index of long-term exposures could be informative to those who seek to understand trends in air pollution and to examine differences in exposures that may contribute to disparities in health outcomes.

Methods

We obtained air quality monitoring data for metropolitan areas in the United States for 1995. We developed a method to represent the aggregate burden of long-term exposure to five of the six criteria air pollutants. We identified the number of days that the U.S. EPA found exceedances of the NAAQS for various metropolitan areas. We compared the two ways of looking at air pollution, identified the differences, and considered their policy significance.

Air Quality Monitoring Data from 1995

We obtained observations of concentrations for PM_{10}, ozone, NO_2, SO_2, and CO for metropolitan areas from the Aerometric Information Retrieval System (AIRS), which contains data collected by state and local air quality monitoring stations and is maintained by the U.S. EPA. We used data for 1995, although data for any year could be used. Data were retrieved for metropolitan areas (as defined by the Office of Management and Budget) (*75*).

Table 1 shows the number of metropolitan areas in which each pollutant was monitored by state and local agencies. The greatest number of metropolitan statistical area (MSAs; $n = 266$) monitored particulates. Ozone was monitored in 235 MSAs, SO_2 in 178, CO in 174, and NO_2 in 131. A total of 107 metropolitan areas monitored all five pollutants. The AIRS database includes designations for the monitoring objective for many monitors. We included data from monitors with no designation (labeled "None" in Table 1), maximum concentration monitors, and population-oriented monitors. We did not include data from monitors designated to measure concentrations associated with particular sources or background levels.

Days When Standards Were Exceeded

We consulted the annual report on air quality trends from the U.S. EPA for 1995 (*30*) and obtained the number of days that the U.S. EPA found exceedances of any of the NAAQS for various metropolitan areas. We matched these MSAs to those for which we had obtained monitoring data.

Method for Development of an Index

Our third step was to develop a way to represent the net burden of long-term exposure to the five pollutants included in the study. First, we selected an approach to represent the long-term concentration for each pollutant. Second, we computed an annual estimate for each pollutant for each metropolitan area. Third, we weighted these estimates by the long-term standard for the relevant pollutant. Finally, we combined these weighted estimates into a single index that represents the aggregate burden of long-term exposure to all five pollutants in a metropolitan area over a period of a year.

Defining a value for each MSA for each pollutant. The time periods of the NAAQS vary among different pollutants in ways that affect monitoring. Some pollutants have only short-term standards; others have only long-term standards. Table 2 shows the averaging period for the short-term and the long-term standards for the pollutants and the averaging time for the data that we obtained.

Three pollutants—NO_2, PM_{10}, and SO_2—have 1-year standards expressed as arithmetic means. For these pollutants, 24-hr values were available, although not all pollutants were measured every day. PM_{10} is typically measured every sixth day, for example. We averaged these over the year to generate annual arithmetic means.

Ozone and CO do not have 1-year standards. The NAAQS for ozone in effect in 1995 had only a standard for the highest hour in a day. The CO standard was for the highest 8 hours in a day. We used the highest 1-hr value for ozone for each day and the highest 8-hr average for CO for each day. For ozone, we obtained the highest 1-hr value per day for each monitor. We averaged the values for monitors within each MSA to obtain an average daily 1-hr maximum value. For CO, we obtained the highest 8-hr value per day for each monitor. We averaged the daily values from different monitors within an MSA to obtain an average daily 8-hr value.

Ozone and CO are typically monitored daily in certain months but not in every month of the year. Ozone concentrations tend to be higher during warmer months,

Table 1. Number of monitors for criteria pollutants in metropolitan areas in the United States in 1995.

Pollutant	Number of MSAs that monitor[a]	Number of monitors	Monitor designation				
			None[b]	Maximum[c]	Population-oriented[d]	Background[e]	Source[f]
CO	174	518	234	156	123	4	1
NO_2	131	372	209	58	94	9	2
Ozone	236	831	341	186	275	26	3
PM_{10}	266	1125	357	327	414	21	6
SO_2	178	542	216	176	130	10	10

[a]Number of metropolitan areas with monitors for each pollutant. [b]Number of monitors for which there is no designation. [c]Number of monitors designated to measure maximum pollutant concentrations. [d]Number of monitors designated to measure exposures experienced by the general population. [e]Number of monitors designated to monitor background concentrations of pollutants. [f]Number of monitors designated to monitor concentrations of pollutants identified with particular pollution sources. Observations from background and source monitors were not included in the data set used for this study.

Table 2. Time periods for short-term and long-term standards for criteria pollutants and method used to develop values for long-term aggregate index.

Pollutant	Time period for short-term standard	Time period for longest standard	Averaging time for daily measurement	Method used to develop annual value for MSAs	Method for index ratio
CO	Maximum 1 hr per day	Maximum daily 8-hr rolling average	Highest 8-hr rolling average	Annual arithmetic mean of highest daily 8-hr rolling average; for January through March and October through December	Divide 6-month seasonal measure by standard for daily 8-hr rolling average
NO_2	None	Annual arithmetic mean	24-hr average	Annual arithmetic mean of daily (24-hr) values	Divide annual mean by standard for annual mean
Ozone	Maximum 1 hr per day	None	Highest 1-hr average	Annual arithmetic mean of daily 1-hr maximum for April through September	Divide 6-month seasonal measure by standard for daily 1-hr maximum
Particulate matter	24-hr average	Annual arithmetic mean	24-hr average	Annual arithmetic mean of daily (24-hr) values	Divide annual mean by standard for annual mean
SO_2	24-hr average	Annual arithmetic mean	24-hr average	Annual arithmetic mean of daily (24-hr) values	Divide annual mean by standard for annual mean

while CO concentrations tend to be higher during cool months. In many MSAs, ozone is monitored only in summer months and CO only in winter months. So selecting a comparable period to compare MSAs is important. We analyzed all ozone measurements and determined that the 6 months with the highest values were April through September. We used values only for these 6 months in this analysis. Analogously, we analyzed all CO measurements and determined that the 6 months with the highest values were October through April. We used values only for these 6 months in this analysis. We averaged values by month and then for the designated 6-month period.

We applied data completeness criteria to the data set. Table 3 shows the criteria for including monitors in the index. For each pollutant, Table 3 shows the number of measurements per month required before a month would be considered to have sufficient data. For pollutants that are to be monitored daily, 15 measurements were required. We found that 92 MSAs had monitors that met these criteria for all pollutants.

Combining pollutants. In the previous step, we generated one concentration estimate for each pollutant for each MSA. In this step, we combined these estimates into an index that represents the aggregate burden of long-term exposure.

Table 3. Data completeness criteria for air quality monitors included in this study and numbers of monitors meeting criteria.

Pollutant	Minimum number of observations per month	Minimum number of months monitored	Months included	Monitors that met criteria	MSAs with monitors that met criteria
CO	15 values per month	4	October through March	462 of 518	168 of 174
NO_2	15 values per month	4	All	351 of 372	128 of 131
Ozone	15 values per month	4	April through September	780 of 831	223 of 236
PM_{10}	3 values per month	6	All	1,034 of 1,125	260 of 266
SO_2	15 values per month	4	All	511 of 524	171 of 178

Table 4. Reported daily exceedances in 1995.

Number of days with exceedances	Number of metropolitan areas
0	18 (22.5%)
1 to 10	44 (55%)
11 to 20	11 (13.8%)
21 to 50	5 (5%)
51 to 100	1 (1.3%)
>100	2 (2%)

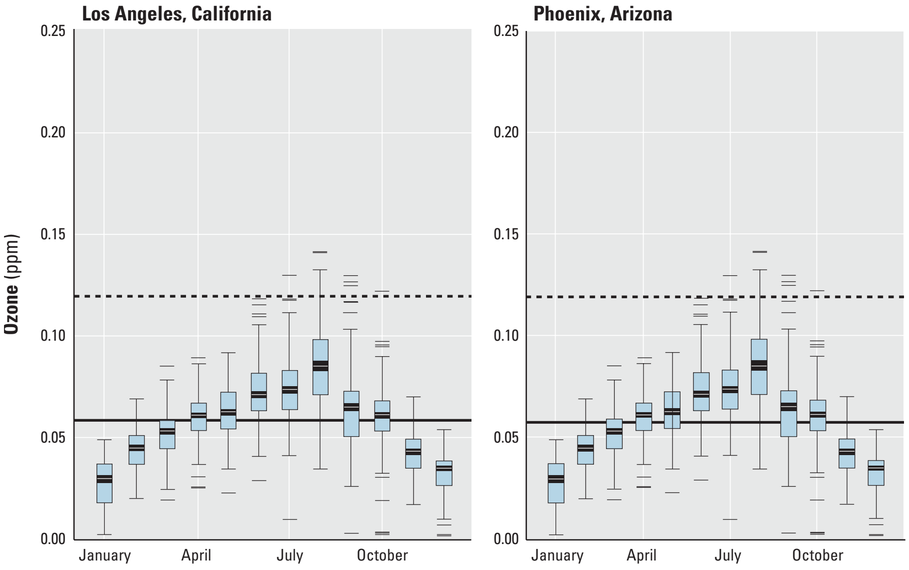

Figure 1. Comparison of ozone levels in Los Angeles, California, and Phoenix, Arizona, in 1995. This plot shows that cities with very different numbers of daily exceedances of an air quality standard, ozone in this case, may have similar long-term pollution burdens. The plot shows the distribution of daily 1-hr maximum values for ozone at monitors in Los Angeles and Phoenix in 1995. In this plot, the solid horizontal line within the box represents the median value (Los Angeles, 0.059; Phoenix, 0.058). The bottom and top of the box represent the 25th and 75th percentile values, respectively. The horizontal dashed line shows the standard in effect for ozone at that time (0.12 ppm). Only values higher than that line would be reported as exceedances.

We used the NAAQS in effect in 1995 to weight the annual values. We used this approach in part because it is analogous to what the U.S. EPA does with the air quality index. The difference is that we weighted values for long-term exposure with long-term standards, while the U.S. EPA, in its air quality index, weights values for short-term exposure with short-term standards. This provides a way to combine the five pollutants into a single index. So for NO_2, SO_2, and particulate matter, we divided the annual estimate (arithmetic mean of the 24-hr monitored values) for each metropolitan area by the annual standard to create a ratio, which we call an "index ratio."

Similar to the manner in which NO_2 presents difficulties for the U.S. EPA daily air quality index because it has no short-term standard, ozone and CO present difficulties for this analysis because they have no long-term standards. So, for ozone, we compared the arithmetic mean of the daily 1-hr maximum values for the 6 months from April to September with the 1-hr standard. For CO, we compared the arithmetic mean of the daily 8-hr maximum values for the 6 months from October to March with the 8-hr standard. For each pollutant, this left us with an index ratio. For PM_{10}, SO_2, and NO_2—the pollutants with annual standards—an index ratio of 1.0 would represent pollution at the level of the standard for the year. For ozone, and CO, an index ratio of 1.0 would represent pollution at the level of the standard for the six-month period.

To combine the pollutants, we added the index ratios for CO, NO_2, SO_2, PM_{10}, and ozone, thereby weighting all pollutants equally. We converted the result onto a 100-point scale where 100 would represent pollution equal to the five standards for all five pollutants on a long-term basis.

Results

Table 4 shows the number of days when air quality standards were exceeded in metropolitan areas in 1995 as reported by the U.S. EPA for all five pollutants. Two metropolitan areas had more than 100 exceedances (at least one pollutant exceeded its short-term standard for that day), while 17 had between 11 and 100 exceedances. Most metropolitan areas had 10 or fewer. This way of reporting the data shows a few metropolitan areas with a very high number of exceedances, very few metropolitan areas with some exceedances, and the great majority with few or no exceedances. These results are for the metropolitan areas for which U.S. EPA reported numbers of exceedances that are included in this study (*29*).

We looked at the distribution of measured values for ozone for individual metropolitan areas. Figure 1 shows two ways of looking at ozone for two cities—Los Angeles, California, and Phoenix, Arizona. We summarized all measured values for ozone from all monitors for 1995 and compared the distributions. Reporting the number of exceedances reflects the upper portion of this distribution, above the 0.12 ppm standard. For example, Los Angeles, which has a long tail at the top of the distribution of values, has numerous days of exceedance, as 118 were reported for 1995. Phoenix, which has a very comparable mean value for daily maximums, had only 18 exceedances. The mean values for the two areas are almost identical. The values at the top of the distribution, but not the mean values, are captured in the daily air quality index.

Results for the Aggregate Index of Long-Term Exposure to Air Pollutants

The average value for the aggregate index for the 92 metropolitan areas with complete data was 33.4 on a 100-point scale. PM$_{10}$, ozone, and NO$_2$ make the greatest numeric contribution to the long-term index, representing, on average, 31% for PM$_{10}$, 29% for ozone, 20% for NO$_2$, whereas SO$_2$ and CO each contribute about 10%. The minimum value was 15.4, and the maximum was 51.2. Examples of results for the long-term air quality index are shown in Figure 2, which shows the contribution of each pollutant for metropolitan areas with the highest overall values. This figure also shows the number of exceedances for each metropolitan area, in parentheses after the name of the area. Of the top metropolitan areas for which all five pollutants were monitored, highest values were in Los Angeles; Phoenix; Riverside County, California; Orange County, California; New York; El Paso, Texas; Fresno, California; and Philadelphia, Pennsylvania.

Comparing the Short-Term and Long-Term Index

The plots in Figure 3 show the relationship between the daily index measure and the long-term measure. The top plot shows the values of the long-term index for metropolitan areas. The bottom plot shows the number of exceedances for the same metropolitan areas, in the same order. The patterns for values in these two plots are quite dissimilar. Some of the metropolitan areas with high values for the long-term index had many days when standards were exceeded, whereas others did not.

A scatter plot in Figure 4 shows the relationship between the daily index measure and the long-term measure. This figure plots the number of days over a standard for a metropolitan area for 1995 against the long-term index. The plot shows that the measures do not always identify the same areas as being of greatest concern.

These results show that areas most affected by the highest net burden of long-term exposures to the five pollutants in this study are not identical with the areas that have the highest daily values.

Discussion

There is no doubt that exposure to elevated concentrations of air pollutants results in significant adverse health effects and that air pollution control warrants considerable regulatory and public attention. To date, much attention has focused on elevated concentrations that people experience for short time periods, such as 1 day. However, emerging research suggests that exposure to lower concentrations of pollutants over longer periods also results in adverse health effects. We believe that methods to represent long-term exposures to multiple pollutants are needed.

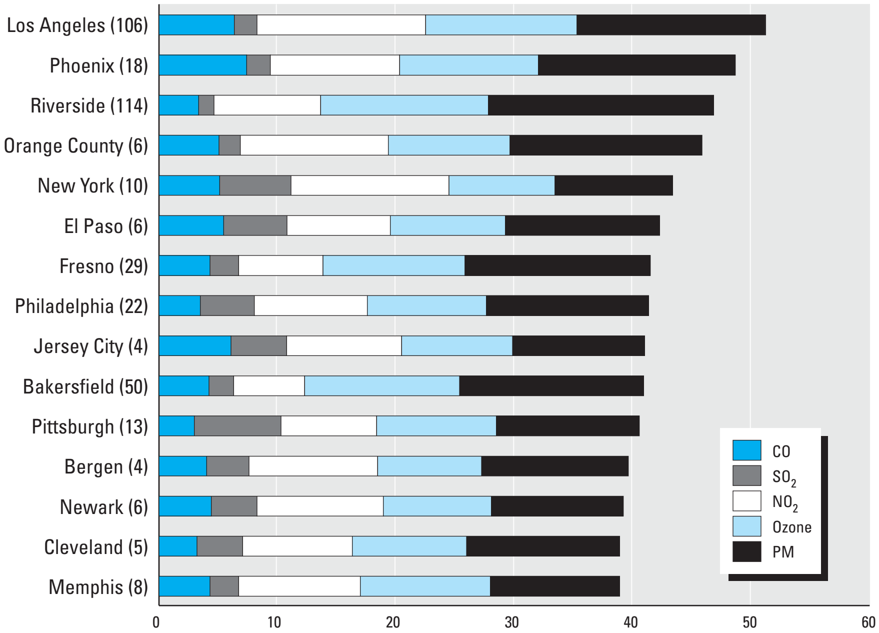

Figure 2. Aggregate index of long-term exposure to air pollutants in 1995. This figure shows the components of the long-term index for selected metropolitan areas in the United States. The bar shows, by different colors, the contributions of each pollutant. The number of daily exceedances for that year for each area is also shown in parentheses beside the name of the metropolitan areas on the *y*-axis. This graph suggests the differences in pollution identification patterns between identifying the number of exceedances and an index that reflects net pollution burdens for long-term exposure to multiple pollutants.

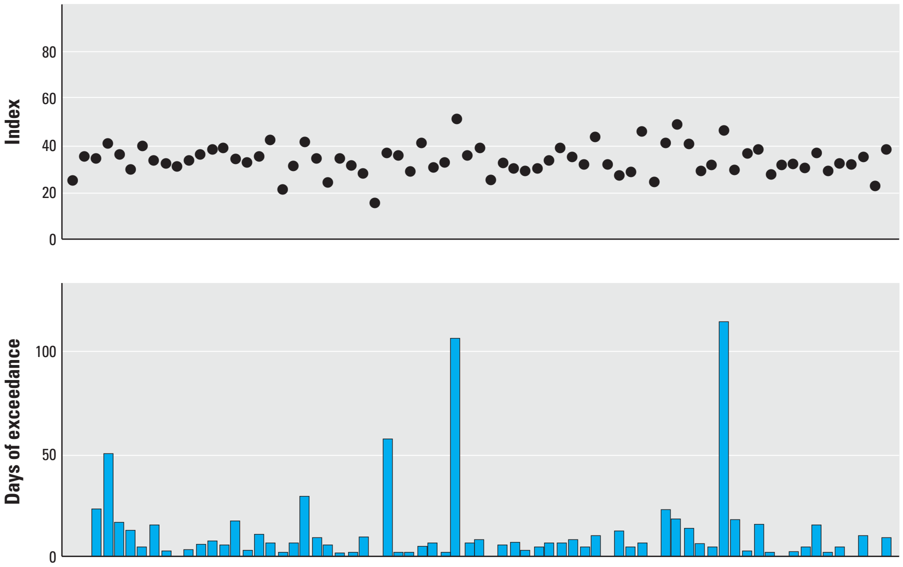

Figure 3. Distribution of number of exceedances and aggregate long-term index. This figure provides a comparison of the distribution of values for number of daily exceedances and for the aggregate long-term air pollution index for metropolitan areas in the United States for 1995.

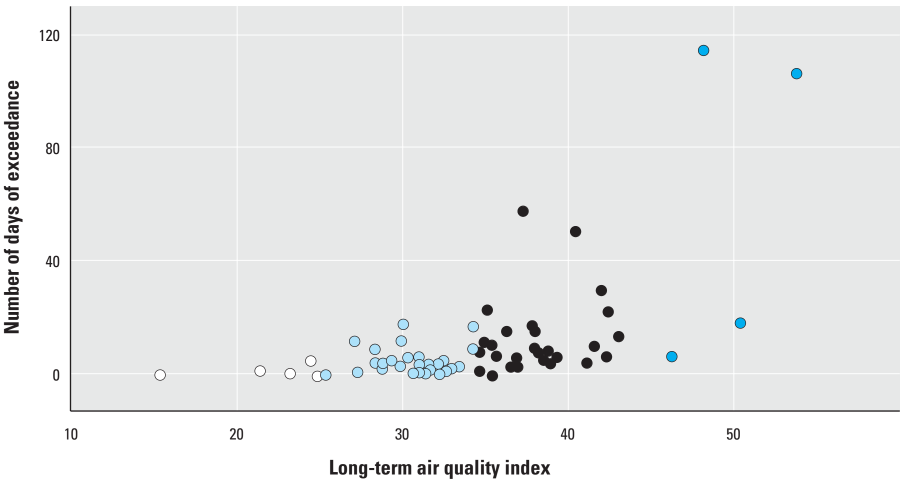

Figure 4. Relationship between daily and long-term air quality measures. This figure shows the relationship between the number of daily exceedances of short-term standards reported by the U.S. EPA and the value of the long-term air pollution index for metropolitan areas in the United States for 1995.

This analysis presents one approach for representing long-term exposures to five criteria air pollutants. The results show that looking at aggregate, long-term exposures, rather than at daily maximums for individual pollutants, yields a different view of the nature of the air pollution problem. Considering daily exceedances of short-term standards shows that few areas have very high numbers of exceedances and many others have few or no exceedances. By contrast, the aggregate index of long-term exposure makes clear that the net air pollution burden of major metropolitan areas is similar. Moreover, the areas identified as being of greater concern on the basis of long-term exposure are not, in many cases, the same as those that are identified as having the highest daily maximums.

Our findings suggest that the health burden from long-term exposures to multiple pollutants may be lessened by pursuing further pollutant reductions in many geographic areas. Important gains in health outcomes may be achieved by pollution reductions in areas that would not be targeted by an approach that relies solely upon exceedances of short-term standards.

These results are obviously preliminary. The index has important limitations. It is designed to be analogous to the U.S. EPA air quality index and to compare measured concentrations with the NAAQS. Clearly, this approach makes the most sense for pollutants for which long-term standards have been adopted—PM_{10}, SO_2, and NO_2. It may make less sense for ozone and CO. It would clearly strengthen our approach if sufficient research and analysis were completed to set long-term standards for CO and ozone and to better understand the effects of the individual pollutants over the long term. An alternative approach would be to look at mean values for all the pollutants. This would reveal differences between areas and trends over time but would not allow for an aggregate index.

The aggregate index, like the short-term air quality index, is limited by the national air quality monitoring network, which has limitations in coverage. As noted previously, only 107 MSAs monitor for the five criteria pollutants considered in this study, and only 92 of these met data completeness criteria. Even within these areas, monitoring coverage is limited. Monitoring locations may not represent air quality conditions throughout each MSA. The annual averages would be less easily influenced by meteorologic conditions that may create variant values for a few days in a given year.

In this article we have not examined which metric may best predict adverse health outcomes. As noted here, many health outcomes are of interest and relevant. Considerable work would be required to develop the best approach for each pollutant and health outcome. For example, it could be that the number of days over a certain threshold may prove to be a better predictor of adverse health outcomes than an annual mean. However, the best metric may also vary for different pollutants and outcomes.

The aggregate index uses the NAAQS to convert pollutants to a common point scale. The question of how best to combine pollutants is a difficult one to answer. This approach gives equal weight to each of the five pollutants and is only one of many that could be used. If the standards of the NAAQS do not accurately represent the health significance of the pollutants, then this approach will underpredict their significance.

Although both are based on comparison of measured values to NAAQS, the aggregate air quality index differs from the short-term index in that it is presented as a continuous measure. Rather than classifying the results into categories corresponding to air quality designations such as “fair,” “moderate,” or “good,” the aggregate index presents numeric results across the 100-point scale. It is not limited to identifying only those concentrations above the standards. It reports values at all concentrations and is not limited to reflecting concentration over a threshold that may prove to be artificial. A wide range of research on animals and humans increasingly suggests that there may be no threshold for health effects of most air pollutants. This would mean that levels of pollution below current standards would pose some risk, with lower levels posing proportionally less risk. This also means that it makes sense to consider pollution levels as continuous variables. The approach allows identification of differences in areas that have attained the standards.

Mixtures of pollutants are of concern. Some compounds contribute to synthesis of others. Different pollutants may contribute to similar effects. Therefore, it may be more informative from a public health perspective to look at the overall burden of pollution rather than to consider each pollutant in isolation. The combined exposure to multiple pollutants may prove to be of health significance and may contribute to disparities in health outcomes.

The aggregate index is intended to assess larger trends and overall levels of air pollution rather than compliance status. While the index reveals overall patterns of pollution, it cannot be said to be associated with particular health effects or to directly predict health outcomes. The types of warning words developed for the daily index would not be appropriate here.

Air pollution control is an important and expensive undertaking that is guided to a large degree by monitoring of ambient concentrations. How we interpret the results of that monitoring determines the types of control actions deemed necessary. We believe that we have enough evidence suggesting possible adverse health effects associated with long-term exposures to pollutants to justify looking at the cumulative burden of pollutants. The proposed aggregate index considers multiple pollutants and looks at the full distribution of concentrations. The aggregate index provides a view of air quality that is fundamentally different from that which results from looking only at daily maximum values. We believe that both views are important and that further work on a long-term, aggregate index is warranted.

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