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Does one size fit all? The suitability of standard ozone exposure metric conversion ratios and implications for epidemiology

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Abstract

Several exposure metrics have been applied in health research and policy settings to represent ozone exposure, such as the 24 h average and daily 8 h maximum. Frequently, results calculated using one exposure metric are converted using a simple ratio to compare or combine findings with results using a different metric. This conversion, however, assumes that such a ratio is constant across locations and time periods. We investigated the appropriateness of this conversion method by examining the relationships among various forms of ozone concentrations (24 h average, daily 1 h maximum, and daily 8 h maximum) within and between communities for 78 US communities from 2000 to 2004 and compared results to commonly used conversion ratios. We explored whether the relationships between ozone exposure metrics differ by region, weather, season, and city-specific characteristics. Analysis revealed variation in the relationship among ozone metrics, both across communities and across time within individual communities, indicating that conversion of ozone exposure metrics with a standard ratio introduces uncertainty. For example, the average ratio of the daily 8 h maximum to the daily concentration ranged from 1.23 to 1.83. Within a community, days with higher ozone levels had lower ratios. Relationships among metrics within a community were associated with daily temperature. The community-average exposure metric ratios were lower for communities with higher long-term ozone levels. Ozone metric ratios differed by season because of the different rate of change of ozone metrics throughout the year. We recommend that health effects studies present results from multiple ozone exposure metrics, if possible. When conversions are necessary, more accurate estimates can be obtained using summaries of data for a given location and time period if available, or by basing conversion ratios on data from a similar city and season, such as the results provided in this study.

Keywords

criteria pollutants; environmental monitoring; exposure modeling

Introduction

Tropospheric ozone is a common urban air pollutant that harms human health, vegetation, ecosystems, and materials (US EPA, 2006). The health consequences of ozone include an increase in the frequency of respiratory illnesses and risk of mortality. The US Environmental Protection Agency (US EPA) regulates ozone through the National Ambient

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Air Quality Standards (NAAQS) as required by the Clean Air Act. The US EPA first set the health-based ozone standard in 1971, later revised in 1979, based on the daily 1 h maximum ozone average (i.e., the highest hourly value recorded for a given day). The US EPA revised the standard in 1997 to regulate the daily 8 h maximum average when health studies found that lower ozone levels also affect human health and that a longer averaging time more accurately reflects human response to ozone exposure (US EPA, 2006). The US EPA recently evaluated whether to revise the level and form of the existing standard, changing the 8 h standard to 75 p.p.b. (US EPA, 2008). The agency noted the challenge in synthesizing across health-based research due to the use of a variety of ozone metrics in epidemiological studies (US EPA, 2006). A recent report by the National Research Council (NRC) of the National Academies noted the complications caused by use of multiple ozone exposure metrics in epidemiological studies and concluded that the choice of metric could impact results of studies aimed at evaluating the costs and benefits of ozone control policies (NRC, 2008).

Epidemiological and other health studies analyzing ozone use a variety of concentration metrics for the time frame of exposure, such as the daily 1 h maximum, daily 8 h maximum average, 8 h average for a specified time frame (e.g., noon to 8 pm), and the daily (24 h) average. The transition in the exposure metric used in studies and health-based regulation reflects a growing understanding of what exposure time frames best capture the impact of ozone on human health. Previous research has investigated which ozone metric is most associated with human health response (Abbey and Burchette, 1996). Identification of the ozone exposure metric that best reflects impacts on vegetation is similarly complex, and in fact the most appropriate metric may differ by plant species (Paoletti et al., 2007).

Although these pollution metrics are related, the use of a particular metric can affect the meaning of results. For example, the preference of various policy scenarios for ozone control can depend on which ozone metric is used to summarize air quality (Bell et al., 2005a). Multiple ozone metrics based on different temporal duration of exposure, spatial coverage, and concentration level have been investigated for ozone to evaluate the response to air quality control measures (Georgopoulos et al., 1997; Smith and Durrenberger, 1997). Conversions of the daily metric are particularly important as health estimates based on the 24 h ozone concentration may be affected by increased night-time ozone due to NO_x titration even as daytime levels are lowered, although daytime exposure is likely to be more relevant for human health.

Because epidemiological studies often give results for only one of the many possibilities of exposure metrics (e.g., daily 1 h maximum), the synthesis of the scientific evidence of ozone's impact on human health by US EPA and other decision-makers, as well as by scientific researchers, necessitates comparison of health studies using different metrics. For example, US EPA's recent review of the ozone NAAQS incorporated concentration–response functions based on the 24, 8 h maximum, and 1 h maximum ozone levels (US EPA, 2007).

The standard approach to relate results generated based on different ozone exposure metrics is to convert all results to a common metric through assumption of a standard ratio. For instance, a value of 2.5 has been applied for the ratio of the daily 1 h maximum average to the 24 h average ozone concentration (1:24 h ratio) (Thurston and Ito, 2001), whereas the US EPA suggests an index of 2 for the same comparison (US EPA, 2006). This type of simple conversion using an assumed ratio is commonly conducted for a variety of purposes: to allow comparison of results across multiple studies (e.g., US EPA, 2006); to pool results from multiple studies to generate an overall effect estimate (e.g., Bell et al., 2005b; Ito et al., 2005; Levy et al., 2005); and to apply results for policy analysis (Ostro et al., 2006). Table 1

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provides examples of ratios that have been recommended or applied for conversion between ozone metrics. The entry for the US EPA shows the values recently suggested in the ozone Air Quality Criteria Document for calculating risks using different ozone concentration measurements (US EPA, 2006, Vol. I, Section 7.1.3.2). Table 1 demonstrates that although conversion of ozone metrics with an assumed ratio is frequently performed, there exists no standard value for such ratios. Further, several studies have estimated regression coefficients relating daily 1 and 8 h maximum values, finding different results (Husar, 1996; St. John and Chameides, 1997; Jo et al., 2000).

Although conversion of one ozone exposure metric to another based on an assumed ratio is useful and a reasonable approach, this method carries implicit assumptions. Owing to meteorology and emissions patterns, ozone concentrations follow a diurnal cycle, with peak levels in the afternoon. However, the shape of this diurnal cycle differs seasonally and between locations. As an example, Figure 1 shows the ozone concentrations over 2 days, one in winter and one in summer, for three communities. Ozone concentrations also vary between weekdays and weekends as a result of emission patterns (Pryor and Steyn, 1995; Marr and Harley, 2002). Thus, the relationship among various ozone metrics may differ based on location, season, emission patterns, weather, and day of the week. Given the potential heterogeneity in the ratio of ozone exposure metrics, we explored the consequences of the practice of applying a standard conversion ratio.

This study investigates the common approach of using a single assumed ratio to convert between ozone metrics. Synthesizing recent and older research based on multiple metrics presents a challenge given the evolving nature of our understanding of which representation of ozone is most relevant to human health response. Our purpose is not to identify or promote the use of particular ozone metric as most appropriate to represent the association between ozone and human health, but rather to explore the relationships among these commonly applied metrics and the ratio conversion approach. To evaluate the implications of this practice, we analyzed the relationships among ozone metrics most often used in the epidemiological literature (daily 1 h maximum, daily 8 h maximum, and 24 h average) and investigated how the relationships among these metrics can differ within a single community over time and between communities. We examined whether the relationship among exposure metrics differs by season, meteorology, and city-specific characteristics. The aims of this research are to explore the appropriateness of ozone metric ratio approximations, to better understand the assumptions and uncertainties of simple conversion ratios, and to provide more accurate approaches to convert between ozone metrics. We characterize the uncertainty introduced by use of a standard ratio for metric conversions and discuss the implications for health effects studies.

Although the effects of ozone have been predominantly identified to occur at the higher ozone levels during the summer, several studies have found associations between ozone and health at very low levels. As two examples, links were identified between low levels of ozone and children's respiratory symptoms (Gent et al., 2003) and human mortality (Bell et al., 2006). To present a complete evaluation of the exposure spectrum and the proper interpretation of epidemiological studies that are based on data throughout the entire year, we included non-summer seasons in the analysis and investigate differences by season.

Methods

Data

Most of the epidemiological studies investigating the health impacts of ozone generated estimates of exposure based on ambient monitoring data, especially those established to estimate population-level exposure by regulatory agencies. Therefore we generated daily

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community-level estimates of ozone exposure metrics based on US EPA population-based monitors. Hourly ozone averages for a 5-year period (2000–2004) for the continental United States were obtained from the US EPA's AirData website (US EPA AirData). Data from a monitor were included in analysis if the monitor satisfied the following requirements:

1. The monitor had data for at least 3 of the 5 years.
2. Ozone was measured throughout the entire year, not only for the warm period.
3. Data for each year were missing no more than 15% of the hourly data points.

A total of 459 monitors in the Air Quality System database satisfied these conditions for the years considered. These 459 monitors were separated by Metropolitan Statistical Areas (MSAs) as defined by the US EPA's AirData program, and only communities with two or more monitors that operated year-round were used. A total of 78 communities met these requirements, with 365 monitors providing data for the 5-year data set. Figure 2 shows the geographical distribution of the communities used and indicates their relative population size. Hourly values across multiple monitors were averaged to generate community-level hourly concentrations. Our selection criteria were designed to allow comparison of metric ratios across seasons. However, this excluded communities that measure only during the summer or warm period or did not have adequate year-round data.

Weather data were acquired from the National Climatic Data Center (NCDC). The daily mean temperature and mean dew point temperature were available for 71 of the 78 communities. If a community contained multiple weather monitors, the daily values for all monitors within the community were averaged to generate daily values for temperature and dew point temperature. Supplementary Table S.1 of the Supplementary Material lists the communities considered in this study as well as the number of ozone monitors and weather monitors providing data for each community.

Individual communities had on average 4.7 ozone monitors (range 2–16). Of the 71 communities with weather data, communities had an average of 2.0 weather monitors each (range 1–8). Elevations for each ozone monitor were obtained from the US EPA's AirData database (US EPA AirData). For each community, elevation values were averaged across the available monitors to estimate a community value. Population values for each community reflect the 2000 US Census. Urbanization values, defined as percent of the population living in urban areas, were obtained from the 2000 US Census (US Census, 2000). These data were used to perform three types of analysis to investigate whether: (1) ozone metric ratios varied by community or by season; (2) community-level ozone metric ratios are associated with community characteristics such as long-term weather and pollution levels or population; and (3) ozone metrics vary within a community throughout the year.

Estimation of Community-Specific and Overall Ratios of Ozone Exposure Metrics

The hourly ozone concentrations were used to calculate the 1 h maximum, 8 h maximum, and 24 h average ozone metrics for each day of the 5-year period for each of the 78 communities. These metrics were chosen as they are the most commonly used to estimate exposure in epidemiological literature. The daily 1 h maximum was calculated as the highest hourly concentration for a given day. The daily 8 h maximum was calculated as the highest moving 8 h average to occur on a given day. The ratio of various metrics (e.g., 8 h maximum to 24 h average) was computed for each community for each day, season, and the total study period. Seasons were based on four 3-month periods (e.g., summer as June, July, and August). Missing data were not imputed; rather, data sets were generated by averaging across all monitors with available data for each hour. A comparison of this approach with imputation methods for missing data in three communities resulted in highly similar ratios of ozone metrics (correlation coefficient of 0.999).

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The average values of the ratios for each community were combined to create an overall average for all of the communities studied, to reflect nationwide values. Overall values were generated using both a simple average and a fixed effects average using inverse variance weighting. The simple average gives all communities equal weight when calculating an overall average, whereas the fixed effects average gives more weight to communities with stable metric ratios.

Analysis of Community-Specific Ozone Metric Ratios and Community Characteristics

We investigated whether community characteristics (e.g., long-term pollution levels) were associated with the ratio of ozone exposure metrics. Linear regression analysis was performed to identify relationships between community metric ratios (1:8 and 8:24 h) and community characteristics. The average metric value for the total study period for each community was used as the response, and community-specific variables included the average mean temperature, average dew point temperature, elevation, various metrics for overall ozone concentration (24 h average, 1 h daily maximum, 8 h daily maximum), and the related metrics of population and urbanization, averaged over the study period. These variables were chosen based on their potential influence on ozone concentration patterns due to photochemistry, emissions in relation to urbanicity, and regional differences in ozone behavior (US EPA, 2006). Regressions using weather variables (i.e. mean temperature and dew point temperature) considered only the 71 communities with weather data; for all other regressions, all 78 communities were used.

To explore how the relationships between community characteristics and ratios of ozone metrics may differ by season, community-specific average values of the two ozone ratios of interest, as well as mean temperature and average values for all three ozone concentration metrics, were calculated for winter, spring, summer, and fall in all communities with weather data. Correlations between the community-specific average ozone ratios and different community characteristics were determined by season.

Day-to-Day Variation in Ozone Metric Ratios within a Community

Whereas the previously described analysis evaluates how the relationship among ozone metrics differs among communities, we also explored how ratios vary over time within a given community. If metric ratios are not consistent within a given community, metric conversion ratios used for epidemiological studies incorporate uncertainty even if the metric ratio conversion is specific to the city of interest. Variation by season is of particular importance as some epidemiological studies examine only the warm period. Linear regression was performed within each community to determine the influence of daily temperature and ozone concentrations on the daily 1:8 and 8:24 h ratios. These community-specific estimates were then combined using a fixed effects model to provide an overall assessment of how daily characteristics affect ozone metric ratios.

Results

Ozone metric ratios vary substantially between communities (Table 2). The average community values range from 1.08 to 1.26 for the 1:8 h ratio; from 1.23 to 1.83 for the 8:24 h ratio; and from 1.35 to 2.20 for the 1:24 h ratio. As anticipated, the 1:8 h has the smallest average value and the smallest range, whereas the 1:24 h ratio has the largest average value and largest range. The 8:24 and 1:24 h ratios are distributed roughly normally across the communities, whereas the 1:8 h metric ratio values skewed to higher values (Figure 3). Average values of the 1:8 and 8:24 h metric ratios across the study period for all communities studied are given in Supplementary Table S.1 of the Supplementary Material. Geographical variation in the 1:8 and 8:24 h ratios are shown in Figure 4. Visual inspection

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does not reveal strong regional patterns in ozone metric ratios, although these maps demonstrate the heterogeneity of metric ratios between communities. Ozone metric ratios seem particularly high along the northeast coast and in northern California near San Francisco.

Ozone metric ratios also vary by season (Table 2). In most communities, both the 1:8 h ratio values and 8:24 h ratio values are highest in the winter and lowest in the spring. The largest difference across seasons in average 1:8 h ratio values was from 1.15 in the spring to 1.42 in the winter in Stockton-Lodi, CA, whereas the smallest seasonal variation was in Rockford, IL (1.09 in both the spring and summer). The 8:24 h ratio values showed a maximum change from 1.35 in the summer to 1.83 in the winter in San Francisco, CA, and a minimum change in McAllen-Edinburg-Mission, TX, where the ratio was 1.53 in both the winter and summer. Heterogeneity existed between community seasonal averages as with yearly averages. Supplementary Table S.2 of the Supplementary Material shows ranges of seasonal ratio values across communities.

Relationship between Ozone Metric Ratios and Community Characteristics

Table 3 provides results of analysis evaluating whether a community's overall ratio of ozone metrics is associated with community characteristics. Results are presented as the percent change in an ozone metric ratio per interquartile (IQR) increase in a community-specific variable. Ratios of ozone metrics were not associated with weather variables (temperature, dew point temperature), elevation, or population (Table 3). Both metric ratios (1:8 and 8:24 h) were higher for communities with lower average ozone levels. Both indicators of urbanicity (population and urbanization) were associated with higher metric ratios, although results were statistically significant only for the 1:8 h ratio and the variable for urbanization.

Of all community characteristics considered, long-term ozone levels showed the strongest relationship with average community ozone metric ratios. An IQR increase in long-term ozone concentration lowered the average 1:8 and 8:24 h metric ratios by 2.14% and 6.28% evaluated at the mean, respectively (Table 3). A significantly negative correlation existed between average ozone concentration and average community ratio values for all seasons, with the strongest correlations in the fall (−0.63 for the 1:8 h ratio and −0.68 for the 8: 24 h ratio) and weakest correlations in the winter for the 1:8 h ratio (−0.44) and in the summer for the 8:24 h ratio (−0.35). Seasonal metric ratios for each community are provided in Supplementary Table S.1 of the Supplementary Material.

Variation in Daily Ozone Metric Ratio Values Over Time within Communities

The relationship between day-to-day variation in weather and ozone levels and ozone metric ratios was investigated within each community using community-specific regression analysis. In other words, we estimated whether each day's ratio of ozone exposure metrics was associated with that day's ozone and weather values, within a single community, repeating analysis for all communities. Estimates of these community-specific relationships were then combined to generate an overall estimate of how daily variation in weather and ozone levels affects the daily ratio metrics (Table 4).

Days with higher ozone levels corresponded to lower ozone metric ratios. An IQR increase in daily ozone levels lowered ozone metric ratios by 5.64 to 7.51% evaluated at the mean metric ratios, for the 1:8 and 8:24 h ratios, respectively. Of the 78 communities studied, statistically significant associations between daily ozone concentrations and daily metric ratio values were observed in all cases with only one exception: Vallejo, CA (8:24 h ratio).

Higher daily ozone metric ratios were associated with lower daily temperature in many communities, however not in communities with consistent high temperatures. A relationship

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was also observed between daily mean temperature and the daily 1:8 h metric ratio within most communities, with higher daily temperatures generally associated with lower 1:8 h ratio values. This negative relationship was statistically significant overall across the 71 communities, and in 49 individual communities ($P<0.05$). Most communities without a significant association were characterized by temperatures that were higher (average temperature of 69.2 *versus* 60.2 °F for cities with a significant negative relationship) and less variable (standard error of 13.6 *versus* 16.1 °F), and 15 of the 22 communities without significantly negative associations were in Florida or Texas. Of the 71 communities with weather data, 31 showed significant negative associations between daily community temperature and the 8:24 h metric ratio value, however the overall relationship was higher for ozone metric ratios with higher daily mean temperatures.

Discussion

Given the daily and yearly cycle of ozone concentrations and variation in emissions of ozone precursors, we hypothesized that the relationship among ozone metrics may vary by factors such as location, season, weather, ozone levels, urbanization, or population. This study found that such variation exists across communities and across time within a given community. Our research shows substantial heterogeneity in the ratio of ozone exposure metrics, and indicates that the use of a single conversion ratio to assimilate different ozone metrics is likely to introduce error, which may vary by community or season. In contrast to the standard assumption of a simple conversion ratio, ozone metric ratio values vary both within communities across time and between different communities. Because of this heterogeneity, the use of single ratio values to describe the relationship between different ozone exposure metrics introduces uncertainty that may be avoidable. Although this study focused on the association between ozone and human health, similar issues may be relevant for the impact of ozone on ecological systems or visibility. For example, studies of ozone's impact on vegetation have applied a variety of exposure metrics (Heck and Cowling, 1997; Arbaugh et al., 1998; Kohut, 2007).

In this study, ozone concentration was identified as the most important predictor for ozone metric ratio values, both for comparison across multiple communities (Table 3) and comparison across time within a community (Table 4). Regional areas with particularly high ozone metric ratios such as the Northeast coast and in communities near San Francisco CA tend to have low ozone concentrations (Figure 4a and b). Supplementary Figure S.1 provides a map depicting long-term ozone concentrations for each community.

This relationship between ozone levels and metric ratios can be understood by examining the annual ozone cycle of a community, such as the example shown in Figure 5. This graph shows the variation in the three ozone concentration metrics (daily 1 h maximum, daily 8 h maximum, 24 h average) and two ratios of interest (8:24 and 1:8 h) over 2002 for the Chicago metropolitan area. As is evident from this graph, the 1:8 h ratio follows the inverse of the 1 h maximum ozone concentration and 8 h maximum ozone concentration. The absolute difference in these two metrics (1 and 8 h maximum concentrations) does not vary widely during the course of the year, so as the metrics both increase in the warmer months, their proportionate difference decreases. The annual cycle of the 8:24 h ratio is a bit different, because the absolute difference in the 8 h maximum concentration and 24 h average concentration changes over the course of the year. This ratio decreases in the spring, as both metrics (8 and 24 h) rise at the same rate, but the ratio increases in the summer when the 8 h maximum ozone values start to increase at a higher rate than the daily average. The process is reversed in the fall, when the 8 h maximum concentration values begin to decrease at a more rapid rate than the daily ozone average concentration. Although all three ozone metrics follow roughly the same pattern, with higher values in summer, the

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relationship among ozone metrics changes throughout the year because the 1 and 8 h maximum values change temporally at a different rate than the 24 h average. The negative association between average ozone concentration and overall ratio values across communities might relate to the importance of long-range ozone transport.

The overall average 1:8 h ratios calculated in this study are in general lower than the standard ratios previously used (Tables 1 and 2). On average across the communities, the 1:8 h ratio was 1.14, compared to commonly used ratios of 1.88 or 1.33. The 8:24 h ratios calculated in this study are more similar to the ratios previously used at 1.53 on average across the communities compared to commonly used ratios of 1.33 or 1.5. Given the dependence of the exposure metric ratios on community characteristics, the overall ratios are a function of the communities selected for this study. When only summer ozone concentrations are considered, the 1:8 h ozone ratios calculated in this study are even lower than ratios previously used (1.13). Figure 6 compares ratio values for several communities, selected to demonstrate communities from across the United States, to ratios used in previous studies, such as those listed in Table 1.

Our results have several important implications for those conducting and interpreting health effects studies. Simple conversion ratios are often used to compare or pool data across different locations or results from various studies. However the heterogeneity of ozone exposure metric ratios, both within and among cities, demonstrates that the use of any single measure to summarize ozone (e.g., yearly average) does not fully capture variability of ozone pollution and the use of simple conversion metrics (e.g., 1:24 h value = 2.0) may distort the actual relationship of ozone pollution patterns, and thereby the health effects estimates. For example, we identified differences in ozone metric ratios by season. Therefore, a different conversion among ozone metrics may be appropriate for health effects estimates based on a warm period (e.g., April to October or summer) as opposed to effect estimates based on yearly data. More correct estimates of metric ratios can help make such comparisons more accurate.

We recommend that, when possible, epidemiological and other health studies present results using multiple metrics (e.g., findings for the daily average, daily 1 h maximum, and daily 8 h maximum), which would facilitate comparability among studies, by eliminating the need for the assumption of standard conversion ratios. A National Academies committee similarly recommended that epidemiological studies explore a full suite of ozone exposure metrics (NRC, 2008). A recent review of ozone and mortality time-series studies identified effect estimates from 64 studies, a subset of which were used in a meta-analysis (Bell et al., 2005b). Of the 64 studies, 40.6% presented results for the daily average, 34.4% for the daily 1-h max, and 18.8% for the daily 8-h max. Other metrics used were an 8-h average over a specified time frame (noon to 8 pm, 8 am to 4 pm, 10 am to 6 pm, or 9 am to 5 pm) for 14.1% of studies, the 1-h maximum over a specified time frame (10 am to 6 pm and 6 am to 7 pm) for 3.1% of studies, the 8 h average around the daily 1 h maximum for 1.6% of studies, the daily 4 h maximum in 1.6% of studies, and the 3-day average for 1.6% of studies. Only eight of the studies (12.5%) provided results for multiple metrics, and only three studies (4.7%) presented results for two of the most frequently used metrics (24 h and daily 1 h maximum). No studies gave results for the three most commonly applied metrics (24 h, daily 1 h maximum, and daily 8 h maximum).

Although the use of a variety of ozone exposure metrics reflects growing knowledge of the ways in which ozone impacts human health, as echoed in US EPA's revisions to the form of ozone health-based standards, the presentation of results in multiple metrics would facilitate comparison of results from multiple studies, and aid in the use of information from earlier conducted studies as the metric of interest changes over time. Similarly, summary data

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reflecting pollution levels for communities could be presented with multiple metrics to provide other researchers with an overall ratio of ozone metrics for the study period and community, eliminating the need to rely on an assumed standard ratio.

For cases in which results are not provided for multiple metrics, effect estimates from one ozone exposure metric often must be converted to another in order to compare or combine results. Because of the variability of metric ratios within and among cities, ratios should be calculated with the community- and time-specific data when possible, such as using data from the same location and season. This study provides yearly and seasonal ratios that can be used for the 78 communities considered here (Supplementary Table S.1 in the Supplementary Material). Otherwise, ratios calculated from a similar location and season may be more suitable than application of a single assumed value to all cases, such as has been performed previously. Owing to variation within cities, different conversions may be appropriate for studies that used summer or warm season ozone data *versus* those that used yearly data. Finally, the variation in ozone metric ratios could be incorporated into comparisons and pooling of health effects studies in order to incorporate the uncertainty in metric ratios. When results from multicity studies are used, a pooled ratio representing those communities could be generated, although still the uncertainty introduced by converting using a standard ratio should be acknowledged and could be incorporated.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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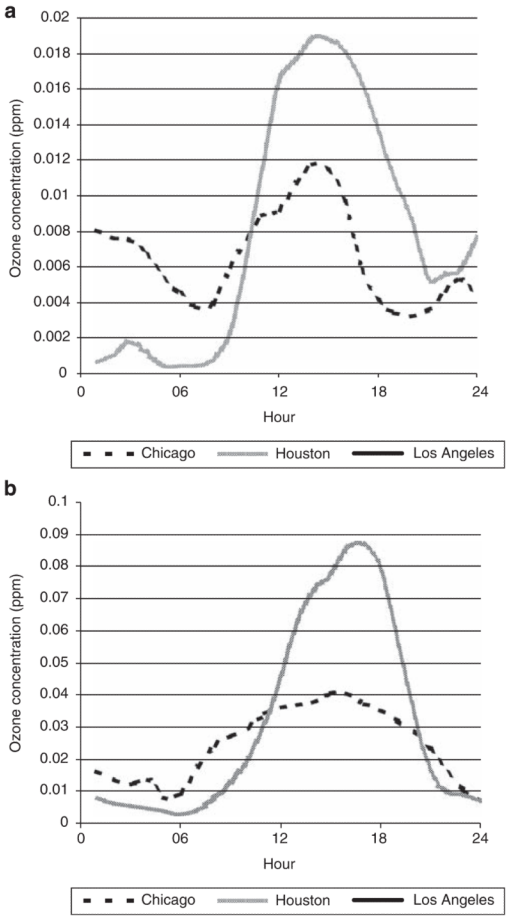

Figure 1.
Example of daily cycle of ozone for three communities for sample days with typical ozone patterns for: (a) winter (15 January 2000); and (b) summer (15 July 2000). *Note*: Scales differ for (a, b).

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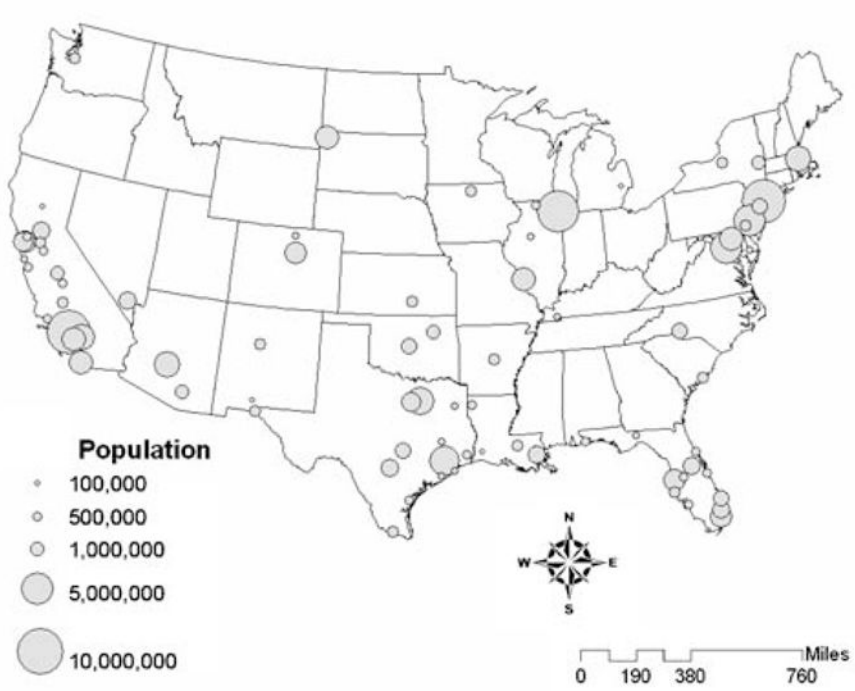

Figure 2.
Locations of the 78 study communities. The size of the symbol corresponds to the community's population.

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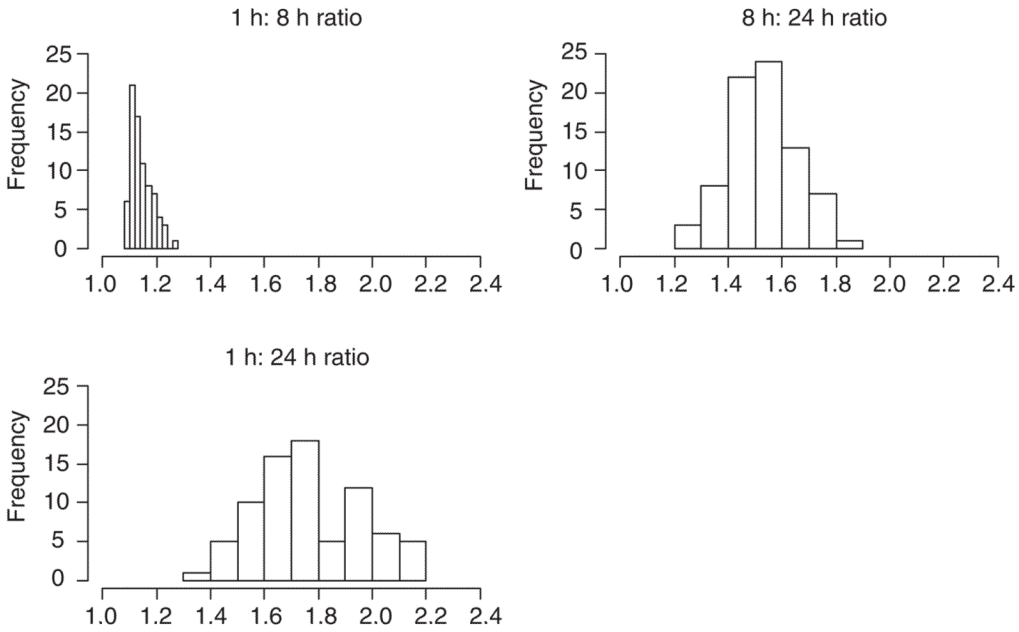

Figure 3.
Distributions of community average ozone metric ratios for 78 communities.

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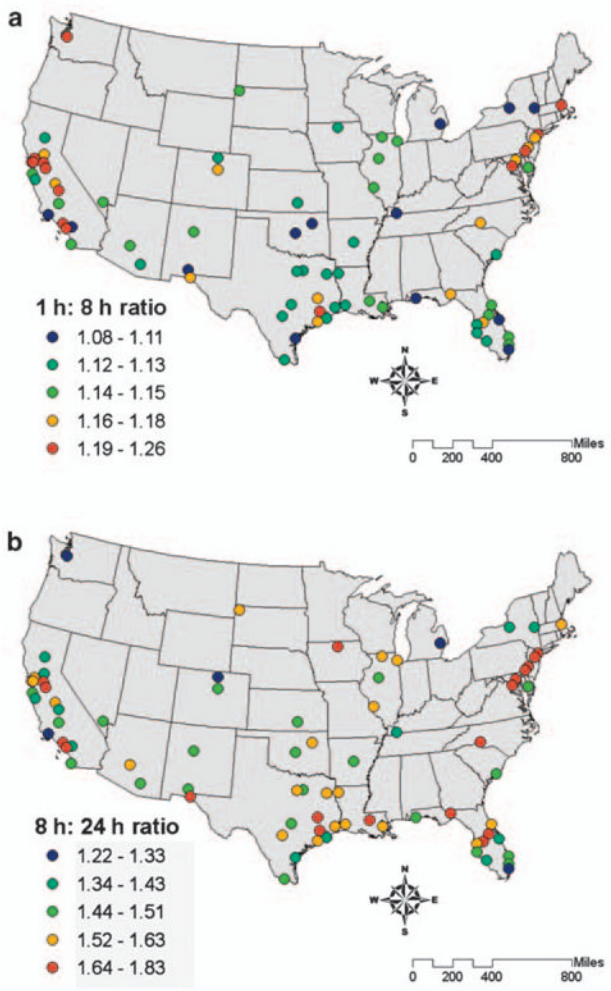

Figure 4.

Community-specific metric ratios for 2000 to 2004 for 78 communities for: (a) daily 1 h maximum to daily 8 h maximum; and daily 8 h maximum to daily 24 h concentration. Note that the scales differ in (a, b).

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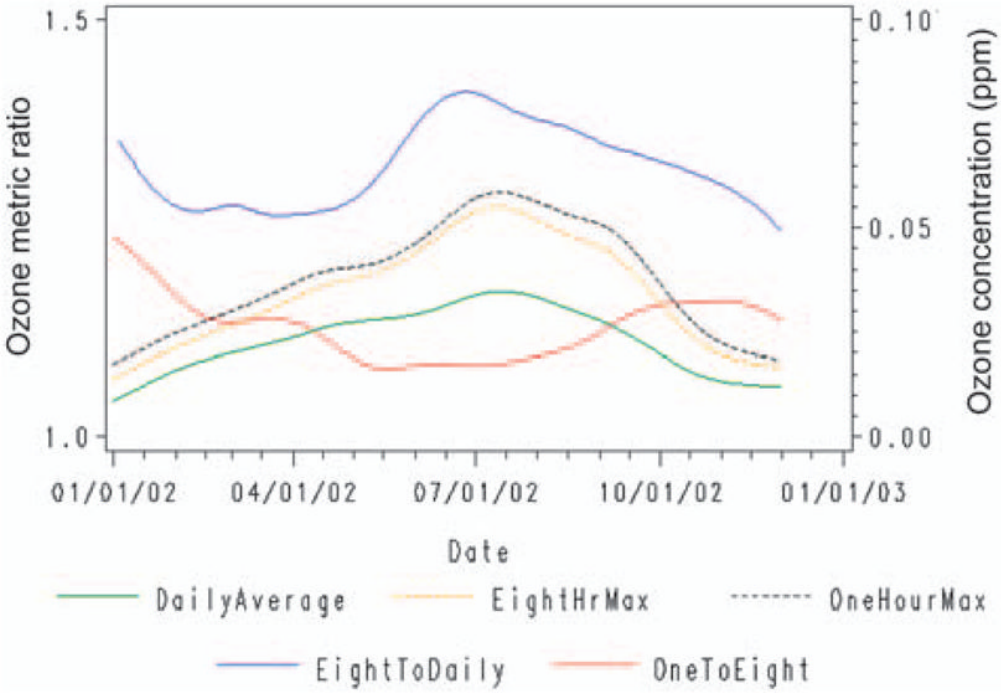

Figure 5.
Annual cycle of ozone exposure metrics and ratios in Chicago for 2002.

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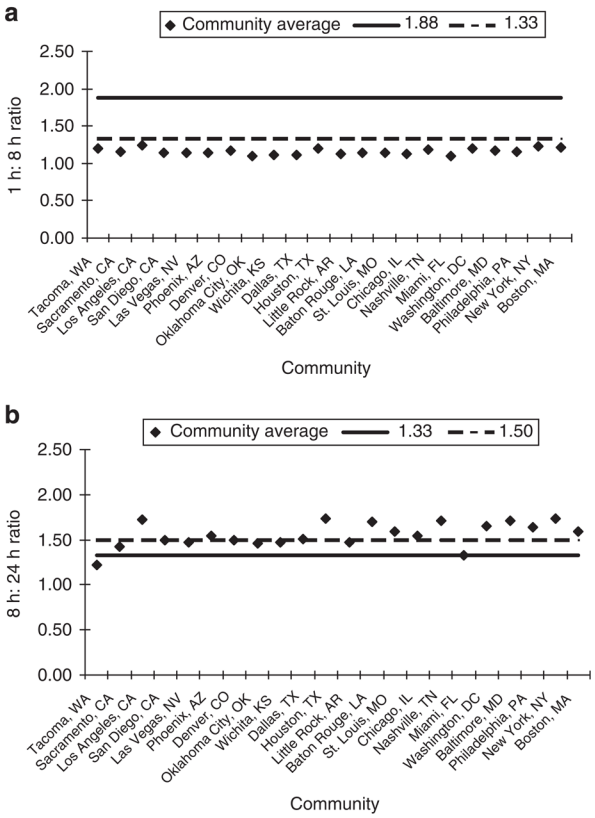

Figure 6.

Comparison of observed exposure metric ratios for selected communities to previously suggested ratios for: (a) 1:8 h; and (b) 8:24 h. *Note*: Standard conversion ratios (1.88 and 1.33 for the 1:8 h ratio, 1.33 and 1.50 for the 8:24 h) are provided for comparison.

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Table 1

Previously applied ratios of ozone metrics.

Source	Conversion (1:8:24 h)	Area studied
Thurston and Ito (2001)	2.5:1.33:1	United States, Mexico, Europe
Bell et al. (2005b)	2.5:1.33:1	Worldwide
Ito et al. (2005)	2:1.5:1	Worldwide
Levy et al. (2005)	2:1.5:1	United States, Canada, Europe
US EPA (2006) suggested indices	2:1.5:1	United States

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Table 2

Summary of ozone metric ratios for 78 US communities, 2000 to 2004.

Metric ratio	Average (fixed effects average)	Median	Range	Seasonal averages			
				Winter	Spring	Summer	Fall
1:8 h	1.14 (1.13)	1.14	1.08–1.26	1.19	1.10	1.13	1.17
8:24 h	1.53 (1.45)	1.53	1.23–1.83	1.56	1.43	1.53	1.61
1:24 h	1.76 (1.64)	1.73	1.35–2.20	1.86	1.57	1.73	1.89

Note: The median reflects the median of community-specific average values. The range provides the lowest and highest community-specific averages.

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Table 3

Comparisons across communities for associations between community characteristics and metric ratio values.

Variable (X_i)	IQR of X_i	Change in ozone metric/IQR increase in community-specific variable (%)	
		1:8 h	8:24 h
Mean temperature	13.6 °F	−1.15% (−2.49, 0.19)	0.87% (−2.38, 4.12)
Dew point	15.8 °F	−0.83% (12.07, 0.41)	1.13% (−1.86, 4.12)
Elevation	187 m	−0.22% (10.58, 0.15)	−0.76% (−1.62, 0.10)
Average ozone levels	4.84 p.p.b.	−2.14% (−2.92, −1.37)***	−6.28% (−7.97, −4.59)***
Population	1,320,000	0.22% (−0.31, 0.75)	0.63% (−0.65, 1.91)
Urbanization	0.120	1.31% (0.38, 2.24)**	0.46% (−1.90, 2.82)

Abbreviation: IQR, interquartile range.

Note:

* *P*-value <0.05,

** *P*-value <0.01,

*** *P*-value <0.001.

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Table 4

Comparisons within communities over time for overall change in daily metric values in relation to daily temperature and ozone levels.

Variable (X_i)	IQR of X_i	Change in ozone metric/change in IQR increase in ozone or temperature (%)	
		1:8 h	8:24 h
Daily ozone	0.0158 p.p.m.	−5.64% (−5.69%, −5.58%)***	−7.51% (−7.52%, −7.50%)***
Daily mean temperature	23.3 °F	−2.32% (−2.39%, −2.25%)***	0.54% (0.43%, 0.65%)***

Abbreviation: IQR, interquartile range.

Note:

*P-value <0.05,

**P-value <0.01,

***P-value <0.001. These results were generated by combining community-specific estimates on the association between daily characteristics and daily metric ratios, thus they reflect the overall effect.