Asian Journal of Atmospheric Environment
Vol. 2-1, pp.47-53, June 2008

The Measures of Ozone Pollution: An Analysis of Ozone Concentration Data in USA

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ABSTRACT

In this study, we analyzed how ozone pollution could be differently measured and how these different measures varied year to year and across the ten most populated cities in the United States, from 1980 to 2000. Although peak values of ozone concentration have been significantly reduced in most polluted U.S. cities for the last 20 years, the annual average values of ozone concentration have not been lowered as much as peak values. Ozone concentration data for each city shows a unique pattern of distribution, central tendency, and also there is a wide variation among different ozone measures. Two different cities with the same annual mean concentration of ozone can experience very different distributions of ozone concentration within a year. Ozone measures also show a wide margin of variability as they are estimated from different ozone monitoring sites within each city. Ozone pollution statistics can be largely varied depending on the choice of measures, monitoring sites, and averaging time period. EPA's new ozone standard of 0.08 ppm averaged over an eight-hour appears to be more stringent than the current maximum ozone standard of 0.12 ppm averaged over one hour.

Key words: Ozone concentration, Peak, Average, Cumulative, Measures

1. INTRODUCTION

The harmful effects of excessive ground-level ozone concentrations on human health and welfare have been the subjects of numerous studies over the past several decades (US EPA, 2000, 1997). Many studies have found that at levels above 0.12 ppm, which are frequently found in metropolitan areas during summer months, ozone is associated with acute respiratory symptoms (Abbey *et al.*, 1995; Ito *et al.*, 1995; Li and Roth, 1995; Dockery *et al.*, 1993). Once ozone enters the body through the respiratory tract, it can disrupt the cell renewal processes and can cause dehydration and inflammation. The inflammation of cells, together with reduced renewal processes in the respiratory tract, can reduce the normal transport of respiratory gases and thus cause respiratory symptoms which include coughing, wheezing, sore throat, and sinus congestion.

More recently, it has been indicated that long-term exposure to moderate ozone concentration levels below the current maximum standard of 0.12 ppm may lead to inflammation and the potential development of chronic lung disease. A few studies have tried to assess long-term effects of ozone on lung function (US EPA, 1999; HEI, 1998). These studies showed that long-term exposure to moderate levels of ozone pollution could aggregate chronic lung diseases and also accelerate the natural aging process of lung function. Ozone is also suspected to contribute to mortality as well as to chronic symptoms, but the relationships have not been clearly identified.

In addition to affecting human health, agricultural crop yields have also been adversely impacted by ozone. By affecting the crops' photosynthetic processes, ozone exposure lowers crop yields. The effects of ozone on agricultural crops are well documented and many studies have demonstrated that crop damage occurs at ozone concentrations far below the current federal standards (Kim *et al.*, 1998; US EPA, 1997). Finally ozone pollution can affect materials, visibility, and forestry, but the quantification of such effects are still subject to a wide margin of variability (US EPA, 2000, 1997).

The Clean Air Act (CAA) has been effective in reducing maximum one-hour ozone concentrations in the most polluted U.S. cities. VOC and NO_x emissions from both stationary and mobile sources have been significantly reduced and maximum one-hour ozone concentrations for those cities have been substantially lowered. However, data for the past 20 years show that annual average values of ozone concentrations have not been lowered as much as maximum values. Although excessively high ozone concentrations have been reduced, people are still frequently exposed to moderate ozone concentrations.

For the past 20 years, the EPA-established federal standard for maximum ozone concentration has been an ambient standard of 0.12 ppm averaged over one hour. This standard was based primarily on clinical studies of short-term acute health effects, while overlooking the potential risks of long-term exposure to moderate ozone levels to human health. In 1997, EPA set a new ozone standard of 0.08 ppm averaged over an eight-hour period to replace the one-hour standard of 0.12 ppm. This more stringent ozone standard is designed to provide more protection to human health as more evidences show that human health can be adversely affected below the ozone concentration level of 0.12 ppm.

In order to associate ozone pollution to human health, it is necessary to use measures of ozone pollution, which are relevant to human health. Ozone concentrations at a monitoring site are reported hourly. Different ozone measures can therefore be developed when hourly ozone data is summarized into daily or even annual statistics. Different ozone measures from the same hourly ozone data from the same monitoring site may show different correlation with each other. We expect that ozone may have important detrimental long-term effects on human health and that one reason there is a lack of consensus on this relationship is that researchers are not using same measures of ozone pollution in their studies. For example, the relative risk factors of ozone pollution on human health significantly vary across different study approaches and even within the same approach. Ozone measures used to capture the human health effects ranges from a daily maximum to an annual average.

Each city might have a unique pattern of distribution of ozone concentration over time. Two different cities with the same annual mean concentration of ozone can experience very different distributions of ozone concentration within a year. Very different levels of ozone pollution can be calculated by choosing different sets of ozone monitors within a city. Therefore, ozone pollution statistics can be largely varied depending on the choice of measures, monitoring sites, and averaging time period. Little attention has been given to the differences among ozone measures and no study has been identified to investigate the implications of using different ozone measures in estimating a potential association between human health and ozone pollution.

In this study, we analyzed how ozone pollution could be measured in different ways and how such different measures varied year to year and across the top ten most populated cities in the United States. We also analyzed differences in the correlation of the various ozone pollution measures across cities. We compared EPA's new ozone standard of 0.08 ppm averaged over an eight-hour to the maximum ozone standard of 0.12 ppm averaged over one hour. This study is designed to provide policy makers and researchers with as complete a picture as possible of the time variations of ozone concentration within a city and spatial differences in ozone concentrations across cities as calculated by different ozone measures.

2. METHODS AND DATA

Information on ozone concentration data was collected from the ten most populated cities in the United States, as reported in the 1995 Statistical Abstract of the U.S. The ten cities are New York, Los Angeles, Chicago, Houston, Philadelphia, San Diego, Phoenix, Dallas, San Antonio, and Denver.

EPA maintains the most comprehensive source of air pollution monitoring data in the country in its Air Information Retrieval System (AIRS) database. The AIRS database contains hourly and daily ozone concentration from each monitoring site in operation (US EPA, 2002). Ozone pollution data exists as far back as 1959, although due to changes in collecting and reporting data, there is considerable variation in the data for the earlier years. For these reasons, we excluded any data collected before 1980. We sought to

Table 1. Description of ozone pollution measures.

Ozone pollution measures	Description
YR1HMAX	Annual peak of daily peak 1-hour ozone concentration in part per million (ppm)
YR8HMAX	Annual peak of daily 8-hour average ozone concentration (10:00 AM to 6:00 PM) in ppm
YR8HMEAN	Annual average of daily 8-hour average ozone concentration in ppm
12PS	Number of days exceeding daily peak 1-hour ozone concentration of 0.12 ppm per year
8AS	Number of days exceeding daily 8-hour average ozone concentration of 0.08 ppm per year

construct a database starting from 1980 to 2000, the most recent data available.

For each city, the raw monitoring data for ozone contain hourly readings for each monitoring site. Using this raw data, we developed five measures of ozone exposure. We developed measures that indicate peak, average, and cumulative levels of ozone for each city for each year. There are two peak measures (YR1HMAX and YR8HMAX), one average measure (YR8HMEAN), and two cumulative measures (12PS and 8AS). Table 1 describes ozone measures developed in this study.

Each of the top ten cities except Los Angeles has more than one monitoring site for ozone. Because there are 14 more monitoring sites within the Los Angeles Metropolitan area, this study included those monitoring sites to represent ozone pollution levels in Los Angeles City area. Table 2 shows the number of monitoring sites used in this study for each city.

3. RESULTS OF THE ANALYSIS

For the ten cities in this study, daily maximum ozone concentration from 1980 to 2000 showed a highly positively skewed distribution. The highest daily maximum concentrations were reported at 0.49 and 0.39 ppm in 1980 and 1986, respectively in Los Angeles. Houston also experienced a daily maximum concentration of 0.34 ppm both in 1980 and 1982. However, the average value of daily maximum concentrations of ozone from 1980 to 2000 for the 10 cities was 0.035 ppm. Only 1.5 percent of the daily maximum ozone concentrations exceeded the federal ozone standard of 0.12 ppm. Los Angeles appeared to be the most polluted city with over 9 percent of daily maximum ozone concentration exceeding the standard, followed by Houston with 2.2 percent. All other cities experienced less than 1 percent of the daily maximum ozone concentrations over 0.12 ppm. Table 3 shows the distribution of daily maximum ozone concentrations for the ten cities from 1980 to 2000.

Table 2. Number of ozone monitoring sites for each city.

City	Number of ozone monitoring sites
New York	6
Los Angeles	15
Chicago	7
Houston	9
Philadelphia	4
San Diego	2
Phoenix	5
Dallas	3
San Antonio	2
Denver	2

Since 1970, the CAA has brought many non-attainment cities for ozone into compliance by significantly reducing VOC and NO_x emissions from both stationary and mobile sources. Maximum one-hour ozone concentrations for those cities have been substantially reduced. In 1980, for example, Houston experienced 58 days exceeding the ozone standard of 0.12 ppm with the highest concentration reported at 0.34 ppm. In 2000, the city experienced only 14 day exceeding the standard with the highest concentration reported at 0.22 ppm. In 1980, New York experienced 21 days above 0.12 ppm with the highest concentration reported at 0.17 ppm, while in 1999, only 1 day exceeding the standard was reported with the highest concentration at 0.12 ppm.

However, data for the past 20 years show that annual average values of ozone concentration have not been lowered as much as maximum values. For some cities, annual averages have only fluctuated whereas maximum values have significantly decreased over time. The annual mean concentration for ozone in Houston in 1980 was measured at 0.038 ppm and at

Table 3. Distribution of daily maximum ozone concentrations from 1980 to 2000 (in %).

City	Ranges of ozone concentration in ppm						
	0-0.02	0.02-0.04	0.04-0.06	0.06-0.08	0.08-0.10	0.10-0.12	0.12+
New York	41.20%	30.00%	15.00%	7.58%	3.78%	1.76%	0.77%
Los Angeles	29.45%	24.94%	15.66%	9.84%	6.48%	4.50%	9.13%
Chicago	49.84%	30.65%	13.8%	4.33%	0.98%	0.28%	0.12%
Houston	39.65%	30.30%	14.90%	7.21%	3.71%	2.05%	2.18%
Philadelphia	41.54%	27.71%	16.70%	8.65%	3.65%	1.23%	0.52%
San Diego	13.50%	47.00%	26.50%	8.63%	2.66%	1.00%	0.75%
Phoenix	33.08%	17.57%	19.54%	16.57%	9.09%	3.22%	0.93%
Dallas	31.60%	34.43%	19.79%	9.37%	3.11%	1.16%	0.54%
San Antonio	33.41%	42.29%	16.64%	5.75%	1.54%	0.32%	0.05%
Denver	37.83%	36.07%	18.85%	5.64%	1.31%	0.24%	0.06%
Average	35.11%	32.09%	17.74%	8.36%	3.60%	1.58%	1.50%

Table 4. Trend of annual maximum and average ozone concentration from 1980 to 2000 for New York and Houston.

Year	New York			Houston		
	Annual maximum in ppm	Annual average in ppm	Number of days exceeding 0.12 ppm	Annual maximum in ppm	Annual average in ppm	Number of days exceeding 0.12 ppm
1980	0.17	0.035	21	0.34	0.038	58
1981	0.21	0.034	18	0.23	0.034	15
1982	0.18	0.030	9	0.28	0.036	27
1983	0.19	0.036	23	0.34	0.040	54
1984	0.22	0.032	12	0.25	0.046	22
1985	0.19	0.035	16	0.26	0.037	29
1986	0.27	0.034	6	0.19	0.035	15
1987	0.29	0.035	12	0.21	0.038	26
1988	0.28	0.036	24	0.23	0.038	20
1989	0.14	0.032	10	0.25	0.032	20
1990	0.18	0.031	11	0.24	0.035	25
1991	0.18	0.034	18	0.21	0.019	14
1992	0.13	0.026	3	0.23	0.032	9
1993	0.13	0.028	5	0.18	0.031	9
1994	0.14	0.031	7	0.19	0.032	9
1995	0.14	0.03	4	0.19	0.036	25
1996	0.14	0.032	4	0.18	0.034	14
1997	0.18	0.035	7	0.23	0.035	17
1998	0.14	0.033	2	0.23	0.036	14
1999	0.15	0.034	5	0.23	0.040	20
2000	0.12	0.028	1	0.22	0.035	14

Table 5. Correlation coefficients among ozone measures in Los Angeles.

	YR1HMAX	YR8HMAX	12PS	8AS	YR8HMEAN
YR1HMAX[1)]	1				
YR8HMAX[2)]	0.99	1			
12PS[3)]	0.87	0.87	1		
8AS[4)]	0.78	0.79	0.96	1	
YR8HMEAN[5)]	0.93	0.93	0.90	0.86	1

[1)]Annual peak of daily peak 1-hour ozone concentration in part per million (ppm).
[2)]Annual peak of daily 8-hour average ozone concentration (10:00 AM to 6:00 PM) in ppm.
[3)]Number of days exceeding daily peak 1-hour ozone concentration of 0.12 ppm per year.
[4)]Number of days exceeding daily 8-hour average ozone concentration of 0.08 ppm per year.
[5)]Annual average of daily 8-hour average ozone concentration in ppm.

0.035 ppm in 2000. It was 0.034 and 0.028 ppm in 1980 and 2000, respectively, in New York. Although excessively high ozone concentrations have been significantly reduced, people are still frequently exposed to moderate levels of ozone pollution.

We did not explore the reasons behind the persistent annual mean concentrations. However, we can think of one such reason. In the summer when ozone is excessively high (ozone action days), people and businesses are discouraged to produce ozone precursors. For example, use of public transportation are encouraged while lawn mowing and gas refueling are discouraged. This might contribute to reduce annual peak ozone concentrations, but wouldn't help to reduce annual average ozone concentration because people still need to mow the lawn and refill gas when such activities are not discouraged. Table 4 details annual maximum and average ozone concentrations along with number of days exceeding the federal ozone standard of 0.12 ppm from 1980 to 2000 for Houston and New York.

Different ozone measures show different correlation with each other and the results vary across cities considered in this study. Table 5 shows the correlation coefficients among ozone measures from 1980 to 2000 in Los Angeles, and Table 6 shows those for Phoenix. The ozone measures in Los Angeles show strong correlation with each other, while weak correlation are

Table 6. Correlation coefficients among ozone measures in Phoenix.

	YR1HMAX	YR8HMAX	12PS	8AS	YR8HMEAN
YR1HMAX[1)]	1				
YR8HMAX[2)]	0.59	1			
12PS[3)]	0.86	0.42	1		
8AS[4)]	0.54	0.55	0.66	1	
YR8HMEAN[5)]	0.21	0.19	−0.05	0.005	1

[1)]Annual peak of daily peak 1-hour ozone concentration in part per million (ppm).
[2)]Annual peak of daily 8-hour average ozone concentration (10:00 AM to 6:00 PM) in ppm.
[3)]Number of days exceeding daily peak 1-hour ozone concentration of 0.12 ppm per year.
[4)]Number of days exceeding daily 8-hour average ozone concentration of 0.08 ppm per year.
[5)]Annual average of daily 8-hour average ozone concentration in ppm.

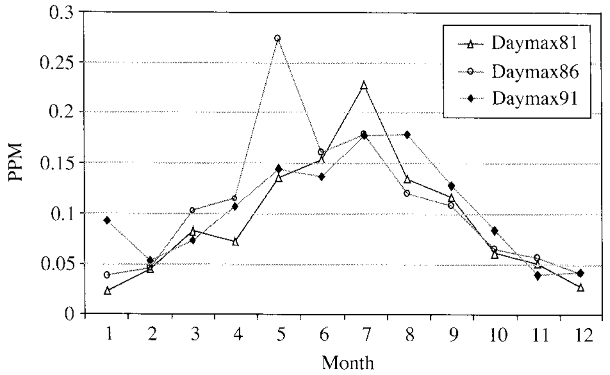

Fig. 1. Monthly ozone variation in New York.

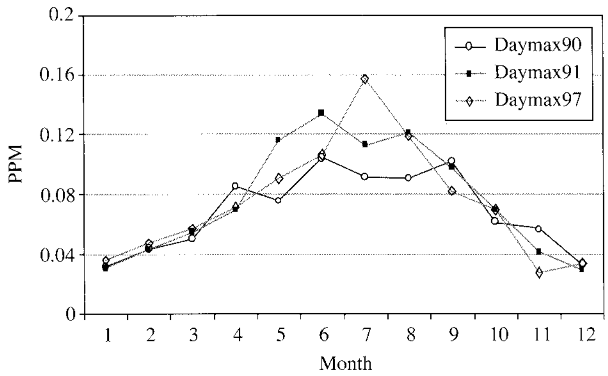

Fig. 2. Monthly ozone variation in Chicago.

displayed in Phoenix. In fact, cumulative measures (12PS and 8AS) and average measure (YR8HMEAN) in Phoenix show no correlation to each other. It also shows weak correlation between two peak measures (YR1HMAX and YR8HMAX) and average measure (YR8HMEAN). This implies that the selection of a measure to estimate ozone's effects on human health might make a difference in Phoenix. For the other cities, correlation among ozone measures were positive, but ranged from strong to weak.

Each city has a unique pattern of the distribution of ozone concentrations within a year. Different years with the same annual average ozone concentration can show very different distributions of ozone concentrations within a year. Fig. 1 shows monthly variations of peak ozone concentrations for the years 1981, 1986, and 1991 in New York, and Fig. 2 shows those for years 1987, 1993, and 1997 for Chicago. Although annual average ozone concentrations were the same at 0.034 ppm for all these years in both cities, the distribution of monthly peak ozone concentrations within each year displays significantly different variations year to year and also between the two cities. The studies based on annual summary measures to relate ozone pollution to human health would necessarily ignore the different variation of ozone pollution within a year, which might bias the estimated effects of ozone pollution on human health.

Ozone measures also show a wide margin of variability as they are estimated from different ozone monitoring sites within each city. Table 7 shows annual ozone measures for YR1HMAX, YR8HMAX, 12PS, and 8AS and their reported ranges from all monitoring sites within each city for the year of 1980 and 2000. In general, as levels of ozone concentrations are high and there are more monitoring sites, the variation of ozone concentration within a city becomes larger. Individuals can be exposed to very different levels of ozone concentrations depending on where they are located within a city. A citywide average ozone concentration can not be an appropriate measure to estimate an association between ozone pollution and individual human health when there is a wide variation of ozone concentration within a city.

Fig. 3 shows the measures 8AS and 12PS from 1980 to 2000 in Philadelphia. 8AS shows a strong positive correlation with 12PS. Almost all days over one-hour daily maximum of 0.12 ppm (12PS) also exceeded an eight-hour daily maximum of 0.08 ppm (8AS), but not vise versa. The strong correlation between 12PS

Table 7. Variation of ozone concentrations among monitors within a city.

	1980				2000			
	YR1HMAX (in ppm)	YR8HMAX (in ppm)	12PS (# of days)	8AS (# of days)	YR1HMAX (in ppm)	YR8HMAX (in ppm)	12PS (# of days)	8AS (# of days)
New York	0.174-0.174 (0.17)*	0.138-0.120 (0.129)	21-12 (15)	22-17 (18.7)	0.098-0.123 (0.110)	0.114-0.090 (0.100)	1-0 (0.5)	10-1 (6.25)
Los Angeles	0.490-0.170 (0.325)	0.337-0.09 (0.198)	131-8 (79)	129-3 (72)	0.174-0.089 (0.134)	0.139-0.061 (0.10)	13-0 (5.6)	30-1 (11)
Chicago	0.129-0.107 (0.118)	0.103-0.081 (0.092)	1-0 (0.5)	3-1 (2)	0.104-0.074 (0.088)	0.082-0.045 (0.07)	0-0 (0)	1-1 (1)
Houston	0.340-0.260 (0.287)	0.20-0.138 (0.166)	58-16 (30.5)	64-16 (34)	0.255-0.160 (0.192)	0.138-0.101 (0.112)	14-6 (9)	16-7 (12)
Philadelphia	0.180-0.160 (0.170)	0.132-0.117 (0.125)	26-1 (15)	50-1 (26)	0.128-0.101 (0.118)	0.108-0.081 (0.099)	1-0 (0.5)	5-1 (3)
San Diego	0.180-0.140 (0.160)	0.107-0.099 (0.103)	21-10 (16)	20-11 (16)	0.118-0.118 (0.118)	0.082-0.071 (0.076)	0-0 (0)	2-2 (2)
Phoenix	0.174-0.124 (0.153)	0.098-0.089 (0.094)	10-1 (6.5)	15-2 (7.25)	0.108-0.094 (0.1)	0.085-0.081 (0.082)	0-0 (0)	5-1 (2.7)
Dallas	0.180-0.120 (0.15)	0.120-0.08 (0.10)	20-1 (10.5)	41-1 (21)	0.128-0.119 (0.124)	0.1-0.096 (0.098)	6-0 (3)	23-4 (13.5)
San Antonio	0.12-0.11 (0.115)	0.108-0.093 (0.101)	5-0 (2.5)	8-5 (6.5)	0.108-0.096 (0.102)	0.09-0.086 (0.088)	0-0 (0)	2-1 (1.5)
Denver	0.165-0.151 (0.158)	0.132-0.094 (0.113)	3-1 (2)	4-1 (2.5)	0.098-0.098 (0.098)	0.075-0.075 (0.075)	0-0 (0)	0-0 (0)

*Numbers in parenthesis are average values.

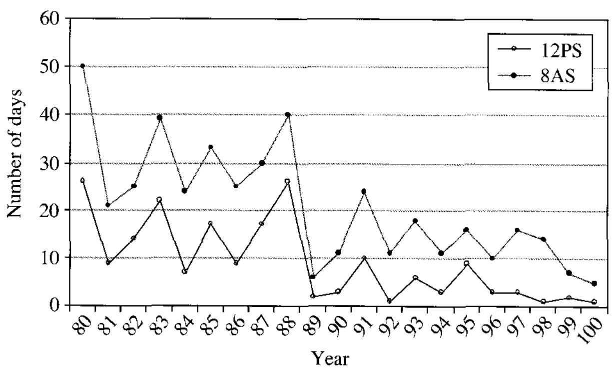

Fig. 3. Trend of cumulative measures of ozone (12PS and 8AS) in Philadelphia.

and 8AS applies to all the cities considered in this study. Therefore, EPA's new supplemental ozone standard of 0.08 ppm averaged over an eight-hour appears to be a stricter standard than the maximum ozone standard of 0.12 ppm over one-hour.

4. CONCLUSION

This study analyzed how ozone pollution could be measured in different ways and how these measures varied year to year and across the top ten most populated cities in the United States from 1980 to 2000. Ozone pollution data for each city has a unique pattern of distribution, central tendency, and also there is a wide variation among ozone measures. Estimating a statistical association between ozone pollution and individual human health can therefore largely depends on what ozone measures are used. It can be further complicated by the fact that individuals are traveling across regions within a city, where ozone concentration can be significantly different.

This study is, however, limited in fully analyzing variations of ozone pollution across cities and over time. We chose to delete all missing observations in calculating values of the ozone measures in this study. Different interpolation methods to fill the missing observations might produce different values for the same ozone measures. Therefore, it is likely that the results of this study are biased; however, the magnitude of bias cannot be measured accurately.

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(Received 4 May 2008, accepted 10 July 2008)