Trend Analyses

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Is ozone air quality improving and are improvements likely to be in response to the implemented emissions control program?

Overview of Trend Analysis

- **Rationale for assessing trends.** One of the PAMS data analysis objectives is to provide data to access trends in ozone and precursor data over time and reconcile these data with trends in precursor emissions.
- **Indicator selection is important.** Trends in extreme values in a data set may differ significantly from trends observed in a statistic that describes the bulk of the data.
- **Understanding the data uncertainties is necessary.** Uncertainties could obscure our ability to discern air quality trends.
- **Changes in meteorology can obscure trends.** Meteorology, which can significantly affect air quality, can vary among years.
- **Discerning trends can be tricky.**

Trend Analysis Procedure

- Beginning with validated data, select indicators (summary statistics) such as mean, median, maximum, minimum, selected percentiles, etc.
- Select an appropriate time period to investigate (e.g., season, episode, annual, etc.).
- Adjust indicators to remove meteorological influences.
- Apply statistical procedures for detecting trends.
- Evaluate the trend for direction, rate of change, etc.

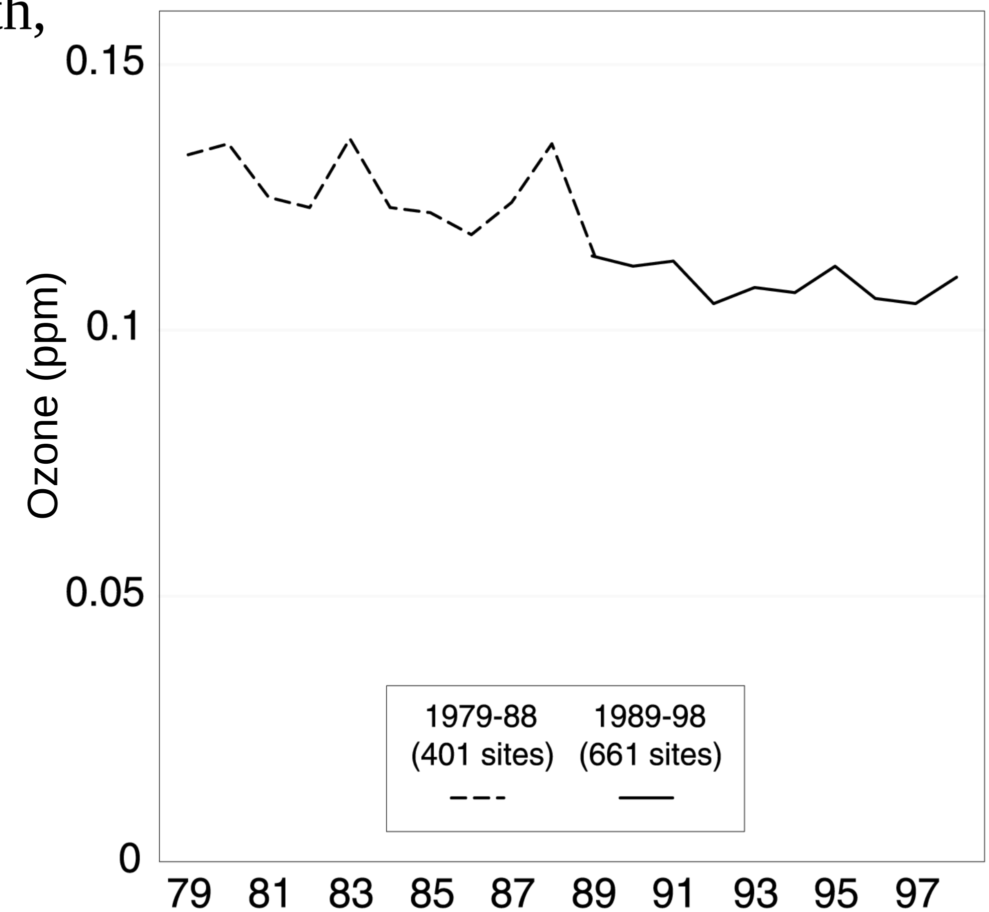
Consensus among trends in indicators gives the analyst more confidence in the results.

Example Indicators (1 of 9)

Ozone

- Percentile of daily maximum 1-hr concentration (i.e., 99th, 95th, 90th)
- Second highest daily 1-hr maximum
- Fourth highest daily 8-hr maximum
- Seasonal mean or median of daily maxima
- Number of annual exceedance days or hours
- Average of highest 30 maximum daily concentrations

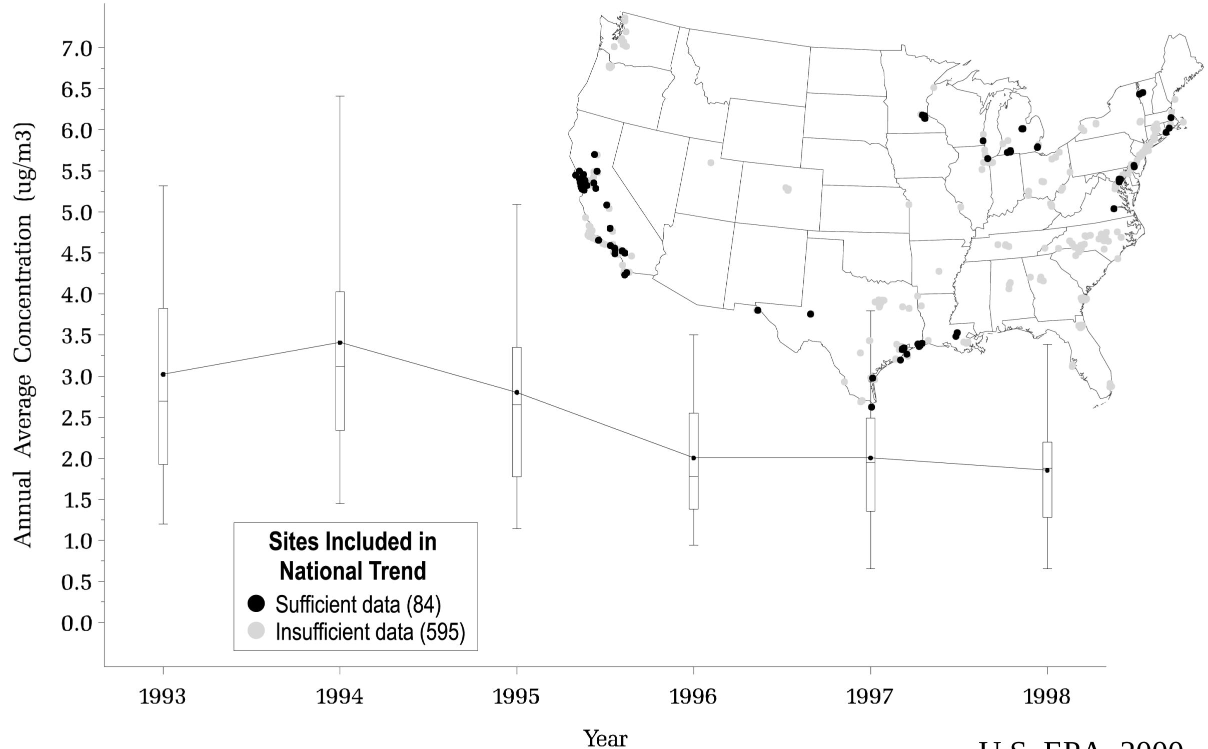
Trend in annual second highest daily maximum 1-hr ozone concentrations, 1979-1998.



U.S. EPA, 2000

Example Indicators (2 of 9)

National trend in annual average benzene concentrations in metropolitan areas, 1993-1998

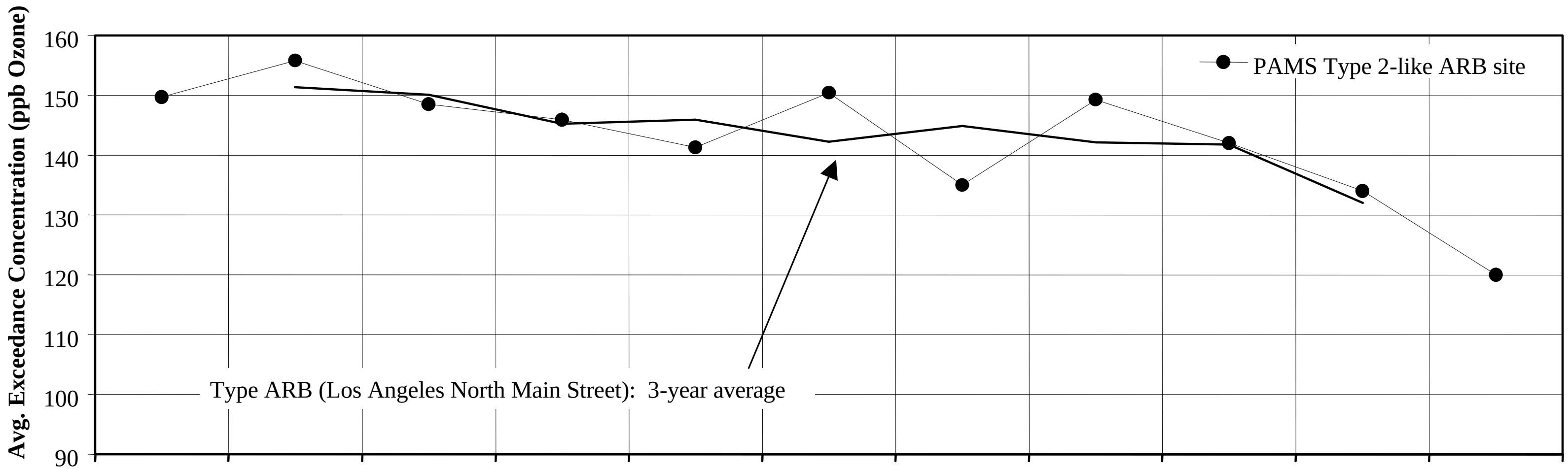


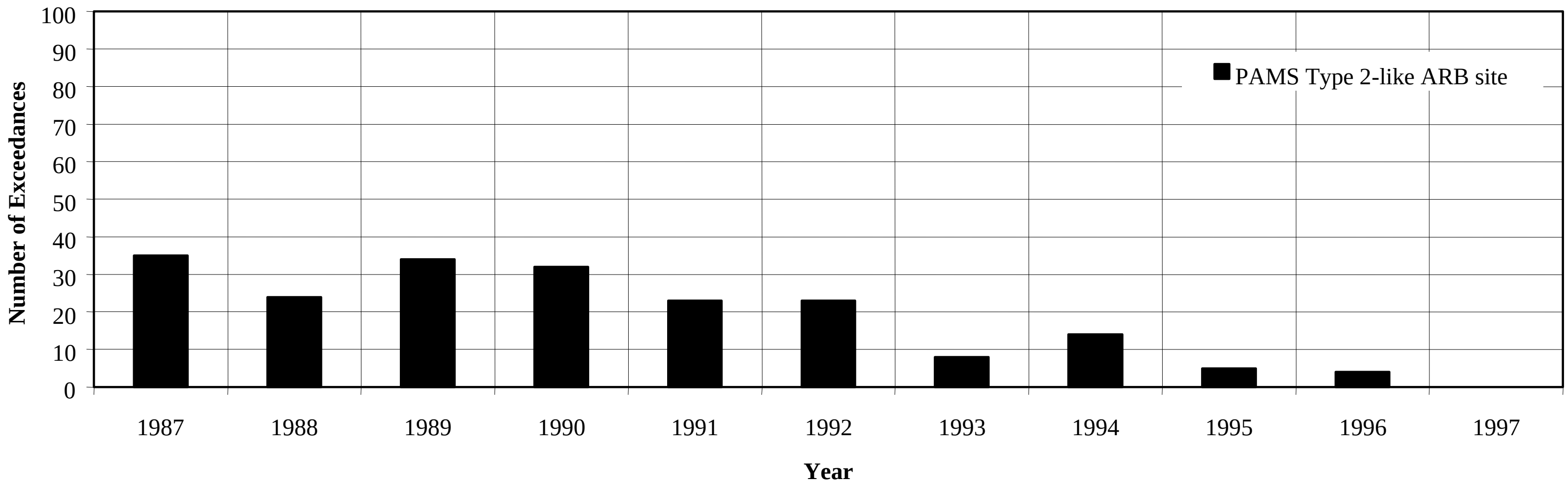
U.S. EPA, 2000

Hydrocarbons

- Mean 6 a.m.-9 a.m. total NMHC concentrations
- Mean 6 a.m.-9 a.m. individual chemical species concentrations or species ratios
- Annual average concentration

Example Indicators (3 of 9)

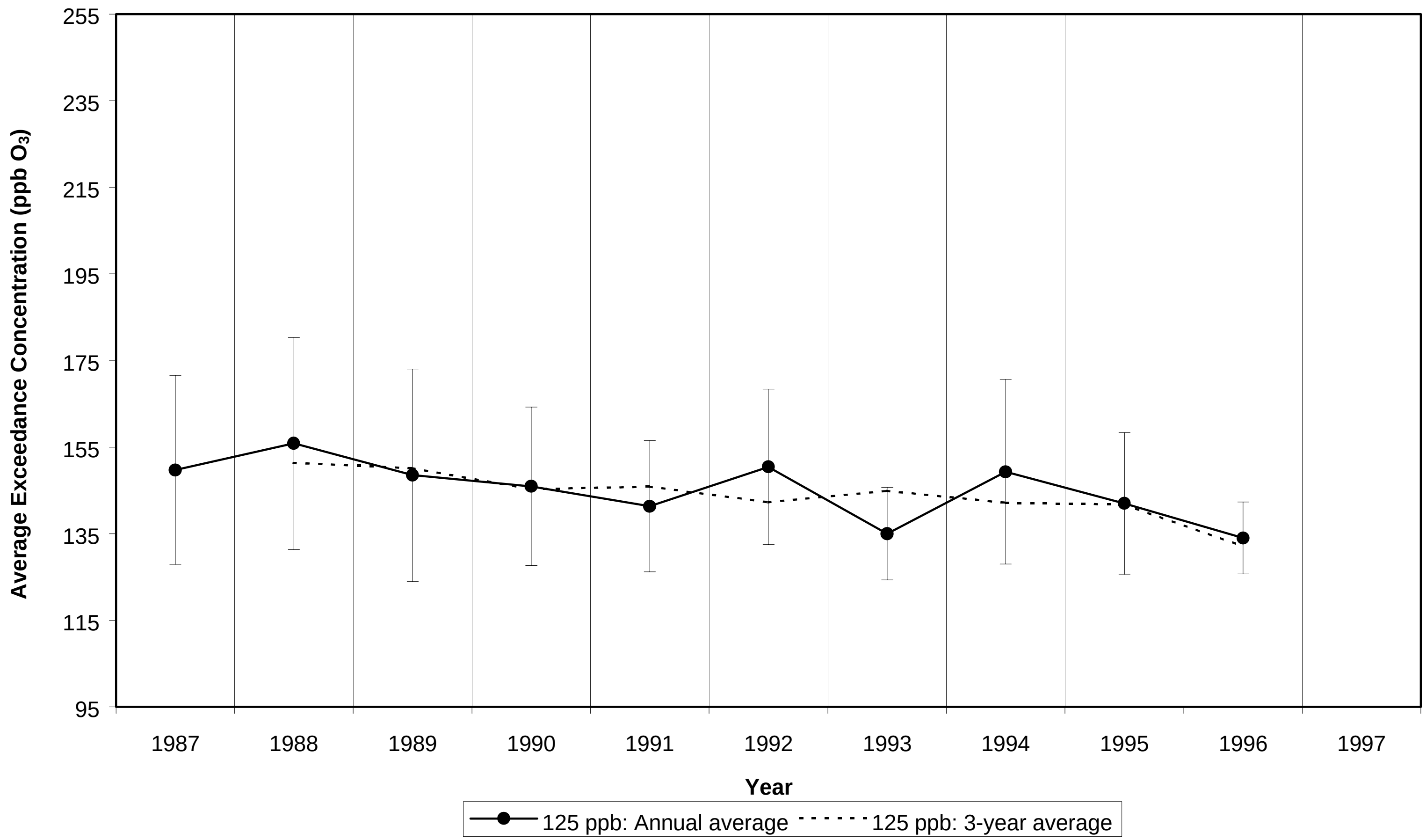




Average exceedance concentration by year and as a 3-yr running average (top) and number of exceedances of the 1-hr Ozone NAAQS at the Los Angeles North Main Street site. Three-year averages were determined using the highest non-exceedance concentrations in 1997 (the year in which the 1-hr Ozone NAAQS threshold concentration was not reached) (Wittig et al., 1999).

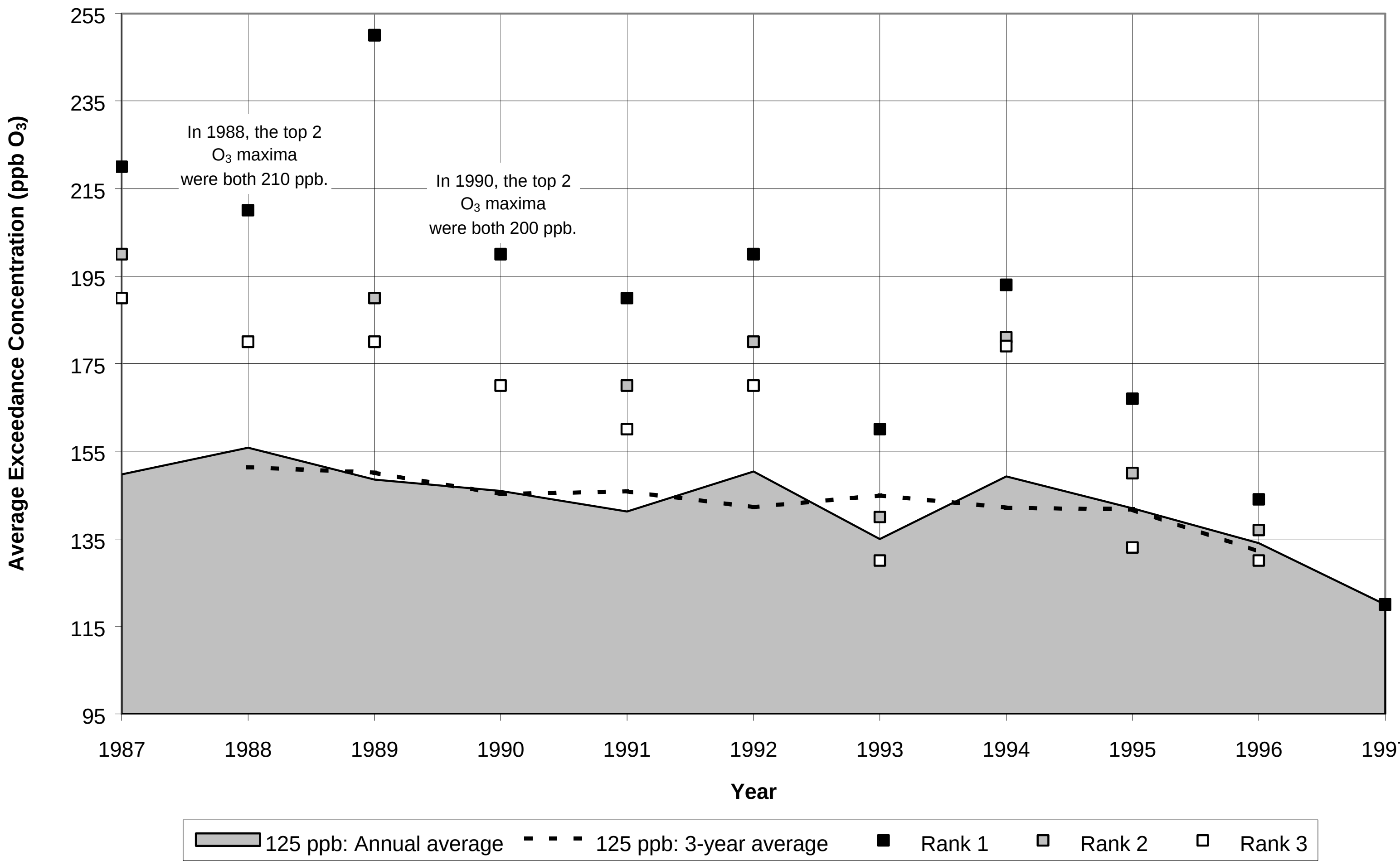
The ozone concentrations using these metrics show a decline since the late 1980's.

Example Indicators (4 of 9)



Exceedances of the 1-hr Ozone NAAQS with analysis uncertainty for the Los Angeles North Main Street site. Three-year averages were determined using the highest non-exceedance ozone concentrations in 1997 (year in which the 1-hr Ozone NAAQS threshold concentration was not reached). Error bars indicate the analysis uncertainty on the average ozone concentrations (Wittig et al., 1999). Taking this metric and the uncertainty into account, it is harder to discern a trend.

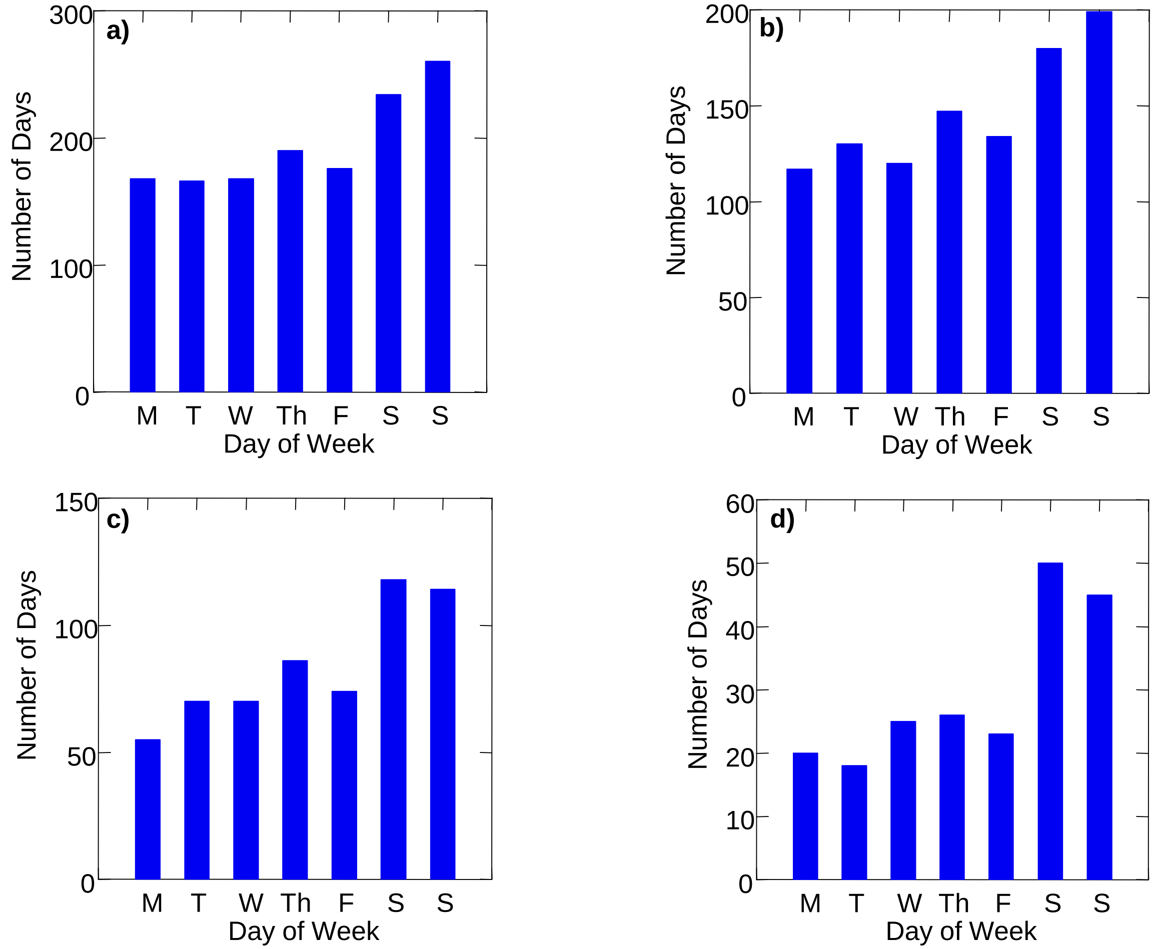
Example Indicators (5 of 9)



Identification of the highest exceedance concentrations of the 1-hr Ozone NAAQS for the Los Angeles North Main Street site. Three-year averages were determined using the highest non-exceedance concentrations in 1997 (a year in which the 1-hr Ozone NAAQS threshold concentration was not reached) (Wittig et al., 1999).

The three highest peak daily values show a decline over this period.

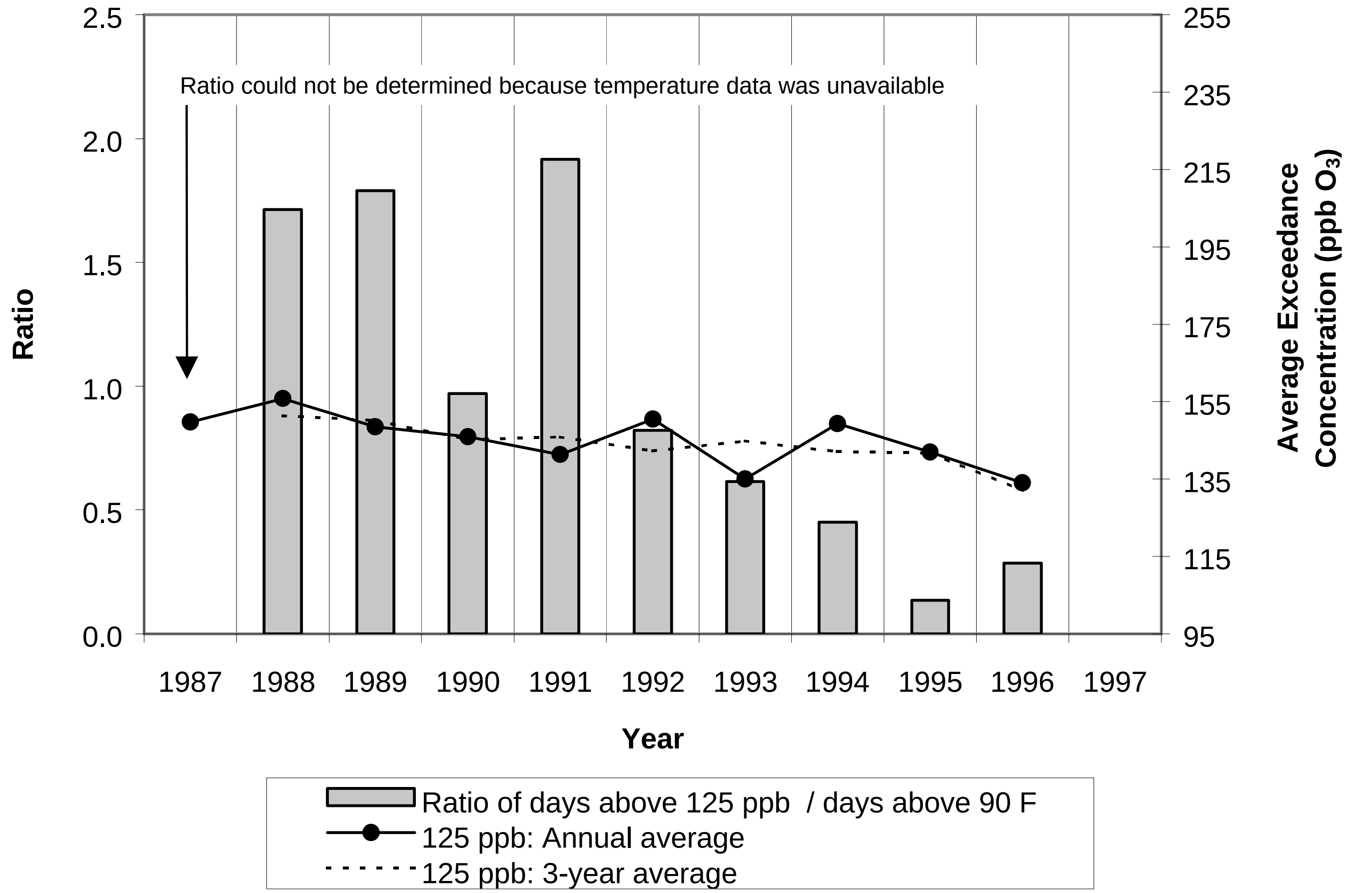
Example Indicators (6 of 9)



Number of days above a threshold ozone concentration by day of week for the Los Angeles North Main Street site from 1987 to 1997: a) above 70 ppb, b) above 80 ppb, c) above 95 ppb California Standard), and d) above 125 ppb (1-hr NAAQS) (Wittig et al., 1999).

More exceedances appear to occur on the weekend than on weekdays at all thresholds.

Example Indicators (7 of 9)

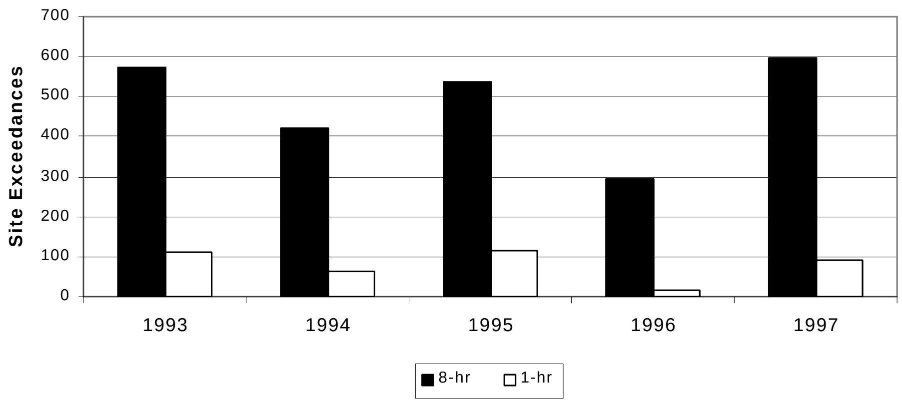


Number and ratio of the exceedances of the 1-hr Ozone NAAQS by meteorology for the Los Angeles North Main Street site. Three-year averages were determined using the highest non-exceedance concentrations in 1997 (a year in which the 1-hr Ozone NAAQS threshold concentration was not reached) (Wittig et al., 1999).

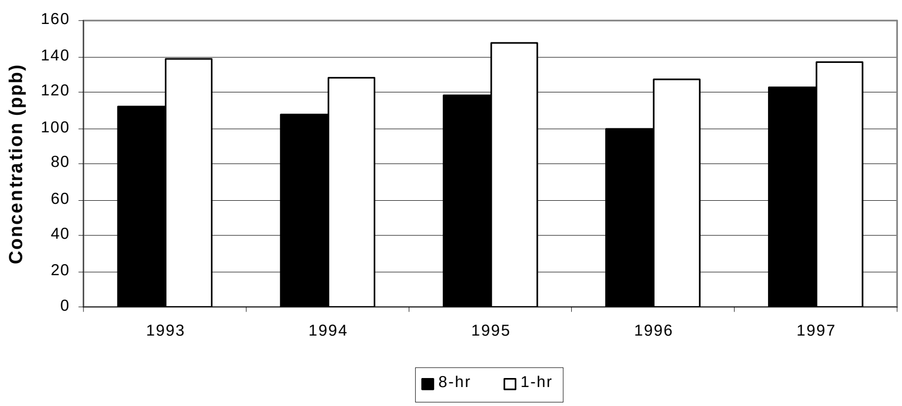
Using days above 90°F as an indicator of meteorological effects on ozone, the ratio of days above 125 ppb to days above 90°F also shows a decline over the period.

Example Indicators
(8 of 9)

(a)



(b)

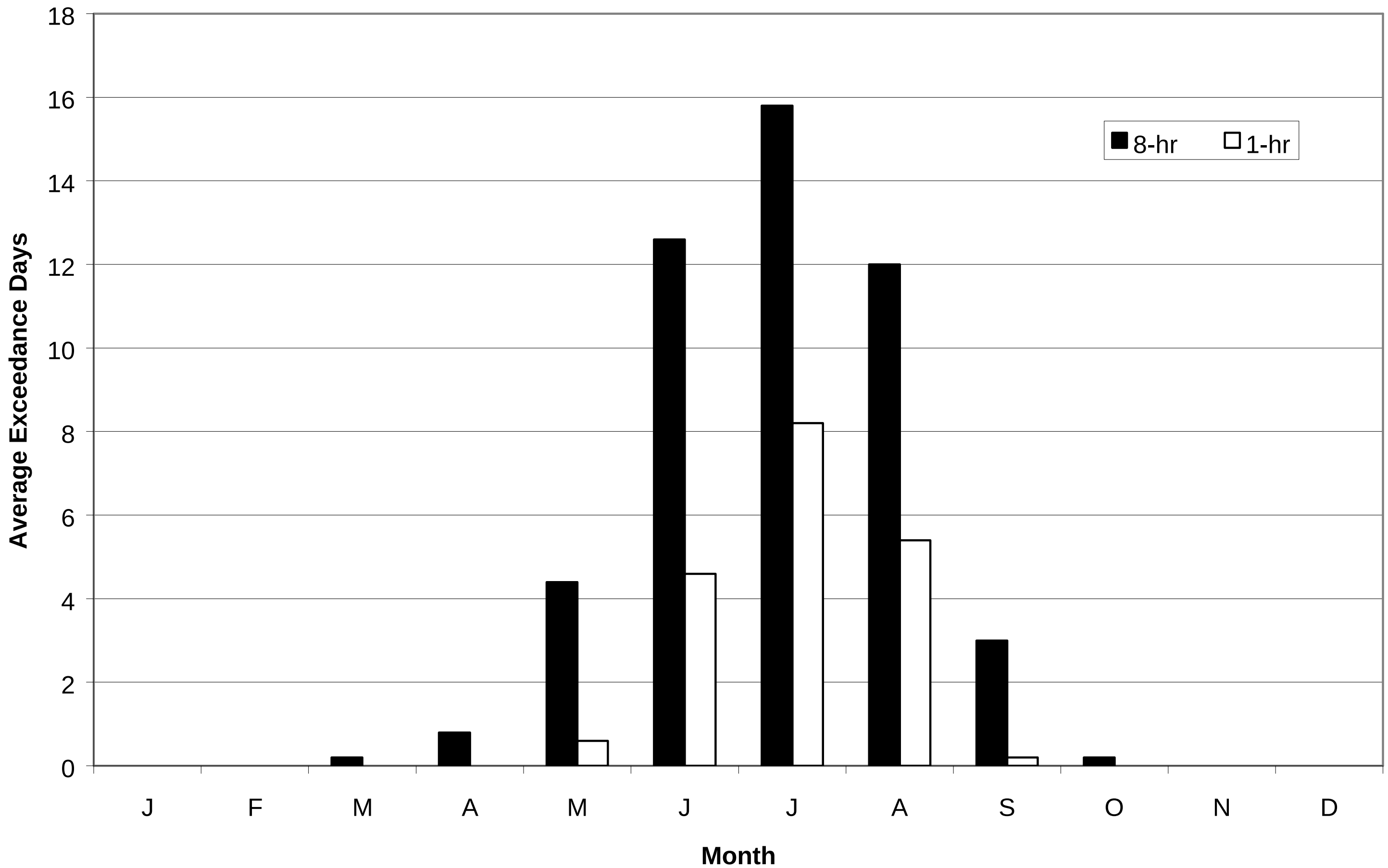


(c)

Total number of (a) exceedance days, (b) site exceedances, and (c) highest 4th-highest concentration for the NESCAUM region for the 8-hr and 1-hr ozone standards (1993-1997) (Dye et al., 1998).

There is an apparent downward trend in the number of 8-hr ozone exceedance days in the region. Compared to the number of 1-hr exceedance days, the number of 8-hr exceedance days is less valuable from year to year. Generally, the number of 8-hr days is two to three times higher than the number of 1-hr exceedance days.

Example Indicators (9 of 9)



Seasonal distribution of the average number of exceedance days by month for the 8-hr and 1-hr ozone standards for the NESCAUM region from 1993 to 1997 (Dye et al., 1998).

Whereas nearly all the 1-hr exceedance days occur in June, July, and August, a significant portion of 8-hr exceedance days occur in May and September, with a few more in March, April, and October. Also, twice as many 8-hr exceedance days occur in July than 1-hr exceedance days, but three times as many occur in June and August.

Assessing Uncertainties in Trend Analyses

- Uncertainties impact one's ability to clearly discern air quality trends in an analysis.
- Uncertainties that affect trends in air quality are:
  - **Atmospheric variability** associated with short-term fluctuations in meteorological conditions and source emissions.
  - **Meteorological variability** associated with synoptic seasonal cycles.
  - **Measurement uncertainty** associated with instrument accuracy and precision.
  - **Analysis uncertainty** associated with trend indicator interpretation.
- Methods exist to account or adjust for variations in meteorology.

Wittig et al., 1999

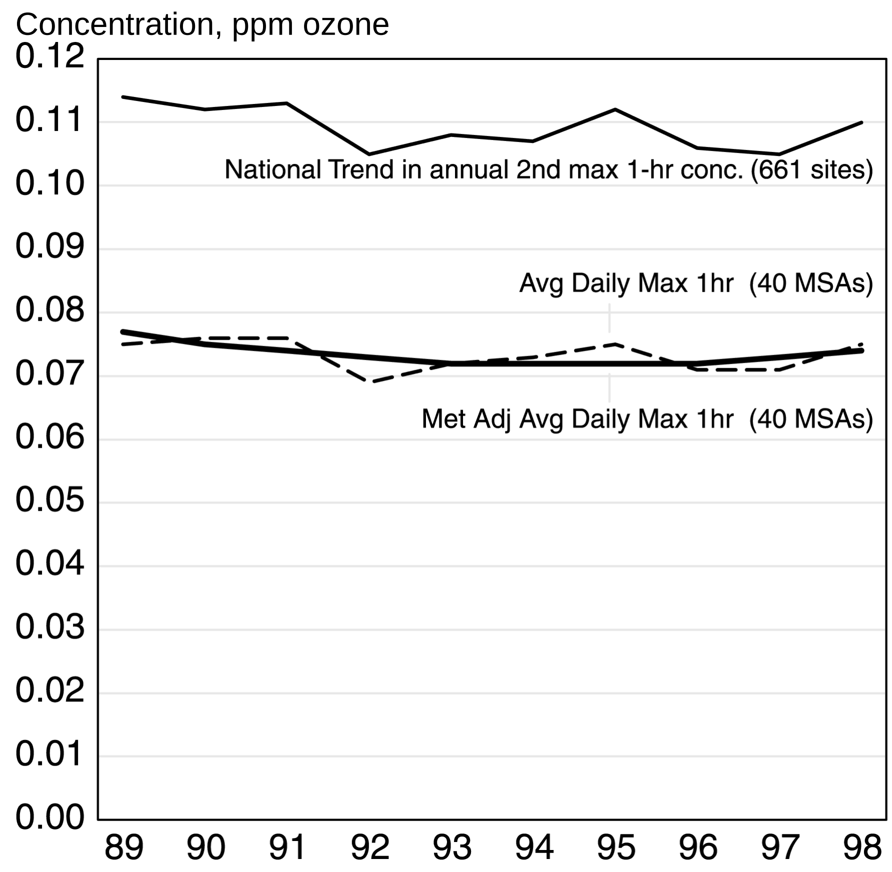
Adjusting for Meteorological Variability (1 of 2)

Meteorological conditions may have a confounding influence on air quality, which could obscure underlying trends. For example, techniques to adjust ozone statistics for the effects of meteorological variability include:

- Classification of days on the basis of meteorological conditions into categories that define their ozone formation potential, examine classified data for trends.
- Development of mathematical relationships between ozone concentration and meteorological factors, use the relationship to predict ozone concentrations expected to occur under standardized meteorological conditions, examine "adjusted" concentrations for trends.
- Development of statistical methods of filtering out effects of meteorology from ozone concentration data, examine modified ozone data for trends.

Adjusting for Meteorological Variability (2 of 2)

- Adjustment techniques involve some processing of the PAMS measurements to remove the influence of particular events or conditions from the data prior to any trends analysis.
- Adjustment techniques are compared in the following tables so that an analyst can decide which methods are the most reasonable to consider depending upon the data available.
- The figure here illustrates some of the meteorological parameters that have an effect on ozone concentrations. One of the next steps is whether or not these parameters show a significant interannual impact.



U.S. EPA, 2000

Adjustment Techniques (1 of 3)

Method	Pros	Cons	Data Requirements
Expected peak day concentration (EPDC) (California Air Resources Board, 1993)	• Accounts for variability in the measurements.	• Does not explicitly account for meteorology. • Ignores the highest concentration days. • Requires daily observations over an entire year.	• Special software. • Daily maximum concentration measurements for three consecutive years.
Native variability (California Air Resources Board, 1993)	• Accounts for variability in the measurements. • Estimates the uncertainty in a parameter that is used to assess trends using a different approach than a measurement uncertainty or an average standard deviation. • Uses any parameter that is measured on a daily basis.	• Does not explicitly account for meteorology. • Ignores the highest days. • To develop trending conclusions using this technique, the user must assume that emissions do not change over a running 3-yr period of time. • Requires daily observations over an entire year.	• Special software. • Daily maximum concentration measurements for three consecutive years.
Meteorological adjustment using a filtering technique (Rao and Zurbenko, 1994; Rao et al., 1995; Zurbenko et al., 1995; Anh et al., 1997; Flaum et al., 1996; Milanchus et al., 1997; 1998; Porter, 1996)	• A meteorological adjustment technique. • Is intended to be used as a predictive tool. • Separates the concentrations into different time scales to discern trends in the concentrations that are due to emissions changes.	• To develop trending conclusions, the user must assume that concentrations that are not affected by meteorologically anomalous events can be fit to a periodic function. • Numerically intensive. • Most current versions of this technique use parameters that are not commonly measured and require some parameters to be modeled. • Currently applied only to ozone.	• Special software. • Daily maximum concentration and daily maximum temperature measurements. • Daily maximum concentration and daily maximum temperature, dew point temperature and depression, specific humidity, wind speed, opaque cloud cover, ceiling height, and solar radiation measurements at most.

Wittig et al., 1999

Adjustment Techniques (2 of 3)

Method	Pros	Cons	Data Requirements
Meteorological adjustment using a probability distribution technique (Cox and Chu, 1998)	• A meteorological adjustment technique. • Is intended to be used as a predictive tool.	• To develop trending conclusions using this technique, the user must assume that concentrations that are not affected by meteorologically anomalous events can be fit to a Weibull distribution. • Problem establishing a baseline – uses average parameters to define the base case. • Numerically intensive.	• Special software. • Daily maximum concentration and daily maximum surface temperature at minimum. • Daily maximum concentration and daily maximum surface temperature, relative humidity, wind speed and wind direction measurements at most.
Transported ozone estimation by analysis of wind speed and wind direction against measured ozone (Husar and Renard, 1997)	• Accounts for meteorology. • Considers a regional approach to ozone formation. • Does not fit ozone measurements to an equation.	• Not a meteorological adjustment technique. • Uses meteorological parameters that require substantial classification. • Uses parameters that are not available over a long enough period at the sites of interest.	• Daily maximum ozone concentration, daily wind speed and wind direction measurements.
CART (Classification and Regression Tree) analysis of ozone concentrations against numerous meteorological conditions (Stoeckenius, 1990; Deuel and Douglas, 1996)	• Accounts for meteorology. • Does not fit measurements to an equation.	• Not a meteorological adjustment technique. • Uses meteorological parameters that require substantial classification. • Numerically intensive. • Uses parameters that are not available over a long enough period at the sites of interest.	• Special software. • Daily maximum concentration, daily maximum surface temperature, number of daylight hours, ceiling height, surface pressure, rainfall, relative humidity, wind speed, and wind direction measurements.

Wittig et al., 1999

Adjustment Techniques (3 of 3)

Method	Pros	Cons	Data Requirements
Linear regression of ozone against meteorological parameters (Davidson, 1993; Zeldin et al., 1990; Cohanim et al., 1998)	• Accounts for meteorology. • Not numerically intensive.	• Not a meteorological adjustment technique. • Fits the overall nonlinear process of transport and reaction to a linear function. • No real insight or physical meaning of coefficients. • Can use meteorological parameters that are not widely measured.	• Daily maximum concentrations and daily T850 at minimum. • Daily maximum concentrations and inversion parameters, synoptic parameters, surface pressure gradients, and T850 measurements at most.
Nonlinear regression of ozone against meteorological parameters (Bloomfield et al., 1996; Holland et al., 1999)	• Accounts for meteorology. • Fits a nonlinear process to a nonlinear function. • Not numerically intensive.	• Not a meteorological adjustment technique. • No real insight or physical meaning of coefficients. • Uses parameters that are not available over a long enough period at the sites of interest. • Can use meteorological parameters that are not widely measured.	• Daily maximum concentrations and daily temperature, relative humidity, wind speed measurements.

Wittig et al., 1999

Meteorological Variables Potentially Associated With Ozone Formation

- **Insolation:** Sky cover, integrated clear or cloudy sky photolysis rate, ceiling height, number of daylight hours
- **Ventilation:** Vector and scalar average wind speeds, wind fluctuation ratio (ratio of scalar to vector average wind speed), mixing height, ventilation coefficient (mixing height times wind speed)
- **Transport:** Wind direction, recirculation index
- **Indirect Measures:** Previous day's daily maximum ozone concentration, temperature (daily maximum, range), humidity indicators, surface pressure and range, precipitation, temperature at 500 and 850 mb, synoptic weather pattern type

Classification Methods

High ozone is likely to occur with wind patterns that bring, keep, or return high background concentrations to the region; elevated temperature; intense solar radiation (i.e., no cloud cover); and shallow mixing depth. VOC concentrations are most affected by wind speed, wind direction when there is inhomogeneity in the spatial distribution of sources, and temperature (e.g., for isoprene). Examples include:

- Number of days ozone exceedances/number of ozone-conducive days (e.g., ozone-conducive days defined as temperature in excess of 90°F).
- Classify days by high, moderate, low ozone formation potential and calculate year-to-year trend on number of days in each category.
- Group years according to frequency of occurrence of ozone-conducive days and calculate trend in annual summary statistics only for years with similar numbers.

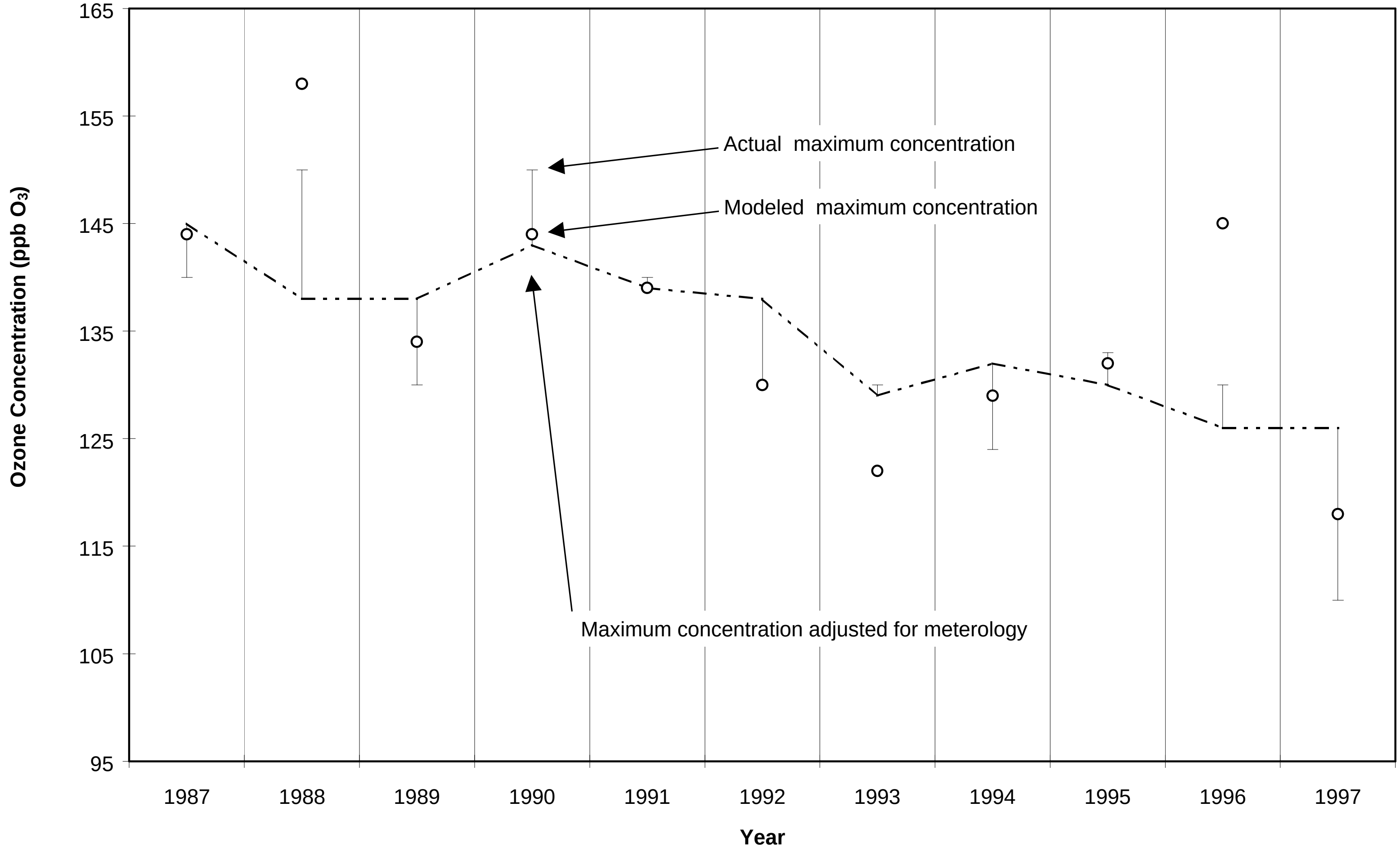
EPA Meteorological Trend Adjustment Method
(Cox and Chu Trend Analysis Method)

The Cox and Chu Method is a regression model that can be used to predict the probability distribution of daily maximum ozone concentrations in a metropolitan area given the values of several meteorological parameters including:

- Surface temperature
- Average 0700-0900 wind speed
- Average 1300-1600 wind speed
- Average morning wind direction
- Average afternoon wind direction
- Total opaque cloud cover
- Relative humidity

The model includes a term to account for the long-term trends in ozone air quality.

Example Cox and Chu Adjustment



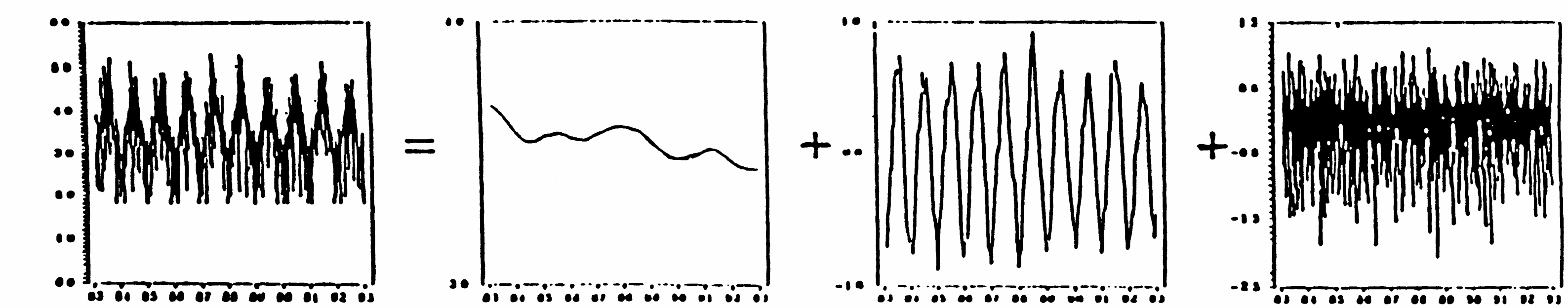
Meteorology adjustment of the maximum ozone concentrations using the Cox and Chu probability distribution techniques for a site in the Sacramento, CA MSA (Wittig et al., 1999).

The plot shows the actual measured concentration, the modeled maximum concentration, and the maximum concentration adjusted for meteorology. Note the large upward adjustment for meteorology in 1997. In spite of the adjustments, ozone concentrations appear to be declining since 1987.

Rao and Zurbenko Trend Analysis Method (1 of 2)

- The Rao and Zurbenko method is a statistical method of moderating the influence of meteorology on surface ozone concentrations.
- Surface temperature is used as a surrogate for all meteorological parameters assumed to affect ozone.
- This method assumes that peak daily ozone concentrations mostly reflect the quasi-periodic behavior in certain meteorological variables on time scales ranging from several days (short-term) to seasonal (annual) to several years (long-term).

Rao and Zurbenko Trend Analysis Method (2 of 2)



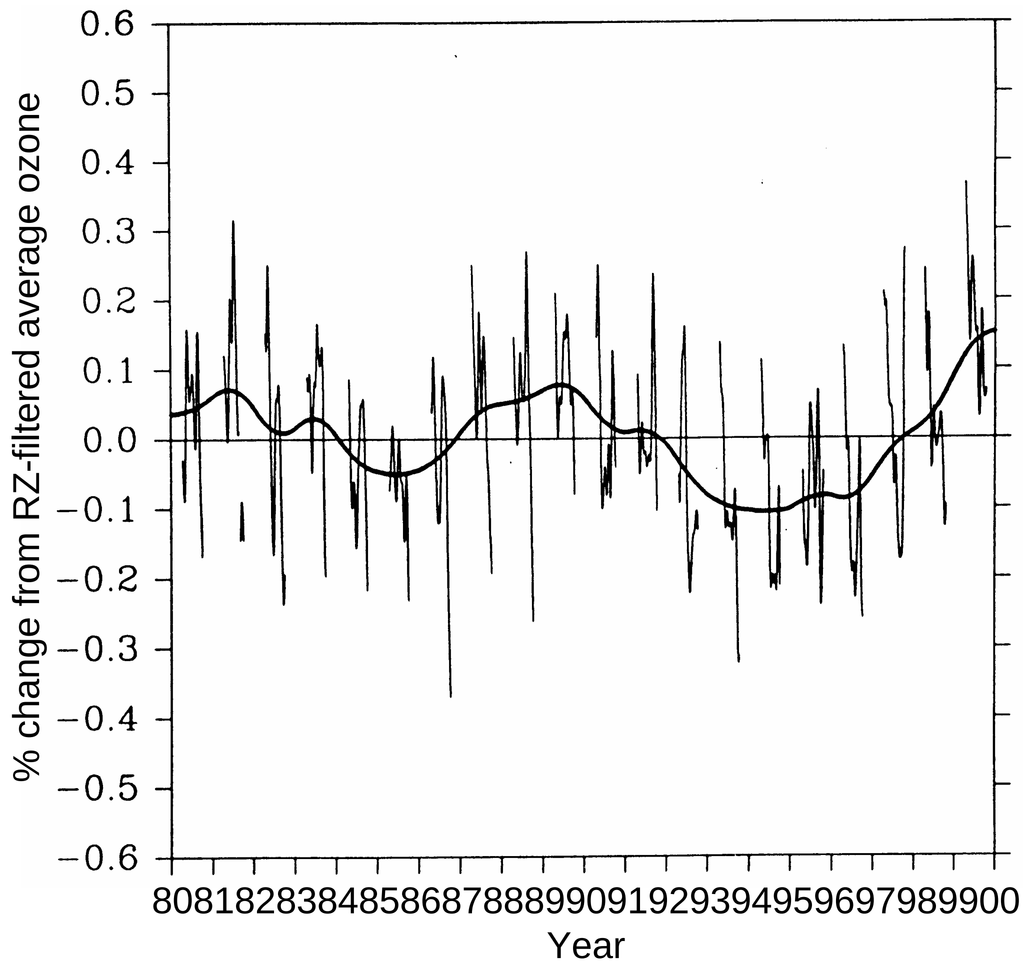
Original time series = Long-term (multi-year) + Seasonal (annual) + Short-term (1-several days)

- In the mid-latitudes, temporal cycles in the weather from synoptic (daily to a week) to seasonal (annual) dominate the contributions to peak daily 1-hr ozone levels.
- Changes in ozone levels due to changes in local ozone precursor emissions (long-term) can be quite small relative to meteorological influences.
- A moving average filter called the Kolmogorov-Zurbenko (KZ) filter is used to separate data spectra into short-term (synoptic) to seasonal (annual) to long-term (several years) process cycle.

Adamski, 2000

Example Rao and Zurbenko Trend

- This example shows a temperature-adjusted ozone time series of peak daily 8-hr ozone at Racine, WI, for the period 1980-1999.
- 8-hr ozone concentrations adjusted for temperature do not show an obvious sustained up or down trend.



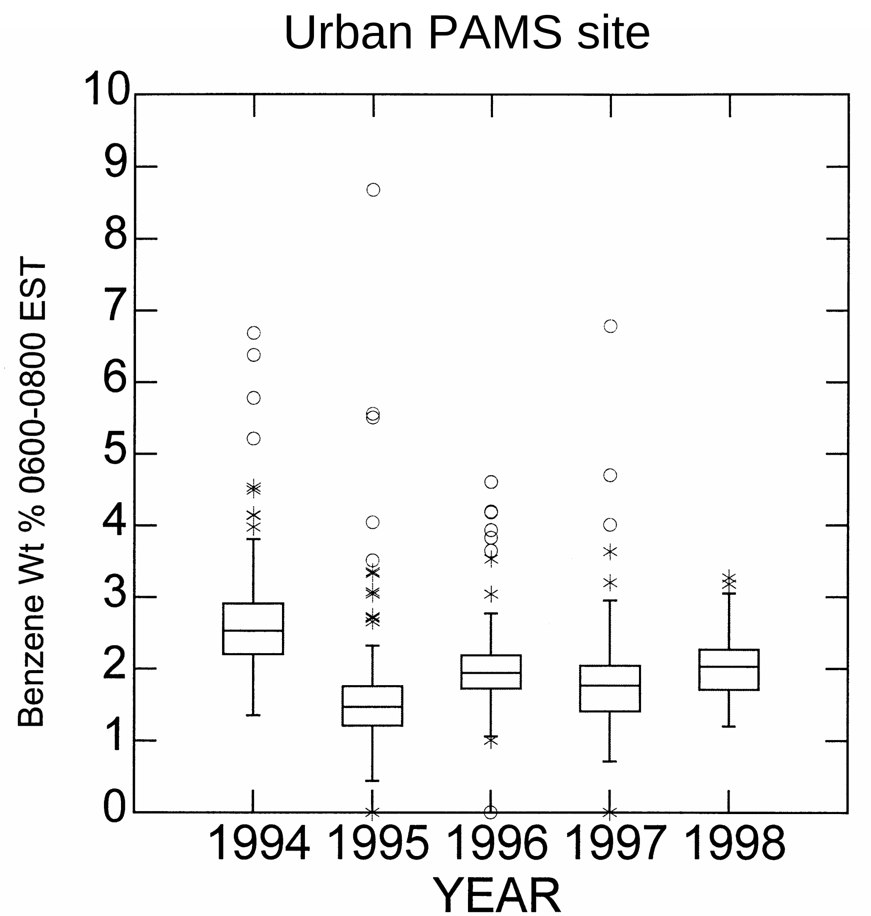
Adamski, 2000

Detecting Trends

- **Linear Model:** Use simple linear regression on annual summary statistics or to logged statistics (if lognormal); perform analysis of variance.
- **Nonparametric Methods:** To test for and estimate a trend without making distributional assumptions (e.g., Spearman's rho test of trend, Kendall's tau test of trend).
- **Time Series Models: S**tatistical modeling of ozone concentrations taking into account their serial dependence (e.g., auto-regressive integrated moving average – ARIMA).
- **Extreme Value Theory:** To estimate distributions of annual maximum hourly concentrations, estimate distributions of the number of days exceeding the standard (e.g., Chi-square test, Poisson process approximation).

Using Box Plots to Investigate Trends

- Box plots are useful for displaying trends in data.
- Box plots illustrate the trends in the high values, the low values, and the means.
- In this graph, the variability is about the same from year to year - the boxes for each year are about the same height.
- Also note a statistically significant drop in ambient benzene weight percent between 1994 and succeeding years. This change is probably attributable to a decrease in benzene in gasoline.

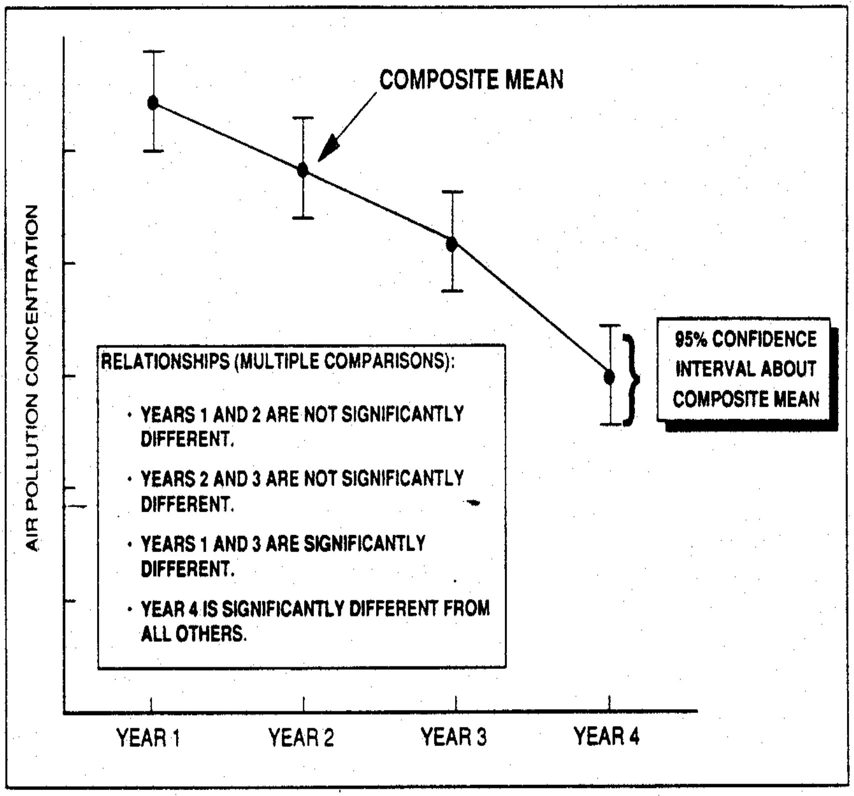


Prepared using box plot by year with SYSTAT.

Using Confidence Intervals to Investigate Trends (1 of 2)

- Confidence intervals are shown for four years of data.
- Since the plotted confidence intervals overlap for years 1 and 2 but not for years 1 and 3, years 1 and 2 are not significantly different, but years 1 and 3 are significantly different.

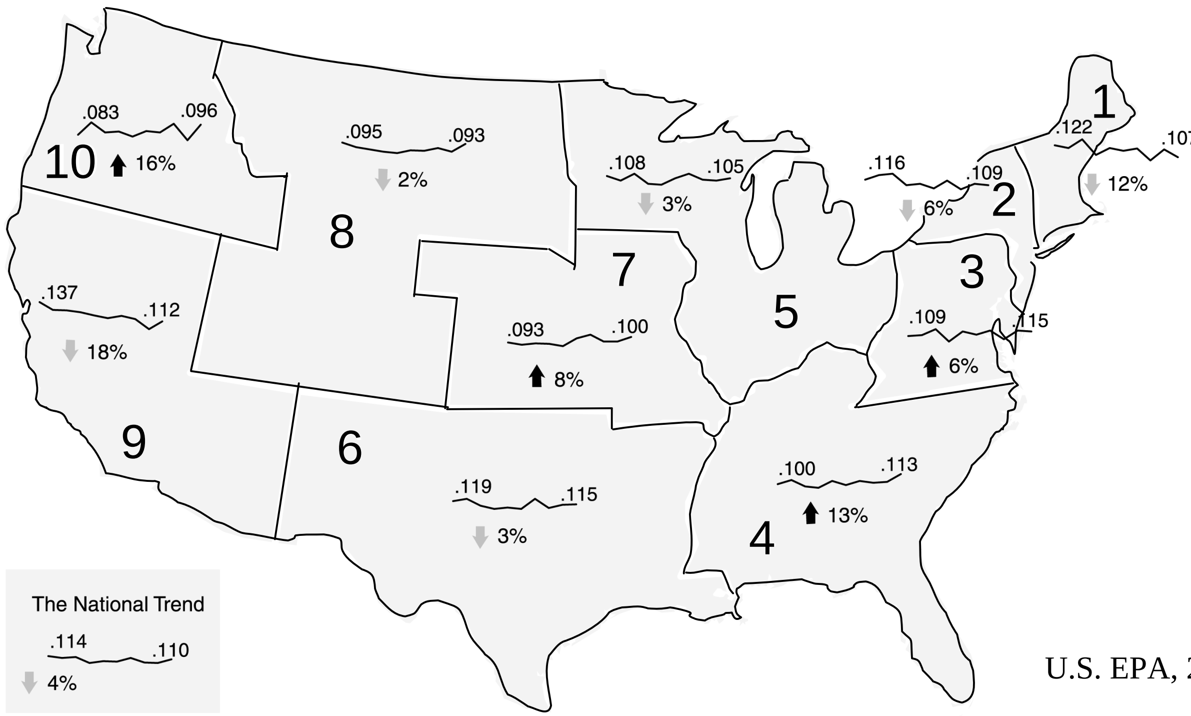
Illustration of the use of confidence intervals to determine statistically significant changes.



U.S. EPA, 1994

Using Confidence Intervals to Investigate Trends (2 of 2)

Trend in ozone second maximum 1-hr concentration by EPA region, 1989-1998.

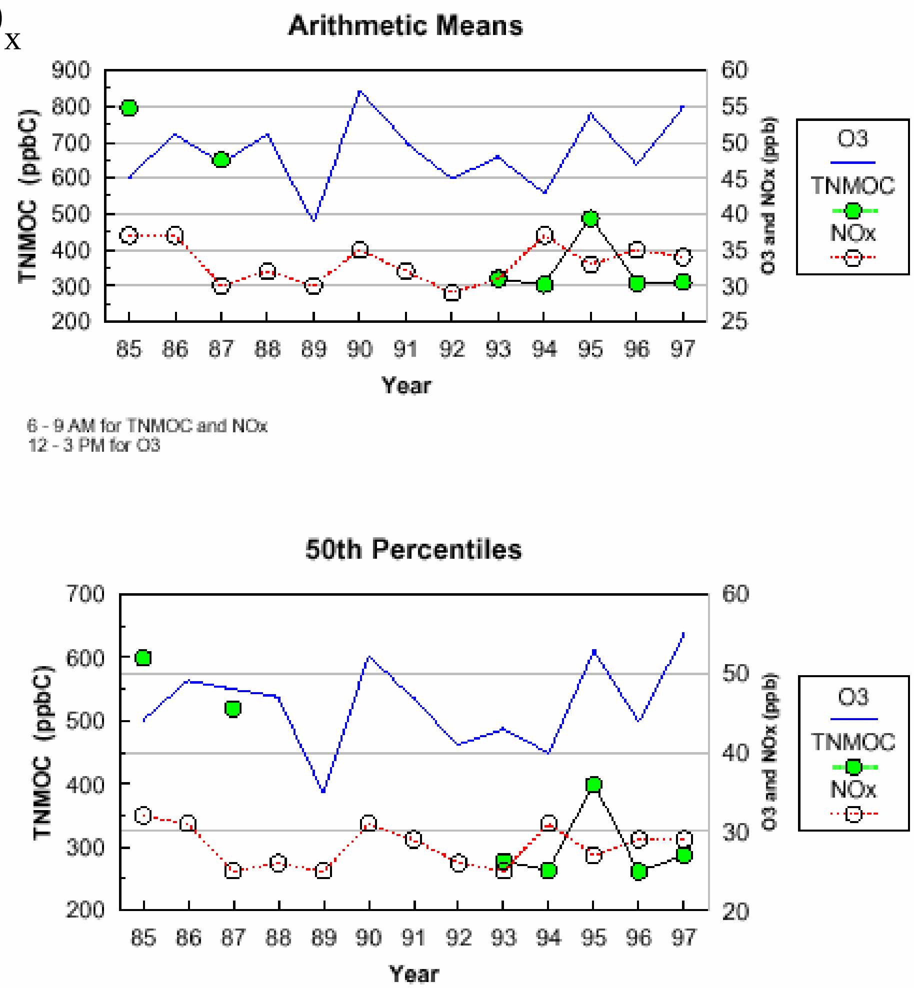


U.S. EPA, 2000

Simple line graphs can be used to assess trends in selected indicators. In this graph, a map was combined with plots of the second maximum 1-hr ozone concentration per year for each region.

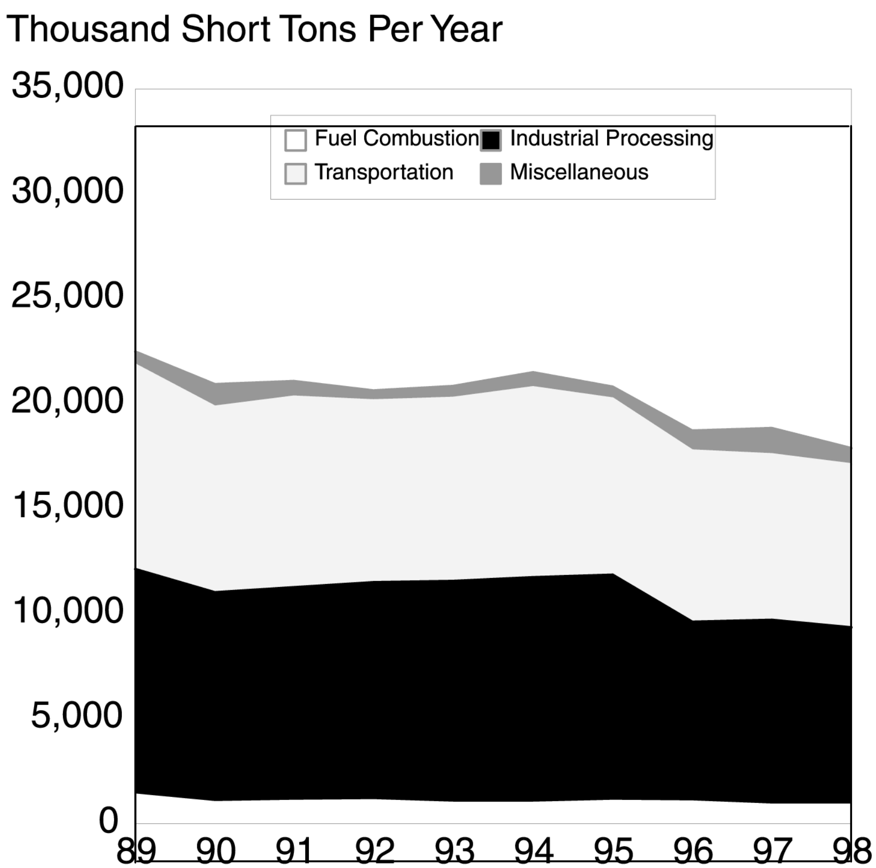
Ozone and Precursor Trends

- Example ozone, VOC, and NO_x trends at the Baton Rouge Capitol site for June-August 1985-1997.
- Morning VOC concentrations have declined since the mid-1980s using both the mean and median (50th percentile) as metrics.
- Morning NO_x concentrations have not shown a significant trend.
- Midday ozone concentrations also have not changed significantly.

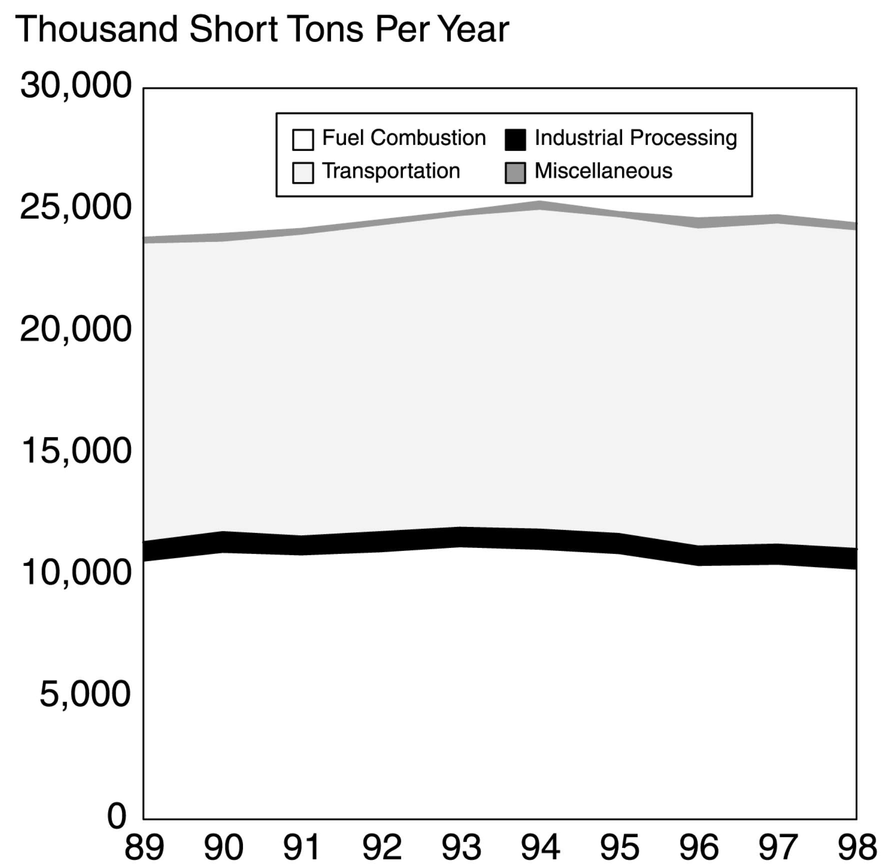


Sather and Kemp, 1998

Emission Trends



Trends in national total anthropogenic VOC emissions, 1989-1998 (U.S. EPA, 2000).



Trends in national total NO_x emissions, 1989-1998 (U.S. EPA, 2000).

U.S. EPA, 2000

Available Tools and Methods (1 of 2)

Available statistical and mapping software includes:

- AIRS graphics (e.g., *http://www.epa.gov/airsweb/maps.htm*)
- ArcInfo and ArcView (*http://www.esri.com/*)
- MapInfo (*http://www.mapinfo.com/*)
- SAS (*http://www.sas.com/*)
  SYSTAT (*http://www.spssscience.com/systat*)
  SPLUS (*http://www.splus.mathsoft.com/*)
- Surfer (*http://www.goldensoftware.com/*)
- Other similar statistical and GIS-based software.

Available Tools and Methods (2 of 2)

Available methods for trend analysis include (with reference):

- Classification and regression tree analysis: Stoeckenius, 1990
- De-seasonalizing annual trends: Frechtel et al., 1999
  http://capita.wustl.edu/PMFine/Workgroup/Status&Trends/Reports/Completed/LongTermIMPROVE/LongTermIMPROVE.html
- EPA Trends Report (e.g., *http://www.epa.gov/oar/aqtrnd98/*)
- Meteorological adjustment using filtering: Rao and Zurbenko, 1994
- Meteorological adjustment using probability distribution: Cox and Chu, 1998
  http://capita.wustl.edu/OTAG/reports/otagwind/OTAGWIN4.html
- Also, see the table on Adjustment Techniques earlier in this chapter

Handling Missing Data

- In the assessment of long-term trends for the EPA trends report, analysts handle missing annual data in the following manner:
  - Missing the last year: set the missing year equal to the second-to-last year.
  - Missing the first year: set the missing year equal to the second year.
  - Missing any other year: interpolate between the adjacent two years.
- Data handling conventions for missing data and for determining whether a site is in compliance with the NAAQS are discussed in detail in U.S. EPA, 1999.

Summary

- One of the key issues of the PAMS monitoring program is how to determine whether or not ozone air quality is improving.
- This workbook section provides examples of methods for displaying and assessing trends in ozone and precursor data. Methods and tools for assessing uncertainties and adjusting for meteorology are also discussed.

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