Quantifying Trends in PM and Its Precursors

- Overview of Trend Analysis
- Selecting Indicators
- Assessing Uncertainties in Trend Analyses
- Adjusting for Meteorology
  - Adjustment Techniques
  - Important Meteorological Variables
  - Example Meteorology Adjusted Trends
- Discerning Trends
  - Statistics
  - Graphical Methods
  - Examples
- Spatial Trends in PM
  - Examples
- Ambient and Emission Inventory Trends
- Tools and Methods for Trend Analyses
- Handling Missing Data
- Summary
- References

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

Overview of Trend Analysis

Rationale for assessing trends in PM. One of the major programmatic objectives for the routine $PM_{2.5}$ chemical speciation is providing data for the analysis of air quality trends and to track progress of control programs. The ability to detect trends in ambient concentrations that are associated with planned air quality control efforts must be incorporated in State Implementation Plan (SIP) assessments. For example, if specific control strategies have been implemented in an area to reduce fugitive emissions from construction activities, do the ambient data indicate lower concentrations of PM species associated with crustal material since the implementation of the control?

Indicator selection is important. Air quality data typically do not fit a normal distribution. The data tend to be more skewed and exhibit a few high concentration events. Thus, trends in extreme values in a data set may differ significantly from trends observed in a statistic that describes the bulk of the data. Data can be statistically adjusted to assess trends in peak days and on more typical days. For example, one can plot the annual maximum PM concentrations to assess how annual peak days are changing over time, or one can plot the median PM concentrations to assess how the 50th percentile of the days are changing. In addition, in order to assess a trend in air quality, sufficient data are required over a sufficient time period.

Understanding the data uncertainties is necessary. Uncertainties impact the ability to clearly discern air quality trends. For example, measurement accuracy, precision, bias, and interferences need to be understood to properly interpret the data. Also uncertainties arising from compiling large amounts of measurements into a single performance indicator can be important.

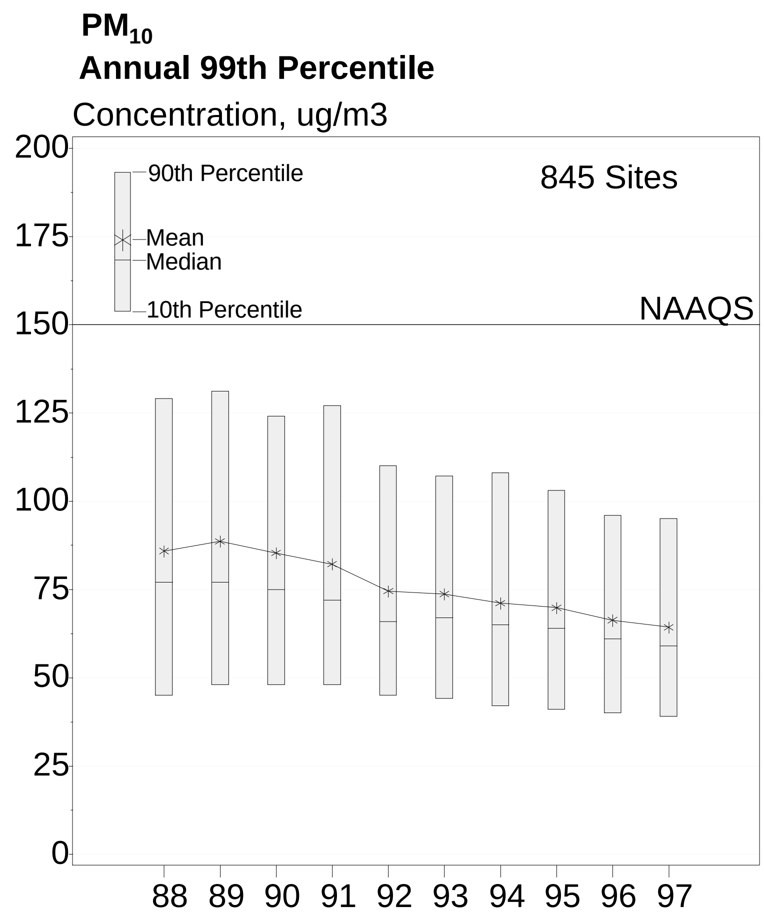
Changes in meteorology can obscure trends in air quality. We know that the meteorology can vary significantly among years (e.g., El Niño), and meteorology can have a significant affect on air quality. We also want to understand changes in air quality that are attributed to emission controls. Therefore, when we assess trends in air quality, we need to be able to adjust the data to account for meteorological conditions that were very different from average conditions. By properly accounting for the portion of the variability in the data attributable to changes in meteorology, we can compare air quality among years with widely different meteorological conditions. This is important because we do not have control over how meteorology changes (and meteorology is not an excuse for nonattainment).

Discerning trends can be tricky. The analyst needs to understand methods for quantifying trends and determining their statistical significance. The analyst also needs to be able to communicate the results in a meaningful and understandable way.

U.S. EPA, 1998

Selecting Indicators (assuming 24-hr data)

- Statistical indicators include arithmetic mean, geometric mean, median, maximum, minimum, 2^{nd} and 3^{rd} maximums, and selected percentiles.
- Time periods over which to apply the statistics include quarterly, seasonally, episode (i.e., days above some threshold) versus non-episode, annually.
- PM measurements upon which to apply the statistics include mass, species groups (e.g., total metals), individual species (e.g., lead), ratios of species. Concentrations and weight percent of total mass can be used.
- Consensus among trends in indicators gives the analyst more confidence in the results.



U.S. EPA, 1998

Assessing Uncertainties in Trend Analyses

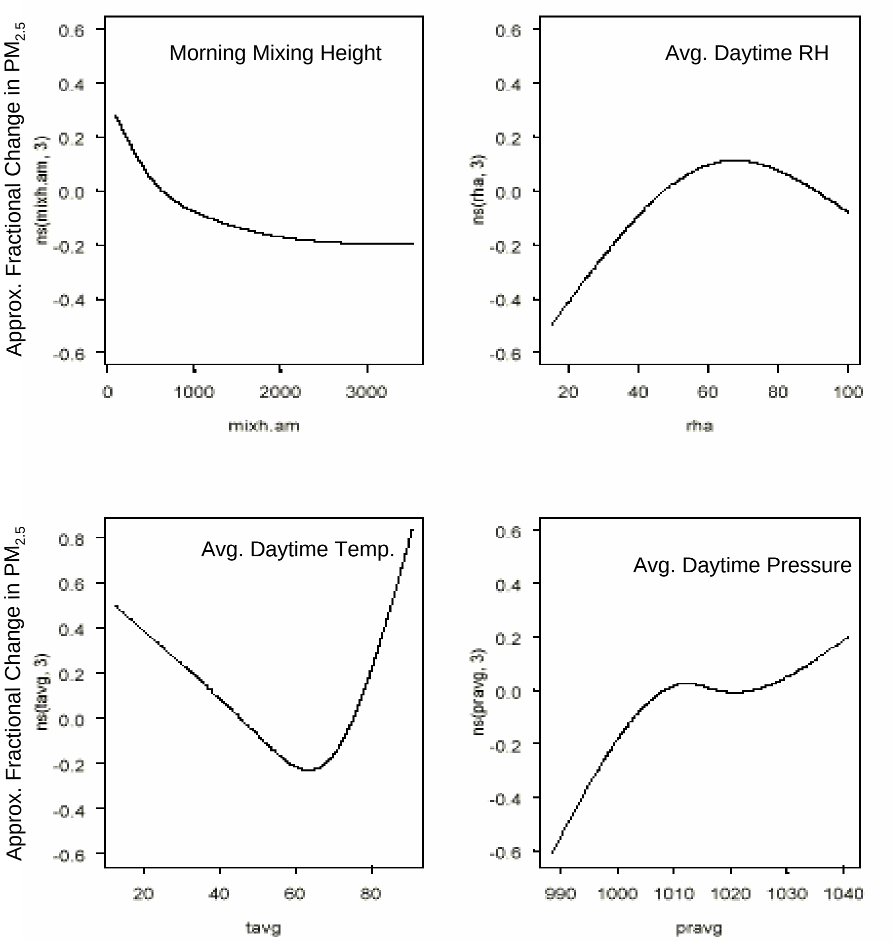
- Uncertainties impact one's ability to clearly discern air quality trends in an analysis.
- Uncertainties that affect trends in air quality are
  - **Atmospheric variability** associated with short-term fluctuations in meteorological conditions and source emissions.
  - **Meteorological variability** 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 Meteorology

- Adjustment techniques involve some processing of the PM 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.
- These figures illustrate some of the meteorological parameters that have an effect on $PM_{2.5}$ concentrations. For example, lower morning mixing height was linked to higher $PM_{2.5}$ concentrations. One of the next steps is whether or not these parameters show a significant interannual impact.

Exploratory Investigation of $PM_{2.5}$ Dependence on Meteorology on Washington DC IMPROVE Data



Frechtel et al., 1999

Summary of Adjustment Techniques

Methods for adjusting pollutant concentrations to account for methodology:

- Expected peak-day concentration (California Air Resources Board, 1993)
- Native variability (California Air Resources Board, 1993)
- Filtering techniques (e.g., Rao and Zurbenko, 1994)
- Probability distribution technique (Cox and Chu, 1998)
- Classification and Regression Tree (CART) analysis (e.g., Stoeckenius, 1990)
- Linear regression (e.g., Davidson, 1993)
- Nonlinear regression (e.g., Bloomfield et al., 1996)

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

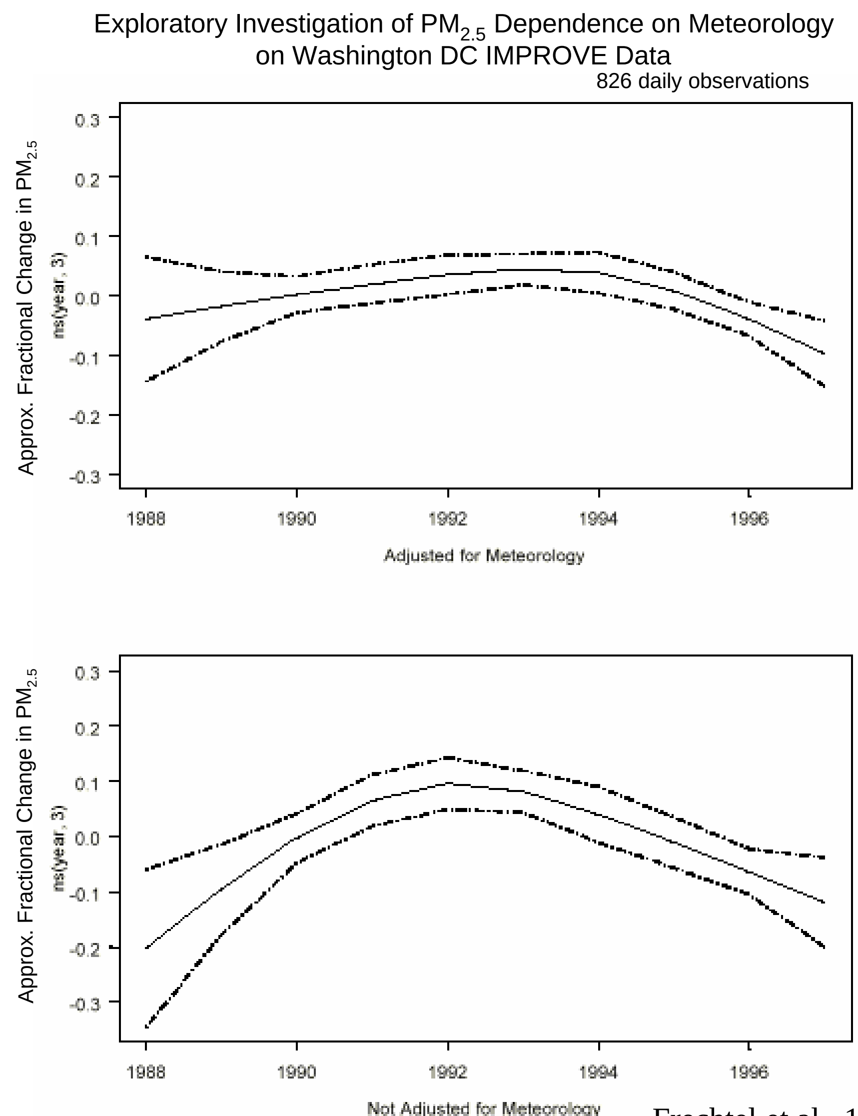
Important Meteorological Variables

- Possible meteorological variables important to PM trend analysis include daily average specific humidity, average morning (0600-0900) wind speed, average afternoon (1300-1600) wind speed, morning mixing height, average 1000-1600 relative humidity, daily average temperature, daily average barometric pressure, wind direction, and transport/recirculation measures.
- To assess possible important meteorological variables, the following analyses are helpful: examine a matrix of scatter plots of fine mass and all possible independent variables available; perform Classification and Regression Tree (CART) analysis; perform cluster or factor analysis; perform other multivariate analyses.
- The correlation between some variables can be improved by offsetting ambient data and meteorological parameters by a lag time.

Cox and Chu, 1998

Example: Meteorology Adjusted Trends

- In this example, a general linear model was developed in which each of the independent variables was modeled using a natural cubic spline with three degrees of freedom. Meteorological parameters were stepwise deleted from the full model.
- The trend components (with twice standard errors) are shown here with and without meteorology included in the model. Important variables (averages) included are daily specific humidity, morning and afternoon wind speeds, morning mixing height, daytime relative humidity, and daytime surface temperature and pressure.
- The meteorologically adjusted trends appear to be smoother and flatter than the non-adjusted trends.
- The impact of interannual variations in meteorological conditions do not appear to be large enough to alter any conclusions about long-term PM trends at this site.



Frechtel et al., 1999

Discerning Trends

- **Linear Model**: Use simple linear regression on annual summary statistics or logged statistics (if lognormal); perform analysis of variance.
- **Nonparametric Methods**: 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**: Statistically model PM concentrations (and other air quality parameters) taking into account their serial dependence (e.g., auto-regressive integrated moving average - ARIMA).
- **Extreme Value Theory**: Estimate distributions of annual maximum hourly concentrations and the number of days exceeding the standard (e.g., Chi-square test, Poisson process approximation).

Stoeckenius et al., 1994

Statistics

Measure	Parametric	Nonparametric
Measure of central tendency	Mean	Median
Deviation or dispersion	Standard deviation Coefficient of variation Variance	Inner quartile
Determining whether or not two samples come from the same population	Students t-test	Mann-Whitney U test
Test for randomness		Runs test
Measure of correlation between two variables	Pearson correlation	Spearman's rank correlation

- Many tests of hypotheses and significance require various assumptions about the distribution of the population from which the samples are drawn.
- For some data sets, these assumptions may not apply, as in a case where the data are highly skewed.
- There are many excellent texts on statistics as well as on-line information such as
<http://www.math.sfu.ca/stats/Courses/Stat-301/Handouts/node1.html>

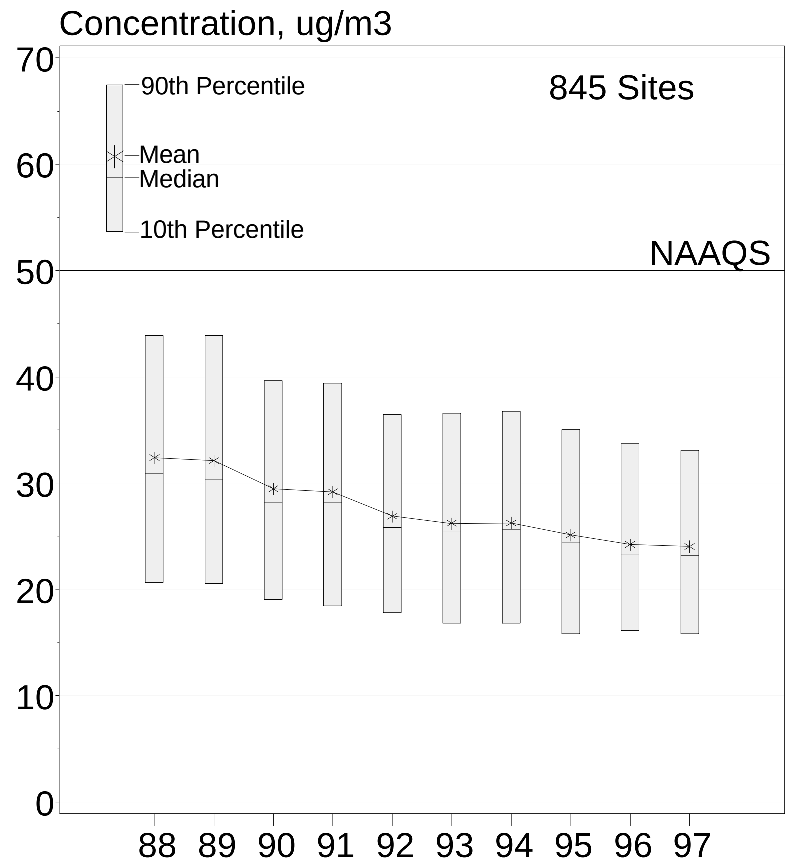
Graphical Methods for Discerning Trends

- Box plots (high and low values, median values, outliers)
- Plots of mean or median values with confidence intervals
- Line graph of selected indicator
- Interpolated or contoured maps of PM indicators
- Combination of map with temporal information

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 gradual, steady downward trend over the years 1988-1997, for the high values, the low values, and the central values.
- For PM, both the high, episodic values, and the annual means are interesting because PM has both episodic, short-term health effects and chronic, long-term health effects.

Trend in Annual Mean PM_{10} Concentrations, 1988-1997

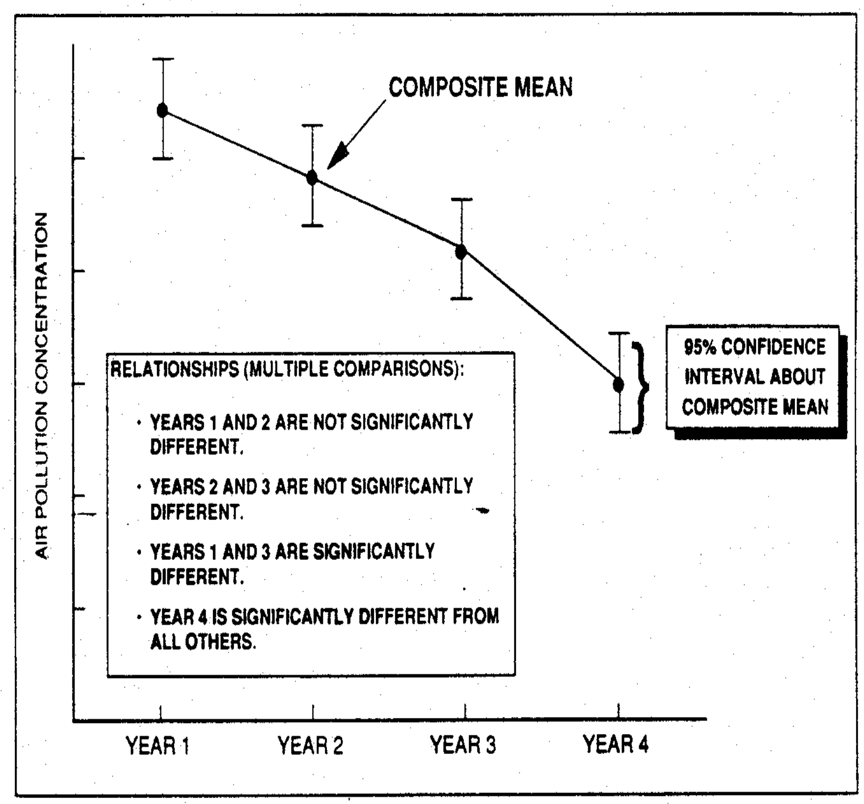


U.S. EPA, 1998

Using Confidence Intervals to Investigate Trends

- Confidence intervals are shown for fours 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.

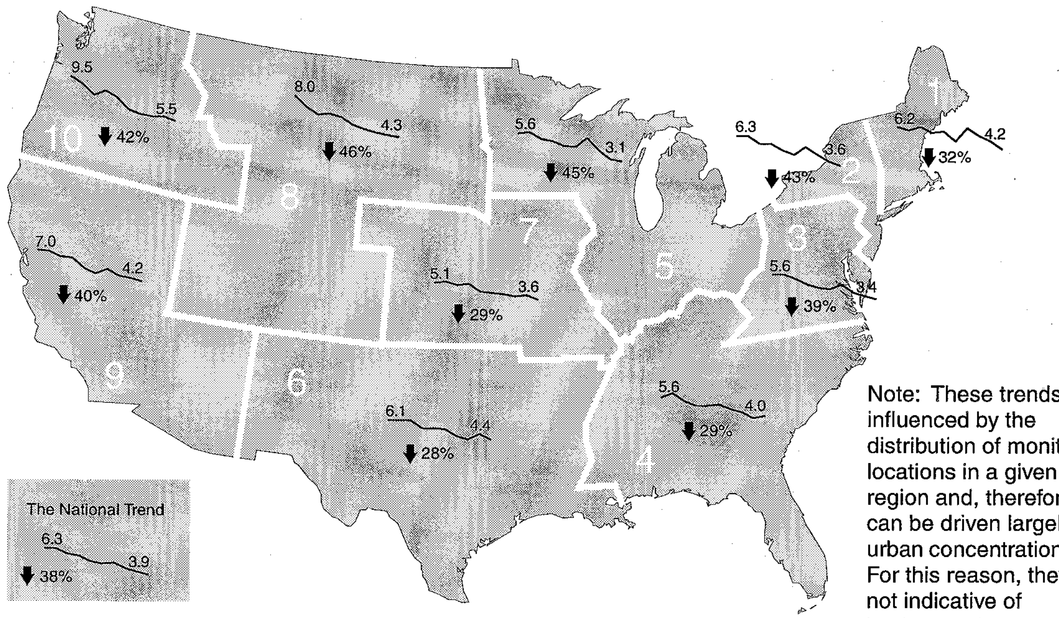
Illustration of the use of confidence intervals to determine statistically significant changes.



U.S. EPA, 1994

Using Line Graphs to Investigate Trends (1 of 2)

Trend in CO second maximum 8-hour concentrations by EPA Region, 1988-97.



Alaska is in EPA Region 10; Hawaii, EPA Region 9; and Puerto Rico, EPA Region 2. Concentrations are ppm.

Note: These trends are influenced by the distribution of monitoring locations in a given region and, therefore, can be driven largely by urban concentrations. For this reason, they are not indicative of background regional concentrations.

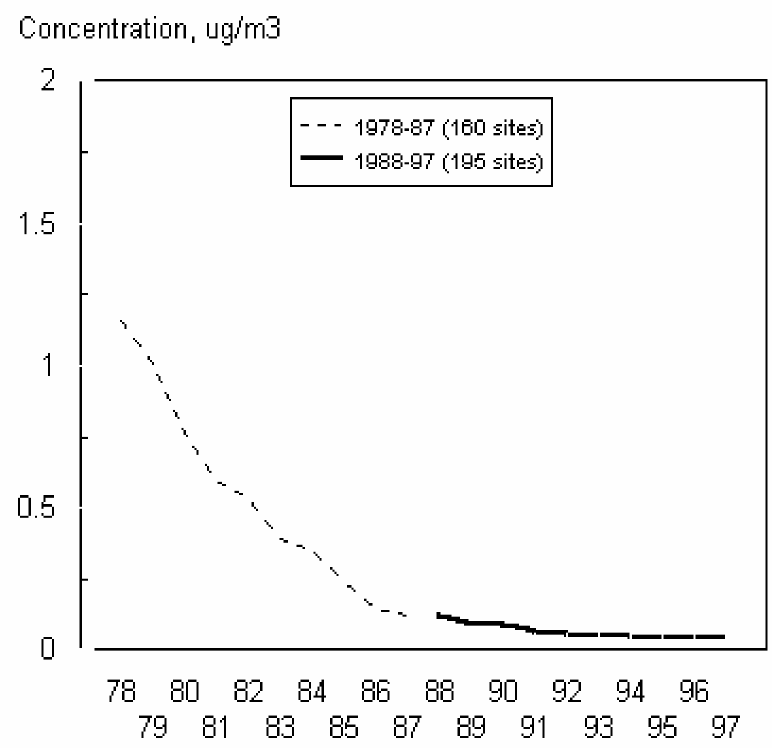
U.S. EPA, 1998

Line graphs can be used to assess trends in selected indicators. In this graph, a map was combined with plots of the second maximum 8-hr CO concentration per year for each region. A similar plot could be prepared for $PM_{2.5}$ concentrations.

Using Line Graphs to Investigate Trends (2 of 2)

- It is sometimes useful to break a long-term trend into shorter time intervals because of significant changes in emissions.
- For example, leaded gasoline was phased out starting in the late 1970s. Dramatic reductions were observed in ambient particulate Pb concentrations up to the 1980s. Since the late 1980s, Pb concentrations are near the minimum detectable level.
- Similar dramatic reductions in ambient benzene concentrations have been observed because of the introduction of reformulated fuels (e.g., Main et al., 1998).

Long-term Ambient Lead (Pb) Trend, 1977-1997

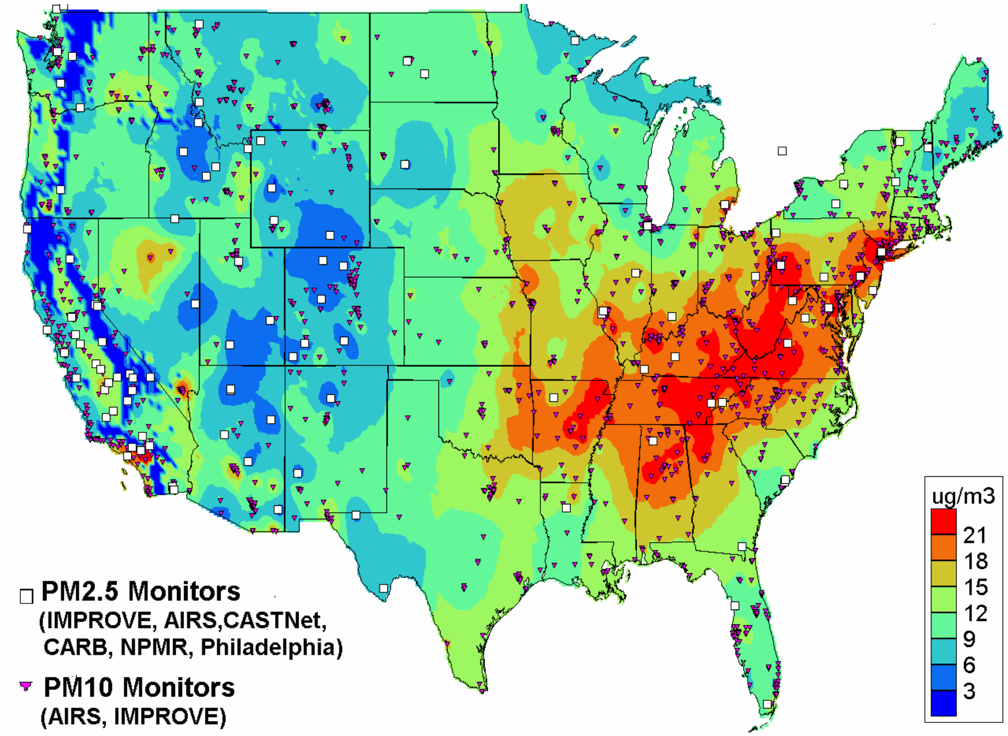


U.S. EPA, 1998

Spatial Trends in PM

- It is important to use consistent data records (e.g., same site operating over all years of the trend period) when assessing spatial and temporal trends.
- From the map, summer $PM_{2.5}$ concentrations are highest in the southern Appalachian mountains and in the eastern metropolitan corridor. Concentrations decline outside these areas. Moving east to west, the concentrations mostly decrease except for a few hot spots around western cities.

Average $PM_{2.5}$ Concentrations
July, August, September 1994-1996



This is a work in progress. The map is currently the best available but is expected to change as estimation methods improve and additional data is incorporated. Falke, 1999

Combining Spatial and Temporal Trends

Prepared using SAS and ArcView

Label Units: (ug/(m3*year))*100

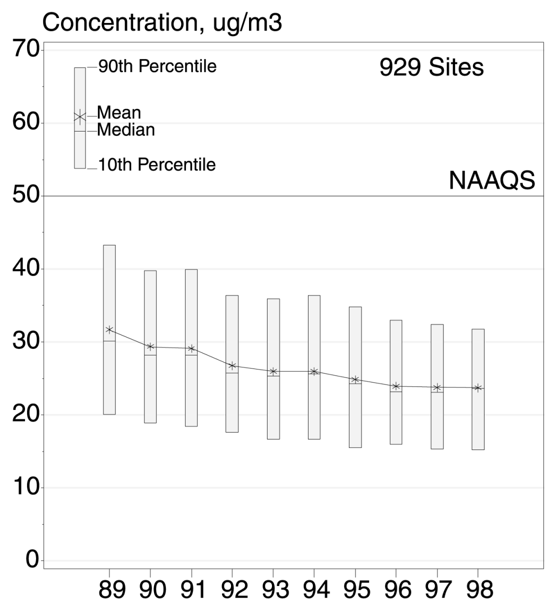
- The map shows the annual trends in overall $PM_{2.5}$ concentration for 1988-1997 at 34 monitoring sites in the continental United States which have been recording $PM_{2.5}$ concentrations for over six years.
- The site labels are the annual trends of $PM_{2.5}$ concentrations at each site. The data were deseasonalized to "take out" the seasonal cycle of $PM_{2.5}$.

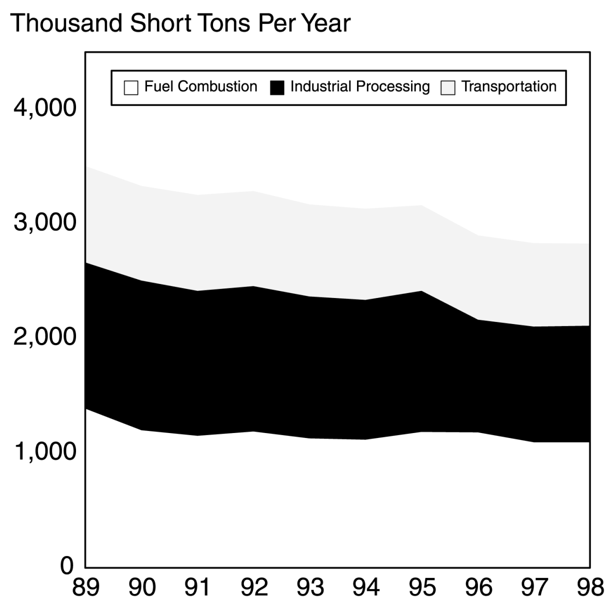
Data Source: IMPROVE Network

[a] Sites labeled X/Y are actually two sites in close proximity.

Frechtel et al., 1999

Ambient and Emission Inventory Trends





National PM_{10} ambient (left) and emissions (right) trends, 1989-1998 (traditionally inventoried sources only). U.S. EPA, 1999a, 1999b

- It is important to compare ambient trends with trends in the emission inventory. Do the ambient trends corroborate changes in emissions?
- The example here compares trends in national PM_{10} concentrations and emissions from 1989 through 1998. Both plots show a decline since 1989.
- As $PM_{2.5}$ emission inventory and ambient data become available, these types of comparisons should be made.

Tools and Methods for Trend Analysis (1 of 2)

Available mapping software includes

- Surfer <http://www.goldensoftware.com/>
- MapInfo <http://www.mapinfo.com/>
- ArcInfo and ArcView <http://www.esri.com/>
- SAS <http://www.sas.com/>
- AIRS graphics <http://www.epa.gov/airsweb/maps.htm)>
- TopoUSA <http://www.delorme.com/topousa/>
- Other similar statistical and GIS-based software.

Tools and Methods for Trend Analysis (2 of 2)

Demonstrated methods for trend analysis include (with reference)

- De-seasonalizing annual trends: Frechtel et al., 1999
  <http://capita.wustl.edu/PMFine/Workgroup/Status&Trends/Reports/Completed/LongTermIMPROVE/LongTermIMPROVE.html>
- Assessing seasonal trends: Eldred, 1994
- Meteorological adjustment using filtering: Rao and Zurbenko, 1994
- Meteorological adjustment using probability distribution: Cox and Chu, 1998; Cox et al., 1999
- Classification and regression tree analysis: Stoeckenius, 1990

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. Environmental Protection Agency, 1999b.

Summary

- One of the key issues of the $PM_{2.5}$ monitoring program is how to determine whether or not PM air quality is improving.
- This workbook section provides examples of methods for displaying and assessing trends in PM data. Methods and tools for assessing uncertainties and adjusting for meteorology are also discussed.

References (1 of 4)

Bloomfield P., Royle J.A., Steinberg L.J., and Yang Q. (1996) Accounting for meteorological effects in measuring urban ozone levels and trends. *Atmos. Environ*. **30**, 3067-3077.

Butler A . J ., Mulholland J . A ., Russell SA . G ., Tolbert P . E ., Wilkinson J . G . (1998) Temporal and Spatial Distributions of Ozone in Atlanta: Regulatory and Epidemiologic Implications. *J. Air & Waste Manag. Assoc*. **48,** 418 - 426.

California Air Resources Board (1993) Guidance for using air quality-related indicators in reporting progress in attaining the State Ambient Air Quality Standards. Report prepared for the California Air Resources Board, Sacramento, CA., September.

California Air Resources Board (1995) Air quality indicators for 1981 to 1993 to report progress in attaining the State ambient air quality standards for ozone, carbon monoxide, and nitrogen dioxide. Report prepared by the California Environmental Protection Agency Air Resources Board, Air Quality Analysis Section, Technical Support Division, Sacramento, CA, September.

California Air Resources Board (1997) California ambient air quality data: 1980-1996. Prepared by Technical Support Division, Air Quality Data Branch, California Air Resources Board, Sacramento, CA, CD Number: TSD-97-008-CD, December.

California Air Resources Board (1999) The 1999 California almanac of emissions and air quality. Report prepared by the California Air Resources Board, Planning and Technical Support Division, Sacramento, CA.

Chu S. and W. Cox (1998) Relationship of PM fine to Ozone and Meteorology. Paper 98-RA90A.03 presented at the *Air & Waste Management Association's 91st Annual Meeting & Exhibition, June 14-18, 1998, San Diego, California*.

Cohanim S., Cassmassi J., and Bassett M. (1998) Ozone trends in California's South Coast Air Basin, 1976-1996. Presented at the *Air & Waste Management Association's 91st Annual Meeting & Exhibition, San Diego, June 14-18.*

Cox W.M. and Chu S.H. (1993) Meteorologically adjusted ozone trends in urban areas: a probabilistic approach. *Atmos. Environ.* **27B**, 425-434.

Cox W.M. and Chu S.H. (1996) Assessment of interannual ozone variation in urban areas from a climatological perspective. *Atmos. Environ*. **30**, 2615-2625.

References (2 of 4)

Cox W.M. and Chu S.H. (1998) Cox-Chu meteorologically-adjusted ozone trends (1-hour and 8-hour): 1986-1997., Web page for Center for Air Pollution Impact and Trend Analysis (CAPITA), Washington University, St. Louis, MO <http://capita.wustl.edu/EnhancedOzone/Resources/Bibliography/Reports/PAMS/o3trends.pdf>, October.

Davidson A. (1993) Update on ozone trends in California's South Coast Air Basin. *J. Air & Waste Manag. Assoc*. **43**, 226-227.

Deuel H.P. and Douglas S.G. (1996) Regional ozone patterns in the Eastern U.S. 1985-1995: Statistical pattern analysis and classification and regression tree (CART) analysis in support of the Ozone Transport and Assessment Group (OTAG) modeling effort. Prepared for Southeast Modeling Center by Systems Applications International, Inc., San Rafael, CA, SYSAPP-96/50, October.

Eldred R. A. and Cahill T.A. (1994) Trends in elemental concentrations of fine particles at remote sites in the United States of America. *Atmos. Environ*. **28 ,** 1009 - 1019.

Falke, S. (1999) Draft PM2.5 topic summary available at <http://capita.wustl.edu/PMFine/Workgroup/Status&Trends/Reports/In-progress/PM25Maps/PM25Maps/sld001.htm>

Flaum J.B., Rao S.T., and Zurbenko I.G. (1996) Moderating the influence of meteorological conditions on ambient ozone concentrations. *J. Air & Waste Manag. Assoc*. 46, 35-46.

Frechtel P., Eberly S., and Cox W.M. (1999) Trends analysis using the IMPROVE database. Web page for Center for Air Pollution Impact and Trend Analysis (CAPITA), Washington University, St. Louis, MO, <http://capita.wustl.edu/PMFine/Workgroup/Status&Trends/Reports/Completed/LongTermIMPROVE/LongTermIMPROVE.html>.

Frechtel P., Eberly S., Cox W. (1999) PM-Fine Trends at Long-Term IMPROVE Sites. Paper available at <http://capita.wustl.edu/PMFine/reports/WashingtonPMf/WASHPMF.pdf>. Last accessed 02/01/01.

Holland D.M., Principe P.P., and Vorburger L. (1999) Rural ozone: trends and exceedances at CASTNet sites. *Environ. Sci. Technol*. **33**, 43-48.

Husar R.B. and Renard W.P. (1997) Ozone as a function of local wind speed and direction: evidence of local and regional transport. Web page for Center for Air Pollution Impact and Trend Analysis (CAPITA), Washington University, St. Louis, MO, <http://capita.wustl.edu/OTAG/reports/otagwind/OTAGWIN4.html>, July.

References (3 of 4)

Johnson N.L. (1979) A comparison of the two-parameter Weibull and lognormal distributions fitted to ambient ozone data. Proc. Specialty Conf. on Quality Assurance in Air Pollution Measurement, New Orleans, LA.

Larsen L.C., Bradley R.A., and Honcoop G.L. (1990) A new method of characterizing the variability of air quality-related indicators. Presented at the *Air & Waste Management Association's International Specialty Conference on Tropospheric Ozone and the Environment, Los Angeles, CA, March 19-22*.

Main H.H., Roberts P.T., and Ligocki M.P. (1995) Assessing the usefulness of VOC data as indicators of change in fuel composition in the South Coast Air Basin (California). Paper No. 95-FA113C.02 presented at the *Air & Waste Management Association 88th Annual Meeting, San Antonio, TX, June 18-23*, (STI-1501).

Main H.H., Roberts P.T., and Reiss R. (1998) Analysis of photochemical assessment monitoring station (PAMS) data to evaluate a reformulated gasoline (RFG) effect. Report prepared for the U.S. Environmental Protection Agency, Office of Mobile Sources, Fuels and Energy Division, Washington, DC by Sonoma Technology, Inc., Santa Rosa, CA, STI-997350-1774-FR2, April. Available online at <http://www.epa.gov/oar/oaqps/pams/rfg_oms.pdf>.

Milanchus M.L., Rao S.T., and Zurbenko I.G. (1997) Discerning changes in anthropogenic ozone in the presence of meteorological fluctuations. *Environ. Man. J*. 17-21.

Milanchus M.L., Rao S.T., and Zurbenko I.G. (1998) Evaluating the effectiveness of ozone management efforts in the presence of meteorological variability. *J. Air & Waste Manag. Assoc*. **48**, 201-215.

Porter P.S., Rao S.T., Zurbenko I., Zalewsky E., Henry R.F., and Ku J.Y. (1996) Statistical characteristics of spectrally-decomposed ambient ozone time series data. Final report prepared for the Ozone Transport Assessment Group by the University of Idaho, the State University of New York at Albany and the New York Department of Environmental Conservation, August.

Rao S.T. and Zurbenko I.G. (1994) Detecting and tracking changes in ozone air quality. *J. Air & Waste Manag. Assoc*. **44**, 1089-1092.

Rao S.T., Zalewsky E., and Zurbenko I.G. (1995) Determining spatial and temporal variations in ozone air quality. *J. Air & Waste Manag. Assoc*. **45**, 57.

References (4 of 4)

Scheff P.A., R.A. Wadden, D.M. Kenski, J.Chung, and G. Wolff (1996) Receptor model evaluation of the Southeast Michigan ozone study ambient NMOC measurements. J *J. Air & Waste Manag. Assoc*. **46,** 1048-1057.

Stoeckenius T.E. (1990) Adjustment of ozone trends for meteorological variation. Presented at the *Air and Waste Management Association's Specialty Conference, Tropospheric Ozone and the Environment, Los Angeles, CA, March 19-22.*

Stoeckenius T.E., Ligocki M.P., Cohen B.L., Rosenbaum A.S., and Douglas S.G. (1994) Recommendations for analysis of PAMS data. Final report prepared by Systems Applications International, San Rafael, CA, SYSAPP94-94/011r1, February.

U.S. Environmental Protection Agency (1994) Clean air act ozone design value study: a report to Congress. Final report prepared by OAQPS, U.S. Environmental Protection Agency, Research Triangle Park, NC, EPA-454/R-94-035, December.

U.S. Environmental Protection Agency (1998) National air quality and emissions trends report, 1997. Prepared by the Office of Air Quality Planning and Standards, Emissions monitoring and analysis division, air quality trends analysis group, Research Triangle Park, 454/R-98-016, December.

U.S. Environmental Protection Agency (1999a) Particulate matter ($PM_{2.5}$) speciation guidance document. Available at <http://www.epa.gov/ttn/amtic/files/ambient/pm25/spec/specpln3.pdf>.

U.S. Environmental Protection Agency (1999b) Guideline on data handling conventions for the PM NAAQS. EPA-454/R-99-008, April.

Wittig A.E., Main H.H., Roberts P.T., and Hurwitt S.B. (1999) Analysis of PAMS data in California Volume III: Trends analysis of California PAMS and long-term trend air quality data (1987-1997). Report prepared for the U.S. Environmental Protection Agency, Research Triangle Park, NC, STI-998393-1885-FR, May.

Zeldin M.D., Cassmassi J.C.C., and Hoggan M. (1990) Ozone trends in the South Coast Air Basin: an update. Presented at the *Air and Waste Management Association's International Conference on Tropospheric Ozone and the Environment, Los Angeles, CA, March 19-22*, pp. 760-771.

Zurbenko I.G., Rao S.T., and Henry R.F. (1995) Mapping ozone in the Eastern United States. *Environ. Man. J*. **1**, February.