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## Receptor modeling application framework for particle source apportionment

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John G. Watson, Tan Zhu, Judith C. Chow, Johann Engelbrecht, Eric M. Fujita, and William E. Wilson



## Receptor modeling application framework for particle source apportionment

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### Abstract

Receptor models infer contributions from particulate matter (PM) source types using multivariate measurements of particle chemical and physical properties. Receptor models complement source models that estimate concentrations from emissions inventories and transport meteorology. Enrichment factor, chemical mass balance, multiple linear regression, eigenvector, edge detection, neural network, aerosol evolution, and aerosol equilibrium models have all been used to solve particulate air quality problems, and more than 500 citations of their theory and application document these uses. While elements, ions, and carbons were often used to apportion TSP, PM<sub>10</sub>, and PM<sub>2.5</sub> among many source types, many of these components have been reduced in source emissions such that more complex measurements of carbon fractions, specific organic compounds, single particle characteristics, and isotopic abundances now need to be measured in source and receptor samples. Compliance monitoring networks are not usually designed to obtain data for the observables, locations, and time periods that allow receptor models to be applied. Measurements from existing networks can be used to form conceptual models that allow the needed monitoring network to be optimized. The framework for using receptor models to solve air quality problems consists of: (1) formulating a conceptual model; (2) identifying potential sources; (3) characterizing source emissions; (4) obtaining and analyzing ambient PM samples for major components and source markers; (5) confirming source types with multivariate receptor models; (6) quantifying source contributions with the chemical mass balance; (7) estimating profile changes and the limiting precursor gases for secondary aerosols; and (8) reconciling receptor modeling results with source models, emissions inventories, and receptor data analyses.

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*Keywords:* Receptor model; PM<sub>10</sub>; PM<sub>2.5</sub>; Chemical mass balance; Enrichment factor; Principal component analysis; Factor analysis

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## 1. Introduction

Receptor models infer contributions from different source types using multivariate measurements taken at one or more receptor locations. These receptors can be fixed indoor or outdoor monitors or mobile samplers that follow the activities of an individual or group of people. Source models estimate receptor concentrations from source emissions and meteorological measurements. Receptor models use ambient concentrations and the abundances of chemical components in source emissions to quantify source contributions. Source and receptor models are complementary rather than competitive. Each has strengths and weaknesses that compensate for the other. Both types of models can and should be used in an air quality source assessment of outdoor and indoor air.

Chemical and physical analysis methods are often termed receptor models. A chemical “tracer” is often sought for certain sources. Microscopic analysis, gas chromatograms, X-ray spectra, carbon-14 ( $^{14}\text{C}$ ) and other isotopic abundances, and many other analytical outputs provide patterns that might allow a source contribution to be identified and quantified. Without the receptor model mathematics and applications framework, however, these analytical methods do not quantify source contributions.

True receptor models are not statistical black boxes. They are based on the same scientific principles as source models, but they are explanatory rather than predictive of source contributions. Receptor models include the enrichment factors (EFs), chemical mass balance (CMB), eigenvector analysis (also termed principal component analysis (PCA), factor analysis (FA), and empirical orthogonal functions (EOF)), multiple linear regression, neural networks, edge detection, cluster analysis, Fourier Transform time series, and a number of other multivariate data analysis methods. Chemical models that are usually embedded in source-oriented models can also be used as receptor models to estimate how emissions characteristics might change between

source and receptor and to determine limiting precursors for secondary aerosols that form during transport.

Several books (Hopke, 1985, 1991), specialty conference proceedings (Macias and Hopke, 1981; Hopke and Dattner, 1982; Pace, 1986; Watson, 1989; Watson et al., 1989; Chow et al., 1993c), and review articles (Cooper and Watson, 1980; Gordon, 1980, 1988; Watson, 1984; Javitz et al., 1988a; Watson et al., 2001a; Chow and Watson, 2002; Watson and Chow, 2002b) examine different types and variations of receptor models. Table 1 describes several receptor model types and classifies published references by theory and application. Examples are drawn from many countries throughout the world. Some of the receptor model applications apply to indoor air and personal exposure, but most determine contributions to particles in outdoor air. Neural networks, edge detection, and chemical evolution receptor models are still under development and are of greater interest to researchers than to those attempting to solve air pollution problems. EFs and the CMB are well established and have been widely used to develop pollution control strategies. The multivariate PCA, FA, and EOF models have been used to confirm and sometimes identify unrecognized source types; their use for estimating source profiles for input to the CMB is still under study.

The particle size fractions normally monitored throughout the world are total suspended particulate (TSP, mass of particles with aerodynamic diameters  $\leq 30 \mu\text{m}$ ),  $\text{PM}_{10}$  (aerodynamic diameters  $<10 \mu\text{m}$ ), and  $\text{PM}_{2.5}$  (aerodynamic diameters  $<2.5 \mu\text{m}$ ).  $\text{PM}_{2.5}$  is becoming more commonly measured because this fraction can penetrate deep into the human lung and more efficiently penetrates between outdoor and indoor environments.  $\text{PM}_{2.5}$  contains most of the carbon, sulfate, nitrate, and heavy metal components, while the larger particles are dominated by suspended dust, with some contributions from sea salt, pollen and plant detritus.

This article provides a framework for using receptor models to determine those sources requiring emissions reductions to improve air quality in populated areas

Table 1  
Summary of receptor model types with references to their theory and use

Explanation	Theory and evaluation	Application
<i>Enrichment factors</i>		
The ratios of atmospheric concentrations of elements to a reference element are compared to the same ratios in geological or marine material. Differences are explained in terms of anthropogenic sources. Heavy metal enrichments are usually attributed to industrial emitters. Sulfur enrichment is attributed to secondary sulfate. Potassium enrichment is attributed to burning and cooking. Local soil and road dust compositions often differ from global crustal compositions	Vinogradov (1959), Turekian and Wedepohl (1961), Taylor (1964), Mason (1966), Gordon et al. (1973), Zoller et al. (1974), Rahn (1976), Lawson and Winchester (1979a), Reimann and de Caritat (2000)	Dams et al. (1971), Hoffman and Duce (1972), Hoffman et al. (1972), Moyers and Duce (1972), Tsunogai et al. (1972), Wilkniss and Bressan (1972), Bogen (1973), Bressan et al. (1973), Zoller et al. (1973, 1974), Heindryckx and Dams (1974), Mroz and Zoller (1975), Struempler (1975), King et al. (1976), Neustadter et al. (1976), Meinert and Winchester (1977), Moyers et al. (1977), Rahn et al. (1977), Buat-Ménard and Arnold (1978), Lawson and Winchester (1978, 1979b), Husain and Samson (1979), Fogg and Rahn (1984), Husain et al. (1984), Pacyna (1986), Lowenthal and Rahn (1987b), Sturges (1989), Carter and Borys (1993), Rashid and Griffiths (1993), Benner et al. (1995), Aunela-Tapola et al. (1998), Gatz et al. (1998), Deboudt et al. (1999), Reimann and de Caritat (2000), Chen et al. (2001), Choi et al. (2001), Paciga et al. (1975, 1976), Winchester et al. (1974, 1979)
<i>Chemical mass balance</i>		
Ambient chemical concentrations are expressed as the sum of products of species abundances and source contributions. These equations are solved for the source contributions when ambient concentrations and source profiles are supplied as input. Several different solution methods have been applied, but the effective variance least squares estimation method is most commonly used because it incorporates precision estimates for all of the input data into the solution and propagates these errors to the model outputs	Britt and Luecke (1973), Friedlander (1973a, 1981), Watson (1979), Belsley et al. (1980), Cooper and Watson (1980), Gordon et al. (1981), Core et al. (1982), deCesar and Cooper (1982), Gerlach et al. (1982), Anderson et al. (1984), Dzubay et al. (1984), Stevens and Pace (1984), Daisey (1985), Gordon and Olmez (1986), Holzman et al. (1986), US EPA (1987), Vong et al. (1988), Larson and Vong (1989), Wang and Hopke (1989), Matamala and Nininger (1990), Kim et al. (1992a), Song and Hopke (1996a,b), Gleser (1997), Hopke and Song (1997), Gordon (1980, 1988), Watson et al. (1981, 1984, 1990b, 1991, 1997b, 1998c), Henry (1982, 1992, 1997a), Currie et al. (1984, 1994), deCesar et al. (1985, 1986), Cheng and Hopke (1986, 1989), Lowenthal et al. (1987, 1988, 1992, 1994), Javitz et al. (1988a,b), Lowenthal and Rahn (1988a,b, 1989), Kim and Henry (1989, 1999)	Hidy and Friedlander (1971), Winchester and Nifong (1971), Miller et al. (1972), Kneip et al. (1973), Friedlander (1973a,b), Gartrell and Friedlander (1975), Hammerle and Pierson (1975), Kowalczyk et al. (1978, 1982), Mizohata and Mamuro (1979), Watson (1979), Alpert and Hopke (1980, 1981), Cooper (1980), Dzubay (1980, 1989), Rheingrover and Gordon (1980, 1988), Heisler et al. (1980), Gatz et al. (1981), Stelson and Seinfeld (1981), Houck et al. (1982, 1992), Johnson and McIntyre (1982), Liljestrand (1982), Stolzenburg et al. (1982), Cass and McRae (1983), Feeley and Liljestrand (1983), Rahn and Lowenthal (1984, 1985), Scheff et al. (1984), Stevens et al. (1990), Chow (1985), Lowenthal and Rahn (1985), Mangelson et al. (1985), Sexton et al. (1985), Chow and Spengler (1986), Lewis et al. (1986, 1988), Rau (1986), Eatough et al. (1987, 1992, 1996, 1997a, 1997b, 2000), Iyer et al. (1987), Batterman et al. (1988), Chow et al. (1988b, 1990a,b, 1991a,b, 1992a,b, 1995, 1996b, 1999, 2000), Cooper et al. (1988, 1989), Dresser and Baird (1988), Dzubay et al. (1988), Gray et al. (1988), Hlavinka and Bullin (1988), Magliano (1988), Vong et al. (1988), Casuccio et al. (1989), Dzubay and Mamane (1989), Eatough (1989), Ge et al. (1989), Miller et al. (1989), Rau and Khalil (1989), Stafford and Liljestrand (1989), Vossler et al. (1989), Egami et al. (1990), Kasahara et al. (1990), Kim and Hopke (1990), Pistikopoulos et al. (1990), van Borm et al. (1990), Conner and Stevens (1991), Glover et al. (1991), Toriyama et al. (1991), White and Macias (1991), Yoshizumi (1991), Hawthorne et al. (1992), Heaton et al. (1992), Kim et al. (1992b), Müller (1992), Skidmore and Chow (1992), Vermette et al. (1992), Zelenka et al. (1992, 1993), Annegarn and Pzybylowicz (1993), Wadden et al. (1993), Bighouse and Houck (1994), Sharma and Patil (1994), Sheffield et al. (1994), Venkataraman and Friedlander (1994), Watson et al. (1994b, 1996, 1997a, 1998b, 1999b), Adachi et al. (1995), Kao and Friedlander (1995), Zhu et al. (1995a,b, 1996, 1998, 1999), Lowenthal et al. (1996, 1997a,b), Miguel et al. (1995), Harrison et al. (1996), Hidy and Venkataraman (1996), Schauer et al. (1996), South Coast Air Quality Management District (1996), Chen et al. (1997, 2001), Fujita et al. (1997, 1998), Malm and Gebhart (1997), Vega et al. (1997), Willis et al. (1997), Adgate et al. (1998), Artaxo et al. (1998a,b, 1999), Biegalski et al. (1998), Coe and Chinkin (1998), Liu et al. (1998), Magliano et al. (1998, 1999), Pinto et al. (1998), R.J. Lee Group (1998), Zhang et al. (1998a), Hosiokangas et al. (1999), Pitchford et al. (1999), Brook et al. (2000), Green and Tombach (2000), Engelbrecht et al. (2000, 2001, 2002), Schauer and Cass (2000), Mazzeri et al. (2001), Park et al. (2001a,b), Shu et al. (2001), Temesi et al. (2001), Chow and Watson (2002)

Table 1 (continued)

Explanation	Theory and evaluation	Application
<i>Linear regression</i>		
Mass, sulfate concentrations or light extinction are expressed as a linear sum of unknown regression coefficients times source marker concentrations measured at a receptor. The markers must originate only in the source type being apportioned, which is a stringent assumption rarely met in practice. The regression coefficients represent the inverse of the chemical abundance of the marker species in the source emissions. The product of the regression coefficient and the marker concentration for a specific sample is the tracer solution to the CMB that yields the source contribution	Ito et al. (1986), White (1986, 1989), White and Macias (1987), Milionis and Davies (1994a,b), Lowenthal et al. (1995), Ayers (2001)	Kleinman et al. (1980), Ouimette et al. (1981), Ouimette and Flagan (1982), Kneip et al. (1983), Morandi et al. (1987, 1991), Trijonis et al. (1987), Lowenthal and Rahn (1989), Malm et al. (1990b), Okamoto et al. (1990), Malm and Gebhart (1997), Chan et al. (1999), Green and Tombach (2000)
<i>Temporal and spatial correlation eigenvectors (PCA, FA, EOF)</i>		
Temporal correlations are calculated from a time series of chemical concentrations at one or more locations. Eigenvectors of this correlation matrix are determined and a subset is rotated to maximize and minimize correlations of each factor with each measured species. The factors are interpreted as source profiles by comparison of factor loadings with source measurements. Several different normalization and rotation schemes have been used, but their physical significance has not been established	Armstrong (1967), Blifford and Meeker (1967), Prinz and Stratmann (1968), Crawford (1975), Duerwer et al. (1976), Gether and Seip (1979), Hopke (1981, 1988), Richman (1981, 1986), Hopke et al. (1982, 1983, 1995), Karl et al. (1982), Bergametti et al. (1983), Cooper (1983), Henry (1984, 1986, 1987, 1991, 1997b), Hwang et al. (1984), Chow and Spengler (1986), Ito et al. (1986), Derde et al. (1987), Heidam (1987), Lowenthal and Rahn (1987a), Cheng and Lioy (1989), Henry and Kim (1989, 1990), Zeng and Hopke (1989, 1992a), Henry et al. (1991, 1999), Glover and Hopke (1992, 1994), Green et al. (1992a), Kuik et al. (1993a), Paatero and Tapper (1993, 1994), Richman and Vermette (1993), Nitta et al. (1994), Poissant (1994), Brunet and Vautard (1996), Centner et al. (1996), Moro et al. (1997), Paatero (1997, 1998, 2000) Brumelis et al. (2000)	Blifford and Meeker (1967), Prinz and Stratmann (1968), Vavilova et al. (1969), Peterson (1970), Padmanabhamarty (1975), Hopke (1976, 1981, 1982), Hopke et al. (1976, 1980, 1982, 1988, 1993), Gaarenstroom et al. (1977), Barone et al. (1978), Gatz (1978), Hardy and Walton (1978), Gether and Seip (1979), Henry and Hidy (1979, 1981, 1982), Alpert and Hopke (1980, 1981), Boutron and Martin (1980), Throgmorton (1980), Cox and Clark (1981), Rohbock et al. (1981), Chang et al. (1982), Houck et al. (1982), Lioy et al. (1982), Liu et al. (1982, 1995), Overland and Preisendorfer (1982), Rahn et al. (1982), Roscoe et al. (1982, 1984), Bergametti et al. (1983), Cheng et al. (1993a,b), Hoogerbrugge et al. (1983), Severin et al. (1983), Ashbaugh et al. (1984), Malm et al. (1985, 1987, 1990a), Smeyers-Verbeke et al. (1984), Pitchford and Pitchford (1985), Thurston and Spengler (1985a,b), Wolff and Korsog (1985), Wolff et al. (1985a,b), Chow and Spengler (1986), Crawley and Sievering (1986), Daisey et al. (1986), Thomas (1986), Johnson and Malm (1987), Keiding et al. (1987), Kim et al. (1987), Koutrakis and Spengler (1987), Kim and Hopke (1988), Lowenthal and Rahn (1987a), Lowenthal et al. (1992), Pratsinis et al. (1988), Valaoras et al. (1988), Henry and Kim (1989), Koutrakis et al. (1989), Pio et al. (1989), Artaxo et al. (1990), Artaxo et al. (1998a, 1990), Bomboi et al. (1990), Gebhart et al. (1990), Okamoto et al. (1990), Henry et al. (1991), Morandi et al. (1991), Bridgman (1992), Buhr et al. (1992, 1995, 1996), Green et al. (1992a,b, 1993), Rouhani et al. (1992), Sharma and Patil (1992), Sharma and Singh (1992), Zeng and Hopke (1992b), Gao et al. (1993a,b), Kuik et al. (1993a,b), Michaud et al. (1993, 1996), Richman and Vermette (1993), Anttila et al. (1994), Berg et al. (1994), Brown and Lund (1994), Nitta et al. (1994), Xie et al. (1994a,b, 1999a,b), Plumb and Zheng (1996), Sjögren et al. (1996), Swietlicki et al. (1996), Veltkamp et al. (1996), Deininger and Saxena (1997), Gebhart and Malm (1997), Henry (1997b,c,d), Yoo and Kim (1997), Echalar et al. (1998), Norris et al. (1998), Statheropoulos et al. (1998), Polissar et al. (1998, 1999, 2001a,b), Currie et al. (1999), Huang et al. (1999, 2001), Lee et al. (1999), Li and Deng (1999), Paterson et al. (1999), Rocha et al. (1999), Yakovleva et al. (1999), Ames et al. (2000), Chan et al. (2000), Chueinta et al. (2000), Kim and Henry (2000), Kusmierczyk-Michulec and Marks (2000), Ogawa et al. (2000), Pryor and Barthelmie (2000), Ramadan et al. (2000), Tsai et al. (2000), Hien et al. (2001), Jeon et al. (2001), Kavouras et al. (2001), Park et al. (2001a), Poirot et al. (2001), Roberts et al. (2001), Song et al. (2001)
Spatial correlations are calculated from chemical measurements taken on simultaneous samples at a large number of locations. Eigenvectors of this correlation matrix represent a spatial distribution of source influence over the area, providing that the samplers have been located to represent the gradients in source contributions. As with temporal correlation models, several normalization and rotation schemes have been applied		

*Neural networks*

Known inputs and outputs are presented to a neural network that simulates the human thought process. The network assigns weights to the inputs that reproduce the outputs. Once these patterns have been established for cases where outputs are known, the weights can be applied to input data to estimate outputs. Neural networks can also be used to provide function relationships and represent a solution to the CMB equations

Reibnegger and Weiss (1991), Wienke and Hopke (1994a,b), Wienke et al. (1994a,b, 1995), Song and Hopke (1996a,b), Gardner and Dorling (1998), Reich et al. (1999)

Zelenka et al. (1992, 1994), Boznar et al. (1993), Gao et al. (1994), Wienke et al. (1994a,b, 1995), Xie et al. (1999b,c), Fan et al. (1995), Cheng et al. (1996), Liu et al. (1996), Rege and Tock (1996), Song and Hopke (1996a,b), Comrie (1997), Potukuchi and Wexler (1997), Mihalakakou et al. (1998), Reifman and Feldman (1998), Gardner and Dorling (1999), Reich et al. (1999), Soja and Soja (1999), Song et al. (1999a,b,c), Kao and Huang (2000), Krijnsen et al. (2000), Perez et al. (2000), Silverman and Dracup (2000), Bhave et al. (2001), Pasini et al. (2001)

*Edge detection*

Edges are constant ratios among chemical components that are detected in multi-dimensional space. The data set must contain many samples with multivariate measurements and several samples in which sources types are both present and absent. The “edges” detected by models such as UMIX, are translated into source profile abundances that are used in an implicit or explicit CMB

Henry (1997a, 2000, 2002)

Willis (2000), Poirot et al. (2001)

*Aerosol evolution*

Source profiles containing particle chemical components and gaseous precursors are mathematically “aged” using a chemical reaction scheme. Source profile evolution has been done using Lagrangian source models to simulate the conditions that a profile might encounter en route between source and receptor

Grosjean and Friedlander (1975), Bassett et al. (1981), Friedlander (1981), Lewis and Stevens (1985), Stockwell et al. (1988, 1997), Grosjean and Seinfeld (1989), Wexler and Seinfeld (1991), Pandis et al. (1992), Stockwell (1994), Wexler et al. (1994), Bowman et al. (1995), Fraser et al. (1996), Seinfeld (1997), Kuhn et al. (1998), Seinfeld and Pandis (1998), Zhang et al. (1999), Watson et al. (2002)

Grosjean and Friedlander (1975), Roberts and Friedlander (1975), White et al. (1977), Bassett et al. (1981), Friedlander (1981), Russell et al. (1983), Robinson and Whitbeck (1985), Gordon and Olmez (1986), Iyer et al. (1987), Grosjean and Seinfeld (1989), Latimer et al. (1990), Wexler and Seinfeld (1990, 1991), Pandis et al. (1992), Pankow (1993), Stockwell (1994), Venkataraman and Friedlander (1994), Wexler et al. (1994), McDonald et al. (1996), Kleeman et al. (1997), Lurmann et al. (1997), Gray and Cass (1998), Stockwell et al. (1988, 1990, 2000), Kleeman and Cass (1999), West et al. (1999), Capaldo et al. (2000), Eatough et al. (2000), Chen et al. (2002), Tsuang et al. (2002)

*Gas/particle equilibrium*

The portions of a semi-volatile species in the gas and particle phase are estimated based on receptor measurements. This shows which precursor is in excess and which needs to be diminished in order to reduce

Hänel (1965), Stelson et al. (1979), Stelson and Seinfeld (1982a,b, 1982c), Saxena et al. (1986), Pankow (1987, 1988, 1992, 1994a, 1994b, 1998), Pilinis et al. (1987), Harrison et al. (1990), Harrison and MacKenzie (1990), Pankow and Bidleman (1992),

Stelson et al. (1979), Stelson and Seinfeld (1982a,b, 1982c), Bassett and Seinfeld (1983, 1984), Harrison and Pio (1983), Saxena and Seigneur (1983), Saxena et al. (1986), Pilinis and Seinfeld (1987), Pilinis and Farber (1991), Barrett et al. (1992), Tanner and Harrison (1992), Wexler and Seinfeld (1992), Kim et al. (1993a,b), Koutrakis and Kelly (1993), Mozurkewich (1993), Koloutsou-Vakakis and Rood (1994), Watson et al. (1994c), Kim and Seinfeld (1995), Meng et al. (1995), Hayami and Carmichael (1997),

Table 1 (continued)

Explanation	Theory and evaluation	Application
concentrations in the particle phase. The theory is most highly developed for ammonium nitrate and has been used to determine the extent to which ammonia or oxides of nitrogen reductions are needed to reduce ambient ammonium nitrate levels	Kim et al. (1993a,b), Pankow et al. (1993), Harrison and Msibi (1994), Kim and Seinfeld (1995), Meng et al. (1995, 1997), Matsumoto and Tanaka (1996), Meng and Seinfeld (1996), Jang and Kamens (1998), Ansari and Pandis (1999a,b), Lazaridis (1999), Blanchard et al. (2000), Zhang et al. (2000)	Audiffren et al. (1998), Ansari and Pandis (1999a,b), Diaz et al. (1999), Jacobson (1999), Blanchard et al. (2000), Clegg et al. (2001), Moya et al. (2001)

with a variety of industrial, area, and mobile emissions. An eight-step receptor source apportionment procedure is outlined and illustrated with examples from winter-time Denver, CO (Watson et al., 1998b). These examples are complemented by information extracted from several of the references in Table 1.

## 2. Receptor modeling procedure

Semi-quantitative source apportionment can be applied to existing samples from air quality compliance networks (Chow et al., 2002b), but these networks are seldom designed for source apportionment. Compliance monitoring sites do not usually provide the contrast needed between different times of the day and proximity to or distance from suspected contributors. Filter substrates used for compliance are not usually compatible with all of the needed measurements. Chow and Watson (1994a) and Chow et al. (1996a) describe a “Level 1” (i.e., preliminary or first-level) particulate matter (PM) assessment that can be completed with existing filters as a pilot study to form a conceptual model. The inaccuracy of the Level 1 assessment usually precludes justification for advanced emissions reduction strategies. The following eight steps should be performed when conducting a source apportionment study.

(1) *Formulate conceptual model*: The conceptual model provides a plausible, though not necessarily accurate, explanation of the sources, their zones of influence, transport from distant areas, timing of emissions throughout the day, and meteorology that affects relative emissions rates, transport, dispersion, transformation, and receptor concentration. The conceptual model guides the location of monitoring sites, sampling periods, sampling frequencies, sample durations, the selection of samples for laboratory analysis, and the species that are quantified in those samples. A conceptual model can be postulated from studies in similar areas, from smaller pilot studies (e.g., analysis of archived filters), and analysis of existing air quality and meteorological data.

(2) *Compile emissions inventory*: Receptor models need to be supplied with sources that are potential contributors. A receptor model inventory requires only source categories, not the locations and emission rates of specific sources. While ducted point source emissions can be reasonably estimated through source tests and operating records, area and mobile source emissions are inexact. The most common cause of differences between relative source contributions from source and receptor models is inaccurate emissions estimates (Core et al., 1981; Ryan et al., 1988; Watson and Chow, 2000; Watson et al., 2000). Receptor model results focus resources on those source emissions that are the most important contributors to excessive PM concentrations.



(3) *Characterize source emissions*: Chemical or physical properties that are believed to distinguish among different source types are measured on representative emitters. Source profiles are the mass abundances (fraction of total mass) of chemical species in source emissions. Source profiles are intended to represent a category of source rather than individual emitters. The number and meaning of these categories is limited by the degree of similarity between the profiles. Several compilations of particle profiles have been produced that might be applicable to a Level 1 source assessment (Watson, 1979; Sheffield and Gordon, 1986; Cooper et al., 1988; Olmez et al., 1988; Ahuja et al., 1989; Chow and Watson, 1989, 1994b; Core, 1989; Houck et al., 1989, 1990; Shareef et al., 1989; Watson and Chow, 2001a; Watson et al., 2001b). These profiles do not necessarily represent those that affect an area where they were not measured.

(4) *Analyze ambient samples for mass, elements, ions, carbon, and other components from sources*: Elements, ions (chloride, nitrate, sulfate, ammonium, water-soluble sodium, and water-soluble potassium), and organic (OC) and elemental carbon (EC) are sufficient to account for most of the particle mass. Additional properties such as molecular organic compounds, isotopic abundances, and single particle characteristics further distinguish source contributions from each other, even though they may not constitute large mass fractions.

(5) *Confirm source types with multivariate model*: If a sufficient number of chemically characterized ambient samples is available (more than 50), PCA and other multivariate analyses are helpful to determine the source types and profile characteristics that might be contributors.

(6) *Quantify source contribution*: The CMB model estimates source contributions based on the degree to which source profiles can be combined to reproduce ambient concentrations. The CMB attributes primary particles to their source types and determines the chemical form of secondary aerosol when the appropriate chemical components have been measured. Modern CMB software (Watson et al., 1990b, 1997b) requires specification of input data uncertainty and calculates standard errors for source contribution estimates. Table 1 provides detailed references on how to use the CMB.

(7) *Estimate profile changes and limiting precursors*: Source characteristics may change during transport to the receptor, the most common being changes of sulfur dioxide and oxide of nitrogen gaseous emissions to sulfate and nitrate particles. These changes can be simulated with aerosol evolution models (Watson and Chow, 2002a). Secondary ammonium sulfate and ammonium nitrate involve ammonia from non-combustion sources that may be a limiting precursor. Chemical equilibrium receptor models determine the extent to which one

precursors need to be diminished to achieve reductions in ammonium nitrate levels.

(8) *Reconcile source contributions with other data analyses and source models*: Since no model, source or receptor, is a perfect representation of reality the results must be independently challenged. Receptor model source contributions should be consistent between locations and sampling times. Discrepancies between source contributions estimated by receptor models and emissions inventories or source model should be reconciled. A “weight of evidence” from multiple source attribution approaches should add confidence to the control strategies that are developed.

Examples are given below for each of the eight steps to be performed in a source apportionment study.

### 2.1. Step 1: Form a conceptual model

A conceptual model describes the relevant physical and chemical processes that affect emissions, transport, and transformation by taking advantage of the large body of scientific knowledge already acquired. Citations in Table 1 propose several conceptual models (e.g., Pun and Seigneur, 1999; Watson and Chow, 2002a) that might be adapted to other areas. Widely applicable conceptual models and their implications for receptor model monitoring are:

*Motor vehicle exhaust is the major PM contributor and originates mostly from downtown traffic during morning rush hours.* Carbon measurements are taken before, during, and after rush hours at downtown and residential locations. Specific organic markers for diesel and gasoline exhaust are quantified.

*The majority of particulate sulfate forms by regional photochemical reactions.* Sulfate measurements are taken at an urban site and at an upwind regional site during the summer and compared with similar sulfate measurements during winter.

*The majority of personal exposure results from side-stream cigarette smoke.* Nicotine measurements are acquired from personal samplers attached to representative individuals that spend time in smoking and non-smoking environments.

*Non-urban windblown dust is a major source of urban particle concentrations.* Elemental measurements are taken at a downtown site and in an up-wind barren area (e.g. desert, playa, unplanted field) during windy and non-windy situations. Short time duration (<5 min) particle measurements are acquired with a continuous monitor and correlated with wind speeds of similar duration.

Denver measurements were based on the following conceptual model for PM<sub>2.5</sub>: (1) secondary ammonium nitrate is a large component of wintertime PM<sub>2.5</sub>, is of local rather than regional origin, is dominated by oxides

of nitrogen emissions from mobile emissions rather than elevated power station emissions, and is limited by nitric acid production rather than by available ammonia; (2) PM carbon is dominated by diesel exhaust and wood smoke, with less important contributions from gasoline exhaust and cooking; and (3) fugitive dust contributions are minimal, except when roads are sanded after snow, and is from manmade deposits rather than natural wind erosion during winter. To evaluate these concepts, nitric acid and ammonia gas measurements were needed with particulate ammonium nitrate and ammonium sulfate measurements at urban and non-urban sites. Specific organic compounds were needed to separate the different carbon source contributions. Elemental concentrations were needed to differentiate coal fly ash from suspended dust. Urban and non-urban monitors were needed with nighttime and morning samples that would bracket morning traffic and nighttime heating emissions. Testing this conceptual model also required extensive meteorological measurements at the surface and aloft to determine how surface and elevated emissions would mix throughout the day.

## 2.2. Step 2: Compile emissions

Emission models (Dickson and Oliver, 1991) estimate temporal and spatial emission rates based on activity level, emission rate per unit of activity, and meteorology. Emissions models apply emission factors measured for a range of activity levels from representative sources to values for those activities estimated for a study area. Commonly used activity surrogates are: (1) fuel consumed, product produce, or material inputs for industrial sources; (2) vehicle miles traveled, fuel sales, miles of roadway, or vehicle registrations for mobile source emissions; and (3) population density, number of households or businesses, amount of residential wood or coal sold for area source emissions. Activity data are often unavailable for the spatial scales desired of source models, and emissions are estimated for a larger area (e.g., a county, state, or province) and spatially allocated to a smaller scale based on population census tracts, land-use maps, and roadway networks. An accurate inventory for source modeling often requires greater effort and expense than field monitoring for air quality concentrations and meteorology.

US EPA (1999) publishes AP-42 emission factors used to formulate national inventories, but these are often inappropriate for specific airsheds, especially those outside of the US. This is recognized in the AP-42 introduction that recommends locally derived emission factors, where possible, and reiterates the limitations of factors derived from a few tests at other times and places.

Emissions inventory models are often used to develop control strategies by linear rollback modeling

(Barth, 1970; deNevers and Morris, 1975; Cass, 1981; Cass and McRae, 1981, 1983). The linear rollback model assumes that atmospheric concentrations in excess of background are proportional to aggregate emission rates. Reducing excessive concentrations of a pollutant to levels below a pre-set standard requires emissions reductions that are proportionally equal to the relative amount by which the standard is exceeded. Receptor models are often used in conjunction with linear rollback to determine the contribution of source categories to excessive concentrations. The linear rollback is then performed on a category-specific basis, starting with the largest contributors. This is a more accurate method of justifying emissions reductions than a rollback of un-specified PM because the relative emissions from individual sources within a category are believed to be more accurate than the absolute emissions within the category or the relative emissions between source categories (e.g., Cass and McRae, 1981, 1983).

While source models need spatial and temporal resolution and very accurate emissions rates, receptor models need only a seasonal or annual average, area-wide inventory to identify potential source categories. Individual emitters must be grouped into more generalized categories with similar source profiles. For example, an outdoor inventory will often contain separate entries for power generation, industrial, and institutional coal combustion. Since these combustion processes, and often the coal, are similar in a given airshed, it is unlikely that their contributions can be distinguished by the CMB and they must be combined into a "coal-burning category". Source categories that are often combined for particulate receptor modeling are:

*Vegetative burning and cooking:* Fireplaces, wood stoves, prescribed burns, wildfires, char-broiling, and meat cooking. Some of these sub-categories may be separated when appropriate organic compounds are measured.

*Diesel exhaust:* Heavy and light duty cars and trucks, off-road equipment, stationary engines for pumps and generators, and locomotives.

*Gasoline exhaust:* Heavy and light duty cars and trucks, and small engines. Emissions inventories do not usually contain breakdowns by cold-starts and poorly maintained vehicles, although these might be discriminated by certain organic compounds in a profile. Since leaded fuels are no longer used in the US, there is no need to separately apportion use of this fuel, but leaded gasoline is still in use in many other countries.

*Fugitive dust:* Paved roads, unpaved roads, agricultural tilling, construction, wind erosion, and industrial aggregate. These can sometimes be divided into sub-categories based on single particle shape and elemental content or the measurement of specific mineral composition.

**Metals:** Copper smelters, lead smelters, steel mills, and aluminum mills. These often have similar metal emissions but in different abundances depending on the process.

**Aggregate handling:** Cement, quarrying, and mining. Ores, in particular, are often enriched in the materials being extracted and sub-categories may be defined for these cases. When low level measurements of trace elements such as copper, zinc, and lead are made, metal processing operations that use these materials can be classified into separate categories.

Indoor inventories might include the following particulate source types (Sexton et al., 1986; Sexton and Hayward, 1987; Koutrakis et al., 1992): (1) outdoor air that infiltrates through doors, windows, and poor insulation; (2) house dust from track-in and resuspension from vacuuming and personal movement; (3) cooking, both from the fuel combustion and the food, especially during frying; (4) sidestream smoke when the building contains smokers; (5) animal dander and fur in the presence of pets and other animals; (6) molds, spores, and fungi, especially those that form and are entrained from ventilation ducts; (7) vehicle exhaust in commuter transport compartments; and (8) a large variety of occupational emissions, depending on the type of work involved.

Table 2 summarizes wintertime outdoor emission rates for several source categories in the Denver, CO, metropolitan area. Similar sources and pollutants are found in most urban areas. Inventories should include primary particles that are directly emitted by sources (PM<sub>10</sub> and PM<sub>2.5</sub>) as well as gaseous precursors for

secondary particles that form in the atmosphere. Sulfur dioxide, ammonia, and oxides of nitrogen are the precursors for sulfuric acid, ammonium bisulfate, ammonium sulfate, and ammonium nitrate particles that often constitute major fractions of PM<sub>2.5</sub> and PM<sub>10</sub>. Volatile organic compounds (VOC) are involved in photochemical reactions that engender sulfuric acid, nitric acid, particle-phase organics, as well as ozone. VOC precursors that convert to secondary organic particles are those with more than 6–8 carbon atoms (Pandis et al., 1992), and canister-based hydrocarbons are only valid for species with less than 12 carbon atoms.

Table 2 reflects the fact that most particle emissions from combustion sources are in the PM<sub>2.5</sub> fraction, while fugitive dust emissions are mostly in the coarse (PM<sub>10</sub> – PM<sub>2.5</sub>) fraction. This is consistent with source measurements of particle size fractions. Coarse particles are produced by grinding of larger particles to smaller particles while fine particles are produced by condensation, coagulation, and gas-to-particle conversion common to combustion sources.

Table 2 indicates that fugitive dust sources from paved and unpaved roads, sanding, and construction constitute 79% of PM<sub>10</sub> and 43% of PM<sub>2.5</sub> emissions. Fugitive dust is a large fraction of all emissions inventories and is inconsistent with the amount of geological material found in ambient air in most locations. Detailed examination of fugitive dust emission factors (Watson and Chow, 2000; Watson et al., 2000; Countess et al., 2001) shows that these are derived from horizontal fluxes in upwind/downwind experiments in

Table 2  
Wintertime emissions estimates for the Denver, CO, metropolitan area<sup>a</sup>

Source type	Source emission rate estimates (tons/day)						
	PM <sub>10</sub>	PM <sub>2.5</sub>	SO <sub>2</sub>	NO <sub>x</sub>	NH <sub>3</sub>	VOC	CO
Gasoline exhaust	1.7	1.6	3.3	137.7	– <sup>b</sup>	157.6	1340.8
Visibly smoking gas exhaust	0.2	0.2	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>
Diesel exhaust	5.0	4.9	1.5	36.1	– <sup>b</sup>	8.4	30.9
Off-road diesel exhaust	1.8	1.8	1.7	27.4	– <sup>b</sup>	14.3	111.7
Wood burning	1.8	1.8	0.0	0.0	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>
Road dust and sand	49.6	7.4	0.0	0.0	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>
Coal power stations	1.3	0.7	62.1	64.3	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>
Other industries	7.8	2.6	16.7	47.8	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>
Natural gas	0.5	0.5	0.0	28.4	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>
Unpaved road dust	28.2	4.2	0.0	0.0	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>
Restaurant cooking	1.4	1.4	0.0	0.0	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>
Construction dust	2.2	0.3	0.0	0.0	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>
Biogenic	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>	3.0	– <sup>b</sup>	31.3	0.0
Industrial	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>	34.8	22.3
Area sources	– <sup>b</sup>	– <sup>b</sup>	– <sup>b</sup>	1.0	– <sup>b</sup>	89.8	72.3
Total	101.6	27.5	85.2	345.7	– <sup>b</sup>	336.2	1578.0

<sup>a</sup> From Regional Air Quality Council (1998), “Review of Blueprint for Clean Air Emissions Inventory”, April 8 as summarized in Watson et al. (1998b).

<sup>b</sup> Not estimated for the Denver area owing to lack of activity data or emissions factors.

which 60–90% of the emissions are within the lowest two meters above ground level. Since these low level emissions are likely to deposit within a few hundred meters of the emissions point, they should not be part of emission factors used to represent urban-scale inventories.

Mobile source combustion emissions from diesel and gasoline engines operating on- and off-road are important contributions in nearly all urban areas. Fujita et al. (1997) identified two-stroke engines, common on small motorbikes, as an important mobile source category in Bangkok, Thailand. For the Denver area, Table 2 shows that motor vehicle exhaust (the sum of gasoline, diesel, and off-road emissions) constitutes 31% of  $PM_{2.5}$  emissions, with diesel (including off-road) representing more than 79% of vehicle exhaust. Poorly maintained gasoline vehicles, identified by visible exhaust, constitute 11% of gasoline-fueled vehicle emissions and only 2% of total vehicle emissions.

Vehicle emission testing is expensive, and it is difficult to recruit commercially used trucks for testing; as a result, the California emissions inventory is based on tests of 6000 light-duty gasoline vehicles, as compared to only 70 heavy-duty diesel trucks (Lloyd and Cackette, 2001a,b). Recent tests have shown large discrepancies between motor vehicle emission factors and on-road tests for a variety of pollutants. Hansen and Rosen (1990) report measurements from Berkeley, CA, of carbon emissions from individual vehicles in on-road operation. They measured the ratio of light-absorbing carbon to  $CO_2$  as vehicles drove past the Lawrence Berkeley Laboratory, and found a factor of 250 between the highest and lowest ratio for 60 gasoline-fueled vehicles. They did not categorize vehicles by weight and age, but the range of ratios shows the potential for large uncertainties in these factors. Further evidence of these discrepancies was found by using remote sensing of individual tailpipe emissions for carbon monoxide, hydrocarbons, and oxides of nitrogen (Bishop et al., 1989, 1996, 1997; Ashbaugh et al., 1992; Stedman et al., 1993; Zhang et al., 1993; Cadle and Stephens, 1994; Stephens et al., 1996; Johnson et al., 1998; Singer et al., 1998). Remote sensing shows that approximately 20% of the on-road vehicles emit nearly 80% of the pollutants. Excess emissions are due to off-cycle operating conditions and poor-maintenance that are not well represented by laboratory dynamometer studies. Remote sensors for suspended particles are still being developed, although excessive gaseous emissions detected by current technology probably indicate poor combustion properties that also increase particle emissions over those currently estimated by emissions models.

Table 2 shows that residential wood combustion (RWC) constitutes  $\sim 7\%$  of  $PM_{2.5}$  emissions for wintertime Denver. This estimate includes the effectiveness of control measures such as new technology stoves and no-

burn days that were implemented after a 1988 receptor modeling study found wood-burning contributing 25% of wintertime  $PM_{2.5}$  in Denver (Watson et al., 1988). Special tests of wood-burning emissions (McDonald et al., 2000) using contemporary wood-burning methods were made for the Denver area.

The impact of cooking on indoor air has been well documented (Truesdale, 1982; Davidson et al., 1986; Reid et al., 1986; Ahuja et al., 1987; Raiyani et al., 1993; Smith, 1995; Ballard-Tremeer and Jawurek, 1996; Fan and Zhang, 1998; Albalak et al., 1999; Lee et al., 2001), and its effects on outdoor  $PM_{2.5}$  concentrations have been identified (Hildemann et al., 1991; Rogge et al., 1991; McDonald et al., 1998; Kleeman et al., 1999; Nolte et al., 1999; Schauer et al., 1999; Mugica et al., 2001). Table 2 indicates that  $\sim 5\%$  of  $PM_{2.5}$  is emitted by this source. For Table 2 emissions, refineries, cement production, grain handling, and aggregate handling operations were quantified with 12% of  $PM_{2.5}$  emissions; coal-fired power stations emitted 2.5% of  $PM_{2.5}$  while other combustion, mostly with natural gas, is estimated to contribute  $\sim 2\%$  of the total.

Table 2 shows nearly 60% of the oxides of nitrogen deriving from mobile sources, with coal-fired power generation emitting 19% of the total. Coal is the major sulfur dioxide emitter in areas where it is used, and this is evident for Denver. Motor vehicle fuels also include sulfur that may be more influential for the formation of wintertime sulfate if it is emitted into ground-level fogs under stagnant conditions where conversion can be very rapid. A significant quantity (8%) of sulfur dioxide derives from mobile sources, with half of that deriving from on-road and off-road diesel exhaust.

Fig. 1 shows how inventory  $PM_{2.5}$  emissions are combined into source categories that can be distinguished at receptors by their chemical components. This figure assumes that measured organic compounds used in CMB calculations can distinguish among different carbon sub-types such as cooking/burning and gasoline/diesel exhaust. These sub-types usually cannot be distinguished by commonly applied elemental/ion/carbon analyses. All of the fugitive dust sources are combined because distinguishing species have not yet been developed that conclusively separate paved road, unpaved road, and construction sources. Salt used as a de-icing material can be detected, but it does not have a constant abundance relative to other geological materials because it is applied intermittently and is soon washed away by melting snow.

### 2.3. Step 3: Characterize sources

Analogous to the measurement of emission factors, source profiles are created by sampling emissions from a variety of single emitters or small groups of emit-

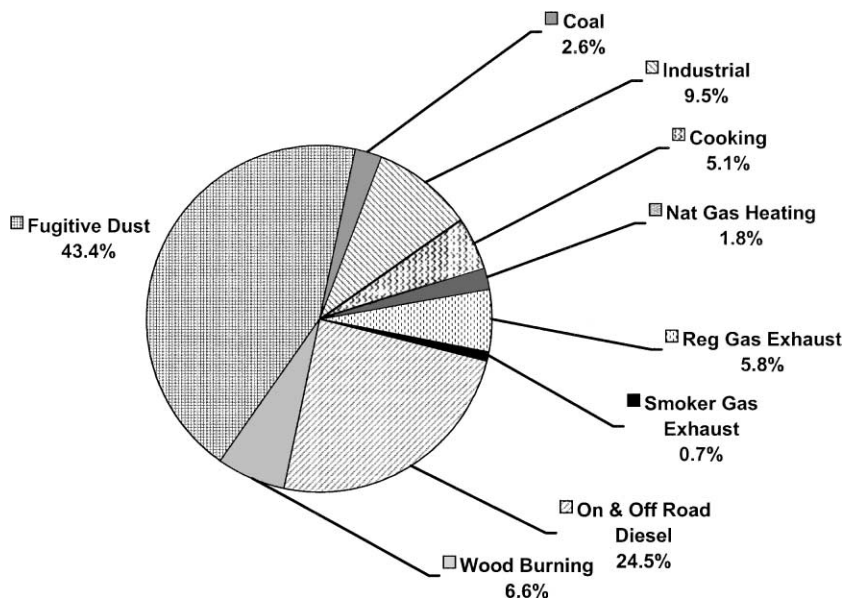


Fig. 1.  $PM_{2.5}$  emissions from Table 2 are combined into categories that might be resolved by receptor models. Paved road dust, unpaved road dust, and construction emissions are summed, as are on-road and off-road diesel emissions.

ters. These samples are then submitted to a variety of chemical and physical analyses to determine those properties that will allow contributions from the sources they represent to be distinguished at receptors. The mass for each of these properties is normalized to a common property in the emissions from all sources, typically the  $PM_{10}$  or  $PM_{2.5}$  mass emissions rate. This mass fraction is termed the species abundance.

Individual profiles are formed from single samples, and the precisions of the numerator and denominator of the species abundances are propagated (Watson et al., 2001c) to obtain the individual profile uncertainties. These individual profiles are further composited to obtain the source profiles used for CMB source apportionment. The simplest composite consists of the average and standard deviation of species abundances for all individual profiles within a group. For example, if ten tests of diesel vehicle exhaust are taken, the composite species abundance is an average of the ten individual profile abundances and the uncertainty is the standard deviation of that average. Outlier tests are applied to reject individual profiles that unduly bias the average and standard deviation of the composite profile. There are always some outliers in any series of source tests, usually for reasons that can never be determined. It is important to obtain ten or more samples that run the range of operating conditions and fuels in an area to develop source profiles.

The ideal source sampling method would allow for chemical and physical transformations of source emissions to occur prior to sample collection. Lacking this

ideal, the sampling would at least quantify the precursors of the receptor profile so that a theoretically or empirically derived transformation could be applied. The following methods (Gordon et al., 1984; Chow et al., 1988a; Watson and Chow, 2001a; Watson et al., 2001b) are commonly used for different source types to obtain samples from which profiles may be determined:

**Hot exhaust sampling:** Effluent is extracted from a duct or stack at emissions temperatures and drawn through filters. The EPA “Method 201” stack test method is most commonly applied in the US to determine compliance with  $PM_{10}$  emissions standards. Hot exhaust does not permit the condensation of vapors into particles prior to sampling, and it sometimes interferes with the sampling substrate or container. In coal-fired station emissions, the selenium does not condense on other particles until temperatures approach ambient. Hot exhaust samples are not often taken on substrates or in containers amenable to extensive chemical analysis. Even though it is widely used for compliance, hot exhaust sampling is not appropriate for receptor modeling studies.

**Diluted exhaust sampling:** Effluent extracted from a duct is mixed with clean ambient air so that gases can condense on particles (Heinsohn et al., 1980; Hildemann et al., 1989; Zielinska et al., 1998; England et al., 2000). The near-ambient temperature effluent is then drawn through substrates that are analyzed for the desired properties. Diluted exhaust samplers are used for laboratory simulations of emissions from individual sources. Dynamometer simulations use diluted exhaust sampling to estimate emissions for different vehicle types, fuels,

and driving conditions. Wood stove, fireplace, and cookstove emissions can also be simulated by dilution sampling of representatives in a laboratory or field environment.

*Airborne sampling:* Effluent is drawn from a plume aloft after it has cooled to near ambient temperatures but before it is dominated by the particles present in the background air. Aircraft, balloons, and cranes have been used to elevate sampling systems into the plume (Anderson et al., 1977, 1998; Armstrong et al., 1981; Hering et al., 1981; Gillani and Wilson, 1983; Shah et al., 1989; Cahill et al., 1992; Baxter and Pederson, 1994; Lagomarsino and Latner, 1997; Hofmann et al., 1998; Greenberg et al., 1999). With airborne sampling it is possible to follow a large plume and examine how source profiles change as secondary aerosol is formed. Difficulties of airborne plume sampling are: (1) locating the sampler in the plume instead of ambient air; (2) staying in the plume long enough to obtain a sufficient sample for chemical analysis; and (3) mixing of ambient air with the plume, so the source profile is really a combination of emissions and ambient air.

*Ground-based sampling:* Ambient samples are taken in locations and during time periods for which a single source type dominates the emissions. Ground-based source sampling methods are identical to receptor sampling methods with the requirements that: (1) meteorological conditions and sampling times are conducive to domination by a particular source; (2) samples are of short enough duration to take advantage of those conditions; and (3) aerosol from other interfering sources is low or can be apportioned and removed from the sample. Tunnels, parking garages, vehicle staging areas, and isolated but heavily traveled roadways are often used to obtain samples for motor vehicle exhaust. Tunnels are especially useful for this because a large number of vehicles can be evaluated with little interference from sources other than suspended road dust (Pierson and Brachaczek, 1976, 1983; Chang et al., 1981; Hering et al., 1984; Miguel, 1984; Lonneman et al., 1986; Benner et al., 1989; Dannecker et al., 1990; Pierson et al., 1990, 1996; Zielinska and Fung, 1994; Khalili et al., 1995; Barrefors, 1996; Bishop et al., 1996; Duffy and Nelson, 1996; Gertler and Pierson, 1996; Moeckli et al., 1996; Gertler et al., 1997; Weingartner et al., 1997; Fraser et al., 1998; Gillies et al., 1998, 2001; Rogak et al., 1998; Staehelin et al., 1998). Using short-duration source-dominated samples, Rheingrover and Gordon (1988) and Annegarn et al. (1992) characterized several point sources using ambient sampling downwind of the source. Chow (1985) examined the effects of an elevated coal-fired power plant emission on ground-based samples in a rural environment with this method.

*Grab sampling and laboratory resuspension:* A sample of pollution residue is obtained and suspended in a chamber for sampling onto filters (Chow et al., 1994;

Carvacho et al., 1996). This is most applicable to nonducted fugitive and industrial dust emissions. A sample swept, shoveled, or vacuumed from a storage pile, transfer system, or roadbed can be taken to represent these source types. Five to ten different samples from the same source are averaged to obtain a representative source profile.

Ground-based and grab sampling are the most cost-effective and practical methods for most situations, although large industrial stack emissions require diluted sampling and mobile source sub-types (e.g., high emitting vehicles) can only be isolated in laboratory dynamometer tests.

Source profiles for Denver are qualitatively similar to those found elsewhere, although the abundances vary depending on local conditions. In geological material, aluminum (Al), silicon (Si), potassium (K), calcium (Ca), and iron (Fe) have large abundances with low variabilities. The total potassium (K) abundance is often 10–30 times the abundance of soluble potassium ( $K^+$ ) in fugitive dust. Aluminum (Al), potassium (K), calcium (Ca), and iron (Fe) abundances are similar among dust profiles. Lead (Pb) is sometimes abundant in paved road dust, but it is <0.005% in the other geological profiles, probably due to deposition from previously emitted leaded-gasoline vehicle exhaust or remnants of lead from the exhaust trains of older vehicles. EC abundances are highly variable in geological material, and are often negligible in natural soil samples. OC is typically 5–15% in geological emitters. OC is most abundant in paved road and agricultural dusts, although the specific compounds probably differ for these two sources. Vehicle brake wear, tire wear, and oil drips could result in greater abundances of Pb, EC, and OC in paved road dust. Soluble sulfate, nitrate, and ammonium abundances are usually low, in the range of 0–0.5%. Sodium and chloride are also low, with less than 0.5% in abundance. Larger abundances of these materials may occur soon after roadway de-icing.

OC and EC are the most abundant species in motor vehicle exhaust, typically accounting for over 95% of the total mass. Lead, bromine, and chloride are good markers for gasoline exhaust in areas where leaded fuels are used, but lead is quickly being eliminated in most areas and is completely gone from fuels used in the United States. Watson et al. (2001b) found an OC/TC ratio of 0.58 in the composite vehicle profile for northwestern Colorado. Earlier measurements in Denver, CO (Watson et al., 1990a) reported an OC/TC ratio of 0.39 for the cold transient cycle and 0.81 for the cold stabilized cycle.

OC and EC are also abundant in wood burning and cooking emissions. Watson et al. (2001b) compared RWC, residential coal combustion (RCC), and forest fire  $PM_{2.5}$  profiles. Average OC abundances ranged from ~50% in RWC and the forest fire profiles to ~70% in the

RCC profile. EC averaged 3% in forest fire, 12% in RWC, and 26% in RCC. The OC/TC ratio was highest in the forest fire profile (0.94) and similar for the two residential combustion profiles, with 0.73 in RCC and 0.81 in RWC. Watson and Chow (2001a) measured profiles for asparagus field burning in California's Imperial Valley with OC/TC ratios of 0.93, similar to the 0.94 ratio for forest fire emissions. A similar observation was made for charbroil cooking emissions, with 60–70% OC abundances and high (>0.95) OC/TC ratios. The  $K^+/K$  ratios of 0.80–0.90 in burning profiles (Calloway et al., 1989) are in large contrast to the low soluble to total potassium ratios found in geological material.

Coal-fired power generation profiles differ substantially from residential coal burning, even though the fuels are similar, owing to the different combustion conditions and different emissions. Sulfate is one of the most abundant constituents in the particle phase and sulfur dioxide can be hundreds to thousands of times higher than the particle mass. Sulfur dioxide is a good indicator of contributions from nearby coal-fired power stations when it has not reacted or deposited significantly during transport to a receptor. Crystal elements such as Si, Ca, and Fe are often present at 30–50% of the corresponding levels in geological material, while Al abundances are similar to or enriched over those found in surface soils. Other elements such as phosphorus (P), potassium (K), titanium (Ti), chromium (Cr), manganese (Mn), strontium (Sr), zirconium (Zr), and barium (Ba) are often detectable at less than 1% levels.

All of the elemental abundances are highly dependent on the ash composition of the parent coal, as well as the specific combustion process and pollution control devices. Watson et al. (2001b) detected selenium (Se) at the level of 0.2–0.4% in coal-fired power station emissions with no scrubbers or wet scrubbers, but not in emissions from a unit with a dry limestone scrubber. Se is usually in the gaseous phase within hot stack emissions, and it condenses on particles when air is cooled in the dilution chamber. Abundances of Ca (15%), Cl (1%), and nitrate (1%) in the limestone-scrubbed unit were a few times higher than in the other units. These differences may have resulted from the dry lime scrubber, which added some calcium and absorbed the selenium in the vapor phase.

These examples show that although there are similarities in chemical compositions for different sources, using source profiles from one airshed or time period may not provide a valid CMB apportionment for ambient samples in another airshed or in another time period. Source emissions of precursor gases and primary particles are highly variable due to differences in fuel use, operating conditions, and sampling methods. Source and ambient measurements must be paired in time to establish reasonable estimates of source/receptor relationships. Trace metals acquired from elemental analysis

of Teflon-membrane filters are only abundant in the geological and some industrial profiles. Elemental measurements by themselves are necessary, but insufficient, for a receptor modeling study. Chemical speciation must also include ammonium, sulfate, nitrate, OC, and EC. Separating carbon fractions with the use of different combustion temperatures and atmospheres can also be a useful tool in source apportionment studies (Chow et al., 1993b). Watson et al. (1994a), using the thermal evolution method in the IMPROVE protocol (Chow et al., 1993b, 2001), showed that gasoline- and diesel-powered vehicle emissions exhibit different abundances of different fractions of OC and EC. Engelbrecht et al. (2002) used seven carbon fractions in their CMB analysis to distinguish source contributions between regular and low-smoke RCC. Simultaneous gas measurements as well as other characteristics of suspended particles will be needed as more refined control strategies are developed using receptor models.

The Denver example measured organic compounds such as those listed in Table 3 in both source and receptor samples to apportion source sub-types such as meat cooking, wood burning, and exhaust from different vehicle operating modes. Sampling and analysis methods for organic compounds are still being perfected. Organic analyses are more difficult or costly to apply than currently available elemental, ion, and carbon measurements.

#### 2.4. Step 4: Analyze samples for material balance

A material balance is a preliminary source apportionment that allocates TSP,  $PM_{10}$ , or  $PM_{2.5}$  to geological material, OC, EC, sulfate, nitrate, ammonium, and possibly salt (from marine aerosol, de-icing, or windblown dry lake beds). Several summaries of particle sampling and analysis methods (Watson and Chow, 1993, 1994, 2001b; Chow and Watson, 1994a, 1998; Chow, 1995) describe ambient sampling and chemical analysis options. The material balance requires elemental, ionic, and carbon analyses. Although not a source apportionment, the material balance provides guidance on which components are the major cause of excessive mass concentrations. This knowledge can focus efforts to improve the emissions inventory for source modeling and allows a speciated linear rollback model to be applied for initial control strategy development. The following sample analysis hierarchy (updated from Chow et al., 1996a) demonstrates how elemental, ionic, and carbon concentrations can be measured for different levels of resources:

*Analyze archived filter samples:* High-volume quartz-fiber filter samples used to determine mass for compliance with air quality standards are sub-optimal for chemical analysis, but they are commonly available throughout the world. These filters have already been

Table 3  
Organic compounds from different OC emission and in ambient air

Species	Predominant sources	Particle–gas phase distribution
<i>PAH</i>		
Naphthalene	Motor vehicles, wood smoke	Gas phase
Methylnaphthalenes	Motor vehicles, wood smoke	Gas phase
Dimethylnaphthalenes	Motor vehicles, wood smoke	Gas phase
Biphenyl	Motor vehicles, wood smoke	Gas phase
Acenaphthylene	Motor vehicles, wood smoke	Gas phase
Acenaphthene	Motor vehicles, wood smoke	Gas phase
Fluorene	Motor vehicles, wood smoke	Gas phase
Phenanthrene	Motor vehicles, wood smoke	Particle–gas phase
Anthracene	Motor vehicles, wood smoke	Particle–gas phase
Fluoranthene	Motor vehicles, wood smoke	Particle–gas phase
Pyrene	Motor vehicles, wood smoke	Particle–gas phase
Retene	Motor vehicles, wood smoke	Particle–gas phase
Benzo[ <i>b</i> ]naphtho[2,1]thiophene	Motor vehicles	Particle phase
Benz[ <i>a</i> ]anthracene	Motor vehicles, wood smoke	Particle phase
Chrysene	Motor vehicles, wood smoke	Particle phase
Benzo[ <i>b + j + k</i> ]fluoranthene	Motor vehicles, wood smoke	Particle phase
Benzo[ <i>a</i> ]pyrene	Motor vehicles, wood smoke	Particle phase
Indene[123- <i>cd</i> ]pyrene	Motor vehicles, wood smoke	Particle phase
Dibenzo[ <i>ah + ac</i> ]anthracene	Motor vehicles, wood smoke	Particle phase
Benzo[ <i>ghi</i> ]perylene	Motor vehicles, wood smoke	Particle phase
Coronene	Motor vehicles, wood smoke	Particle phase
<i>Hopanes and Steranes</i>		
Cholestanes	Motor vehicles	Particle phase
Trisnorhopanes	Motor vehicles	Particle phase
Norhopanes	Motor vehicles	Particle phase
Hopanes	Motor vehicles	Particle phase
<i>Guaiacols</i>		
4-Methylguaiacol	Wood smoke	Gas phase
4-Allylguaiacol	Wood smoke	Particle–gas phase
Isouegenol	Wood smoke	Particle–gas phase
Acetovanillone	Wood smoke	Particle phase
<i>Syringols</i>		
Syringol	Wood smoke, mostly hardwood	Particle–gas phase
4-Methylsyringol	Wood smoke, mostly hardwood	Particle–gas phase
Syringaldehyde	Wood smoke, mostly hardwood	Particle phase
<i>Lactones</i>		
Caprolactone	Meat cooking	Gas phase
Decanolactone	Meat cooking	Particle–gas phase
Undecanoic- $\gamma$ -lactone	Meat cooking	Particle–gas phase
<i>Sterols</i>		
Cholesterol	Meat cooking	Particle phase
Sitosterol	Meat cooking, wood smoke	Particle phase

weighed to determine mass concentration. They can be analyzed for elements by X-ray fluorescence (Watson et al., 1999a) with appropriate corrections for filter absorption and blank subtraction; for ions by ion chromatography (Chow and Watson, 1999) and atomic absorption spectrophotometry (Chow et al., 2002b), and for carbon by thermal combustion carbon analysis (Chow et al., 1993b, 2001). Aluminum and silicon cannot be quantified on these samples because they are part

of the filter matrix. Other trace elements may also be present in the filter matrix as impurities, and large fractions of volatile species such as ammonium nitrate may have evaporated during storage (Witz et al., 1990). For PM<sub>2.5</sub> standard attainment, US EPA requires sampling with low-volume federal reference method (FRM) samplers equipped with Teflon-membrane filters. These samples can be analyzed for elements by X-ray fluorescence. Sulfate can be estimated from the sulfur concen-



tration. Nitrate and sulfate ions can be subsequently measured by ion chromatography, except that heating and vacuum stages during X-ray fluorescence analysis enhances nitrate volatilization and results in a low estimate of nitrate concentration.

**Planned compliance sampling:** If it is known that chemical analyses will be applied to some or all of the high-volume  $PM_{10}$  or low-volume  $PM_{2.5}$  samples, several precautions should be taken. When procuring filters, minimally acceptable blank concentrations should be stated for each chemical to be quantified. Filter holders that mate to the high-volume  $PM_{10}$  sampler or  $PM_{2.5}$  FRM sampler should be obtained, and filters should be loaded and unloaded using gloved hands in a laboratory setting to minimize contamination. The passive period in the sampler before and after air is drawn through the filter should be minimized, and filters should be stored in clean containers under refrigeration after weighing.

**Collocated filter sampling:** An additional sampler with a Teflon-membrane filter appropriate for complete elemental analysis can be collocated with the high-volume  $PM_{10}$  compliance sampler. This filter should also be pre- and post-weighed and submitted to the same acceptance testing and storage conditions described for planned compliance sampling. For the  $PM_{2.5}$  FRM, collocated quartz-fiber filters appropriate for ion and carbon analysis are needed. Chow (1995) identifies several sampling systems that can be collocated. A Minivol sampler with a  $5 \text{ l min}^{-1}$  flow rate (Baldauf et al., 2001; Chow et al., 2002a) is a cost-effective method of adding additional filter media to a sampling site.

**Collocated continuous monitor sampling:** Watson et al. (1998a) and McMurry (2000) describe several continuous particle detectors that can obtain mass, mass-surrogates, and chemical- or size-specific concentrations over averaging periods of 1–60 min duration. These monitors can identify diurnal patterns, associate high concentrations with wind directions from sources, and provide indicators of concentrations between infrequent filter samples (which are often every sixth day). Nephelometers with “smart” heaters are the most cost-effective continuous monitors. These measure light scattering rather than particle mass, but good relationships between the two variables can often be established (Chow et al., 2002c). Since light scattering increases rapidly as soluble particles take on water at humidities exceeding 70%, a smart heater in the sample line provides a temperature increase sufficient to maintain sampler humidities below this threshold. Constant heating at high temperatures (typically  $>30 \text{ }^\circ\text{C}$ ) causes volatile particles to evaporate, thereby negatively biasing the mass estimate.

**Sequential filter sampling:** Daily samples, or samples taken during different parts of the day, are often needed to evaluate pollution buildups or to relate concentra-

tions to human exposure or observed health end-points. Sequential filter samplers using several filter media in parallel have been used to acquire these types of filters for subsequent analysis (e.g., Chow et al., 1993a; Chow, 1995). Sequential sampling systems have been applied in  $PM_{2.5}$  FRM networks across the US. Several filters are loaded and a timing mechanism switches the flow through different sets of filters at pre-set intervals.

**Saturation sampling:** An area can be saturated with small, battery-powered samplers to evaluate the zone of representation for long-term monitors and the zone of influence for source emissions. This strategy is useful for spatial correlation receptor models and when chemical profiles of specific emitters are too similar to differentiate them from each other. Samplers are located within and around the suspected emitters (Tropp et al., 1998; Blanchard et al., 1999; Chow et al., 1999, 2002a; Gillies et al., 1999).

**Denuder and absorbant sampling:** Volatile substances such as ammonium nitrate and organic compounds require denuders and gas-absorbing backup filters (Kitto and Colbeck, 1999). Precursor gases for chemical receptor models can also be obtained from these sampling strategies.

Fig. 2 illustrates a material balance for a single high volume TSP sample from a sample in Xian, China. This sample had a relatively high TSP mass loading ( $336 \mu\text{g m}^{-3}$ ) and was measured on a day with stagnant meteorology in a residential area. The commonly held conceptual model in Xian is that most of the high TSP concentrations result from dust storms in the region

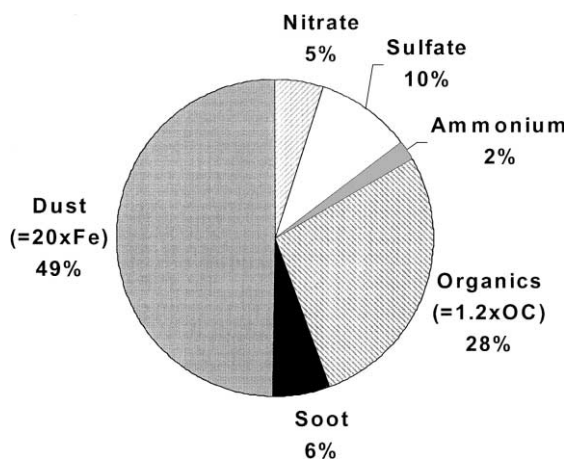


Fig. 2. Material balance for a 24-h  $336 \mu\text{g m}^{-3}$  TSP quartz filter sample from an eastern urban site in Xian, China for October 27, 1997. Aluminum and silicon cannot be quantified on these samples because they are in the filter matrix and much of the nitrate may have volatilized before analysis. Fugitive dust emissions are estimated as 20 times the iron concentration and OC is multiplied by 1.2 to account for unmeasured hydrogen and oxygen associated with urban organic compounds.

(Zhang et al., 1996, 1997, 1998b). The simple material balance in Fig. 2 demonstrates that only half of the TSP is due to dust. Given the low wind speeds during the sampling period, most of this is probably from nearby roads and vacant land rather than windblown loess in the desert. This could be further verified by comparison with simultaneous samples taken at other sites closer to cleaner or dirtier roadways. OC and EC account for 34% of TSP mass, indicating that combustion sources are a major portion of TSP. Secondary sulfate constitutes a relatively low fraction. Although the nitrate concentration is a minor portion of TSP, it is probable that much of the original nitrate sampled was lost from the filter prior to chemical analysis. Additional archived samples for different time periods and locations would need to be analyzed and compared to form a conceptual model. Some of these should include periods of high winds

when desert dust might be a large contributor. This simple analysis on archived filters helps to focus emissions characterization efforts and future network design by establishing the most abundant components of the suspended particle mass. It suggests that primary emissions reductions for local dust and combustion sources (both mobile and area) should be pursued to reduce ambient concentrations.

The other extreme for the material balance is illustrated in Fig. 3 for two  $PM_{2.5}$  pollution episodes near Denver, CO. Samples were taken during the morning, afternoon, and overnight on consecutive days. The days selected for detailed chemical analysis were determined after examining mass concentrations measured on each sample, thereby reducing the study cost by minimizing analyses on low concentration samples. Three pollution episodes can be detected in these data, each with dif-

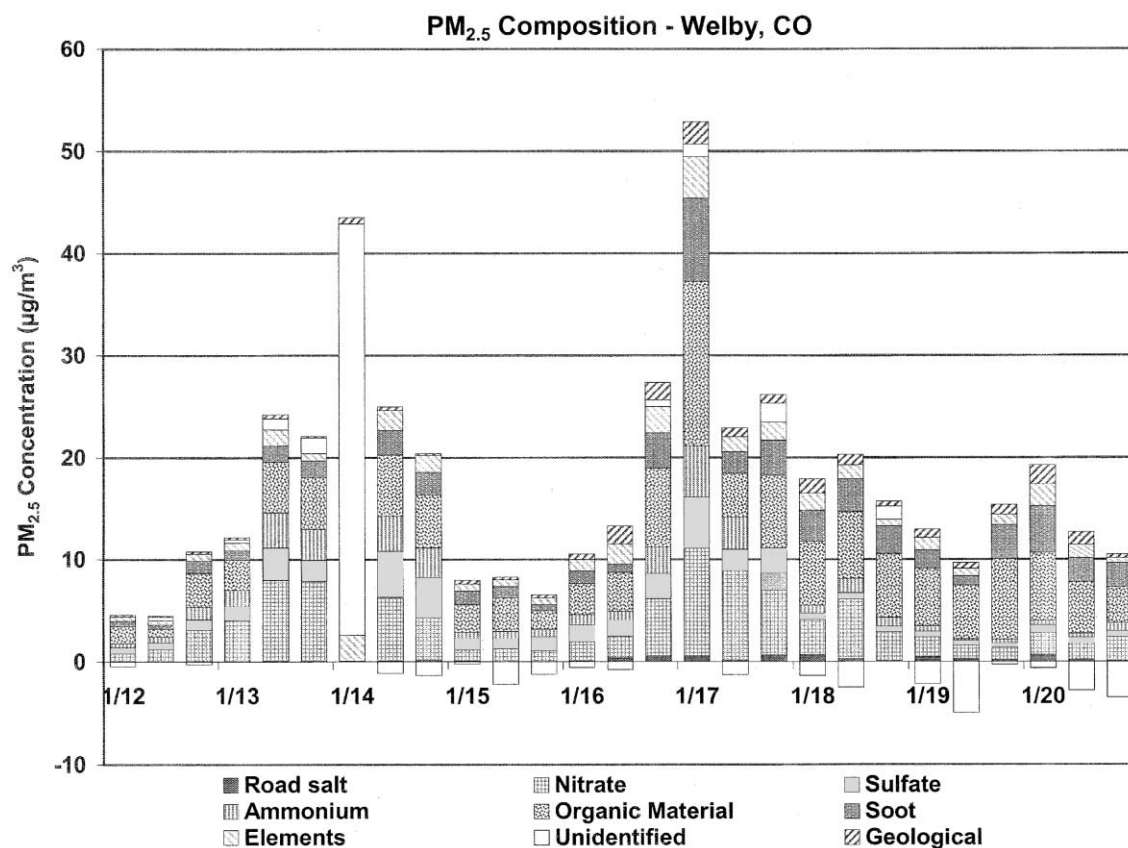


Fig. 3. Material balance for  $PM_{2.5}$  concentrations measured at Welby, CO, located on the northern edge of Denver, resulting from gravimetric, elemental, ion, and carbon analysis (Watson et al., 1998b). Three samples per day were acquired from 0600 to 1200, 1200 to 1800, and 1800 to 0600 MST with the first sample centered over the date in 1996. Organic material is 1.4 times the OC measurement to compensate for unmeasured hydrogen and oxygen (Turpin and Lim, 2001). Geological is defined as  $1.89Al + 2.14Si + 1.4Ca + 1.43Fe$  to account for unmeasured oxides in minerals. Soot is operationally defined as EC reported by the IMPROVE thermal/optical reflectance method (Chow et al., 1993b, 2001). The unidentified fraction is the difference between measured mass and the sum of other components. This is negative when the sum exceeds the measured mass. The unidentified amount is typically within measurement uncertainties when elements, ions, and carbon are measured.

ferent compositions. The first two that peak on the mornings of January 14, 1996 and January 17, 1996 have secondary ammonium nitrate and OC and EC as their most abundant components. The episode peaking on the morning of January 20, 1996 is dominated by OC and EC. Examining wind directions in conjunction with the evolution of these episodes shows  $PM_{2.5}$  levels are highest when secondary sulfate and nitrate are transported back into the city where they mix with fresh emissions.

The morning sample on January 14, 1996 experienced an invalid sample for the quartz filter, so carbon and ion analyses were not performed. This sample illustrates the need for ions and carbon to obtain a material balance. The elements account for less than 10% of the measured  $PM_{2.5}$  mass, even when the geological marker elements are weighted for unmeasured oxides.

### 2.5. Step 5: Multivariate analysis

Several multivariate data analysis methods should be applied to the data to confirm potential source contributions. These should make use of whatever air quality and meteorological measurements are available within the study area. Several useful analyses are described below.

*Time series plots:* Mass concentrations are plotted for each sampling period, similar to that illustrated in Fig. 3, and compared among different monitoring locations. Similar temporal patterns and concentrations indicate urban or regional scale source contributions, while a large divergence at one site indicates a middle-scale or neighborhood-scale source influence. This is extremely useful in short duration, continuous measurements. Using a successive moving average subtraction method, Watson and Chow (2001a) demonstrated that short-duration pulses in 5-min black carbon concentrations caused by nearby sources can be used in urban areas to estimate spatial zones of influence. Seasons and days of the week on which highest concentrations occur can be detected. Examination of these plots and comparisons among different sampling sites assists the selection of a sample subset for chemical analysis.

*Diurnal plots:* When continuous particle monitoring data are available, average concentrations can be calculated for each hour over a subset of days to identify patterns. These patterns can be associated with meteorological conditions and emissions for different sites. These plots often reveal increases in concentrations during morning and evening rush hours on weekdays at downtown locations that are not seen on weekends or at residential sites. This indicates that local traffic emissions are large contributors. The evening traffic peak may not appear during summer when mixed layers are deep later into the evening, but it will be very evident during winter when sunset corresponds to evening traf-

fic. Residential heating with wood or coal often appears as an elevated nighttime concentration that does not decay until very early the following morning.

*Pollution roses:* Averages of hourly or shorter time duration data can be calculated for wind direction sectors. Watson and Chow (2002a) showed that large concentrations associated with a given wind direction indicate a major source from that direction. Frequent wind direction shifts over a 24-h period usually preclude this type of analysis for day-long samples.

*Time series correlation:* Correlation coefficients can be calculated for chemical concentrations to determine which ones vary together and which ones do not. High correlation coefficients usually indicate origin from a common source or effects of common meteorology on all sources.

*Spatial correlation:* High spatial correlations among chemical components indicate urban or regional source influences, while low correlations indicate that the chemical component is mostly from nearby origin.

*Eigenvector analysis:* As explained in Table 1, time series or spatial eigenvector analysis in the form of PCA, FA, or EOF defines a smaller sample space for the measured chemical concentrations that can sometimes be related to source contributions. Source profiles from direct measurements are needed to interpret these eigenvectors.

All of these methods except the spatial eigenvector analysis were applied by Watson et al. (1998b) for the Denver study prior to estimating source contributions. These analyses provided the conceptual bases for selecting the source profiles applied to each individual sample on which chemical components were measured.

### 2.6. Step 6: Calculate source contributions

All of the multivariate models include, implicitly or explicitly, a CMB that quantifies source contributions. The CMB expresses each aerosol property concentration measured at a receptor as the sum of a source contribution multiplied by the abundance of the corresponding aerosol property in the source emissions. When these equations are not collinear (i.e., source profiles substantially differ among different emitters) and the chemical abundances in the source profile are reasonably constant (i.e., standard deviations less than half the average abundance for representative source tests), these equations can be solved for the source contributions. Species abundances and the receptor concentrations, with appropriate uncertainty estimates, serve as input data to the CMB model. The output consists of the amount contributed by each source type represented by a profile to the total mass and each chemical species.

The CMB modeling procedure requires: (1) identification of the contributing sources types; (2) selection of

chemical species or other properties to be included in the calculation; (3) estimation of the fraction of each of the chemical species which is contained in each source type (source profiles); (4) estimation of the uncertainty in both ambient concentrations and source profiles; and (5) solution of the CMB equations. Several solutions methods have been proposed for the CMB equations that are documented in Table 1 citations. Of these, the effective variance weighted solution (Watson et al., 1984) is almost universally applied because it: (1) theoretically yields the most likely solutions to the CMB equations, providing model assumptions are met; (2) uses all available chemical measurements, not just so-called “tracer” species; (3) analytically estimates the uncertainty of the source contributions based on precisions of both the ambient concentrations and source profiles; and (4) gives greater influence to chemical species with higher precisions in both the source and receptor measurements than to species with lower precisions.

CMB model assumptions are: (1) compositions of source emissions are constant over the period of ambient and source sampling; (2) chemical species do not react with each other (i.e., they add linearly); (3) all sources with a potential for contributing to the receptor have been identified and have had their emissions characterized; (4) the number of sources or source categories is less than or equal to the number of species; (5) the source profiles are linearly independent of each other; and (6) measurement uncertainties are random, uncorrelated, and normally distributed.

The degree to which these assumptions are met in applications depends to a large extent on the particle and gas properties measured at source and receptor. CMB model performance is examined generically, by applying analytical and randomized testing methods, and specifically for each application by following an applications and validation protocol. The six assumptions are fairly restrictive and they will never be totally complied with in actual practice. Fortunately, the CMB model can tolerate reasonable deviations from these assumptions, as documented in the theory and testing references of Table 1. Deviations from assumptions may increase the stated uncertainties of the source contribution estimates.

The formalized protocol for CMB model application and validation (Pace and Watson, 1987; Watson et al., 1991, 1998c) is applicable to the apportionment of gaseous organic compounds and particles. This seven-step protocol: (1) determines model applicability; (2) selects a variety of profiles to represent identified contributors; (3) evaluates model outputs and performance measures; (4) identifies and evaluates deviations from model assumptions; (5) identifies and corrects of model input deficiencies; (6) verifies consistency and stability of source contribution estimates; and (7) evaluates CMB results with respect to other data analysis and source

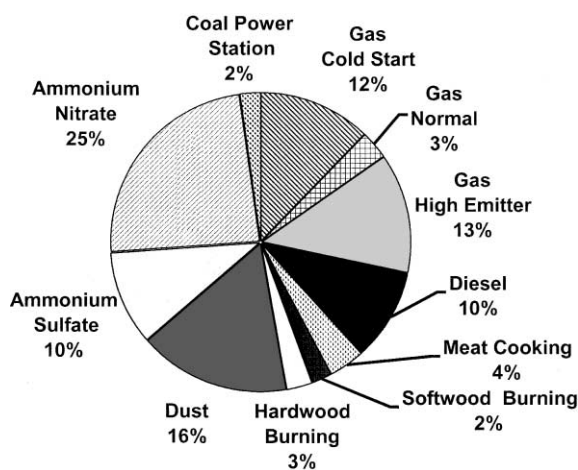


Fig. 4. Average 1997 wintertime source contribution estimates to  $PM_{2.5}$  determined by the CMB receptor model for samples taken at Welby, CO, located on the northern edge of Denver, CO.

assessment methods. Chow and Watson (2002) found that this protocol was seldom followed in more than 20 recent CMB applications.

Fig. 4 shows average source contributions for the Denver samples obtained by following this protocol. Using organic compounds measured at source and receptor, it was demonstrated that meat cooking could be distinguished from wood burning. The three classes of gasoline vehicle exhaust (hot stabilized, cold start, and high emitters) could be distinguished by CMB from their source profiles. These sub-groups needed to be combined for receptor sites where only the elements, ions, and carbon were measured.

#### 2.7. Step 7: Evaluate limiting precursors of secondary aerosol

Most applications use source profiles measured at the source, with at most dilution to ambient temperatures and <1 min of aging prior to collection to allow for condensation and rapid transformation. Profiles have been “aged” with aerosol evolution models (Watson et al., 2002), prior to submission to the CMB. These models simulate changes between source and receptor; they are often overly simplified and require additional assumptions regarding chemical mechanisms, relative transformation and deposition rates, mixing volumes, and transport times.

Changes in ammonia or nitric acid precursor concentrations do not proportionally result in reductions in ammonium nitrate concentrations. Ammonia concentrations might increase with emissions (e.g., larger fertilizer applications, a larger number of farm animals) or from reductions in sulfur dioxide emissions that would

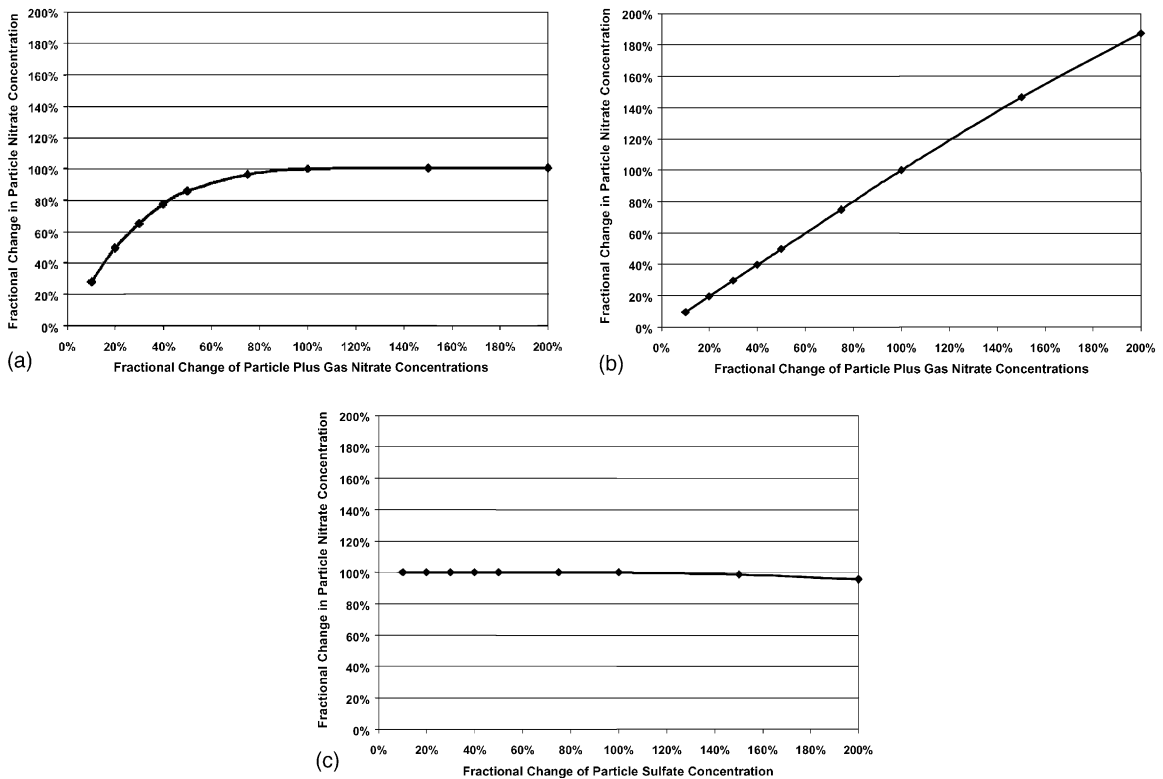


Fig. 5. Effects of changes in (a) ammonia, (b) nitric acid, and (c) sulfate levels that might result from emissions control strategies on average ammonium nitrate concentrations estimated using the simulating composition of atmospheric particles at equilibrium (SCAPE) method (Kim et al., 1993a,b; Kim and Seinfeld, 1995). SCAPE, an example of an aerosol equilibrium receptor model, apportions sodium, nitrate, sulfate, ammonium, and chloride among gas, liquid, and solid phases using thermodynamic equilibrium theory. These averages were derived from thousands of individual SCAPE simulations applied to 3-h periods over which particulate nitrate, sulfate, and ammonium and gaseous nitric acid and ammonia were measured at urban and non-urban receptor sites in the Denver area. Ambient temperature and relative humidity corresponding to the samples are the other SCAPE inputs. The horizontal axis represents the fraction of the measured 1997 concentration.

provide less sulfuric acid to react with existing ammonia. Conversely, ammonia emission reductions owing to urbanization might reduce ammonia concentrations. Ansari and Pandis (1998) and Blanchard et al. (2000) have created nomographs that allow a screening process for limiting precursors.

Fig. 5a–c shows how change in ammonia, nitric acid, and sulfate affect ambient concentrations in wintertime Denver. Fig. 5a shows no increases in ammonium nitrate result from increases in ammonia concentrations; a 25% reduction in ammonia results in a minor reduction in particle nitrate and a 50% ammonia reduction reduces particle nitrate by only 15%. After a 50% ammonia reduction, however, particulate nitrate decreases are nearly proportional to ammonia reductions. Ammonia levels must be reduced by more than half before large reductions of particulate nitrate are realized.

This contrasts with Fig. 5b that examines effects of nitric acid reductions on particulate nitrate. Change in

nitric acid, presumably resulting from changes in  $\text{NO}_x$  emissions that contribute to nitric acid, result in a direct and proportional reduction in  $\text{PM}_{2.5}$  ammonium nitrate concentrations. Fig. 5c shows that there is no sensitivity to changes in sulfate levels. There is sufficient free ammonia in the Denver area that the small amount of ammonia freed by removing ammonium sulfate from the atmosphere has no effect on ammonium nitrate levels. Sulfate concentrations would need to increase by more than double to engender even a slight decrease in ammonium nitrate concentrations.

## 2.8. Step 8: Reconcile source contributions

Fig. 4 shows discrepancies with the proportional contributions from the inventory in Fig. 1. Comparisons between emissions inventories and receptor source contributions are not exact because: (1) primary particle inventories do not include the secondary aerosol

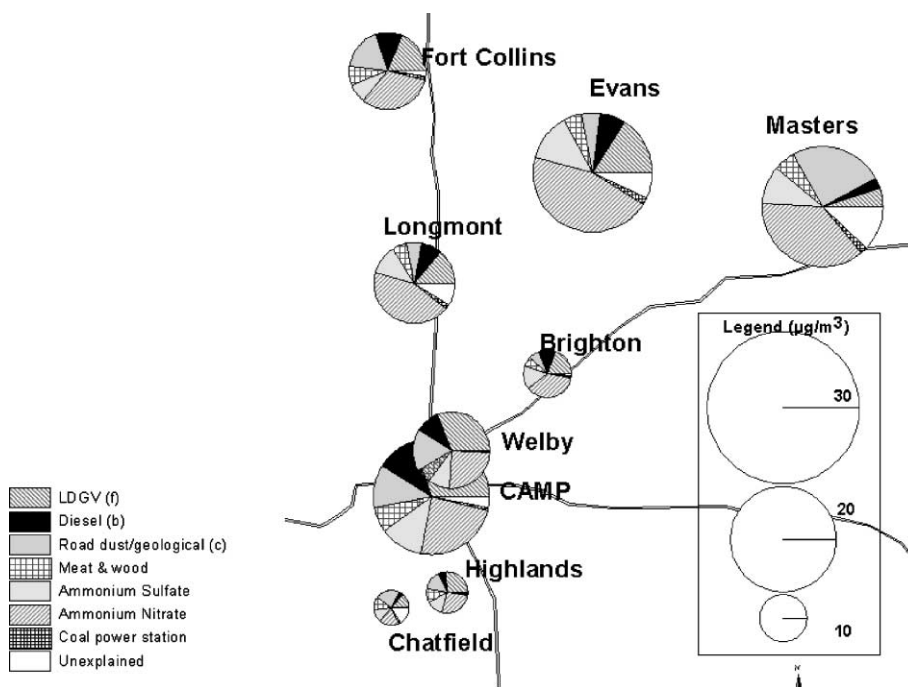


Fig. 6. Average source contributions to  $PM_{2.5}$  at seven receptor locations around Denver, CO, during the winter of 1995–1996.

determined by receptor models; and (2) inventories are usually averaged over large areas and time periods while receptor model source contributions apply to the zone of representation of the receptor and to the time period over which samples were taken.

Major discrepancies were found between emissions estimates and receptor source apportionment of ambient samples for wintertime Denver, CO. Secondary ammonium sulfate and ammonium nitrate accounted for 35% of  $PM_{2.5}$  in the receptor samples. Although sulfur dioxide and oxides of nitrogen emissions are often included in urban inventories, the fraction that converts to sulfate and nitrate can only be determined by source or receptor modeling. Ammonia emissions that engender the ammonium portion of these secondary contributions are seldom estimated. The emissions inventory estimated that 45% of emissions resulted from fugitive dust sources, while the receptor model source apportionment found the dust contribution to be 16%. The inventory showed that diesel exhaust constituted 80% of mobile source emissions, while receptor analysis with organic compounds showed that diesel exhaust constituted only ~25% of the mobile source contributions. This finding has resulted in focusing efforts on better representing the emissions from gasoline vehicles in the inventory used for control strategy development and source modeling. This was a substantial deviation from the conceptual model stated earlier, and it is justification for refining that model.

Fig. 6 shows how source contributions vary among the seven measurement locations in the Denver area. There were similar  $PM_{2.5}$  mass concentrations at both urban (Welby, CAMP, Fort Collins) and non-urban (Brighton, Evans, and Masters) sites, but the composition was quite different. The non-urban sites were dominated by secondary sulfate and nitrate. Analyzing sequential and diurnal samples along with wind flow patterns shows that oxides of nitrogen generated in the urban area mix in low lying fogs with ammonia from the rural areas results in higher secondary sulfate and nitrate levels that add mass to the primary particles generated within the city. This is another refinement to the original conceptual model.

### 3. Summary and conclusions

Receptor models complement source models for evaluating the contributions from different sources to measured concentrations. They use chemical characteristics measured at both source and receptor to accomplish this apportionment. Elemental analysis is necessary, but not sufficient for receptor models. Elements, ions, and carbon must be measured at a minimum. Additional chemical components such as organic compounds, carbon fractions, isotopic abundances, and single particle characteristics are methods that are being developed to further distinguish among source types.

Substantial information can be obtained from relatively inexpensive chemical analyses of archived filters, although these are not optimal for quantitative receptor source apportionment. The cost of a receptor modeling study needs to be balanced against the value of the information obtained from the study. Examples from a modern receptor study in wintertime Denver showed that emission estimates from gasoline vehicles were substantially underestimated and fugitive dust emissions were overestimated. The planned emissions reduction strategies to focus on diesel emissions reductions would not yield the expected benefits. Gasoline vehicle exhaust from cold starts and high emitting (poorly maintained) vehicles were identified as large contributors that were not adequately represented by the inventory. The intended control strategy of reducing oxides of nitrogen emissions to improve ammonium nitrate levels was confirmed by demonstrating that there is sufficient ammonia to neutralize available nitric acid. The costs of implementing emissions reduction strategies that did not result in the desired effects on air quality would be hundreds of times the cost of the receptor modeling study and would prolong human exposure in the area to excessive particle concentrations until the effective control strategies were identified.

### Disclaimer

This paper was supported in part by EPA. However, it has not undergone technical review by EPA. Therefore, the views are those of the authors and do not represent EPA policy. Mention of trade names or commercial products does not constitute EPA endorsement or recommendation.

### References

- Adachi, A., Okiayu, M., Nishikawa, A., Kobayashi, T., 1995. Evaluation of source apportionment to suspended particulate matter in air samples collected from Kobe area by chemical mass balance method. *J. Hyg. Chem.* 41 (2), 167–171.
- Adgate, J.L., Willis, R.D., Buckley, T.J., Chow, J.C., Watson, J.G., Rhoads, G.G., Liroy, P.J., 1998. Chemical mass balance source apportionment of lead in house dust. *Environ. Sci. Technol.* 32 (1), 108–114.
- Ahuja, D.R., Joshi, V., Smith, K.R., Venkataraman, C., 1987. Thermal performance and emission characteristics of unvented biomass-burning cookstoves: A proposed standard method for evaluation. *Biomass* 12, 247–270.
- Ahuja, M.S., Paskind, J.J., Houck, J.E., Chow, J.C., 1989. Design of a study for the chemical and size characterization of particulate matter emissions from selected sources in California. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 145–158.
- Albalak, R., Keeler, G.J., Frisancho, A.R., Haber, M., 1999. Assessment of PM<sub>10</sub> concentrations from domestic biomass fuel combustion in two rural Bolivian highland villages. *Environ. Sci. Technol.* 33 (15), 2505–2509.
- Alpert, D.J., Hopke, P.K., 1980. A quantitative determination of sources in the Boston urban aerosol. *Atmos. Environ.* 14, 1137–1146.
- Alpert, D.J., Hopke, P.K., 1981. A determination of the sources of airborne particles collected during the regional air pollution study. *Atmos. Environ.* 15 (5), 675–687.
- Ames, M.R., Gullu, G., Beal, J., Olmez, I., 2000. Receptor modeling for elemental source contributions to fine aerosols in New York state. *J. Air Waste Mgmt. Assoc.* 50 (5), 881–887.
- Anderson, J.A., Blumenthal, D.L., Sem, G.J., 1977. Characterization of Denver's urban plume using an instrumented aircraft. In: Russel, P.A. (Ed.), *Denver Air Pollution Study-1973*. US Environmental Protection Agency, Research Triangle Park, NC.
- Anderson, B.E., Cofer, W.R., Bagwell, D.R., Barrick, J.W., Hudgins, C.H., Brunke, K.E., 1998. Airborne observations of aircraft aerosol emissions—1. Total nonvolatile particle emission indices. *Geophys. Res. Lett.* 25 (10), 1689–1692.
- Anderson, M.K., Brookman, E.T., Londergan, R.J., Yocom, J.E., Watson, J.G., Liroy, P.J., 1984. Source apportionment techniques and considerations in combining their use. In: *Receptor Model Technical Series, vol. V. Report No. EPA-450/4-84-020*. US Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.
- Annegarn, H.J., Braga Marcazzan, G.M., Cereda, E., Marchionni, M., Zucchiatti, A., 1992. Source profiles by unique ratios (SPUR) analysis: Determination of source profiles from receptor-site streaker samples. *Atmos. Environ. A* 26 (2), 333–343.
- Annegarn, H.J., Pzybylowicz, W.J., 1993. Total CMB analysis of streaker aerosol samples by PIXE, PIGE, beta- and optical-absorption analyses. *Nucl. Instrum. Meth. Phys. Res. Sec. B—Beam Interact. Mater. Atoms B* 75 (1–4), 582–587.
- Ansari, A.S., Pandis, S.N., 1998. Response of inorganic PM to precursor concentrations. *Environ. Sci. Technol.* 32 (18), 2706–2714.
- Ansari, A.S., Pandis, S.N., 1999a. An analysis of four models predicting the partitioning of semivolatile inorganic aerosol components. *Aerosol Sci. Technol.* 31 (2–3), 129–153.
- Ansari, A.S., Pandis, S.N., 1999b. The effect of metastable equilibrium states on the partitioning of nitrate between the gas and aerosol phases. *Atmos. Environ.* 34 (1), 157–168.
- Anttila, P., Paatero, P., Tapper, U., Järvinen, O., 1994. Application of positive matrix factorization to source apportionment: Results of a study of bulk deposition chemistry in Finland. *Atmos. Environ.* 29, 1705–1718.
- Armstrong, J.S., 1967. Derivation of theory by means of factor analysis or Tom Swift and his electric factor analysis machine. *Am. Stat.* 12, 17–21.
- Armstrong, J.A., Russell, P.A., Sparks, L.E., Drehmel, D.C., 1981. Tethered balloon sampling systems for monitoring air pollution. *J. Air Pollut. Control Assoc.* 31, 735–743.

- Artaxo, P., Andrade, F., Maenhaut, W., 1990. Trace elements and receptor modelling of aerosols in the Antarctic peninsula. *Nucl. Instrum. Meth. Phys. Res. B* 49, 383–387.
- Artaxo, P., Fernandes, E.T., Martins, J.V., Yamasoe, M.A., Hobbs, P.V., Maenhaut, W., Longo, K.M., Castanho, A., 1998a. Large-scale aerosol source apportionment in Amazonia. *J. Geophys. Res.* 103 (D24), 31837–31847.
- Artaxo, P., Fernandes, E.T., Martins, J.V., Yamasoe, M.A., Hobbs, P.V., Maenhaut, W., Longo, K.M., Castanho, A., 1998b. Large-scale aerosol source apportionment in Amazonia. *J. Geophys. Res.* 103 (D24), 31837–31847.
- Ashbaugh, L.L., Myrup, L.O., Flocchini, R.G., 1984. A principal component analysis of sulphur concentrations in the western United States. *Atmos. Environ.* 18 (4), 783–791.
- Ashbaugh, L.L., Lawson, D.R., Johnson, B.J., Huang, S., Bishop, G.A., Guenther, P.L., Stedman, D.H., Stephens, R., Groblicki, P.J., Parikh, J., 1992. On-road remote sensing of carbon monoxide and hydrocarbons emissions during several vehicle operating conditions. In: Chow, J.C., Ono, D.M. (Eds.), *Transactions, PM<sub>10</sub> Standards and Nontraditional Source Controls*. Air and Waste Management Association, Pittsburgh, PA, pp. 885–898.
- Audiffren, N., Renard, M., Buisson, E., Chaumerliac, N., 1998. Deviations from the Henry's law of equilibrium during cloud events: A numerical approach of the mass transfer between phases and its specific numerical effects. *Atmos. Res.* 49 (2), 139–162.
- Aunela-Tapola, L., Hatanpaa, E., Hoffren, H., Laitinen, T., Larjava, K., Rasila, P., Tolvanen, M., 1998. A study of trace element behavior in two modern coal-fired power plants—II. Trace element balances in two plants equipped with semi-dry flue gas desulphurisation facilities. *Fuel Processing Technology* 55 (1), 13–34.
- Ayers, G.P., 2001. Comment of regression analysis of air quality data. *Atmos. Environ.* 35 (13), 2423–2425.
- Baldauf, R.W., Lane, B.D., Marotz, G.A., Wiener, R.W., 2001. Performance evaluation of the portable MiniVol particulate matter sampler. *Atmos. Environ.* 35, 6087–6091.
- Ballard-Tremere, G., Jawurek, H.H., 1996. Comparison of five rural wood-burning cooking devices: Efficiencies and emissions. *Biomass Bioenergy* 11, 419–430.
- Barrefors, G., 1996. Air pollutants in road tunnels. *Sci. Total Environ.* 189–190, 431–436.
- Barrett, J.C., Clement, C.F., Ford, I.J., 1992. The effect of redistribution on aerosol removal rates. *J. Aerosol Sci.* 23 (6), 639–656.
- Barth, D., 1970. Federal motor vehicle emissions goals for CO, HC, and NO<sub>x</sub> based on desired air quality levels. *J. Air Pollut. Control Assoc.* 20 (8), 519–527.
- Barone, J.B., Cahill, T.A., Eldred, R.A., Flocchini, R.G., Shadoan, D.J., Dietz, T.M., 1978. A multivariate statistical analysis of visibility degradation at four California cities. *Atmos. Environ.* 12, 2213–2221.
- Bassett, M.E., Gelbard, F.G., Seinfeld, J.H., 1981. Mathematical model for multicomponent aerosol formation and growth in plumes. *Atmos. Environ.* 15, 2395–2406.
- Bassett, M.E., Seinfeld, J.H., 1983. Atmospheric equilibrium model of sulfate and nitrate aerosols. *Atmos. Environ.* 17 (11), 2237–2252.
- Bassett, M.E., Seinfeld, J.H., 1984. Atmospheric equilibrium model of sulfate and nitrate aerosols. II. Particle size analysis. *Atmos. Environ.* 18 (6), 1163–1170.
- Batterman, S.A., Dzubay, T.G., Baumgardner, R.E., 1988. Development of crustal profiles for receptor modeling. *Atmos. Environ.* 22 (9), 1821–1828.
- Baxter, R.A., Pederson, J.R., 1994. A measurement method for sampling pollutants aloft in complex terrain. In: Solomon, P.A. (Ed.), *Planning and Managing Regional Air Quality, Modeling and Measurement Studies*. CRC Press, Boca Raton, FL, pp. 699–710.
- Belsley, D.A., Kuh, E.D., Welsch, R.E., 1980. *Regression Diagnostics: Identifying Influential Data and Sources of Collinearity*. John Wiley, New York, NY.
- Benner, B.A., Gordon, G.E., Wise, S.A., 1989. Mobile sources of atmospheric PAH: A roadway tunnel study. *Environ. Sci. Technol.* 23, 1269–1278.
- Benner, B.A., Wise, S.A., Currie, L.A., Klouda, G.A., Klinedinst, D.B., Zweidinger, R.B., Stevens, R.K., Lewis, C.W., 1995. Distinguishing the contributions of residential wood combustion and mobile source emissions using relative concentrations of dimethylphenanthrene isomers. *Environ. Sci. Technol.* 29 (9), 2382–2389.
- Berg, T., Røyset, O., Steinnes, E., 1994. Component analysis of data for trace elements and main components in precipitation falling on Norway. *Environ. Monit. Assess.* 31 (3), 259–274.
- Bergametti, G., Dutot, A.L., Quisefit, J.P., Vie Le Sage, R., 1983. Correspondence analysis applied to volcanic aerosols. *J. Volcanol. Geotherm. Res.* 15, 355–367.
- Bhave, P.V., Fergenson, D.P., Prather, K.A., Cass, G.R., 2001. Source apportionment of fine particulate matter by clustering single-particle data: Tests of receptor model accuracy. *Environ. Sci. Technol.* 35 (10), 2060–2072.
- Biegalski, S.R., Landsberger, S., Hoff, R.M., 1998. Source-receptor modeling using trace metals in aerosols collected at three rural Canadian Great Lakes sampling stations. *J. Air Waste Mgmt. Assoc.* 48 (3), 227–237.
- Bighouse, R.D., Houck, J.E., 1994. Chemical mass balance source profile data for Weirton, West Virginia. In: Development of a PM<sub>10</sub> SIP for the City of Weirton, West Virginia, vol. 3, Report No. EPA No. 68-D3-0030; AGI No. 30,401.001. Prepared for Science Applications Intl. Corp., Falls Church, VA, by AGI Technologies, Portland, OR.
- Bishop, G.A., Starkey, J.R., Ihlenfeldt, A., Williams, W.J., Stedman, D.H., 1989. IR long-path photometry: A remote sensing tool for automobile emissions. *Anal. Chem.* 61 (10), 671A–677A.
- Bishop, G.A., McLaren, S.E., Stedman, D.H., Pierson, W.R., Zweidinger, R.B., Ray, W., 1996. Method comparisons of vehicle emissions measurements in the Fort McHenry and Tuscarora mountain tunnels. *Atmos. Environ.* 30 (12), 2307–2316.
- Bishop, G.A., Stedman, D.H., Castro, J., Dávalos, F.J., 1997. On-road remote sensing of vehicle emissions in Mexico. *Environ. Sci. Technol.* 31 (12), 3505–3510.
- Blanchard, C.L., Carr, E.L., Collins, J.F., Smith, T.B., Lehrman, D.E., Michaels, H.M., 1999. Spatial representativeness and scales of transport during the 1995 Integrated Monitoring Study in California's San Joaquin Valley. *Atmos. Environ.* 33 (29), 4775–4786.



- Blanchard, C.L., Roth, P.M., Tanenbaum, S.J., Ziman, S.D., Seinfeld, J.H., 2000. The use of ambient measurements to identify which precursor species limit aerosol nitrate formation. *J. Air Waste Mgmt. Assoc.* 50 (12), 2073–2084.
- Blifford, I.H., Meeker, G.O., 1967. A factor analysis model of large scale pollution. *Atmos. Environ.* 1, 147–157.
- Bogen, J., 1973. Trace elements concentrations in atmospheric aerosol in the Heidelberg area measured by instrumental neutron activation analysis. *Atmos. Environ.* 7, 1117–1125.
- Bomboi, M.T., Hernandez, A., Mariño, F., Hontoria, E., 1990. Application of multivariate analysis for characterization of organic compounds from urban runoff. *Sci. Total Environ.* 93, 523–536.
- Boutron, C., Martin, S., 1980. Source of 12 trace metals in Antarctic snows determined by principal component analysis. *J. Geophys. Res.* 85 (C10), 5631–5638.
- Bowman, F.M., Pilinis, C., Seinfeld, J.H., 1995. Ozone and aerosol productivity of reactive organics. *Atmos. Environ.* 29 (5), 579–590.
- Boznar, M., Lesjak, M., Mlakar, P., 1993. A neural network-based method for short-term predictions of ambient SO<sub>2</sub> concentrations in highly polluted industrial areas of complex terrain. *Atmos. Environ. B* 27 (2), 221.
- Bressan, D.J., Carr, R.A., Wilkiss, P.E., 1973. Geochemical aspects of inorganic aerosols near the ocean–atmosphere interface. In: Kothny, E.L. (Ed.), *Trace Elements in the Environment*. American Chemical Society, Washington, DC, pp. 55–63.
- Bridgman, H.A., 1992. Evaluating rainwater contamination and sources in southeast Australia using factor analysis. *Atmos. Environ. A* 26 (13), 2401–2412.
- Britt, H.I., Luecke, R.H., 1973. The estimation of parameters in nonlinear, implicit models. *Technometrics* 15 (2), 233–247.
- Brook, J.R., Woodhouse, S.A., Blanchard, P., Dann, T., Dabek-Zlotorzynska, E., Goldthorp, S., Wiebe, A., Li, S.M., Guise-Bagley, L., Hoff, R., Mamedov, A., Hanson-Smith, L., Nejedly, Z., Campbell, J.L., Chow, J.C., 2000. Chemical mass balance analyses of Toronto area PM<sub>2.5</sub>. Environment Canada, Toronto, ON, Canada, Report No. AES/AQRB-PERD-04.
- Brown, A.D., Lund, L.J., 1994. Factors controlling throughfall characteristics at a high elevation Sierra Nevada site, California. *Environ. Qual.* 23 (4), 844–850.
- Brumelis, G., Lapina, L., Nikodemus, O., Tabors, G., 2000. Use of an artificial model of monitoring data to aid interpretation of principal component analysis. *Environ. Modell. Software* 15 (8), 755–763.
- Brunet, G., Vautard, R., 1996. Empirical normal modes versus empirical orthogonal functions for statistical prediction. *J. Atmos. Sci.* 53 (23), 3468–3489.
- Buat-Ménard, P., Arnold, M., 1978. The heavy metal chemistry of atmospheric particulate matter emitted by Mount Etna volcano. *Geophys. Res. Lett.* 5, 245–248.
- Buhr, M.P., Trainer, M., Parrish, D.D., Sievers, R.E., Fehsenfeld, F.C., 1992. Assessment of pollutant emission inventories by principal component analysis of ambient air measurements. *Geophys. Res. Lett.* 19 (10), 1009–1012.
- Buhr, M.P., Parrish, D.D., Elliot, J., Holloway, J., Carpenter, J., Goldan, P., Kuster, W., Trainer, M., Montzka, S., McKeen, S., Fehsenfeld, F.C., 1995. Evaluation of ozone precursor source types using principal component analysis of ambient air measurements in rural Alabama. *J. Geophys. Res.* 100 (D11), 22853–22860.
- Buhr, M.P., Hsu, K.J., Liu, C.M., Liu, R., Wei, L., Liu, Y.C., Kuo, Y.S., 1996. Trace gas measurements and air mass classification from a ground station in Taiwan during the PEM-West A experiment, 1991. *J. Geophys. Res.* 101 (D1), 2025–2035.
- Cadle, S.H., Stephens, R., 1994. Remote sensing of vehicle exhaust emissions. *Environ. Sci. Technol.* 28 (6), 258A–264A.
- Cahill, T.A., Wilkinson, K., Schnell, R.C., 1992. Composition analyses of size-resolved aerosol samples taken from aircraft downwind of Kuwait, spring 1991. *J. Geophys. Res.* 97 (D13), 14513–14520.
- Calloway, C.P., Li, S.M., Buchanan, J.W., Stevens, R.K., 1989. A refinement of the potassium tracer method for residential wood smoke. *Atmos. Environ.* 23 (1), 67–69.
- Capaldo, K.P., Pilinis, C., Pandis, S.N., 2000. A computationally efficient hybrid approach for dynamic gas/aerosol transfer in air quality models. *Atmos. Environ.* 34 (21), 3617–3627.
- Carter, E.J., Borys, R.D., 1993. Aerosol-cloud chemical fractionation: Enrichment factor analysis of cloud water. *J. Atmos. Chem.* 17 (3), 277–292.
- Carvacho, O.F., Ashbaugh, L.L., Matsumura, R.T., Southard, R.J., Flocchini, R.G., 1996. Measurement of PM<sub>10</sub> potential from agricultural soils using a dust resuspension test chamber. In: *Proceedings, International Conference on Air Pollution from Agricultural Operations*. Midwest Plan Service, Kansas City, MO.
- Cass, G.R., 1981. Sulfate air quality control strategy design. *Atmos. Environ.* 15 (7), 1227–1249.
- Cass, G.R., McRae, G.J., 1981. Minimizing the cost of air pollution control. *Environ. Sci. Technol.* 15 (7), 748–757.
- Cass, G.R., McRae, G.J., 1983. Source–receptor reconciliation of routine air monitoring data for trace metals: An emission inventory assisted approach. *Environ. Sci. Technol.* 17 (3), 129–139.
- Casuccio, G.S., Schwoeble, A.J., Henderson, B.C., Lee, R.J., Hopke, P.K., Sverdrup, G.M., 1989. The use of CCSEM and microimaging to study source/receptor relationships. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 39–58.
- Centner, V., Massart, D.L., deNoord, O.E., deJong, S., Vandeginste, B.M., Sterna, C., 1996. Elimination of uninformative variables for multivariate calibration. *Anal. Chem.* 68 (21), 3851–3858.
- Chan, Y.C., Simpson, R.W., McTainsh, G.H., Vowles, P.D., Cohen, D.D., Bailey, G.M., 1999. Source apportionment of visibility degradation problems in Brisbane (Australia) using the multiple linear regression techniques. *Atmos. Environ.* 33 (19), 3237–3250.
- Chan, Y.C., Vowles, P.D., McTainsh, G.H., Simpson, R.W., Cohen, D.D., Bailey, G.M., Mcorist, G.D., 2000. Characterisation and source identification of PM<sub>10</sub> aerosol samples collected with a high volume cascade impactor in Brisbane (Australia). *Sci. Total Environ.* 262 (1–2), 5–19.
- Chang, S., Hopke, P.K., Rheingrover, S.W., Gordon, G.E., 1982. Target transformation factor analysis of wind-trajectory selected samples. In: *Proceedings of the 75th Annual*

- Meeting, June 20, 1982, New Orleans, LA. Air Pollution Control Association, Pittsburgh, PA.
- Chang, T.Y., Modzelewski, S.W., Norbeck, J.M., Pierson, W.R., 1981. Tunnel air quality and vehicle emissions. *Atmos. Environ.* 15 (6), 1011–1016.
- Chen, C.L., Tsuang, B.J., Pan, R.C., Tu, C.Y., Liu, J.H., Huang, P.L., Bai, H., Cheng, M.T., 2002. Quantification on source/receptor relationship of primary pollutants and secondary aerosols from ground sources—Part II. Model description and case study. *Atmos. Environ.* 36 (3), 421–434.
- Chen, K.S., Lin, C.F., Chou, Y.M., 2001. Determination of source contributions to ambient PM<sub>2.5</sub> in Kaohsiung, Taiwan, using a receptor model. *J. Air Waste Mgmt. Assoc.* 51 (4), 489–498.
- Chen, W.C., Wang, C.S., Wei, C.C., 1997. An assessment of source contributions to ambient aerosols in central Taiwan. *J. Air Waste Mgmt. Assoc.* 47 (4), 501–509.
- Cheng, M.D., Hopke, P.K., 1986. Linear programming procedure and regression diagnostics for least-squares solution using CMB receptor model. In: Pace, T.G. (Ed.), *Transactions, Receptor Methods for Source Apportionment: Real World Issues and Applications*. Air Pollution Control Association, Pittsburgh, PA, pp. 94–104.
- Cheng, M.D., Hopke, P.K., 1989. Identification of markers for chemical mass balance receptor model. *Atmos. Environ.* 23 (6), 1373–1384.
- Cheng, M.D., Liou, P.J., 1989. Simulation study of target transformation factor analysis: Determination of the number of sources using eigenvalues. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 196–213.
- Cheng, M.D., Hopke, P.K., Barrie, L.A., Rippe, A., Olson, M.P., Landsberger, S., 1993a. Qualitative determination of source regions of aerosol in Canadian High Arctic. *Environ. Sci. Technol.* 27 (10), 2063–2071.
- Cheng, M.D., Hopke, P.K., Zeng, Y., 1993b. A receptor-oriented methodology for determining source regions of particulate sulfate observed at Dorset, Ontario. *J. Geophys. Res.* 98 (D9), 16839–16850.
- Cheng, M.D., Gao, N., Hopke, P.K., 1996. Source apportionment study of nitrogen species measured in Southern California in 1987. *J. Environ. Eng.* 122 (March), 183–190.
- Choi, J.C., Lee, M., Chun, Y., Kim, J., Oh, S., 2001. Chemical composition and source signature of spring aerosol in Seoul, Korea. *J. Geophys. Res.* 106 (D16), 18067–18074.
- Chow, J.C., 1985. A composite modeling approach to assess air pollution source/receptor relationships. Sc.D. Dissertation, Harvard University, Cambridge, MA.
- Chow, J.C., 1995. Critical review: Measurement methods to determine compliance with ambient air quality standards for suspended particles. *J. Air Waste Mgmt. Assoc.* 45 (5), 320–382.
- Chow, J.C., Spengler, J.D., 1986. A method of combining dispersion models and trajectory models with principal component analysis and chemical mass balance receptor models. In: Pace, T.G. (Ed.), *Transactions, Receptor Methods for Source Apportionment: Real World Issues and Applications*. Air Pollution Control Association, Pittsburgh, PA, pp. 194–211.
- Chow, J.C., Frazier, C.A., Watson, J.G., 1988a. A survey of existing fugitive/area source characterization methods for receptor modeling. In: Hoffnagle, G.F., Lebowitz, M. (Eds.), *Proceedings, Particulate Matter/Fugitive Dusts: Measurements and Control in Western Arid Regions*. Air Pollution Control Association, Pittsburgh, PA, pp. 176–189.
- Chow, J.C., Watson, J.G., Frazier, C.A., Egami, R.T., Goodrich, A., Ralph, C., 1988b. Spatial and temporal source contributions to PM<sub>10</sub> and PM<sub>2.5</sub> in Reno, NV. In: Mathai, C.V., Stonefield, D.H. (Eds.), *Transactions, PM<sub>10</sub>: Implementation of Standards*. Air Pollution Control Association, Pittsburgh, PA, pp. 438–457.
- Chow, J.C., Watson, J.G., 1989. Summary of particulate data bases for receptor modeling in the United States. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 108–133.
- Chow, J.C., Egami, R.T., Watson, J.G., DeLong, T., 1990a. Applying the air quality source apportionments to geothermal power plant emissions. *Geotherm. Resour. Council Bull.* 19 (8), 208–213.
- Chow, J.C., Watson, J.G., Egami, R.T., Frazier, C.A., Lu, Z., Goodrich, A., Bird, A., 1990b. Evaluation of regenerative-air vacuum street sweeping on geological contributions to PM<sub>10</sub>. *J. Air Waste Mgmt. Assoc.* 40 (8), 1134–1142.
- Chow, J.C., Watson, J.G., Richards, L.W., Haase, D.L., McDade, C., Dietrich, D.L., Moon, D., Sloane, C.S., 1991a. The 1989–1990 Phoenix PM<sub>10</sub> Study, vol. II, Source apportionment, Report No. DRI 8931.6F2. Prepared for Arizona Department of Environmental Quality, Phoenix, AZ, by Desert Research Institute, Reno, NV.
- Chow, J.C., Watson, J.G., Richards, L.W., Haase, D.L., McDade, C., Dietrich, D.L., Moon, D., Sloane, C.S., 1991b. The 1989–1990 Pilot Tucson PM<sub>10</sub> Study, vol. II, Source apportionment, Report No. DRI 8931.8F2. Prepared for Arizona Department of Environmental Quality, Phoenix, AZ, by Desert Research Institute, Reno, NV.
- Chow, J.C., Liu, C.S., Cassmassi, J.C., Watson, J.G., Lu, Z., Pritchett, L.C., 1992a. A neighborhood-scale study of PM<sub>10</sub> source contributions in Rubidoux, California. *Atmos. Environ.* A 26 (4), 693–706.
- Chow, J.C., Watson, J.G., Lowenthal, D.H., Solomon, P.A., Magliano, K.L., Ziman, S.D., Richards, L.W., 1992b. PM<sub>10</sub> source apportionment in California's San Joaquin Valley. *Atmos. Environ.* A 26 (18), 3335–3354.
- Chow, J.C., Watson, J.G., Bowen, J.L., Frazier, C.A., Gertler, A.W., Fung, K.K., Landis, D., Ashbaugh, L.L., 1993a. A sampling system for reactive species in the western United States. In: Winegar, E.D., Keith, L.H. (Eds.), *Sampling and Analysis of Airborne Pollutants*. Lewis Publishers, Ann Arbor, MI, pp. 209–228.
- Chow, J.C., Watson, J.G., Ono, D.M., Mathai, C.V., 1993b. PM<sub>10</sub> standards and nontraditional particulate source controls: A summary of the A&WMA/EPA International Specialty Conference. *J. Air Waste Mgmt. Assoc.* 43 (1), 74–84.
- Chow, J.C., Watson, J.G., Pritchett, L.C., Pierson, W.R., Frazier, C.A., Purcell, R.G., 1993c. The DRI thermal/optical reflectance carbon analysis system: Description, evaluation and applications in US air quality studies. *Atmos. Environ.* A 27 (8), 1185–1201.

- Chow, J.C., Watson, J.G., 1994a. Guidelines for PM<sub>10</sub> sampling and analysis applicable to receptor modeling. Report No. EPA-452/R-94-009. Prepared for US EPA, Office of Air Quality Planning and Standards, Research Triangle Park, NC, by Desert Research Institute, Reno, NV.
- Chow, J.C., Watson, J.G., 1994b. Contemporary source profiles for geological material and motor vehicle emissions. Report No. DRI 2625.2F. Prepared for US EPA, Office of Air Quality Planning and Standards, Research Triangle Park, NC, by Desert Research Institute, Reno, NV.
- Chow, J.C., Watson, J.G., 1998. Guideline on speciated particulate monitoring. Prepared for US EPA, Research Triangle Park, NC, by Desert Research Institute, Reno, NV.
- Chow, J.C., Watson, J.G., 1999. Ion chromatography in elemental analysis of airborne particles. In: Landsberger, S., Creatchman, M. (Eds.), *Elemental Analysis of Airborne Particles*, vol. 1. Gordon and Breach Science, Amsterdam, pp. 97–137.
- Chow, J.C., Watson, J.G., Houck, J.E., Pritchett, L.C., Rogers, C.F., Frazier, C.A., Egami, R.T., Ball, B.M., 1994. A laboratory resuspension chamber to measure fugitive dust size distributions and chemical compositions. *Atmos. Environ.* 28 (21), 3463–3481.
- Chow, J.C., Fairley, D., Watson, J.G., de Mandel, R., Fujita, E.M., Lowenthal, D.H., Lu, Z., Frazier, C.A., Long, G., Cordova, J., 1995. Source apportionment of wintertime PM<sub>10</sub> at San Jose, CA. *J. Environ. Eng.* 21, 378–387.
- Chow, J.C., Watson, J.G., Divita Jr., F., 1996a. Particulate matter with aerodynamic diameters smaller than 10 μm—Measurement methods and sampling strategies. In: Keith, L.H. (Ed.), *Principles of Environmental Sampling*, second ed. American Chemical Society, Washington, DC, pp. 539–573.
- Chow, J.C., Watson, J.G., Lowenthal, D.H., Countess, R.J., 1996b. Sources and chemistry of PM<sub>10</sub> aerosol in Santa Barbara County, CA. *Atmos. Environ.* 30 (9), 1489–1499.
- Chow, J.C., Watson, J.G., Green, M.C., Lowenthal, D.H., DuBois, D.W., Kohl, S.D., Egami, R.T., Gillies, J.A., Rogers, C.F., Frazier, C.A., Cates, W., 1999. Middle- and neighborhood-scale variations of PM<sub>10</sub> source contributions in Las Vegas, Nevada. *J. Air Waste Mgmt. Assoc.* 49 (6), 641–654.
- Chow, J.C., Watson, J.G., Green, M.C., Lowenthal, D.H., Bates, B.A., Oslund, W., Torres, G., 2000. Cross-border transport and spatial variability of suspended particles in Mexicali and California's Imperial Valley. *Atmos. Environ.* 34 (11), 1833–1843.
- Chow, J.C., Watson, J.G., Crow, D., Lowenthal, D.H., Merrifield, T., 2001. Comparison of IMPROVE and NIOSH carbon measurements. *Aerosol Sci. Technol.* 34 (1), 23–34.
- Chow, J.C., Watson, J.G., 2002. Review of PM<sub>2.5</sub> and PM<sub>10</sub> apportionment for fossil fuel combustion and other sources by the chemical mass balance receptor model. *Energy Fuels* 16 (2), 222–260.
- Chow, J.C., Watson, J.G., Edgerton, S.A., Vega, E., Ortiz, E., 2002a. Spatial differences in outdoor PM<sub>10</sub> mass and aerosol composition in Mexico City. *J. Air Waste Mgmt. Assoc.* 52 (4), 423–434.
- Chow, J.C., Watson, J.G., Hackett, E.I., Stone, R.H., Hinsvark, B.A., 2002b. Method No. 822: General atomic absorption procedure for trace metals in airborne material collected on filters. In: Lodge, J.P. (Ed.), *Methods of Air Sampling and Analysis*, fourth ed. Air and Waste Management Association, Pittsburgh, PA, in press.
- Chow, J.C., Watson, J.G., Lowenthal, D.H., Richards, L.W., 2002c. Comparability between PM<sub>2.5</sub> and light scattering measurements. *Environ. Monit. Assess.*, in press.
- Chueinta, W., Hopke, P.K., Paatero, P., 2000. Investigation of sources of atmospheric aerosol at urban and suburban residential areas in Thailand by positive matrix factorization. *Atmos. Environ.* 34 (20), 3319–3329.
- Clegg, S.L., Seinfeld, J.H., Brimblecombe, P., 2001. Thermodynamic modelling of aqueous aerosols containing electrolytes and dissolved organic compounds. *J. Aerosol Sci.* 32 (6), 713–738.
- Coe, D.L., Chinkin, L.R., 1998. The use of a day-specific source activity database to augment CMB source apportionment modeling. In: Chow, J.C., Koutrakis, P. (Eds.), *Proceedings, PM<sub>2.5</sub>: A Fine Particle Standard*. Air Waste Management Association, Pittsburgh, PA, pp. 463–474.
- Comrie, A.C., 1997. Comparing neural networks and regression models for ozone forecasting. *J. Air Waste Mgmt. Assoc.* 47 (6), 653–663.
- Conner, T.L., Stevens, R.K., 1991. Receptor modeling of fine particles in the Tacoma tideflats airshed. In: *Proceedings of the 84th Annual Meeting*, Vancouver, BC, Canada. Air and Waste Management Association, Pittsburgh, PA.
- Cooper, J.A., 1980. Environmental impact of residential wood combustion emissions and its implications. *J. Air Pollut. Control Assoc.* 30 (8), 855–861.
- Cooper, J.C., 1983. Factor analysis: An overview. *Am. Stat.* 37, 141–147.
- Cooper, J.A., Watson, J.G., 1980. Receptor oriented methods of air particulate source apportionment. *J. Air Pollut. Control Assoc.* 30 (10), 1116–1125.
- Cooper, J.A., Sherman, J.R., Miller, E., Redline, D., Valdovinos, L., Pollard, W.L., 1988. CMB source apportionment of PM<sub>10</sub> downwind of an oil-fired power plant in Chula Vista, California. In: Mathai, C.V., Stonefield, D.H. (Eds.), *Transactions, PM<sub>10</sub>: Implementation of Standards*. Air and Waste Management Association, Pittsburgh, PA, pp. 495–507.
- Cooper, J.A., Miller, E.A., Redline, D.C., Spidell, R.L., Caldwell, L.M., Sarver, R.H., Tansy, B.L., 1989. PM<sub>10</sub> source apportionment of Utah Valley winter episodes before, during, and after closure of the West Orem steel plant. Prepared for Kimball, Parr, Crockett and Waddops, Salt Lake City, UT, by NEA, Inc., Beaverton, OR.
- Core, J.E., 1989. Source profile development for PM<sub>10</sub> receptor modeling. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 134–144.
- Core, J.E., Hanrahan, P.L., Cooper, J.A., 1981. Air particulate control strategy development. In: Macias, E.S., Hopke, P.K. (Eds.), *Atmospheric Aerosol: Source/Air Quality Relationships*. American Chemical Society, Washington, DC, pp. 107–123.
- Core, J.E., Cooper, J.A., Hanrahan, P.L., Cox, W.M., 1982. Particulate dispersion model evaluation: A new approach

- using receptor models. *J. Air Pollut. Control Assoc.* 32 (11), 1142–1147.
- Countess, R.J., Barnard, W.R., Claiborn, C.S., Gillette, D.A., Latimer, D.A., Pace, T.G., Watson, J.G., 2001. Methodology for estimating fugitive windblown and mechanically resuspended road dust emissions applicable for regional scale air quality modeling. Report No. 30203-9. Western Regional Air Partnership, Denver, CO.
- Cox, W.M., Clark, J., 1981. Ambient ozone concentration patterns among eastern US urban areas using factor analysis. *J. Air Pollut. Control Assoc.* 31 (7), 762–766.
- Crawford, C.B., 1975. Determining the number of interpretable factors. *Psychol. Bull.* 82 (2), 226–237.
- Crawley, J., Sievering, H., 1986. Factor analysis of the MAP3S/RAINE precipitation chemistry network: 1976–1980. *Atmos. Environ.* 29 (5), 1001–1013.
- Currie, L.A., Gerlach, R.W., Lewis, C.W., Balfour, W.D., Cooper, J.A., Dattner, S.L., deCesar, R.T., Gordon, G.E., Heisler, S.L., Hopke, P.K., Shah, J.J., Thurston, G.D., Williamson, H.J., 1984. Interlaboratory comparison of source apportionment procedures: Results for simulated data sets. *Atmos. Environ.* 18 (8), 1517–1537.
- Currie, L.A., Sheffield, A.E., Riederer, G., Gordon, G.E., 1994. Improved atmospheric understanding through exploratory data analysis and complementary modeling: The urban K–Pb–C system. *Atmos. Environ.* 28 (8), 1359–1369.
- Currie, L.A., Klouda, G.A., Benner Jr., B.A., Garrity, K., Eglinton, T.I., 1999. Isotopic and molecular fractionation in combustion: Three routes to molecular marker validation, including direct molecular ‘dating’ (GC/AMS). *Atmos. Environ.* 33 (17), 2789–2806.
- Daisey, J.M., 1985. A new approach to the identification of sources of airborne mutagens and carcinogens: Receptor source apportionment modeling. *Environ. Int.* 11, 285–291.
- Daisey, J.M., Kebbekus, B.B., Bozzelli, J.W., Liroy, P.J., 1986. Exploratory application of factor analysis to volatile organic compound concentration data from urban sites in New Jersey. In: Pace, T.G. (Ed.), *Transactions, Receptor Methods for Source Apportionment: Real World Issues and Applications*. Air Pollution Control Association, Pittsburgh, PA, pp. 149–160.
- Dams, R., Robbins, J.A., Rahn, K.A., Winchester, J.W., 1971. Quantitative relationships among trace elements over industrialized N.W. Indiana. In: *Nuclear Techniques in Environmental Pollution*. International Atomic Energy Agency, Vienna, Austria, pp. 139–145.
- Dannecker, W., Schröder, B., Stechmann, H., 1990. Organic and inorganic substances in highway tunnel exhaust air. *Sci. Total Environ.* 93, 293–300.
- Davidson, C., Borrazzo, J.E., Hendrickson, C.T., 1986. Pollutant emission factors for gas stoves: A literature survey. Report No. CR-812543-01-0. US EPA, Research Triangle Park, NC.
- Deboudt, K., Flament, P., Weis, D., Mennessier, J.P., Maquinghen, P., 1999. Assessment of pollution aerosols sources above the Straits of Dover using lead isotope geochemistry. *Sci. Total Environ.* 236, 57–74.
- deCesar, R.T., Cooper, J.A., 1982. Evaluation of multivariate and chemical mass balance approaches to aerosol source apportionments using synthetic data and an expanded PACS data set. In: Hopke, P.K., Dattner, S.L. (Eds.), *Receptor Models Applied to Contemporary Pollution Problems*. Air Pollution Control Association, Pittsburgh, PA, pp. 127–140.
- deCesar, R.T., Edgerton, S.A., Khalil, M.A.K., Rasmussen, R.A., 1985. Sensitivity analysis of mass balance receptor modeling: methyl chloride as an indicator of wood smoke. *Chemosphere* 14 (10), 1495–1501.
- deCesar, R.T., Edgerton, S.A., Khalil, M.A.K., Rasmussen, R.A., 1986. A tool for designing receptor model studies to apportion source impacts with specified precisions. In: Pace, T.G. (Ed.), *Transactions, Receptor Methods for Source Apportionment: Real World Issues and Applications*. Air Pollution Control Association, Pittsburgh, PA, pp. 56–67.
- Deininger, C.K., Saxena, V.K., 1997. A validation of back trajectories of air masses by principal component analysis of ion concentrations in cloud water. *Atmos. Environ.* 31 (2), 295–300.
- deNevers, N., Morris, J.R., 1975. Rollback modeling: Basic and modified. *J. Air Pollut. Control Assoc.* 25 (9), 943–947.
- Derde, M.P., Buydens, L., Guns, C., Massart, D.L., Hopke, P.K., 1987. Comparison of rule-building expert systems with pattern recognition for the classification of analytical data. *Anal. Chem.* 59, 1868–1871.
- Diaz, J.M.F., Braña, M.A.R., Garcia, B.A., Muñoz, C.G.P., Nieto, P.J.G., 1999. Difficulties inherent to the use of analytic solution of the condensation–evaporation equation for multicomponent aerosols. *Atmos. Environ.* 33 (8), 1245–1260.
- Dickson, R.J., Oliver, W.R., 1991. Emissions models for regional air quality studies. *Environ. Sci. Technol.* 25 (9), 1533–1535.
- Dresser, A.L., Baird, B.K., 1988. A dispersion and receptor model analysis of the wintertime PM<sub>10</sub> problem in Telluride, Colorado. In: Mathai, C.V., Stonefield, D.H. (Eds.), *Transactions, PM<sub>10</sub>: Implementation of Standards*. Air Pollution Control Association, Pittsburgh, PA, pp. 458–471.
- Duewer, D.L., Kowalski, B.R., Fasching, J.L., 1976. Improving the reliability of factor analysis of chemical data by utilizing the measured analytical uncertainty. *Anal. Chem.* 48 (13), 2002–2010.
- Duffy, B.L., Nelson, P.F., 1996. Non-methane exhaust composition in the Sydney Harbour Tunnel: A focus on benzene and 1,3-butadiene. *Atmos. Environ.* 30 (15), 2759–2768.
- Dzubay, T.G., 1980. Chemical element balance method applied to dichotomous sampler data. *Ann. N.Y. Acad. Sci.* 338, 126–144.
- Dzubay, T.G., 1989. Evaluation of composite receptor methods. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 367–378.
- Dzubay, T.G., Mamane, Y., 1989. Use of electron microscopy data in receptor models for PM<sub>10</sub>. *Atmos. Environ.* 23, 467–476.
- Dzubay, T.G., Stevens, R.K., Balfour, W.D., Williamson, H.J., Cooper, J.A., Core, J.E., deCesar, R.T., Crutcher, E.R., Dattner, S.L., Davis, B.L., Heisler, S.L., Shah, J.J., Hopke, P.K., Johnson, D.L., 1984. Interlaboratory comparison of receptor model results for Houston aerosol. *Atmos. Environ.* 18 (8), 1555–1566.
- Dzubay, T.G., Stevens, R.K., Gordon, G.E., Olmez, I., Sheffield, A.E., Courtney, W.J., 1988. A composite receptor

- method applied to Philadelphia aerosol. *Environ. Sci. Technol.* 22 (1), 46–52.
- Eatough, D.J., 1989. The chemical composition of ETS III: Identification of conservative tracers of ETS. *Environ. Int.* 15, 19–28.
- Eatough, D.J., Bennett, J.R., Lytle, N., Brutsch, M., Luke, T.T., Houtrouw, S., Mangelson, N.F., Hill, M.W., Lewis, E.A., Hansen, L.D., Eatough, N.L., Farber, R.J., 1987. Identification of the presence of coal-fired power plant emissions using spherical particles and total fluoride as tracers. In: Bhardwaja, P.S. (Ed.), *Transactions, Visibility Protection: Research and Policy Aspects*. Air Pollution Control Association, Pittsburgh, PA, pp. 720–735.
- Eatough, D.J., Eatough, M., Hansen, L., Lewis, E.A., 1992. Apportionment of sulfur oxides and sulfate at Canyonlands during the winter of 1990. In: Chow, J.C., Ono, D.M. (Eds.), *Transactions, PM<sub>10</sub> Standards and Nontraditional Particulate Source Controls*. Air and Waste Management Association, Pittsburgh, PA, pp. 293–308.
- Eatough, D.J., Eatough, M., Lewis, L.J., Lewis, E.A., Tomlinson, E.M., Gordon, J.L., Eatough, N.L., 1996. Apportionment of sulfur oxides at Canyonlands during the winter of 1990. II. Fingerprints of emissions from point and regional sources impacting Canyonlands. *Atmos. Environ.* 30 (2), 283–294.
- Eatough, D.J., Du, A., Joseph, J.M., Caka, F.M., Sun, B., Lewis, L., Mangelson, N.F., Eatough, M., Rees, L.B., Eatough, N.L., Farber, R.J., Watson, J.G., 1997a. Regional source profiles of sources of SO<sub>x</sub> at the Grand Canyon during Project MOHAVE. *J. Air Waste Mgmt. Assoc.* 47 (2), 101–118.
- Eatough, D.J., Farber, R.J., Watson, J.G., 1997b. Second generation chemical mass balance source apportionment of sulfur oxides and sulfate at the Grand Canyon during the Project Mohave 1992 summer intensive. In: Tombach, I.H. (Ed.), *Proceedings, Visual Air Quality: Aerosols and Global Radiation Balance*. Air and Waste Management Association, Pittsburgh, PA, pp. 1153–1160.
- Eatough, D.J., Farber, R.J., Watson, J.G., 2000. Second-generation chemical mass balance source apportionment of sulfur oxides and sulfate at the Grand Canyon during the Project MOHAVE summer intensive. *J. Air Waste Mgmt. Assoc.* 50 (5), 759–774.
- Echalar, F., Artaxo, P., Martins, J.V., Yamasoe, M., Gerab, F., Maenhaut, W., Holben, B., 1998. Long-term monitoring of atmospheric aerosols in the Amazon Basin: Source identification and apportionment. *J. Geophys. Res.* 103 (D24), 31849–31864.
- Egami, R.T., Chow, J.C., Watson, J.G., de Long, T., 1990. PM<sub>10</sub> source apportionment study in Pleasant Valley, Nevada. In: *Transactions, 1990 International Symposium on Geothermal Energy*. Geothermal Resources Council, Davis, CA, pp. 1115–1120.
- Engelbrecht, J.P., Swanepoel, L., Zunckel, M., Chow, J.C., Watson, J.G., Egami, R.T., 2000. Modelling PM<sub>10</sub> aerosol data from the Qalabotjha low-smoke fuels macro-scale experiment in South Africa. *Ecol. Modell.* 127, 235–244.
- Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G., Egami, R.T., 2001. PM<sub>2.5</sub> and PM<sub>10</sub> concentrations from the Qalabotjha low-smoke fuels macro-scale experiment in South Africa. *Environ. Monit. Assess.* 69 (1), 1–15.
- Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G., Egami, R.T., 2002. A comparison of source contributions from residential coal and low-smoke fuels, using CMB modeling, in South Africa. *Environ. Sci. Policy* 5 (2), 157–167.
- Fan, A., Hopke, P.K., Raunemaa, T., Oblad, M., Pacyna, J.M., 1995. A study on the potential sources of air pollutants observed at Tjörn, Sweden. *Environ. Sci. Pollut. Res.* 2 (2), 107–115.
- Fan, C.W., Zhang, J., 1998. Particulate matter and other air pollutants from several portable household combustion devices: Particle size distributions, emission rates, emission factors, and potential exposures. In: Chow, J.C., Koutrakis, P. (Eds.), *Proceedings, PM<sub>2.5</sub>: A Fine Particle Standard*. Air and Waste Management Association, Pittsburgh, PA, pp. 876–888.
- Feeley, J.A., Liljestrand, H.M., 1983. Source contributions to acid precipitation in Texas. *Atmos. Environ.* 17 (4), 807–814.
- Fogg, T.R., Rahn, K.A., 1984. Boron as a tracer of aerosol from combustion of coal. *Geophys. Res. Lett.* 1 (9), 854–857.
- Fraser, M.P., Grosjean, D., Grosjean, E., Rasmussen, R.A., Cass, G.R., 1996. Air quality model evaluation data for organics: 1. Bulk chemical and gas/particle distribution factors. *Environ. Sci. Technol.* 30 (5), 1731–1743.
- Fraser, M.P., Cass, G.R., Simoneit, B.R.T., 1998. Gas-phase and particle-phase organic compounds emitted from motor vehicle traffic in a Los Angeles roadway tunnel. *Environ. Sci. Technol.* 32 (14), 2051–2060.
- Friedlander, S.K., 1973a. Chemical element balances and identification of air pollution sources. *Environ. Sci. Technol.* 7 (3), 235–240.
- Friedlander, S.K., 1973b. Relating particulate pollution to sources: Case of the Los Angeles aerosol. In: *Third International Clean Air Congress*, Dusseldorf, Federal Republic of Germany.
- Friedlander, S.K., 1981. New developments in receptor modeling theory. In: Macias, E.S., Hopke, P.K. (Eds.), *Atmospheric Aerosol: Source/Air Quality Relationships*. American Chemical Society, Washington, DC, pp. 1–19.
- Fujita, E.M., Lu, Z., Frazier, C.A., Watson, J.G., 1997. Application of the chemical mass balance receptor model to apportionment of suspended particulate matter in the Bangkok metropolitan region. Prepared for Radian International Corporation, Austin, TX, by Desert Research Institute, Reno, NV.
- Fujita, E.M., Watson, J.G., Chow, J.C., Robinson, N.F., Richards, L.W., Kumar, N., 1998. Northern Front Range Air Quality Study. vol. C: Source apportionment and simulation methods and evaluation. Prepared for Colorado State University, Cooperative Institute for Research in the Atmosphere, Ft. Collins, CO, by Desert Research Institute, Reno, NV.
- Gaarenstroom, P.D., Perone, S.P., Moyers, J.L., 1977. Application of pattern recognition and factor analysis for characterization of atmospheric particulate composition in southwest desert atmosphere. *Environ. Sci. Technol.* 11 (8), 795–800.
- Gao, N., Cheng, M.D., Hopke, P.K., 1993a. Potential source contribution function analysis and source apportionment

- of sulfur species measured at Rubidoux, CA during the Southern California Air Quality Study, 1987. *Anal. Chim. Acta* 277 (2), 369–380.
- Gao, N., Cheng, M.D., Hopke, P.K., 1993b. PSCF analysis and source apportionment of sulfur species measured at Rubidoux, CA during SCAQS, 1987. *Anal. Chim. Acta* 277, 369–380.
- Gao, N., Cheng, M.D., Hopke, P.K., 1994. Receptor modeling of airborne ionic species collected in SCAQS, 1987. *Atmos. Environ.* 28 (8), 1447–1470.
- Gardner, M.W., Dorling, S.R., 1998. Artificial neural networks (the multilayer perceptron)—A review of applications in the atmospheric sciences. *Atmos. Environ.* 32 (14–15), 2627–2636.
- Gardner, M.W., Dorling, S.R., 1999. Neural network modelling and prediction of hourly  $\text{NO}_x$  and  $\text{NO}_2$  concentrations in urban air in London. *Atmos. Environ.* 33 (5), 709–720.
- Gartrell Jr., G., Friedlander, S.K., 1975. Relating particulate pollution to sources: The 1972 California Aerosol Characterization Study. *Atmos. Environ.* 9, 279–299.
- Gatz, D.F., 1978. Identification of aerosol sources in the St. Louis area using factor analysis. *J. Appl. Meteorol.* 17, 600–608.
- Gatz, D.F., Stensland, G.J., Miller, M.V., Leslie, A.C.D., 1981. Sources of airborne calcium in rural central Illinois. In: Macias, E.S., Hopke, P.K. (Eds.), *Atmospheric Aerosol: Source/Air Quality Relationships*. American Chemical Society, pp. 303–325.
- Gatz, D.F., Stensland, G.J., Miller, M.V., 1998. Element enrichment in some soil dust  $\text{PM}_{2.5}$  source compositions. In: Chow, J.C., Koutrakis, P. (Eds.), *Proceedings,  $\text{PM}_{2.5}$ : A Fine Particle Standard*. Air and Waste Management Association, Pittsburgh, PA, pp. 699–712.
- Ge, S., Khalil, M.A.K., Rau, J.A., 1989. The application of a chemical mass balance model in China. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 12–19.
- Gebhart, K.A., Latimer, D.A., Sisler, J.F., 1990. Empirical orthogonal function analysis of the particulate sulfate concentrations measured during WHITEX. In: Mathai, C.V. (Ed.), *Transactions, Visibility, and Fine Particles*. Air and Waste Management Association, Pittsburgh, PA, pp. 860–871.
- Gebhart, K.A., Malm, W.C., 1997. Spatial and temporal patterns in particle data measured during the MOHAVE study. *J. Air Waste Mgmt. Assoc.* 47 (2), 119–135.
- Gether, J., Seip, H.M., 1979. Analysis of air pollution data by the combined use of interactive graphic presentation and a clustering technique. *Atmos. Environ.* 13, 87–96.
- Gerlach, R.W., Currie, L.A., Lewis, C.W., 1982. Review of the Quail Roost II receptor model simulation exercise. In: Hopke, P.K., Dattner, S.L. (Eds.), *Proceedings, Receptor Models Applied to Contemporary Pollution Problems*. Air Pollution Control Association, Pittsburgh, PA, pp. 96–109.
- Gertler, A.W., Pierson, W.R., 1996. Recent measurements of mobile source emission factors in North American tunnels. *Sci. Total Environ.* 189–190, 107–113.
- Gertler, A.W., Wittorff, D.N., McLaren, R., Belzer, W., Dann, T., 1997. Characterization of vehicle emissions in Vancouver, BC during the 1993 Lower Fraser Valley Oxidants Study. *Atmos. Environ.* 31 (14), 2107–2112.
- Gillani, N.V., Wilson, W.E., 1983. Gas-to-particle conversion of sulfur in power plant plumes—II. Observations of liquid-phase conversion. *Atmos. Environ.* 17, 1739.
- Gillies, J.A., Gertler, A.W., Sagebiel, J.C., Dippel, W.A., 1998. On-road  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  emissions in the Sepulveda Tunnel, Los Angeles, California. In: Chow, J.C., Koutrakis, P. (Eds.), *Proceedings,  $\text{PM}_{2.5}$ : A Fine Particle Standard*. Air and Waste Management Association, Pittsburgh, PA, pp. 677–698.
- Gillies, J.A., Watson, J.G., Rogers, C.F., DuBois, D.W., Chow, J.C., Langston, R., Sweet, J., 1999. Long term efficiencies of dust suppressants to reduce  $\text{PM}_{10}$  emissions from unpaved roads. *J. Air Waste Mgmt. Assoc.* 49 (1), 3–16.
- Gillies, J.A., Gertler, A.W., Sagebiel, J.C., Dippel, W.A., 2001. On-road particulate matter ( $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  emissions in the Sepulveda Tunnel, Los Angeles, California). *Environ. Sci. Technol.* 35 (6), 1054–1063.
- Gleser, L.J., 1997. Some thoughts on chemical mass balance models. *Chemom. Intell. Lab. Sys.* 37 (1), 15–22.
- Glover, D.M., Hopke, P.K., 1992. Exploration of multivariate chemical data by projection pursuit. *Chemom. Intell. Lab. Sys.* 16, 45–59.
- Glover, D.M., Hopke, P.K., 1994. Exploration of multivariate atmospheric particulate compositional data by projection pursuit. *Atmos. Environ.* 28 (8), 1411–1424.
- Glover, D.M., Hopke, P.K., Vermette, S.J., Landsberger, S., D'Auben, D.R., 1991. Source apportionment with site specific source profiles. *J. Air Waste Mgmt. Assoc.* 41 (3), 294–305.
- Gordon, G.E., Zoller, W.H., Gladney, E.S., 1973. Abnormally enriched trace elements in the atmosphere. In: *Trace Substances in Environmental Health*. University of Missouri Environmental Trace Substances Center, Columbia, MO, pp. 167–177.
- Gordon, G.E., 1980. Receptor models. *Environ. Sci. Technol.* 14, 792–800.
- Gordon, G.E., Olmez, I., 1986. Hybrid receptor modeling with multiple sources and vertical mixing. In: Pace, T.G. (Ed.), *Transactions, Receptor Methods for Source Apportionment: Real World Issues and Applications*. Air Pollution Control Association, Pittsburgh, PA, pp. 229–238.
- Gordon, G.E., 1988. Receptor models. *Environ. Sci. Technol.* 22 (10), 1132–1142.
- Gordon, G.E., Zoller, W.H., Kowalczyk, G.S., Rheingrover, S.W., 1981. Composition of source components needed for aerosol receptor models. In: Macias, E.S., Hopke, P.K. (Eds.), *Atmospheric Aerosol: Source Air/Quality Relationships*. American Chemical Society, Washington, DC, pp. 51–74.
- Gordon, G.E., Pierson, W.R., Daisey, J.M., Liroy, P.J., Cooper, J.A., Watson, J.G., Cass, G.R., 1984. Considerations for design of source apportionment studies. *Atmos. Environ.* 18 (8), 1567–1582.
- Gray, H.A., Cass, G.R., 1998. Source contributions to atmospheric fine carbon particle concentrations. *Atmos. Environ.* 32 (22), 3805–3825.
- Gray, H.A., Landry, B., Liu, C.S., Henry, R.C., Cooper, J.A., Sherman, J.R., 1988. Receptor modeling for  $\text{PM}_{10}$  source apportionment in the South Coast Air Basin of California.

- In: Mathai, C.V., Stonefield, D.H. (Eds.), Transactions, PM<sub>10</sub>: Implementation of Standards. Air Pollution Control Association, Philadelphia, PA, pp. 399–418.
- Green, M.C., Flocchini, R.G., Myrup, L.O., 1992a. The relationship of the extinction coefficient distribution to wind field patterns in Southern California. *Atmos. Environ.* A 26 (5), 827–840.
- Green, M.C., Myrup, L.O., Flocchini, R.G., 1992b. A method for classification of wind field patterns and its application to Southern California. *Int. J. Climatol.* 12, 111–135.
- Green, M.C., Flocchini, R.G., Myrup, L.O., 1993. Use of temporal principal components analysis to determine seasonal periods. *Appl. Meteorol.* 32 (5), 986–995.
- Green, M.C., Tombach, I.H., 2000. Use of Project MOHAVE perfluorocarbon tracer data to evaluate source and receptor models. *J. Air Waste Mgmt. Assoc.* 50 (5), 717–723.
- Greenberg, J.P., Guenther, A., Zimmerman, P., Baugh, W., Geron, C., Davis, K., Helmig, D., Klinger, L.F., 1999. Tethered balloon measurements of biogenic VOCs in the atmospheric boundary layer. *Atmos. Environ.* 33 (6), 855–867.
- Grosjean, D., Friedlander, S.K., 1975. Gas–particle distribution factors for organic and other pollutants in the Los Angeles atmosphere. *J. Air Pollut. Control Assoc.* 25 (10), 1038–1044.
- Grosjean, D., Seinfeld, J.H., 1989. Parameterization of the formation potential of secondary organic aerosols. *Atmos. Environ.* 23 (8), 1733–1747.
- Hammerle, R.H., Pierson, W.R., 1975. Sources and elemental composition of aerosol in Pasadena, California, by energy-dispersive X-ray fluorescence. *Environ. Sci. Technol.* 9 (12), 1058–1068.
- Hansen, A.D.A., Rosen, H., 1990. Individual measurements of the emission factor of aerosol black carbon in automobile plumes. *J. Air Waste Mgmt. Assoc.* 40 (12), 1654–1657.
- Hardy, D.M., Walton, J.J., 1978. Principal components analysis of vector wind measurements. *J. Appl. Meteorol.* 17, 1153–1162.
- Harrison, R.M., MacKenzie, A.R., 1990. A numerical simulation of kinetic constraints upon achievement of the ammonium nitrate dissociation equilibrium in the troposphere. *Atmos. Environ.* A 24 (1), 91–102.
- Harrison, R.M., Msibi, I.M., 1994. Validation of techniques for fast response measurement of HNO<sub>3</sub> and NH<sub>3</sub> and determination of the [NH<sub>3</sub>][HNO<sub>3</sub>] concentration product. *Atmos. Environ.* 28 (2), 247–256.
- Harrison, R.M., Pio, C.A., 1983. An investigation of the atmospheric HNO<sub>3</sub>, NH<sub>3</sub>, NH<sub>4</sub>NO<sub>3</sub> equilibrium relationship in a cool, humid climate. *Tellus* 35B, 155–159.
- Harrison, R.M., Sturges, W.T., Kitto, A.M.N., Li, Y., 1990. Kinetics of evaporation of ammonium chloride and ammonium nitrate aerosols. *Atmos. Environ.* A 24 (7), 1883–1888.
- Harrison, R.M., Smith, D.J.T., Luhana, L., 1996. Source apportionment of atmospheric polycyclic aromatic hydrocarbons collected from an urban location in Birmingham, UK. *Environ. Sci. Technol.* 30 (3), 825–832.
- Hawthorne, S.B., Miller, D.J., Langenfeld, J.J., Krieger, M.S., 1992. PM<sub>10</sub> high-volume collection and quantitation of semi- and nonvolatile phenols, methoxylated phenols, alkanes, and polycyclic aromatic hydrocarbons from winter urban air and their relationship to wood smoke. *Environ. Sci. Technol.* 26 (11), 2251–2262.
- Hayami, H., Carmichael, G.R., 1997. Analysis of aerosol composition at Cheju Island, Korea, using a two-bin gas–aerosol equilibrium model. *Atmos. Environ.* 31 (20), 3429–3440.
- Hänel, G., 1965. The properties of atmospheric aerosol particles as functions of the relative humidity at thermodynamic equilibrium with the surrounding moist air. *Adv. Geophys.* 19, 73.
- Heaton, R.W., Rahn, K.A., Lowenthal, D.H., 1992. Regional apportionment of sulfate and tracer elements in Rhode Island precipitation. *Atmos. Environ.* A 26 (8), 1529–1544.
- Heidam, N.Z., 1987. Bootstrap estimates of factor model variability. *Atmos. Environ.* 21, 1203–1217.
- Heindryckx, R., Dams, R., 1974. Continental, marine and anthropogenic contributions to the inorganic composition of the aerosol of an industrial zone. *J. Radioanal. Chem.* 19, 339–349.
- Heinsohn, R.J., Davis, J.W., Knapp, K.T., 1980. Dilution source sampling systems. *Environ. Sci. Technol.* 14, 1205.
- Heisler, S.L., Henry, R.C., Watson, J.G., Hidy, G.M., Anderson, J., Hall, J.S., van Valin, C.C., Waggoner, A.P., 1980. The nature and origins of the Denver winter haze—Findings of the 1978 experiment, vol. I. Report No. ERT no. P-5417 D. Prepared for Motor Vehicle Manufacturers Assoc. of the US Environmental Research and Technology, Inc., Westlake Village, CA.
- Henry, R.C., Hidy, G.M., 1979. Multivariate analysis of particulate sulfate and other air quality variables by principal components—Part I. Annual data from Los Angeles and New York. *Atmos. Environ.* 13, 1581–1596.
- Henry, R.C., Hidy, G.M., 1981. Authors' reply to discussions: Multivariate analysis of particulate sulfate and other air quality variables by principal components—Part I. Annual data from Los Angeles and New York. *Atmos. Environ.* 15, 425–426.
- Henry, R.C., Hidy, G.M., 1982. Multivariate analysis of particulate sulfate and other air quality variables by principal components—Part II. Salt Lake City, Utah and St. Louis, Missouri. *Atmos. Environ.* 16, 929–943.
- Henry, R.C., 1982. Stability analysis of receptor models that use least squares fitting. In: Hopke, P.K., Dattner, S.L. (Eds.), Proceedings, Receptor Models Applied to Contemporary Air Pollution Problems. Air Pollution Control Association, Pittsburgh, PA, pp. 141–162.
- Henry, R.C., 1984. Fundamental limitations of factor analysis receptor models. In: Liu, B.Y.H., Pui, D.Y.H., Fissan, H.J. (Eds.), Aerosols: Science, Technology and Industrial Applications of Airborne Particles. Elsevier Press, New York, pp. 359–362.
- Henry, R.C., 1986. Fundamental limitations of receptor models using factor analysis. In: Pace, T.G. (Ed.), Transactions, Receptor Methods for Source Apportionment: Real World Issues and Applications. Air Pollution Control Association, Pittsburgh, PA, pp. 68–77.
- Henry, R.C., 1987. Current factor analysis receptor models are ill-posed. *Atmos. Environ.* 21 (8), 1815–1820.
- Henry, R.C., 1991. Multivariate receptor models. In: Hopke, P.K. (Ed.), Receptor Modeling for Air Quality Management. Elsevier, Amsterdam, The Netherlands, pp. 117–147.

- Henry, R.C., 1992. Dealing with near collinearity in chemical mass balance receptor models. *Atmos. Environ. A* 26 (5), 933–938.
- Henry, R.C., 1997a. History and fundamentals of multivariate air quality receptor models. *Chemom. Intell. Lab. Sys.* 37, 37–42.
- Henry, R.C., 1997b. Receptor model applied to patterns in space (RMAPS) Part I—Model description. *J. Air Waste Mgmt. Assoc.* 47 (2), 216–219.
- Henry, R.C., 1997c. Receptor model applied to patterns in space (RMAPS) Part II—Apportionment of airborne particulate sulfur from Project MOHAVE. *J. Air Waste Mgmt. Assoc.* 47 (2), 220–225.
- Henry, R.C., 1997d. Receptor modeling applied to patterns in space (RMAPS) Part III—Apportionment of airborne particulate sulfur in western Washington state. *J. Air Waste Mgmt. Assoc.* 47 (2), 226–230.
- Henry, R.C., Kim, B.M., 1989. A factor analysis receptor model with explicit physical constraints. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 214–225.
- Henry, R.C., Kim, B.M., 1990. Extension of self-modeling curve resolution to mixtures of more than three components Part 1. Finding the basic feasible region. *Chemom. Intell. Lab. Sys.* 8, 205–216.
- Henry, R.C., Wang, Y.J., Gebhart, K.A., 1991. The relationship between empirical orthogonal functions and sources of air pollution. *Atmos. Environ. A* 25 (2), 503–509.
- Henry, R.C., Park, E.S., Spiegelman, C.H., 1999. Comparing a new algorithm with the classic methods for estimating the number of factors. *Chemom. Intell. Lab. Sys.* 48, 91–97.
- Henry, R.C., 2000. UNMIX Version 2 Manual. Ronald C. Henry, Ph.D., West Hills, CA.
- Henry, R.C., 2002. Multivariate receptor modeling by  $n$ -dimensional edge detection. *Chemom. Intell. Lab. Sys.*, accepted.
- Hering, S.V., Bowen, J.L., Wengert, J.G., Richards, L.W., 1981. Characterization of the regional haze in the southwestern United States. *Atmos. Environ.* 15 (10/11), 1999–2009.
- Hering, S.V., Miguel, A.H., Dod, R.L., 1984. Tunnel measurements of the PAH, carbon thermogram and elemental source signature for vehicular exhaust. *Sci. Total Environ.* 36, 39–45.
- Hidy, G.M., Friedlander, S.K., 1971. The nature of the Los Angeles aerosol. In: Englund, H.M., Beery, W.T. (Eds.), *Proceedings of the Second International Clean Air Congress*. Academic Press, New York, pp. 391–404.
- Hidy, G.M., Venkataraman, C., 1996. The chemical mass balance method for estimating atmospheric particle sources in southern California. *Chem. Eng. Commun.* 151, 187–209.
- Hien, P.D., Binh, N.T., Truong, Y., Ngo, N.T., Sieu, L.N., 2001. Comparative receptor modelling study of TSP, PM<sub>2</sub> and PM<sub>2-10</sub> in Ho Chi Minh City. *Atmos. Environ.* 35 (15), 2669–2678.
- Hildemann, L.M., Cass, G.R., Markowski, G.R., 1989. A dilution stack sampler for collection of organic aerosol emissions: Design, characterization and field tests. *Aerosol Sci. Technol.* 10 (10–11), 193–204.
- Hildemann, L.M., Markowski, G.R., Jones, M.C., Cass, G.R., 1991. Submicrometer aerosol mass distributions of emissions from boilers, fireplaces, automobiles, diesel trucks, and meat-cooking operations. *Aerosol Sci. Technol.* 14 (1), 138–152.
- Hlavinka, M.W., Bullin, J.A., 1988. Validation of mobile source emission estimates using mass balance techniques. *J. Air Pollut. Control Assoc.* 38 (8), 1035–1039.
- Hoffman, G.L., Duce, R.A., Hoffman, E.J., 1972. Trace metals in the Hawaiian marine atmosphere. *J. Geophys. Res.* 77, 5322–5329.
- Hoffman, G.L., Duce, R.A., 1972. Consideration of the chemical fractionation of alkali and alkaline earth metals in the Hawaiian marine atmosphere. *J. Geophys. Res.* 77, 5161–5169.
- Hofmann, D.J., Stone, R.S., Wood, M.E., Deshler, T., Harris, J.M., 1998. An analysis of 25 years of balloon-borne aerosol data in search of a signature of the subsonic commercial aircraft fleet. *Geophys. Res. Lett.* 25, 2433–2436.
- Holzman, M.I., Scheff, P.A., Yusoff, M.R., 1986. Application and evaluation of four regression techniques for a chemical mass balance receptor model. In: *Proceedings of the 79th Annual Meeting*, 22 June, 1986, Minneapolis, MN. Air Pollution Control Association, Pittsburgh, PA.
- Hoogerbrugge, R., Willig, S.J., Kistemaker, P.G., 1983. Discriminant analysis by double stage principal component analysis. *Anal. Chem.* 55, 1710–1712.
- Hopke, P.K., 1976. The application of multivariate analysis for interpretation of the chemical and physical analysis of lake sediments. *J. Environ. Sci. Health A* 11 (6), 367–383.
- Hopke, P.K., 1981. The application of factor analysis to urban aerosol source resolution. In: Macias, E.S., Hopke, P.K. (Eds.), *Atmospheric Aerosol: Source/Air Quality Relationships*. American Chemical Society, Washington DC, pp. 21–49.
- Hopke, P.K., 1982. Discussion: ‘Trace element concentrations in summer aerosols at rural sites in New York state and their possible sources’ and ‘Seasonal variation in the composition of ambient sulfate-containing aerosols in the New York area’. *Environ. Sci. Technol.* 16, 1279–1281.
- Hopke, P.K., 1985. *Receptor Modeling in Environmental Chemistry*. John Wiley, New York.
- Hopke, P.K., 1988. Target transformation factor analysis as an aerosol mass apportionment method: A review and sensitivity study. *Atmos. Environ.* 22 (9), 1777–1792.
- Hopke, P.K., Gladney, E.S., Gorden, G.E., Zoller, W.H., Jones, A.G., 1976. The use of multivariate analysis to identify sources of selected elements in Boston urban aerosol. *Atmos. Environ.* 10, 1015–1025.
- Hopke, P.K., Lamb, R.E., Natusch, D.F.S., 1980. Multielemental characterization of urban roadway dust. *Environ. Sci. Technol.* 14, 164–172.
- Hopke, P.K., Dattner, S.L., 1982. *Receptor Models Applied to Contemporary Pollution Problems*. Air and Waste Management Association, Pittsburgh, PA.
- Hopke, P.K., Severin, K.G., Chang, S.N., 1982. Application and verification studies of target transformation factor analysis as an aerosol receptor model. In: Hopke, P.K., Dattner, S.L. (Eds.), *Proceedings, Receptor Models Applied to Contemporary Pollution Problems*. Air Pollution Control Association, Pittsburgh, PA, pp. 110–126.



- Hopke, P.K., Alpert, D.J., Roscoe, B.A., 1983. FANTASIA—A program for target transformation factor analysis to apportion sources in environmental samples. *Comput. Chem.* 7 (3), 149–155.
- Hopke, P.K., Wlaschin, W., Landsberger, S., Sweet, C.W., Vermette, S.J., 1988. The source apportionment of PM<sub>10</sub> in South Chicago. In: Mathai, C.V., Stonefield, D.H. (Eds.), *Transactions, PM<sub>10</sub>: Implementation of Standards*. Air Pollution Control Association, Pittsburgh, PA, pp. 484–494.
- Hopke, P.K., 1991. In: Hopke, P.K. (Ed.), *Receptor Modeling for Air Quality Management*. Elsevier, Amsterdam, The Netherlands.
- Hopke, P.K., Gao, N., Cheng, M.D., 1993. Combining chemical and meteorological data to infer source areas of airborne pollutants. *Chemom. Intell. Lab. Sys.* 19 (2), 187–199.
- Hopke, P.K., Li, C.L., Ciszek, W., Landsberger, S., 1995. The use of bootstrapping to estimate conditional probability fields for source locations of airborne pollutants. *Chemom. Intell. Lab. Sys.* 30 (1), 69–79.
- Hopke, P.K., Song, X.H., 1997. The chemical mass balance as a multivariate calibration problem. *Chemom. Intell. Lab. Sys.* 37, 5–14.
- Hosiokangas, J., Ruuskanen, J., Pekkanen, J., 1999. Effects of soil dust episodes and mixed fuel sources on source apportionment of PM<sub>10</sub> particles in Kuopio, Finland. *Atmos. Environ.* 33 (21), 3821–3829.
- Houck, J.E., Cooper, J.A., Frazier, C.A., deCesar, R.T., Mohan, J.F., Maughan, D., Roberts, J., 1982. Receptor model source apportionment of lead in an airshed with lead smelters. In: Hopke, P.K., Dattner, S.L. (Eds.), *Receptor Models Applied to Contemporary Pollution Problems*. Air Pollution Control Association, Pittsburgh, PA, pp. 34–45.
- Houck, J.E., Chow, J.C., Ahuja, M.S., 1989. The chemical and size characterization of particulate material originating from geological sources in California. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 322–333.
- Houck, J.E., Goulet, J.M., Chow, J.C., Watson, J.G., Pritchett, L.C., 1990. Chemical characterization of emission sources contributing to light extinction. In: Mathai, C.V. (Ed.), *Transactions, Visibility and Fine Particles*. Air and Waste Management Association, Pittsburgh, PA, pp. 437–446.
- Houck, J.E., Rau, J.A., Body, S., Chow, J.C., 1992. Source apportionment—Pocatello, Idaho PM<sub>10</sub> nonattainment area. In: Chow, J.C., Ono, D.M. (Eds.), *Transactions, PM<sub>10</sub> Standards and Nontraditional Particulate Source Controls*. Air and Waste Management Association, Pittsburgh, PA, pp. 219–230.
- Huang, S., Rahn, K.A., Arimoto, R., 1999. Testing and optimizing two factor-analysis techniques on aerosol at Narragansett, Rhode Island. *Atmos. Environ.* 33 (14), 2169–2185.
- Huang, S., Arimoto, R., Rahn, K.A., 2001. Sources and source variations for aerosol at Mace Head, Ireland. *Atmos. Environ.* 35 (8), 1421–1437.
- Husain, L., Samson, P.J., 1979. Long-range transport of trace elements. *J. Geophys. Res.* 84 (C3), 1237–1240.
- Husain, L., Webber, J.S., Canelli, E., Dutkiewicz, V.A., Halstead, J.A., 1984. Mn/V ratio as a tracer of aerosol sulfate transport. *Atmos. Environ.* 18 (6), 1059–1071.
- Hwang, C.S., Severin, K.G., Hopke, P.K., 1984. A comparison of R- and Q-modes in target transformation factor analysis for resolving environmental data. *Atmos. Environ.* 18 (2), 345–352.
- Ito, K., Kneip, T.J., Liyo, P.J., 1986. The effects of number of samples and random error on the factor analysis/multiple linear regression (FA/MLR) receptor modeling technique. *Atmos. Environ.* 20, 1433.
- Iyer, H.K., Malm, W.C., Ahlbrandt, R.A., 1987. A mass balance method for estimating the fractional contributions of pollutants from various sources to a receptor site. In: Bhardwaja, P.S. (Ed.), *Transactions, Visibility Protection: Research and Policy Aspects*. Air Pollution Control Association, Pittsburgh, PA, pp. 861–871.
- Jacobson, M.Z., 1999. Studying the effects of calcium and magnesium on size-distributed nitrate and ammonium with EQUISOLV II. *Atmos. Environ.* 33 (22), 3635–3650.
- Jang, M., Kamens, R.M., 1998. A thermodynamic approach for modeling partitioning of semivolatile organic compounds on atmospheric particulate matter: Humidity effects. *Environ. Sci. Technol.* 32 (9), 1237–1243.
- Javitz, H.S., Watson, J.G., Guertin, J.P., Mueller, P.K., 1988a. Results of a receptor modeling feasibility study. *J. Air Pollut. Control Assoc.* 38 (5), 661–667.
- Javitz, H.S., Watson, J.G., Robinson, N.F., 1988b. Performance of the chemical mass balance model with simulated local-scale aerosols. *Atmos. Environ.* 22 (10), 2309–2322.
- Jeon, S.J., Meuzelaar, H.L.C., Sheya, S.A.N., Lighty, J.S., Jarman, W.M., Kasteler, C., Sarofim, A.F., Simoneit, B.R.T., 2001. Exploratory studies of PM<sub>10</sub> receptor and source profiling by GC/MS and principal component analysis of temporally and spatially resolved ambient samples. *J. Air Waste Mgmt. Assoc.* 51 (5), 766–784.
- Johnson, B.J., Huang, S.C., Pitchford, M.L., Ayoub, H.C., Naylor, M.H., 1998. Preliminary on-road measurement of the effect of oxygenated fuel on CO emissions near Las Vegas, Nevada. *J. Air Waste Mgmt. Assoc.* 48 (1), 59–64.
- Johnson, C.E., Malm, W.C., 1987. Identifying visibility-reducing pollution sources using principal component analysis. In: Bhardwaja, P.S. (Ed.), *Transactions, Visibility Protection: Research and Policy Aspects*. Air Pollution Control Association, Pittsburgh, PA, pp. 823–836.
- Johnson, D.L., McIntyre, B.L., 1982. A particle class balance receptor model for aerosol apportionment in Syracuse, NY. In: Dattner, S.L., Hopke, P.K. (Eds.), *Proceedings, Receptor Models Applied to Contemporary Problems*. Air Pollution Control Association, Pittsburgh, PA, pp. 238–247.
- Kao, A.S., Friedlander, S.K., 1995. Frequency distributions of PM<sub>10</sub> chemical components and their sources. *Environ. Sci. Technol.* 29 (1), 19–28.
- Kao, J.J., Huang, S.S., 2000. Forecasting using neural network versus Box–Jenkins methodology for ambient air quality monitoring data. *J. Air Waste Mgmt. Assoc.* 50 (2), 219–226.
- Karl, T.R., Koscielny, A.J., Diaz, H.F., 1982. Potential errors in the application of principal component (eigenvector) analysis to geophysical data. *J. Appl. Meteorol.* 21, 1183–1186.

- Kasahara, M., Choi, K.C., Takahashi, K., 1990. Source contribution of atmospheric aerosols in Japan by chemical mass balance method. *Atmos. Environ. A* 24 (3), 457–466.
- Kavouras, I.G., Koutrakis, P., Cereceda-Balic, F., Oyola, P., 2001. Source apportionment of PM<sub>10</sub> and PM<sub>2.5</sub> in five Chilean cities using factor analysis. *J. Air Waste Mgmt. Assoc.* 51 (3), 451–464.
- Keiding, K., Sorensen, M.S., Pind, N., 1987. A receptor model for urban aerosols based on oblique factor-analysis. *Anal. Chim. Acta* 193, 295–307.
- Khalili, N.R., Scheff, P.A., Holsen, T.M., 1995. PAH source fingerprints for coke ovens, diesel and gasoline engines, highway tunnels, and wood combustion emissions. *Atmos. Environ.* 29 (4), 533–542.
- Kim, B.M., Henry, R.C., 1989. Analysis of multicollinearity indicators and influential species for chemical mass balance receptor model. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 379–390.
- Kim, B.M., Henry, R.C., 1999. Diagnostics for determining influential species in the chemical mass balance receptor model. *J. Air Waste Mgmt. Assoc.* 49 (12), 1449–1455.
- Kim, B.M., Henry, R.C., 2000. Application of SAFER model to the Los Angeles PM<sub>10</sub> data. *Atmos. Environ.* 34 (11), 1747–1759.
- Kim, B.M., Lewis, R., Hogo, H., 1992a. Source apportionment by chemical mass balance: A comparison between measured source profiles and SAFER model estimated source profiles. In: Chow, J.C., Ono, D.M. (Eds.), *Transactions, PM<sub>10</sub> Standards and Nontraditional Particulate Source Controls*. Air and Waste Management Association, Pittsburgh, PA, pp. 146–162.
- Kim, B.M., Zeldin, M.D., Liu, C., 1992b. Source apportionment study for state implementation plan development in the Coachella Valley. In: Chow, J.C., Ono, D.M. (Eds.), *Transactions, PM<sub>10</sub> Standards and Nontraditional Particulate Source Controls*. Air and Waste Management Association, Pittsburgh, PA, pp. 979–991.
- Kim, D.S., Hopke, P.K., Massart, D.L., Kaufman, L., Casuccio, G.S., 1987. Multivariate analysis of CCSEM auto emission data. *Sci. Total Environ.* 59, 141–155.
- Kim, D.S., Hopke, P.K., 1988. The classification of individual particles based on computer-controlled scanning electron microscopy data. *Aerosol Sci. Technol.* 9, 133–151.
- Kim, D.S., Hopke, P.K., 1990. Particle class balance for apportioning aerosol mass with size segregation scheme. *J. Korea Soc. Environ. Eng.* 12 (3), 9–19.
- Kim, Y.P., Seinfeld, J.H., 1995. Atmospheric gas-aerosol equilibrium—III. Thermodynamics of crustal elements Ca<sup>2+</sup>, K<sup>+</sup>, and Mg<sup>2+</sup>. *Aerosol Sci. Technol.* 22 (1), 93–110.
- Kim, Y.P., Seinfeld, J.H., Saxena, P., 1993a. Atmospheric gas-aerosol equilibrium—I. Thermodynamic model. *Aerosol Sci. Technol.* 19 (2), 157–181.
- Kim, Y.P., Seinfeld, J.H., Saxena, P., 1993b. Atmospheric gas-aerosol equilibrium—II. Analysis of common approximations and activity coefficient calculation methods. *Aerosol Sci. Technol.* 19 (2), 182–198.
- King, R.B., Fordyce, J.S., Antoine, A.C., Leibecki, H.F., Neustadter, H.E., Sidik, S.M., 1976. Elemental composition of airborne particulates and source identification: An extensive one year survey. *J. Air Pollut. Control Assoc.* 26, 1073–1078.
- Kitto, A.M., Colbeck, I., 1999. Filtration and denuder sampling techniques. In: Spurny, K.R. (Ed.), *Analytical Chemistry of Aerosols*. CRC Press LLC, Boca Raton, FL, pp. 103–132.
- Kleeman, M.J., Cass, G.R., Eldering, A., 1997. Modeling the airborne particle complex as a source-oriented external mixture. *J. Geophys. Res.* 102 (D17), 21355–21372.
- Kleeman, M.J., Cass, G.R., 1999. Effect of emissions control strategies on the size and composition distribution of urban particulate air pollution. *Environ. Sci. Technol.* 33 (1), 177–189.
- Kleeman, M.J., Schauer, J.J., Cass, G.R., 1999. Size and composition distribution of fine particulate matter emitted from wood burning, meat charbroiling, and cigarettes. *Environ. Sci. Technol.* 33 (20), 3516–3523.
- Kleinman, M.T., Pasternack, B.S., Eisenbud, M., Kneip, T.J., 1980. Identifying and estimating the relative importance of sources of airborne particulates. *Environ. Sci. Technol.* 14 (1), 62–65.
- Kneip, T.J., Kleinman, M.T., Eisenbud, M., 1973. Relative contribution of emission sources to the total airborne particulates in New York City. In: *Third International Clean Air Congress*, Dusseldorf.
- Kneip, T.J., Mallon, R.P., Kleinman, M.T., 1983. The impact of changing air quality on multiple regression models for coarse and fine particle fractions. *Atmos. Environ.* 17 (2), 299–304.
- Koloutsou-Vakakis, S., Rood, M.J., 1994. The (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>–Na<sub>2</sub>SO<sub>4</sub>–H<sub>2</sub>O system: Comparison of deliquescence humidities measured in the field and estimated from laboratory measurements and thermodynamic modeling. *Tellus B* 46 (1), 1–15.
- Koutrakis, P., Kelly, B.P., 1993. Equilibrium size of atmospheric aerosol sulfates as a function of particle acidity and ambient relative humidity. *J. Geophys. Res.* 98 (D4), 7141–7147.
- Koutrakis, P., Spengler, J.D., 1987. Source apportionment of ambient particles in Steubenville, OH using specific rotation factor analysis. *Atmos. Environ.* 21 (7), 1511–1519.
- Koutrakis, P., Keeler, G.J., Spengler, J.D., Lowenthal, D.H., 1989. Analysis of simulated data using specific rotation factor analysis. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 190–195.
- Koutrakis, P., Briggs, S.L.K., Leaderer, B.P., 1992. Source apportionment of indoor aerosols in Suffolk and Onodaga Counties, New York. *Environ. Sci. Technol.* 26 (3), 521–527.
- Kowalczyk, G.S., Choquette, C.E., Gordon, G.E., 1978. Chemical element balances and identification of air pollution sources in Washington, DC. *Atmos. Environ.* 12, 1143–1153.
- Kowalczyk, G.S., Gordon, G.E., Rheingrover, S.W., 1982. Identification of atmospheric particulate sources in Washington, DC using chemical element balances. *Environ. Sci. Technol.* 16, 79–90.
- Krijnsen, H.C., van Kooten, W.E.J., Calis, H.P.A., Verbeek, R.P., van den Bleek, C.M., 2000. Evaluation of an artificial

- neural network for NO<sub>x</sub> emission prediction from a transient diesel engine as a base for NO sub(x) control. *Can. J. Chem. Eng.* 78 (2), 408–417.
- Kuhn, M., Bultjes, P.J.H., Poppe, D., Simpson, D., Stockwell, W.R., Andersson-Sköld, Y., Baart, A., Das, M., Fiedler, F., Hov, Ø, Kirchner, F., Makar, P.A., Milford, J.B., Roemer, M.G.M., Ruhnke, R., et al., 1998. Intercomparison of the gas-phase chemistry in several chemistry and transport models. *Atmos. Environ.* 32 (4), 693–709.
- Kuik, P., Blaauw, M., Sloof, J.E., Wolterbeck, H.T., 1993a. The use of Monte Carlo methods in factor analysis. *Atmos. Environ. A* 27 (13), 1967–1974.
- Kuik, P., Sloof, J.E., Wolterbeck, H.T., 1993b. Application of Monte Carlo-assisted factor analysis to large sets of environmental pollution data. *Atmos. Environ. A* 27 (13), 1975–1984.
- Kusmierczyk-Michulec, J., Marks, R., 2000. The influence of sea-salt aerosols on the atmospheric extinction over the Baltic and the North Seas. *J. Aerosol Sci.* 31 (11), 1299–1316.
- Lagomarsino, R.J., Latner, N., 1997. A tethered balloon air sampling system for determining the vertical distribution of atmospheric tracers. *J. Air Waste Mgmt. Assoc.* 47 (9), 990–994.
- Larson, T.V., Vong, R.J., 1989. Partial least squares regression methodology: Application to source receptor modeling. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 391–403.
- Latimer, D.A., Iyer, H.K., Malm, W.C., 1990. Application of a differential mass balance model to attribute sulfate haze in the Southwest. In: Mathai, C.V. (Ed.), *Transactions, Visibility and Fine Particles*. Air and Waste Management Association, Pittsburgh, PA, pp. 819–830.
- Lawson, D.R., Winchester, J.W., 1978. Sulfur and trace element concentration relationships in aerosols from the South American continent. *Geophys. Res. Lett.* 5, 195–198.
- Lawson, D.R., Winchester, J.W., 1979a. A standard crustal aerosol as a reference for elemental enrichment factors. *Atmos. Environ.* 13, 925–930.
- Lawson, D.R., Winchester, J.W., 1979b. Sulfur, potassium, and phosphorus associations in aerosols from South American tropical rain forests. *J. Geophys. Res.* 84, 3723–3727.
- Lazaridis, M., 1999. Gas-particle partitioning of organic compounds in the atmosphere. *J. Aerosol Sci.* 30 (9), 1165–1170.
- Lee, E., Chan, C.K., Paatero, P., 1999. Application of positive matrix factorization in source apportionment of particulate pollutants in Hong Kong. *Atmos. Environ.* 33 (19), 3201–3212.
- Lee, S.C., Li, W.M., Yin Chan, L., 2001. Indoor air quality at restaurants with different styles of cooking in metropolitan Hong Kong. *Sci. Total Environ.* 279 (1–3), 181–193.
- Lewis, C.W., Stevens, R.K., 1985. Hybrid receptor model for secondary sulfate from an SO<sub>2</sub> point source. *Atmos. Environ.* 19 (6), 917–924.
- Lewis, C.W., Baumgardner, R.E., Stevens, R.K., 1986. Receptor modeling study of Denver winter haze. *Environ. Sci. Technol.* 20, 1126–1136.
- Lewis, C.W., Baumgardner, R.E., Stevens, R.K., Claxton, L.D., Lewtas, J., 1988. Contribution of woodsmoke and motor vehicle emissions to ambient aerosol mutagenicity. *Environ. Sci. Technol.* 22 (8), 968–971.
- Li, Z.Y., Deng, X.M., 1999. Optimization of environmental monitoring sites by principal component subset selection based on comprehensive relative importance of pollutants. *China Environ. Sci.* 19 (5), 458–460.
- Liljestrand, H.M., 1982. Acidic precipitation source identification by chemical mass balance methods employing fractionation factors. In: Dattner, S.L., Hopke, P.K. (Eds.), *Proceedings, Receptor Models Applied to Contemporary Pollution Problems*. Air Pollution Control Association, Pittsburgh, PA, pp. 212–223.
- Lioy, P.J., Mallon, R.P., Lippmann, M., Kneip, T.J., Samson, P.J., 1982. Factors affecting the variability of summertime sulfate in a rural area using principal component analysis. *J. Air Pollut. Control Assoc.* 32 (10), 1043–1047.
- Liu, C.K., Roscoe, B.A., Severin, K.G., Hopke, P.K., 1982. The application of factor analysis to source apportionment of aerosol mass. *J. Am. Ind. Hyg. Assoc.* 43, 314–318.
- Liu, X.D., Hopke, P.K., Cohen, D., Bailey, G.M., 1995. Sources of fine particle lead, bromine, and elemental carbon in southeastern Australia. *Sci. Total Environ.* 175 (1), 65–79.
- Liu, X., Gao, N., Hopke, P.K., Cohen, D., Bailey, G., Crisp, P., 1996. Evaluation of spatial patterns of fine particle sulfur and lead concentrations in New South Wales, Australia. *Atmos. Environ.* 30 (1), 9–24.
- Liu, X., Feng, Y., Jia, H., Zhang, Y., Ma, Q., Shao, Y., 1998. Source apportionment of Qingdao atmospheric aerosol with chemical mass balance method. *Res. Environ. Sci.* 11 (5), 51–54.
- Lloyd, A.C., Cackette, T.A., 2001a. 2001 Critical review—Diesel engines: Environmental impact and control. *J. Air Waste Mgmt. Assoc.* 51 (6), 809–847.
- Lloyd, A.C., Cackette, T.A., 2001b. Diesel engines: Environmental impact and control. *EM* 8 (6), 34–41.
- Lonneman, W.A., Sella, R.L., Meeks, S.A., 1986. Non-methane organic composition in the Lincoln Tunnel. *Environ. Sci. Technol.* 20, 790–796.
- Lowenthal, D.H., Rahn, K.A., 1985. Regional sources of pollution aerosol at Barrow, Alaska during winter 1979–1980 as deduced from elemental tracers. *Atmos. Environ.* 19, 2011–2024.
- Lowenthal, D.H., Rahn, K.A., 1987a. Application of the factor-analysis receptor model to simulated urban- and regional-scale data sets. *Atmos. Environ.* 21 (9), 2005–2013.
- Lowenthal, D.H., Rahn, K.A., 1987b. The Mn/V ratio in retrospect. *J. Air Pollut. Control Assoc.* 37 (7), 829–830.
- Lowenthal, D.H., Rahn, K.A., 1988a. Tests of regional elemental tracers of pollution aerosols. 2. Sensitivity of signatures and apportionments to variations in operating parameters. *Atmos. Environ.* 22, 420–426.
- Lowenthal, D.H., Rahn, K.A., 1988b. Reproducibility of regional apportionments of pollution aerosol in the north-eastern United States. *Atmos. Environ.* 22 (9), 1829–1833.
- Lowenthal, D.H., Rahn, K.A., 1989. The relationship between secondary sulfate and primary regional signatures in north-eastern aerosol and precipitation. *Atmos. Environ.* 23 (7), 1511–1515.
- Lowenthal, D.H., Hanumara, R.C., Rahn, K.A., Currie, L.A., 1987. Effects of systematic error, estimates and uncertainties

- in chemical mass balance apportionments: Quail Roost II revisited. *Atmos. Environ.* 21 (3), 501–510.
- Lowenthal, D.H., Wunschel, K.R., Rahn, K.A., 1988. Tests of regional elemental tracers of pollution aerosols. 1. Distinctness of regional signatures, stability during transport, and empirical validation. *Environ. Sci. Technol.* 22, 413–420.
- Lowenthal, D.H., Chow, J.C., Watson, J.G., Neuroth, G.R., Robbins, R.B., Shafritz, B.P., Countess, R.J., 1992. The effects of collinearity on the ability to determine aerosol contributions from diesel- and gasoline-powered vehicles using the chemical mass balance model. *Atmos. Environ. A* 26 (13), 2341–2351.
- Lowenthal, D.H., Zielinska, B., Chow, J.C., Watson, J.G., Gautam, M., Ferguson, D.H., Neuroth, G.R., Stevens, K.D., 1994. Characterization of heavy-duty diesel vehicle emissions. *Atmos. Environ.* 28 (4), 731–743.
- Lowenthal, D.H., Rogers, C.F., Saxena, P., Watson, J.G., Chow, J.C., 1995. Sensitivity of estimated light extinction coefficients to model assumptions and measurement errors. *Atmos. Environ.* 29 (7), 751–766.
- Lowenthal, D.H., Chow, J.C., Watson, J.G., Dipple, W.A., Mazzer, D.M., 1996. PM<sub>10</sub> source apportionment at McMurdo Station, Antarctica. *EM* 2, 28–30.
- Lowenthal, D.H., Chow, J.C., Mazzer, D.M., 1997a. PM<sub>10</sub> source apportionment at McMurdo Station, Antarctica. *Antarctic J.* 32, 165–167.
- Lowenthal, D.H., Wittorff, D.N., Gertler, A.W., Sakiyama, S.K., 1997b. CMB source apportionment during REVEAL. *J. Environ. Eng.* 123 (1), 80–87.
- Lurmann, F.W., Wexler, A.S., Pandis, S.N., Musarra, S., Kumar, N., Seinfeld, J.H., 1997. Modelling urban and regional aerosols—II. Application to California's South Coast Air Basin. *Atmos. Environ.* 31 (17), 2695–2716.
- Macias, E.S., Hopke, P.K., 1981. *Atmospheric Aerosol: Source/Air Quality Relationships*. American Chemical Society, Washington, DC.
- Magliano, K.L., 1988. Level 1 PM<sub>10</sub> assessment in a California air basin. In: Mathai, C.V., Stonefield, D.H. (Eds.), *Transactions, PM<sub>10</sub>: Implementation of Standards*. Air Pollution Control Association, Pittsburgh, PA, pp. 508–517.
- Magliano, K.L., Ranzieri, A.J., Solomon, P.A., 1998. Chemical mass balance modeling of the 1995 integrated monitoring study database. In: Chow, J.C., Koutrakis, P. (Eds.), *Proceedings, PM<sub>2.5</sub>: A Fine Particle Standard*. Air and Waste Management Association, Pittsburgh, PA, pp. 824–838.
- Magliano, K.L., Hughes, V.M., Chinkin, L.R., Coe, D.L., Haste, T.L., Kumar, N., Lurmann, F.W., 1999. Spatial and temporal variations in PM<sub>10</sub> and PM<sub>2.5</sub> source contributions and comparison to emissions during the 1995 integrated monitoring study. *Atmos. Environ.* 33 (29), 4757–4773.
- Malm, W.C., Johnson, C.E., Bresch, J.F., 1985. Application of principal component analysis for purposes of identifying source–receptor relationships. In: Pace, T.G. (Ed.), *Transactions, Receptor Methods for Source Apportionment: Real World Issues and Applications*. Air Pollution Control Association, Pittsburgh, PA, pp. 127–148.
- Malm, W.C., Johnson, C.E., Bresch, J.F., Cahill, T.A., 1987. An eigenvector analysis of particulate data in the western United States. In: Bhardwaja, P.S. (Ed.), *Transactions, Visibility Protection: Research and Policy Aspects*. Air Pollution Control Association, Pittsburgh, PA, pp. 837–860.
- Malm, W.C., Gebhart, K.A., 1997. Source apportionment of sulfur and light extinction using receptor modeling techniques. *J. Air Waste Mgmt. Assoc.* 47 (3), 250–268.
- Malm, W.C., Gebhart, K.A., Henry, R.C., 1990a. An investigation of the dominant source regions of fine sulfur in the Western United States and their areas of influence. *Atmos. Environ. A* 24, 3047–3060.
- Malm, W.C., Iyer, H.K., Gebhart, K.A., 1990b. Application of tracer mass balance regression to WHITEX data. In: Mathai, C.V. (Ed.), *Transactions, Visibility and Fine Particles*. Air and Waste Management Association, Pittsburgh, PA, pp. 806–818.
- Mangelson, N.F., deCesar, R.T., Fields, S.M., Cooper, J.A., 1985. Effects of sampling duration on aerosol source apportionment by the chemical mass balance method. In: Pace, T.G. (Ed.), *Williamsburg Specialty Conference*. Air Pollution Control Association, Pittsburgh, PA.
- Mason, B., 1966. *Principles of Geochemistry*, third ed. John Wiley, New York, NY.
- Matamala, L.V., Nininger, R.C., 1990. A Monte-Carlo simulation to assess the sensitivity of structured regression coefficients to measurement precision. In: Mathai, C.V. (Ed.), *Transactions, Visibility and Fine Particles*. Air and Waste Management Association, Pittsburgh, PA, pp. 700–707.
- Matsumoto, K., Tanaka, H., 1996. Formation and dissociation of atmospheric particulate nitrate and chloride; an approach based on phase equilibrium. *Atmos. Environ.* 30 (4), 639–648.
- Mazzer, D.M., Lowenthal, D.H., Chow, J.C., Watson, J.G., 2001. Sources of PM<sub>10</sub> and sulfate aerosol at McMurdo Station, Antarctica. *Chemosphere* 45 (3), 347–356.
- McDonald, J.D., Zielinska, B., Fujita, E.M., Chow, J.C., Watson, J.G., Sagebiel, J.C., 1998. The development of chemical emission profiles for residential wood combustion and meat cooking for use in the apportionment of atmospheric carbonaceous aerosol. In: Chow, J.C., Koutrakis, P. (Eds.), *Proceedings, PM<sub>2.5</sub>: A Fine Particle Standard*. Air and Waste Management Association, Pittsburgh, PA, pp. 645–660.
- McDonald, J.D., Zielinska, B., Fujita, E.M., Sagebiel, J.C., Chow, J.C., Watson, J.G., 2000. Fine particle and gaseous emission rates from residential wood combustion. *Environ. Sci. Technol.* 34 (11), 2080–2091.
- McDonald, K.M., Cheng, L., Olson, M.P., Angle, R.P., 1996. A comparison of box and plume model calculations for sulphur deposition and flux in Alberta, Canada. *Atmos. Environ.* 30 (17), 2969–2980.
- McMurry, P.H., 2000. A review of atmospheric aerosol measurements. *Atmos. Environ.* 34 (12–14), 1959–1999.
- Meinert, D.L., Winchester, J.W., 1977. Chemical relationships in the North Atlantic marine aerosol. *J. Geophys. Res.* 82, 1778–1782.
- Meng, Z., Seinfeld, J.H., 1996. Time scales to achieve atmospheric gas–aerosol equilibrium for volatile species. *Atmos. Environ.* 30 (16), 2889–2900.
- Meng, Z., Seinfeld, J.H., Saxena, P., Kim, Y.P., 1995. Atmospheric gas–aerosol equilibrium IV. Thermodynamics of carbonates. *Aerosol Sci. Technol.* 23 (2), 131–154.

- Meng, Z., Seinfeld, J.H., Saxena, P., Kim, Y.P., 1997. Gas/aerosol distribution of formic and acetic acids. *Aerosol Sci. Technol.* 23, 561–578.
- Michaud, D., Baril, M., Perrault, G., 1993. Characterization of airborne dust from cast iron foundries by physico-chemical methods and multivariate statistical analyses. *J. Air Waste Mgmt. Assoc.* 43 (5), 729–735.
- Michaud, D., Baril, M., Dion, C., Perrault, G., 1996. Characterization of airborne dust from two nonferrous foundries by physico-chemical methods and multivariate statistical analyses. *J. Air Waste Mgmt. Assoc.* 46 (5), 450–457.
- Miguel, A.H., 1984. “Atmospheric” reactivity of particulate polycyclic aromatic hydrocarbons collected in an urban tunnel. *Sci. Total Environ.* 36, 305–311.
- Miguel, A.H., Dos Reis Pedreira Filho, W., Allen, A.G., 1995. Chemical mass balance source apportionment of indoor PM<sub>15</sub> in Brazilian corporate offices and restaurants. *Indoor Environ.* 4 (6), 355–361.
- Mihalakakou, G., Santamouris, M., Asimakopoulos, D.N., 1998. Modeling ambient air temperature time series using neural networks. *J. Geophys. Res.* 103 (D16), 19509–19518.
- Miller, E.A., Cooper, J.A., Guimaraes, F., Alonso, C.D., Filho, B., 1989. Cubatao aerosol source apportionment study. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air Pollution Control Assoc., Pittsburgh, PA, pp. 23–36.
- Miller, M.S., Friedlander, S.K., Hidy, G.M., 1972. A chemical element balance for the Pasadena aerosol. *J. Colloid Interface Sci.* 39 (1), 165–176.
- Milonis, A.E., Davies, T.D., 1994a. Regression and stochastic models for air pollution—I. Review, comments and suggestions. *Atmos. Environ.* 28 (17), 2801–2810.
- Milonis, A.E., Davies, T.D., 1994b. Regression and stochastic models for air pollution—II. Application of stochastic models to examine the links between ground-level smoke concentrations and temperature inversions. *Atmos. Environ.* 28 (17), 2811–2823.
- Mizohata, A., Mamuro, T., 1979. Chemical element balances in aerosol over Sakai, Osaka. *Ann. Rep. Radiat. Center Osaka Prefecture* 20, 55–69.
- Morandi, M.T., Daisey, J.M., Lioy, P.J., 1987. Development of a modified factor analysis/multiple regression model to apportion suspended particulate matter in a complex urban airshed. *Atmos. Environ.* 21 (8), 1821–1831.
- Morandi, M.T., Lioy, P.J., Daisey, J.M., 1991. Comparison of two multivariate modeling approaches for the source apportionment of inhalable particulate matter in Newark, NJ. *Atmos. Environ.* A 25 (5–6), 927–937.
- Moro, G., Lasagni, M., Rigamonti, N., Cosentino, U., Pitea, D., 1997. Critical review of the receptor model based on target transformation factor analysis. *Chemosphere* 35 (8), 1847–1865.
- Moya, M., Ansari, A.S., Pandis, S.N., 2001. Partitioning of nitrate and ammonium between the gas and particulate phases during the 1997 IMADA-AVER study in Mexico City. *Atmos. Environ.* 35 (10), 1791–1804.
- Moyers, J.L., Duce, R.A., 1972. Gaseous and particulate iodine in the marine atmosphere. *J. Geophys. Res.* 77, 5229–5238.
- Moyers, J.L., Ranweiler, L.E., Hopf, S.B., Karte, N.E., 1977. Evaluation of particulate trace species in southwest desert atmosphere. *Environ. Sci. Technol.* 11 (8), 789–795.
- Mozurkewich, M., 1993. The dissociation constant of ammonium nitrate and its dependence on temperature, relative humidity and particle size. *Atmos. Environ.* A 27 (2), 261–270.
- Mroz, E.J., Zoller, W.H., 1975. Composition of atmospheric particulate matter from the eruption of Heimaey, Iceland. *Science* 190, 461–464.
- Mugica, V., Vega, E., Chow, J.C., Reyes, E., Sanchez, G., Arriaga, J.L., Egami, R.T., Watson, J.G., 2001. Speciated non-methane organic compounds emissions from food cooking in Mexico. *Atmos. Environ.* 35 (10), 1729–1734.
- Müller, C., 1992. Source apportionment study of atmospheric particulates in the Vaal Triangle. M.Sc. Thesis, University of Witwatersrand, Johannesburg, South Africa.
- Neustadter, H.E., Fordyce, J.S., King, R.B., 1976. Elemental composition of airborne particulates and source identification: Data analysis techniques. *J. Air Pollut. Control Assoc.* 26 (11), 1079–1084.
- Nitta, H., Ichikawa, M., Sato, M., Konishi, S., Ono, M., 1994. A new approach based on a covariance structure model to source apportionment of indoor fine particles in Tokyo. *Atmos. Environ.* 28 (4), 631–636.
- Norris, G., Larson, T.V., Koenig, J., Sullivan, W., Claiborn, C.S., Finn, D., Edgar, R., 1998. Sources of fine particulate composition variability in Spokane, Washington. In: Chow, J.C., Koutrakis, P. (Eds.), *Proceedings, PM<sub>2.5</sub>: A Fine Particle Standard*. Air and Waste Management Association, Pittsburgh, PA, pp. 28–37.
- Nolte, C.G., Schauer, J.J., Cass, G.R., Simoneit, B.R.T., 1999. Highly polar organic compounds present in meat smoke. *Environ. Sci. Technol.* 33 (19), 3313–3316.
- Ogawa, N., Kikuchi, R., Okamura, T., Inotsume, J., Adzuhata, T., Ozeki, T., Kajikawa, M., 2000. Evaluation of ionic pollutants in cloud droplets at a mountain ridge in northern Japan using constrained oblique rotational factor analysis. *Atmos. Res.* 54, 279–283.
- Okamoto, S., Hayashi, M., Nakajima, M., Kainuma, Y., Shiozawa, K., 1990. A factor analysis-multiple regression model for source apportionment of suspended particulate matter. *Atmos. Environ.* A 24 (8), 2089–2097.
- Olmez, I., Sheffield, A.E., Gordon, G.E., Houck, J.E., Pritchett, L.C., Cooper, J.A., Dzubay, T.G., Bennett, R.L., 1988. Compositions of particles from selected sources in Philadelphia for receptor model applications. *J. Air Pollut. Control Assoc.* 38 (11), 1392–1402.
- Ouimette, J.R., Flagan, R.C., Kelso, A.R., 1981. Chemical species contributions to light scattering by aerosols at a remote arid site: Comparison of statistical and theoretical results. In: Macias, E.S., Hopke, P.K. (Eds.), *Atmospheric Aerosol, Source/Air Quality Relationships*. American Chemical Society, Washington, DC, pp. 125–156.
- Ouimette, J.R., Flagan, R.C., 1982. The extinction coefficient of multicomponent aerosols. *Atmos. Environ.* 16 (10), 2405–2419.
- Overland, J.E., Preisendorfer, R.W., 1982. A significance test for principal components applied to a cyclone climatology. *Mon. Weather Rev.* 110 (1), 1–4.
- Paatero, P., 1997. Least squares formulation of robust non-negative factor analysis. *Chemom. Intell. Lab. Sys.* 37, 23–35.

- Paatero, P., 1998. User's guide for positive matrix factorization programs PMF2 and PMF3 Part 1: Tutorial. University of Helsinki, Helsinki, Finland.
- Paatero, P., 2000. User's guide for positive matrix factorization programs PMF2 and PMF3 Part 2: Reference. University of Helsinki, Helsinki, Finland.
- Paatero, P., Tapper, U., 1993. Analysis of different modes of factor analysis as least squares fit problems. *Chemom. Intell. Lab. Sys.* 18, 183–194.
- Paatero, P., Tapper, U., 1994. Positive matrix factorization: A non-negative factor model with optimal utilization of error estimates of data values. *Environmetrics* 5, 111–126.
- Pace, T.G., 1986. In: Pace, T.G. (Ed.), *Transactions, Receptor Methods for Source Apportionment: Real World Issues and Applications*. Air Pollution Control Association, Pittsburgh, PA.
- Pace, T.G., Watson, J.G., 1987. Protocol for applying and validating the CMB model. Report No. EPA 450/4-87-010. US Environmental Protection Agency, Research Triangle Park, NC.
- Paciga, J.J., Roberts, T.M., Jervis, R.E., 1975. Particle size distributions of lead, bromine, and chlorine in urban-industrial aerosols. *Environ. Sci. Technol.* 9, 1141–1144.
- Paciga, J.J., John, J., Jervis, R.E., 1976. Multielement size characterization of urban aerosols. *Environ. Sci. Technol.* 10, 1124–1128.
- Pacyna, J.M., 1986. Atmospheric trace elements from natural and anthropogenic sources. In: Nriagu, J.O., Davidson, C.I. (Eds.), *Toxic Metals in the Atmosphere*. John Wiley, New York, pp. 33–52.
- Padmanabhamarty, U.K., 1975. Eigenvectors of sulfur dioxide in metropolitan Toronto and their association with meteorological parameters. *Atmos. Environ.* 9, 365–366.
- Pandis, S.N., Harley, R.A., Cass, G.R., Seinfeld, J.H., 1992. Secondary organic aerosol formation and transport. *Atmos. Environ.* A 26 (13), 2269–2282.
- Pankow, J.F., 1987. Review and comparative analysis of the theories on partitioning between the gas and aerosol particulate phases in the atmosphere. *Atmos. Environ.* 21 (11), 2275–2283.
- Pankow, J.F., 1988. The calculated effects of non-exchangeable material on the gas–particle distributions of organic compounds. *Atmos. Environ.* 22 (7), 1405–1409.
- Pankow, J.F., 1992. Application of common  $\gamma$ -intercept regression parameters for  $\log K_p$  vs  $1/T$  for predicting gas–particle partitioning in the urban environment. *Atmos. Environ.* A 26 (14), 2489–2498.
- Pankow, J.F., 1993. A simple box model for the annual cycle of partitioning of semi-volatile organic compounds between the atmosphere and the Earth's surface. *Atmos. Environ.* A 27 (7), 1139–1152.
- Pankow, J.F., 1994a. An absorption model of gas/particle partitioning of organic compounds in the atmosphere. *Atmos. Environ.* 28 (2), 185–188.
- Pankow, J.F., 1994b. An absorption model of the gas/aerosol partitioning involved in the formation of secondary organic aerosol. *Atmos. Environ.* 28 (2), 189–194.
- Pankow, J.F., 1998. Further discussion of the octanol/air partition coefficient  $K_{oa}$  as a correlating parameter for gas/particle partitioning coefficient. *Atmos. Environ.* 32 (9), 1493–1498.
- Pankow, J.F., Bidleman, T.F., 1992. Interdependence of the slopes and intercepts from log–log correlations of measured gas–particle partitioning and vapor pressure: I. Theory and analysis of available data. *Atmos. Environ.* A 26 (6), 1071–1080.
- Pankow, J.F., Storey, J.M.E., Yamasaki, H., 1993. Effects of relative humidity on gas/particle partitioning of semivolatile organic compounds to urban particulate matter. *Environ. Sci. Technol.* 27 (10), 2220–2226.
- Park, S.S., Bae, M.S., Kim, Y.J., 2001a. Chemical composition and source apportionment of PM<sub>2.5</sub> particles in the Sihwa area, Korea. *J. Air Waste Mgmt. Assoc.* 51 (3), 393–405.
- Park, S.S., Kim, Y.J., Fung, K., 2001b. Characteristics of PM<sub>2.5</sub> carbonaceous aerosol in the Sihwa industrial area, Korea. *Atmos. Environ.* 35 (4), 657–665.
- Pasini, A., Pelino, V., Potesta, S., 2001. A neural network model for visibility nowcasting from surface observations: Results and sensitivity to physical input variables. *J. Geophys. Res.* 106 (D14), 14951–14959.
- Paterson, K.G., Sagady, J.L., Hooper, D.L., 1999. Analysis of air quality data using positive matrix factorization. *Environ. Sci. Technol.* 33 (4), 635–641.
- Perez, P., Trier, A., Reyes, J., 2000. Prediction of PM<sub>2.5</sub> concentrations several hours in advance using neural networks in Santiago, Chile. *Atmos. Environ.* 34 (8), 1189–1196.
- Peterson, J.T., 1970. Distribution of sulfur dioxide over metropolitan St. Louis as described by empirical orthogonal functions, and its relation to meteorological parameters. *Atmos. Environ.* 4, 501–518.
- Pierson, W.R., Brachaczek, W.W., 1976. Particulate matter associated with vehicles on the road. *Trans. Soc. Automot. Eng.* 85, 209–227.
- Pierson, W.R., Brachaczek, W.W., 1983. Particulate matter associated with vehicles on the road II. *Aerosol Sci. Technol.* 2, 1–40.
- Pierson, W.R., Gertler, A.W., Bradow, R.L., 1990. Comparison of the SCAQS tunnel study with other on-road vehicle emission data. *J. Air Waste Mgmt. Assoc.* 40 (11), 1495–1504.
- Pierson, W.R., Gertler, A.W., Robinson, N.F., Sagebiel, J.C., Zielinska, B., Bishop, G.A., Stedman, D.H., Zweidinger, R.B., Ray, W.D., 1996. Real-world automotive emissions—Summary of studies in the Fort McHenry and Tuscarora Mountain tunnels. *Atmos. Environ.* 30 (12), 2233–2256.
- Pilinis, C., Farber, R.J., 1991. Evaluation of the effects of emission reductions on secondary particulate matter in the South Coast Air Basin of California. *J. Air Waste Mgmt. Assoc.* 41 (5), 702–709.
- Pilinis, C., Seinfeld, J.H., 1987. Continued development of a general equilibrium model for inorganic multicomponent atmospheric aerosols. *Atmos. Environ.* 21 (11), 2453–2466.
- Pilinis, C., Seinfeld, J.H., Seigneur, C., 1987. Mathematical modeling of the dynamics of multicomponent atmospheric aerosols. *Atmos. Environ.* 21 (4), 943–955.
- Pinto, J.P., Stevens, R.K., Willis, R.D., Kellogg, R.B., Mamane, Y., Novak, J., Santroch, J., Benes, I., Lenicek, J., Bures, V., 1998. Czech air quality monitoring and receptor modeling study. *Environ. Sci. Technol.* 32 (7), 843–854.
- Pio, C.A., Nunes, T.V., Borrego, C.S., Martins, J.G., 1989. Assessment of air pollution sources in an industrial atmo-

- sphere using principal component and multilinear regression analysis. *Sci. Total Environ.* 66, 65–72.
- Pistikopoulos, P., Masplet, P., Mouvrier, G., 1990. A receptor model adapted to reactive species: Polycyclic aromatic hydrocarbons—Evaluation of source contributions in an open urban site I. Particle compounds. *Atmos. Environ.* A 24 (5), 1189–1197.
- Pitchford, M.L., Pitchford, A., 1985. Analysis of regional visibility in the southwest using principal component and back trajectory techniques. *Atmos. Environ.* 19 (8), 1301–1316.
- Pitchford, M.L., Green, M.C., Kuhns, H.D., Tombach, I.H., Malm, W.C., Scruggs, M., Farber, R.J., Mirabella, V.A., White, W.H., McDade, C., Watson, J.G., Koracin, D., Hoffer, T.E., Lowenthal, D.H., Vimont, J.C., et al., 1999. Project MOHAVE Final Report. US Environmental Protection Agency, Region IV, San Francisco, CA.
- Plumb, R.A., Zheng, X., 1996. Source determination from trace gas observations: An orthogonal function approach and results for long-lived gases with surface sources. *J. Geophys. Res.* 101 (D13), 18569–18586.
- Poirot, R.L., Wishinski, P.R., Hopke, P.K., Polissar, A.V., 2001. Comparative application of multiple receptor methods to identify aerosol sources in northern Vermont. *Environ. Sci. Technol.* 35 (23), 4622–4636.
- Poissant, L., 1994. A practical demonstration of the absolute PCA's bias. *Atmos. Environ.* 28 (12), 2129–2135.
- Polissar, A.V., Hopke, P.K., Paatero, P., Malm, W.C., Sisler, J.F., 1998. Atmospheric aerosol over Alaska 2. Elemental composition and sources. *J. Geophys. Res.* 103 (D15), 19045–19057.
- Polissar, A.V., Hopke, P.K., Paatero, P., Kaufmann, Y.J., Hall, D.K., Bodhaine, B.A., Dutton, E.G., Harris, J.M., 1999. The aerosol at Barrow, Alaska: Long-term trends and source locations. *Atmos. Environ.* 33 (16), 2441–2458.
- Polissar, A.V., Hopke, P.K., Harris, J.M., 2001a. Source regions for atmospheric aerosol measured at Barrow, Alaska. *Environ. Sci. Technol.* 35 (21), 4214–4226.
- Polissar, A.V., Hopke, P.K., Poirot, R.L., 2001b. Atmospheric aerosol over Vermont: Chemical composition and sources. *Environ. Sci. Technol.* 35 (23), 4604–4621.
- Potukuchi, S., Wexler, A.S., 1997. Predicting vapor pressures using neural networks. *Atmos. Environ.* 31 (5), 741–754.
- Pratsinis, S.E., Zeldin, M.D., Ellis, E.C., 1988. Source resolution of the fine carbonaceous aerosol by principal component-stepwise regression analysis. *Environ. Sci. Technol.* 22 (2), 212–216.
- Prinz, B., Stratmann, H., 1968. The possible use of factor analysis in investigating air quality. *Staub-Reinhalft. Luft* 28 (1), 33–39.
- Pryor, S.C., Barthelmie, R.J., 2000. REVEAL II: Seasonality and spatial variability of particle and visibility conditions in the Fraser Valley. *Sci. Total Environ.* 257 (2-3), 95–110.
- Pun, B.K., Seigneur, C., 1999. Understanding particulate matter formation in the California San Joaquin Valley: Conceptual model and data needs. *Atmos. Environ.* 33 (29), 4865–4875.
- Rahn, K.A., 1976. Silicon and aluminum in atmospheric aerosols: Crust-air fractionation. *Atmos. Environ.* 10, 597–601.
- Rahn, K.A., Borys, R.D., Shaw, G.E., 1977. The Asian source of Arctic haze bands. *Nature* 268, 712–714.
- Rahn, K.A., Lewis, N.F., Lowenthal, D.H., 1982. Elemental tracers of Canadian smelter aerosol transported into the Northeastern United States. In: Hopke, P.K., Dattner, S.L. (Eds.), *Proceedings, Receptor Modeling Applied to Contemporary Pollution Problems*. Air Pollution Control Association, Pittsburgh, PA, pp. 163–174.
- Rahn, K.A., Lowenthal, D.H., 1984. Northeastern and mid-western contributions to pollution aerosol in the northwestern United States. *Science* 223, 132.
- Rahn, K.A., Lowenthal, D.H., 1985. Pollution aerosol in the northeast: Northeastern–midwestern contributions. *Science* 228, 275–284.
- Raiyani, C.V., Shah, S.H., Desai, N.M., Kenkaiah, K., Patel, J.S., Parikh, D.J., Kashyap, S.K., 1993. Characterization and problems of indoor pollution due to cooking stove smoke. *Atmos. Environ.* A 27, 1643–1655.
- Ramadan, Z., Song, X.H., Hopke, P.K., 2000. Identification of sources of Phoenix aerosol by positive matrix factorization. *J. Air Waste Mgmt. Assoc.* 50 (8), 1308–1320.
- Rashid, M., Griffiths, R.F., 1993. Ambient K, S, and Si in fine and coarse aerosols of Kuala Lumpur, Malaysia. *J. Aerosol Sci.* 24 (1), S5–S6.
- Rau, J.A., 1986. Residential wood combustion aerosol characterization as a function of size and source apportionment using chemical mass balance modeling. Ph.D. Dissertation, Oregon Graduate Center, Beaverton, OR.
- Rau, J.A., Khalil, M.A.K., 1989. Tracers of pollution from wood burning and receptor modeling. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 353–364.
- Rege, M.A., Tock, R.W., 1996. A simple neural network for estimating emission rates of hydrogen sulfide and ammonia from single point sources. *J. Air Waste Mgmt. Assoc.* 46 (10), 953–962.
- Regional Air Quality Council, 1998. Review of blueprint for clean air emissions inventories. Regional Air Quality Council, Denver, CO.
- Reibnegger, G., Weiss, G., 1991. Neural networks as a tool for utilizing laboratory information: Comparison with linear discriminant analysis and with classification and regression trees. *Proc. Natl. Acad. Sci. USA* 88 (24), 11426–11430.
- Reich, S.L., Gomez, D.R., Dawidowski, L.E., 1999. Artificial neural network for the identification of unknown air pollution sources. *Atmos. Environ.* 33 (18), 3045–3052.
- Reid, H.F., Smith, K.R., Sherchand, B., 1986. Indoor smoke exposures from traditional and improved cookstoves: Comparisons among rural Nepali women. *Mountain Res. Develop.* 6, 293–304.
- Reifman, J., Feldman, E.E., 1998. Identification and control of NO<sub>x</sub> emissions using neural networks. *J. Air Waste Mgmt. Assoc.* 48 (5), 408–417.
- Reimann, C., de Caritat, P., 2000. Intrinsic flaws of element enrichment factors (EFs) in environmental geochemistry. *Environ. Sci. Technol.* 34 (24), 5084–5091.
- Rheingrover, S.W., Gordon, G.E., 1980. Identifying locations of dominant point sources of elements in urban atmospheres from large multi-element data sets. In: 4th International Conference on Nuclear Methods in Environmental and Energy Research, 14 April, 1980, Columbia, MO.

- Rheingrover, S.W., Gordon, G.E., 1988. Wind-trajectory method for determining compositions of particles from major air pollution sources. *Aerosol Sci. Technol.* 8, 29–61.
- Richman, M.B., 1981. Obliquely rotated principal components: An improved meteorological map typing technique? *J. Appl. Meteorol.* 20, 1145–1159.
- Richman, M.B., 1986. Rotation of principal components. *J. Clim.* 6 (3), 293–335.
- Richman, M.B., Vermette, S.J., 1993. The use of Procrustes Target Analysis to discriminate dominant source regions of fine sulfur in the western USA. *Atmos. Environ. A* 27 (4), 475–481.
- RJ Lee Group, 1998. Weirton Steel Receptor Model Project: Source apportionment of particulate matter collected during PM<sub>10</sub> exceedance days in Weirton, West Virginia using CCSEM data and the CMB7 receptor model. Prepared for Weirton Steel Corporation, Weirton, WV, by RJ Lee Group, Monroeville, PA.
- Roberts, P.T., Friedlander, S.K., 1975. Conversion of SO<sub>2</sub> to sulfur particulate in the Los Angeles atmosphere. *Environ. Health Perspect.* 10, 103–108.
- Roberts, G.C., Andreae, M.O., Maenhaut, W., Fernandez-Jimenez, M.T., 2001. Composition and sources of aerosol in a central African rain forest during the dry season. *J. Geophys. Res.* 106 (D13), 14423–14434.
- Robinson, N.F., Whitbeck, M.R., 1985. A flexible nonempirical model for cloud chamber studies. *J. Air Pollut. Control Assoc.* 35 (7), 746–748.
- Rocha, T.A.P., Horvath, H., Oliveira, J.A.B.P., Duarte, A.C., 1999. Trends in alkanes and PAHs in airborne particulate matter from Oporto and Vienna: Identification and comparison. *Sci. Total Environ.* 236, 231–236.
- Rogak, S.N., Green, S.I., Pott, U., 1998. Use of tracer gas for direct calibration of emission-factor measurements in a traffic tunnel. *J. Air Waste Mgmt. Assoc.* 48 (6), 545–552.
- Rogge, W.F., Hildemann, L.M., Mazurek, M.A., Cass, G.R., Simoneit, B.R.T., 1991. Sources of fine organic aerosol 1. Charbroilers and meat cooking operations. *Environ. Sci. Technol.* 25 (6), 1112–1125.
- Rohbock, E., Georgii, H.W., Müller, J., 1981. Discussion: Multivariate analysis of particulate sulfate and other air quality variables by principal components—Part I. Annual data from Los Angeles and New York. *Atmos. Environ.* 15, 424.
- Roscoe, B.A., Hopke, P.K., Dattner, S.L., Jenks, J.M., 1982. The use of principal component factor analysis to interpret particulate compositional data sets. *J. Air Pollut. Control Assoc.* 32 (6), 637–642.
- Roscoe, B.A., Chen, C.Y., Hopke, P.K., 1984. Comparison of the target transformation factor analysis of coal composition data with X-ray diffraction analysis. *Anal. Chim. Acta* 160, 121–134.
- Rouhani, S., Ebrahimpour, M.R., Yaqub, I., Gianella, E., 1992. Multivariate geostatistical trend detection and network evaluation of space-time acid deposition data—II. Application to NADP/NTN data. *Atmos. Environ. A* 26 (14), 2615–2626.
- Russell, A.G., McRae, G.J., Cass, G.R., 1983. Mathematical modeling of the formation and transport of ammonium nitrate aerosol. *Atmos. Environ.* 17 (5), 949–964.
- Ryan, W.M., West, C.R., Holtz, D.R., Peters, T.A., Cooper, J.A., Ono, D.M., 1988. Reconciliation of receptor and dispersion modeling impacts of PM<sub>10</sub> in Hayden, Arizona. In: Mathai, C.V., Stonefield, D.H. (Eds.), *Transactions, PM<sub>10</sub>: Implementation of Standards*. Air Pollution Control Association, Pittsburgh, PA, pp. 419–429.
- Saxena, P., Seigneur, C., 1983. Modeling of multiphase atmospheric aerosols. *Atmos. Environ.* 17 (7), 1315–1329.
- Saxena, P., Hudischewskyj, A.B., Seigneur, C., Seinfeld, J.H., 1986. A comparative study of equilibrium approaches to the chemical characterization of secondary aerosols. *Atmos. Environ.* 20 (7), 1471–1483.
- Schauer, J.J., Cass, G.R., 2000. Source apportionment of wintertime gas-phase and particle-phase air pollutants using organic compounds as tracers. *Environ. Sci. Technol.* 34 (9), 1821–1832.
- Schauer, J.J., Rogge, W.F., Mazurek, M.A., Hildemann, L.M., Cass, G.R., Simoneit, B.R.T., 1996. Source apportionment of airborne particulate matter using organic compounds as tracers. *Atmos. Environ.* 30 (22), 3837–3855.
- Schauer, J.J., Kleeman, M.J., Cass, G.R., Simoneit, B.R.T., 1999. Measurement of emissions from air pollution sources. C<sub>1</sub> through C<sub>29</sub> organic compounds from meat charbroiling. *Environ. Sci. Technol.* 33 (10), 1566–1577.
- Scheff, P.A., Wadden, R.A., Allen, R.J., 1984. Development and validation of a chemical element mass balance for Chicago. *Environ. Sci. Technol.* 18 (12), 923–931.
- Seinfeld, J.H., 1997. Dynamics of urban and regional atmospheric aerosols. *J. Aerosol Sci.* 28 (Suppl. 1), S417.
- Seinfeld, J.H., Pandis, S.N., 1998. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*. John Wiley, New York, NY.
- Severin, K.G., Roscoe, B.A., Hopke, P.K., 1983. The use of factor analysis in source determination of particulate emissions. In: *Particulate Science and Technology*. Hemisphere Publishing Corporation, New York, pp. 183–192.
- Sexton, K., Hayward, S.B., 1987. Source apportionment of indoor air pollution. *Atmos. Environ.* 21 (2), 407–418.
- Sexton, K., Liu, K.S., Hayward, S.B., Spengler, J.D., 1985. Characterization and source apportionment of wintertime aerosol in a wood-burning community. *Atmos. Environ.* 19 (8), 1225–1236.
- Sexton, K., Liu, K.S., Treitman, R.D., Spengler, J.D., Turner, W.A., 1986. Characterization of indoor air quality in wood-burning residences. *Environ. Int.* 12, 265–278.
- Shah, J.J., Johnson, R.L., Houck, J.E., 1989. Source characterization using tethered balloons and lightweight samplers. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 334–345.
- Shareef, G.S., Bravo, L.A., Stelling, J.H.E., Kuykendal, W.B., Mobley, J.D., 1989. Air emissions species data base. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 73–83.
- Sharma, V.K., Patil, R.S., 1992. Size distribution of atmospheric aerosols and their source identification using factor analysis in Bombay, India. *Atmos. Environ. B* 26 (1), 135–140.
- Sharma, V.K., Patil, R.S., 1994. Chemical mass balance model for source apportionment of aerosols in Bombay. *Environ. Monit. Assess.* 29 (1), 75–88.



- Sharma, P.K., Singh, G., 1992. Distribution of suspended particulate matter with trace element composition and apportionment of possible sources in the Raniganj Coalfield, India. *Environ. Monit. Assess.* 22 (2), 237–244.
- Sheffield, A.E., Gordon, G.E., 1986. Variability of particle composition from ubiquitous sources: Results from a new source-composition library. In: Pace, T.G. (Ed.), *Transactions, Receptor Methods for Source Apportionment: Real World Issues and Applications*. Air Pollution Control Association, Pittsburgh, PA, pp. 9–22.
- Sheffield, A.E., Gordon, G.E., Currie, L.A., Reiderer, G.E., 1994. Organic elemental and isotopic tracers of air pollution sources in Albuquerque, NM. *Atmos. Environ.* 28 (8), 1371–1384.
- Shu, J., Dearing, J.A., Morse, A.P., Yu, L., Yuan, N., 2001. Determining the sources of atmospheric particles in Shanghai, China, from magnetic and geochemical properties. *Atmos. Environ.* 35 (15), 2615–2625.
- Silverman, D., Dracup, J.A., 2000. Artificial neural networks and long-range precipitation prediction in California. *J. Appl. Meteorol.* 39, 57–66.
- Singer, B.C., Harley, R.A., Littlejohn, D., Ho, J., Vo, T., 1998. Scaling of infrared remote sensor hydrocarbon measurements for motor vehicle emission inventory calculations. *Environ. Sci. Technol.* 32 (21), 3241–3248.
- Sjögren, M., Li, H., Rannug, U., Westerholm, R., 1996. Multivariate analysis of exhaust emissions from heavy-duty diesel fuels. *Environ. Sci. Technol.* 30 (1), 38–49.
- Skidmore, L., Chow, J.C., 1992. PM<sub>10</sub> air quality assessment for the Jefferson County, Ohio air quality control region. In: Chow, J.C., Ono, D.M. (Eds.), *Transactions, PM<sub>10</sub> Standards and Nontraditional Particulate Source Controls*, pp. 1016–1031.
- Smeyers-Verbeke, J., Den Hartog, J.C., Dekker, W.H., Coomans, D., Buydens, L., Massart, D.L., 1984. The use of principal components analysis for the investigation of an organic air pollutants data set. *Atmos. Environ.* 18 (11), 2471–2478.
- Smith, K.R., 1995. Health, energy, and greenhouse-gas impacts of biomass combustion. *Energy for Sustainable Develop.* 1 (4), 23–29.
- Soja, G., Soja, A.M., 1999. Ozone indices based on simple meteorological parameters: Potentials and limitations of regression and neural network models. *Atmos. Environ.* 33 (26), 4299–4308.
- Song, X.H., Hopke, P.K., 1996a. Analysis of source contributions to the ambient aerosol sample by simulated annealing. *Chemom. Intell. Lab. Sys.* 34, 275–281.
- Song, X.H., Hopke, P.K., 1996b. Solving the chemical mass balance problem using an artificial neural network. *Environ. Sci. Technol.* 30 (2), 531–535.
- Song, X.H., Hadjiiski, L., Hopke, P.K., Ashbaugh, L.L., Carvacho, O., Casuccio, G.S., Schlaegle, S., 1999a. Source apportionment of soil samples by the combination of two neural networks based on computer-controlled scanning electron microscopy. *J. Air Waste Mgmt. Assoc.* 49 (7), 773–783.
- Song, X.H., Hopke, P.K., Bruns, M.A., Graham, K., Scow, K., 1999b. Pattern recognition of soil samples based on the microbial fatty acid contents. *Environ. Sci. Technol.* 33 (20), 3524–3530.
- Song, X.H., Hopke, P.K., Fergenson, D.P., Prather, K.A., 1999c. Classification of single particles analyzed by ATO-FMS using an artificial neural network ART-2a. *Anal. Chem.* 71 (4), 860–865.
- Song, X.H., Polissar, A.V., Hopke, P.K., 2001. Sources of fine particle composition in the northeastern US. *Atmos. Environ.* 35 (31), 5277–5286.
- South Coast Air Quality Management District, 1996. 1997 air quality maintenance plan: Appendix V, Modeling and attainment demonstrations. South Coast Air Quality Management District, Diamond Bar, CA.
- Staehelin, J., Keller, C., Stahel, W., Schläpfer, K., Wunderli, S., 1998. Emission exhaust factors from road traffic from a tunnel study (Gubrist tunnel, Switzerland)—Part III: Results of organic compounds, SO<sub>2</sub> and speciation of organic emission. *Atmos. Environ.* 32 (6), 999–1010.
- Stafford, M.A., Liljestrand, H.M., 1989. The use of fractionated coarse and fine fingerprints for the source apportionment of PM<sub>10</sub>. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 159–171.
- Statheropoulos, M., Vassiliadis, N., Pappa, A., 1998. Principal component and canonical correlation analysis for examining air pollution and meteorological data. *Atmos. Environ.* 32 (6), 1087–1096.
- Stedman, D.H., Zhang, Y., Bishop, G.A., Guenther, S.P., Beaton, S.P., 1993. On-road hydrocarbon remote sensing. In: *Proceedings of the 86th Annual Meeting*, 13 June, 1993, Denver, CO. Air and Waste Management Association, Pittsburgh, PA.
- Stelson, A.W., Friedlander, S.K., Seinfeld, J.H., 1979. A note on the equilibrium relationship between ammonia and nitric acid and particulate ammonium nitrate. *Atmos. Environ.* 13, 369–371.
- Stelson, A.W., Seinfeld, J.H., 1981. Chemical mass accounting of urban aerosol. *Environ. Sci. Technol.* 15 (6), 671–679.
- Stelson, A.W., Seinfeld, J.H., 1982a. Relative humidity and temperature dependence of the ammonium nitrate dissociation constant. *Atmos. Environ.* 16 (5), 983–992.
- Stelson, A.W., Seinfeld, J.H., 1982b. Relative humidity and pH dependence of the vapor pressure of ammonium nitrate–nitric acid solutions at 25 °C. *Atmos. Environ.* 16 (5), 993–1000.
- Stelson, A.W., Seinfeld, J.H., 1982c. Thermodynamic prediction of the water activity, NH<sub>4</sub>NO<sub>3</sub> dissociation constant, density and refractive index for the NH<sub>4</sub>NO<sub>3</sub>–(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>–H<sub>2</sub>O system at 25 °C. *Atmos. Environ.* 16 (10), 2507–2514.
- Stephens, R.D., Mulawa, P.A., Giles, M.T., Kennedy, K.G., Groblicki, P.J., Cadle, S.H., Knapp, K.T., 1996. An experimental evaluation of remote sensing-based hydrocarbon measurements: A comparison to FID measurements. *J. Air Waste Mgmt. Assoc.* 46 (2), 148–158.
- Stevens, R.K., Pace, T.G., 1984. Review of the mathematical and empirical receptor models workshop (Quail Roost II). *Atmos. Environ.* 18, 1499–1506.
- Stevens, R.K., Lewis, C.W., Dzubay, T.G., Cupitt, L.T., Lewtas, J., 1990. Sources of mutagenic activity in urban fine particles. *Toxicol. Ind. Health* 6 (5), 81–93.
- Stockwell, W.R., Milford, J.B., McRae, G.J., Middleton, P., Chang, J.S., 1988. Nonlinear coupling in the NO<sub>x</sub>–SO<sub>x</sub>

- reactive organic system. *Atmos. Environ.* 22 (11), 2481–2490.
- Stockwell, W.R., Middleton, P., Chang, J.S., Tang, X., 1990. The second generation regional acid deposition model chemical mechanism for regional air quality modeling. *J. Geophys. Res.* 95, 16343–16367.
- Stockwell, W.R., 1994. The effect of gas-phase chemistry on aqueous-phase sulfur dioxide oxidation rates. *J. Atmos. Chem.* 19 (3), 317–329.
- Stockwell, W.R., Kirchner, F., Kuhn, M., Seefeld, S., 1997. A new mechanism for regional atmospheric chemistry modeling. *J. Geophys. Res.* 102, 25847–25879.
- Stockwell, W.R., Watson, J.G., Robinson, N.F., Steiner, W.E., Sylte, W.W., 2000. The ammonium nitrate particle equivalent of  $\text{NO}_x$  emissions for continental wintertime conditions. *Atmos. Environ.* 34 (27), 4711–4717.
- Stolzenburg, T.R., Andren, A.W., Stolzenburg, M.R., 1982. Source reconciliation of atmospheric aerosols. *Water Air Soil Pollut.* 17, 75–85.
- Struempfer, A.W., 1975. Trace element composition in atmospheric particulates during 1973 and the summer of 1974 at Chadron, Nebraska. *Environ. Sci. Technol.* 9, 1164–1168.
- Sturges, W.T., 1989. Identification of pollution sources of anomalously enriched elements. *Atmos. Environ.* 23 (9), 2067–2072.
- Swietlicki, E., Puri, S., Hansson, H.C., Edner, H., 1996. Urban air pollution source apportionment using a combination of aerosol and gas monitoring techniques. *Atmos. Environ.* 30 (15), 2795–2809.
- Tanner, R.L., Harrison, R.M., 1992. Acid–base equilibria of aerosols and gases in the atmosphere. In: Buffle, J., Van Leeuwen, H.P. (Eds.), *Environmental Particles*. Lewis Publishers, Ann Arbor, MI, pp. 75–106.
- Taylor, S.R., 1964. Abundance of chemical elements in the continental crust: A new table. *Geochim. Cosmochim. Acta* 28, 1273.
- Temesi, D., Molnar, A., Meszaros, E., Feczko, T., Gelencser, A., Kiss, G., Krivacsy, Z., 2001. Size resolved chemical mass balance of aerosol particles over rural Hungary. *Atmos. Environ.* 35 (25), 4347–4355.
- Thomas, W.W., 1986. Principal component analysis of trace substance concentration in rainwater samples. *Atmos. Environ.* 20 (5), 995–1000.
- Throgmorton, J.A., 1980. Identification of major sources of particulate matter in the ambient air through the use of factor analysis. In: *Proceedings of the 73th Annual Meeting, 22 June, 1980, Montreal, PQ, Canada*. Air Pollution Control Association, Pittsburgh, PA.
- Thurston, G.D., Spengler, J.D., 1985a. A multivariate assessment of meteorological influences on inhalable particle source impacts. *J. Climatol. Appl. Meteorol.* 24, 1245–1256.
- Thurston, G.D., Spengler, J.D., 1985b. A quantitative assessment of source contributions to inhalable particulate matter pollution in metropolitan Boston. *Atmos. Environ.* 19 (1), 9–25.
- Toriyama, S., Shimada, H., Arakawa, H., Takata, T., Sakamori, S., 1991. An estimate of source contribution of atmospheric aerosols in Toyama prefecture by chemical mass balance method. *Nippon Kagaku Kaishi May* (5), 454–464.
- Trijonis, J.C., Pitchford, M.L., McGown, M., Blumenthal, D.L., Dodson, T., Flocchini, R.G., Kelso, R., Knuth, W.R., Macias, E.S., Gara, J.E., Pitchford, A., Smith, T.B., Waggoner, A.P., Watson, J.G., Weiss, R.E., White, W.H., 1987. Preliminary extinction budget results from the RESOLVE program. In: Bhardwaja, P.S. (Ed.), *Transactions, Visibility Protection: Research and Policy Aspects*. Air Pollution Control Association, Pittsburgh, PA, pp. 872–883.
- Tropp, R.J., Jones, K., Kuhn, G., Berg Jr., N.J., 1998. Comparison of  $\text{PM}_{2.5}$  saturation samplers with prototype  $\text{PM}_{2.5}$  federal reference method samplers. In: Chow, J.C., Koutrakis, P. (Eds.), *Proceedings,  $\text{PM}_{2.5}$ : A Fine Particle Standard*. Air and Waste Management Association, Pittsburgh, PA, pp. 215–225.
- Truesdale, R.S., 1982. Residential stove emissions from coal and other alternative fuels combustion. In: Frederick, E.R. (Ed.), *Residential Wood and Coal Combustion*. Air Pollution Control Association, Pittsburgh, PA.
- Tsai, F.C., Apte, M.G., Daisey, J.M., 2000. An exploratory analysis of the relationship between mortality and the chemical composition of airborne particulate matter. *Inhal. Toxicol.* 12 (suppl. 2), 121–135.
- Tsuang, B.J., Chen, C.L., Pan, R.C., Liu, J.H., 2002. Quantification on source/receptor relationship of primary pollutants and secondary aerosols from ground sources—Part 1. *Theory. Atmos. Environ.* 36 (3), 411–419.
- Tsunogai, S., Saito, K., Nakaya, S., 1972. Chemical composition of oceanic aerosol. *J. Geophys. Res.* 77, 5283–5292.
- Turekian, K.K., Wedepohl, K.H., 1961. Distribution of the elements in some major units of the Earth's crust. *Geol. Soc. Am. Bull.* 72, 175–191.
- Turpin, B.J., Lim, H.J., 2001. Species contributions to  $\text{PM}_{2.5}$  mass concentrations: Revisiting common assumptions for estimating organic mass. *Aerosol Sci. Technol.* 35 (1), 602–610.
- US EPA, 1987. Receptor model technical series, Volume III (Revised). CMB user's manual (Version 6.0). Report No. EPA-450/4-83-014R. US Environmental Protection Agency, Research Triangle Park, NC.
- US EPA, 1999. Compilation of air pollutant emission factors, vol. I, Stationary point and area sources. Report No. AP-42, fifth ed. US Environmental Protection Agency, Research Triangle Park, NC.
- Valaoras, G., Huntzicker, J.J., White, W.H., 1988. On the contribution of motor vehicles to the Athenian “Nephos”: An application of factor signatures. *Atmos. Environ.* 22 (5), 965–971.
- van Borm, W.A., Adams, F.C., Maenhaut, W., 1990. Receptor modeling of the Antwerp aerosol. *Atmos. Environ.* 24B, 419–435.
- Vavilova, N.G., Genikhovich, Y.L., Son'kin, L.R., 1969. Statistical analysis of data on air pollution in cities by means of natural functions. In: *Glavnaiia Geofizicheskaiia Observatoriia im A.I. Voeikova*. Hydrometeorological Publishers, Leningrad, Soviet Union, pp. 27–32.
- Vega, E., Garcia, I., Apam, D., Ruiz, M.E., Barbiaux, M., 1997. Application of a chemical mass balance receptor model to respirable particulate matter in Mexico City. *J. Air Waste Mgmt. Assoc.* 47 (4), 524–529.
- Veltkamp, P.R., Hansen, K.J., Barkley, R.M., Sievers, R.E., 1996. Principal component analysis of summertime organic

- aerosols at Niwot Ridge, Colorado. *J. Geophys. Res.* 101 (D14), 19495–19504.
- Venkataraman, C., Friedlander, S.K., 1994. Source resolution of fine particulate polycyclic aromatic hydrocarbons using a receptor model modified for reactivity. *J. Air Waste Mgmt. Assoc.* 44 (9), 1103–1108.
- Vermette, S.J., Williams, A.L., Landsberger, S., 1992. PM<sub>10</sub> source apportionment using local surface dust profiles: Examples from Chicago. In: Chow, J.C., Ono, D.M. (Eds.), *Transactions, PM<sub>10</sub> Standards and Nontraditional Particulate Source Controls*. Air and Waste Management Association, Pittsburgh, PA, pp. 262–271.
- Vinogradov, A.P., 1959. *The Geochemistry of Rare and Dispersed Chemical Elements in Soils*, second ed. Consultants Bureau, Inc., New York, NY.
- Vong, R.J., Geladi, P., Wold, S., Esbensen, K., 1988. Source contributions to ambient aerosol calculated by discriminant partial least squares regression (PLS). *J. Chemom.* 2, 281–296.
- Vossler, T.L., Lewis, C.W., Stevens, R.K., Dzubay, T.G., Gordon, G.E., Tuncel, S.G., Russwurm, G.M., Keeler, G.J., 1989. Compositions and origin of summertime air pollutants at Deep Creek Lake, Maryland. *Atmos. Environ.* 23 (7), 1535–1547.
- Wadden, R.A., Lee, H.S., Scheff, P.A., Lin, J., 1993. Sulfur and nitrogen balances for the Chicago area by receptor modeling. In: *Proceedings of the 86th Annual Meeting*, 13 June, 1993, Denver, CO. Air and Waste Management Association, Pittsburgh, PA.
- Wang, D., Hopke, P.K., 1989. The use of constrained least-squares to solve the chemical mass balance problem. *Atmos. Environ.* 23 (10), 2143–2150.
- Watson, J.G., 1979. Chemical element balance receptor model methodology for assessing the sources of fine and total suspended particulate matter in Portland, Oregon. Ph.D. Dissertation, Oregon Graduate Center, Beaverton, OR.
- Watson, J.G., 1984. Overview of receptor model principles. *J. Air Pollut. Control Assoc.* 34 (6), 619–623.
- Watson, J.G., 1989. *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA.
- Watson, J.G., Henry, R.C., Cooper, J.A., Macias, E.S., 1981. The state of the art of receptor models relating ambient suspended particulate matter to sources. In: Macias, E.S., Hopke, P.K. (Eds.), *Atmospheric Aerosol, Source/Air Quality Relationships*. American Chemical Society, Washington, DC, pp. 89–106.
- Watson, J.G., Cooper, J.A., Huntzicker, J.J., 1984. The effective variance weighting for least squares calculations applied to the mass balance receptor model. *Atmos. Environ.* 18 (7), 1347–1355.
- Watson, J.G., Chow, J.C., Richards, L.W., Andersen, S.R., Houck, J.E., Dietrich, D.L., 1988. The 1987–1988 Metro Denver Brown Cloud Air Pollution Study, Volume III: Data interpretation. Report No. DRI 8810.1. Prepared for 1987–88 Metro Denver Brown Cloud Study, Inc., Greater Denver Chamber of Commerce, Denver, CO, by Desert Research Institute, Reno, NV.
- Watson, J.G., Chow, J.C., Mathai, C.V., 1989. Receptor models in air resources management: A summary of the APCA International Specialty Conference. *J. Air Pollut. Control Assoc.* 39 (4), 419–426.
- Watson, J.G., Chow, J.C., Pritchett, L.C., Houck, J.E., Ragazzi, R.A., 1990a. Chemical source profiles for particulate motor vehicle exhaust under cold and high altitude operating conditions. *Sci. Total Environ.* 93, 183–190.
- Watson, J.G., Robinson, N.F., Chow, J.C., Henry, R.C., Kim, B.M., Pace, T.G., Meyer, E.L., Nguyen, Q., 1990b. The US EPA/DRI chemical mass balance receptor model, CMB 7.0. *Environ. Software* 5 (1), 38–49.
- Watson, J.G., Chow, J.C., 1993. Ambient air sampling. In: Willeke, K., Baron, P.A. (Eds.), *Aerosol Measurement: Principles, Techniques and Applications*. Van Nostrand, Reinhold, New York, NY, pp. 622–639.
- Watson, J.G., Chow, J.C., 1994. Particle and gas measurements on filters. In: Markert, B. (Ed.), *Environmental Sampling for Trace Analysis*. VCH, New York, pp. 125–161.
- Watson, J.G., Chow, J.C., 2000. Reconciling urban fugitive dust emissions inventory and ambient source contribution estimates: Summary of current knowledge and needed research. Report No. 6110.4D2. Prepared for US Environmental Protection Agency, Research Triangle Park, NC, by Desert Research Institute, Reno, NV.
- Watson, J.G., Chow, J.C., Pace, T.G., 2000. Fugitive dust emissions. In: Davis, W.T. (Ed.), *Air Pollution Engineering Manual*, second ed. John Wiley, New York, pp. 117–135.
- Watson, J.G., Chow, J.C., 2001a. Source characterization of major emission sources in the Imperial and Mexicali valleys along the US/Mexico border. *Sci. Total Environ.* 276 (1–3), 33–47.
- Watson, J.G., Chow, J.C., 2001b. Ambient air sampling. In: Baron, P., Willeke, K. (Eds.), *Aerosol Measurement: Principles, Techniques, and Applications*, second ed. John Wiley, New York, NY, pp. 821–844.
- Watson, J.G., Chow, J.C., Pace, T.G., 1991. Chemical mass balance. In: Hopke, P.K. (Ed.), *Receptor Modeling for Air Quality Management*. Elsevier, New York, NY, pp. 83–116.
- Watson, J.G., Chow, J.C., Lowenthal, D.H., Pritchett, L.C., Frazier, C.A., Neuroth, G.R., Robbins, R., 1994a. Differences in the carbon composition of source profiles for diesel- and gasoline-powered vehicles. *Atmos. Environ.* 28 (15), 2493–2505.
- Watson, J.G., Chow, J.C., Lu, Z., Fujita, E.M., Lowenthal, D.H., Lawson, D.R., 1994b. Chemical mass balance source apportionment of PM<sub>10</sub> during the Southern California air quality study. *Aerosol Sci. Technol.* 21 (1), 1–36.
- Watson, J.G., Chow, J.C., Lurmann, F.W., Musarra, S., 1994c. Ammonium nitrate, nitric acid, and ammonia equilibrium in wintertime Phoenix, Arizona. *J. Air Waste Mgmt. Assoc.* 44 (4), 405–412.
- Watson, J.G., Blumenthal, D.L., Chow, J.C., Cahill, C.F., Richards, L.W., Dietrich, D., Morris, R., Houck, J.E., Dickson, R.J., Andersen, S.R., 1996. Mt. Zirkel Wilderness Area reasonable attribution study of visibility impairment, vol. II: Results of data analysis and modeling. Prepared for Colorado Department of Public Health and Environment, Denver, CO, by Desert Research Institute, Reno, NV.
- Watson, J.G., Chow, J.C., Rogers, C.F., Green, M.C., Kohl, S.D., Frazier, C.A., Robinson, N.F., DuBois, D.W., 1997a. Annual report for the Robbins Particulate Study—October 1995–September 1996. Report No. 7100.3F2. Prepared for

- VERSAR Inc., Lombard, IL, by Desert Research Institute, Reno, NV.
- Watson, J.G., Robinson, N.F., Lewis, C.W., Coulter, C.T., Chow, J.C., Fujita, E.M., Lowenthal, D.H., Conner, T.L., Henry, R.C., Willis, R.D., 1997b. Chemical mass balance receptor model version 8 (CMB) user's manual. Prepared for US Environmental Protection Agency, Research Triangle Park, NC, by Desert Research Institute, Reno, NV.
- Watson, J.G., Chow, J.C., Moosmüller, H., Green, M.C., Frank, N.H., Pitchford, M.L., 1998a. Guidance for using continuous monitors in PM<sub>2.5</sub> monitoring networks. Report No. EPA-454/R-98-012. Prepared for US EPA, Office of Air Quality Planning and Standards, Research Triangle Park, NC, by Desert Research Institute, Reno, NV.
- Watson, J.G., Fujita, E.M., Chow, J.C., Zielinska, B., Richards, L.W., Neff, W.D., Dietrich, D., 1998b. Northern Front Range Air Quality Study. Final report. Prepared for Colorado State University, Fort Collins, CO, by Desert Research Institute, Reno, NV.
- Watson, J.G., Robinson, N.F., Lewis, C.W., Coulter, C.T., Chow, J.C., Fujita, E.M., Conner, T.L., Pace, T.G., 1998c. CMB8 applications and validation protocol for PM<sub>2.5</sub> and VOCs. Report No. 1808.2D1. Prepared for US Environmental Protection Agency, Research Triangle Park, NC, by Desert Research Institute, Reno, NV.
- Watson, J.G., Chow, J.C., Frazier, C.A., 1999a. X-ray fluorescence analysis of ambient air samples. In: Landsberger, S., Creatchman, M. (Eds.), *Elemental Analysis of Airborne Particles*, vol. 1. Gordon and Breach Science, Amsterdam, pp. 67–96.
- Watson, J.G., Chow, J.C., Kohl, S.D., Kuhns, H.D., Robinson, N.F., Frazier, C.A., Etyemezian, V., 1999b. Annual report for the Robbins Particulate Study: October 1996 through September 1997. Report No. 7100.4F3. Prepared for VERSAR, Inc., Lombard, IL, by Desert Research Institute, Reno, NV.
- Watson, J.G., Chow, J.C., Fujita, E.M., 2001a. Review of volatile organic compound source apportionment by chemical mass balance. *Atmos. Environ.* 35 (9), 1567–1584.
- Watson, J.G., Chow, J.C., Houck, J.E., 2001b. PM<sub>2.5</sub> chemical source profiles for vehicle exhaust, vegetative burning, geological material, and coal burning in northwestern Colorado during 1995. *Chemosphere* 43 (8), 1141–1151.
- Watson, J.G., Turpin, B.J., Chow, J.C., 2001c. The measurement process: Precision, accuracy, and validity. In: Cohen, B.S., McCammon, C.S.J. (Eds.), *Air Sampling Instruments for Evaluation of Atmospheric Contaminants*, ninth ed. American Conference of Governmental Industrial Hygienists, Cincinnati, OH, pp. 201–216.
- Watson, J.G., Chow, J.C., 2002a. A wintertime PM<sub>2.5</sub> episode at the Fresno, CA, supersite. *Atmos. Environ.* 36 (3), 465–475.
- Watson, J.G., Chow, J.C., 2002b. Particulate pattern recognition. In: Murphy, B.L., Morrison, R. (Eds.), *Introduction to Environmental Forensics*. Academic Press, New York, NY, pp. 429–460.
- Watson, J.G., Chow, J.C., Lowenthal, D.H., Robinson, N.F., Cahill, C.F., 2002. Simulating changes in source profiles from coal-fired power stations: Use in chemical mass balance of PM<sub>2.5</sub> in the Mt. Zirkel Wilderness. *Energy Fuels* 16 (2), 311–324.
- Weingartner, E., Keller, C., Stahel, W.A., Burtscher, H., Baltensperger, U., 1997. Aerosol emission in a road tunnel. *Atmos. Environ.* 31 (3), 451–462.
- West, J.J., Ansari, A.S., Pandis, S.N., 1999. Marginal PM<sub>2.5</sub>: Nonlinear aerosol mass response to sulfate reductions in the eastern United States. *J. Air Waste Mgmt. Assoc.* 49 (12), 1415–1424.
- Wexler, A.S., Seinfeld, J.H., 1990. The distribution of ammonium salts among a size and composition dispersed aerosol. *Atmos. Environ. A* 24 (5), 1231–1246.
- Wexler, A.S., Seinfeld, J.H., 1991. Second-generation inorganic aerosol model. *Atmos. Environ. A* 25 (12), 2731–2748.
- Wexler, A.S., Seinfeld, J.H., 1992. Analysis of aerosol ammonium nitrate: Departures from equilibrium during SCAQS. *Atmos. Environ. A* 26 (4), 579–591.
- Wexler, A.S., Lurmann, F.W., Seinfeld, J.H., 1994. Modeling urban and regional aerosols—I. Model development. *Atmos. Environ.* 28 (3), 531–546.
- White, W.H., 1986. On the theoretical and empirical basis for apportioning extinction by aerosols: A critical review. *Atmos. Environ.* 20 (9), 1659–1672.
- White, W.H., 1989. MLRCLS: A basic routine for multiple regression by corrected least squares. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 269–275.
- White, W.H., Husar, R.B., Friedlander, S.K., 1977. A Study of Los Angeles Smog Aerosol Dynamics by Air Trajectory Analysis. In: *Proceedings of the 66th Annual Meeting*, Chicago, IL. Air Pollution Control Association, Pittsburgh, PA.
- White, W.H., Macias, E.S., 1987. On measurement error and the empirical relationship of atmospheric extinction to aerosol composition in the non-urban west. In: Bhardwaja, P.S. (Ed.), *Transactions, Visibility Protection: Research and Policy Aspects*. Air Pollution Control Association, Pittsburgh, PA, pp. 783–794.
- White, W.H., Macias, E.S., 1991. Chemical mass balancing with ill defined sources: Regional apportionment in the California desert. *Atmos. Environ. A* 25 (8), 1547–1557.
- Wienke, D., Gao, N., Hopke, P.K., 1994a. Multiple site receptor modeling with a minimal spanning tree combined with a neural network. *Environ. Sci. Technol.* 28 (6), 1023–1030.
- Wienke, D., Hopke, P.K., 1994a. Projection of Prim's minimal spanning tree into Kohonen's neural network for identification of airborne particle sources by their multielement trace patterns. *Anal. Chim. Acta* 291, 1–18.
- Wienke, D., Hopke, P.K., 1994b. Visual neural mapping technique for locating fine airborne particles sources. *Environ. Sci. Technol.* 28 (6), 1015–1022.
- Wienke, D., Xie, Y., Hopke, P.K., 1994b. An adaptive resonance theory based artificial neural network (ART-2a) for rapid identification of airborne particle shapes from their scanning electron microscopy images. *Chemom. Intell. Lab. Sys.* 25, 367–387.
- Wienke, D., Xie, Y., Hopke, P.K., 1995. Classification of airborne particles by analytical scanning electron microscopy imaging and a modified Kohonen neural network (3MAP). *Anal. Chim. Acta* 310 (1), 1–14.

- Wilkniess, P.E., Bressan, D.J., 1972. Fractionation of the elements F, Cl, Na and K at the sea-air interface. *J. Geophys. Res.* 77, 5307–5315.
- Willis, R.D., Ellenson, W.D., Pinto, J.P., Hartlage, T.A., Novak, J., Dosdalek, H., Cernikovskiy, L., Bures, V., 1997. Ostrava ambient monitoring and source receptor modeling study. Report No. EPA/600/R-97/030. US EPA.
- Willis, R.D., 2000. Workshop on UNMIX and PMF as applied to PM<sub>2.5</sub>. Report No. EPA/600/A-00/048. U.S. Environmental Protection Agency, Research Triangle Park, NC.
- Winchester, J.W., Nifong, G.D., 1971. Water pollution in Lake Michigan by trace elements from aerosol fallout. *Water Air Soil Pollut.* 1, 50–64.
- Winchester, J.W., Meinert, D.L., Nelson, J.W., Johansson, T.B., VanGrieken, R.E., Orsini, C., Kaufmann, H.C., Akselsson, R., 1974. Trace metals in the St. Louis aerosol. In: *Proceedings, Second International Conference on Nuclear Methods in Environmental Research*. University of Missouri, Rolla, MO.
- Winchester, J.W., Ferek, R.J., Lawson, D.R., Pilote, J.O., Thiemens, M.H., Wangen, L.E., 1979. Comparison of aerosol sulfur and crustal element concentrations in particle size fractions from continental US locations. *Water Air Soil Pollut.* 12, 431–440.
- Witz, S., Eden, R.W., Wadley, M.W., Dunwoody, C., Papa, R.P., Torre, K.J., 1990. Rapid loss of particulate nitrate, chloride and ammonium on quartz fiber filters during storage. *J. Air Waste Mgmt. Assoc.* 40 (1), 53–61.
- Wolff, G.T., Korsog, P.E., 1985. Estimates of the contribution of sources to inhalable particulate concentrations in Detroit. *Atmos. Environ.* 19 (9), 1399–1409.
- Wolff, G.T., Korsog, P.E., Kelly, N.A., Ferman, M.A., 1985a. Relationships between fine particulate species, gaseous pollutants and meteorological parameters in Detroit. *Atmos. Environ.* 19 (8), 1341–1349.
- Wolff, G.T., Korsog, P.E., Stroup, D.P., Ruthkosky, M.S., Morrissey, M.L., 1985b. The influence of local and regional sources on the concentration of inhalable particulate matter in southeastern Michigan. *Atmos. Environ.* 19 (2), 305–313.
- Xie, Y.L., Hopke, P.K., Casuccio, G.S., Henderson, B.C., 1994a. Use of multiple fractal dimensions to quantify airborne particle shape. *Aerosol Sci. Technol.* 20, 161–168.
- Xie, Y.L., Hopke, P.K., Wienke, D., 1994b. Airborne particle classification with a combination of chemical composition and shape index utilizing an adaptive resonance artificial neural network. *Environ. Sci. Technol.* 28 (11), 1921–1928.
- Xie, Y.L., Hopke, P.K., Paatero, P., Barrie, L.A., Li, S.M., 1999a. Identification of source nature and seasonal variations of Arctic aerosol by positive matrix factorization. *Atmos. Sci.* 56 (2), 249–260.
- Xie, Y.L., Hopke, P.K., Paatero, P., Barrie, L.A., Li, S., 1999b. Identification of source nature and seasonal variations of Arctic aerosol by the multilinear engine. *Atmos. Environ.* 33 (16), 2549–2562.
- Xie, Y.L., Hopke, P.K., Paatero, P., Barrie, L.A., Li, S., 1999c. Locations and preferred pathways of possible sources of Arctic aerosol. *Atmos. Environ.* 33 (14), 2229–2239.
- Yakovleva, E., Hopke, P.K., Wallace, L., 1999. Receptor modeling assessment of particle total exposure assessment methodology data. *Environ. Sci. Technol.* 33 (20), 3645–3652.
- Yoo, S.J., Kim, D.S., 1997. Classification of ambient particulate samples using cluster analysis and disjoint principal component analysis. *J. Korea Air Poll. Res.* 13 (1), 51–63.
- Yoshizumi, K., 1991. Source apportionment of aerosols in the Tokyo metropolitan area by chemical element balance. *Energy Buildings* 16 (1–2), 711–717.
- Zelenka, M.P., Lioy, P.J., Qing-Ci, H., Wilson, W.E., 1992. Development of a new methodology for characterizing air pollution sources in China. In: Chow, J.C., Ono, D.M. (Eds.), *Transactions, PM<sub>10</sub> Standards and Nontraditional Particulate Source Controls*. Air and Waste Management Association, Pittsburgh, PA, pp. 163–182.
- Zelenka, M.P., Wilson, W.E., Lioy, P.J., 1993. Source apportionment of air pollution in China: Extending the usefulness of receptor modeling by combining multivariate and chemical mass balance models. In: *Proceedings of the 86th Annual Meeting*, 13 June, 1993, Denver, CO. Air and Waste Management Association, Pittsburgh, PA.
- Zelenka, M.P., Wilson, W.E., Chow, J.C., Lioy, P.J., 1994. A combined TFA/CMB receptor modeling approach and its application to air pollution sources in China. *Atmos. Environ.* 28 (8), 1425–1435.
- Zeng, Y., Hopke, P.K., 1989. Three-mode factor analysis: A new multivariate method for analyzing spatial and temporal composition variation. In: Watson, J.G. (Ed.), *Transactions, Receptor Models in Air Resources Management*. Air and Waste Management Association, Pittsburgh, PA, pp. 173–189.
- Zeng, Y., Hopke, P.K., 1992a. A new receptor model: A direct trilinear decomposition followed by a matrix reconstruction. *Chemometrics* 6 (2), 65–83.
- Zeng, Y., Hopke, P.K., 1992b. The application of three-mode factor analysis (TMFA) to receptor modeling of SCENES particle data. *Atmos. Environ.* 26 (9), 1701–1711.
- Zhang, J., Chen, Z., Wang, W., 1998a. Source apportionment on fine particulates in atmosphere in Beijing. *Acta Scientiae Circumstantiae* 18 (1), 62–67.
- Zhang, X.Y., Arimoto, R., An, Z.S., Chen, T., Zhang, G., Zhu, G., Wang, X., 1993. Atmospheric trace elements over source regions for Chinese dust: Concentrations, sources, and atmospheric deposition on the Loess Plateau. *Atmos. Environ.* 27 (13), 2051–2067.
- Zhang, X.Y., Zhang, G.Y., Zhu, G.H., Zhang, D.E., An, Z.S., Chen, T., Huang, X.P., 1996. Elemental tracers for Chinese source dust. *Sci. China, Ser. D* 39 (5), 512–521.
- Zhang, X.Y., Arimoto, R., An, Z.S., 1997. Dust emission from Chinese desert sources linked to variations in atmospheric circulation. *J. Geophys. Res.* 102 (D23), 28041–28047.
- Zhang, X.Y., Arimoto, R., Zhu, G.H., Chen, T., Zhang, G.Y., 1998b. Concentration, size-distribution and deposition of mineral aerosol over Chinese desert regions. *Tellus B* 50 (4), 317–330.
- Zhang, Y., Seigneur, C., Seinfeld, J.H., Jacobson, M.Z., Binkowski, F.S., 1999. Simulation of aerosol dynamics: A comparative review of algorithms used in air quality models. *Aerosol Sci. Technol.* 31 (6), 487–514.
- Zhang, Y., Seigneur, C., Seinfeld, J.H., Jacobson, M., Clegg, S.L., Binkowski, F.S., 2000. A comparative review of inorganic aerosol thermodynamic equilibrium modules: similarities, differences, and their likely causes. *Atmos. Environ.* 34 (1), 117–137.

- Zhu, T., Bai, Z., Chen, W., 1995a. Source analysis of air particulate in Qinhuangdao city. *Res. Environ. Sci.* 8 (5), 49–55.
- Zhu, T., Zhou, J., Bai, Z., 1995b. Source apportionment for air particulate matter in Dagang oil field. *Pure Appl. Chem.* 67, 1477–1481.
- Zhu, T., Bai, Z., Chen, W., Xie, X., 1996. Application of receptor model chemical mass balance source apportionment for air particulate matters in TEDA. *Urban Environ. Urban Ecol.* 9 (1), 9–14.
- Zhu, T., Sun, R., Zhang, L., Jiang, L., 1998. Study on identifying the distribution and pollution sources of PAHs in airborne particulate in Dagang Area, Tianjin. *China Environ. Sci.* 18 (4), 289–292.
- Zhu, T., Zhu, X., Liu, W., Lu, Y., Wang, Y., 1999. Application and prospect of chemical mass balance for the source apportionment of air pollutants. In: *Proceedings, 7th National Conference on Aerosol*, Xi'an, China.
- Zielinska, B., Fung, K.K., 1994. The composition and concentration of hydrocarbons in the range of C<sub>2</sub> to C<sub>18</sub> emitted from motor vehicles. *Sci. Total Environ.* 146–147, 281–288.
- Zielinska, B., McDonald, J.D., Hayes, T., Chow, J.C., Fujita, E.M., Watson, J.G., 1998. Northern Front Range Air Quality Study. vol. B: Source measurements. Prepared for Colorado State University, Fort Collins, CO, by Desert Research Institute, Reno, NV.
- Zoller, W.H., Gordon, G.E., Gladney, E.S., Jones, A.G., 1973. The sources and distribution of vanadium in the atmosphere. In: Kothny, E.L. (Ed.), *Trace Elements in the Environment*. American Chemical Society, Washington, DC, pp. 123–132.
- Zoller, W.H., Gladney, E.S., Duce, R.A., 1974. Atmospheric concentrations and sources of trace metals at the South Pole. *Science* 183, 198–200.