8

Air Quality

Air is a vital resource, so its quality must fall within a tightly bound range. This quality is the level needed to protect public health. In addition, the quality must be able to support other life, notably diverse and sustainable ecosystems. Finally, air must be of a quality to protect welfare, including the prevention of the corrosion of materials, preservation of vistas, and protection of agricultural crops.

The terms *ambient air, ambient air pollution, ambient levels, ambient concentrations, ambient air monitoring, ambient air quality,* etc. occur frequently in air pollution parlance. The adjective "ambient" distinguishes pollution of the air outdoors (i.e. ambient air pollution) from contamination of the air indoors by the same substances.

The air inside a factory building can be polluted by release of contaminants from industrial processes to the air of the workroom. This is a major cause of occupational disease. Prevention and control of such contamination are part of the practice of industrial hygiene. To prevent exposure of workers to such contamination, industrial hygienists use industrial ventilation systems that remove the contaminated air from the workroom and discharge it, either with or without treatment to remove the contaminants, to the ambient air outside the factory building.

The air inside a home, office, or public building is the subject of much interest and is referred to as indoor air pollution or indoor air quality (see Chapter 3). These interior spaces may be contaminated by such sources as fuel-fired cooking or space heating ranges, ovens, or stoves that discharge their gaseous and aerosol combustion products to the room; by solvents evaporated from coatings, paints, adhesives, cleaners, or other products; by formaldehyde, radon, and other products emanating from building materials; and by other pollutant sources indoors [1]. If some of these sources exist inside a building, the pollution level of the indoor air might be higher than that of the outside air. However, if none of these sources are inside the building, the pollution level inside would be expected to be lower than the ambient concentration outside because of the ability of the surfaces inside the building—walls, floors, ceilings, furniture, and fixtures—to adsorb or react with gaseous pollutants and to attract and retain particulate pollutants, thereby partially removing them from the air breathed by occupants of the building. This adsorption and retention would occur even if doors and windows were open, but the difference between outdoor and indoor concentrations would be even greater if they were closed, in which case air could enter the building only by infiltration through cracks and walls.

For example, volatile organic compounds, such as the carbonyls (aldehydes and ketones), are frequently found in residences. Various sources of carbonyls are often present inside homes, but little is known about their indoor source strengths; that is, the amount generated indoors versus outdoors. A recent study[1] using a database established in the relationships of indoor, outdoor, and personal air (RIOPA) estimated indoor source strengths of 10 carbonyls and outdoor contributions to measured indoor concentrations of these carbonyls. A mass balance model was applied to analyze paired indoor and outdoor carbonyl concentrations simultaneously measured in 234 RIOPA homes. Table 8.1 shows indoor and outdoor concentrations of carbonyls. Scatter plots of paired indoor and outdoor carbonyl concentrations are shown in Fig. 8.1.

Table 8.2 indicates that the study found variations in the estimated decay rate (rate of chemical breakdown) constants across the RIOPA homes.

Across-home estimates of indoor source strengths are presented in Fig. 8.2.

Myriad factors influence indoor air pollutant concentrations, but this study found that house volume and indoor source strength were the most influential parameters in determining indoor concentrations for compounds with strong indoor sources, whereas the outdoor concentration had the most significant impact for compounds mainly generated from outdoor sources. Interestingly the air exchange rates and the decay rate constant were the least sensitive parameters in the model used to determine the indoor concentrations for the RIOPA homes.

Many materials used and dusts generated in buildings and other enclosed spaces are allergenic to their occupants. Occupants who do not smoke are exposed to tobacco and its associated gaseous and particulate emissions

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[1] Liu, W., Zhang, J., Zhang, L., Turpin, B. J., Weisel, C. P., Morandi, M. T., Stock, T. H., Colome, S., and Korn, L. R., 2006. Estimating contributions of indoor and outdoor sources to indoor carbonyl concentrations in three urban areas of the United States. *Atmos. Environ.* **40**(12), 2202–2214 (2006).

TABLE 8.1

Residential Indoor and Outdoor Carbonyl Concentrations ($\mu g\,m^{-3}$) Measured in 234 Homes

	Indoor samples ($N = 353$)				Outdoor samples ($N = 353$)				
Compounds	5 percentile	Median	95 percentile	% above MDL	5 percentile	Median	95% percentile	% above MDL	P-value[a]
Formaldehyde	12.5	20.1	32.5	100	2.21	6.42	9.95	100	<0.001
Acetaldehyde	7.53	18.6	50.2	100	1.47	5.44	14.9	98	<0.001
Acetone	0.98	8.08	45.8	97	MDL	4.19	19.5	91	<0.001
Acrolein	MDL	0.59	5.54	71	MDL	0.46	4.58	68	0.125
Propionaldehyde	0.23	1.74	3.65	97	0.05	1.37	3.68	95	<0.001
Crotonaldehyde	MDL	0.44	2.51	72	MDL	0.26	2.03	63	0.002
Benzaldehyde	0.98	2.92	5.25	98	MDL	1.88	4.21	94	<0.001
Glyoxal	1.12	2.53	4.37	100	0.44	1.81	3.48	99	<0.001
Methylglyoxal	1.13	2.75	4.77	99	0.26	2.05	3.99	96	<0.001
Hexaldehyde	1.63	3.81	9.94	100	0.23	2.01	4.69	99	<0.001

[a] P values based on Wilcoxon signed-ranked test for residential indoor and outdoor carbonyl concentration differences in medians.

$P < 0.05$ indicates the difference is significant at $\alpha = 0.05$.

MDL: measurement detection limit.

Source: Liu, W., Zhang, J., Zhang, L., Turpin, B. J., Weisel, C. P., Morandi, M. T., Stock, T. H., Colome, S., and Korn, L. R., Estimating contributions of indoor and outdoor sources to indoor carbonyl concentrations in three urban areas of the United States. *Atmos. Environ.* **40**(12), 2202–2214 (2006).

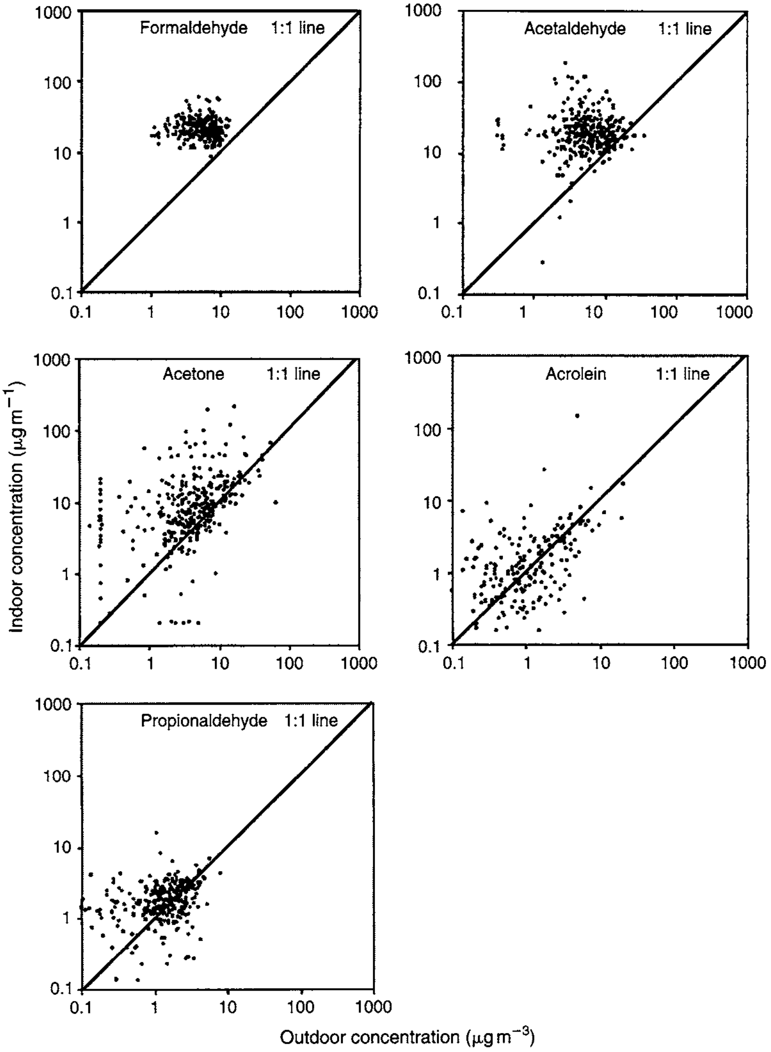

Fig. 8.1. Scatter plots of carbonyl concentrations measured in residential indoor and outdoor air of homes (indoor concentration versus outdoor concentration, $N = 353$). *Source*: Liu. W., Zhang, J., Zhang, L., Turpin, B. J., Weisel, C. P., Morandi, M. T., Stock, T. H., Colome, S., and Korn, L. R., Estimating contributions of indoor and outdoor sources to indoor carbonyl concentrations in three urban areas of the United States. *Atmos. Environ.* **40**(12), 2202–2214 (2006).

from those who do. This occurs to a much greater extent indoors than in the outdoor air. Many ordinances have been established to limit or prohibit smoking in public and work places. Attempts have been made to protect occupants of schoolrooms from infections and communicable diseases by using ultraviolet light or chemicals to disinfect the air. These attempts have been unsuccessful because disease transmission occurs instead outdoors

TABLE 8.2

Estimated Carbonyl Decay Rate Constants Using the Data Collected in 234 Homes

Compounds (k, 1 h^{-1})	*N*	5th Percentile	25th Percentile	Median	75th Percentile	95th Percentile	Ratio 95%/5%
Acetaldehyde	19	0.023	0.057	0.23	0.66	1.4	61.3
Acetone	75	0.011	0.078	0.34	0.97	4.0	360
Acrolein	153	0	0.072	0.54	3.2	14	NA
Propionaldehyde	121	0.011	0.085	0.39	1.4	2.0	183
Crotonaldehyde	152	0	0.098	0.62	3.9	12	NA
Benzaldehyde	79	0.019	0.082	0.24	0.61	1.5	78.9
Glyoxal	71	0.032	0.053	0.15	0.48	8.1	253
Methylglyoxal	76	0.020	0.062	0.17	0.45	1.2	60
Hexaldehyde	29	0.032	0.073	0.32	1.2	3.6	113

Source: Liu, W., Zhang, J., Zhang, L., Turpin, B. J., Weisel, C. P., Morandi, M. T., Stock, T. H., Colome, S., and Korn, L. R., Estimating contributions of indoor and outdoor sources to indoor carbonyl concentrations in three urban areas of the United States. *Atmos. Environ.* **40**(12), 2202–2214 (2006).

and in unprotected rooms. There is, of course, a well-established technology for maintaining sterility in hospital operating rooms and for manufacturing operations in pharmaceutical, semiconductor and similar plants.

I. AVERAGING TIME

The variability inherent in the transport and dispersion process, the time variability of source strengths, and the scavenging and conversion mechanisms in the atmosphere cause pollutants to have an effective half-life. In turn, these factors result in variability in the concentration of a pollutant arriving at a receptor. Thus, a continuous record of the concentration of a pollutant at a receptor, as measured by an instrument with rapid response, might look like Fig. 8.3(a). If, however, instead of measuring with a rapid-response instrument, the measurement at the receptor site was made with sampling and analytical procedures that integrated the concentration arriving at the receptor over various time periods, e.g., 15 min, 1 h, or 6 h, the resulting information would look variously like Figs. 8.3(b)–(d), respectively. It should be noted that from the information in Fig. 8.3(a), it is possible to derive mathematically the information in Figs. 8.3(b)–(d), and it is possible to derive the information in Figs. 8.3(c) and (d) from that in Fig. 8.3(b). The converse is not true. With only the information from Fig. 8.3(d) available, Figs. 8.3(a)–(c) could never be constructed, nor could Figs. 8.3(a) and (b) be constructed from Fig. 8.3(c), nor Fig. 8.3(a) from Fig. 8.3(b). In these examples, the time intervals involved in Figs. 8.3(b)–(d)—15 min, 1 h, and 6 h, respectively—are the *averaging times* of the measurement of pollutant exposure at the receptor.

The averaging time of the rapid-response record [Fig. 8.3(a)] is an inherent characteristic of the instrument and the data acquisition system. It can become

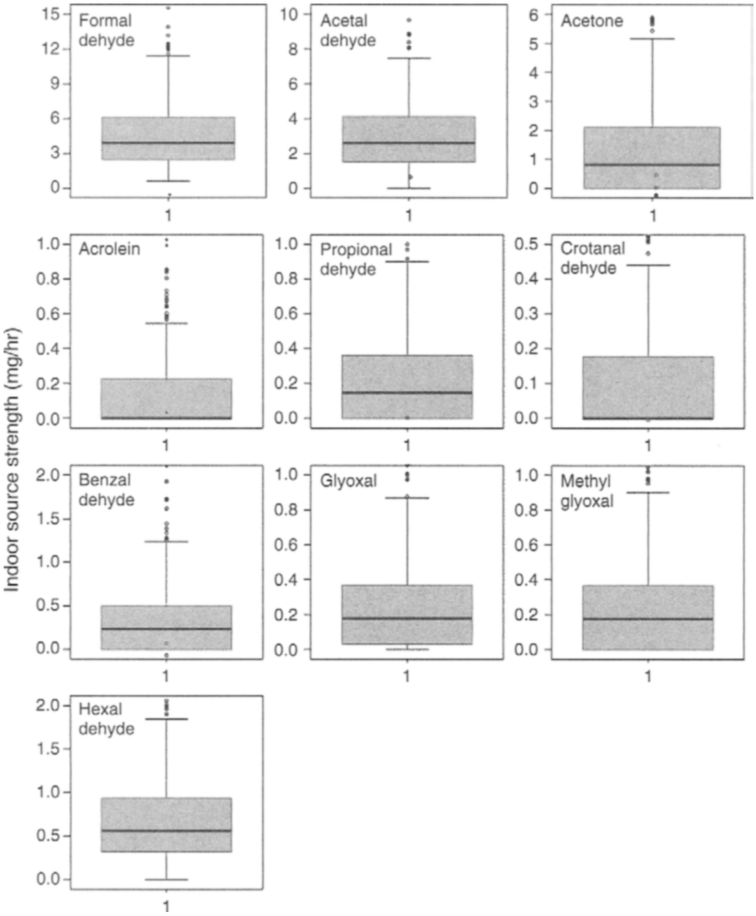

Fig. 8.2. Estimated indoor carbonyl source strengths in the RIOPA homes. The box plots summarize the median, lower quartile, upper quartile, lower range, and upper range of the distribution of indoor source strengths. "o" represents outliers with more than 1.5 box lengths from the upper or lower edge of the box. Some outliers were not presented in the plots because of the scale limit. *Source*: Liu, W., Zhang, J., Zhangm L., Turpin, B.J., Weisel, C.P., Morandi, M.T., Stock, T.H., Colome, S., and Korn, L.R., Estimating contributions of indoor and outdoor sources to indoor carbonyl concentrations in three urban areas of the United States. *Atmos. Environ.* **40**(12), 2202–2214 (2006).

almost an instantaneous record of concentration at the receptor. However, in most cases this is not desirable, because such an instantaneous record cannot be put to any practical air pollution control use. What such a record reveals is something of the turbulent structure of the atmosphere, and thus it has some utility in meteorological research. In communications science parlance, an instantaneous recording has too much *noise* (see Fig. 8.4), preventing a proper interpretation of the measurements. It is therefore necessary to filter or damp out the noise in order to extract the useful information about pollution

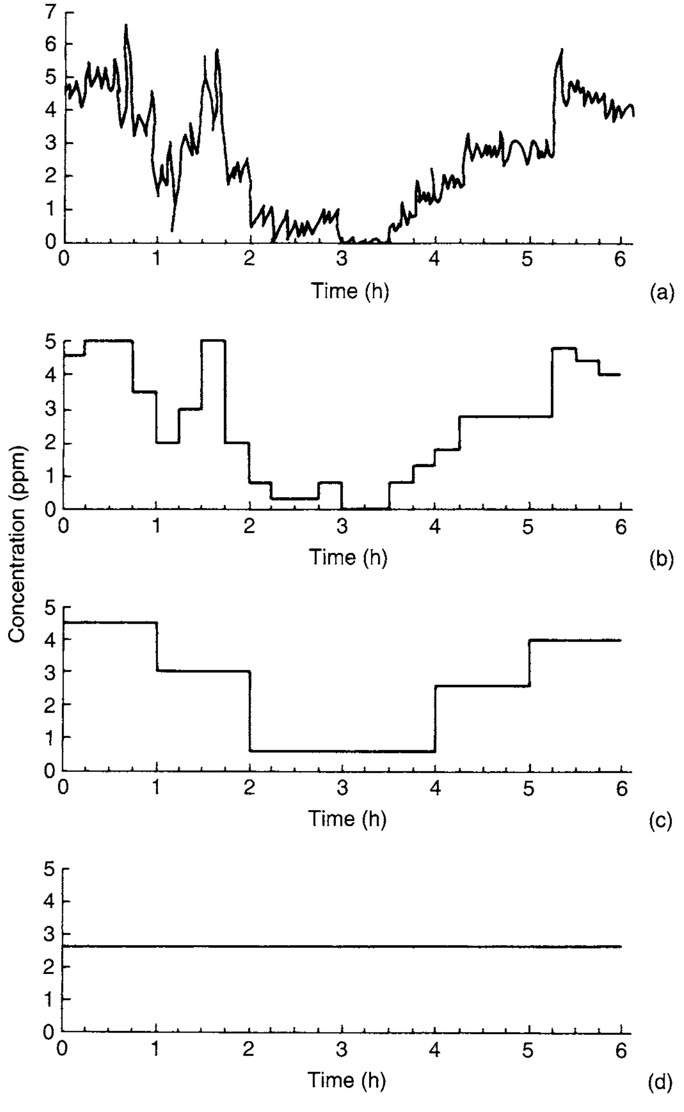

Fig. 8.3. The same atmosphere measured by (a) a rapid-response instrument and by sampling and analytical procedures that integrate the concentration arriving at the receptor over a time period of (b) 15 min, (c) 1 h, and (d) 6 h.

concentration at the receptor that the signal is trying to reveal. This damping is achieved by building time lags into the response of the sampling, analysis, and recording systems (or into all three); by interrogating the instantaneous output of the analyzer at discrete time intervals, e.g., once every minute or once every 5 min, and recording only this extracted information; or by a combination of damping and periodic interrogation.

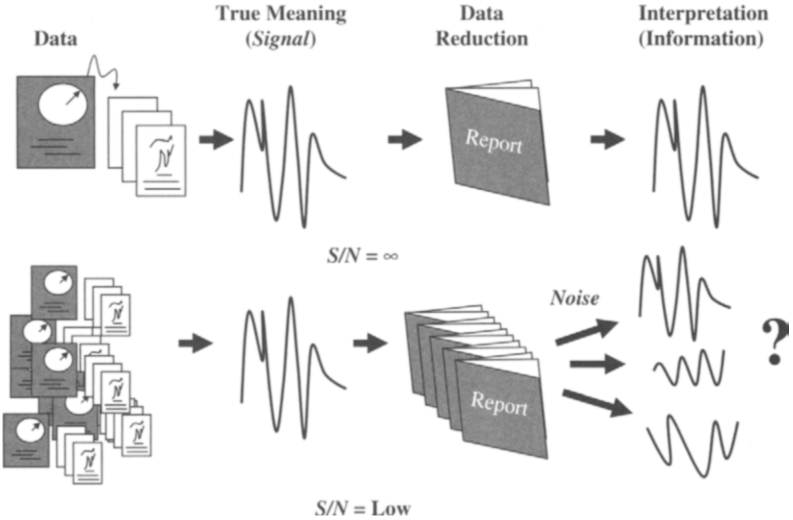

Fig. 8.4. Scientific communication of air quality measurements depends on high quality data that is properly reduced and interpreted in order to become useful information for users. However, even data that are properly collected may become noisy if their volume is so large that they are not able to be interpreted in a timely manner. This leads to a low signal to noise (S/N) ratio.

II. CYCLES

The most significant of the principal cyclic influences on variability of pollution concentration at a receptor is the diurnal cycle (Fig. 8.5). First, there is a diurnal pattern to source strength. In general, emissions from almost all categories of sources are less at night than during the day. Factories and businesses shut down or reduce activity at night. There is less automotive, aircraft, and railroad traffic, use of electricity, cooking, home heating, and refuse burning at night. Second, there is a diurnal pattern to transport and diffusion that will be discussed in detail later in this book.

The next significant cycle is the weekend–weekday cycle. This is entirely a source strength cycle associated with the change in the pattern of living on weekends as compared with weekdays.

Finally, there is the seasonal cycle associated with the difference in climate and weather over the four seasons: winter, spring, summer, and fall (Fig. 8.6). The climatic changes affect source strength, and the weather changes affect transport and dispersion.

On an annual basis, some year-to-year changes in source strength may be expected as a community, a region, a nation, or the world increases in population or changes its patterns of living. Source strength will be reduced if control efforts or changes in technology succeed in preventing more pollution emission than would have resulted from increases in population (Fig. 8.7). These changes are called *trends.* Although an annual trend in

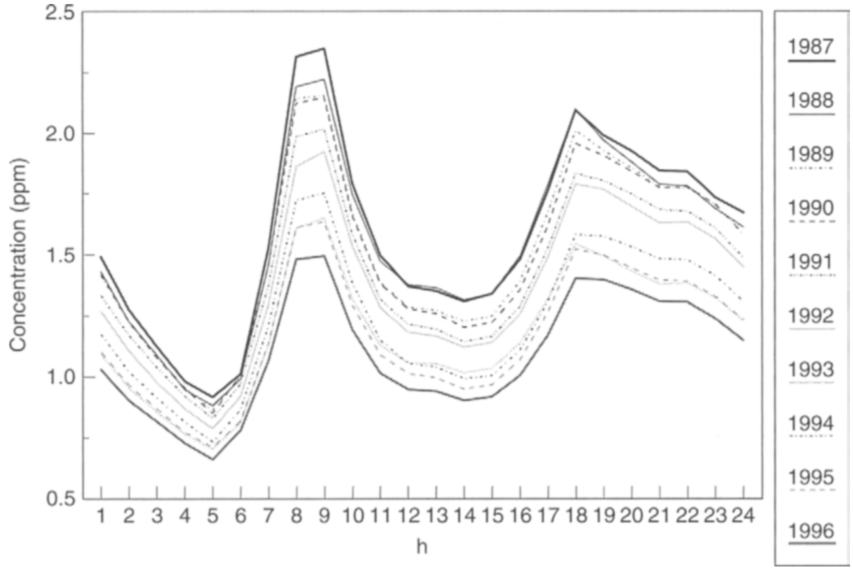

Fig. 8.5. Diurnal patterns in hourly carbon monoxide (CO) concentrations averaged across 2778 monitoring stations located throughout the United States for the 10-year period, 1987–1996. The trends are derived from the composite average of these direct measurements. *Source*: US Environmental Protection Agency, *National Air Quality and Emissions Trends Report*, 1997, http://www.epa.gov/oar/aqtrnd97/chapter2.pdf; accessed February 18, 2007.

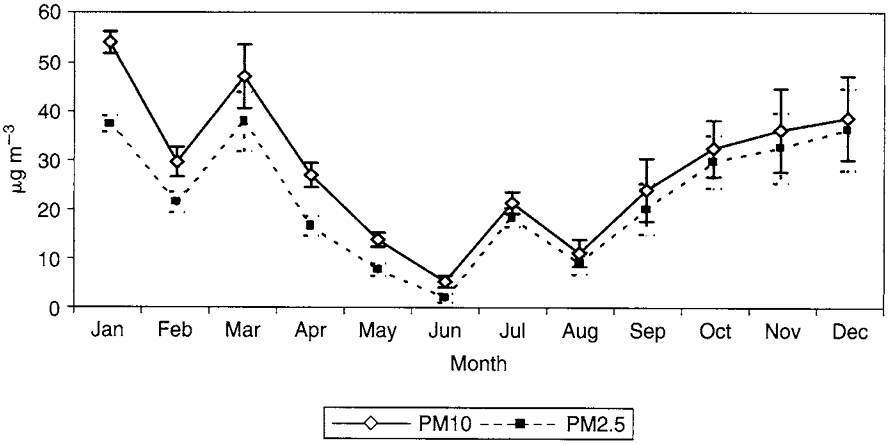

Fig. 8.6. Seasonal variations of particle concentrations in the Hyderabad, India (178 10′–178 50′N latitude and 788 10′–788 50′E longitude). The climate of the study area is of semi-arid type with total rainfall of 700 mm occurring mostly during monsoon season corresponding to July–October. Measurements were gathered approximately at hourly intervals for 4–5 days, with the sampling duration of 6 min during January–December, 2003. *Source*: Latha, K. M., and Badarinath, K. V. S., Seasonal variations of PM_{10} and $PM_{2.5}$ particles loading over tropical urban environment. *Int. J. Environ. Health Res.* **15** (1), 63–68 (2005).

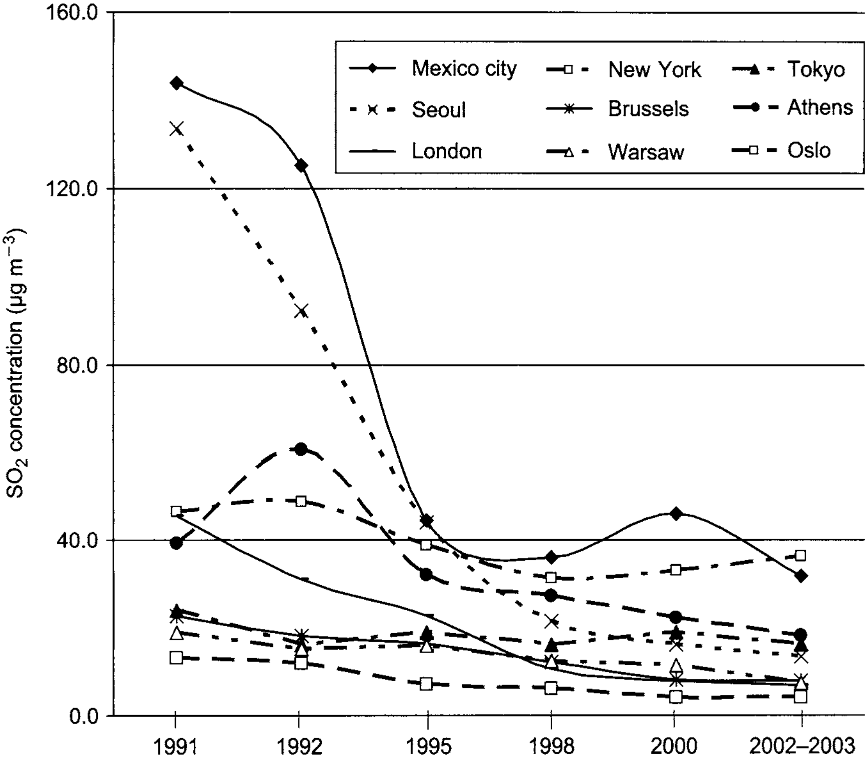

Fig. 8.7. Urban trends in sulfur dioxide (SO_2) concentrations. Data source: *United Nations Environmental Programme, 2006, Geodata Portal,* http://geodata.grid.unep.ch/download/archive/2006_yearbook/airpollution_indicators_cities.xls; accessed on October 11, 2006.

source strength is expected, no such trend is expected in climate or weather, even though each year will have its own individuality with respect to its weather. However, there is at present an ongoing debate as to whether global mean temperatures will continue to increase due to increasing concentration of global greenhouse gases, especially carbon dioxide and methane. If so, this would be a climatic trend.

Other examples of trends come from Great Britain, where the emission of industrial smoke was reduced from 1.4 million tons per year in 1953 to 0.1 million tons per year in 1972; domestic smoke emission was reduced from 1.35 million tons per year in 1953 to 0.58 million tons per year in 1972; and the number of London fogs (smogs) capable of reducing visibility at 9 a.m. to less than 1 km was reduced from 59 per year in 1946 to 5 per year in 1976.

Annual trends in urban ozone are much more subtle because of the complex interaction among precursors (hydrocarbons and oxides of nitrogen) and meteorology (including solar radiation) (Fig. 8.8).

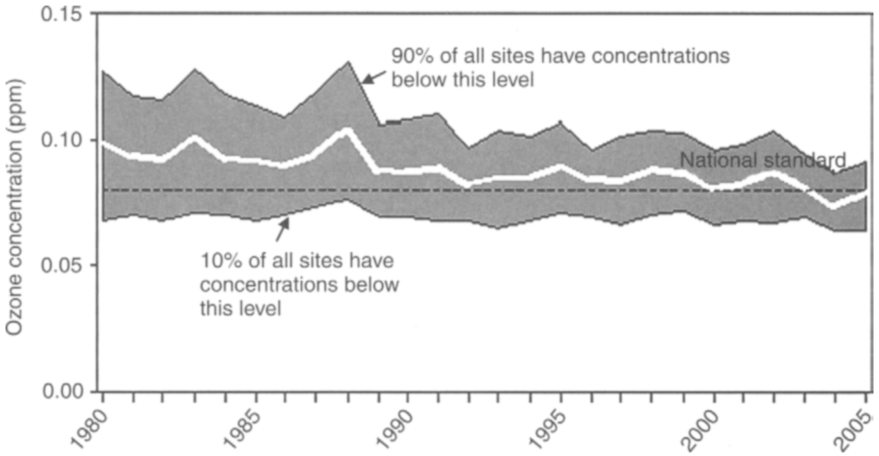

Fig. 8.8. In the United States, average ozone concentrations have been decreasing, but the rate of decrease for 8-h levels slowed during the 1990s. Concentrations are based on the annual fourth-highest daily maximum 8-h average ozone concentration. The gray area around the trend line (white) represents the distribution of air pollution levels among the 286 trend sites, displaying the middle 80%. *Source*: US Environmental Protection Agency, 2006, *National Trends in Ozone Levels*, http://www.epa.gov/airtrends/ozone.html#oznat; accessed on October 11, 2006.

III. PRIMARY AND SECONDARY POLLUTANTS

A substantial portion of the gas and vapors[2] emitted to the atmosphere in appreciable quantity from anthropogenic sources tends to be relatively simple in chemical structure: carbon dioxide, carbon monoxide, sulfur dioxide, and nitric oxide from combustion processes; hydrogen sulfide, ammonia, hydrogen chloride, and hydrogen fluoride from industrial processes. The solvents and gasoline fractions that evaporate are alkanes, alkenes, and aromatics with relatively simple structures.

In addition, more complex molecules such as polycyclic aromatic hydrocarbons (PAHs) and dioxins are released from industrial processes and combustion sources and are referred to as toxic pollutants. Substances such as these, emitted directly from sources, are called *primary pollutants*. They are certainly not innocuous, as will be seen when their adverse effects are discussed in later chapters. However, the primary pollutants do not, of themselves, produce all

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[2] The terms gas and vapor are often used synonymously; however, a vapor is a gaseous substance that is a solid or liquid at standard temperature and pressure (STP), i.e. at 0°C and 101.325 kPa. Thus, CO_2 is a gas, but ethanol is predominantly a liquid under these conditions. Note that not all of ethanol is liquid, since it is vaporizing. However, with increasing temperature and constant pressure, a greater amount of ethanol will move to the gas phase (according to Henry's law). That is, at lower temperatures only a small number of ethanol molecules are sufficiently excited to move to the gas phase, but with increasing temperature, the number of molecules escaping increases. Thus, when we measure these ethanol molecules in the gas phase, we consider this to be a vapor measurement.

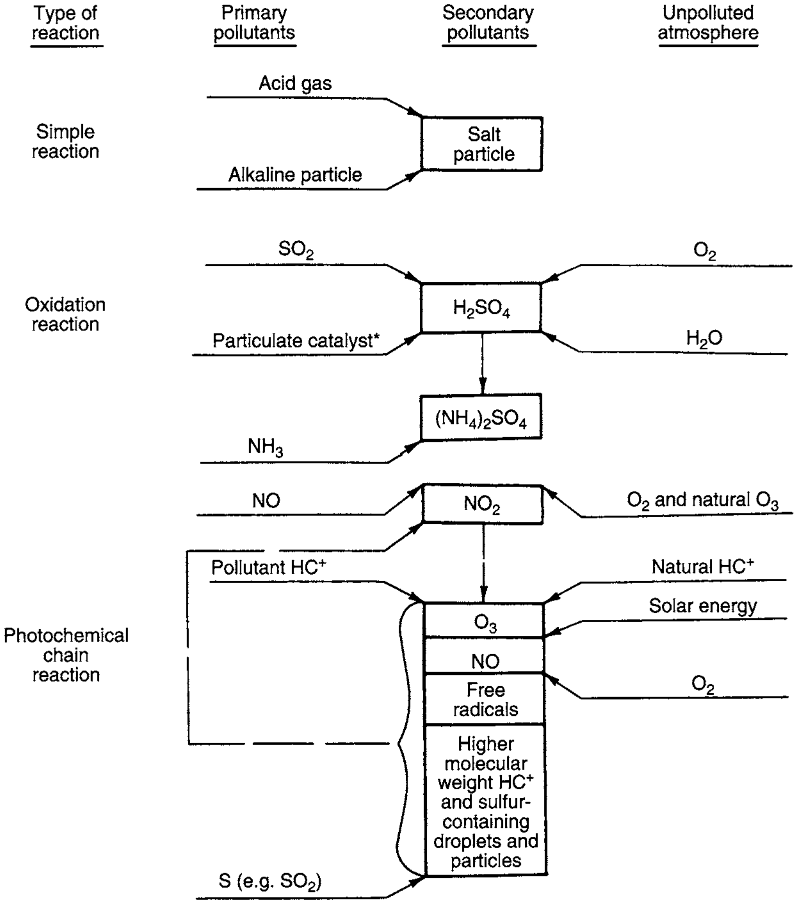

Fig. 8.9. Primary and secondary pollutants. *Reaction can occur without catalysis (HC$^+$, hydrocarbons).

of the adverse effects of air pollution. Chemical reactions may occur among the primary pollutants and the constituents of the unpolluted atmosphere (Fig. 8.9). The atmosphere may be viewed as a reaction vessel into which are poured reactable constituents and in which are produced a tremendous array of new chemical compounds, generated by gases and vapors reacting with each other and with the particles in the air. The pollutants manufactured in the air are called *secondary pollutants*; they are responsible for most of the smog, haze, and eye irritation and for many of the forms of plant and material damage attributed to air pollution. In air pollution parlance, the primary pollutants that react are termed the *precursors* of the secondary pollutants. With the knowledge that each secondary pollutant arises from specific chemical reactions involving specific primary reactants, we must control secondary pollutants by controlling how much of each primary pollutant is allowed to be emitted. Note that the use of primary and secondary pollutants used here is different from the regulatory definitions of primary and secondary pollutants. The Clean Air Act sets primary standards to protect public health and secondary standards to protect welfare.

IV. MEASUREMENT SYSTEMS

Many methods of air quality measurement have inherent averaging times. In selecting methods for measuring air quality or assessing air pollution effects, this fact must be borne in mind (Table 8.3). Thus, an appropriate way to assess the influence of air pollution on metals is to expose identical specimens at different locations and compare their annual rates of corrosion among the several locations. Since soiling is mainly due to the sedimentation of particulate matter from the air, experience has shown that this can be conveniently measured by exposing open-topped receptacles to the atmosphere for a month and weighing the settled solids. Human health seems to be related to day-to-day variation in pollutant level.

Because a filter sample includes particles both larger and smaller than those retained in the human respiratory system (see Chapter 11, Section III), various types of samplers are used which allow measurement of the size ranges of particles retained in the respiratory system. Some of these are called *dichotomous samplers* because they allow separate measurement of the respirable and nonrespirable fractions of the total. *Size-selective samplers* rely on impactors, miniature cyclones, and other means. The United States has selected the size fraction below an aerodynamic diameter of 2.5 μm ($PM_{2.5}$) for compliance with the air quality standard for airborne particulate matter. However, there continues to be concern coarse-sized particles (>2.5 to <10 μm).

Because an agricultural crop can be irreparably damaged by an excursion of the level of several gaseous pollutants lasting just a few hours, recording such an excursion requires a measuring procedure that will give hourly data. The least expensive device capable of doing this is the *sequential sampler*, which will allows a sequence of 1- or 2-h samples day after day for as long as the bubblers in the sampler are routinely serviced and analyzed.

TABLE 8.3

Air Quality Measurement

Measure of averaging time	Cyclic factor measured	Measurement method with same averaging time	Effect with same averaging time
Year	Annual trend	Metal specimen	Corrosion
Month	Seasonal cycle	Dustfall	Soiling
Day	Weekly cycle	Dichotomous	Human health
Hour	Diurnal cycle	Sequential sampler	Vegetation damage
Minute	Turbulence	Continuous instrument	Irritation (odor)

As discussed, the hourly data from sequential samplers can be combined to yield daily, monthly, and annual data.

None of the foregoing methods will tell the frequency or duration of exposure of any receptor to irritant or odorous gases when each such exposure may exceed the irritation or odor response threshold for only minutes or seconds. The only way that such an exposure can be measured instrumentally is by an essentially continuous monitoring instrument, the record from which will yield not only this kind of information but also all the information required to assess hourly, daily, monthly, and annual phenomena. Continuous monitoring techniques may be used at a particular location or involve remote sensing techniques, such as the so-called open path systems (e.g. open path infrared or differential optical absorption spectrometers, DOAS) (see Fig. 8.10 and Table 8.4). All of these techniques are considered to be "active" monitoring devices, since they involve mechanical movement of air through the filters and sensors. Passive systems are also gaining use in detecting air pollution, especially for detecting those gases where diffusion

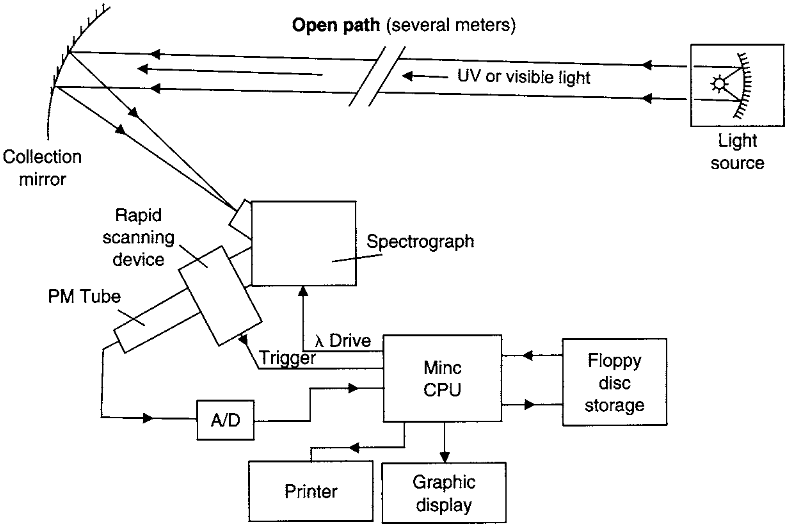

Fig. 8.10. Schematic of an open path air measurement device: differential optical adsorption spectrometer (DOAS), which measures the absorption through an atmospheric path (typically 0.5–1.5 km) of two closely spaced wavelengths of light from an artificial source. One wavelength is chosen to match an absorption line of the specific compound of interest, and the other is near that line to account for atmospheric effects (EPA/600/P-93/004aF, pp. 3–98). The term absorption line is used to mean a wavelength that a given atom or molecule absorbs more than it does other wavelengths. For example, if ozone is the compound of interest, a wavelength would be identified which ozone absorbs more than other wavelengths. As in other open path systems (e.g. FTIR) a beam of electromagnetic radiation (in this case, visible or ultraviolet light) containing this particular wavelength is directed at a segment (open path) of the atmosphere, and the amount of the wavelength absorbed would be measured and calibrated against a known concentration of the compound of interest. *Source*: US Environmental Protection Agency, *Air Quality Criteria for Ozone and Photochemical Oxidants* (EPA/600/P-93/004aF), July 1996.

TABLE 8.4

Minimum Detection Level Defined as the Lowest Concentration of a Species that DOAS Devices Can Distinguish from Background Noise

Compound	Minimum detection limit in parts per billion volume (ppbv)	Reference
p-Xylene	0.3	Axelsson, H. *et al.*, Measurement of aromatic hydrocarbons with the DOAS technique. *Appl. Spect.* **49** (9), 1254–1260 (1995).
Ethylbenzene	2	Axelsson, H. *et al.*, 1258 (1995)
1,2,3-Trimethylbenzene	6	Axelsson, H. *et al.*, 1258 (1995)
NO_2	4	Biermann, H. W., *et al.*, Simultaneous absolute measurements of gaseous nitrogen species in urban ambient air by long pathlength infrared and ultraviolet-visible spectroscopy, *Atmos. Environ.* **22** (8), 1545–1554 (1988).
NO_3	0.02	Biermann, H. W., *et al.*, 1551 (1988)
Ozone (O_3)	3	Stevens, R. K., *et al.*, A long path DOAS and EPA-approved fixed-point methods intercomparison. *Atmos. Environ.* **27B** (2), 231–236 (1993).
SO_2	10	Stevens, R. K. *et al.*, 234 (1993)

Source: US Environmental Protection Agency.

(following Fick's laws) is well understood. In passive systems, passive monitors are exposed to the air over a defined time period and the amount of the gas that has diffused is measured and integrated for that time period to give the concentration, often reported as a mean for that reporting period (e.g. a daily or weekly mean).

V. AIR QUALITY LEVELS

A. Levels

Air quality levels vary between concentrations so low that they are less than the minimum detectable values of the instruments we use to measure them and maximum levels that are the highest concentrations ever measured. Figure 8.11 gives national data (1980–2005) for CO in the United States. The mean chemical composition and atmospheric concentration of suspended particulate matter (total, coarse, and fine) measured in the United States in 1980 are shown in Table 8.5. The percentages do not add up to 100% because they exclude the oxygen (except for the nitrate and sulfate components),

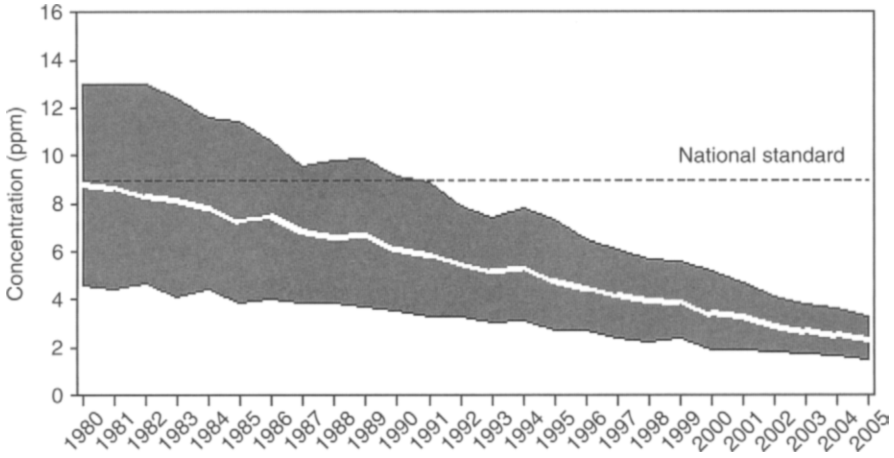

Fig. 8.11. Trend in ambient concentrations of carbon monoxide, based on the annual second maximum 8-h average concentrations from 152 sites across the United States. The gray band shows the distribution of air pollution levels among the trend sites, displaying the middle 80%. The white line represents the average among all the trend sites. Ninety percent of sites have concentrations below the top line, while 10% of sites have concentrations below the bottom line. The 16-year trend shows a 74% improvement overall. *Source*: US Environmental Protection Agency, 2007, *Air Trends*, http://www.epa.gov/airtrends/carbon.html; accessed on February 18, 2007.

nitrogen (except for the nitrate component), hydrogen, and other components of the compounds of the listed elements in the form in which they actually exist in the atmosphere; for example, the most common form of particulate sulfur and sulfate in the atmosphere is $(NH_4)_2(SO_4)$. The table indicates that about 30% of the mass of particulate matter is in the fine fraction (>2.5 μm), 30% is in the coarse fraction >15 μm), and 40% is coarser still—between 15 and *ca.* 50 μm.

It is a general rule that the larger the population base, the dirtier the air will be. Urban air in the United States is cleaner than it was in the 1950s and 1960s because of the tremendous efforts made to clean up the air in the intervening decades (Table 8.6).

B. Display of Air Quality Data

Information about air quality usually starts with observed measurements, which are either presented "as is," but more often as a *sample* representing a larger population. The data are also frequently enhanced using various air quality models. Inferential statistics are applied to the observed sample so that the condition of the population (e.g. an airshed) can be inferred from the limited number of observations (e.g. from State and Local Ambient Air Monitoring Sites (SLAMS); see Fig. 8.12).

TABLE 8.5

Mean Chemical Composition and Atmospheric Concentrations of Suspended Particulate Matter Sampled by the United States Environmental Protection Agency's Inhalable Particle and National Air Surveillance Networks—μg m^{-3} and Percentage of Total Mass Sampled, 1980

Type of sample	Urban				Rural			
Number of samples			745		2255^{a}		133^{b}	
Particle size	Coarse, 15–2.5 μm		Fine, less than 2.5 μm		All less than *ca.* 50 μm			
	Mean value of 745 values	%	Mean value of 745 values	%	Mean value of 2255 values	%	Mean value of 133 values	%
All (total mass)	21.655	100.00	22.680	100.00	74.990	100.00	36.504^{a}	100.00
Aluminum	1.797	8.30	0.353	1.56	—	—	—	—
Antimony	0.051	0.24	0.050	0.22	—	—	—	—
Arsenic	0.003	0.01	0.004	0.02	0.005^{c}	0.01	0.003^{d}	0.01
Barium	0.060	0.28	0.060	0.26	0.273	0.36	0.281	0.77
Beryllium^{c}	—	—	—	—	(0.095)	—	(0.084)	—
Bromine	0.019	0.09	0.077	0.34	—	—	—	—
Cadmium	0.006	0.03	0.007	0.03	0.002	0.01	0.001	0.01
Calcium	1.503	6.94	0.340	1.50	—	—	—	—
Chlorine	0.440	2.03	0.155	0.68	—	—	—	—
Chromium	0.008	0.04	0.006	0.03	0.013^{c}	0.02	0.015^{d}	0.05
Cobalt	—	—	—	—	0.001^{c}	0.01	0.001^{d}	0.01
Copper	0.019	0.09	0.026	0.12	0.143	0.19	0.136	0.37
Iron	0.743	3.43	0.205	0.90	0.923	1.23	0.254	0.70
Lead	0.083	0.38	0.314	1.38	0.353	0.47	0.066	0.18
Manganese	0.021	0.10	0.013	0.06	0.031	0.04	0.008	0.02
Mercury	0.003	0.01	0.003	0.01	—	—	—	—
Molybdenum	—	—	—	—	0.002	0.01	0.001	0.01
Nickel	0.004	0.02	0.007	0.03	0.007	0.01	0.002	0.01
Phosphorus	0.056	0.26	0.021	0.09	—	—	—	—
Potassium	0.222	1.03	0.156	0.69	—	—	—	—
Selenium	0.001	0.01	0.002	0.01	—	—	—	—
Silicon	2.561	11.83	0.360	1.59	—	—	—	—
Strontium	0.246	0.21	0.051	0.22	—	—	—	—
Sulfur	0.339	1.56	2.056	9.07	—	—	—	—
Tin	0.006	0.03	0.006	0.03	—	—	—	—
Titanium	0.042	0.19	0.015	0.07	—	—	—	—
Vanadium	0.008	0.04	0.010	0.04	0.015	0.02	0.004	0.01
Zinc	0.038	0.18	0.067	0.30	0.147	0.20	0.114	0.31
Nitrate	0.699	3.23	1.071	4.72	4.647	6.20	2.341	6.41
Sulfate	0.706	3.26	5.30	23.37	10.811	14.42	8.675	23.77
Sum of percentages	—	43.82^{f}	—	47.34^{f}	—	23.20	—	32.64

[a] Except for arsenic, chromium, and cobalt where the number of samples was 1245.
[b] Except for arsenic, chromium, and cobalt where the number of samples was 30.
[c] Except for arsenic, chromium, and cobalt where the mean total mass was 76.647 μg m^{-3}.
[d] Except for arsenic, chromium, and cobalt where the mean total mass was 30.367 μg m^{-3}.
[e] ng m^{-3}.
[f] Sulfur is counted twice: as sulfur and as sulfate. Some of this sulfur exists as sulfides, sulfites, and forms other than sulfate.

TABLE 8.6

Distribution of Cities by Population Class and Particulate Matter Concentration, 1957–1967

	Average particulate matter concentration ($\mu m\ m^{-3}$)										
Population class	Less than 40	40–59	60–79	80–99	100–119	120–139	140–159	160–179	180–199	More than 200	Total
Over 3 million	—	—	—	—	—	—	1	—	1	—	2
1–3 million	—	—	—	—	—	—	2	1	—	—	3
0.7–1 million	—	—	1	—	2	—	4	—	—	—	7
400–700 000	—	—	—	4	5	6	1	1	1	—	18
100–400 000	—	3	7	30	24	17	12	3	2	1	99
50–100 000	—	2	20	28	16	12	6	5	1	3	93
25–50 000	—	5	24	12	12	10	2	1	2	3	71
10–25 000	—	7	18	19	9	5	2	3	1	—	64
Under 10 000	1	5	7	15	11	2	1	2	—	—	44
Total	1	22	77	108	79	52	31	16	8	7	401

Source: US Environmental Protection Agency, *Air Quality Data from 1967* (Rev. 1971). Office of Air Programs, Publication No. APTD 0471, Research Triangle Park, NC, 1971.

Fig. 8.12. The SLAMS consist of a network of ~4000 monitoring stations whose size and distribution is largely determined by the needs of State and local air pollution control agencies to meet their respective State Implementation Plan (SIP) requirements. *Source*: US Environmental Protection Agency 2006, *The Ambient Air Monitoring Program*, http://epa.gov/oar/oaqps/qa/monprog.html#SLAMS; accessed on October 30, 2006.

Often, a relatively small number of samples represent a large population. Air quality data are highly variable. For example, they vary diurnally (within the same 24-h interval), seasonally, and year-over-year.

A sample of n individual values is:

$$\{x\} = x_1, x_2, x_3, \ldots, x_n \tag{8.1}$$

where { } indicates a vector of individual values, and the n individual observations are a sample taken from the set of possible outcomes of the population. Another important concept used to characterize air quality data is *probability*, which is the likelihood that some outcome will occur. Thus, the likelihood ranges from not all (0%) to 100%. Accordingly, the range of probability is between 0 and 1.

Once data are collected, they are displayed graphically. Drawing a frequency histogram from the observed data is often a first step. This gives an estimate of the data's *probability distribution*. The data are grouped into discrete intervals, with the number of samples falling in each interval shown by a bar (intervals on the x-axis and frequency of occurrence on the y-axis). For example, a stack test measuring the concentration of mercury (Hg) from a fossil fuel power plant is shown in Fig. 8.13.

The intervals must be mutually exclusive of the next interval. In other words, a value must fall in one and only one interval. Thus, in the stack test, the intervals are $0 < 1$; $1 < 2$; $2 < 3$; …; $14 < 15\,\mu\text{g m}^{-3}$ Hg in the stack gas. This means that the value of $2.5\,\mu\text{g m}^{-3}$ Hg falls in the $2 < 3$ interval (shown as "3" in the figure) and that the value of 11.99 $\mu g\,m^{-3}$ Hg falls in the 11 < 12 interval (shown as "12" in the figure). So, the relative number of occurrences of an event is shown as $P(E_1)$, meaning the probability of event E_1, which is equal to n_1/n if the event happened to occur n_1 times in n samples. For example, samples of mercury 8 < 9 $\mu g\,m^{-3}$ occurred 28 times out of the total 130 samples taken in the stack test. This means that 21.5% of the samples fell within the 8 < 9 $\mu g\,m^{-3}$ interval. Finding this relative frequency of each interval yields a relative frequency of occurrence histogram (see Fig. 8.14).

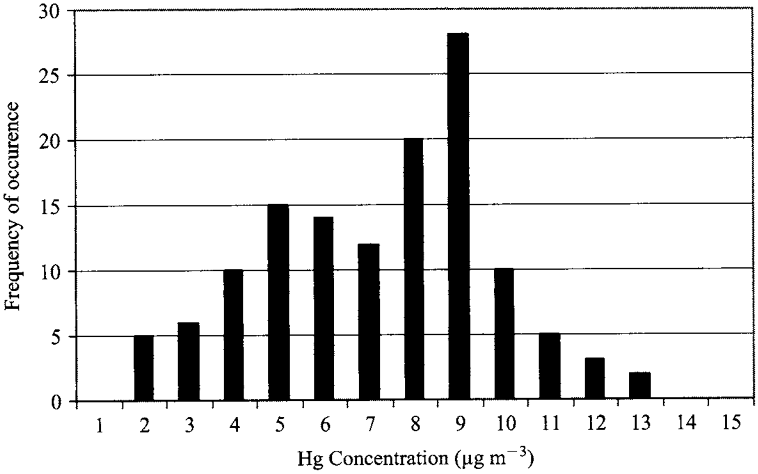

Fig. 8.13. Histogram of hypothetical stack test data.

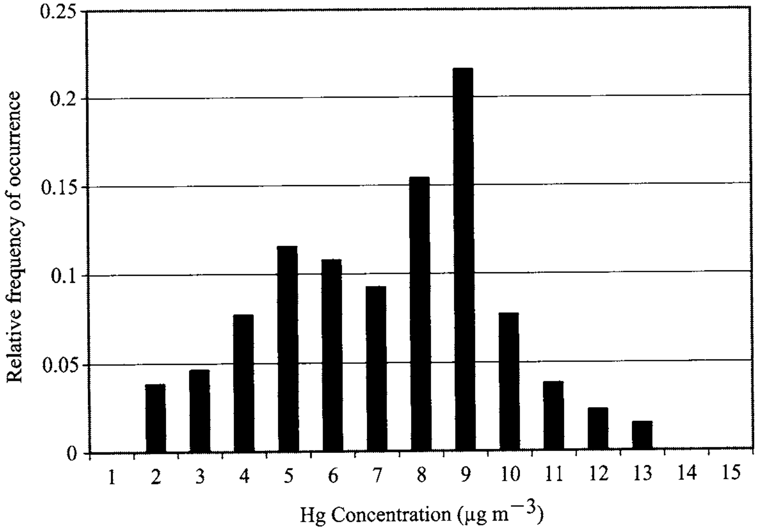

Fig. 8.14. Relative frequency of occurrence of hypothetical stack test data.

A very useful format in which to display air quality data for analysis is that of Fig. 8.15, which has as its abscissa averaging time expressed in two different time units and, as its ordinate, concentration of the pollutant at the receptor. This type of chart is called an *arrowhead chart* and includes enough information to characterize fully the variability of concentration at the receptor.

To understand the meaning of the information given, let us concentrate on the data for 1-h averaging time. In the course of a year there will be 8760 such values, one for each hour. If all 8760 are arrayed in decreasing value, there will be one maximum value and one minimum value. (For some pollutants the minimum value is indefinite if it is below the minimum detectable value of the analytical method or instrument employed.) In this array, the value 2628 from the maximum will be the value for which 30% of all values are greater and 70% are lower. Similarly, the value 876 from the maximum will be the one for which 10% of all values are greater and 90% are lower. The 1% value will be between the 87th and 88th values from the maximum, and the 0.1% value will lie between the 8th and 9th values in the array.

The 50% value, which is called the *median value*, is not the same as the average value, which is also called the *arithmetic mean value*. Both are types of measures of central tendency. The median value is the middle value of the data set; half values exceed the median, while the other half are less than the median. The arithmetic mean value is obtained by adding all 8760 values and then dividing the total by 8760. The arithmetic average value obtained for other averaging times, e.g., by adding all 365 24-h values and dividing the

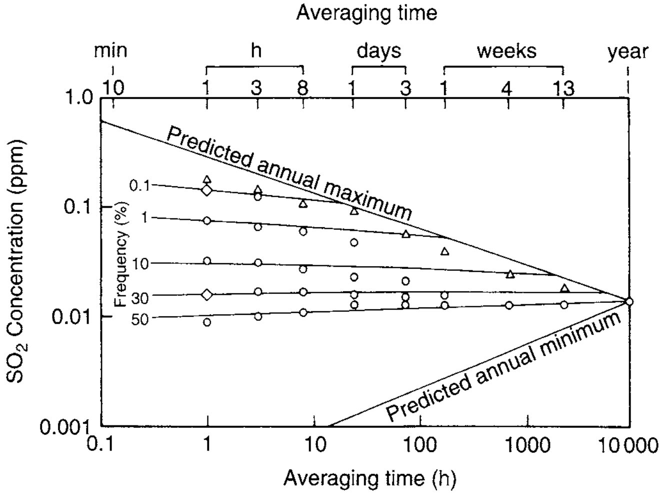

Fig. 8.15. Sulfur dioxide concentration versus averaging time and frequency for 1980 at US National Aerometric Data Bank (NADB) Site 264280007 HO1, 8227 S. Broadway, St. Louis, Missouri. *Source*: Chart courtesy of Dr. Larsen, R. I., US Environmental Protection Agency, Research Triangle Park, NC; see also Fig. 21.13.

total by 365, will be the same and will equal the annual arithmetic average value. The median value will equal the arithmetic average value only if the distribution of all values allows this to occur. For example:

1 2 3 4 5 6 7 8 9 10 Median = 5.5 Mean = 5.5

1 3 3 3 5 6 7 7 8 12 Median = 5.5 Mean = 5.5

In most instances, however, the mean is different from the median. Consider the following example. A monitor collects the following naphthalene daily average values ($\mu g\,m^{-3}$):

100 m to the north: 0.1, 0.2, 0.6, 0.7, 0.5, 0.1, 0.7

100 m to the south: 5.2, 3.3, 11.1, 12.7, 5.8, 7.7, 11.8

To find the median, the values are shown in ascending order (Table 8.7).

Since the number of values is odd (i.e. seven), we simply select the middle value (the fourth). Had the number of values been even, the two middle values would be averaged to give the mean (e.g. if the two middle values are 1.1 and 1.3, the median would be 1.2). Thus, the median of the two data sets are 0.5 and 7.7 $\mu g\,m^{-3}$, respectively. However, the mean ($\bar{x}$) is found as the quotient of the sum of the values divided by the number of values:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{8.2}$$

The north data set's mean, then, is

$$\bar{x} = \frac{2.9}{7} = 0.47$$

TABLE 8.7

Daily Naphthalene Measurements ($\mu g\,m^{-3}$)

North	South
0.1	3.3
0.1	5.2
0.2	5.8
0.5	7.7
0.6	11.1
0.7	11.8
0.7	12.7

The south data set's mean is:

$$\bar{x} = \frac{57.6}{7} = 8.2$$

So, this is the common instance of a skewed data set. In the north data, the median is larger than the mean, but in the south data set, the mean is larger than the median.

If air quality data at a receptor for any one averaging time are lognormally distributed, these data will plot as a straight line on log probability graph paper (Fig. 8.16) which bears a note $S_g = 2.35$. S_g is the standard geometric deviation about the geometric mean (the geometric mean is the Nth root of the product of the n values of the individual measurements):

$$S_g = \exp\sum_{i=1}^{n}\left[\frac{(\ln X_i - \overline{\ln X_i})^2}{n-1}\right]^{1/2} \tag{8.3}$$

where $X_i = X_1, X_2, \ldots, X_n$ are the individual measurements and n is the number of measurements.

Further discussion of the significance of mean values and standard deviations can be found in Chapters 22 and 36 and in any textbook on statistics.

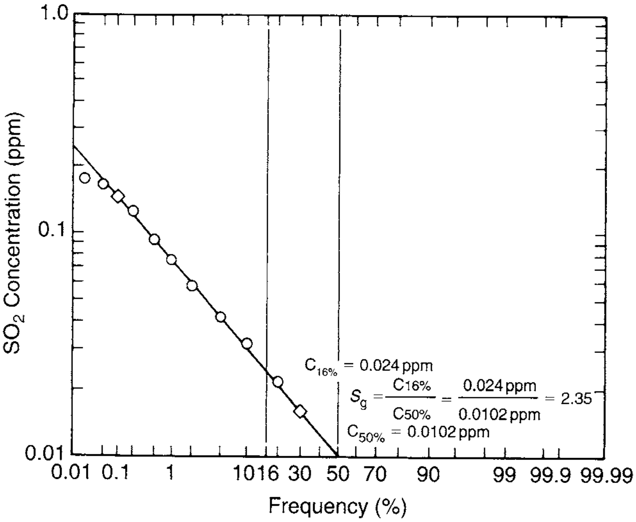

Fig. 8.16. Frequency of 1-h average sulfur dioxide concentrations equal to or greater than stated values during 1980 at US National Aerometric Data Bank (NADB) Site 264280007 HO1, 8227 S. Broadway, St. Louis. Missouri. *Source*: Chart courtesy of Larsen, R. I., US Environmental Protection Agency, Research Triangle Park, NC.

C. Adverse Responses to Air Quality Levels

The objective of air pollution control is to prevent adverse responses by all receptor categories exposed to the atmosphere: human, animal, vegetable, and material. These adverse responses have characteristic response times: short-term (i.e. seconds or minutes), intermediate-term (i.e. hours or days), and long-term (i.e. months or years) (Table 8.8). For there to be no adverse responses, the pollutant concentration in the air must be lower than the concentration level at which these responses occur. Figure 8.16 illustrates the relationship between these concentration levels. This figure displays response curves, which remain on the concentration duration axes because they are characteristic of the receptors, not of the actual air quality to which the receptors are exposed. The odor response curve, e.g. to hydrogen sulfide, shows that a single inhalation requiring approximately 1 s can establish the presence of the odor but that, due to odor fatigue, the ability to continue to recognize that odor can be lost in a matter of minutes. Nasopharyngeal and eye irritation, e.g. by ozone, is similarly subject to acclimatization due to tear and mucus production. The three visibility lines correlate with the concentration of suspended particulate matter in the air. Attack of metal, painted surfaces, or nylon hose is shown by a line starting at 1 s and terminating in a matter of minutes (when the acidity of the droplet is neutralized by the material attacked).

Vegetation damage can be measured biologically or socioeconomically. Using the latter measure, there is a 0% loss when there is no loss of the sale value of the crops or ornamental plants but a 100% loss if the crop is damaged to the extent that it cannot be sold. These responses are related to dose, i.e. concentration times duration of exposure, as shown by the percent loss

TABLE 8.8

Examples of Receptor Category Characteristic Response Times

	Characteristic response times		
Receptor category	Short-term (seconds–minutes)	Intermediate-term (hours–days)	Long-term (months–years)
Human	Odor, visibility, nasopharyngeal and eye irritation	Acute respiratory disease	Chronic respiratory disease and lung cancer
Animal, vegetation	Field crop loss and ornamental plant damage	Field crop loss and ornamental plant damage	Fluorosis of livestock, decreased fruit and forest yield
Material	Acid droplet pitting and nylon hose destruction	Rubber cracking, silver tarnishing, and paint blackening	Corrosion, soiling, and materials deterioration

curves on the chart. A number of manifestations of material damage, e.g. rubber cracking by ozone, require an exposure duration long enough for the adverse effects to be significant economically. That is, attack for just a few seconds or minutes will not affect the utility of the material for its intended use, but attack for a number of days will.

The biological response line for acute respiratory disease is a dose–response curve which for a constant concentration becomes a duration–response curve. The shape of such a curve reflects the ability of the human body to cope with short-term, ambient concentration respiratory exposures and the overwhelming of the body's defenses by continued exposure.

Fluorosis of livestock is not induced until there has been a long enough period of deposition of a high enough ambient concentration of fluoride to increase the level of fluoride in the forage. Since the forage is either eaten by livestock or cut for hay at least once during the growing season, the duration of deposition ends after the growing season. The greater the duration of the season, the greater the time for deposition, hence the shape of the line labeled "fluorosis." Long-term vegetation responses—decreased yield of fruit and forest—and long-term material responses—corrosion, soiling, and material deterioration—are shown on the chart as having essentially the same response characteristics as human chronic respiratory disease and lung cancer.

The relationship of these response curves to ambient air quality is shown by lines A, B, and C, which represent the maximum or any other chosen percentile line from a display such as Fig. 8.17, which shows actual air quality.

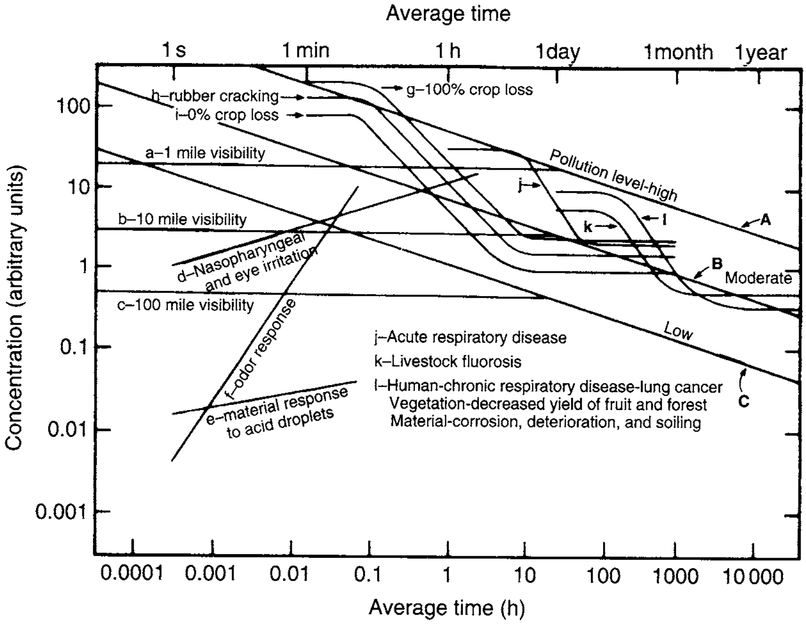

Fig. 8.17. Adverse responses to various pollution levels.

Where the air quality is poor (line A), essentially all the adverse effects displayed will occur. Where the air quality is good (line C), most of the intermediate and long-term adverse effects displayed will not occur. Where the air quality is between good and poor, some of the intermediate and long-term adverse effects will occur, but in an attenuated form compared with those of poor air quality. These concepts will be referred to later in this text when air quality standards are discussed.

D. Air Quality Indices

Air quality indexes (AQIs) have been devised for categorizing the air quality measurements of several individual pollutants by one composite number. The index used by the US Environmental Protection Agency (EPA) as authorized by Section 319 of the Clean Air Act is called the *Pollutant Standards Index* (PSI). In July 1999, the EPH replaced the PSI with the AQI (Table 8.9). Comparable values for international standards are shown in Table 8.10.

The changes from the PSI to the AQI include a new category "unhealthy for sensitive groups;" new breakpoints for the ozone (O_3) sub-index in terms of 8-h average O_3 concentrations, a new sub-index for fine particulate matter ($PM_{2.5}$), and conforming changes to the sub-indices for coarse particulate matter (PM_{10}), carbon monoxide (CO), and sulfur dioxide (SO_2).

The AQI is designed to convey information to the public regarding daily air quality and its associated health risks. The scientific understanding of pollutants, especially particulate matter and O_3, has increased steadily. This is reflected in the National Ambient Air Quality Standards (NAAQS) promulgated in 1997. In particular, much more is now known about nature of the relationships between exposure to ambient concentrations of these pollutants and the health effects likely to be experienced, especially near the level of the NAAQS. These criteria pollutants have no threshold below which health effects are not likely to occur. Rather, there appears to be a continuum of effects potentially extending down to ambient background levels.

Sensitivity varies by pollutant. Thus, when the AQI exceeds 100, the sensitive groups of concern to be at greatest risk include:

- *Ozone*: Children and people with asthma.
- *$PM_{2.5}$*: People with respiratory or heart disease, the elderly and children.
- *PM_{10}*: People with respiratory disease.
- *Carbon monoxide*: People with heart disease.
- *Sulfur dioxide*: People with asthma.
- *Nitrogen dioxide*: Children and people with respiratory disease.

The precautionary statements for the NAAQS pollutants are shown in Table 8.11.

TABLE 8.9

AQI for Criteria Air Pollutants

	Air Quality Index (AQI)						
Category	Good	Moderate	Unhealthy for sensitive groups[a]	Unhealthy	Very unhealthy	Hazardous	
Index value	0–50	51–100	101–150	151 - 200	201–300	301–400	401–500
Pollutant			Concentration ranges				
Carbon monoxide (ppm)	0–4.4	4.5–9.4	9.5–12.4	12.5–15.4	15.5–30.4	30.5–40.4	40.5–50.4
Nitrogen dioxide (ppm)	—	—	—	—	0.65–1.24	1.25–1.64	1.65–2.04
Ozone (average concentration for 1 h in ppm)	—	—	0.125–0.164	0.165 - 0.204	0.205–0.404	0.405–0.504	0.505–0.604
Ozone (average concentration for 8 h in ppm)	0–0.064	0.065–0.084	0.085–0.104	0.105–0.124	0.125–0.374	—	—
PM$_{2.5}$ (μg m^{-3})	0–15.4	15.5–40.4	40.5–65.4	65.5–150.4	150.5–250.4	250.5–350.4	350.5–500.4
PM$_{10}$ (μg m^{-3})	0–54	55–154	155–254	255–354	355–424	425–504	505–604
Sulfur dioxide (ppm)	0–0.034	0.035–0.144	0.145–0.224	0.225–0.304	0.305–0.604	0.605–0.804	0.805–1.004

[a] Each category corresponds to a different level of health concern. The six levels of health concern and what they mean are:

- "Good": The AQI value for your community is between 0 and 50. Air quality is considered satisfactory, and air pollution poses little or no risk.
- "Moderate": The AQI for your community is between 51 and 100. Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people. For example, people who are unusually sensitive to ozone may experience respiratory symptoms.
- "Unhealthy for Sensitive Groups": When AQI values are between 101 and 150, members of sensitive groups may experience health effects. This means they are likely to be affected at lower levels than the general public. For example, people with lung disease are at greater risk from exposure to ozone, while people with either lung disease or heart disease are at greater risk from exposure to particle pollution. The general public is not likely to be affected when the AQI is in this range.
- "Unhealthy": Everyone may begin to experience health effects when AQI values are between 151 and 200. Members of sensitive groups may experience more serious health effects.
- "Very unhealthy: AQI values between 201 and 300 trigger a health alert, meaning everyone may experience more serious health effects.
- "Hazardous": AQI values over 300 trigger health warnings of emergency conditions. The entire population is more likely to be affected.

Source: US Environmental Protection Agency.

TABLE 8.10

WHO Air Quality Guidelines (AQGs) for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide

	PM$_{10}$ (μg m^{-3})	PM$_{2.5}$ (μg m^{-3})	Basis for the selected level
Iinterim target-1 (IT-1)	70	35	These levels are associated with about a 15% higher long-term mortality risk relative to the AQG level
Interim target-2 (IT-2)	50	25	In addition to other health benefits, these levels lower the risk of premature mortality by approximately 6% (2–11%) relative to the IT-1 level
Interim target-3 (IT-3)	30	15	In addition to other health benefits, these levels reduce the mortality risk by approximately 6% (2–11%) relative to the IT-2 level
AQG	20	10	These are the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to PM$_{2.5}$

WHO AQGs and interim targets for particulate matter[a]: 24-h concentrations[b]

	PM$_{10}$ (μg m^{-3})	PM$_{2.5}$ (μg m^{-3})	Basis for the selected level
Interim target-1 (IT-1)	150	75	Based on published risk coefficients from multicentre studies and meta-analyzes (about 5% increase of short-term mortality over the AQG value)
Interim target-2 (IT-2)	100	50	Based on published risk coefficients from multicentre studies and meta-analyzes (about 2.5% increase of short-term mortality over the AQG value)
Interim target-3 (IT-3)[c]	75	37.5	Based on published risk coefficients from multicentre studies and meta-analyzes (about 1.2% increase in short-term mortality over the AQG value)
AQG	50	25	Based on relationship between 24-h and annual PM levels

WHO AQG and interim target for ozone: 8-h concentrations

	Daily maximum 8-h mean (μg m^{-3})	Basis for the selected level
High levels	240	Significant health effects; substantial proportion of vulnerable populations affected
Interim target-1 (IT-1)	160	Important health effects; does not provide adequate protection of public health. Exposure to this level of ozone is associated with: • Physiological and inflammatory lung effects in healthy exercising young adults exposed for periods of 6.6 h

(*continued*)

TABLE 8.10 (*Continued*)

	Daily maximum 8-h mean ($\mu g\,m^{-3}$)	Basis for the selected level
		• Health effects in children (based on various summer camp studies in which children were exposed to ambient ozone levels) • An estimated 3–5% increase in daily mortality[d] (based on findings of daily time-series studies)
AQG	100	Provide adequate protection of public health, though some health effects may occur below this level. Exposure to this level of ozone is associated with: • An estimated 1–2% increase in daily mortality[d] (based on findings of daily time-series studies) • Extrapolation from chamber and field studies based on the likelihood that real-life exposure tends to be repetitive and chamber studies exclude highly sensitive or clinically compromised subjects, or children • Likelihood that ambient ozone is a marker for related oxidants

WHO AQGs for nitrogen dioxide: annual mean

	Annual mean ($\mu g\,m^{-3}$)	
AQG	40	Recent indoor studies have provided evidence of effects on respiratory symptoms among infants at NO_2 concentrations below 40 $\mu g\,m^{-3}$. These associations cannot be completely explained by co-exposure to PM, but it has been suggested that other components in the mixture (such as organic carbon and nitrous acid vapor) might explain part of the observed association

WHO AQGs for nitrogen dioxide: 1-h mean

	1-h mean ($\mu g\,m^{-3}$)	
AQG	200	Epidemiological studies have shown that bronchitic symptoms of asthmatic children increase in association with annual NO_2 concentration, and that reduced lung function growth in children is linked to elevated NO_2 concentrations within communities already at current North American and European urban ambient air levels. A number of recently published studies have demonstrated that NO_2 can have a higher spatial variation than other traffic-related air pollutants, for example, particle mass. These studies also found adverse effects on the health of children living in metropolitan areas characterized by higher levels of NO_2 even in cases where the overall city-wide NO_2 level was fairly low. Since the existing WHO AQG short-term NO_2 guideline value of 200 m^{-3}(1-h) has not been challenged by more recent studies, it is retained

(*continued*)

TABLE 8.10 (*Continued*)

WHO AQGs and interim targets for SO_2: 24-h and 10-min concentrations

	24-h average ($\mu g\, m^{-3}$)	10-min average ($\mu g\, m^{-3}$)	Basis for the selected level
Interim target-1 (IT-1)[e]	125	—	
Interim target-2 (IT-2)	50	—	Intermediate goal based on controlling either motor vehicle emissions, industrial emissions and/or emissions from power production. This would be a reasonable and feasible goal for some developing countries (it could be achieved within a few years) which would lead to significant health improvements that, in turn, would justify further improvements (such as aiming for the AQG value)
AQG	20	500	

[a] The use of $PM_{2.5}$ guideline value is preferred.

[b] 99th percentile (3 days per year).

[c] For management purposes. Based on annual average guideline values precise number to be determined on basis of local frequency distribution of daily means. The frequency distribution of daily $PM_{2.5}$ or PM_{10} values usually approximates to a log-normal distribution.

[d] Deaths attributable to ozone. Time-series studies indicate an increase in daily mortality in the range of 0.3–0.5% for every $10\,\mu g\, m^{-3}$ increment in 8-h ozone concentrations above an estimated baseline level of $70\,\mu g\, m^{-3}$.

[e] Formerly the WHO Air Quality Guideline (WHO, 2000).

Source: World Health Organization. 2006. Report No. WHO/SDE/PHE/OEH/06.02.

TABLE 8.11

Cautionary Statements for Criteria Air Pollutants in the United States

Index values	Levels of health concern	Cautionary statements[a]			
		Ozone	Particulate matter	Carbon monoxide	Sulfur dioxide
0–50	Good	None	None	None	None
51–100[a]	Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion outdoors	Unusually sensitive people should consider reducing prolonged or heavy exertion	None	People with asthma should consider reducing exertion outdoors
101–150	Unhealthy for sensitive groups	Active children and adults, and people with lung disease, such as asthma, should reduce prolonged or heavy exertion outdoors	People with heart or lung disease, older adults, and children should reduce prolonged or heavy exertion	People with heart disease, such as angina, should reduce heavy exertion and avoid sources of CO, such as heavy traffic	Children, asthmatics, and people with heart or lung disease should reduce exertion outdoors
151–200	Unhealthy	Active children and adults, and people with lung disease, such as asthma, should avoid prolonged or heavy exertion outdoors. Everyone else, especially children, should reduce prolonged or heavy exertion outdoors	People with heart or lung disease, older adults, and children should avoid prolonged or heavy exertion. Everyone else should reduce prolonged or heavy exertion	People with heart disease, such as angina, should reduce moderate exertion and avoid sources of CO, such as heavy traffic	Children, asthmatics, and people with heart or lung disease should avoid outdoor exertion. Everyone else should reduce exertion outdoors

(continued)

TABLE 8.11 (*Continued*)

Index values	Levels of health concern	Cautionary statements[a]			
		Ozone	Particulate matter	Carbon monoxide	Sulfur dioxide
201–300	Very unhealthy	Active children and adults, and people with lung disease, such as asthma, should avoid all outdoor exertion. Everyone else, especially children, should avoid prolonged or heavy exertion outdoors	People with heart or lung disease, older adults, and children should avoid all physical activity outdoors. Everyone else should avoid prolonged or heavy exertion	People with heart disease, such as angina, should avoid exertion and sources of CO, such as heavy traffic	Children, asthmatics, and people with heart or lung disease should remain indoors. Everyone else should avoid exertion outdoors
301–500	Hazardous	Everyone should avoid all physical activity outdoors	People with heart or lung disease, older adults, and children should remain indoors and keep activity levels low. Everyone else should avoid all physical activity outdoors	People with heart disease, such as angina, should avoid exertion and sources of CO, such as heavy traffic. Everyone else should reduce heavy exertion	

[a] Nitrogen dioxide can cause respiratory problems in children and adults who have respiratory diseases, such as asthma. The AQI for nitrogen dioxide is not included here because ambient nitrogen dioxide concentrations in the US have been below the national air quality standard for the past several years. These concentrations are sufficiently low so as to pose little direct threat to human health. Nitrogen dioxide, however, is a concern because it plays a significant role in the formation of tropospheric ozone, particulate matter, haze, and acid rain.

As concentrations increase, the proportion of people prone to experience health effects and the seriousness of these effects are expected to increase. Thus, the 1997 standards were intended to include an ample margin of safety (as required by Section 109(b) of the Clean Air Act Amendments. The margin includes special concern about protection the health of sensitive individuals. However, they were not considered risk free and exposures to ambient concentrations just below the numerical level of the standards may be problematic for the most sensitive individuals. On the other hand, exposures to levels just above the NAAQS are not expected to be associated with health concerns for most healthy individuals. Such is the complicated nature of individual response to air pollutants, and one of the objectives of the revised index is to provide sufficient information to allow sensitive people to avoid unhealthy exposures.

REFERENCES

1. Samet, J. M., and Spengler, J. D. (eds.), *Indoor Air Pollution: A Health Perspective.* Johns Hopkins University Press, Baltimore, MD, 1991.
2. *Environmental Protection Agency Air Quality Index Reporting,* 40 CFR Port 58, Final Rule, August 4, 1999.

SUGGESTED READING

Benedick, R. E., *Ozone Diplomacy: New Directions in Safeguarding the Planet.* Harvard University Press, Cambridge, MA, 1991.

Brooks, B. O., and Davis, W. F., *Understanding Indoor Air Quality.* CRC Press, Boca Raton, FL, 1992.

Council on Environmental Quality, Annual Reports, Washington, DC, 1984–1992.

QUESTIONS

1. How does the range of concentrations of air pollutants of concern to the industrial hygienist differ from that of concern to the air pollution specialist? To what extent are air sampling and analytical methods in factories and in the ambient air the same or different?
2. Using the data in Fig. 8.3, draw the variation in concentration over the 6-h period as it would appear using sampling and analytical procedures which integrate the concentrations arriving at the receptor over 30 min and 2 h, respectively.
3. Sketch the appearance of a stripchart record measuring one pollutant for a week to show the weekday–weekend cycle.
4. Draw a chart showing the most probable trend of the concentration of airborne particles of horse manure in the air of a large midwestern US city from 1850 to 1950.
5. Describe an air quality measurement system used to assess the levels and types of aeroallergens.
6. Using the data of Fig. 8.15, determine the frequency with which a 30-min average SO_2 concentration of 0.2 ppm would probably have been exceeded at site 26428007 HO1 in St. Louis, Missouri in 1980.
7. Prepare a table describing air quality levels in your community, or in the nearest community to you that has such data available.
8. If you were to prepare a figure representing the relationship between air quality levels and the effects caused by these levels, what changes would you make in Fig. 8.17?
9. Discuss the extent and usefulness of dissemination by the media of the AQI values in the communities in which you have lived.
10. What do these findings tell you about the source strength of carbonyls shown in Tables 8.1 and 8.2 and Figures 8.1 and 8.2? How and why do you think these source strengths differ for various carbonyls? What actions and controls would you recommend to reduce exposures to each of these carbonyls?