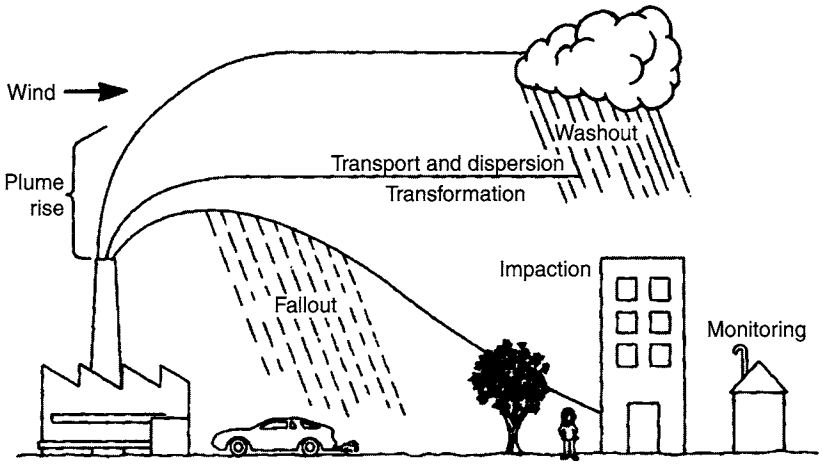
# 20

# *The Meteorological Bases of Atmospheric Pollution*

Air pollutants reach receptors by being transported and perhaps transformed in the atmosphere (Fig. 20.1). The location of receptors relative to sources and atmospheric influences affect pollutant concentrations, and the sensitivity of receptors to these concentrations determines the effects. The location, height, and duration of release, as well as the amount of pollutant released, are also of importance. Some of the influences of the atmosphere on the behavior of pollutants, primarily the large-scale effects, are discussed here, as well as several effects of pollutants on the atmosphere.

## I. VENTILATION

If air movement past a continuous pollutant source is slow, pollutant concentrations in the plume moving downwind will be much higher than they would be if the air were moving rapidly past the source. If polluted air continues to have pollution added to it, the concentration will increase. Generally, a source emits into different volumes of air over time. However, there can be a buildup of concentration over time even with significant air motion if there are many sources.




| Source | Atmosphere | Receptor |
|---|---|---|
| Location | Trasport<br>wind direction<br>local circulations | Location |
| Configuration | Dilution<br>wind speed | Monitoring |
| Emissions time<br>and duration | Dispersion<br>turbulence | Sensitivity plants<br>(weather related)<br>humans |
| Characteristics<br>height volume flow<br>temperature | Transformation<br>chemical physical | Removal<br>fallout deposition<br>washout impaction |

**Fig. 20.1.** The atmosphere's role in air pollution.

Low- and high-pressure systems have considerably different ventilation characteristics. Air generally moves toward the center of a low (Fig. 20.2) in the lower atmosphere, due in part to the frictional turning of the wind toward low pressure. This convergence causes upward vertical motion near the center of the low. Although the winds very near the center of the low are generally light, those away from the center are moderate, resulting in increased ventilation rates. Note the increased wind in the area to the west of the low in Fig. 20.2. Low-pressure systems generally cover relatively small areas (although the low-pressure system shown in Fig. 20.2 covers an extensive area) and are quite transient seldom remaining the same at a given area for a significant period of time. Lows are frequently accompanied by cloudy skies, which may cause precipitation. The cloudy skies minimize the variation in atmospheric stability from day to night. Primarily because of moderate horizontal wind speeds and upward vertical motion, ventilation (i.e. total air volume moving past a location) in the vicinity of low-pressure systems is quite good.

High-pressure systems are characteristically the opposite of lows. Since the winds flow outward from the high-pressure center, subsiding air from higher in the atmosphere compensates for the horizontal transport of mass.

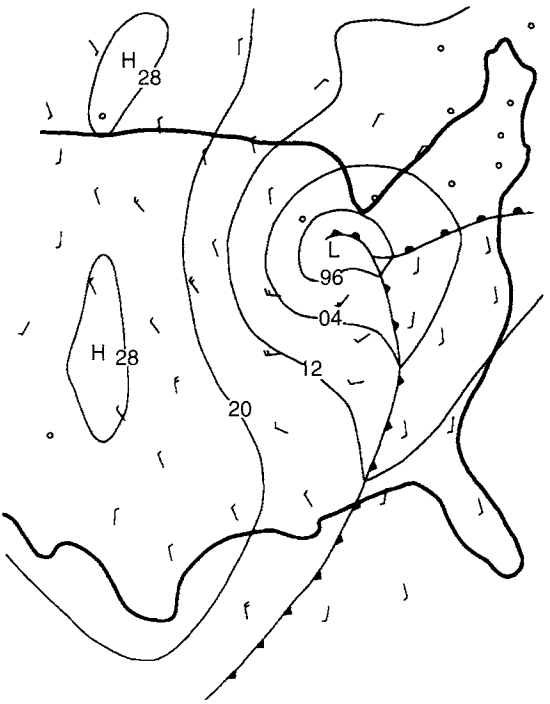



**Fig. 20.2.** Surface chart for 06Z Friday, November 20, 1981. Contours are isobars of atmospheric pressure; 12 is 1012 mb. Line with triangles, cold front; line with semicircles, warm front; line with both triangles and semicircles, an occluded front (a cold front that has caught up with a warm front). Wind direction is with the arrow; wind speed is 10 knots for 1 barb, 5 knots for one-half barb. Small station circles indicate calm. H, center of high pressure; L, center of low pressure.

This sinking air causes a subsidence inversion. Partially because of the subsiding vertical motion, the skies are usually clear, allowing maximum radiation—incoming during the day and outgoing at night—causing extremes of stability; there is instability during the day and stability at night, with frequent radiation inversions. Highs generally occupy large areas, and although they are transient, they are usually slow-moving. Winds over large areas are generally light; note the winds to the south of the high in the lower left corner of Fig. 20.2. Thus, the ventilation in the vicinity of high-pressure systems is generally much less than that of lows.

## II. STAGNATION

At times the ventilation rate becomes very low. Such a lack of air motion usually occurs in the weak pressure gradient near the center of an anticyclone (i.e. of a high). If the high has a warm core, there is likely to be very little air movement near the center, i.e., stagnation. Under such circumstances, winds are very light. Skies are usually cloudless, contributing to the formation of surface-based radiation inversions at night. Although the clear skies contribute to

instability in the daytime, the depth of the unstable layer (i.e. mixing height) may be severely limited due to the subsidence inversion over the high.

The mixing height at a given time may be estimated by use of the morning radiosonde ascent plotted on a thermodynamic chart. The surface temperature at the given time is plotted on the diagram. If a dry adiabat is drawn through this temperature, the height aboveground at the point where this dry adiabat intersects the morning sounding is the mixing height for that time. The mixing height for the time of maximum temperature is the maximum mixing height. Use of this sounding procedure provides an approximation because it assumes that there has been no significant advection since the time of the sounding.

## III. METEOROLOGICAL CONDITIONS DURING HISTORIC POLLUTION EPISODES

### A. Meuse Valley, Belgium

During the period December 1–5, 1930, an intense fog occupied the heavily industrialized Meuse Valley between Liege and Huy (about 24 km) in eastern Belgium [1]. Several hundred persons had respiratory attacks primarily beginning on the 4th and 63 persons died on the 4th and 5th after a few hours of sickness. On December 6 the fog dissipated; the respiratory difficulties improved and, in general, rapidly ceased.

The fog began on December 1 under anticyclonic conditions. What little air motion occurred was from the east, causing air to drift upvalley, moving smoke from the city of Liege and the large factories southwest of it into the narrow valley. The valley sides extend to about 100 m, and the width of the valley is about 1 km. A temperature inversion extended from the ground to a height of about 90 m, transforming the valley essentially into a tunnel deeper than the height of the stacks in the valley, which were generally around 60 m. Much of the particulate matter was in the 2–6 μm range. The fog was cooled by radiation from the top and warmed by contact with the ground. This caused a gentle convection in the "tunnel," mixing the pollutants uniformly and resulting in nearly uniform temperature with height.

The symptoms of the first patients began on the afternoon of December 3 and seemed to occur simultaneously along the entire valley. Deaths took place only on December 4 and 5, with the majority at the Liege end of the valley. Those affected were primarily elderly persons who had lung or heart problems. However, some previously healthy persons were among the seriously ill. There were no measurements of pollutants during the episode, but the five Liege University professors who participated in the subsequent inquiry indicated that part of the sulfur dioxide was probably oxidized to sulfuric acid.

Roholm [2], in discussing the episode, noted that 15 of the 27 factories in the area were capable of releasing gaseous fluorine compounds and suggested that the release of these compounds was of significance.

During the 30 years prior to the episode, fogs lasting for more than 3 days had occurred only five times, always in the winter, in 1901, 1911, 1917, 1919, and 1930. Some respiratory problems were also noted in 1911. Industrial activity was at a low level in 1917 and 1919.

It is prophetic that Firket [1], in speaking about public anxiety about potential catastrophes, said, "This apprehension was quite justified, when we think that proportionately, the public services of London, for example, might be faced with the responsibility of 3200 sudden deaths if such phenomenon occurred there". Indeed in 1952, such a catastrophe occurred (see Section III, C).

## B. Donora, Pennsylvania

A severe episode of atmospheric pollution occurred in Donora, Pennsylvania, during the period October 25–31, 1948 [3]. Twenty persons died, 17 of them within 14 h on October 30.

During this period, a polar high-pressure area remained nearly stationary, with its center in the vicinity of northeastern Pennsylvania. This caused the regional winds, both at the ground and through the lowest layers, to be extremely light. Donora is southeast of Pittsburgh and is in the Monongahela River valley. Cold air accumulated in the bottom of the river valley and fog formed, which persisted past midday for 4 consecutive days. The top of the fog layer has a high albedo and reflects solar radiation, so that only part of the incoming radiation is available to heat the fog layer and eliminate it (Fig. 20.3(a)). During the night, longwave radiation leaves the top of the fog layer, further cooling and stabilizing the layer (Fig. 20.3(b)). Wind speeds at Donora were less than 3.1 m $s^{-1}$ (7 miles $h^{-1}$) from the surface up to 1524 m (5000 ft) for 3 consecutive days, so that pollutants emitted into the air within the valley were not transported far from their point of emission. Maximum temperatures at Donora at an elevation of 232 m (760 ft) mean sea level were considerably lower than those at the Pittsburgh airport, elevation 381 m (1250 ft), indicating the extreme vertical stability of the atmosphere. In the

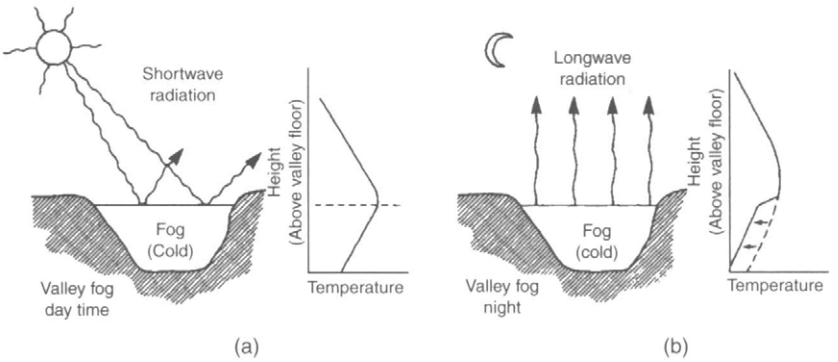



**Fig. 20.3.** Dense fog maintaining stability in a valley. It reflects short-wave radiation during the day and radiates heat from the top of the fog at night. *Source*: Adapted from Schrenk *et al.* [3].

vicinity of Donora there were sources of sulfur dioxide, particulate matter, and carbon monoxide. Previous recorded periods of stagnation had occurred in Donora in October 5–13, 1923 and October 7–18, 1938.

## C. London, England

A dense 4-day fog occurred in London and its surroundings during December 5–9, 1952 [4, 5]. The fog began as the area came under the influence of an anticyclone approaching from the northwest early on December 5. This system became stationary, so that there was almost no wind until milder weather spread into the area from the west on December 9. Temperatures remained near freezing during the fog. The visibility was unusually restricted, with a 4-day average of less than 20 m over an area approximately 20 by 40 km and of less than 400 m over an area 100 by 60 km. The density of the fog was enhanced by the many small particles in the air available for condensation of fog droplets. The result was a very large number of very small fog droplets, more opaque and persistent than fog formed in cleaner air. The depth of the fog layer was somewhat variable, but was generally 100 m or less.

Measurements of particulate matter less than approximately 20 $\mu$m in diameter and of sulfur dioxide were made at 12 sites in the greater London area. The measurements were made by pumping air through a filter paper and then through a hydrogen peroxide solution. The smoke deposit on the filter was analyzed by reflectometer; the sulfur dioxide was determined by titrating the hydrogen peroxide with standard alkali, eliminating interference by carbon dioxide, Using the sampling procedure, sulfur dioxide existing as a gas and dissolved in fine fog droplets was measured. Any sulfur dioxide associated with larger fog droplets or adsorbed on particles collected on the filter would not be measured.

Smoke concentrations ranged from 0.3 to more than 4 mg $m^{-3}$. Daily means of the sampling stations are shown in Fig. 20.4. Sulfur dioxide measurements ranged from less than 0.1 ppm (260 $\mu$g $m^{-3}$) to 1.34 ppm (3484 $\mu$g $m^{-3}$). Also, 4 of the 11 stations had at least one daily value in excess of 1 ppm, and 9 of the 11 stations had at least one daily value in excess of 0.5 ppm. Compare these levels to the US primary standard for sulfur dioxide, which is a maximum 24-h concentration of 365 $\mu$g $m^{-3}$ (0.14 ppm), not to be exceeded more than once per year. Daily means are shown in Fig. 20.4. The smoke and $SO_2$ means rose and later decreased in parallel. Daily concentrations of smoke averaged over all stations rose to about five times normal and sulfur dioxide to about six times normal, peaking on December 7 and 8, respectively. In addition to the daily measurements at 12 sites, monthly measurements at 117 sites were made using lead peroxide candles. This allowed determination of the spatial pattern. The December 1952 concentrations were about 50% higher than those of December 1951.

From the commencement of the fog and low visibility, many people experienced difficulty breathing, the effects occurring more or less simultaneously over a large area of hundreds of square kilometers. The rise in the number of deaths (Fig. 20.4) paralleled the mean daily smoke and sulfur

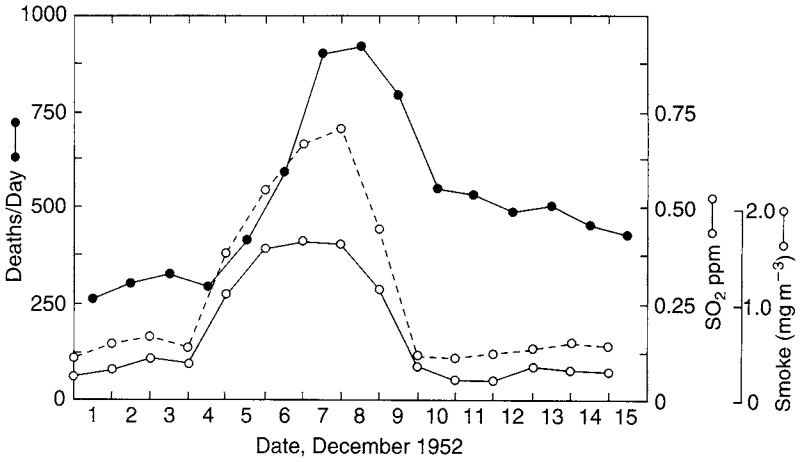



**Fig. 20.4.** Daily air pollution ($SO_2$ and smoke) and deaths during the 1952 London episode. *Source*: Adapted from Wilkins [4].

dioxide concentrations; daily deaths reached a peak on December 8 and 9, with many of them related to respiratory troubles. Although the deaths decreased when the concentrations decreased, the deaths per day remained considerably above the pre-episode level for some days. Would most of the persons who died have died soon afterward anyway? If this were the case, a below-normal death rate would have occurred following the episode. This situation did not seem to exist, but detailed analysis was complicated by increased deaths in January and February 1953 which were attributed primarily to an influenza outbreak.

Those who analyzed these excess deaths (the number of deaths above the normal number for each calendar day) believed that the level of sulfur dioxide was not near the toxic limit of 10 ppm necessary to affect healthy persons. They attributed the deaths to the synergistic effect of fine particles and sulfur dioxide combined. They believed that considerable sulfuric acid mist was formed from the oxidation of sulfur dioxide, but since no measurements were made, its amount was speculative.

## D. Similarities of the Three Episodes

In the Meuse Valley, Donora, and London episodes, the areas were influenced by high pressure with nearly nonexistent surface air motion. Surface inversions caused the condensation of fog, which, once formed, persisted throughout the day, even during mid-afternoon. In each case the fog layer was relatively shallow, extending only about 100 m. The persistence of the fog past the third day and the lack of any air transport out of the region, as well as the existence of considerable emissions of pollutants, seem to separate these episodes from more common meteorological occurrences. Both the Meuse Valley and Donora had topography constraining the volume in which the pollutants were confined. This constraint apparently resulted from

the lack of any transport wind in the London 1952 episode. Measurements of pollutant concentrations were made only in London.

### E. Other Episodes

A number of somewhat less severe episodes are discussed in Goldsmith and Friberg [6]. Mention of the more important ones follows.

An air pollution episode responsible for approximately 300 excess deaths occurred in London between November 26 and December 1, 1948. Concentrations of smoke and sulfur dioxide were 50–70% of the values during the 1952 episode.

An accident complicated by fog, weak winds, and a surface inversion occurred in Poza Rica, Mexico, in the early morning of November 24, 1950, when hydrogen sulfide was released from a plant for the recovery of sulfur from natural gas. There were 22 deaths, and 320 persons were hospitalized.

In November and December 1962, a number of air pollution episodes occurred in the Northern Hemisphere. In London a fog occurred during the period December 3–7, with sulfur dioxide as high as during the 1952 episode, but with particulate concentrations considerably lower due to the partial implementation of the 1956 British Clean Air Act. Excess deaths numbered 340. High pollution levels were measured in the eastern United States between November 27 and December 5, 1962, notably in Washington, DC, Philadelphia, New York, and Cincinnati. Between December 2 and 7 elevated pollution levels were found in Rotterdam; Hamburg, Frankfurt, and the Ruhr area; Paris; and Prague. Pollution levels were high in Osaka between December 7 and 10, and mortality studies, which were under way, indicated 60 excess deaths.

### F. Air Pollution Emergencies

Government authorities increasingly are facing emergencies that may require lifesaving decisions to be made rapidly by those on the scene. Of increasing frequency are transportation accidents involving the movement of volatile hazardous materials. A railroad derailment accident of a tank car of liquefied chlorine on February 26, 1978, at Youngtown, Florida, in which seven people died, and an accident in Houston, Texas, involving a truck carrying anhydrous ammonia on May 11, 1976, which also claimed seven lives, are examples. Two potentially dangerous situations involved barges with tanks of chlorine: one which sank in the lower Mississippi River and another which came adrift and came to rest on the Ohio River dam at Louisville, Kentucky; neither resulted in release of material.

Releases of radioactive materials from nuclear power plants have occurred, as at Three-Mile Island, Pennsylvania. In such situations, releases may be sufficient to require evacuation of residents.

Bhopal, India—On December 2, 1984 the contents of a methyl isocyanate (MIC) storage tank at the Union Carbide India plant in Bhopal became hot. Pressure in the tank became high. Nearly everything that could go wrong

did. The refrigerator unit for the tank, which would have slowed the reactions, was turned off. After midnight, when the release valve blew, the vent gas scrubber that was to neutralize the gas with caustic soda failed to work. The flare tower, which would have burned the gas to harmless by-products, was down for repairs. As a result many tons of MIC were released from the tank. The gas spread as a fog-like cloud over a large, highly populated area to the south and east of the plant [7]. The number of fatalities was in excess of 2000 with thousands of others injured. Although little is available in the way of meteorological measurements, it is assumed that winds were quite light and that the atmosphere at this time of day was relatively stable.

Chernobyl, USSR—On April 26, 1986, shortly after midnight local time, a serious accident occurred at a nuclear power plant in Chernobyl in the Ukraine. It is estimated that 4% of the core inventory was released between April 26 and May 6. Quantities of Cs-137 (cesium) and I-131 (iodine) were released and transported, resulting in contamination, primarily by wet deposition of cesium, in Finland, northern Sweden and Norway, the Alps, and the northern parts of Greece. Because of temperatures of several thousand K during the explosion like release, the resulting pollutant cloud is assumed to have reached heights of 2000 m or more. The estimated southeast winds at plume level initially moved the plume toward Finland, northern Sweden, and northern Norway. As winds at plume level gradually turned more easterly and finally north and northwesterly, contaminated air affected the region of the Alps and northern Greece. A number of investigators, including Hass *et al.* [8], modeled the long-range transport including wet and dry removal processes. These attempts were considered quite successful, as radioactivity measurements provided some confirmation of the regions affected. Elevated levels of radioactivity were measured throughout the Northern Hemisphere. Because of the half-life of about 30 years for Cs-137, the contamination will endure.

World Trade Center, New York—On September 11, 2001, terrorists intentionally crashed fully fueled Boeing 767 jets into the twin towers of the heavily populated World Trade Center. The burning fuel, building materials and building contents, as well as the fibers and particles released during the collapse were the source of dangerous gas and particle phase pollutants released throughout the city. In addition to the immediate threat, the fire smoldered for months following the attack, which was a source of a variety of pollutants (see Fig. 10.19).

In such emergencies, it is most important to know the local wind direction at the accident site, so that the area that should be immediately evacuated can be determined. The next important factor is the wind speed, so that the travel time to various areas can be determined, again primarily for evacuation purposes. Both of these can be estimated on-site by simple means such as watching the drift of bubbles released by a bubble machine. It would be well to keep in mind that wind speeds are higher above ground and that wind direction is usually different. In fact, the World Trade Center episode dramatically demonstrated the importance of local meteorology. The wind

directions at Ground Zero were almost always different than that measured at any of the three nearby, major airports. And, the three airports often have meteorological conditions different from one another.

As evacuation is taking place, it is important to determine whether meteorological events will cause a wind direction shift later on, requiring a change in the evacuation scenario. Particularly in coastal areas, or areas of significant terrain, authorities should be alert to a possible change in wind direction in going from night to day or vice versa. Useful advice may be obtained from the nearest weather forecaster, although accurate forecasting of wind direction for specific locations is not easy. Accurate air movement measurements and predictions are a matter of safety, even life and death. Portable meteorological stations have become accurate, precise and reasonably available. These should be deployed during any emergency involving airborne contaminants, or the potential for such.

If the situation is one of potential rather than current release, specific concentrations at various distances and localities may be estimated for various conditions.

## IV. EFFECTS OF POLLUTION ON THE ATMOSPHERE

Pollutant effects on the atmosphere include increased particulate matter, which decreases visibility and inhibits incoming solar radiation, and increased gaseous pollutant concentrations, which absorb longwave radiation and increase surface temperatures. For a detailed discussion of visibility effects (see Chapter 14).

### A. Turbidity

The attenuation of solar radiation has been studied by McCormick and his associates [9, 10] utilizing the Voltz sun photometer, which uses measurements at a wavelength of 0.5 μm. The ratio of ground-level solar intensity at 0.5 μm to extraterrestrial solar intensity can be as high as 0.5 in clean atmospheres but can drop to 0.2–0.3 in polluted areas, indicating that ground-level solar intensity can be decreased as much as 50% by pollution in the air. By making measurements using aircraft at various heights, the vertical extent of the polluted air can be determined. The turbidity coefficient can also be derived from the measurements and used to estimate the aerosol loading of the atmosphere. By assuming a particle size distribution in the size range 0.1–10 μm and a particle density, the total number of particles can be estimated. The mass loading per cubic meter can also be estimated. Because of the reasonable cost and simplicity of the sun photometer, it is useful for making comparative measurements around the world.

### B. Precipitation

Depending on its concentration, pollution can have opposite effects on the precipitation process. Addition of a few particles that act as ice nuclei can

cause ice particles to grow at the expense of supercooled water droplets, resulting in particles large enough to fall as precipitation. An example of this is commercial cloud seeding, with silver iodide particles released from aircraft to induce rain. If too many such particles are added, none of them will grow sufficiently to cause precipitation. Therefore, the effects of pollution on precipitation are not at all straightforward.

There have been some indications, although controversial, of increased precipitation downwind of major metropolitan areas. Urban addition of nuclei and moisture and urban enhancement of vertical motion due to increased roughness and the urban heat island effect have been suggested as possible causes.

### C. Fogs

As mentioned in the previous section, the increased number of nuclei in polluted urban atmospheres can cause dense persistent fogs due to the many small droplets formed. Fog formation is very dependent on humidity and, in some situations, humidity is increased by release of moisture from industrial processes. Low atmospheric moisture content can also occur, especially in urban areas; two causes are lack of vegetation and rapid runoff of rainwater through storm sewers. Also, slightly higher temperatures in urban areas lower the relative humidity.

### D. Solar Radiation

In the early part of this century, the loss of ultraviolet light in some metropolitan areas due to heavy coal smoke was of concern because of the resulting decrease in the production of natural vitamin D which causes the disease rickets. Recently, measurements in Los Angeles smog have revealed much greater decreases in ultraviolet than visible light. This is due to both absorption by ozone of wavelengths less than 0.32 μm and absorption by nitrogen dioxide in the 0.36–0.4 μm range. Heavy smog has decreased ultraviolet radiation by as much as 90%.

## V. REMOVAL MECHANISMS

Except for fine particulate matter (0.2 μm or less), which may remain airborne for long periods of time, and gases such as carbon monoxide, which do not react readily, most airborne pollutants are eventually removed from the atmosphere by sedimentation, reaction, or dry or wet deposition.

### A. Sedimentation (Settling by Gravity)

Particles less than about 20 μm are treated as dispersing as gases, and effects due to their fall velocity are generally ignored. Particles greater than about 20 μm have appreciable settling velocities. The fall velocity of smooth spheres as a function of particle size has been plotted (Fig. 20.5) by Hanna *et al.*

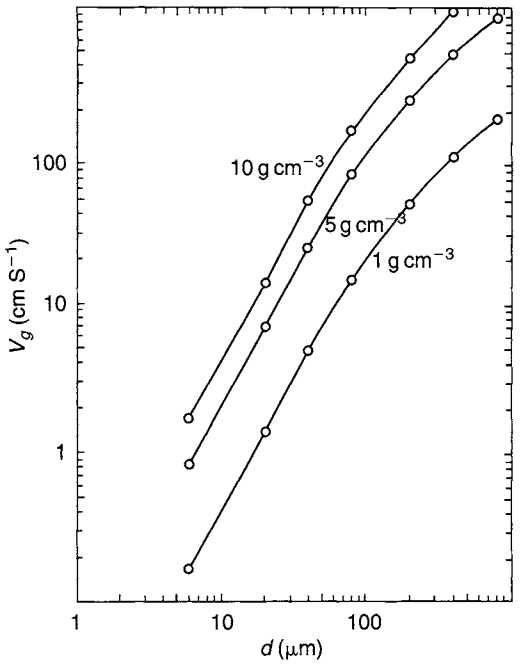



**Fig. 20.5.** Fall velocity of spherical particles as a function of particle diameter and density. *Source*: Adapted from Hanna *et al.* [11].

[11]. Particles in the range 20–100 μm are assumed to disperse approximately as gases, but with their centroid moving downward in the atmosphere according to the fall velocity. This can be accounted for by subtracting $v_g t$ from the effective height of release, where $v_g$ is the gravitational fall velocity of the particles and $t$, in seconds, is $x/u$, where $x$ is downwind distance from the source in m and $u$ is wind speed. This is called the *tilted plume model.* The model may be modified to decrease the strength of the source with distance from the source to account for the particles removed by deposition.

For 20–100 μm particles, the deposition $w$ on the ground is

$$w = v_g \chi(x,y,z) \tag{20.1}$$

where the air concentration $\chi$ is evaluated for a height above ground $z$ of about 1 m.

Particles larger than 100 μm fall through the atmosphere so rapidly that turbulence has less chance to act upon and disperse them. The trajectories of such particles are treated by a ballistic approach.

### B. Reaction (Transformation)

Transformations due to chemical reactions throughout the plume are frequently treated as exponential losses with time. The concentration $\chi(t)$ at

travel time $t$ when pollutant loss is considered compared to the concentration $\chi$ at the same position with no loss is

$$\frac{\chi(t)}{\chi} = \exp -(0.693t/L) \tag{20.2}$$

where $L$ is the half-life of the pollutant in seconds. The half-life is the time required to lose 50% of the pollutant.

## C. Dry Deposition

Although it does not physically explain the nature of the removal process, deposition velocity has been used to account for removal due to impaction with vegetation near the surface or for chemical reactions with the surface. McMahon and Denison [12] gave many deposition velocities in their review paper. Examples (in $\mathrm{cm\,s^{-1}}$) are sulfur dioxide, 0.5–1.2; ozone, 0.1–2.0; iodine, 0.7–2.8; and carbon dioxide, negligible.

## D. Wet Deposition

Scavenging of particles or gases may take place in clouds (rainout) by cloud droplets or below clouds (washout) by precipitation. A scavenging ratio or washout ratio $W$ can be defined as

$$W = \frac{k\rho}{\chi} \tag{20.3}$$

where $k$ is concentration of the contaminant in precipitation in $\mu\mathrm{g\,g^{-1}}$; $\rho$ is the density of air, approximately $1200\,\mathrm{g\,m^{-3}}$; and $\chi$ is the concentration, $\mu\mathrm{g\,m^{-3}}$, of

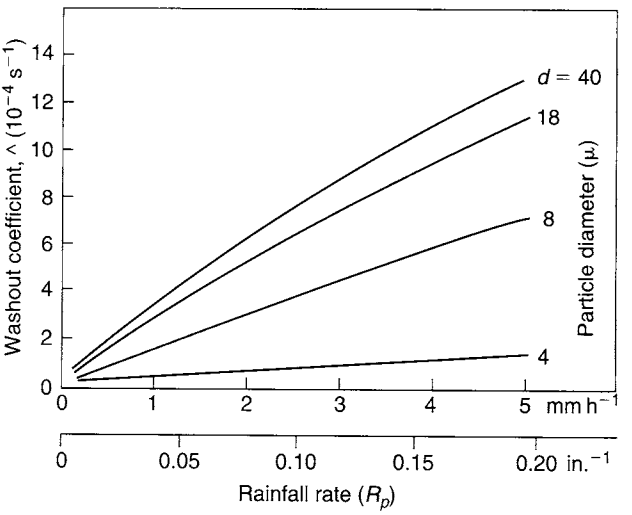



**Fig. 20.6.** Typical values of the washout coefficient as a function of rainfall rate and particle diameter. *Source*: After Engelmann [13].

the pollutant in the air prior to scavenging. McMahon and Denison [12] gave a table of field observations of washout ratios. The values for various pollutants range from less than 100 to more than 4000. These values are a function of particle size and rainfall intensity, generally decreasing with the latter and increasing with the former.

Scavenging may also be considered as an exponential decay process:

$$\chi(t) = \chi(0)e^{-\Lambda t} \tag{20.4}$$

where $\chi(t)$ is the concentration in $\mu g\, m^{-3}$ at time $t$ in seconds, $\chi(0)$ is the concentration at time 0, and $\Lambda$ is the scavenging or washout coefficient, $s^{-1}$. Figure 20.6, after Engelmann [13], gives the washout coefficient as a function of particle diameter and rainfall rate. McMahon and Denison [12] give a table of field measurements of scavenging coefficients. This same concept can be applied to gaseous pollutants. Fewer data are available for gases. Values ranging from $0.4 \times 10^{-5}$ to $6 \times 10^{-5}$ for $SO_2$ are given by McMahon and Denison [12] and compare reasonably well with an equation for $SO_2$ by Chamberlain [14]:

$$\Lambda = 10 \times 10^{-5} J^{0.53} \tag{20.5}$$

where $J$ is rainfall intensity in $mm\, h^{-1}$.

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## QUESTIONS

1. Characterize the conditions typical of low-pressure systems, particularly as they relate to ventilation.
2. Characterize the conditions typical of high-pressure systems, particularly as they relate to ventilation.
3. What atmospheric characteristics are usually associated with stagnating high-pressure systems?
4. What factors contribute to a high mixing height?
5. Discuss the simularities of the three major episodes of pollution (Meuse Valley, Donora, and London).
6. A railroad tank car has derailed and overturned, and some material is leaking out and apparently evaporating. The car is labeled "Toxic." In order to take appropriate emergency action, which meteorological factors would you consider and how would you assess them?
7. In addition to air pollutants, what meteorological factor has a profound effect on decreasing visibility, and what is the approximate threshold of its influence?
8. What pollution factors may affect precipitation?
9. What is the approximate lowering of the centroid of a dispersing cloud of particles at 2 km from the source whose mass medium diameter is 30 $\mu$m and whose particle density is 1 g cm$^{-3}$ in a 5 m s$^{-1}$ wind?
10. Prior to the onset of rain at the rate of 2.5 mm h$^{-1}$, the average concentration of 10-$\mu$m particles in a pollutant plume is 80 $\mu$g m$^{-3}$. What is the average concentration after 30 min of rain at this rate?