

Chapter 8

LOCAL AIR POLLUTION

8.1 Introduction

Air pollution affects humans more than water pollution. Whereas we can always treat the water before we drink it or use it, the air that we breathe must be clean where we happen to be. Also, air quality tends to be worse in large cities where there are more people and also more traffic and other unnatural emissions to the atmosphere. Figures 8-1 and 8-2 show pictures of two nightmares of the 1950s, each in a large city.

In the face of such terrible situations as those in the 1950s, numerous governments have since responded by legislating air-quality standards, and the result is that air quality is noticeably higher today than it was a few decades ago. In the United States, Congress enacted the Clean Air Act with a series of subsequent amendments (in 1963, 1966, 1970, 1977 and 1990). Most of the early regulations concerned point sources, such as smokestack emissions from power plants, but with time regulations have been gradually extended to encompass distributed sources, chiefly road traffic and, more recently, airport emissions.

In the United States, air-quality legislation sets both emission standards and National Ambient Air Quality Standards (NAAQS). Therefore, both emissions (= source) and the air we breathe (= receptor) are regulated. The NAAQS are divided into two categories: the toxic substances, for which extremely low levels are tolerated, and six so-called *criteria pollutants*, which are chemicals that are not immediately harmful except past a certain concentration and/or after a certain time of exposure. These six criteria pollutants and their corresponding standards are listed in Table 8-1.



Figure 8-1. The Crystal Palace television mast protruding through the top of the so-called “Great London Smog” of December 1952. [Courtesy Fairey Air Surveys.]

<i>Pollutant</i>	<i>Exposure duration</i>	<i>Standard</i>	<i>Cause for concern</i>
CO Carbon monoxide	1 hour	35 ppm	headaches asphyxiation
	8 hours	9 ppm	decreased exercise tolerance angina pectoris
NO ₂ Nitrogen dioxide	1 year	0.053 ppm	aggravation of respiratory disease
SO ₂ Sulfur dioxide	3 hours	0.50 ppm	shortness of breath
	1 day	0.14 ppm	wheezing, odor
	1 year	0.03 ppm	acid precipitation damage to vegetation
O ₃ Ozone	1 hour	0.12 ppm	eye irritation
	8 hours	0.08 ppm	interference with breathing damage to materials and plants
Pb Lead	3 months	1.5 $\mu\text{g}/\text{m}^3$	blood poisoning infant development
PM _{2.5}	24 hours	65 $\mu\text{g}/\text{m}^3$	lung damage
	1 year	15 $\mu\text{g}/\text{m}^3$	
PM ₁₀	24 hours	150 $\mu\text{g}/\text{m}^3$	visibility
	1 year	50 $\mu\text{g}/\text{m}^3$	respiratory disease

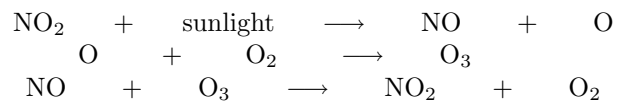
Table 8-1. The six chemicals designated as criteria pollutants by the US Environmental Protection Agency and the corresponding National Ambient Air Quality Standards.



Figure 8-2. Riders of a local message-delivery company in Los Angeles being outfitted with protective gas masks in the fall of 1955.

For particulate matter, one currently distinguishes between particles larger than $10\ \mu\text{m}$ (noted PM_{10}), which mostly impact visibility, and particles larger than $2.5\ \mu\text{m}$ (noted $\text{PM}_{2.5}$), which create respiratory disorders.

In atmospheric pollution, one needs also to distinguish between *primary pollutants*, those directly emitted, and *secondary pollutants*, those chemically created in the atmosphere from reactions among other pollutants. One example is the conversion of sulfur dioxide (SO_2) into sulfuric acid (H_2SO_4), which causes acid rain. Ground-level ozone (O_3) is another example of a secondary pollutant: There is virtually no emission of ozone to the atmosphere, but ozone can be generated from nitrogen oxides in the process called photochemical fog, for which the key reactions are an excitation by sunlight, the formation of ozone, and a subsequent relaxation to the initial nitrogen oxide, according to:



Problems related to pollutant transport and diffusion in the atmosphere exhibit different characteristics depending on their length and time scales. In some broad way, we can distinguish five types in order of increasing scale, as shown in Table 8-2.

<i>Type</i>	<i>Example</i>	<i>Scales</i>	<i>Physics involved</i>
Local	plume from a factory smokestack	up to 1 km in horizontal several 10 m in vertical fraction of 1 hour	near-ground air layer subject to surface roughness and convection
Urban	smog over Los Angeles	several km in horizontal several 100 m in vertical several hours to days	local winds, atmospheric boundary layer, hills and mountains
Regional	acid rain	several 100 km in horizontal 10 km in vertical several days	weather patterns, cloud patterns
Continental	1986 Chernobyl radioactive fallout	size of a continent troposphere days to weeks	weather patterns
Global	climate change due to greenhouse gases	size of earth troposphere and above decades and beyond	prevailing winds, equator-to-pole gradients

Table 8-2. Classification of situations involving atmospheric transport and fate according to length and time scales.

The present chapter deals with local forms of pollution.

8.2 Atmospheric Stability

Thermal stratification is often observed in the atmosphere, especially over the diurnal cycle. When it occurs, stratification is characterized by colder, denser air sinking below lighter, warmer air. This creates buoyancy forces, which form an obstacle to turbulence and dispersion of contaminants. Whatever the air contains by way of contaminants tends to remain at the level where it is instead of being spread across the vertical. Because of this, it is important to have a measure of stratification. This was done in Chapter 5 for lakes and reservoirs, but it needs to be amended to take into consideration the compressibility of the air in the atmosphere.

The neutral atmosphere

First, we need to understand the state of a well-mixed, neutral atmosphere. This state is not trivial because the higher pressure on the ground compresses the air more than the lower pressure aloft, leading to a decrease of density with height that exists irrespectively of a thermal stratification.

To begin, let us consider a vertically stratified atmosphere with density $\rho(z)$ and at rest, and consider in it a small parcel contained between levels z and $z + dz$, as depicted in Figure 8-3. This parcel is subject to pressure forces on all sides from neighboring air parcels and to its own weight mg . If the cross-section of this parcel is A , its volume is Adz , its mass $m = \rho Adz$ and its weight $mg = \rho g Adz$.

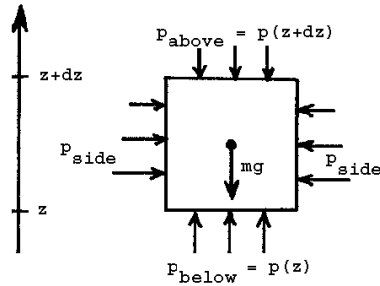


Figure 8-3. A small air parcel and the forces acting on it.

At equilibrium, the upward force from the supporting pressure below is equal to the downward pressure at the top plus the weight:

$$p_{\text{below}}A = p_{\text{above}} + mg,$$

which yields:

$$p(z + dz) - p(z) = -\rho g dz.$$

In differential form, we write:

$$\frac{dp}{dz} = -\rho g. \quad (8.1)$$

In fluid mechanics, this relation is called the *hydrostatic balance*.

Next, we recall the equation of state. The atmosphere is a mixture of gases (78% nitrogen, 21% oxygen and 1% other gases, in dry conditions), collectively called *air*. From a physical point of view, the actual composition does not matter, and within a high degree of accuracy, air can be considered as an ideal gas, with a molecular weight intermediate between that of nitrogen and that of oxygen. So, we can write the following equation linking its pressure p , density ρ and temperature T :

$$p = R\rho T, \quad (8.2)$$

where T must be the absolute temperature (in degrees Kelvin), equal to the temperature in $^{\circ}\text{C} + 273.15$. For air, the constant factor R is $287 \text{ J}/(\text{kg}\cdot\text{K}) = 287 \text{ m}^2/\text{s}^2\cdot\text{K}$.

If we take the z -derivative of this expression, we obtain:

$$\frac{dp}{dz} = R \frac{d\rho}{dz} T + R\rho \frac{dT}{dz}. \quad (8.3)$$

The next and final statement is more subtle. Let us seek the property of a neutral atmosphere, namely one in which air parcels can be exchanged among one another without altering the vertical profile of properties. If a parcel of mass m is moved from level z to a higher level $z + dz$, its pressure

drops and, according to (8.2), so must also its density or temperature or both. Under a decompression, the parcel expands making its pressure do work against surrounding parcels. This work, equal to pressure times change in volume ($p dV$), is spent at a cost to the internal energy ($mC_v T$) of the parcel. Thus, the internal energy of the parcel drops according to:

$$mC_v dT = -p dV.$$

Since density is mass per volume ($\rho = m/V$), a division by m yields:

$$C_v dT = -p d\left(\frac{1}{\rho}\right).$$

Dividing by the incremental height dz and effecting the derivative of $1/\rho$, we obtain:

$$C_v \frac{dT}{dz} = + \frac{p}{\rho^2} \frac{d\rho}{dz}. \quad (8.4)$$

The assumption that the air parcels are interchangeable allows us to consider the preceding changes of temperature and density as those in the vertical in the atmosphere at rest. Equations (8.1), (8.3) and (8.4) form a 3-by-3 system for the three vertical derivatives dp/dz , $d\rho/dz$ and dT/dz . Solving for the temperature gradient dT/dz , we obtain:

$$(C_v + R) \frac{dT}{dz} = -g.$$

Defining $C_p = C_v + R$ for convenience, we arrive at:

$$\frac{dT}{dz} = - \frac{g}{C_p}. \quad (8.5)$$

Thus, the temperature decreases with altitude at a constant rate. This gradient

$$\Gamma = \frac{g}{C_p}, \quad (8.6)$$

is called by meteorologists the *adiabatic lapse rate*. Its value is $(9.81 \text{ m/s}^2)/(1005 \text{ m}^2/\text{s}^2 \cdot \text{K}) = 9.76 \times 10^{-3} \text{ K/m}$, or about 1 degree for every 100 meters.

This drop of temperature with height explains why high mountains are permanently covered with snow and why air is so cold at the altitude where jet planes fly. A lower temperature causes a lower humidity saturation level, and this is why clouds, which consist in fine water droplets, occur at some altitude above the ground.

Thermal stratification

At this point, it is useful to derive again the expression for the natural frequency of oscillations of a parcel in a stratified medium, now accounting for the compressibility of the fluid. For this, consider an air parcel initially at

level z with ambient temperature $T(z)$ and displaced upward slightly by the distance h . Once there, it is subject to a lesser pressure and expands (acquiring a lower density) and loses temperature. The pressure difference is $dp = -\rho gh$, by virtue of (8.1), and the temperature drop is $-gh/C_p$, by virtue of (8.5). If the atmosphere is not in a neutral state, then the ambient temperature $T_a = T(z+h)$ is not equal to the temperature $T_p = T(z) + dT$ acquired by the parcel. In other words, the parcel has adjusted its temperature according to the adiabatic lapse rate but the ambient air does not follow the same rate of temperature decrease with height. The difference is:

$$\begin{aligned} T_a - T_p &= T(z+h) - T(z) + \frac{g}{C_p} h. \\ &\simeq \left(\frac{dT}{dz} + \frac{g}{C_p} \right) h. \end{aligned}$$

Because of this temperature difference, the displaced air parcel experiences a buoyancy force not equal to its own weight and is subject to a net upward force equal to:

$$\begin{aligned} F &= \text{buoyancy force} - \text{weight} \\ &= \rho_a V g - \rho_p V g = (\rho_a - \rho_p) V g \\ &= \left(\frac{p}{RT_a} - \frac{p}{RT_p} \right) V g \\ &= \frac{p}{RT_a T_p} (T_p - T_a) V g \\ &= \rho_p \frac{T_p - T_a}{T_a} V g. \end{aligned}$$

By virtue of Newton's law, this force is equal to the mass times the acceleration:

$$\begin{aligned} m \frac{d^2 h}{dt^2} &= F \\ \rho_p V \frac{d^2 h}{dt^2} &= \rho_p \frac{T_p - T_a}{T_a} V g. \end{aligned}$$

Simplification of this last equation and replacement of the temperature difference by the preceding expression provide:

$$\begin{aligned} \frac{d^2 h}{dt^2} &= g \frac{T_p - T_a}{T_a} \\ &= -\frac{g}{T_a} \left(\frac{dT}{dz} + \Gamma \right) h, \end{aligned} \tag{8.7}$$

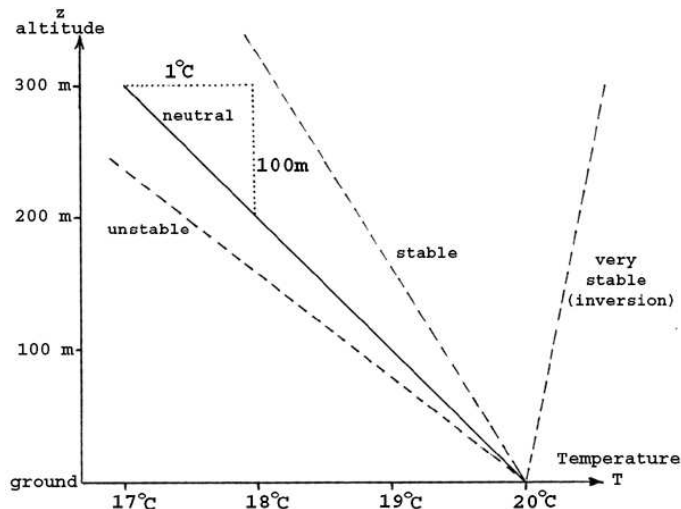


Figure 8-4. The various states of atmospheric stability according to the vertical variation of temperature.

where the adiabatic lapse rate Γ was defined earlier in (8.6).

The discussion now proceeds as for water in lakes. We define

$$N^2 = \frac{g}{T} \left(\frac{dT}{dz} + \Gamma \right), \quad (8.8)$$

where $T(z)$ is the ambient temperature profile, and conclude that the thermal stratification is *stable* if the parcel is drawn back toward its original position, which occurs when $N^2 > 0$, *neutral* if the parcel is at equilibrium at its new location, which occurs when $N^2 = 0$, and *unstable* if the parcel moves further away from its original position, which occurs when $N^2 < 0$. In sum, the redefined N^2 above plays the same role as that defined in (5.6) for lake water.

Since the sign of N^2 depends on the deviation of the ambient temperature gradient dT/dz from the adiabatic lapse rate Γ , we can state:

$$\frac{dT}{dz} < -\Gamma \Rightarrow N^2 < 0 \Rightarrow \text{Unstable atmosphere}$$

$$\frac{dT}{dz} = -\Gamma \Rightarrow N^2 = 0 \Rightarrow \text{Neutral atmosphere}$$

$$\frac{dT}{dz} > -\Gamma \Rightarrow N^2 > 0 \Rightarrow \text{Stable atmosphere.}$$

The last case can be subdivided into two cases depending on the sign of the temperature gradient:

$$-\Gamma < \frac{dT}{dz} \leq 0 \Rightarrow \text{Somewhat stable atmosphere}$$

$$\frac{dT}{dz} > 0 \Rightarrow \text{Very stable atmosphere.}$$

In the first of these last two cases, the temperature decreases with height but not as fast as the adiabatic lapse rate, while in the other, it actually increases with height. This latter case is characterized by air so stable that little ventilation can take place, and, if it occurs near the ground, it creates an uncomfortable situation for people there, especially if there are sources of pollution. Fortunately, such is not usually the case and, for that reason, meteorologists have come to call this situation an *inversion*. The situation is recapitulated in Figure 8-4.

8.3 The Atmospheric Boundary Layer

The diurnal cycle greatly affects the state of the lower atmosphere, with sunlight heating the atmosphere during the day and cooling occurring at night. Because sunlight consists mostly of radiation in the visible spectrum and because air is almost perfectly transparent, the solar radiation penetrates through the atmosphere with little absorption, and most of it is absorbed by the ground surface, which is opaque. This delivers heat to the ground, which then re-radiates it in longer, infrared wavelengths. Being relatively opaque to this other type of radiation, the atmosphere absorbs this second-hand radiation. In effect, therefore, the atmosphere is heated from below, despite the fact that the sun is above!

Heating from below operates similarly to cooling from above, and we can readily apply what we know of seasonal penetrative convection in lakes to the daytime atmosphere: any thermal stratification is gradually eroded during the hours of sun exposure. During the night, the ground surface cools in the absence of sunlight, and this cooling from below creates a thermal stratification that gradually extends upward. Figure 8-5 depicts a typical diurnal cycle of the thermal stratification and convective mixing alternating between night and day. As we can see, there periods of the day when the temperature profile with height can exhibit one or two kinks.

The manner in which temperature varies with height determines zones of stability and instability, which correspond to layers of active mixing and quiet layers (Figure 8-6). Note that an air parcel acquiring speed in an unstable zone, such as parcel 1 in Figure 8-6c will rise, with its temperature dropping according to the adiabatic lapse rate, until it reaches ambient air of temperature equal to itself, which may very well be inside a layer of stability. In other words, a stable layer with thermal stratification can be partially eroded by the mixing occurring across an adjacent zone of instability.

Mixing height

Because the heat source during the day is at ground level, an important characteristic of the temperature profile is the vertical height over which an unstable parcel of air taking off from the ground will rise. The vertical excursion

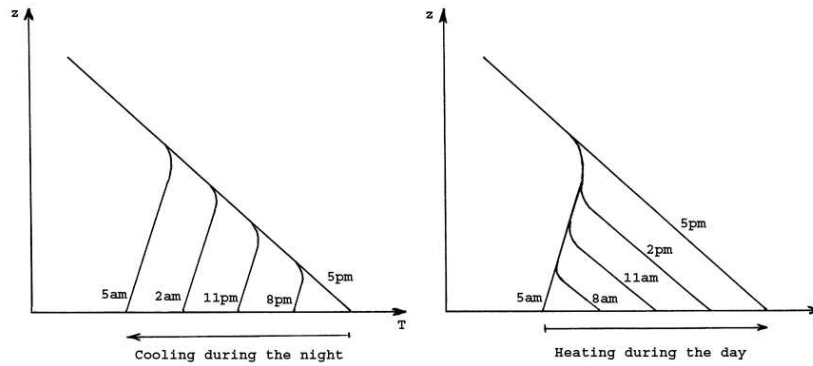


Figure 8-5. Typical variation of the temperature profile over the diurnal cycle. Nighttime cooling generates a progressively thicker inversion, which is gradually eroded in the course of the following day. Sustained convection during the day is usually able to break through the inversion built during the previous night, leading to a neutral atmosphere in the late afternoon.

of such air parcel is called the *mixing height*. Graphically, it is constructed by tracing a line on the temperature–altitude plot from the temperature value at ground level upward with backward slope equal to the adiabatic lapse rate until it intersects the ambient temperature profile, as shown in Figure 8-6c. For pollution sources on the ground, such as road traffic, this height determines how high the pollutants will mix at that time of day.

Because of the diurnal cycle (recall Figure 8-5), the mixing height varies over the 24-hour period. It is inexistent during the night because of the ground inversion, unless there is another source of heat, such as an urban area, then develops starting at sunrise to increase steadily during the day hours. When the sun sets, it collapses quite dramatically. An example is provided in Figure 8-7, which traces the diurnal evolution of the mixing height over the city of Schenectady, in the state of New York, during the summer of 1994. By reaching over 1500 m, this mixing height is relatively large, and the reason is that it was measured in the heat of the summer. Generally, mixing heights reach several hundred meters during the morning and may attain 1000 m at their peak in late afternoon.

8.4 Smokestack Plumes

Various types of plumes

The state of the atmosphere in the lower 1000 meters or so greatly affects the dispersion of emissions. A most important situation is that of smokestack plumes. Depending on the stability or instability of the lower atmosphere, a

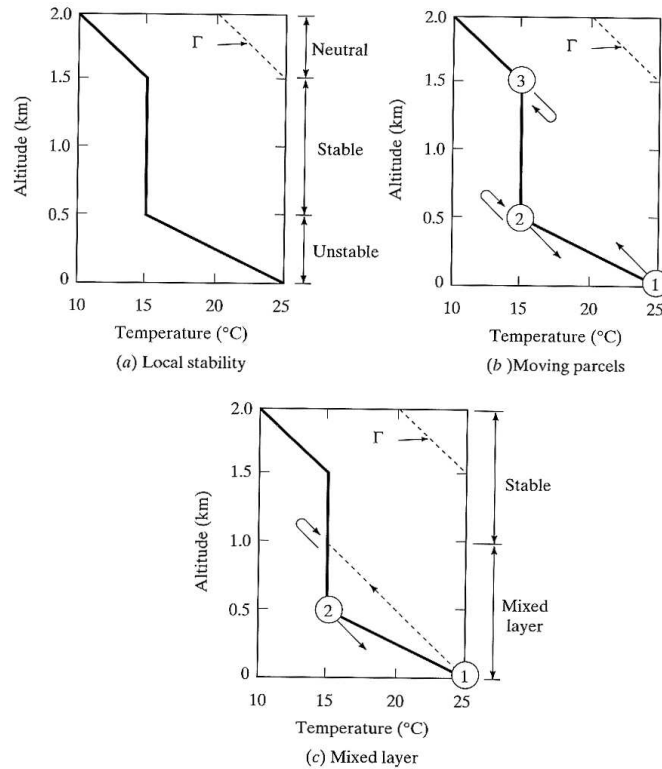


Figure 8-6. Layers of stability and instability in a compound temperature profile and determination of the thickness of the mixed layer, also called mixing height: (a) local stability determined from temperature gradient, (b) parcels 1 and 2 are on the move, and (c) the overshoot of the ground parcel 1 sets the mixing height. [From Masters, 1997]

plume may behave very differently, as shown in Figure 8-8.

If the atmosphere is in a neutral state (Figure 8-8a), the plume gradually expands in the vertical direction, symmetrically upward and downward. It simultaneously expands laterally (in the direction transverse to the wind), although that aspect is usually not perceived by an observer standing on the ground some distance away and therefore looking sideways at the plume. Because it forms an expanding cone, the plume is said to be *coning*. If the atmosphere is unstable (Figure 8-8b), active convection sends thermals of warm air upward while colder air descends. This activity disrupts the plume, alternatively raising some sections and bringing down others. The result is a plume that meanders in the vertical, and for this reason it is said to be *looping*. Such a situation is often observed on warm summer afternoons. By contrast, if the atmosphere is stably stratified, at least up to the level of the smokestack (Figure 8-8c), the low level of turbulence prevents any significant growth of the plume in the vertical. The

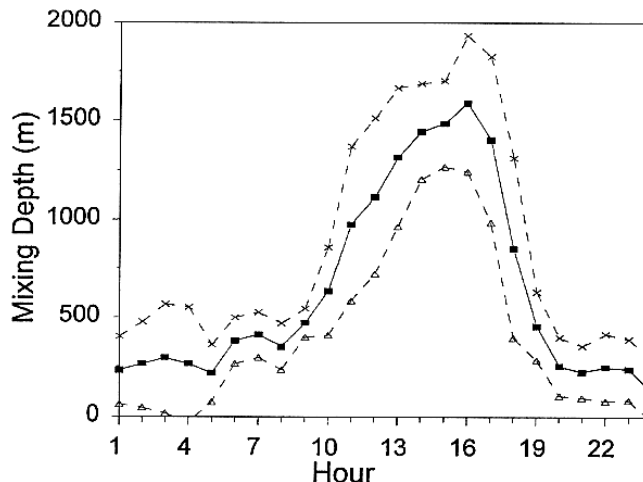


Figure 8-7. Mean and standard deviations of the mixing height averaged over nine summer days with clear sky over Schenectady, New York. [From Berman et al., 1997]

plume still expands in the horizontal direction transverse to the wind and is therefore shallow but opening wide, like a fan, and is said to be *fanning*. Such situation is most typical of winter mornings.

Combination of stable and unstable atmospheric conditions are possible and cases of special interest arise when the level between stable and unstable regions (which varies through the day according to Figure 8-5) reaches the height of the smokestack. During daytime, when new convection gradually erodes the inversion built during the previous night (right panel of Figure 8-5), the situation is one with turbulence on the lower side and calm on the upper side. In such unfortunate case, the emissions from the stack are drawn downward far more effectively than they are taken aloft. The result is *fumigation* of the ground (Figure 8-8d). This is a very unfavorable situation. During nighttime, the opposite situation may occur, with an inversion below some neutral layer remaining from the previous day (left panel of Figure 8-5). The plume is more readily entrained upward than downward, and the result is a much healthier situation with a *lofting* plume (Figure 8-8e).

The Gaussian model

The concentration distribution of a pollutant emitted by a smokestack can be appropriately described by a diffusion model. The situation is highly advective because the Peclet number is high, an assertion to be verified a posteriori. It may also be considered as steady, that is, when one considers an average over the many turbulent fluctuations and assumes that the plume responds relatively quickly to changes in the atmospheric structure. Turbulent diffusion

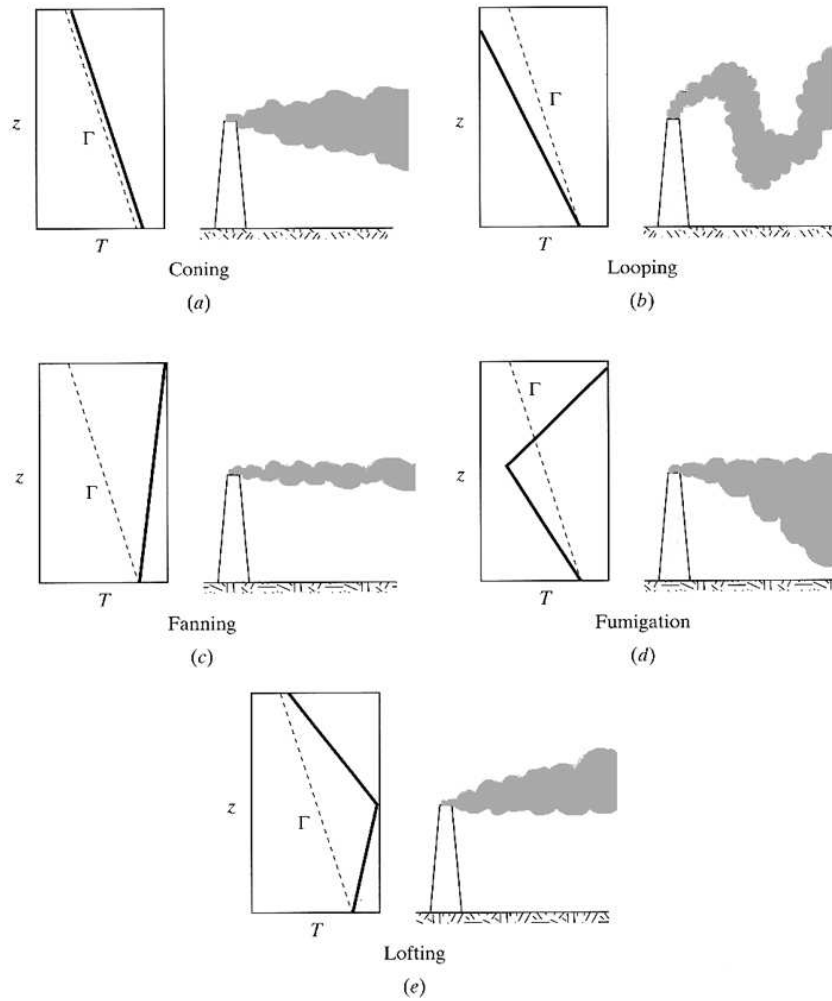


Figure 8-8. A selection of plume types according to ambient thermal stratification. [Adapted from Masters, 1997]

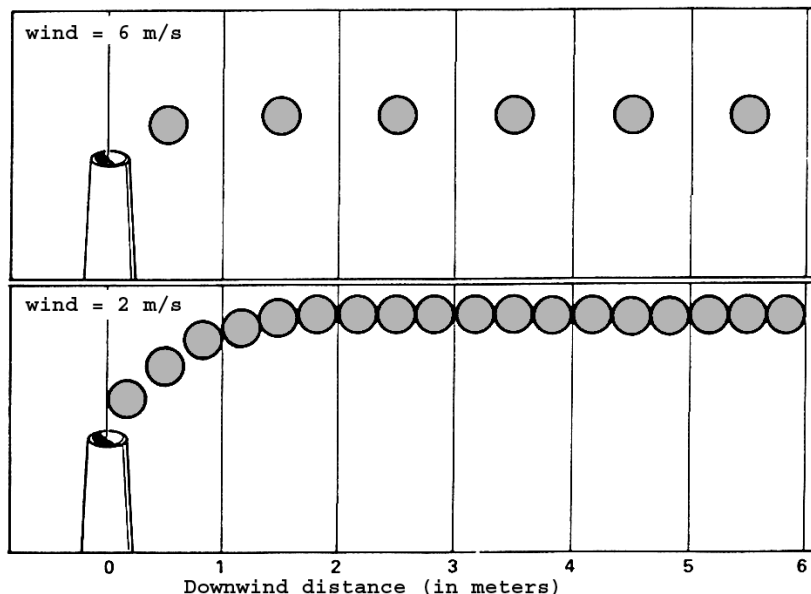


Figure 8-9. How dilution increases proportionally to wind speed. [Adapted from Stern et al., 1984]

occurs in both cross-wind and vertical directions, but at uneven paces. The diffusion is thus two-dimensional and anisotropic. The model equation governing the distribution of the concentration $c(x, y, z)$ of the pollutant is:

$$u \frac{\partial c}{\partial x} = D_y \frac{\partial^2 c}{\partial y^2} + D_z \frac{\partial^2 c}{\partial z^2}, \quad (8.9)$$

where u is the wind velocity at the height of the smokestack, the x -direction is taken downwind, y is the other horizontal direction, transverse to the wind, z is vertical upward, and D_y and D_z are the diffusivities in the y - and z -directions, respectively.

If the origin of the axes is taken on the ground at the foot of the smokestack, then the emission source S (mass of pollutant emitted per time) is located at $x = 0$, $y = 0$ and $z = H$, where H is the height of the smokestack. Because the ground is an impermeable boundary, a virtual source must be imagined at $z = -H$ to negate the flux at $z = 0$. From what we learned in Chapter 2, the solution is then:

$$c(x, y, z) = \frac{M}{\sqrt{4\pi D_y t} \sqrt{4\pi D_z t}} \exp\left(-\frac{y^2}{4D_y t}\right) \times \left[\exp\left(-\frac{(z-H)^2}{4D_z t}\right) + \exp\left(-\frac{(z+H)^2}{4D_z t}\right) \right], \quad (8.10)$$

where time t is actually the travel time to distance x , namely $t = x/u$, and M is the amount released per missing dimension, which is:

$$M = \frac{\text{amount released}}{x - \text{length}} = \frac{\text{amount released}}{\text{time}} \times \frac{\text{time}}{x - \text{length}} = \frac{S}{u}. \quad (8.11)$$

That M has the velocity u in the denominator is a result of dilution, as explained on Figure 8-9.

We are interested almost exclusively in pollution at ground level, where people breathe. Thus, we set z to zero, to obtain:

$$c_{\text{ground}}(x, y) = \frac{2M}{\sqrt{4\pi D_y t} \sqrt{4\pi D_z t}} \exp\left(-\frac{y^2}{4D_y t} - \frac{H^2}{4D_z t}\right)$$

Because observational data are typically captured in terms of standard deviations by fitting observed concentration sections to bell-curve distributions, we eliminate the use of D_y and D_z in favor of the corresponding standard deviations $\sigma_y = \sqrt{2D_y t}$ and $\sigma_z = \sqrt{2D_z t}$, in keeping with (2.19). The revised expression is, after a simplification by a factor 2 in the front fraction:

$$c_{\text{ground}}(x, y) = \frac{S}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2} - \frac{H^2}{2\sigma_z^2}\right). \quad (8.12)$$

At this stage, the x variable hides inside the expressions of σ_y and σ_z , which are growing with distance from the origin. The question of how they vary with the downwind distance x is a complicated one, and tradition has it to rely here almost exclusively on empirical evidence. For this, the most common atmospheric situations are classified in six categories, labeled from **A** to **F**, according to Table 8-3.

Surface wind speed (m/s)	Day solar insolation				Night cloudiness		
	strong	moderate	slight	overcast	overcast	cloudy	clear
<2	A	A-B	B	D	D	E	F
2-3	A-B	B	C	D	D	E	F
3-5	B	B-C	C	D	D	D	E
5-6	C	C-D	D	D	D	D	D
>6	C	D	D	D	D	D	D

Table 8-3. Classification of the most common atmospheric conditions, according to Turner (1970): **A** is very unstable, **B** moderately unstable, **C** slightly unstable, **D** neutral, **E** slightly stable, and **F** stable. “Surface” wind speed is measured 10 m above the ground. A “cloudy night” is one with more than half cloud cover, whereas a “clear” night is one with less than half cloud cover.

The next step is to use the charts provided on Figure 8-10, which provide the values of σ_y and σ_z as functions of the distance x from the base of the

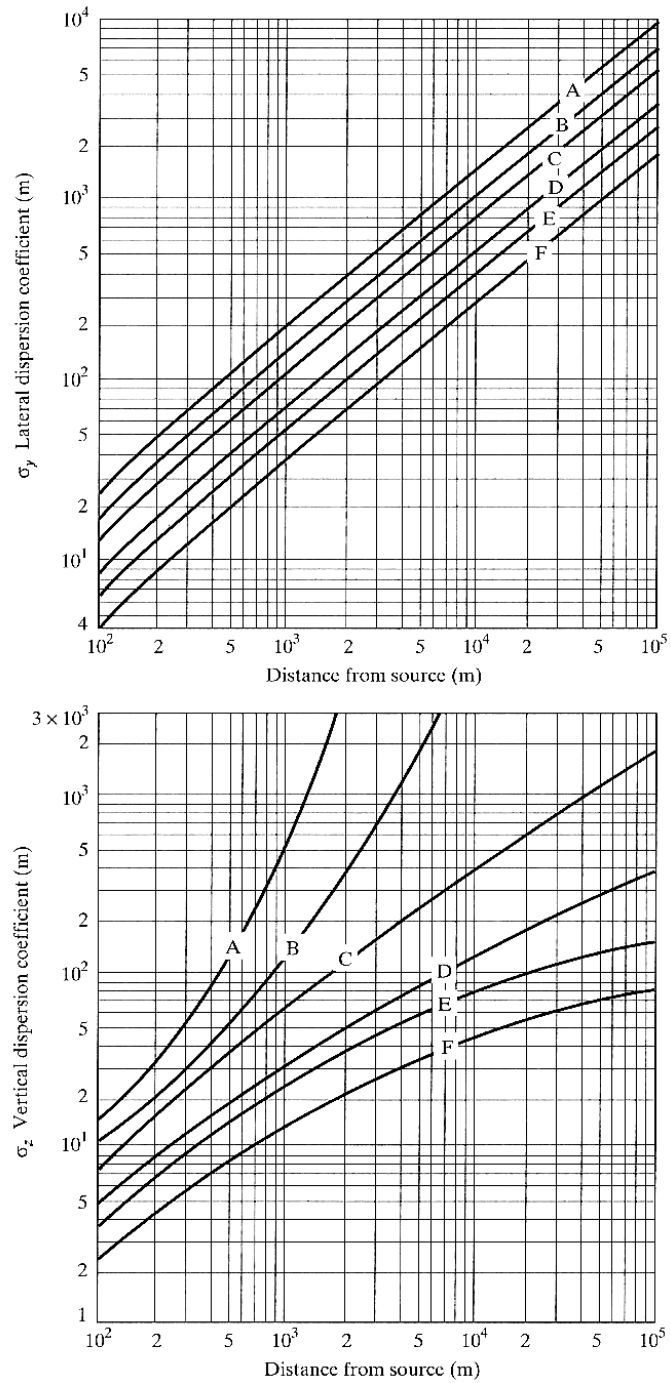


Figure 8-10. Horizontal and vertical standard deviations, σ_y (top panel) and σ_z (bottom panel), as function of downwind distance x and atmospheric stability class. [From Turner, 1970]

smokestack and of the atmospheric stability class. Alternatively, one may use numbers from the Table 8-4.

x (km)	σ_y						σ_z					
	A	B	C	D	E	F	A	B	C	D	E	F
0.2	51	37	25	16	12	8	29	20	14	9	6	4
0.4	94	69	46	30	22	15	84	40	26	15	11	7
0.6	135	99	66	43	32	22	173	63	38	21	15	9
0.8	174	128	85	56	41	28	295	86	50	27	18	12
1.0	213	156	104	68	50	34	450	110	61	31	22	14
2	396	290	193	126	94	63	1953	234	115	51	34	22
4	736	539	359	235	174	117		498	216	78	51	32
8	1367	1001	667	436	324	218		1063	406	117	70	42
16	2540	1860	1240	811	602	405		2274	763	173	95	55
20	3101	2271	1514	990	735	495		2904	934	196	104	59

Table 8-4. Standard deviations σ_y and σ_z (in meters) for the various atmospheric stability classes and for selected distances x (in kilometers) downwind from the smokestack.

We are now in a position to confirm whether the initial assumption of a highly advective situation was indeed correct. For this, we construct the Peclet number [see Equation (2.63)], which consists in a ratio with three quantities. For the velocity scale U , we take the wind speed u , for the length scale L the arbitrary distance x , and for the horizontal diffusivity D_x the same value as the cross-wind diffusivity D_y , since dispersion presumably occurs at the same rate in both downwind and crosswind, horizontal directions. Then, with $\sigma_y = \sqrt{2D_y t}$, we can write:

$$Pe = \frac{UL}{D_x} = \frac{UL}{D_y} = \frac{ux}{\sigma_y^2/2t} = \frac{2utx}{\sigma_y^2} = 2 \left(\frac{x}{\sigma_y} \right)^2,$$

in which we have also used the fact that $ut = x$. Thus, the estimation of the Peclet number reduces to comparing the standard deviation σ_y to the distance x . From the top panel of Figure 8-10 (or the numbers listed in Table 8-4), we note that σ_y ranges between $x/40$ and $x/4$, which implies that the Peclet number ranges between 32 and 3200. The Peclet number is therefore always at least one order of magnitude greater than unity, and the situation can be considered as highly advective.

Effective smokestack height

The gases emitted from a smokestack are typically hot and have therefore a certain buoyancy that tends to raise the plume a certain height above the top of the stack. In addition, it is not unusual to blow the gases at high speed to further increase this height in order to reduce the ground effect further. This creates the necessity to distinguish between the physical height h of the stack from the level H from where the gases actually disperse. This height is called the *effective stack height* and is to be computed from

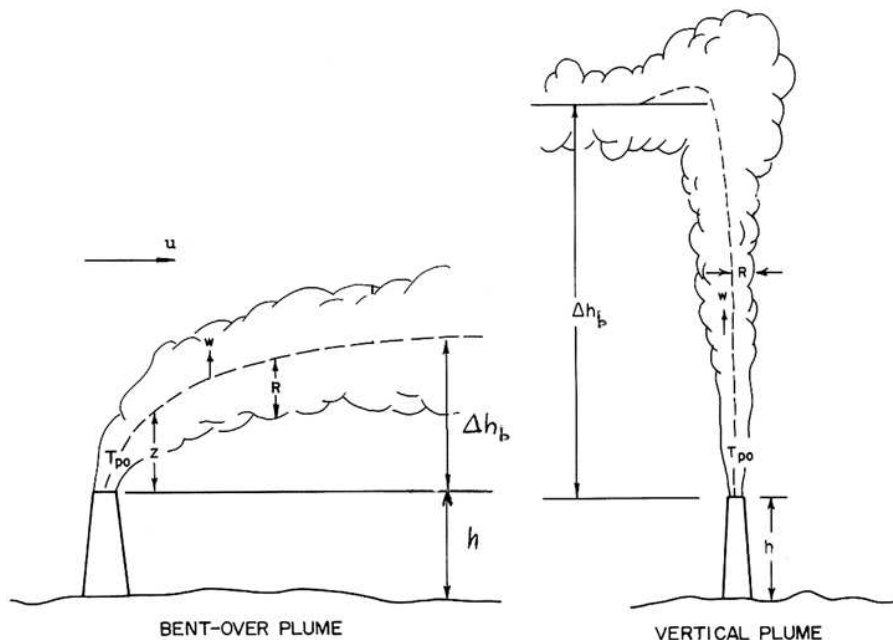


Figure 8-11. Difference between a bent-over plume and a vertical plume. [Adapted from Lyons and Scott, 1990]

$$H = h + \Delta h, \quad (8.13)$$

where Δh is called the *plume rise*. In practice this can be a significant portion of h , if not larger. Needless to say, it is the effective stack height H that needs to be used in Equations (8.10)–(8.12).

To determine the plume rise, there is a series of steps. First, one determines the buoyancy flux parameter F , which is defined as:

$$F = gr^2w_s \left(1 - \frac{T_a}{T_s} \right), \quad (8.14)$$

where r is the inner radius of the stack at its exit section, w_s the upward vertical velocity with which the fumes blow out of the stack, T_a the ambient temperature at stack height (in absolute degrees Kelvin), and T_s the exit temperature of the fumes (in absolute degrees Kelvin).

Next, one needs to distinguish among two types of plumes, as indicated in Figure 8-11. A *bent-over plume* occurs during stability class **A** to **D**, and a *vertical plume* during stability class **E** and **F**.

For a bent-over plume, one calculates the distance x_f over which the plume rises, using one of the following empirical formulas:



Figure 8-12. An example of downwash.

$$\text{If } F < 55 \text{ m}^4/\text{s}^3 \text{ then } x_f = 49 F^{5/8} \quad (8.15)$$

$$\text{If } F \geq 55 \text{ m}^4/\text{s}^3 \text{ then } x_f = 119 F^{2/5} \quad (8.16)$$

with x_f obtained in meters when F is expressed in m^4/s^3 . Once this distance is determined, one can finally calculate the *buoyancy rise*

$$\Delta h_b = 1.6 \frac{F^{1/3} x_f^{2/3}}{u}, \quad (8.17)$$

which, unlike the previous formula, is a dimensionally consistent equation.

For a vertical plume, it is necessary to determine first the stratification parameter N^2 , which was defined in (8.8):

$$N^2 = \frac{g}{T_a} \left(\frac{dT_a}{dz} + \Gamma \right),$$

before calculating the buoyancy rise as follows:

$$\text{If } u < 0.275(FN)^{1/4} \text{ then } \Delta h_b = 4.0 \left(\frac{F}{N^3} \right)^{1/4} \quad (8.18)$$

$$\text{If } u \geq 0.275(FN)^{1/4} \text{ then } \Delta h_b = 2.6 \left(\frac{F}{N^2 u} \right)^{1/3} \quad (8.19)$$

In addition to the buoyancy rise, one needs to worry about the so-called *downwash* if the wind is strong. Downwash is caused by the formation of a vortex in the wind wake behind the stack, and, if the wind speed is large while the gas vertical velocity is weak, the low pressure inside this vortex is capable

of pulling the fumes downward, below the rim of the stack before they can rise again under their buoyancy (Figure 8-12). This explains why sometimes the tip of a smokestack is blackened by repeated exposure to smoke.

Remedies against downwash are: blowing the fumes at a higher speed, building a taller stack, and avoid emissions during strong winds. Another way of alleviating downwash, if the stack is metallic, is to place helicoidal ribs on the outer surface of the stack near its tip of the stack in order to induce a vertical component in the air flow.

The downwash value is calculated as follows: It is nil if $w_s \geq 1.5u$, but if $w_s < 1.5u$, it is equal to

$$\Delta h_d = 4r \left(1.5 - \frac{w_s}{u} \right). \quad (8.20)$$

The overall plume rise is finally obtained from

$$\Delta h = \Delta h_b - \Delta h_d. \quad (8.21)$$

Maximum ground concentration

We are interested in the location on the ground where the concentration is highest. Obviously this will be in the downwind direction, and we can set y to zero:

$$c_{\text{ground,downwind}}(x) = \frac{S}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right). \quad (8.22)$$

Finding the location x where this function reaches a peak value is very difficult because the parameters σ_y and σ_z are complicated functions of x . To alleviate the task, the problem was solved for many possibilities and the results gathered in a chart, reproduced here as Figure 8-13. For a given stability class and stack height, the chart provides the distance x_{max} to the maximum and the value of the ratio uc_{max}/S , in which c_{max} is the maximum concentration.

More complicated situations

The preceding Gaussian model applies only if the atmospheric structure is uniform over the vertical extend of the plume. Should there be an inversion aloft, as it is often the case in mid-morning and around noon, the upward dispersion of the plume will be capped at the base of the inversion. The situation is depicted in Figure 8-14, which also displays the rule to apply.

An important parameter is the distance x_L over which the top side of the plume reaches the base of the inversion, that is, where the plume's half width $2\sigma_z$ equals the height $L - H$ from the tip of the stack to the base of the inversion. Thus, x_L is such that $\sigma_z = 0.50(L - H)$. [Figure 8-14 advocates taking a slightly more conservative coefficient of 0.47.] The situation is quite complex between x_L and $2x_L$, because of the presence of two boundaries, the inversion and the ground surface, but beyond $2x_L$ the plume can be considered as well mixed over the vertical, and the problem is reduced to one with a single

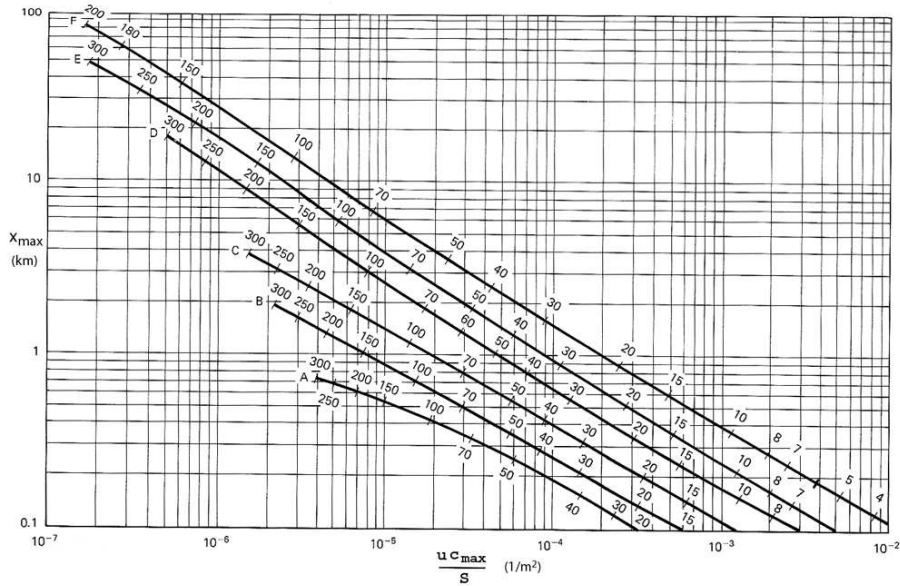


Figure 8-13. Chart to determine the maximum ground concentration from a smokestack. To use this chart, select the curve corresponding to the atmospheric stability class, and on this curve select the point corresponding to the effective smokestack height H . Then, move across to determine the distance x_{\max} (in km), where the maximum occurs, and down to determine the value of $u c_{\max}/S$ (in $1/\text{m}^2$). [From Turner, 1970]

dimension, namely diffusion in the crosswind direction. With M now equal to $S/(uL)$, the ground concentration is given by:

$$\begin{aligned} c_{\text{ground}}(x, y) &= \frac{M}{\sqrt{4\pi D_y t}} \exp\left(-\frac{y^2}{4D_y t}\right) \\ &= \frac{S}{\sqrt{2\pi u L \sigma_y}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right). \end{aligned} \quad (8.23)$$

Figure 8-15 illustrates fumigation caused by a sea breeze. Over land in the proximity to a coastline (seashore or lakeshore), there exists during daytime a temperature difference between the warmer ground and the colder water, which generates an inversion over the sea and a wind carrying this inversion landward. But, upon encountering the roughness of the landscape, a turbulent boundary layer is created that grows from the shore inland, as depicted in Figure 8-15. If a smokestack is placed near the shore, the chance is that its tip will lie above this boundary layer, but its downwind plume, which expands downward toward the boundary layer growing upward, will eventually be drawn into it. Unfortunately, energetic dispersion below an inversion is the recipe

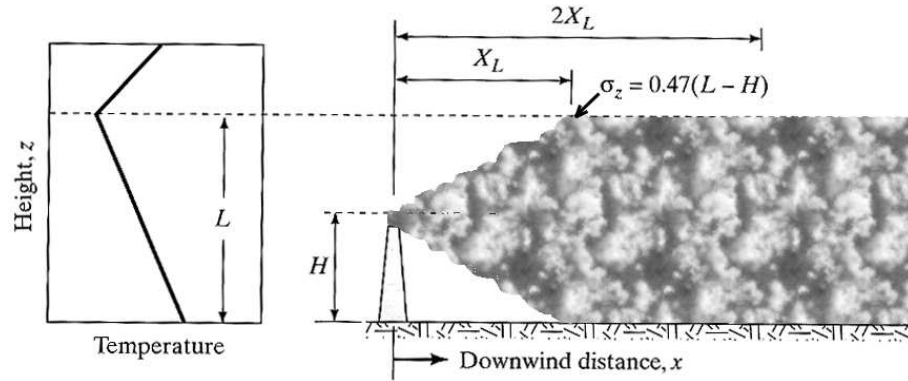


Figure 8-14. The effect of an inversion on the dispersion of a smokestack plume. [Adapted from Masters, 1997]

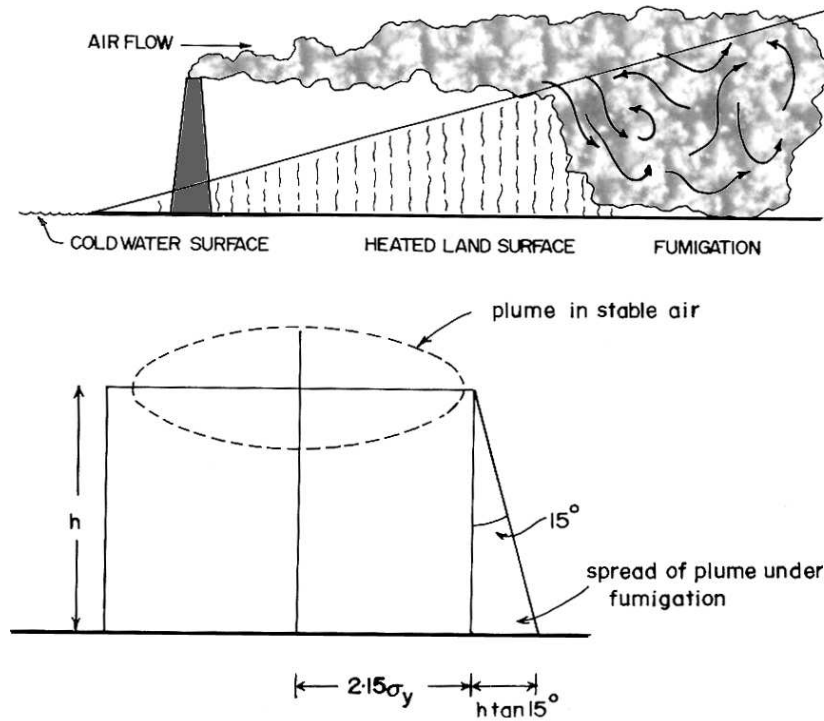


Figure 8-15. How a sea breeze can create fumigation. The upper panel depicts the scenario, while the lower panel provides the rule to determine the footprint of the plume at ground level. Here, h is the local height of the inversion. [Adapted from Lyons and Scott, 1990]

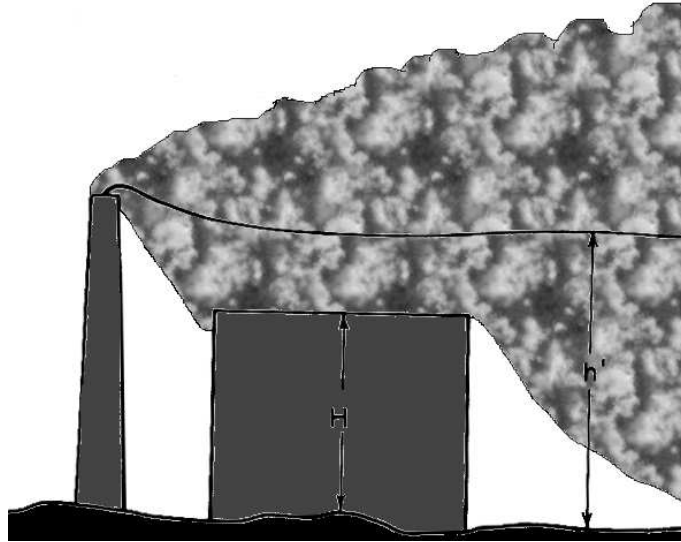


Figure 8-16. How the proximity to a building can create a downwash. [Adapted from Lyons and Scott, 1990]

for fumigation (see Figure 8-8d). The morale is an advice: Never locate a smokestack between a coastline and a residential area!

Among the countless possible situations that affect the behavior of smokestack plumes, we mention here only one more because of its frequency of occurrence. The situation is that of a smokestack near a building, such as a building of the factory or power plant that needs the smokestack. Wind flow around and on top of the building creates low pressure zones that tend to suck the air downward, and the result is a downwash of the plume over the building (Figure 8-16). Also, the building make create a certain shelter against fumes on the downwind side.

The rules used in practice to estimate the vertical drop to the plume's mid-line are quite cumbersome and unreliable, because building come in many different forms and sizes. Wind-tunnel experimentation is to be preferred during the design stage.

Erecting a smokestack at least 2.5 times the height of the highest proximate building will usually overcome any problem.

8.5 Urban Pollution

The problem

The need for electric power and road traffic in and around cities contribute to cause local air pollution problems. At this scale, we are no longer concerned

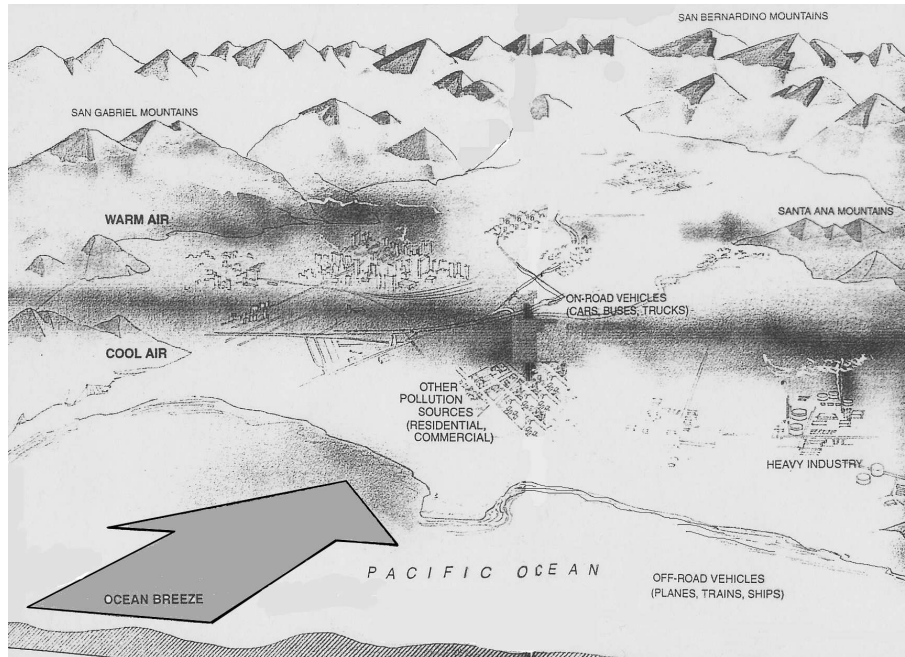


Figure 8-17. A bird's eye view of Los Angeles, as seen from above the ocean. [From an article in *Scientific American*]

by the plume of a single smokestack but by the aggregate effect of several stacks, the distributed sources of road traffic, and the countless other forms of exhaust that activities in a modern city generate.

The problem can be usually analyzed from the perspective of a materials balance over a specific piece of the atmosphere around the city, called the *airshed*. In most instances, this volume cannot be defined with much precision, since an airshed is in no way as contained as water in a lake. An airshed may not always be consistently defined, because its existence is at the mercy of atmospheric conditions, such as the origin of winds and the presence of an inversion. Nonetheless, it is a useful concept.

Los Angeles

Los Angeles provides a nearly perfect example of an airshed. This city is literally cornered between the Pacific Ocean and an arc of mountains and ridges on the opposite side (Figure 8-17). With winds blowing most frequently from the ocean, over the city and up above the mountains and a frequent inversion aloft, the airshed is quite well defined (Figure 8-18). The air over the city is blocked below by land, to the East by a range of mountains, to the West by the incoming wind (including the sea breeze), and above by a frequent inversion.

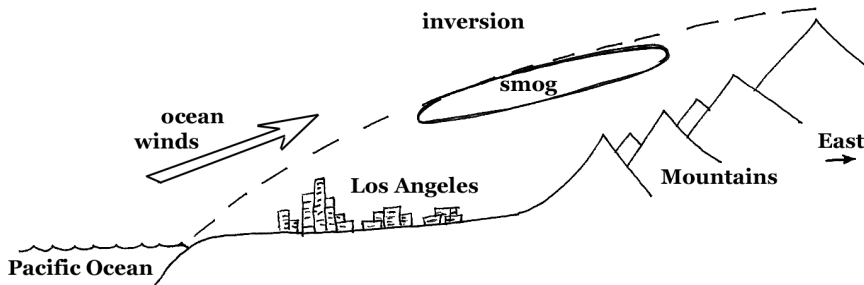


Figure 8-18. The boundaries of the Los Angeles airshed.

The low ventilation through its airshed is not conducive to transporting emissions of the city over a broad region and diluting them by dispersion. Rather, local emissions tend to remain trapped near their place of origin. It is no surprise, therefore, that the city of Los Angeles has been plagued with poor air conditions for a long time (recall Figure 8-2). What exacerbates the pollution problem is the fact that Los Angeles is a sunny city. Indeed, sunlight can induce chemical reactions upon hitting certain chemicals, and the primary pollutants turn into secondary pollutants, which may compound the problem. An important and particularly problematic occurrence is *photochemical smog*.

The city of Los Angeles is notorious for its episodic smog. The combination of processes leading to smog conditions is:

1. The wind blows from the Pacific Ocean, over the city and toward the East,
2. There is an inversion aloft,
3. The sun shines, and
4. Motor traffic is heavy,

Photochemical smog

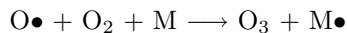
Smog is a word formed by the association of fog and smoke. It occurs when smoke is trapped locally under a combination of winds and orography, and is further made visible by condensation at some level (fog). The chemical soup at the origin of smog consists in nitrogen oxides (NO_x) and volatile organic compounds (nicknamed VOCs), coming from combustion and unburnt hydrocarbons, respectively. The chemical reactions to which these substances are subjected are extremely complex, and more than hundred chemical reactions

have been identified to date, by in-situ measurements and laboratory experimentation. At the core are the following reactions.

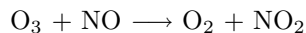
First, the most stable form of nitrogen oxide is NO_2 , and the other two forms (NO and N_2O) are rather quickly oxidized into that form. But, under sunlight NO_2 can be broken up:



The atomic oxygen ($\text{O}\bullet$) is extremely reactive (as indicated by the heavy dot placed after its symbol) and quickly reacts with one of the abundant species in air, namely oxygen (O_2) to form ozone (O_3):



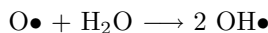
Here, M stands for any neighboring molecule (usually N_2) that absorbs the extra energy. Without this bumper action, the ozone would have too much energy and spontaneously dissociate. Ozone is oxygen with an extra atom, which it is ready to shed on another molecule that would be more stable with it, such as NO . Thus, whenever an ozone molecule encounters a nitrogen monoxide molecule, the two spontaneously exchange an oxygen atom:



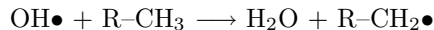
This third reaction forms the relaxation that returns the nitrogen dioxide and oxygen consumed in the first two, closing a loop that can be repeated as long as sunlight strikes. The result is an equilibrium between certain concentrations of nitrogen dioxide, nitrogen monoxide and ozone. (The concentration of oxygen is kept nearly at the constant 21% of the atmosphere.)

This equilibrium can be greatly perturbed, however, by the presence of volatile organic compounds. These VOCs typically have a $-\text{CH}_3$ radical, namely the molecule terminates on one side with a link to a carbon atom, which is itself linked to three hydrogen atoms. A large category of hydrocarbons and other forms of VOCs can therefore be denoted as $\text{R}-\text{CH}_3$, where R is whatever else the molecule contains.

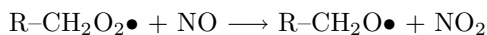
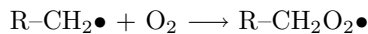
The chemical brew continues as follows. Atomic oxygen occasionally reacts with a water molecule, which is present as long as there is moisture in the air:



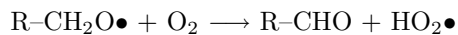
where the so-called hydroxyl radical $\text{OH}\bullet$ is extremely reactive. Upon encountering a VOC, it rips one of its hydrogen



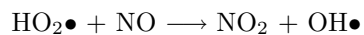
leaving the excited radical do the following, systematically passing the excitation forward



in which we note the disappearance of one NO molecule. The chain reaction continues:



The new VOC (R-CHO) is less reactive, but the radical $\text{HO}_2\bullet$ carries the process forward one more step



and a second NO is converted into NO_2 . Moreover, the hydroxyl radical $\text{OH}\bullet$ is regenerated, acting therefore as a catalyst. The sequence of reactions can thus be repeated as long as VOCs are present. In the process, more NO is converted in NO_2 , reducing the chance of an encounter between NO and O_3 while increasing the level of NO_2 ready to be dissociated by sunlight to form new ozone. The net effect is to maintain the ozone concentration at a higher level than if VOCs were not present. Put in other words, VOCs are doubly harmful: Besides being carcinogenic, they are also responsible for increased ozone levels.

Chapter 9

NEXT CHAPTER

THIS IS TO ENSURE THAT CHAPTER 8 ENDS ON AN EVEN PAGE SO
THAT CHAPTER 9 CAN BEGIN ON AN ODD PAGE.