CHAPTER 12 — AIR QUALITY AND ATMOSPHERIC DISPERSION

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12.1 Air quality

At times during both summer and winter, air quality deteriorates significantly in the UK (see 3.9 for guidance on haze occurrence and visibility forecasting). Under these conditions, the Government has asked the Meteorological Office to prepare air quality bulletins to give advance notice to the general public; these bulletins are issued through NETCEN to the media.

12.1.1 Emission of airborne pollutants

An air pollutant is a substance which, between the points of discharge into the atmosphere and ultimate removal, causes harm to the target. Because emission densities are higher in urban compared with rural areas, air pollutant concentrations are usually higher in urban areas.

Urban air quality reflects the balance between opposing tendencies of emissions to increase concentrations, and meteorology to disperse pollution and ventilate urban areas. The environmental harm caused by air pollutants may occur over spatial scales from the urban, to long-range transport and global scales.

Lyons & Scott (1990) Smith (1992)

12.1.2 Type of emissions

Emissions may be classified by type (e.g. CFC, hydrocarbon) and source; they come from a variety of natural sources and from human activities:

(i) *Particulates* — Urban concentrations of particles have caused a significant public health concern. Motor traffic, particularly diesel vehicles, are the major source but others include (stationary) combustion and industrial processes. Particles with particles with diameters less than 10 μm are of the greatest interest and this includes particles of natural origins: sea salt, wind-blown dust, pollen and spores.

(ii) *Sulphur compounds* — Sources from human activities (released mainly from the burning of coal and oil) wholly predominate over natural sources (dimethyl sulphide from decaying algal blooms) in the northern hemisphere.

(iii) *Carbon monoxide* — is produced by incomplete combustion of carbonaceous fuels, the main source being the internal combustion engine. There are large sources of carbon monoxide from the oxidation of methane and other hydrocarbons.

(iv) *Carbon dioxide* — is not normal regarded as a pollutant; sources are both natural and anthropogenic, including plants, animals and the burning of fossil fuels. Vegetation and oceans provide the main sinks. Since CO_2 is a major absorber of long-wave radiation, increased concentrations are expected to lead to an enhanced greenhouse effect.

(v) *Hydrocarbons* — Combustion and evaporation of fuels such as oil and petrol lead to emissions of highly reactive hydrocarbons which contribute to ozone formation in summertime episodes; some hydrocarbons (benzene and 1,3-butadiene) are cancer-inducing agents. There are large natural sources of hydrocarbons.

(vi) *Oxides of nitrogen* — NO_X emissions occur principally from motor traffic and combustion in power stations and industrial plants; the emissions readily oxidizes to NO_2, which is important in urban areas. Lightning and biomass burning are important global sources.

(vii) *Methane* — Main sources of CH_4 are rice production, cattle rearing, coal mining and the venting and leaking of natural gas. After CO_2, methane is the most important greenhouse gas; the bulk of the methane is removed in the lower atmosphere where it is an important source of tropospheric ozone, an important greenhouse gas in its own right. On entering the stratosphere methane breaks down and oxidizes to form water vapour, raising the stratospheric frost point and making polar stratospheric cloud production more likely.

(viii) *Chlorofluorocarbons* — CFCs have been used as refrigerants etc. only since the 1930s. They are essentially inert until they reach the stratosphere, where the reactive chlorine is is released by photodissociation. CFCs have been identified as major contributors to the destruction of the ozone layer over the (particularly Antarctic) winter poles.

(ix) *Other species* — dioxins and other toxic organic micropollutants are released in small quantities or restricted to certain localities but can be highly toxic.

Note that the hydroxyl radical (OH) is not an emission, being formed by chemical reaction in the atmosphere. However, it plays a significant role in many important chemical reactions, cleansing the troposphere by oxidizing trace gases to harmless products or to those more readily removed from the atmospheric circulation.

Bertorelli & Derwent (1995) Derwent (1994, 1995)

12.1.3 Smog

(i) *Wintertime UK smogs* — In conditions of light winds and high boundary-layer stability, particulate matter provides condensation nuclei for fog formation, for which the term 'smog' was termed after severe incidents in earlier decades. Urban wintertime smogs persist with elevated concentrations of nitrogen dioxide and particles which are associated with detectable short-term changes in public health.

(ii) *Tropospheric ozone and photochemical smog* — During summertime conditions, chemical reactions driven by sunlight, involving hydrocarbons and oxides of nitrogen, give rise to elevated concentrations of ozone which have some general public health significance.

Topography, onshore winds and other factors which will block dispersion, all contribute to making certain (low-latitude) cities infamous for their photochemical smogs. Even at higher latitudes summer days when days are long and solar radiation stronger, ozone can become a problem in anticyclonic weather.

12.1.4 Acid rain

SO_2 is readily oxidized to sulphuric acid which, having a low saturation vapour pressure, readily forms droplets that can serve as condensation nuclei. These droplets have an important acidifying influence on cloud water, rain and snow. Rainfall with a PH as low as 4 (even 2 in extreme cases) has been measured.

Chalk and limestone neutralize low PH rainfall and percolating water, but many upland areas of the UK (e.g. Cambrian Hills) are on geologically hard rock. This, combined with an evergreen forest catchment and spring snow-melt can lead to large surges in acidity which can leach out toxic aluminium from the soil, destroying, for example, whole aquatic ecosystems.

Although pollution sources causing major 'events' are likely to be local, long-range transport is an important element of environmental acidification in Europe. The influence of the UK, for example, on acidic deposition in Norway has been well characterized by both modelling and monitoring. Transport from the USA will give a low but, nevertheless, steady influx of pollution, particularly to western areas.

Smith (1991c)

12.1.5 Chemical and nuclear releases

Emissions from chemical and nuclear releases will generally differ in the following ways:

(a) *Chemical*
- (i) release(s) with gradual reduction over a period of hours;
- (ii) finite store of material released;
- (iii) density/buoyancy of gas at release is important;
- (iv) chemical interactions may change nature of emission with time.

(b) *Nuclear*
- (i) release(s) with gradual reduction over days;
- (ii) effectively an infinite store of material;
- (iii) neutral buoyancy;
- (iv) gas/particle release;
- (v) overseas, as well as domestic releases, may affect UK.

12.2 Dispersion on various scales

This section discusses the various dispersion and deposition mechanisms on the short-, meso-, and long-range to aid forecasters to more authoritatively offer advice under pollution scenarios and, particularly, under the CHEMET (Chemical Meteorology), PACRAM (Procedures and Communications in the event of the Release of Nuclear Material) and NAME (Nuclear Accident Model) emergency procedures (for details of which refer to *Commercial and Public Services Handbook*, Met.O.868, chapter 22). Procedures are also in place for providing the Ministry of Agriculture, Fisheries and Food with areas at risk in the event of outbreaks of, for example, foot and mouth disease.

CPSH
Gloster (1983)

12.2.1 Short-range dispersion

Over short ranges (out to 30 km) wind speed and direction, etc. can be assumed to be approximately constant and is dominated by turbulence (generated by wind shear, and by insolation) within the boundary layer **(Fig. 12.1)**, the depth of which can be estimated from a nomogram **(Fig. 12.2)**. Eventually fine-scale variations are smoothed by molecular diffusion; the result is that concentrations can be very patchy.

The peaks can be important for toxic or inflammable material, or for odours. Most models predict mean concentrations. Dispersion depends on natural mixing processes due to stability as follows:

(a) *unstable boundary layer* — convection rapidly disperses emission into a large volume, diluting it. Near-ground sources lead to lower concentrations of a plume than in neutral or stable conditions; elevated sources can lead to higher ground concentrations than in the latter conditions.

(b) *stable boundary layer* — turbulence is suppressed, resulting in high concentrations for near-ground sources. Unless an elevated plume impacts on downwind topography, ground-level pollution from elevated sources will not be significant.

Wind — high wind increases the dilution at source and reduces the influence of stability.

(i) speed influences distance of travel and concentration;

(ii) there will be directional variability;

(iii) light winds and high stability favour high pollutant concentrations at ground level although unstable conditions can give concentration peaks under 'looping' conditions **(Fig. 12.3)**.

Pasquill & Smith (1983)
Stull (1988)

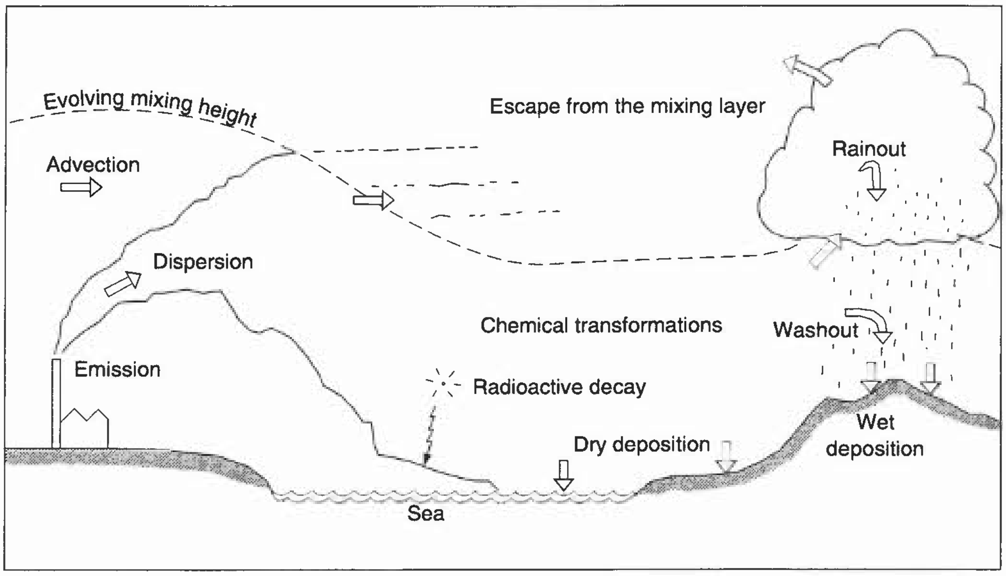

Figure 12.1. Some of the processes affecting airborne pollution.

12.2.1.1 Pasquill stability criteria

Pasquill combined wind speed, insolation and state of sky to categorize the influence of stability on the (horizontal and vertical) dispersion of a pollutant; these stability criteria are used in many short-range dispersion models out to 100 km and are required for the forecast information form in the PACRAM procedure (*Commercial and Public Services Handbook* Met.O.868, chapter 22, Annex D — the criteria are presented in **Table 12.1**.and the dispersion diagrams in **Fig. 12.4**). However, recourse is increasingly made to a method that characterizes the height at which stability effects become important (Monin–Obukhov technique).

Table 12.1. Stability categories in terms of wind speed, insolation and state of sky

Surface wind speed ($m\ s^{-1}$)	Insolation			Night	
	Strong	Moderate	Slight	Thinly overcast or ≥4/8 low cloud	≤3/8 cloud
<2	A	A–B	B	E	F
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D

Strong insolation corresponds to sunny midday in midsummer England, slight insolation to similar conditions in midwinter. Night refers to the period from 1 hour before sunset to 1 hour after dawn. For A–B take averages for A and B etc. The neutral category D should also be used, regardless of wind speed, for overcast conditions during day or night, and for any sky conditions during the hour preceding or following the night as defined above.

CPSH
Pasquill& Smith (1983)

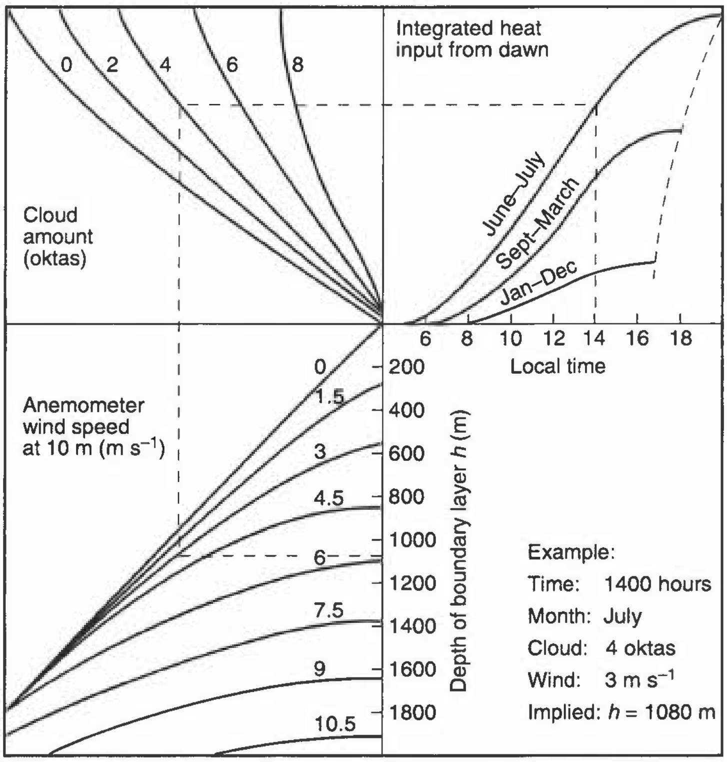

Figure 12.2. A nomogram for estimating the depth of the mixed layer in daytime conditions typical of the United Kingdom, assuming no marked advective effects or basic changes in weather conditions. The broken line shows how the diagram is to be used.

12.2.1.2 Plume characteristics from an elevated stack

Characteristic forms of plumes from an elevated stack are illustrated in **Fig. 12.3**:

(a) *Looping* — daytime conditions on fine summer day. Large eddies dominate which are larger than plume diameter and transport it up and down; high concentrations at ground level close to emission may result.

(b) *Coning* — characteristic of windy/cloudy conditions in near-neutral stability. Small-scale friction-generated eddies from forced convection. Similar lateral and vertical spread; plume may reach ground but further down wind than in looping.

(c) *Fanning* — under very stable conditions. Very weak turbulence; thin plume but may fan horizontally; plume can remain unchanged for 100 km or more downwind. Ground-level pollution virtually nil.

(d) *Lofting* — the most favourable dispersion condition; stable layer below plume inhibits downward transport while instability aloft encourages dispersion.

(e) *Fumigation* — reverse of lofting; buoyant mixing at low levels while inversion above plume inhibits upward dispersion. Occurs most commonly in the morning when nocturnal inversion is being eroded by surface heating. Once mixing layer reaches the plume high concentrations may be brought to the surface simultaneously at various locations along the plume.

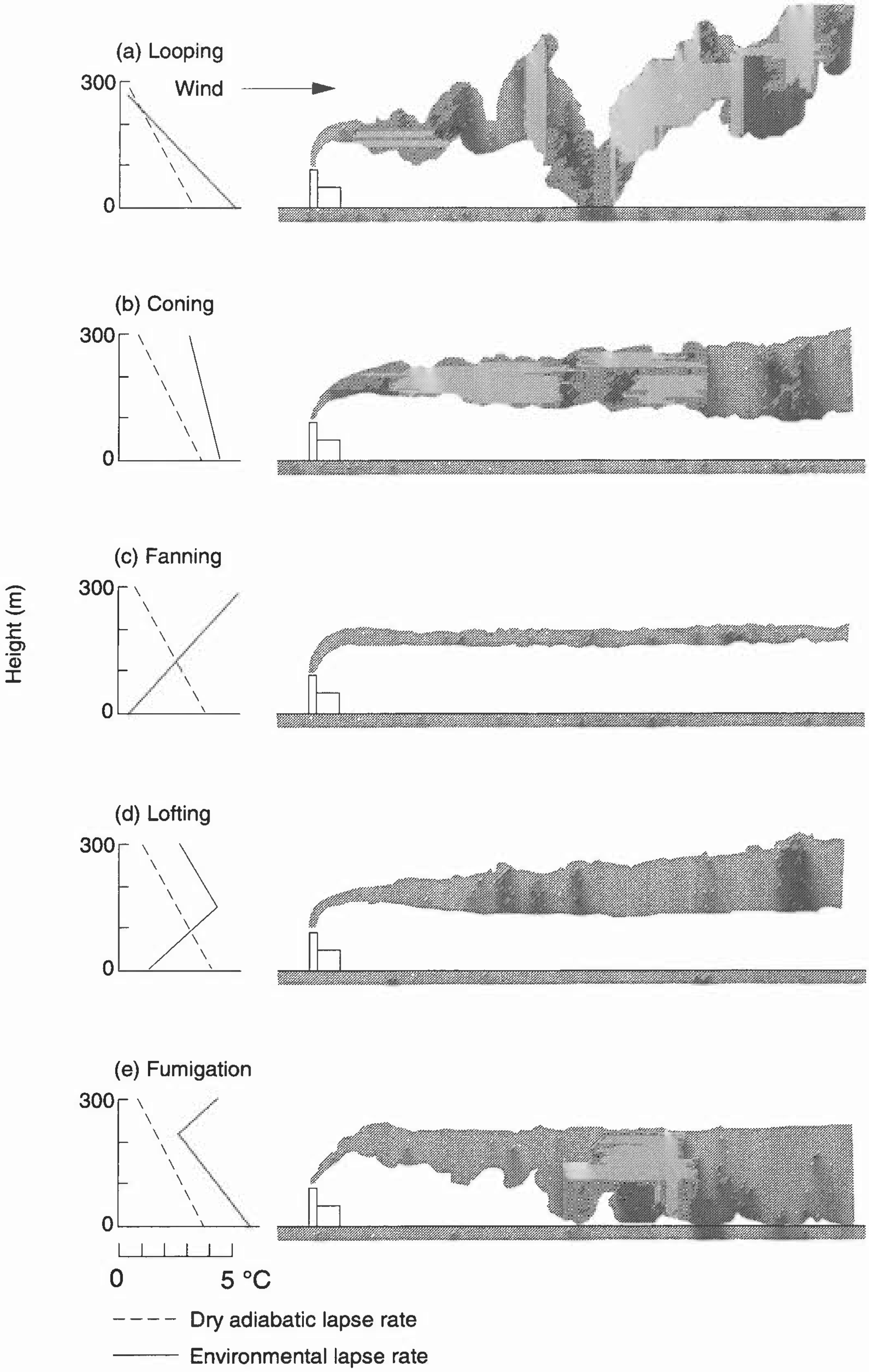

Figure 12.3. Characteristic plume patterns under different stability conditions.

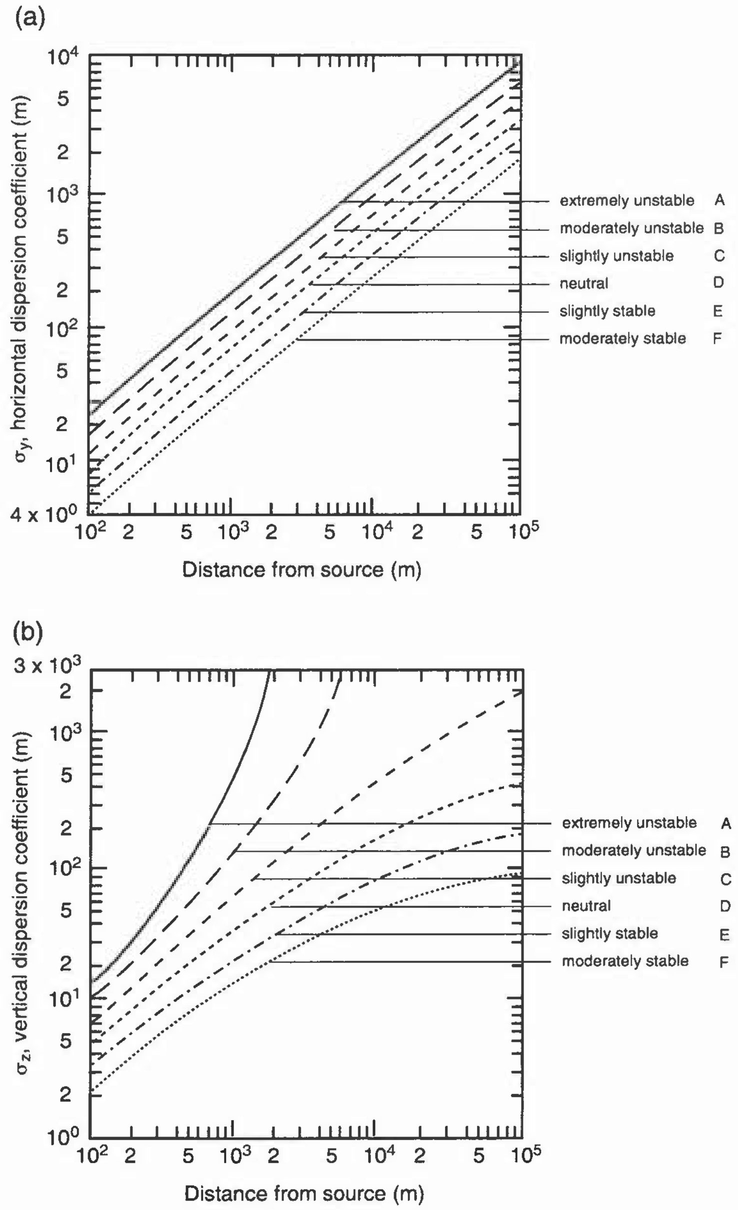

Figure 12.4. Pollutant dispersion diagrams, due to Pasquill–Gifford, illustrating standard deviation, σ, of the concentration about the central line maximum — the dispersion coefficient — for (a) horizontal and (b) vertical dispersion as a function of Pasquill stability criteria (Table 12.1).

12.2.2 Mesoscale dispersion

Examples of mesoscale circulations are sea and land breezes, flows associated with large convective cloud systems, urban circulations and topographically induced flows.

12.2.2.1 Sea and land breezes, storms, and urban circulation (1.3)

Sea breezes can:

(i) suppress convective dispersion through the introduction of cold air at low levels;
(ii) bring down high pollution concentrations, in particular by fumigation from coastal stacks where the plume is engaged by the turbulent internal boundary layer forming in the onshore breeze;
(iii) incorporate emissions from various coastal sources through circulations which cycle the same air repeatedly.

Land breezes

Down-slope flows may reinforce the land breeze under slack pressure gradients and virtually cloudless conditions. Generally, though, land breezes will carry pollution out to sea where, however, the pollutant may constitute a 'reservoir', ready to be engaged by the next sea breeze.

Storms

(i) Large storms will break down normal boundary-layer structure.

(ii) Pollution will be dispersed to other levels and there will be washout of much of the soluble and particulate pollutants.

(iii) A deposition 'episode' may result when heavy precipitation follows a period of stagnation, during which pollutant emissions have accumulated.

Urban circulation

Increased surface roughness and the 'heat island' effect will affect dispersion in several ways:

(i) there will be an increase in vertical mixing;

(ii) it will be difficult to ascribe wind speeds and turbulence levels.

12.2.2.2 Topography

The effect of hills on pollution dispersion is complex; here are guidelines for simple topographic models.

(i) the wind speed-up factor at the top of an isolated hill of height, h, is $2h/l$, where l is the 'half-width' of the hill at height $0.5h$ (1.3.2);

(ii) turbulence levels are increased in proportion: $1 + 2h/l$;

(iii) for slopes >1 in 3 near-neutral airflows tend to separate from the surface and closed eddies can be set up. If a pollution source lies inside one of these eddies (or if pollutant gets into such an area) then high concentrations will be found within it with a relatively slow escape to the main external flow;

(iv) for a source upwind of a hill the dispersion and resulting ground level concentration will depend very much on stability;

(v) unstable and neutral air flows can flow over the hill; under stable conditions there may be a critical height, h_c, below which air will stagnate or be forced around the hill and above which flow over the hill is possible **(Table 12.2)**;

(vi) High and low surface concentrations may be experienced on the forward side of the hill as the airflow responds to upstream variations in flow while on the lee side, complex separated flows may result in a point being continuously subjected to high dosages;

(vii) a persistent single vortex may form and stretch downwind from an isolated hill; the stability of the vortex may inhibit dispersion of material entrained beyond its own dimensions;

(viii) an area of high ground may generate mesoscale horizontal eddies on the sub-synoptic scale with closed circulations inhibiting dispersion (e.g. emissions from Eggborough Power Station have been monitored circulating within the lee eddy generated by North York Moors).

12.2.2.3 Flows near fronts

'Conveyor belt' and associated flows can advect pollution from behind the cold front to ahead of the warm front etc. (see Chapter 7). Wet deposition and rain out (removal as condensation nucleus (12.3)) processes will be important.

Table 12.2. The height below the hill crest ($h-h_c$) at which the airflow has just sufficient kinetic energy to rise over the hill in stable conditions

		Δθ Increase in potential temperature over 100 m				
		0.1	0.3	0.5	1	3
	1	172	100	77	55	32
wind	2	344	199	154	109	63
speed	4	688	397	308	217	126
u	6	1032	596	461	326	188
($m\ s^{-1}$)	8	1375	794	615	435	251
	10	1719	993	769	544	314

12.2.3 Long-range dispersion

(i) Initially dispersion is governed by turbulent and mesoscale diffusive processes.

(ii) After about a day the dispersion is controlled by differential ('chaotic') advection, the plume being stretched into 'tendrils', folded and sheared into 'whorls'.

(iii) Persistent anticyclones may form a barrier to this 'stirring' process, provided the source is outside the circulation.

(iv) Eventually plumes lose coherence as they are stirred by successive wind regimes; the plume has been effectively diffused on a hemispherical or even global scale.
(v) Gradually the material becomes uniformly mixed, assuming it has not been removed by the depletion processes long before then.

Maryon (1994)
Smith & Hunt (1978)
Smith (1988)

12.3 Deposition processes

The persistence of a pollutant within the boundary layer depends on:
(i) the synoptic conditions in which it is released;
(ii) its interception by rain-bearing systems.

Typical lifetime of pollution within the boundary layer is 3 to 4 days, depending on weather type (10 to 20 days in the troposphere and much longer in the stratosphere).

Within the boundary layer the three pathways for deposition are:
(i) *dry deposition* which accounts for ⅓ of all deposition through gravitational settling (particles $<$1 mm), impaction and surface absorption from a near-surface plume;
(ii) *wet deposition* which accounts for about ⅔ of all deposition through wash-out by impact with raindrops and by occult deposition (see below).

Wet deposition is vastly more efficient than dry — 1 hour of rain is equivalent to 2 or 3 days of dry deposition. Thus upland areas have the greatest potential for pollution deposition compared with lowland areas.

Falling snow scavenges pollutants more efficiently than rain, the seeder-feeder rate being about three times that for rainfall at the equivalent rainfall rate.

In turbulent (occult) deposition pollutants act as condensation nuclei within cloud formed by upslope motion. Some 90% of the mass is captured within cloud droplets. This is a source of deposition of acid species on, particularly, European upland forests.

There are other depletion processes, such as chemical transformations and radioactive decay, which do not involve deposition.

Chamberlain (1960)
Mason (1992)
Smith (1991a, 1991b, 1991c, 1992)

BIBLIOGRAPHY

CHAPTER 12 — AIR QUALITY AND ATMOSPHERIC DISPERSION

Bertorelli, V. and Derwent, R. 1995: Air quality A to Z. A directory of air quality data for the United Kingdom in the 1990s. Bracknell, Meteorological Office.

Chamberlain, A.C., 1960: Aspects of the deposition of radioactive and other gases and particles. *Int J Air Poll*, **3**, 63–88.

CPSH: Commercial and Public Services Handbook, Met.O.868, Chapter 22.

Derwent, R.G., 1994: Second generation abatement strategies for NO_x, NH_2, SO_2 and VOCs. *Ambio*, **23**, 425–433.

Derwent, R.G., 1995: Air chemistry and terrestrial gas emissions: a global perspective. *Philos Trans R Soc London*, **A351**, 205–217.

Gloster, J. 1983: Forecasting the airborne spread of Foot and Mouth Disease and Newcastle Disease. *Philos Trans R Soc London*, **B302**, 535–541.

Lyons, T. and Scott, W., 1990: Principles of air pollution meteorology, Bellover Press, London.

Maryon. R.H., 1994: Modelling long-range transport of radio-nuclides following a nuclear accident. *Nuclear Energy*, **33**, 119–128.

Mason, B.J., 1992: Acid rain: Its causes and its effects on inland waters. Oxford University Press.

Pasquill, F. and Smith, F.B., 1983: Atmospheric Diffusion. Ellis Horwood.

Smith, F.B., 1988: Lessons from the dispersion and deposition of debris from Chernobyl. *Meteorol Mag*, **117**, 310–317.

Smith, F.B., 1991a: A scheme for estimating fluctuations in concentration of an airborne pollutant. *Meteorol Mag*, **120**, 124–132.

Smith, F.B., 1991b: Deposition processes for airborne pollutants. *Meteorol Mag*, **120**, 173–182.

Smith, F.B., 1991c: An overview of the acid rain problem. *Meteorol Mag*, **120**, 77–91.

Smith, F.B., 1992: The first 50 years in the study of atmospheric dispersion. *Meteorol Mag*, **121**, 135–141.

Smith, F.B. and Hunt, R.D., 1978: Meteorological aspects of the transport of pollution over long distances. *Atmos Environ,* **12**, 461–478.

Stull, R. B., 1988: An introduction to boundary layer meteorology. Kluwer Academic Publishers.