DEPARTMENT OF ENVIRONMENTAL AFFAIRS AND TOURISM

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AIR POLLUTION DISPERSION AND TOPOGRAPHICAL EFFECTS

ACRONYMS

CFCs	Chlorofluorocarbons
CO	Carbon Monoxide
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
O_3	Ozone
Pb	Lead
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter smaller than or equal to 2.5µm in diameter
SO_2	Sulphur Dioxide
VOC	Volatile Organic Compound

GLOSSARY

Ambient air
Considered to be the air in the environment excluding indoor air.

Anabatic wind
An upslope wind that occurs during the day due to local surface heating.

Anticyclone
A high pressure system in which the winds spiral outwards in an anti-clockwise direction in the Southern Hemisphere

Boundary layer
The lowest layer of the atmosphere, adjacent to the ground and having properties affected by the nature of that surface.

Cyclone
An area of low pressure characterized by converging winds that blow in a clockwise direction in the Southern Hemisphere.

Dispersion
The spreading of pollution through transport and turbulence into a larger volume of air.

Downwash
The downward movement of pollution in the lee of buildings.

Effective stack height
The height of the centreline of a plume from a stack. It is equivalent to the physical stack height plus the plume rise.

Emission
Pollution discharged into the atmosphere from a range of stationary and mobile sources. These include smokestacks, vents and surface areas of commercial or industrial facilities; residential sources; motor vehicles and other transport related sources.

Fumigation
A condition in which pollutants are brought down towards the surface, causing high ground level concentrations, as a result of a low level temperature inversion layer which prevents the upward movement of pollutants. The low level inversion is often a remnant of a nocturnal surface inversion that has decayed from the base upwards as a result of surface heating after sunrise.

Instability

A state of the atmosphere in which a parcel of air when displaced vertically has a tendency to move further away from its original position.

Inversion
A condition in which the temperature of the atmosphere increases with height.

Katabatic wind
A downslope wind that occurs at night due to local surface cooling.

Lapse rate
The rate of change of temperature with respect to height.

Mountain wind
A wind that blows at night from the mountain down the longitudinal axis of a valley.

Neutral stability
A state of the atmosphere in which parcels of air that are vertically displaced remain at that height and are not further displaced.

Plume
A discharge of pollutants or exhaust gases from an emission source. It may often be visible.

Plume rise
The elevation of the plume centerline above the top of the stack. Plume rise is due to the effects of buoyancy and momentum.

Stability
A state of the atmosphere in which a parcel of air when displaced vertically has a tendency to return to its original position.

Valley wind
A wind that blows during the day up the longitudinal axis of a valley towards the higher terrain. It is caused by local heating.

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1. Introduction

The atmosphere is the medium into which pollutants are released and dispersed. Once emitted into the atmosphere, pollutants move away from the source and disperse into a large volume of air, the concentrations generally decreasing. The ability of the atmosphere to disperse pollution varies geographically, i.e. from place to place, and temporally, i.e. as a function of time. Sometimes the atmosphere promotes dispersion, and in such cases the concentration of pollution is generally decreased. At other times, however, the atmosphere may inhibit dispersion, with the result that pollution will accumulate near the source and concentrations will rise.

Knowledge of how the atmosphere behaves assists in understanding the movement of pollutants and hence in determining concentrations at particular locations. The vertical movement of pollutants is governed by atmospheric stability; the horizontal movement of pollutants is dependent on wind speed and direction; chemical transformation of pollutants in the atmosphere is principally governed by solar radiation and moisture; and finally, removal of pollutants from the atmosphere is dependent on precipitation.

Modellers also require an understanding of air pollution meteorology as it forms the basis of air pollution dispersion models. Such knowledge also assists in urban planning when making decisions about siting of residential areas, polluting industries and transport routes, and when establishing an air pollution monitoring network.

2. Air Pollution Meteorology

2.1 Vertical Dispersion and Atmospheric Stability

The concept of atmospheric stability is useful for determining whether air pollutants will rise or whether they will accumulate near the source. An ***unstable atmosphere*** is conducive to the vertical movement of pollutants and lower concentrations as the pollution is dispersed over a much larger volume of air. A ***stable atmosphere*** is one that inhibits vertical movement of pollutants and leads to much higher ground level concentrations. A ***neutral atmosphere*** is one in which pollution is accelerated neither up nor down but will remain at the height at which it was released.

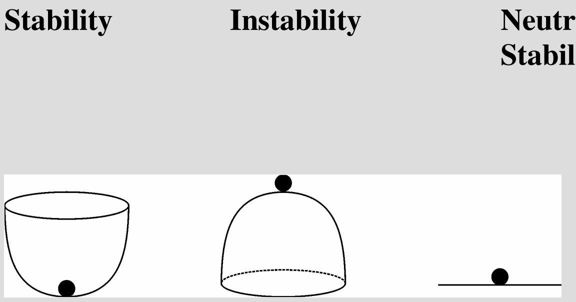
A useful analogy for atmospheric stability is the ball and bowl example illustrated in Box 1.

Box 1: Atmospheric Stability

In the first panel, a ball is placed inside the bowl. If an external force is applied to the ball, it will move up the side of the bowl. Once the force is removed, the ball will oscillate from side to side eventually coming to rest in its original position. This situation is analogous to a stable atmosphere or a condition of ***stability***, in which a force (for example, uplift over a mountain) is applied to a parcel of air, and once the force is removed the parcel of air comes to rest at its original position. Pollutants released into a stable atmosphere are inhibited from moving vertically and will accumulate near the surface leading to higher concentrations.

In the second panel, a ball is placed on top of an inverted bowl. If an external force is applied to the ball, it will move and will continue to move of its own accord after the force is removed. This situation is analogous to an unstable atmosphere or a condition of ***instability***, in which the parcel of air will continue to rise of its own accord. Pollutants released into an unstable atmosphere will be encouraged to rise and will be dispersed over a much greater volume of air.

In the third panel, a ball is placed on a table. If an external force is applied to the ball, it will move across the table. Once the force is removed, the ball will remain at that position. This situation is analogous to a neutral atmosphere or a condition of ***neutral stability***, in which pollutants will remain at the height at which they were released.


Stability **Instability** **Neutral Stability**

In the atmosphere, the determination of whether pollutants will be dispersed vertically or not is achieved by comparing the temperature of the small mass (parcel) of air containing the pollution, with the temperature of the surrounding or ambient air at the same height. If the temperature of the parcel of air is warmer, it will be less dense than the surrounding air and so will rise – a condition of instability; and if the temperature of the parcel of air is colder, then it will be more dense than the surrounding air and so will sink – a condition of stability.

The rate at which the temperature of a parcel of air changes as it moves vertically is constant if the air is dry and varies only a little if the air is saturated with water vapour. However, the rate at which the temperature of the surrounding or ambient air changes with height varies considerably over time and space. Hence it is the vertical temperature structure of the ambient air that determines whether the atmosphere is stable or not.

The vertical temperature structure of the boundary layer or layer closest to the earth's surface has three possible options. The temperature can decrease with height as shown in the left panel of Figure 1, or it can increase with height as in the centre panel, or it can remain constant with height as shown in the right hand panel of Figure 1. Both the inversion and isothermal conditions are always representative of stable conditions. Indeed, an inversion is commonly recognised as a condition that is not favourable for the dispersion of pollutants and is often cited as the cause of poor air quality. It is important to note, however, that it is not only under inversion conditions that the atmosphere is stable. Even under lapse conditions, there are times when the atmosphere can be stable. The critical factor that determines the stability condition of the atmosphere is the difference between the temperature of the parcel of air and that of the environment at the same height. Whenever the parcel of air is warmer it will rise and when it is colder it will sink.

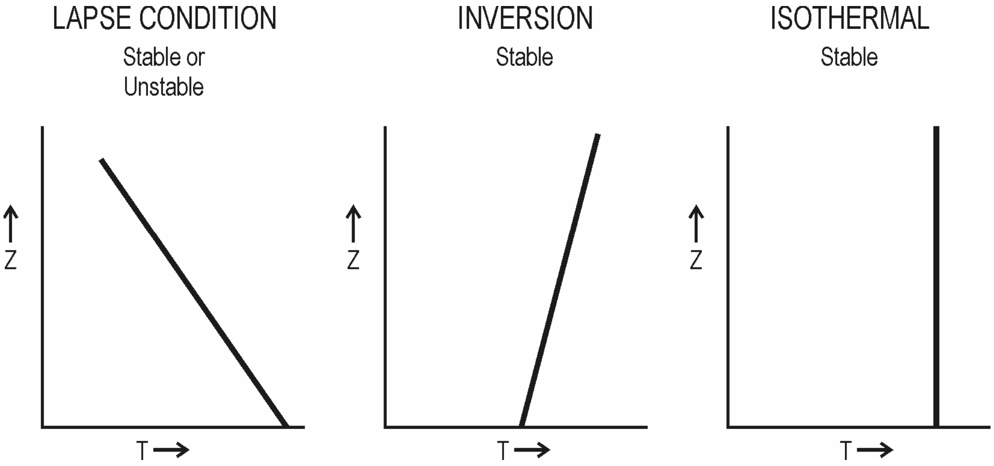


Figure 1: **Variations of the environmental lapse rate**

Lapse conditions are common during the day when the earth is heated by radiation from the sun. The stronger the solar heating, the greater the surface temperature. The slope of the line in the left hand panel of Figure 1 becomes greater (leans more to the left) and the instability is greater.

Temperature inversions on the other hand are caused by cooling of lower layers of air relative to upper layers. In the middle panel of Figure 1, a temperature inversion is shown to exist at the surface. Such an inversion is commonly caused by cooling of the earth by the loss of infrared radiation at night and is known as a radiation inversion. Surface inversions are also common in valleys where cold air collects at night.

The temperature structure of the boundary layer is linked to the diurnal heating cycle as shown in Figure 2. In the early morning, soon after sunrise, the surface begins to heat as a result of the absorption of solar radiation. The temperature of the lowest atmospheric layer increases and the surface inversion that existed throughout the night starts to dissipate from the ground upwards. A remnant of the surface inversion appears a short distance above the surface. With continued solar heating, the inversion is ultimately dissipated completely and a lapse profile (temperature decreases throughout the atmosphere) is evident. Around sunset, the surface begins to cool as it is losing more radiation through infrared radiative transfer than is being received. A surface temperature inversion develops and deepens throughout the night.

This cycle is repeated on a daily basis and is particularly well developed under clear skies and calm conditions and over open terrain. It is expected that daytime surface solar heating and night time cooling will be best developed in the extreme seasons of summer and winter respectively and influence the near-surface temperature profile.

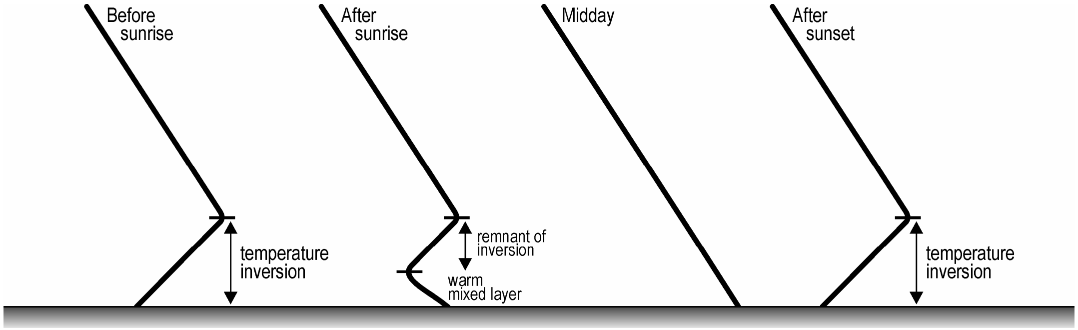


Figure 2: Change in the environmental lapse rate as a function of time of day

2.2 Horizontal Dispersion and Winds

The movement of air horizontally is a function of wind speed and direction. The higher the wind speed, the greater the dispersion of pollution. Direction is also important as it determines where the pollution moves and hence governs the downwind impact areas.

Wind is generated as a result of a pressure gradient in the atmosphere (difference in pressure over a horizontal distance). It is convenient to think of wind as being produced on a range of different scales, ranging from the global or large scale to the local scale. Smaller scale systems are embedded within the larger scale systems and the effects will differ depending on the interactions between them.

At the global scale, there is a set of wind belts and semi-permanent high and low pressure belts which govern climates on earth. In terms of effects on pollution, they produce semi-permanent areas that are either favourable or unfavourable for the dispersion of pollutants. Thus it is generally recognised that wind speeds are low in the equatorial regions and high in the mid-latitudes. South Africa is situated astride a semi-permanent subtropical high pressure belt, which is characterised by light winds, which are not conducive to pollution dispersion. These high pressure systems strengthen during the winter months and so pollution dispersion is generally less favourable in winter over South Africa. As well as being characterised by light winds, high pressure systems are also accompanied by stable atmospheric conditions because of the sinking or subsiding air, which further inhibits dispersion.

At the next scale, we can identify travelling high and low pressure systems, which are depicted on the daily synoptic weather charts. Characteristic weather is associated with each of these systems. For example, a low pressure system or cyclone is associated with strong winds and instability, whereas, a high pressure system or anticyclone is characterised by light winds and stability. The frequent passage of low pressure systems in the westerly wind belt situated to the south of South Africa brings frequent changes in stability and wind conditions particularly to the coastal areas.

At the local level, there are additional circulations that also play a significant role in the dispersion and transport of pollution. These local circulations arise largely because of pressure gradients that are driven by temperature differences caused by uneven surface heating and differences in topography. In some cases, these local winds can be more important than the large scale wind systems. Examples include land and sea breezes, which develop along coastal areas; and topographically-induced winds, which develop in areas of complex terrain.

In areas of complex terrain, topographically-induced circulations may develop. These may be categorized into:

- slope winds
- valley winds
- regional mountain-plain winds

Slope winds flow up and down the sides of a valley cross-section as a result of heating and cooling differences between the valley floor and valley sides. By day, winds blow upslope (anabatic winds) and by night winds blow downslope (katabatic winds) (Fig. 3).

Valley winds blow up and down the longitudinal section of a valley. By day the winds blow up valley (valley winds) and by night they blow down valley (mountain winds) (Fig. 3).

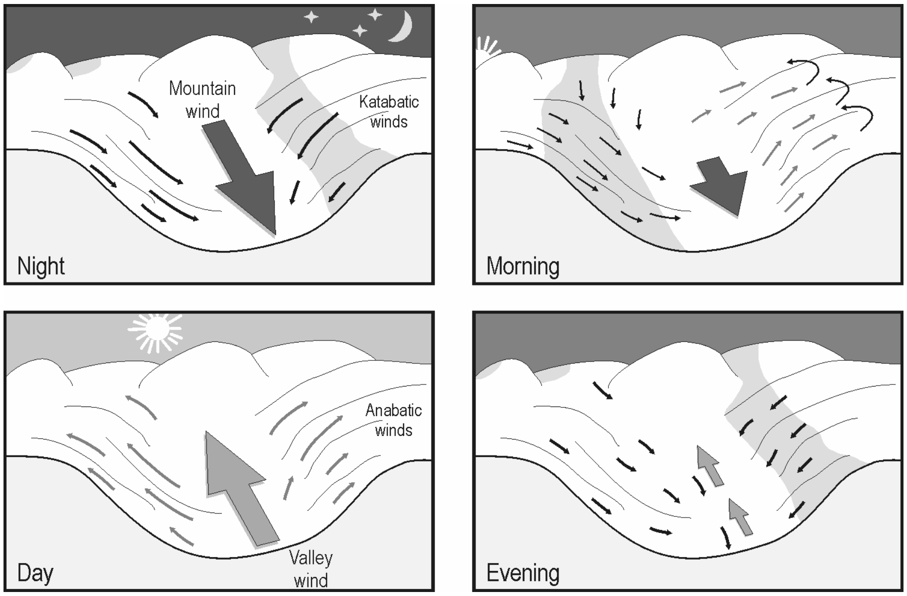


Figure 3 **Diagrammatic sketch of slope and valley winds** (adapted from NILU, 2003)

In areas of strongly dissected topography and where a number of valleys lie adjacent to each other, the valley (mountain) winds may deepen and overflow on to the surrounding terrain so that a widespread sheet of air moves across an entire region. Such regional-scale winds are called mountain-plain winds at night and plain-mountain winds during the day. They are particularly significant in KwaZulu-Natal (KZN) where they play a significant role in the transport of pollution over long distances.

Land and sea breezes develop as a result of the difference in thermal properties between land and water surfaces. During the day, the land heats up more that the sea, and at night the land cools more rapidly than the ocean. The temperature difference between land and sea sets up a pressure gradient that drives a local circulation, in which winds shift in direction with time of day. Sea breezes occur during the day and blow from the sea to the land (Fig. 4). They are characterized by turbulence and instability and as such favour the vertical dispersion of pollution. Sometimes they lead to elevated pollution layers at the level of the offshore flow aloft. Land breezes on the other hand occur at night and flow from land to sea (Fig. 4). The winds are usually light, the wind systems are shallow and they develop in a stable atmosphere. Pollution is not readily dispersed but may be transported long distances as a narrow plume in a stable atmosphere. They tend to be better developed in winter when nighttime cooling is greater.

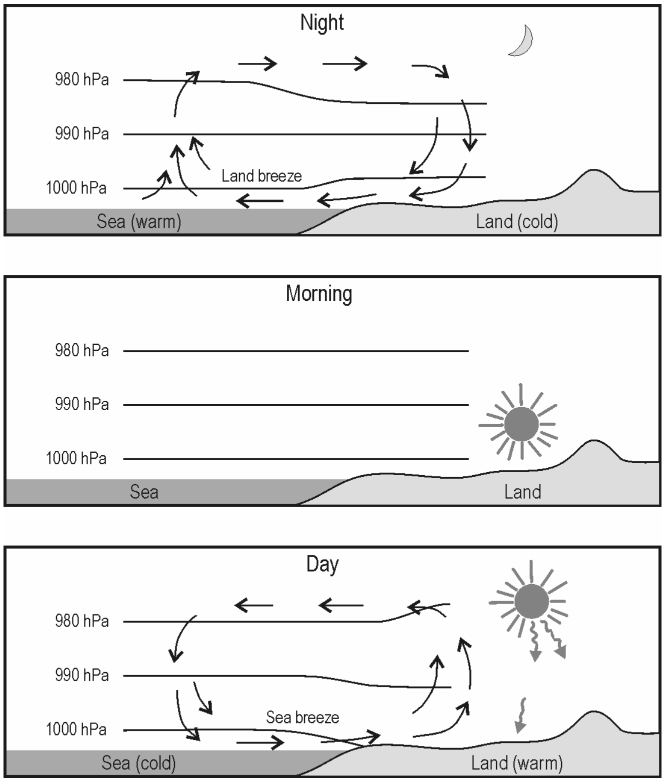


Figure 4: **Diagrammatic sketch of land and sea breeze circulations** (adapted from NILU, 2003)

3. Plume Structure and Behaviour

The typical shape of a plume of pollution emitted from an industrial stack is cone-shaped as shown in Figure 5. Generally, the plume rises a certain distance above the top of the stack because it is either emitted with force or it has a higher temperature than the surrounding air. This distance is known as the plume rise. The plume rise plus the physical stack height gives the effective stack height.

The plume then moves in the downwind direction as indicated by the arrow in Figure 5. The pollutants spread horizontally (in the crosswind direction) and vertically and the concentrations of pollutants decrease away from the centerline of the plume.

The cone-shaped plume shown in Figure 5 is typical of neutral stability conditions, which may not commonly exist in particular regions. Sometimes plumes may take on very different shapes as shown in Figure 6. These are generally the result of varying atmospheric conditions.

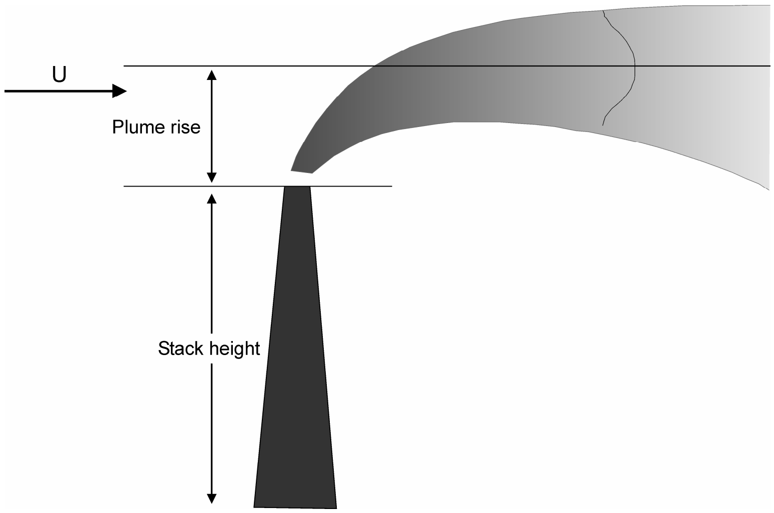


Figure 5: Typical cone-shaped plume from an industrial stack

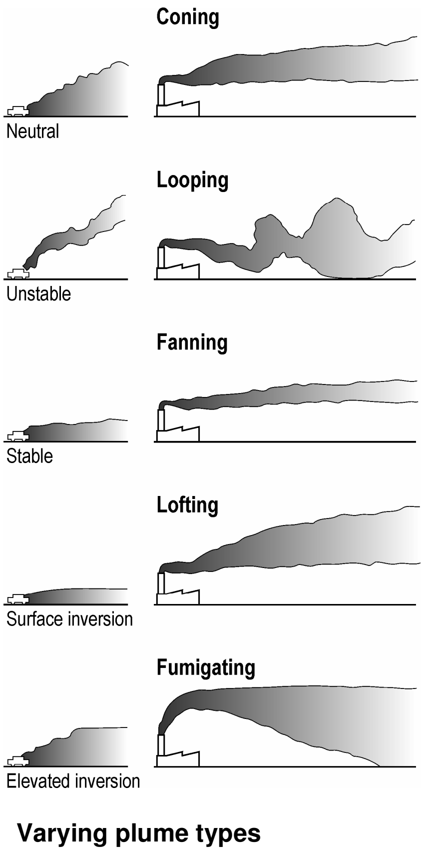


Figure 6: Varying plume types

A coning plume, as stated above, is characteristic of a neutrally stable atmosphere. Pollutants from an elevated plume do not reach the surface. Emissions from low level sources, such as motor vehicles, impact on ground level concentrations.

The looping plume is associated with an unstable atmosphere. Pollutants are moved up and down by turbulence. The plume from an elevated stack may meet the surface and as such give rise to a short-lived period of high concentrations. Emissions from low level sources are moved vertically away from the surface, giving rise to the most favourable ground level situation.

A fanning plume occurs under stable atmospheric conditions. It does not spread vertically because vertical dispersion is inhibited, but fans out in the horizontal cross-wind direction. Pollutants from low level sources are also inhibited from spreading vertically and are concentrated close to the surface, giving rise to high ground level concentrations.

A lofting plume occurs when the height of a stack or the origin of the plume is situated above a surface inversion. Pollutants are unable to penetrate downwards and are lofted upwards. However, emissions from low level sources are released within the inversion layer, which inhibits vertical movement and leads to high ground level concentrations.

A fumigating plume usually occurs in association with a decaying radiation inversion. Pollutants that are released below the base height of the inversion are unable to penetrate it and are fumigated towards the surface leading to high surface pollutant concentrations. Fortunately this situation is short-lived.

4. Effect of Topography on Wind Flow

In addition to the winds which are topographically induced and which are described in section 2.2, topography can influence the wind flow in a number of ways.

An isolated hill causes winds to be squeezed over the top and around the sides of the hill so that the wind is accelerated on the upwind side. In the lee of the hill, winds reduce in speed and are often very turbulent. Topography can also channel winds through narrow gaps and cause an increase in wind speed. After leaving the constriction the winds slow down.

5. Effect of Buildings on Wind Flow

Buildings give rise to many local effects on wind flow and in turn influence air pollution dispersion. The classic pattern of airflow around a flat-roofed building is shown in Figure 7. Four flow zones, known as the undisturbed zone (A), the displacement zone (B), the cavity (C) and the wake (D) are formed. In the displacement zone there is an increase in wind speed and in the cavity zone, the winds decrease in speed and are more turbulent.

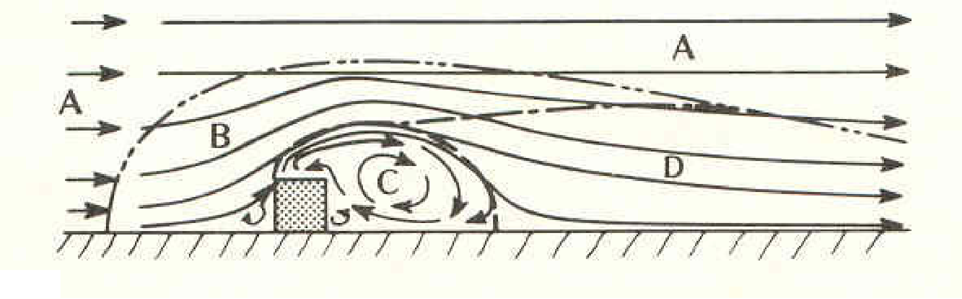


Figure 7: Airflow around a flat-roofed building. A – displacement zone; B – disturbed zone; C – cavity; D – wake (after Oke, 1978)

Varying effects on pollution dispersion occur depending on the location of the exhaust emissions. Serious problems can arise if the pollution becomes caught up in the downwash behind a tall building as shown in Figure 8.

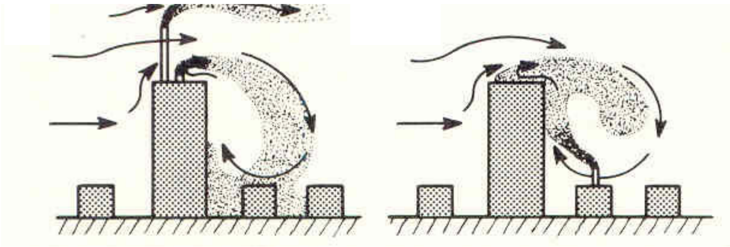


Figure 8: Downwash of pollution behind a tall building (after Oke, 1978)

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