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AIR POLLUTION METEOROLOGY**

Compiled by Professor Roseanne Diab  
University of KwaZulu-Natal, Howard College Campus, Durban 4041

## ACRONYMS

DALR	Dry adiabatic lapse rate
ELR	Environmental lapse rate
SALR	Saturated adiabatic lapse rate
APP	Air pollution potential
KZN	KwaZulu-Natal

## GLOSSARY

### **Absolutely stable**

A condition of the atmosphere in which the environmental lapse rate is less than the saturated adiabatic lapse rate.

### **Absolutely unstable**

A condition of the atmosphere in which the environmental lapse rate is greater than the dry adiabatic lapse rate.

### **Adiabatic lapse rate**

The rate of change of temperature of a parcel of air that is rising or sinking in the air environment.

### **Adiabatic process**

A process in which a temperature change in a system can occur and yet no heat exchange takes place between the system and its surroundings.

### **Air pollution potential**

The ability of the atmosphere to accumulate air pollution.

### **Albedo**

The reflectivity of a surface in respect of solar radiation. It determines the proportion of the incident solar radiation flux that will be reflected rather than absorbed by the surface.

### **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.

### **Cloud condensation nucleus**

A small particle, either solid or liquid, upon which water vapour condenses to form a cloud droplet.

### **Conditional instability**

A condition in which the environmental lapse rate lies between the dry and saturated adiabatic lapse rates, and stability is dependent on whether the air is saturated or not.

### **Conduction**

Heat transfer by molecular motion.

### **Convection**

The vertical mixing of air by turbulent eddies.

**Cyclone**

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

**Diabatic process**

A process in which heat is exchanged across the boundaries of the system, causing a temperature change.

**Dry adiabatic lapse rate**

The rate of change of temperature of a dry or unsaturated parcel of air, which is rising (or sinking) within the air environment. The rate is constant at  $\sim 1^\circ\text{C}$  per 100m.

**Environmental lapse rate**

The rate at which the temperature in the environment or the ambient air changes with respect to height.

**Forced convection**

Uplift of air due to an external or non-buoyancy force such as the generation of mechanical turbulence due to the roughness of the surface or the upward movement of air when it meets a topographic barrier.

**Free convection**

Thermal turbulence caused by differences in density that result from differential heating. Parcels of air that are heated become less dense or buoyant and rise.

**Free troposphere**

The layer of the atmosphere situated above the boundary layer. The temperature decreases with altitude at a rate of approximately 6.5K per km and the layer does not undergo short term temperature changes driven by the diurnal solar radiation cycle.

**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.

**Heat capacity**

The amount of heat required to raise the temperature of a substance by  $1^\circ\text{C}$ .

**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.

**Lapse rate**

The rate of change of temperature with respect to height.

**Mechanical turbulence**

Turbulent eddies created by the roughness of a surface.

**Mixing height**

A layer characterized by turbulence and the promotion of vertical mixing of pollutants.

**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.

**Saturated adiabatic lapse rate**

The rate of change of temperature of a saturated parcel of air, which is rising (or sinking) within the air environment.

**Thermal turbulence**

Turbulent eddies created by the heating of a surface.

**Troposphere**

The layer of the atmosphere situated closest to the earth's surface and the layer within which our weather occurs and pollutants are released. It is approximately 10 km deep but its depth varies with season and latitude.

**Wind shear**

A change in wind velocity (speed and/or direction) with height.

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## 1. Introduction

Once released into the atmosphere, pollutants disperse into a large volume of air and move away from the source. The ability of the atmosphere to disperse pollution varies geographically and temporally. 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.

Atmospheric dispersion depends firstly, on the vertical movement of air, which is a function of atmospheric stability, and secondly, the horizontal movement of air, which is dependent on wind speed and direction. Further, chemical transformation of pollutants in the atmosphere is governed principally by solar radiation and moisture, and removal of pollutants from the atmosphere is dependent on precipitation. Hence the role of meteorology is critical in determining the concentration of pollution at a particular location.

Knowledge of air pollution meteorology is also essential for air quality modelling, it is useful in urban planning when making decisions about siting of residential areas, polluting industries and transport routes, and when establishing an air pollution monitoring network. For all these reasons it is important to understand something about air pollution meteorology.

*In brief, the fate of an air pollutant once it is released into the atmosphere is governed by meteorology.*

## 2. Temperature Structure of the Atmosphere

The sun emits electromagnetic radiation as shortwave or solar radiation. The atmosphere is largely transparent to solar radiation, with the exception of a small amount that is scattered off particulates, reflected by clouds and absorbed by ozone, and so most of the energy travels through the atmosphere relatively unattenuated. This solar radiation then strikes the surface of the earth. Some of the short wave energy is reflected by the surface and as such does not participate in heating the earth or the atmosphere. The remainder that is absorbed by the surface contributes to heating of the surface, and the earth as a radiating body with a temperature much lower than that of the sun then re-emits this energy as infrared or long wave radiation to the atmosphere. The atmosphere is thus heated from below and consequently the temperature of the lower atmosphere generally decreases with height.

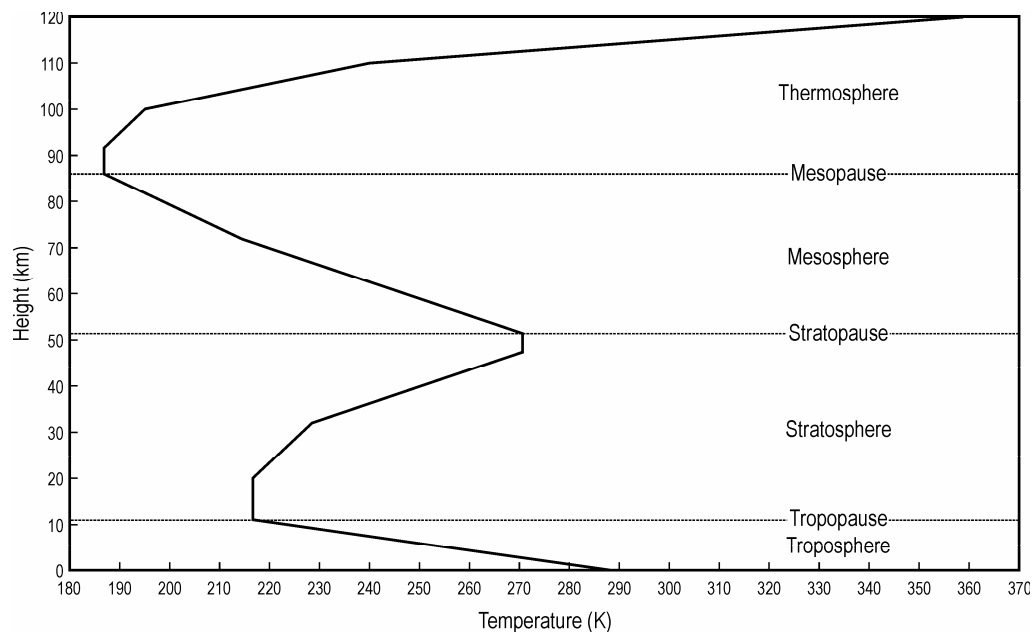
The atmosphere can be divided into four layers on the basis of vertical temperature structure (Figure 1). The **troposphere** is the most important layer from an air pollution perspective. It is the layer within which all our weather occurs and



the layer into which the vast majority of our pollutants are emitted and dispersed. It is approximately 10 km deep, although its depth varies with latitude and season, extending to a higher altitude in the tropics compared with mid-latitudes, and is higher in summer than in winter. On average the temperature of the troposphere decreases with height as explained above.

The troposphere, in turn, can be divided into the **boundary layer** and the **free troposphere**. As the name suggests, the boundary layer is the layer closest to the surface and it is strongly influenced by the nature of the underlying surface. The vertical temperature profile in the boundary layer is governed by heating and cooling of the earth's surface and may undergo short term temperature changes as described in Section 3.4. It is a layer characterized by turbulent mixing, generated by heating of the surface which leads to 'bubbles' of air rising from the surface (**thermal turbulence**) and **mechanical turbulence** caused by air moving across a rough surface. The height of the boundary layer varies during the day. In the daytime, it can extend up to 2-3 km as a result of strong heating of the surface by solar radiation; at night when the earth's surface cools, it can decline to less than 100 m (Oke, 1988). The vertical wind profile in the boundary layer is also affected by the nature of the underlying surface, as described in Section 4.4.

The **free troposphere** lies above the boundary layer and does not undergo the short term temperature changes driven by the diurnal solar radiation cycle that characterize the boundary layer. Here the temperature decreases with altitude at a rate of approximately 6.5K per km. If pollutants are able to escape the boundary layer and enter the free troposphere, they may be transported long distances downwind as a result of the stronger winds at higher altitudes.



**Figure 1: Vertical temperature structure of the atmosphere**

### 3. Vertical Dispersion

Pollutants, as well as heat and moisture, can be moved vertically in the atmosphere by turbulent eddies. The general term used to describe this vertical mixing by turbulent eddies is **convection**, as distinct from **conduction**, in which heat transfer is via molecular processes. Conduction is responsible for the transfer of heat in the lowest few millimetres of the atmosphere, but generally convection is far more dominant. Convection can only occur in gases or liquids and can be free or forced. **Free convection** is caused by differences in density that result from differential heating, giving rise to thermal turbulence. Parcels of air that are heated become less dense or buoyant and rise. **Forced convection** is when uplift occurs due to an external or non-buoyancy force. Examples include the generation of mechanical turbulence due to the roughness of the surface, the upward movement of air when it meets a topographic barrier, and uplift due to convergence of winds at the surface.

The following sections outline the vertical motion that occurs as a result of buoyancy in the atmosphere.

#### 3.1 Lapse Rates

The vertical movement of air or pollutants is determined by the relationship between the temperature structure of the atmosphere (expressed by the environmental lapse rate) and the rate at which a parcel of air (or a pollutant) can rise or sink (expressed by the adiabatic lapse rate).

##### Environmental Lapse Rate (ELR or $\Gamma$ )

This is the rate at which the temperature in the environment or the ambient air changes with respect to height. Temperatures at different heights are measured by a weather balloon or an instrumented tower. The ELR varies considerably in time and space, particularly in the boundary layer, but it is possible to define a standard atmosphere for the troposphere, in which the lapse rate approximates  $6.7^{\circ}\text{C km}^{-1}$ .

##### Adiabatic Lapse Rate

This refers to the rate of change of temperature of a parcel of air, which is rising (or sinking) within the air environment. The sign (positive or negative) of a lapse rate is opposite to that of the temperature change with height. A positive lapse rate indicates that the temperature is decreasing with increasing height. The nature of adiabatic processes are defined in more detail in Box 1.

**Dry Adiabatic Lapse Rate (DALR or  $\Gamma_d$ )** – Rate of change of temperature of a parcel of dry air as it moves vertically. As the air parcel moves upward (downward) it expands (compresses) as it encounters lower (higher) pressure and cools (heats) without exchanging heat with the surroundings. The DALR is constant at  $\sim 1^{\circ}\text{C per km}$ .

100m and can be used not only for dry air but for moist air well, provided the air is unsaturated, i.e. the water is in a vapour rather than a liquid form.

**Saturated Adiabatic Lapse Rate (SALR or  $\Gamma_s$ )** – Once air becomes saturated with water vapour, further lifting can lead to condensation in which case latent heat is released. The rate of cooling is thus retarded and also varies depending on the water vapour content of the atmosphere and the temperature. Typically, the SALR is about 0.2 to 0.6°C per 100m.

**Box 1:  
Adiabatic and Diabatic Processes**

Temperature changes can occur in a variety of ways.

An **adiabatic process** is one in which a temperature change in a system can occur and yet no heat exchange takes place between the system and its surroundings. In the atmosphere we can define a small parcel of air which undergoes a temperature change, despite no heat exchange with the surrounding atmosphere. With a change in height, the parcel of air undergoes a pressure change which leads to a temperature change. Specifically, an increase (decrease) in height results in an expansion (compression) of the parcel of air or an increase (decrease) in volume, which removes (adds) energy by means of work done. As a consequence there is an internal temperature decrease (increase). The temperature changes due to adiabatic processes can often be much larger than those due to diabatic processes.

A **diabatic process**, on the other hand, is one in which heat is exchanged across the boundaries of the system, causing a temperature change. Examples of diabatic heating include solar radiation heating and convective processes.

### 3.2 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 or 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 2.

## Box 2: 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 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 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 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.

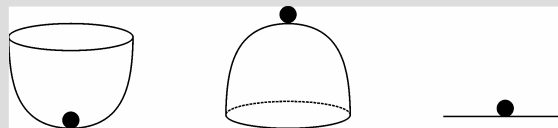
In the third panel, a ball is placed on a table. If an external force is applied to the ball, it will move across the table. Once the force is removed, the ball will remain at that position. This situation is analogous to a neutral atmosphere or a condition of **neutral stability**, in which pollutants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

It is important to note that once the external force is removed, the only force acting on the ball is the gravitational force which is always downward. An air parcel on the other hand is affected by two forces, the gravitational force and the buoyancy force. The latter may be upward or downward depending on whether the air parcel is less or more dense than the ambient air.

**Stability**

**Instability**

**Neutral Stability**



### 3.3 Determination of Atmospheric Stability

This is achieved by comparing the temperature of the ambient air (expressed by the ELR) and the temperature of a rising (or sinking) parcel of air (expressed by the DALR or SALR) at the same height. Figure 2 shows the possible variations of the ELR and Figure 3 depicts the stability states for an unsaturated atmosphere when the ELR and the DALR are compared. From Figure 3 (left hand panel), at height  $z_1$ , it is noted that the temperature of the parcel ( $T_p$ ) is less than the temperature of the ambient or environmental air ( $T_e$ ). If the temperature is less, the density is greater and consequently the air will tend to sink, indicative of a stable atmosphere. In the right hand panel of Figure 3, the temperature of the parcel is greater than the temperature of the ambient air ( $T_p > T_e$ ) and the air will tend to rise because of a lower density, indicative of an unstable atmosphere.

If the air is saturated, a similar comparison could be done between the ELR and SALR to determine stability (not shown here).

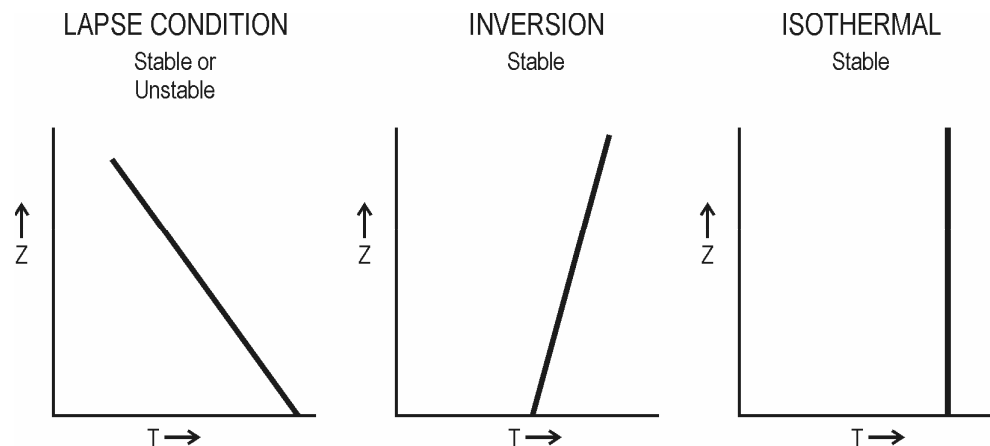


Figure 2: Variations of the environmental lapse rate

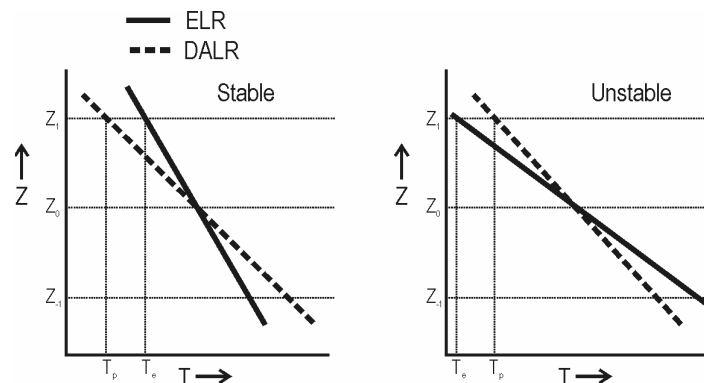


Figure 3: Stability states for an unsaturated atmosphere

In summary, the following conditions apply.

<b>Unsaturated air:</b>	
$\Gamma > \Gamma_d$	dry unstable
$\Gamma = \Gamma_d$	dry neutral
$\Gamma < \Gamma_d$	dry stable
<b>Saturated air:</b>	
$\Gamma > \Gamma_s$	wet unstable
$\Gamma = \Gamma_s$	wet neutral
$\Gamma < \Gamma_s$	wet stable

Although atmospheric stability is always obtained by comparing the ELR with either the DALR or the SALR (not both), it is useful to summarise the criteria by means of Figure 4 and as follows:

$\Gamma > \Gamma_d$	absolutely unstable
$\Gamma = \Gamma_d$	dry neutral
$\Gamma_d > \Gamma > \Gamma_s$	conditionally unstable
$\Gamma = \Gamma_s$	wet neutral
$\Gamma < \Gamma_s$	absolutely stable

An atmosphere that is **absolutely unstable** is unstable irrespective of whether the air is unsaturated or saturated, and similarly, an **absolutely stable** atmosphere is stable irrespective of whether the air is unsaturated or saturated. **Conditional stability** occurs when the ELR lies between the dry and saturated adiabatic lapse rates, and means that the stability is dependent on whether the air is saturated or not.

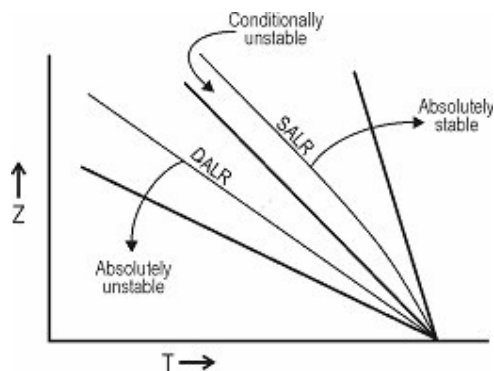


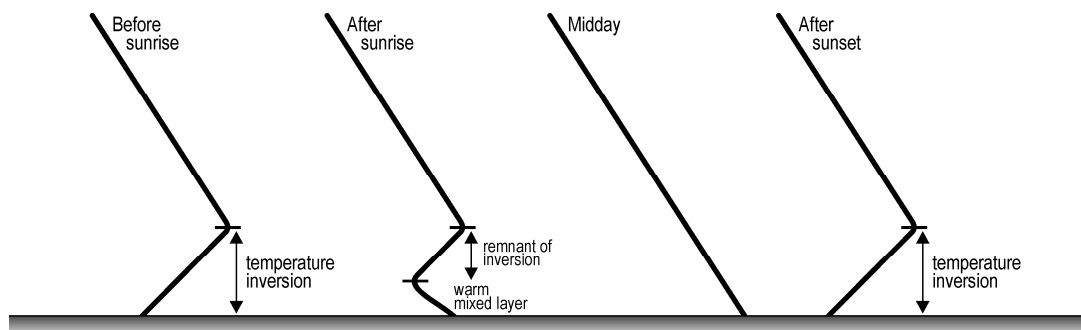
Figure 4: Summary of atmospheric stability states

### 3.4 Variations in Environmental Lapse Rate

The ELR in the boundary layer varies, *inter alia*, as a function of time of day, season, the underlying surface and the prevailing weather conditions.

#### Time of Day

The ELR is linked to the diurnal heating cycle as shown in Figure 5. 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 layers increases and the surface inversion starts to dissipate from the ground upwards. A remnant of the surface inversion appears a short distance above the surface as an elevated inversion. 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.



**Figure 5: Change in the environmental lapse rate as a function of time of day**

This cycle is repeated on a daily basis and is particularly well developed under clear skies and calm conditions and over open terrain. This is the process which leads to the occurrence of radiation inversions (see Section 3.5).

#### Season

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. Surface temperature inversions which result from night time radiative cooling tend to occur most frequently in the winter months.

#### Underlying Surface

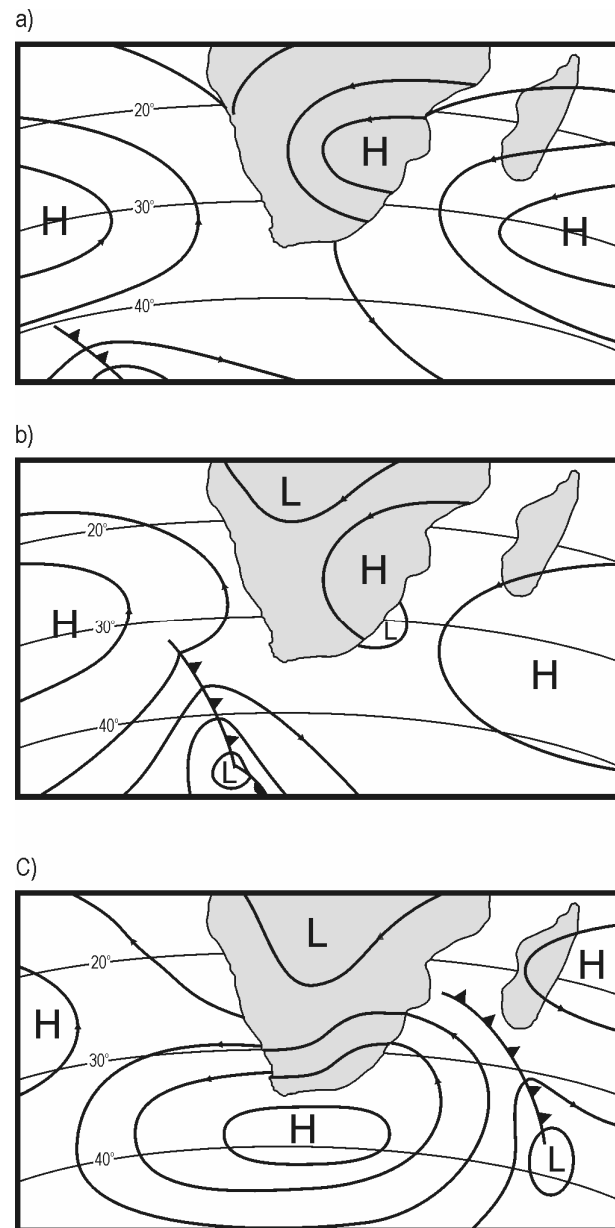
The thermal properties (e.g. heat capacity, albedo) of the underlying surface determine the extent to which a surface will heat up. A surface with a high heat capacity (e.g. concrete) requires a large amount of solar radiation to effect a temperature change but then this is accompanied by good heat storage ability. Heat absorbed during the day may then be released at night and may inhibit surface radiative cooling and consequently the development of surface radiation inversions. A surface with a high albedo (reflectivity) (e.g. snow) is able to reflect a high proportion of incident solar radiation and so absorbs less solar radiation and heats up less strongly. The roughness of a surface will also affect the turbulent mixing over the surface, which in turn impacts on the stability.

### **Synoptic Weather**

Atmospheric stability changes significantly as a function of prevailing weather. Anticyclonic (high pressure) systems are accompanied by strong subsidence (sinking). As air descends it warms adiabatically at the dry adiabatic lapse rate and a subsidence inversion develops above the surface. Subsidence inversions are common features of the atmosphere over southern Africa as a result of the semi-permanent subtropical anticyclone, which strengthens in winter. Anticyclones are also characterised by light winds and cloudless skies and as such favour the development of surface radiation inversions. In contrast, cyclonic (low pressure) systems are accompanied by near-surface convergence and uplift with the result that vertical movement and instability is favoured.

Weather systems are thus characterised by distinctly different dispersion conditions as was described by Preston-Whyte and Diab (1980). This has enabled a categorisation of synoptic weather systems over the east coast regions of South Africa and their air pollution potential (APP – ability of the atmosphere to accumulate pollution) (Fig. 6). The **established high pressure** situation is characterised by moderate APP as a result of light winds and stable atmospheric conditions. Nocturnal surface inversions are generally well developed as a result of the clear skies and low winds and upper level subsidence inversions are common. The **prefrontal** situation, which occurs just prior to the passage of a cold front is accompanied by a very low mixing layer as the subsidence inversion dips towards the surface ahead of the front. APP is high under this condition. Once the front has passed, the **postfrontal** situation with its strong winds, instability, development of clouds and possible rain produces a condition of low APP (Diab *et al.*, 1991).



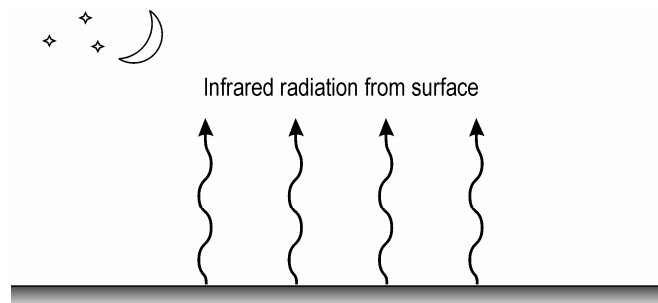


**Figure 6:** Categorisation of synoptic weather regimes for coastal regions of South Africa. a) established high pressure b) prefrontal c) postfrontal (after Diab *et al.*, 1991)

### 3.5 Types of Inversions

#### ***Radiation Inversions***

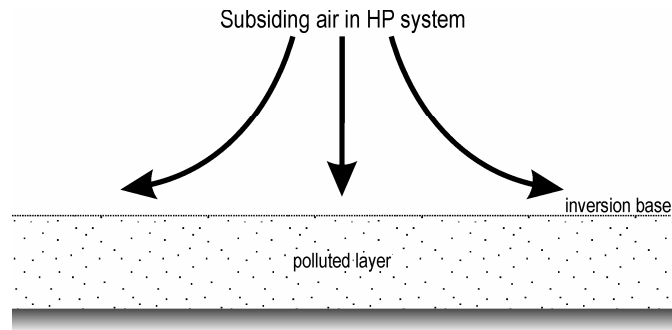
A radiation inversion develops at the surface as a result of infrared radiational cooling at night. It sets in soon after sunset as a result of the loss of infrared radiation from the surface of the earth and consequent cooling of the surface. The inversion will deepen through the night and will dissipate soon after sunrise as a result of surface heating by solar radiation. During the dissipation process, the inversion decays from the base upwards, sometimes leaving a remnant of the inversion at a short distance above the surface. This can lead to particularly dangerous fumigation conditions if the stack height is below the remnant inversion, as pollutants are unable to penetrate the remnant inversion but can be fumigated down to the surface in the unstable near-surface layer (Fig. 7). Radiation inversions are short-lived and seldom cause prolonged accumulation of pollution.



**Figure 7: Development of radiation inversion**

#### ***Subsidence Inversions***

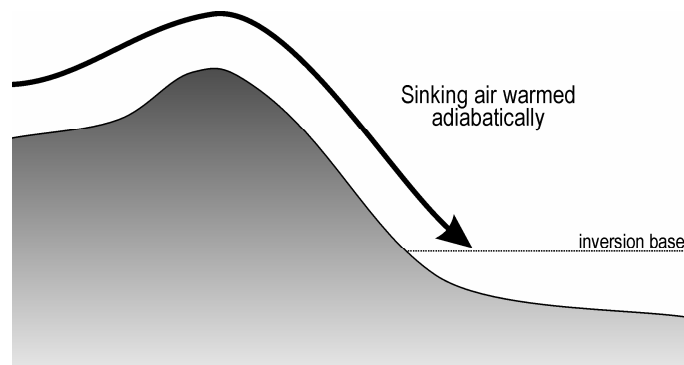
A subsidence inversion develops as a result of subsidence or sinking within an anticyclone (high pressure system). Sinking air warms adiabatically at the dry adiabatic lapse rate and leads to relatively warmer air situated above cooler air (Fig. 8). The inversion base is usually situated hundreds to thousands of metres above the surface. Clearly, the closer to the surface the base of the inversion is situated, the more serious the implications for air pollution concentration as the volume of air available for dispersion is reduced. In South Africa, the subsidence inversion is most prevalent in winter and is situated a few thousand metres above the surface. The base of the inversion tends to be closer to the surface (< 700 m) and the frequency greater along the west coast of South Africa (Preston-Whyte *et al.*, 1977).



**Figure 8: Development of a subsidence inversion**

### ***Regional Subsidence Inversions***

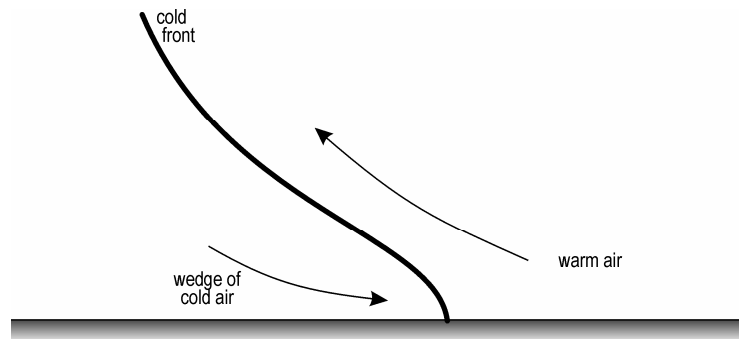
These inversions are also caused through subsidence, but unlike the former are linked to topographic features that induce subsidence. Air that descends over a mountain barrier warms adiabatically on the leeward side leading to the formation of a regional subsidence inversion (Fig. 9). In South Africa, Berg winds which descend from the Drakensberg escarpment to the coast are always accompanied by subsidence inversions as a result of adiabatic warming.



**Figure 9: Regional subsidence inversion caused by sinking air over a mountain barrier**

### ***Frontal Inversions***

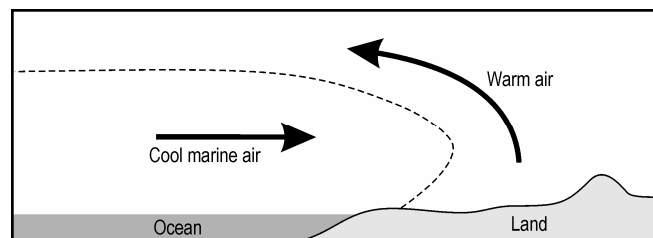
A front marks a boundary between warm and cold air masses. At a cold front, cold dense air undercuts the warmer air, forcing it up and creating a situation where warmer air overlays colder air, hence an inversion (Fig. 10).



**Figure 10: Frontal inversion**

### ***Marine Inversions***

The difference in heating between land and sea creates a sea breeze (see Section 4.3) which causes the movement of relatively cool marine air towards the land (sea breeze). The relatively warmer air over the land rises and overlays the cooler marine air, creating a marine inversion (Fig. 11). This phenomenon is particularly prevalent on the west coasts of continents where the oceans are cold.



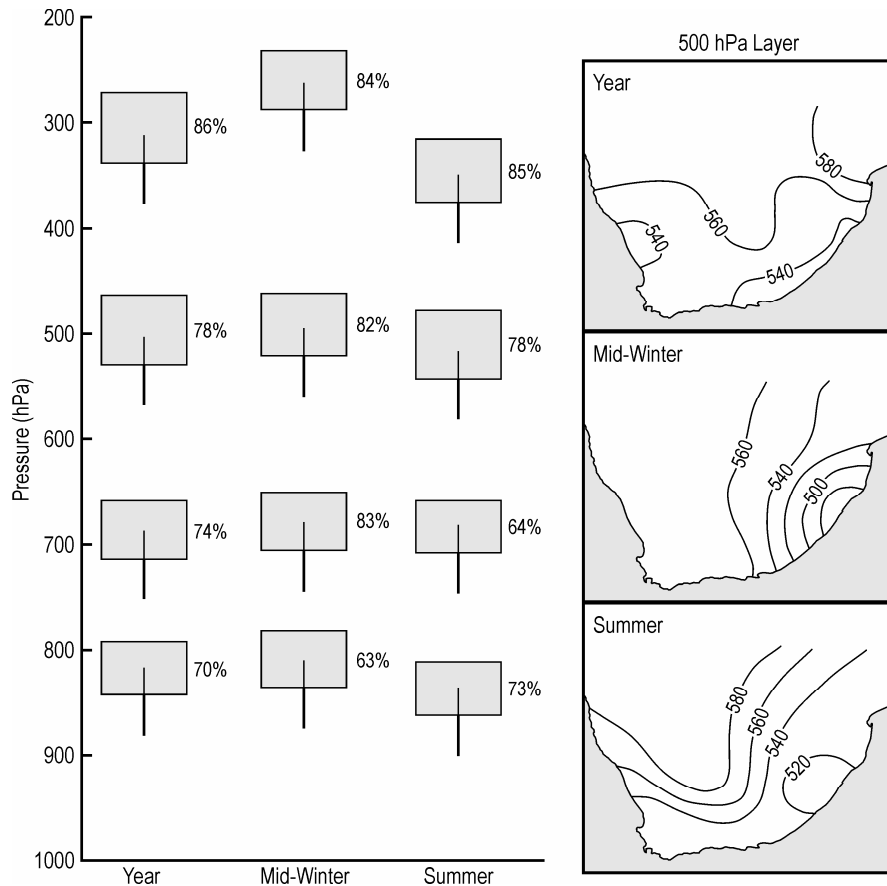
**Figure 11: Marine inversion**

## **3.6 Indicators of Stability**

In view of the importance of atmospheric stability to air pollution dispersion, a number of indicators of stability have been developed. Some of those in common use are:

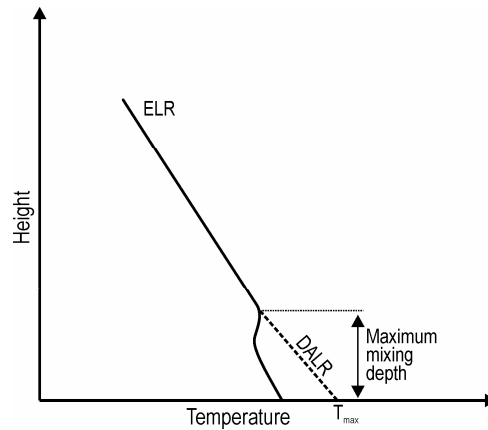
***Inversions*** - A temperature inversion is defined as an increase of ambient temperature with respect to height. Useful parameters are the frequency with which an inversion occurs (usually given as a function of month or season), its base height (at the surface or some height above the surface), its depth and intensity (difference between the temperature at the top of the inversion and the base of the inversion). The drawback of using inversions as an indicator is that they are an extreme form of stability and the atmosphere may be stable without an inversion being present. A climatology of surface and upper level inversion layers over South Africa is given by Tyson *et al.* (1976) and Preston-Whyte *et al.* (1977) respectively.

**Stable Layer** - An absolutely stable layer is defined as one in which the ELR is less than the SALR. This is a less conservative measure of stability than an inversion and has been commonly applied in South Africa in recent years to indicate the prevalence of stable layers over the subcontinent (Cosijn and Tyson, 1996). The present frequency and height of absolutely stable layers as a function of season is shown in Figure 12.



**Figure 12: Frequency and height of absolutely stable layers as a function of season (after Cosijn and Tyson, 1996)**

**Mixing Height** – This is a measure of the height (depth) of the convective layer or the layer within which vertical mixing and turbulence can occur. It is calculated by taking the surface temperature at the time of interest and extending it vertically according to the DALR until it intersects the early morning temperature lapse rate. The maximum mixing depth is estimated in this way from the surface maximum temperature (Fig. 13). A climatology of mixing heights over South Africa is given by Diab (1978).

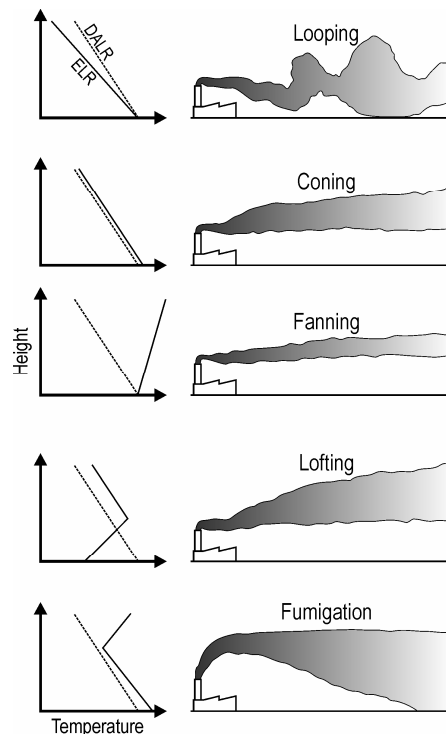


**Figure 13: Computation of maximum mixing height**

**Daily Temperature Range** - In the absence of any vertical temperature data a surrogate measure of the likelihood of the development of a surface temperature inversion is given by daily temperature range. A large value generally indicates intense nocturnal cooling and a stronger chance of a surface inversion developing.

### 3.7 Stability and Plume Types

Plumes from stacks take on a variety of characteristic shapes depending on the stability characteristics of the atmosphere (Fig. 14).



**Figure 14: Plume types as a function of stability conditions**

In a **looping plume** pollutants are moved up and down in turbulent eddies associated with an unstable atmosphere. Such a plume may intercept the surface and give rise to a short-lived period of high concentrations. A **coning plume** is characteristic of a neutral atmosphere. A **fanning plume** has a relatively small vertical dimension because vertical dispersion is inhibited, yet spreads out in the horizontal cross-wind direction. It occurs under stable atmospheric conditions. 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. A **fumigating plume** usually occurs in association with a decaying radiation inversion (see Section 3.5). 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. Horizontal Dispersion

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 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). Various scales of motion ranging from global to local are able to generate pressure gradients and consequently give rise to winds. It is convenient to think of winds as being produced by a whole set of nested systems of different scales. Smaller scale systems are embedded within the larger scale systems and the effects will differ depending on the interactions between them.

### 4.1 Global Scale Winds

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, subsidence and stability and lack of rainfall. Such conditions are generally not conducive to pollution dispersion.

### 4.2 Synoptic Scale Winds

At the next scale there exist 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, low level convergence and rising air. A high pressure system or anticyclone is characterised by light winds and fine weather.

### 4.3 Local Scale Winds

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 because of pressure gradients that are driven by temperature differences caused largely 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. Local winds that develop over urban areas as a result of the urban heat island may also be important.

#### Land and Sea Breezes

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 than the sea, and at night the land cools more rapidly than the ocean (Box 3).

#### **Box 3: Thermal Properties of Land and Water**

Land heats up more than the ocean during the day and cools more during the night for the following reasons:

- Water has a higher heat capacity than land and so for an equivalent heat input the temperature increase will be less.
- The sun's radiation is able to penetrate a small distance into the water spreading the heat input through a larger volume of material.
- Surface heat is able to be mixed downwards in water and be replaced by cooler water from below.

These factors combine to produce a temperature differential between land and sea.

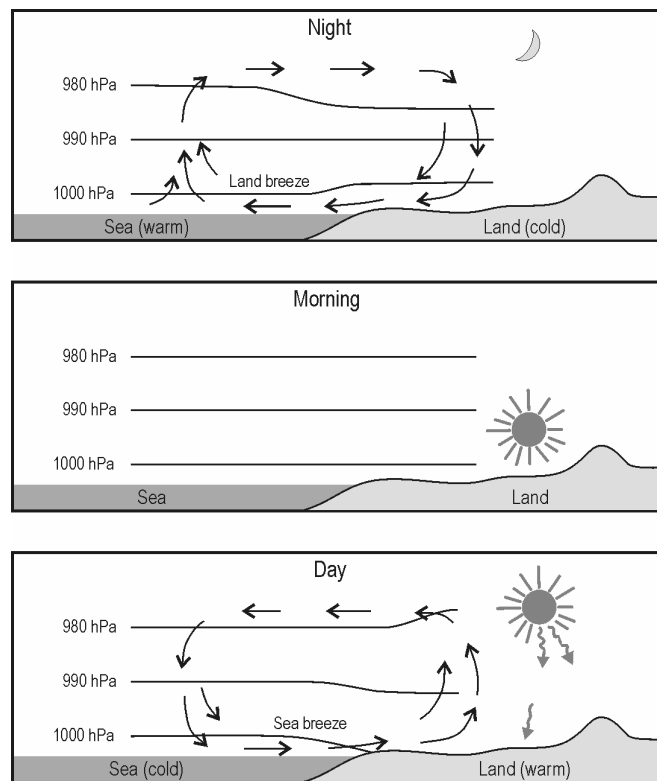
The temperature differential between land and sea sets up a pressure gradient that drives a local circulation, in which winds shift with time of day. Sea breezes occur during the day and blow from the sea to the land (Fig. 15). They can penetrate quite far inland – about 60 km along the KwaZulu-Natal coast (Preston-



Whyte, 1969) and are stronger in summer than in winter. 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. 15). 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 nocturnal cooling is greater.

The strength of land and sea breezes is governed by the overarching large scale or synoptic situation. They are well developed under anticyclonic situations as a result of the clear skies, dry atmosphere and calm conditions. Clear skies favour a greater solar radiation input and hence stronger heating contrasts during the day, and greater infrared radiation losses at night which lead to greater nocturnal cooling. Cyclonic conditions which favour cloudy skies and stronger winds may inhibit the development of circulations which are dependent on the development of a temperature differential between land and sea.



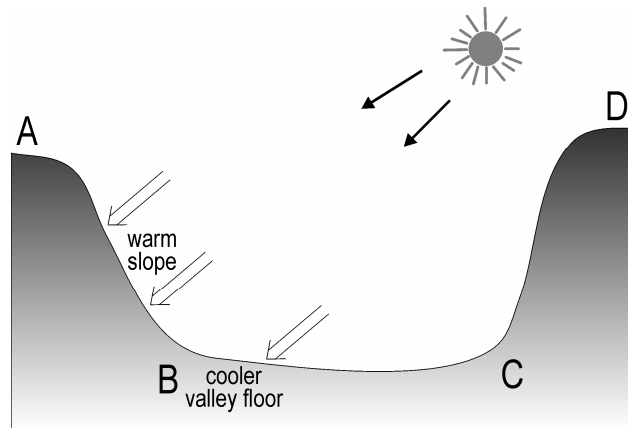
**Figure 15:** Diagrammatic sketch of land and sea breeze circulations (adapted from NILU, 2003)

### Topographically-induced Winds

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

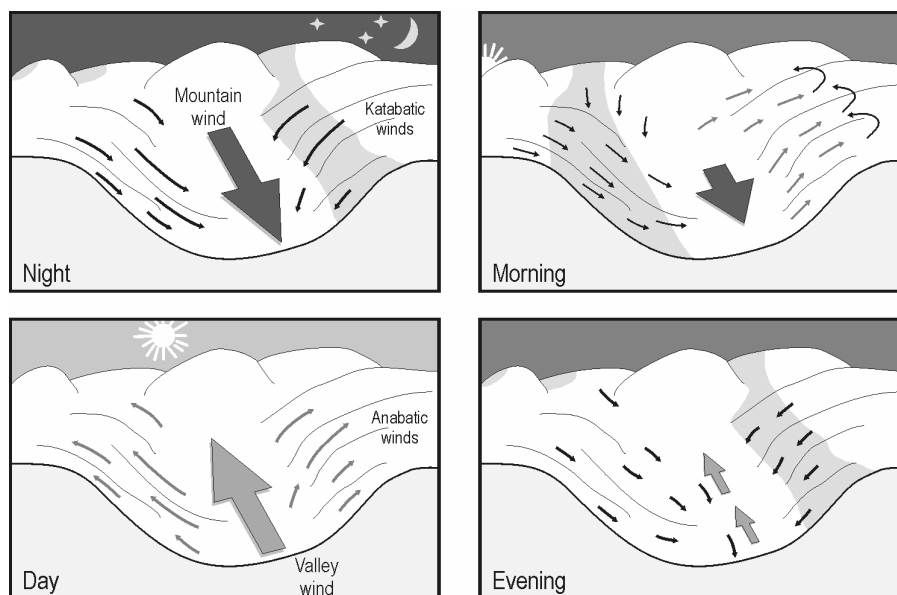
- slope winds
- valley winds
- regional mountain-plain winds

Slope winds flow up and down the sides of a valley cross-section. During the day, in a valley cross-section indicated in Figure 16, the slope AB heats up more than the valley floor, giving rise to pressure gradients which drive local wind circulations within the valley cross section. At night, the slopes cool more than the valley floor and similarly, give rise to local wind circulations in the valley cross section. By day, winds blow upslope (**anabatic winds**) and by night winds blow downslope (**katabatic winds**) (Fig. 17).



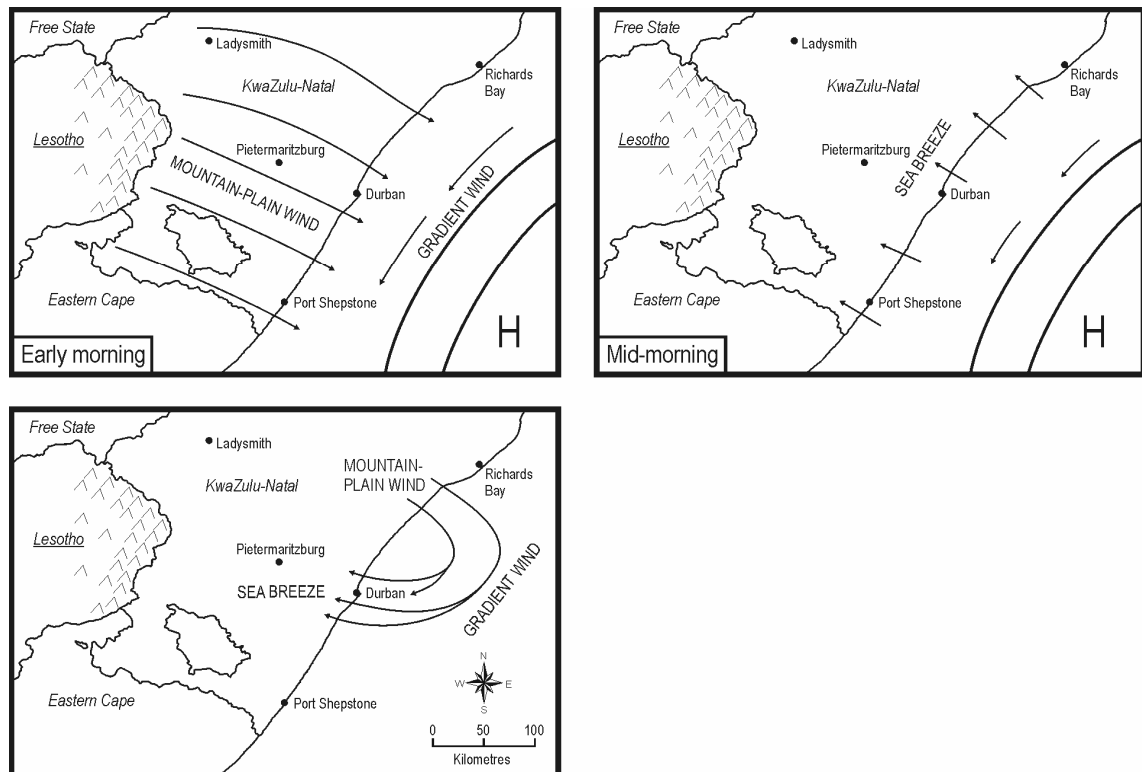
**Figure 16: Valley cross-section showing heating of slope during the day**

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. 17).



**Figure 17:** 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. The characteristics of topographically-induced winds over KZN are described by Tyson and Preston-Whyte (1972). It is evident that pollution released far inland at night may impact on the coast many hundreds of kilometres downwind and that once the sea breeze sets in that these pollutants may be returned to the coast as the air is re-circulated back towards the land (Fig. 18).



**Figure 18:** Re-circulation of pollutants on the east coast of South Africa (after Tyson and Preston-Whyte, 2000)

### Local Winds arising from the Urban Heat Island

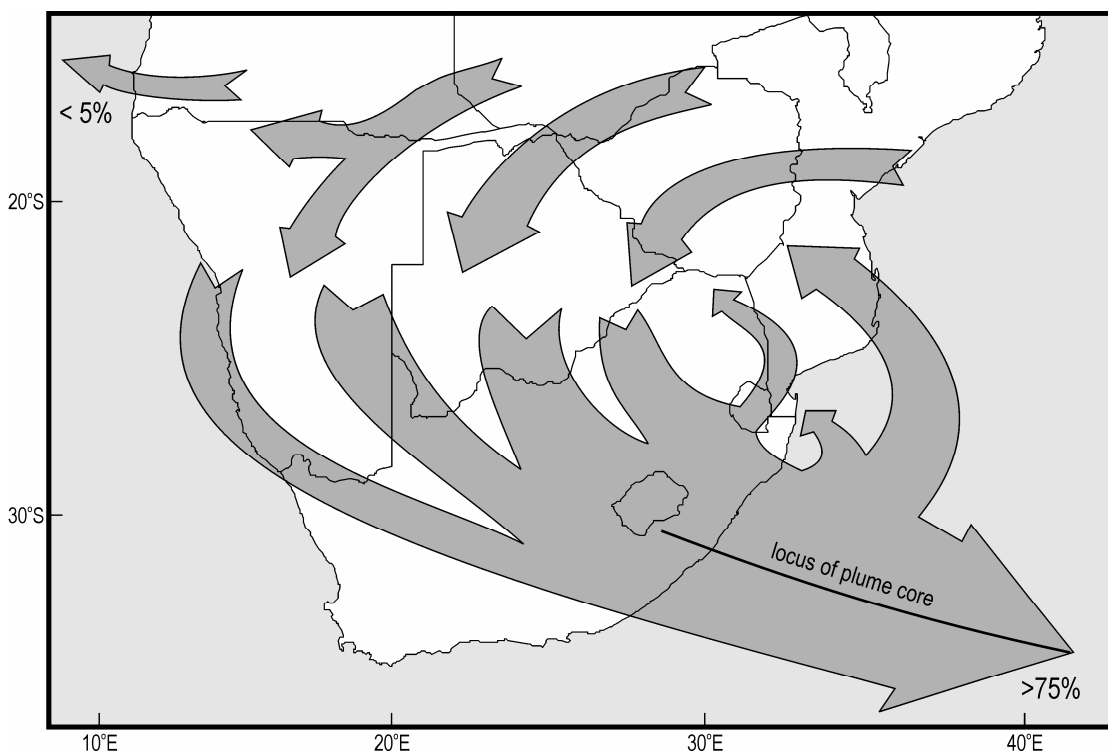
Cities generally have higher temperatures than surrounding rural areas, resulting in an urban heat island, which is sometimes conceived of as a three-dimensional dome of heat over the city. Temperatures are higher over the city as a result of, *inter alia*, the nature of the underlying surfaces of tar, concrete etc, which have high heat capacities, the trapping of heat by an increase of pollutants which prevent the escape of infrared radiation to space, and the emission of heat during combustion processes in industry and motor vehicles.

A temperature difference between the city and its surroundings sets up a pressure gradient, which in turn may lead to the development of a breeze blowing at the surface from the rural area to the city. More important than this hypothetical circulation, the city is responsible for modifying the regional air flow. A reduction in mean wind speed may occur as a result of increased frictional drag due to the greater roughness of the surface, and winds may be channelled by the configuration of streets. Both mechanical and thermal turbulence are increased over cities as a result of the greater roughness of the surface and the greater heating respectively.

#### 4.4 Long Range Transport of Pollutants

Pollutants may be transported considerable distances by wind systems. Figure 18 above shows how pollutants can be transported across an entire province, but it is possible for pollution to move thousands of kilometres and even from one continent to another (intercontinental transport). For example, pollutants generated in countries to the north of South Africa (e.g. Zimbabwe and Zambia) can be re-circulated over the subcontinent in anticyclonic flow and then can exit South Africa over the east coast as a giant plume or river of smoke (Fig. 19). Most of the initial work on long range transport over southern Africa was done by Tyson *et al.* (1996) and Garstang *et al.* (1996).

The circulation types that give rise to this type of pattern are firstly, the dominant subtropical anticyclonic flow over the subcontinent, which produces anticlockwise flow and re-circulation over the eastern seaboard; secondly, tropical easterly flow to the north of South Africa, which is responsible for the movement of air to the Atlantic Ocean; and thirdly, the mid-latitude westerly wind belt situated to the south of the country and the associated passage of mid-latitude cyclones from west to east, which are responsible for the major pathway that exits the subcontinent towards the Indian Ocean.



**Figure 19:** Long range transport of pollutants from the southern African subcontinent (after Tyson and Preston-Whyte, 2000)

## 4.5 Vertical Wind Profile

Wind speed is zero at the surface and increases sharply in the near surface layer such that the wind speed increases exponentially with height (Fig. 20). The shape of the profile is influenced by the nature of the underlying surface, the surrounding topography and nearby obstacles and in practice, may differ markedly from the theoretical exponential profile.

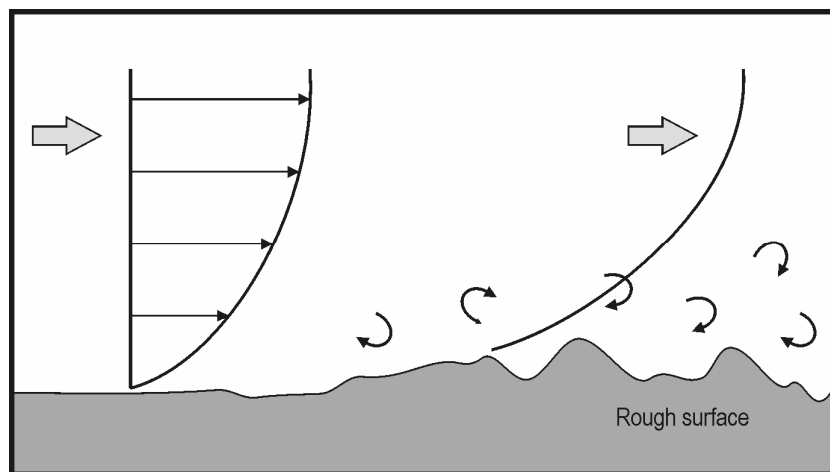


Figure 20: Vertical wind profiles over smooth and rough surfaces

Wind speed shows an increase with respect to height and as such it is generally beneficial to discharge pollutants at a greater height as dispersion is greater. The rate of change with height (known as wind shear) is greatest near the surface.

## 5. Air Pollution Climatology

An important aspect of air quality management is an understanding of the air pollution climatology of a particular location. Knowing the dispersion conditions assists in planning the location of new industries and enables impact areas to be identified.

Once pollution is released into the atmosphere its ability to disperse is governed by meteorological factors. Whilst these factors vary considerably with time, there are also certain locations where dispersion is favourable (or poor) as a result of geographic location. An air pollution climatology gives an indication of the conditions to expect. Graphs and/or tables giving a statistical summary of relevant meteorological parameters as a function of season and time of day are relevant.

The following factors would normally comprise an air pollution climatology:

- **Solar radiation** – The amount of solar radiation received is important in photochemical reactions. Photochemical smog, for example, is usually

found in sunny locations such as Los Angeles. Solar input also determines the extent of surface heating, which influences stability conditions.

- **Temperature** – Higher surface temperatures may prevent surface inversions from developing, e.g. the urban heat island often inhibits development of the nocturnal radiation inversion. High surface temperatures during the day enhance convective mixing and promote dispersion of pollutants. Certain processes, such as chemical reactions, gas-to-particle conversion and emissions from motor vehicles are also temperature dependent.
  - **Relative Humidity** – A key factor in certain chemical reactions and the formation of sulphuric acid mist. It also affects the rate of corrosion.
  - **Wind velocity** – Stronger wind speeds favour dispersion of pollutants and hence reduced local pollution levels, although situations of stack down drafting and entrainment of soil dust may exacerbate local pollution. Wind direction governs the direction of movement of pollution and determines downwind impact areas.
  - **Cloud cover** – During the day, clouds reduce incoming solar radiation, thus lowering surface heating and consequent convective mixing, whereas during the night they prevent the loss of infrared radiation from the earth and inhibit the formation of surface inversions. Reduced solar radiation also reduces the rate of photochemical reactions. Pollutants can dissolve in cloud water and so can be rained out or returned to atmosphere upon cloud evaporation.
  - **Precipitation** – Pollutants may act as cloud condensation nuclei or may dissolve in cloud droplets and be washed out of the atmosphere in rain, thus cleansing the atmosphere. Precipitation is regarded as an efficient scavenging mechanism.
  - **Atmospheric stability** - Critical factor affecting vertical dispersion of pollutants. It can be represented by inversions, stable layers, mixing heights or a stability wind rose, which shows the variation of stability as a function of wind direction.
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## References

- Annegarn, H.J., Otter, L., Swap, R.J. and Scholes, R.J., 2002: Southern Africa's ecosystem is a test tube – A perspective on the Southern African regional Science Initiative (SAFARI 2000). **South African Journal of Science**, 98, 111-113.
- Cosijn, C. and Tyson, P.D., 1996: Stable discontinuities in the atmosphere over South Africa. **South African Journal of Science**, 92, 381 – 386.
- Diab, R.D., 1978: The spatial and temporal distribution of air pollution episode days over Southern Africa. **South African Geographical Journal**, 60(1), 13-22.
- Diab, R.D., Common, S. and Roberts, L.M., 1991: Power line insulator pollution and power dips in Natal, South Africa. **Atmospheric Environment**, 25A (10), 2329 – 2334.
- Garstang, M., Tyson, P.D., Swap, R., Edwards, M., Kallberg, P. and Lindesay, J.A., 1996: Horizontal and vertical transport of air over Southern Africa. **Journal of Geophysical Research**, 101 (D19), 23721-23736.
- NILU, 2003: Air Quality Monitoring Systems and Application. Report Ref. TR3/2003, Q-303.
- Oke, T.R., 1988: **Boundary Layer Climates**. Methuen & Co. Ltd., London.
- Preston-Whyte, R. A., 1969: Sea breeze studies in Natal. **South African Geographical Journal**, 51, 38-49.
- Preston-Whyte, R.A., Diab, R.D. and Tyson, P.D.: Towards an inversion climatology of Southern Africa : Part II, Non-surface inversions in the lower atmosphere. **South African Geographical Journal**, 59(1), 45-59.
- Tyson, P.D., Preston-Whyte, R.A. and Diab, R.D., 1976: Towards an inversion climatology of Southern Africa: Part I, Surface inversions. **South African Geographical Journal**, 58, 151-163.
- Tyson P. D. and Preston-Whyte, R. A., 1972: Observations of regional topographically-induced wind systems in Natal. **Journal of Applied Meteorology**, 11, 643-650.
- Tyson, P.D., Garstang, M., Swap, R., Kallberg, P. and Edwards, M., 1996: An air transport climatology for subtropical southern Africa. *International Journal of Climatology*, 16,265-291..
- Tyson, P.D. and Preston-Whyte, R.A., 2000: *The Weather and Climate of Southern Africa*. Oxford University Press, Cape Town.
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