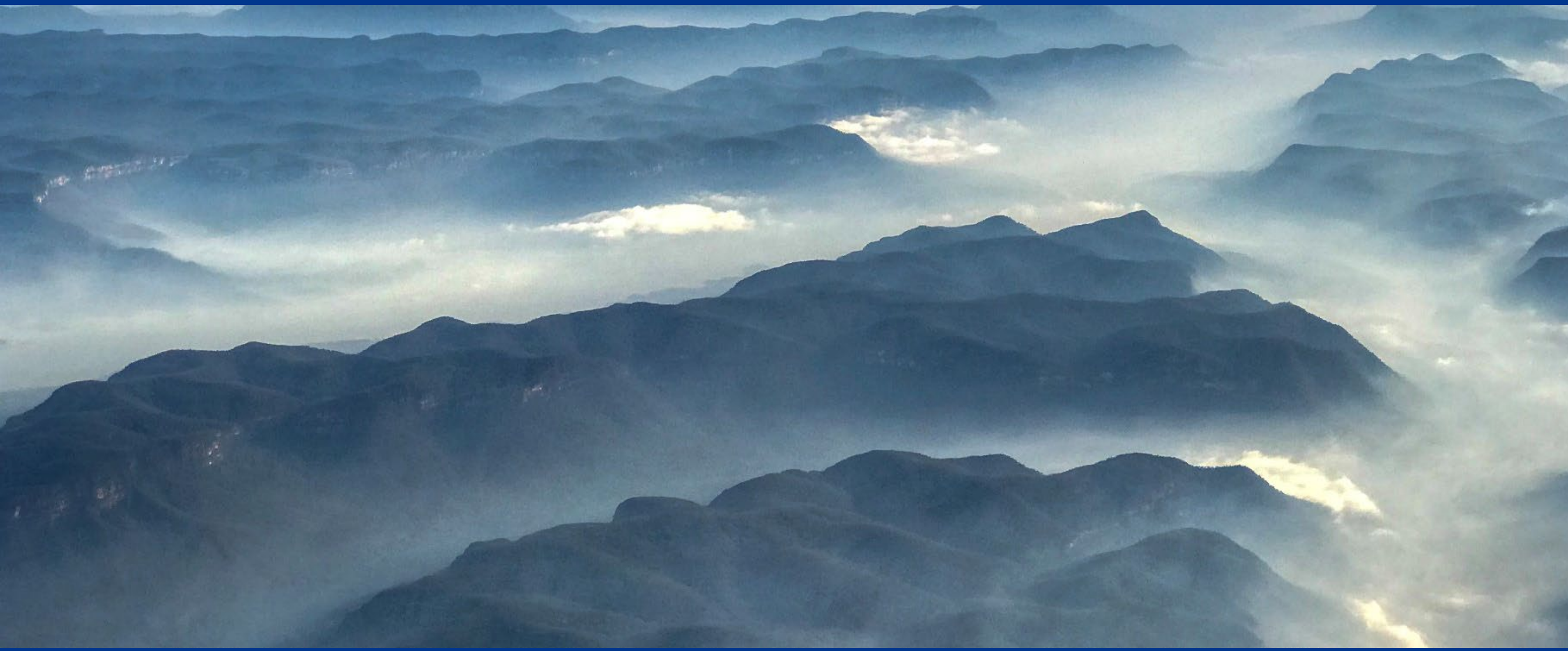

Local Government Air Quality Toolkit

Module 1: The science of air quality

Part 1: Meteorology and air quality

Acknowledgement of Country

Department of Climate Change, Energy, the Environment and Water acknowledges the Traditional Custodians of the lands where we work and live.

We pay our respects to Elders past, present and emerging.

This resource may contain images or names of deceased persons in photographs or historical content.

The Local Government Air Quality Toolkit has been developed by Department of Climate Change, Energy, the Environment and Water in collaboration with the NSW Environment Protection Authority, the NSW Department of Planning, Housing and Infrastructure, Local Government NSW and local councils.

Cover photo: Smoke from hazard reduction burns, Blue Mountains. DCCEEW image library

Artist and designer Nikita Ridgeway from Aboriginal design agency – Boss Lady Creative Designs, created the People and Community symbol.

Published by:
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ISBN 978-1-923200-55-5
EH 2024/0162 July 2024

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1. Pollution discharge and dilution

Pollution is moved by wind from a source into the environment where it changes the quality of the air. The change in air quality essentially depends on 2 factors:

- the amount of pollution discharged
- the way in which the air moves in the atmosphere.

All other things being equal, the higher the amount of emissions (pollutant discharge) the higher the ground level concentrations.

In general, higher wind speeds result in more dilution and therefore lower concentrations.

The further from the source the greater the dilution of the pollution, as it has had more time to disperse. However, there are a few important exceptions explained below.

The effective height of discharge also influences the concentration of pollution at ground level. Generally, the higher the effective height of discharge the less the maximum concentration of pollutant at ground level.

The effective height of a discharge is composed of the physical stack height, plus the plume rise due to its buoyancy and exit velocity. Thus, the temperature, the volume and the velocity of the gas being discharged are important factors determining ground level pollutant concentration.

> The most significant factor for most premises that are regulated by local government will be the height of the stack in relation to its surroundings.

Dilution of emissions in the air, or 'dispersion', is quite complex and is understood through the science of meteorology. The capacity of the atmosphere to dilute an emission is also dependent on the mixing properties of the air blowing over the surface of the ground or water. This is referred to as the 'stability' of the atmosphere.

The concentration of pollution in the atmosphere downwind from a source depends on:

- rate of pollutant discharge
- wind speed
- distance downwind from the source
- effective height of the discharge
- stability of the atmosphere
- ground surface features (e.g. vegetation, trees and hills).

All of the above relationships only apply to the dilution process. If pollutants are reacting in the atmosphere, such as in the case of photochemical pollution, the concentration of a pollutant such as ozone may increase with distance from the source.

2. Behaviour of pollution plumes

Pollution released from a source, typically from a stack, moves in a plume.

There are 6 types of plume behaviour, depending on the wind conditions, atmospheric stability and vertical temperature profile:

- Looping – This takes place when the atmosphere is very unstable, wind speeds are high (>10 m/s) and when there is solar heating. The plume forms a wave-like pattern, and there is a high degree of mixing at lower levels in the atmosphere.
- Coning – This occurs when the atmosphere is slightly unstable, and where there is some horizontal and vertical mixing. Coning usually occurs during cloudy or windy conditions.
- Fanning – These plumes spread out horizontally but with little vertical mixing. Fanning occurs during temperature inversion conditions; however, the plume will rarely reach the ground. Fanning is most common during the night under light winds and clear skies.
- Lofting – A lofting plume will diffuse rapidly upwards but not downwards. It will typically not reach the surface, meaning that there will be less pollution at ground level.
- Fumigation – This results in pollutants being emitted into the atmosphere and then brought rapidly to the ground. Fumigation typically occurs during clear skies and light wind conditions.
- Trapping – The plume is caught between temperature inversions, and can only diffuse within a limited height.

Figure 1 shows the 6 types of plumes described above.

The way plumes disperse depends on the:

- meteorology
- topography
- surrounding buildings
- emission characteristics.

As described above, the wind, the atmospheric stability and the effective height of release (stack height plus plume rise) essentially govern the way the plume disperses under ideal circumstances. However, circumstances are rarely ideal, and some examples will show how meteorology, topography and the surrounding buildings can interfere with 'ideal' dispersion.

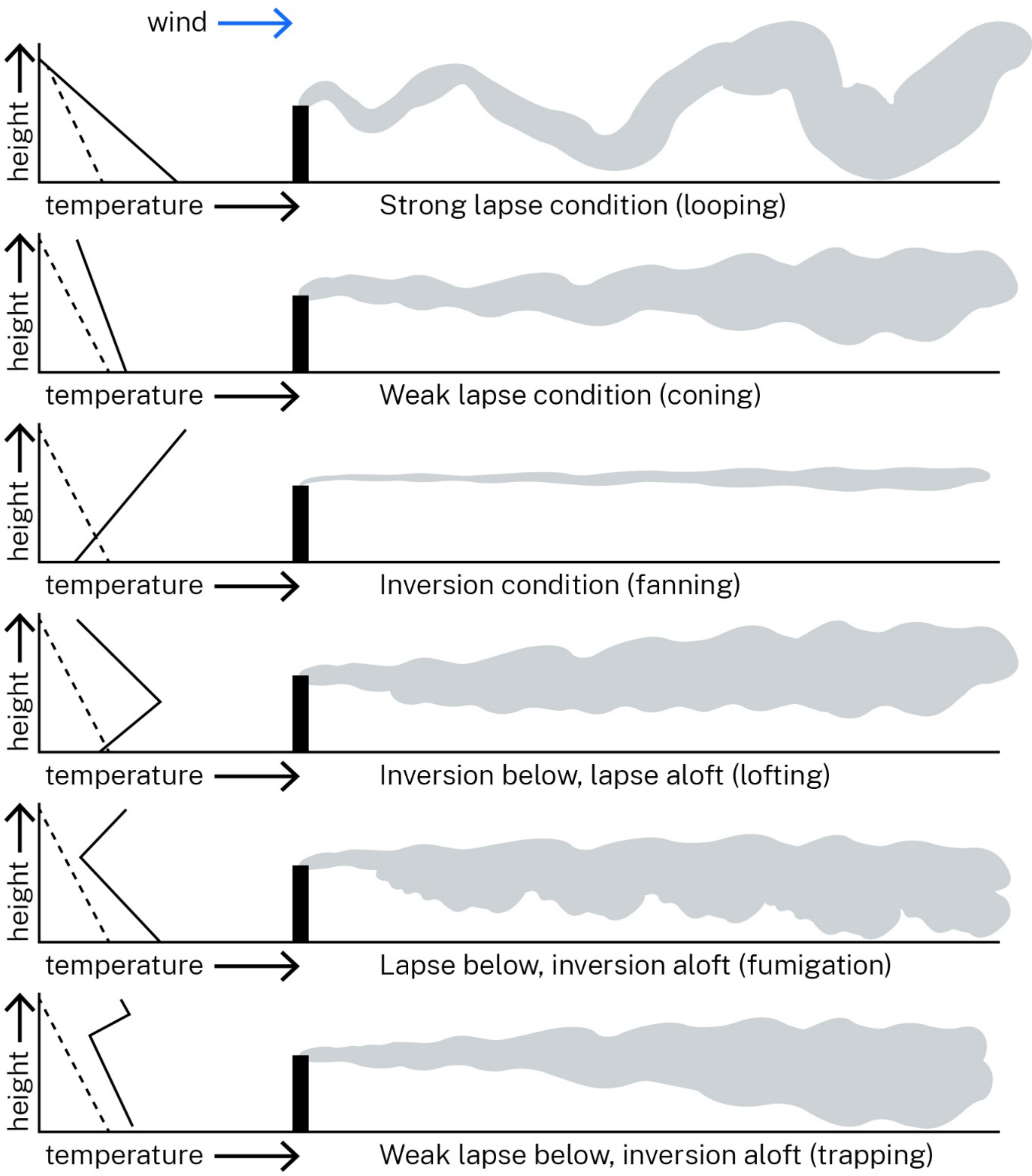

Figure 1 **Plume behaviour**

2.1 Trapping by or above an inversion layer

If the plume becomes trapped in an inversion layer aloft, the pollution can be transported, sometimes a large distance from its source, and then fumigated to ground level once the inversion has lifted. If the emissions are above the stable inversion layer, the phenomenon called 'lofting' occurs. In either case, when the pollution moves to ground level it can be difficult to trace its source. Figure 2 shows fumigation at some distance from the emission source.

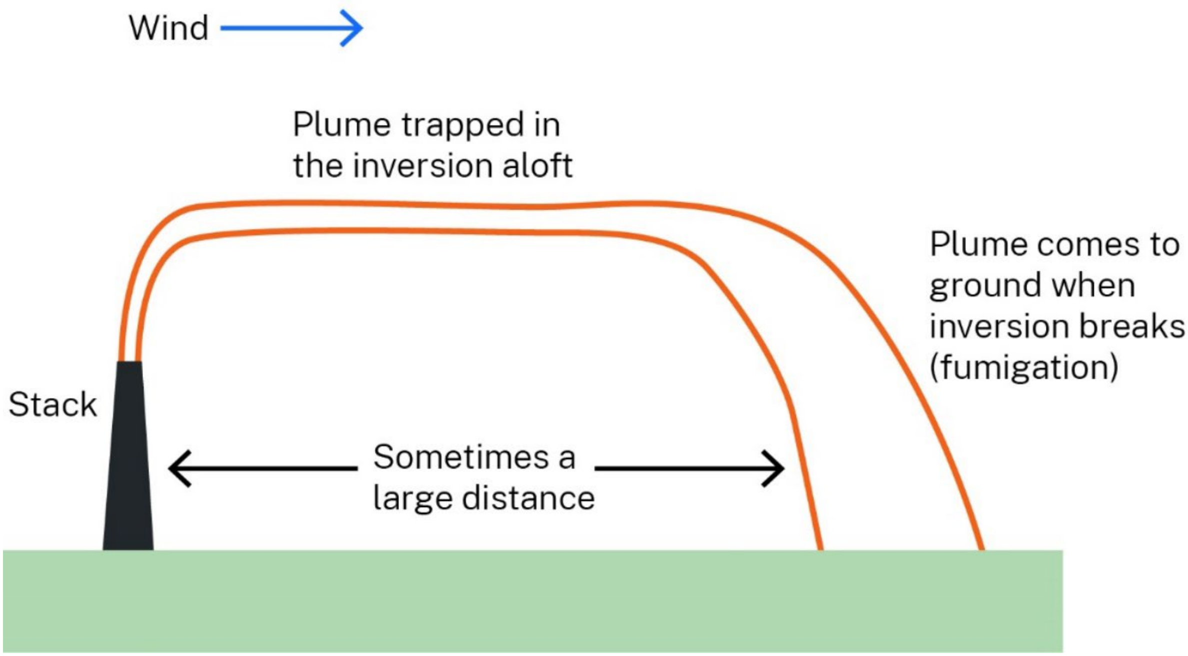

Figure 2 **Trapping by or above an inversion layer**

2.2 Nearby hills

If there are medium to large hills or mountains downwind of the nearby sources, the plumes can intersect these geographical features, causing high concentrations of pollution on the hill or mountain side. This effect is likely to be more important under stable atmospheric conditions. Figure 3 shows a simplification of how a plume may impinge on a nearby hill (blue line). If the exit velocity is high enough to increase the 'effective stack height', the plume may be sufficiently discharged to not be affected by the hill (orange line).

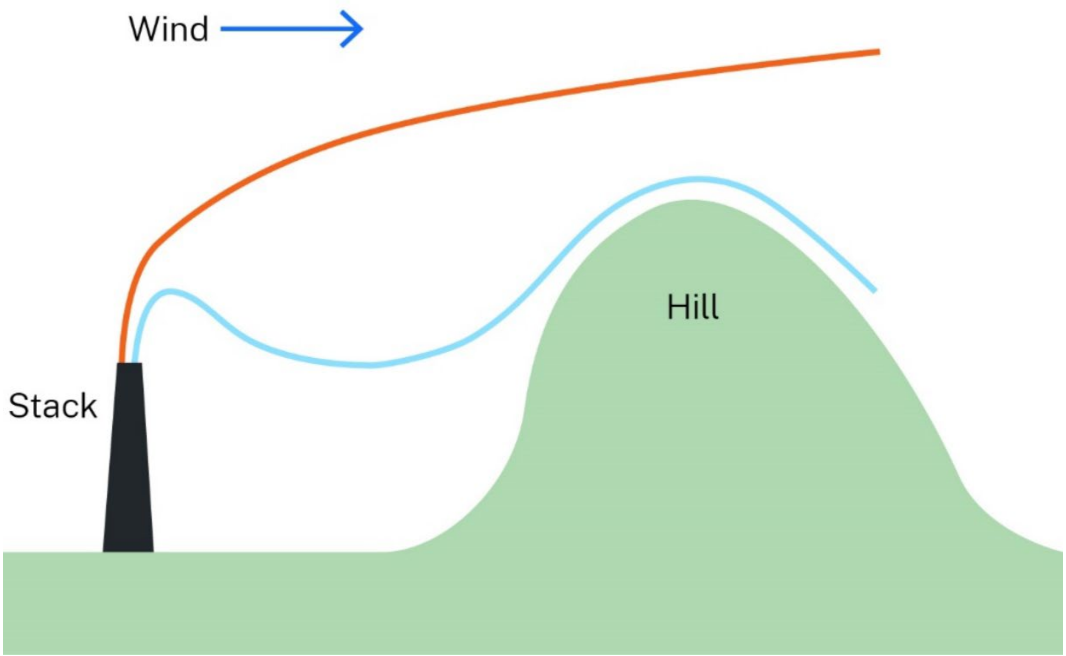

Figure 3 **Downwash causing a plume to impinge on a nearby hill**

2.3 Nearby buildings

Most stacks that release pollutants are on or near buildings. These buildings affect the normal air flow around them. We encounter this in windy weather when we are hit by a blast of air when coming around the corner of a building. Figure 4 shows a simplified representation of the effect of building downwash. The effect on pollutant plumes in all wind conditions is to cause some ‘downwash’ of the plume (blue line in the image below) and higher concentrations closer to the source than would occur for ‘ideal’ dispersion (orange line in the image below).

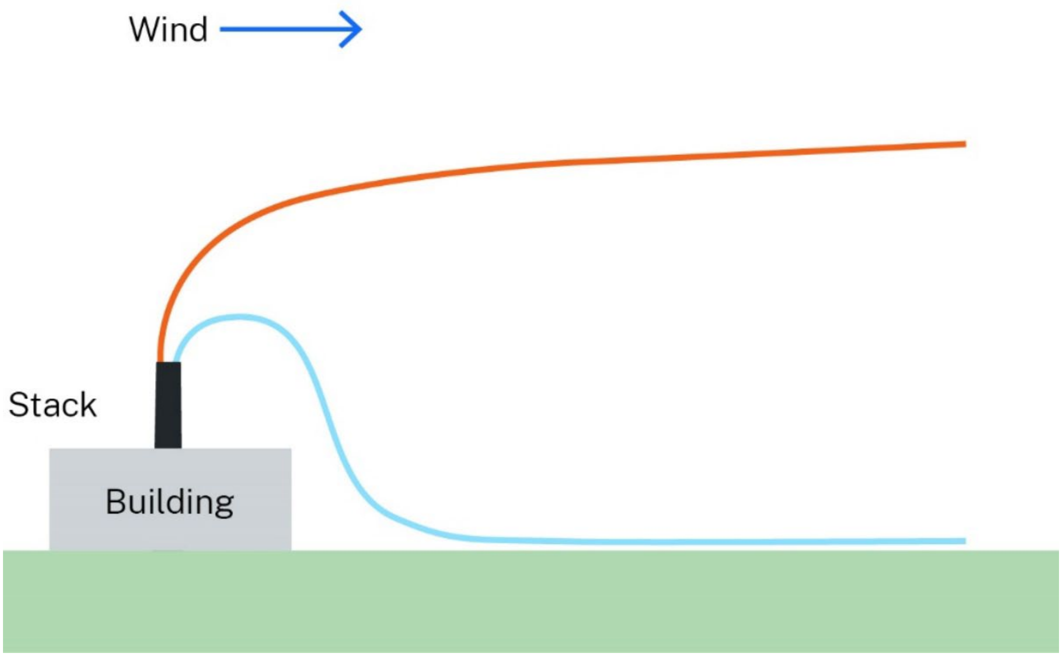

Figure 4 **Building downwash causes high pollutant concentrations close to the source**

3. Atmospheric stability

To manage air quality, it is helpful to understand how atmospheric conditions change during the night and the day, and with wider weather conditions. Bureau of Metrology products such as MetEye (BoM 2024) or synoptic charts can provide useful examples of atmospheric stability or instability.

The main causes of changes in atmospheric stability are heating of land surfaces by the sun during the day, and cooling of the surfaces at night.

A ‘neutral’ atmosphere neither inhibits nor enhances vertical air turbulence.

In an ‘unstable’ atmosphere, vertical turbulence is enhanced by the conditions and so there is an increase in mixing and dilution.

The atmosphere is said to be ‘stable’ when conditions inhibit the vertical motion of air and the resulting turbulence that causes mixing and dilution of pollutants.

Figure 5 illustrates these different atmospheric stability conditions, which are explained further below.

3.1 Neutral stability

With a moderate (approximately 5–10 m/s) to strong (10 m/s or more) wind in moderate sunshine or an overcast sky the atmosphere will be in a state of ‘neutral stability’. This condition depends on the physical properties of the air and water in the atmosphere. In neutral stability the temperature of the air decreases uniformly as it moves upwards, at about 1°C per 100 m. This uniform temperature gradient continues up to about 10 km above the Earth’s surface.

During conditions of neutral stability, a parcel of air moved to a different height will have the same density as the surrounding air at that height. As there is no density difference, or buoyancy acting on the air parcel, the air parcel will only move vertically in the atmosphere if there is an intervening force (e.g. emissions into the atmosphere, or an obstacle).

This explains the term ‘neutral’. Also, pollutants are mixed readily and predictably in the wind in neutral conditions, so they disperse and dilute as they move away from the release point.

3.2 Unstable conditions

During a hot, still day with strong sunshine, the ground surface can become very hot and heats the air directly above it. The warmer, less dense air rises rapidly and results in large eddies (convection) causing an unstable atmosphere. Radiation is not the only force creating this condition, other forces such as air parcels being pushed up over buildings or mountains can also allow the warm air to rise, escaping the environmental conditions it was released in. The turbulence created by an unstable atmosphere generally results in better mixing of pollutants in the air but can also bring pollutants discharged at height to the ground.

3.3 Stable conditions

On a mild–cool day with calm wind (<5 m/s) and a generally clear sky with little to no cloud cover, flat layers of clouds may be present and the atmosphere will be in a stable condition. In a stable condition an air parcel will have enough energy to rise vertically until it loses that energy and becomes equalised with the surrounding air. As the air parcel rises it cools and becomes denser and will subside back to the equalised atmospheric environment. Stable atmospheres will experience layering with minimal vertical mixing, creating an environment where radiative inversions may occur, leading to the formation of fog and/or poor air quality where pollutants may become trapped.

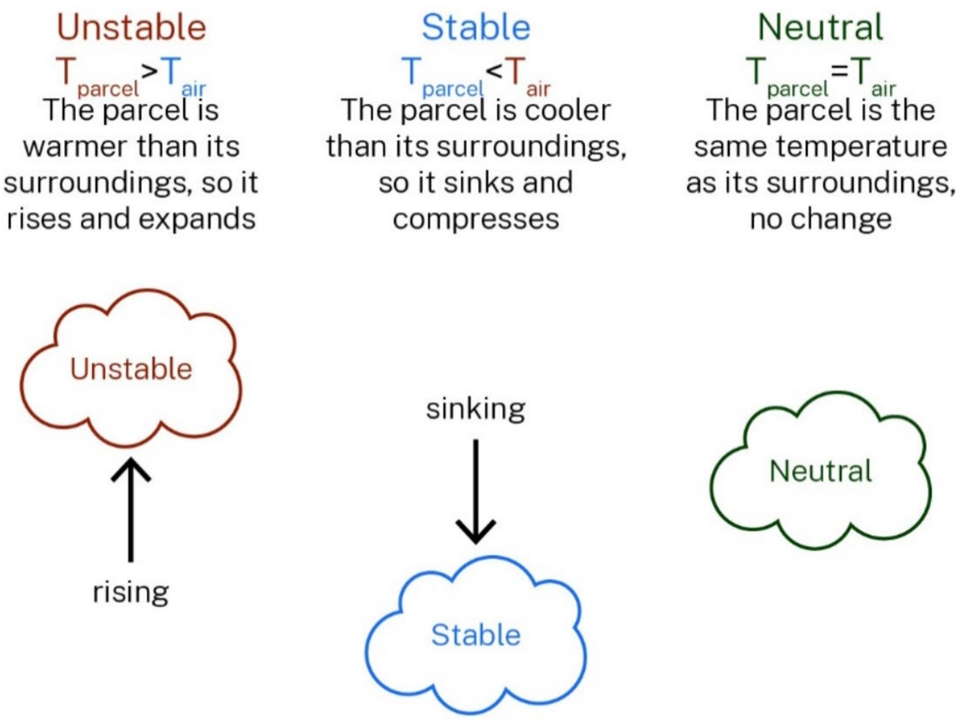

Figure 5 Atmospheric stability conditions

3.4 Types of inversions

Usually, air temperatures decrease with height above the ground. When the air temperature increases (rather than decreases) with height, this is called a temperature inversion.

Inversions occur when the atmosphere is stable and a cooler parcel of air sits nearer the ground with a warmer parcel of air sitting aloft that creates a cap layer of relatively warm air. As the air parcels rise into this capped layer, the air becomes cooler than the surrounding environment and begins to ascend. Smoke and other pollutants can become trapped below the cap layer and are not easily dispersed until the inversion breaks.

Radiative inversion

During the day the ground is heated by incoming solar radiation. After sunset, when there is no incoming solar radiation, the ground loses energy and cools. The air immediately above the ground is also cooled and becomes denser. The thickness of the cold layer of air extends upwards as the night progresses and so the air below is now cooler than the air above.

This is called a 'radiative' or 'nocturnal' inversion. If the term 'temperature inversion' is used without any qualification it usually refers to this type of inversion. The lower atmosphere is now said to be 'stable' because the higher warm layer restricts vertical mixing of air and any pollutants in it.

There are other types of inversions, but the radiative inversion is the most important type when considering dispersion of pollutants emitted near the Earth's surface.

A stable atmosphere and a temperature inversion have some important effects on pollution released:

- The stable atmosphere is less turbulent, and the pollution is less mixed. Both horizontal and vertical mixing are restricted; that is, the concentrations downwind are less diluted. In other words, dilution of a source is less efficient and so pollutants can remain more concentrated for longer.
- The temperature inversion, particularly in the evening and early morning, can trap pollution closer to the ground as there is less (or no) vertical mixing. Downwind concentration is therefore less diluted.
- In some circumstances a temperature inversion can stop elevated pollution from reaching the ground, also as a result of almost no vertical mixing.

These types of conditions can contribute to poor air quality, especially during cooler months (May to September) when inversions are strongest. Inversions generally begin in the late afternoon or early evening and linger until the next morning. In Sydney these inversions generally lift by 8–9am; in parts of regional New South Wales the inversion may linger until 10am. Pollution from vehicles, wood burning, industry and other large surface sources may become trapped near the ground during an inversion, leading to elevated pollutant concentrations. Areas in New South Wales such as Blaxland and the Blue Mountains are prone to temperature inversions associated with poor air quality. Temperature inversions in these areas can occur as frequently as 15 days in a month.

Figure 6 shows an example of a radiative inversion where pollution has become trapped under a layer of warm air.

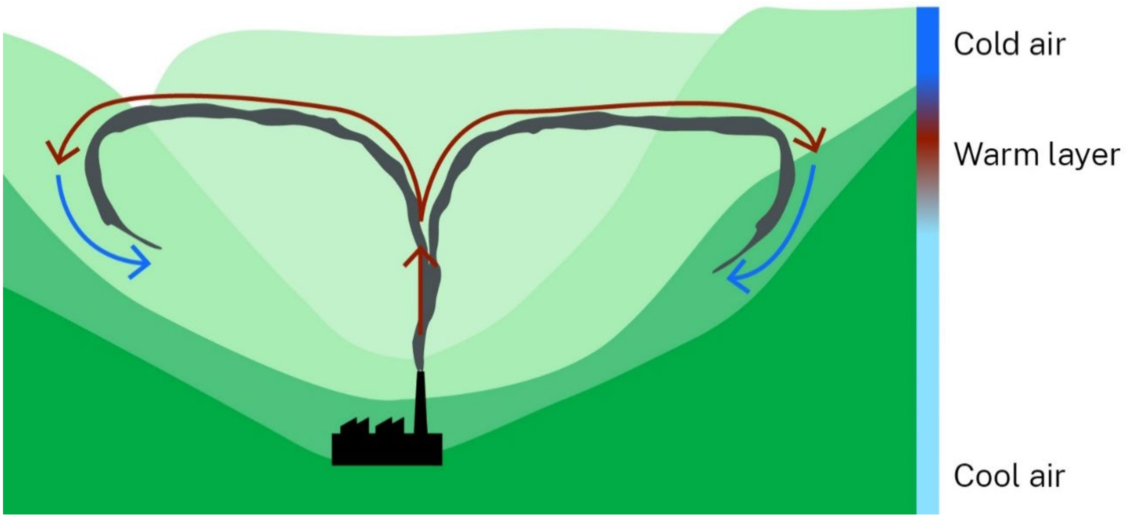

Figure 6 Pollution trapped under a layer of warm air caused by radiative inversion

Figure 7 provides temperature profiles for:

- neutral stability – mild day
- stable inversion – night
- breaking inversion – morning
- unstable – still, hot, sunny day.

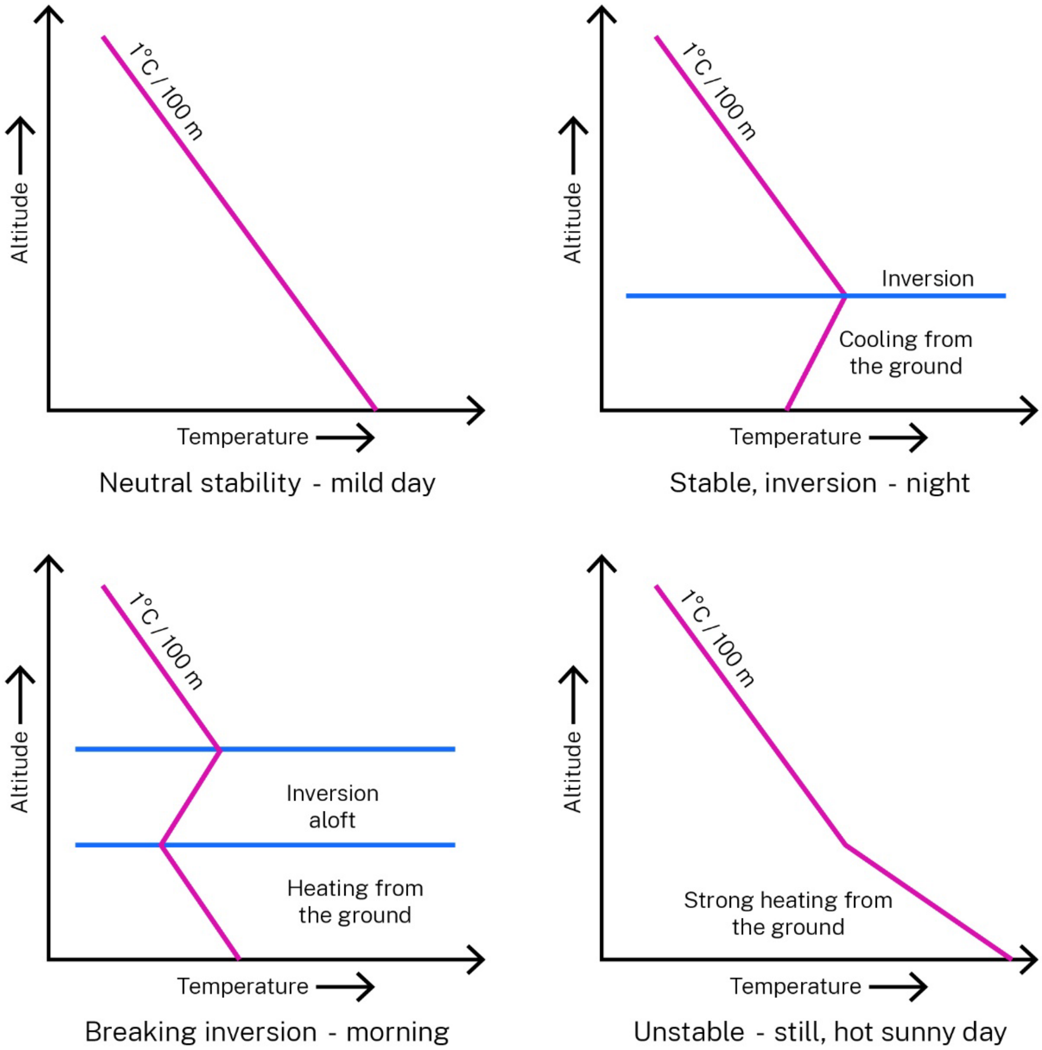

Figure 7 Temperature profiles

Subsidence inversion

In areas where a high-pressure weather system develops over a region, the air parcel can gradually sink over a wide area and the air at a higher altitude becomes warmer than that of the lower altitude, creating a layer that traps pollutants within the lower layer. These types of inversions are less common than radiative inversions but can occur together with a radiative inversion. Subsidence inversions generally occur during warmer months (October to March). A subsidence inversion can be a greater depth and last longer than a typical radiative inversion. Subsidence inversions are also known as synoptic inversions.

Orographic inversion

Orographic inversions are the least common type of inversion. Mountainous areas can occasionally lead to the development on an orographic inversion.

In an orographic inversion the warm air parcel on the windward side of a mountain range is forced to rise up the sides of the mountains. This movement is known as an anabatic flow, and is described further in Section 3.6 below. The warm air cools as it rises to a higher elevation, and this cooling can lead to precipitation on the windward side of the range. On the leeward side of the mountain range the air becomes drier and warmer and may sit aloft of a cooler air parcel, trapping air beneath and minimising the dispersion of pollutants.

3.5 Katabatic or 'down-slope' air movements

Stable cool air, formed near the ground at night, has important consequences for pollutant dilution and dispersion in valleys or land depressions. When it forms on high land such as hills or mountains, this cool air becomes denser and flows down over the sloping land surfaces into the valleys where it can accumulate in low-lying depressions. Figure 8 is a visual representation of katabatic drainage flow.

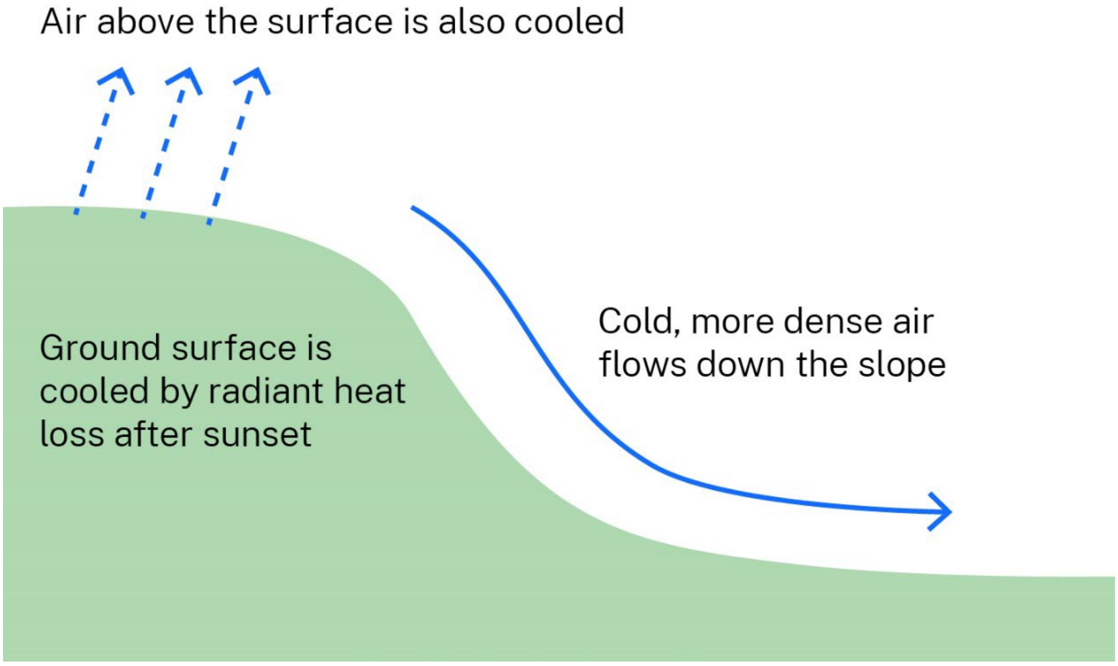

Figure 8 Katabatic drainage flow

Because katabatic drainage flows depend on the cooling and heating of the land, the flows are not usually important when it is heavily overcast or rainy. Under such overcast or rainy conditions, the atmosphere stays 'neutral' during the day and night, the temperature varies less from day to night, and air pollution disperses in the wind in the normal way.

The mass of cold, stable air is also under a temperature inversion and traps and suppresses the dispersion of the pollutants emitted. As the sun heats the ground it warms the air above it and begins to break down the temperature inversion and restore the air to a neutral stability. Mixing improves and the pollution disperses until it is usually no longer visible by late morning.

It is the temperature inversion that traps the emissions; the drainage flow then transports the pollution – often quite effectively – across a large region.

Inversions coupled with katabatic or 'down-slope' drainage flows of cold air at night trap and exacerbate pollution in regions such as Sydney, where it appears as a brown haze on winter mornings and a white haze on summer mornings. The Hunter Valley and localities like Armidale and other towns that may be in a valley can also be affected.

3.6 Anabatic or 'up-slope' air movements

There is a reverse of the katabatic flow, namely an anabatic flow. This is usually only experienced in the vicinity of steeply rising land, such as the cliffs and mountains adjacent to the Illawarra coast. Figure 9 represents an anabatic flow.

The morning sun heats the cliff faces or mountain sides and this in turn heats the air next to it, which rises rapidly. This is less important for air quality than the katabatic flow.

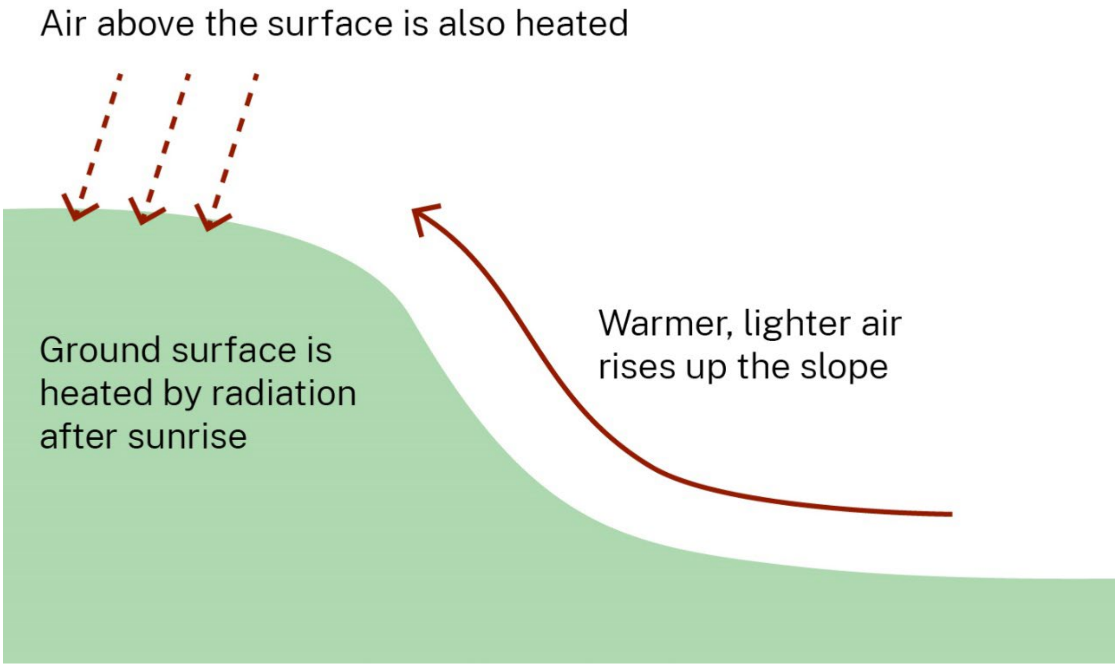

Figure 9 **Anabatic up-slope flow**

3.7 When land and sea meet

There is another important effect whenever land and water meet. The temperature of a large body of water changes very little over the cycle of night-to-day. By contrast the land experiences much larger daily changes in temperature. Thus, the air over the water tends to stay at a reasonably constant temperature day and night. This difference significantly impacts on the atmospheric movements where bodies of water like the ocean or large lakes adjoin land masses.

Sea breezes

The dynamics of air movement mean this difference results in a sea breeze in the mid-morning as the air over the land heats up, rises and is displaced by cooler air from the ocean. If it is not removed by more widespread 'synoptic flows' associated with high- or low-pressure regions, the hot air goes out to sea aloft, is cooled above the water, then settles and flows back over the land again. In other words, a circulating cell may be set up and a sea breeze is created from the ocean to the land. Figure 10 is a visual representation of a sea breeze.

Sea breezes have 2 effects on pollution in places like Sydney. The first is beneficial in that cleaner air from over the ocean is blown towards the land by the sea breeze. The second is a negative effect, when the accumulated pollution of overnight and early morning emissions caught in the drainage flow is blown back over the land by the sea breeze from mid-morning to mid-afternoon.

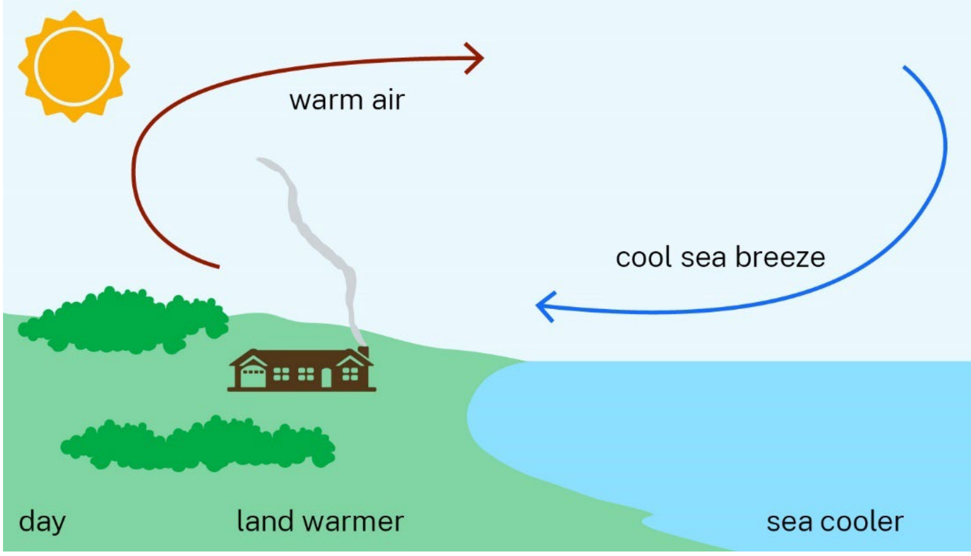

Figure 10 Sea breeze

Smog in Sydney

Sea breezes play an important role in re-distributing photochemical pollution in the Sydney Basin, which usually needs about 3–4 hours for the precursor pollutants to react and form photochemical smog (Figure 11).

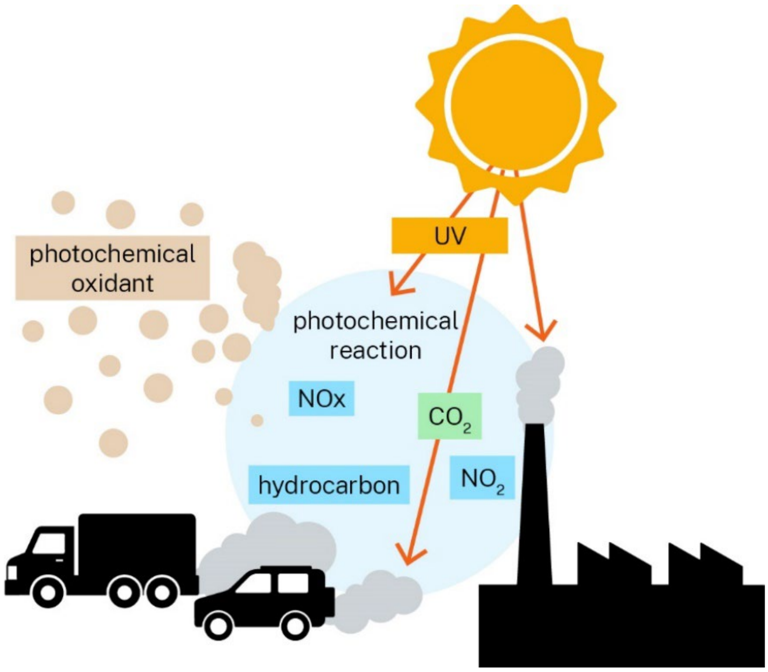

Figure 11 Formation of photochemical smog from precursor pollutants

This smog is transported to south-western parts of Sydney in the mid to late afternoon on north-easterly sea breezes (the predominant wind in the Sydney Basin). Emissions from the whole city, including from large parts of Western Sydney, react, resulting in high concentrations of photochemical smog, including ozone.

Sometimes the emissions from the previous day are also re-circulated by the combination of the sea breeze and drainage flows. The overnight drainage flow and the sea breeze interact to influence pollution in Sydney, especially during summer when photochemical smog may form.

Land breezes

The reverse of a sea breeze is a land breeze at night. At night the air over the ocean remains warmer than the air over the land due to the faster cooling of the land compared to water. The colder, heavier air over the land then flows offshore to replace the warmer air above the water. A circulating cell that is the reverse of the daytime one may be set up, although the offshore land breezes are typically much weaker than the onshore sea breezes.

If the offshore flow is supported by a katabatic drainage flow, as it is in Sydney, this tends to strengthen the flow of air from the land to the ocean at the shore. Similar effects can occur over other waterbodies, notably lakes and dams, depending on their depth and capacity to hold heat. Figure 12 shows a land breeze.

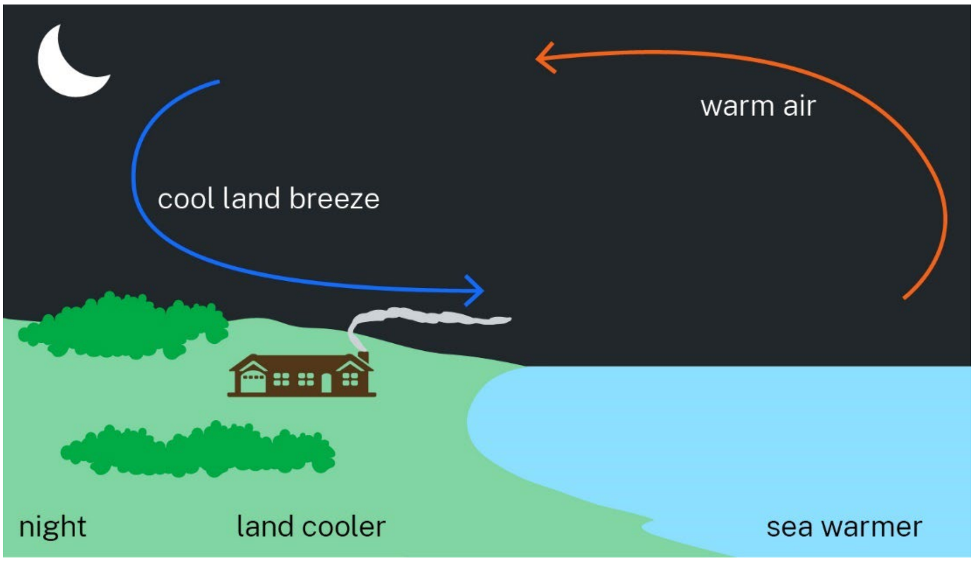

Figure 12 Land breeze

4. References and other resources

All documents and webpages that are part of the Local Government Air Quality Toolkit are available from the EPA website.

BoM (Bureau of Meteorology) (2024) *MetEye – your eye on the environment*, Australian Bureau of Meteorology, www.bom.gov.au/australia/meteye.