METEOROLOGICAL PRINCIPLES

INFLUENCING PESTICIDE APPLICATION

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A TECHNICAL MANUAL

By Graeme Tepper

MicroMeteorology Research and Educational Services

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Meteorological Principles Influencing Pesticide Application – A Technical Manual

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Introduction

For the safe and effective application of pesticides and the mitigation of drift, weather conditions need to be within acceptable limits.

This publication provides managers and operators with a practical and visual guide to atmospheric factors impacting pesticide application. It also explains basic meteorological concepts, describing the forces and motions contributing to the transport, dispersion and eventual fate of drifting pesticides.

It aims to enhance readers' understanding, anticipation and recognition of and response to meteorological events, all of which are critical to decisions about the successful application of pesticides and the mitigation of drift. It supports the wise and sustainable use of valuable pesticides crucial for controlling weeds, insects and diseases in support of food security for an ever-increasing world population – in fact, Tudi et al. (2021) claimed that "The increase in the world's population in the 20th century could not have been possible without a parallel increase in food production.

About one-third of agricultural products produced are dependent upon the application of pesticides. Without the use of pesticides, there would be a 78 per cent loss of fruit production, a 54 per cent loss of vegetable production and a 32 per cent loss of cereal production.

This publication also supports operators and managers in protecting unintended receptors from damaging drift.

GLOSSARY OF TERMS

- **anabatic** (upslope) **wind**: a warm wind that blows up and adjacent to a steep slope.
- **anemometer**: a wind speed sensor. There are two types:
  - **mechanical** – cup and vane (CV) sensors are a type of mechanical sensor; and
  - **ultrasonic** – has no moving parts.
- **atmospheric boundary layer** (**ABL**): the layer of air in contact with the Earth's surface. It responds rapidly to surface conditions of temperature, moisture and wind.
- **Delta T:** is defined as the *dry bulb temperature* minus the *wet bulb temperature* and provides a better indication of droplet evaporation rate than RH.
- **diurnal**: happening cyclically every 24 hours. There are noticeable differences between daytime and night-time weather conditions.
- **high concentration**: similar to the initial concentration of airborne pollutants.
- **inversion**: a condition where the vertical temperature difference (see below) is positive. An inversion can be:
  - **non-hazardous** – has moderate to strong turbulence in the wind flow; or
  - **hazardous** – has weak turbulence in the wind flow.
- **katabatic wind**: a cool air drainage wind.
- **low concentration**: much less than the original concentration of airborne pollutants.
- **receptor**: any surface or object impacted by pesticide reception; includes agricultural crops and products, flora, fauna and humans.
- **synoptic**: summarising; synoptic meteorology is about analysing weather on a large scale. The synoptic scale is a horizontal length scale of 1000 kilometres or more. Common terms used in synoptic meteorology are:
  - **synoptic winds**: winds that flow out of highs and into low pressure systems; and
  - **synoptic situation**: the location of high and low pressure systems, with fronts and troughs.
- **vertical temperature difference** (**VTD**): the upper temperature minus the lower temperature.
- **volatilisation:** the conversion of solids or liquids to vapour.

Mist and fogs in low-lying regions are good indicators of inversions and drainage wind flows.

Photo: Bill Campbell

Importance of understanding and managing spray drift

Apart from the financial incentive to get as much pesticide as you can to the target area, there are many other good reasons to minimise spray drift. For example, minimising spray drift protects:

- human health – that of your family, neighbours and community;
- susceptible crops, which may be unintentionally sprayed, causing economic damage;
- trade, by avoiding unacceptable residues on crops and pastures;
- farm vegetation, native vegetation, animal habitats and biodiversity;
- water quality, including water for human consumption, stock use and irrigation;
- aquatic organisms; and
- beneficial insects (predators and pollinators) and their refuges.

To reduce these risks, it is important for the spray operator to observe changing weather conditions and be able to adapt to them when required leading up to and during spray operations. They must be able to interpret information, plan and be prepared to change the things they have control over. It is also important that they can make good decisions in order to manage the things they cannot control, such as the weather (Gordon 2017).

The stealth factor

Drift is invisible. Receptors may take weeks to show symptoms of incursion. Source detection can be elusive when drift is not direct but widespread and damage is uniform across many hectares. Rates of volatilisation and concentrations vary depending on the time of day making it even more difficult to detect sources. A large proportion of drift will cause no obvious negative effects, but even minor concentrations may critically impact some receptors. Operators may be oblivious to the volume of drift released.

Even the smallest release has some impact. The level of impact depends on the formulation and concentration of the pesticide and the susceptibility of the receptors.

For widespread landscape drift events, it is unlikely that just one drift event would be the cause. Multiple drift events combining over hours or days are more likely to be the culprit.

While it is impossible to eliminate all drift, application technologies and formulations are effective in reducing it when used to full effect. Further, drift effects can be minimised by avoiding times and places when environmental conditions are not ideal. It is the responsibility of the operator to ensure that they take due care during an application to ensure damaging drift does not occur.

It is impossible to obtain an image of invisible drift; however, Figure 1 shows a sunbeam highlighting 'invisible' dust particles. The particles fill the entire space photographed and, although the air in the building in which the photo was taken was supposedly still, the particles are clearly in motion.

Figure 1: Dust particles are highlighted by a sunbeam. If drift were this visible, it would more readily raise alarm and prompt operating changes to combat it.

Photo: E.mil.mil/WikiMedia Commons

What is drift?

The Australian Pesticides and Veterinary Medicines Authority (APVMA) intends the term 'spray drift' to mean: "the physical movement of spray droplets (and their dried remnants) through the air from the nozzle to any non- or off-target site at the time of application or soon thereafter. Spray drift shall not include secondary movement of agricultural chemicals to non- or off-target sites caused by volatility, erosion, surface or groundwater transport or windblown soil particles that occurs after application" (APVMA 2022).

The essential concept of drift is that spray drift does not encompass off-target movement of a pesticide caused by runoff, volatilisation, erosion, or any other mechanism that occurs after spray droplets reach their intended target.

The APVMA recognises that pesticide vapour and off-target movement of pesticides by other means not included in the drift definition can present risks. However, these other routes of movement are not included with spray drift because they need to be assessed and regulated differently.

Primary drift

Primary drift is a function of operating practices and interactions between the spray equipment, the spray sheet and the condition of the atmosphere including stability, humidity, wind, turbulence and temperature.

Primary drift emissions occur at the time of application. Some droplets never make it to the target; rather, they are swept away by wind and raised into the atmosphere by air currents. Smaller droplets immediately drift but larger droplets, which are assumed not to drift at all, when caught up in wake turbulence and vertical winds may evaporate and add to the volume of drift. The aqueous component of many airborne droplets will evaporate and reduce to particles and vapours of the active ingredient.

Airborne pesticides may deposit in the near paddock, while others deposit much further afield. Some may remain in the atmosphere for months. The atmosphere is a major pathway for the transport and deposition of drifting sprays in areas sometimes far removed from their source (Majewski and Capel 1995).

Figure 2: Condensation nuclei have attracted moisture and vapours out of the atmosphere to form mist or fog with peak concentration slightly elevated above the surface within an inversion with Delta T less than 2 (relative humidity greater than 80 per cent). This phenomenon, combined with very light winds, creates conditions conducive to airborne pesticides being incorporated into mist and fog. Photo: Frank Taylor

Secondary drift

Secondary emissions of agricultural chemicals are transported in surface or groundwater, windblown soil particles, fog and rainwater after application. These are important pathways for pesticides to enter the atmosphere and to be transported offsite. They should not be ignored in the assessment of pesticide movement and offsite damage.

Volatility is another factor in secondary drift. Volatile pesticides release vapours from soil and plant surfaces over a number of hours or days. The rate and concentration of vapour release will parallel diurnal variations of temperature, atmospheric stability and, in the case of volatilisation from soil, soil moisture (Bedos et al. 2002).

The APVMA states that "volatility risk is highly dependent on each chemical's properties (such as its inherent vapour pressure and Henry's constant), and since the chemical is moving as a gas rather than in liquid droplets, it must be assessed with different mathematical models and managed according to different methods. The APVMA addresses these alternate routes of potential off-target movement separately during its risk assessment, prior to registration of each product, and makes appropriate label adjustments as necessary". (See the APVMA's operating principles in relation to spray drift risk at https://apvma.gov.au/node/10796.)

Hitch-hiking pesticides

Hitch-hiking is an important mechanism for pesticides to be transported long distances: they can persist in the atmosphere for extended periods of time, resulting in settlement over wide areas.

Pesticides may drift alone but can also act as seed droplets for the formation of mist, fog and cloud and thereby drift with them. Pesticides in the air may also be incorporated into or onto unrelated airborne droplets and particles, including salt particles. Salt particles are ideal building blocks of droplets, which grow by diffusion (the transport of water and other vapours towards a growing droplet) and by collision. Soluble particles tend to then dissolve into the cloud droplet that they are forming, making a solution. In simple terms these are the processes that cause pesticides to be found in fog, mist (see Figure 2) and rain.

Researchers have investigated the hitch-hiking mechanism in some detail. For example, Waite et al. (2005) found that "the primary atmospheric transport mechanism for MCPA and Bromoxynil was shown to be adsorption (attachment) to particles dispersed in the atmosphere, with the same mechanism also confirmed for 2, 4-D and Dicamba, while Trifluralin was shown to be transported mainly in the gas phase. And transportation of Triallate was influenced by particle adsorption".

Seiber and Woodrow found that "wet deposition, which includes the scavenging of particle bound pesticides and pesticide vapours into atmospheric moisture (cloud and fog water, rain and snow), is a potentially major sink for airborne pesticides. Fog water deposition has been implicated as a source of inadvertent residues to non-target foliage, and of high-risk exposures for raptors (birds of prey) residing in and around treated areas" (Seiber and Woodrow 2000).

Figure 2 shows high concentrations of small droplets suspended above the surface; these are conditions suitable for the incorporation of pesticides into fog or mist (Glotfelty, Seiber and Liljedahl 1987).

Cumulative impacts on receptors

During periods of high rates of pesticide application across regions, pesticide residues will peak and accumulate in the atmosphere before returning to the surface to combine with new releases.

The merging of multiple plumes from operations quite separate from each other has the potential to initiate widespread damaging events. The sum of small drift events is likely a critical factor in the overall atmospheric loading of pesticides. However, Dijk et al. concluded that “the extent to which pesticides are lost directly to the atmosphere during application is largely unknown” (Dijk et al. 1999).

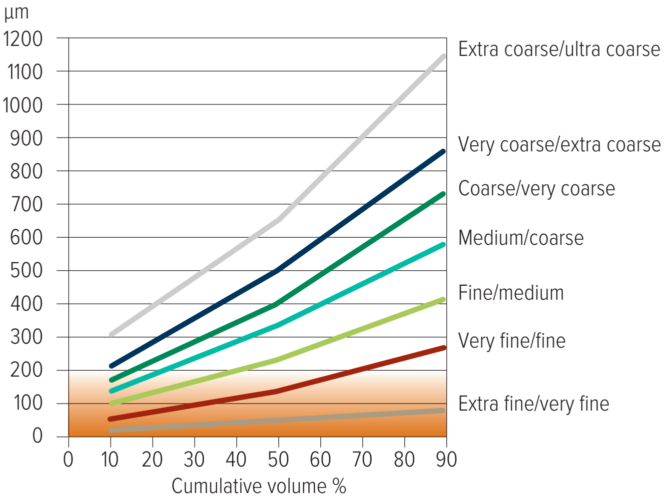
All nozzles produce some drift

On being ejected from the spray nozzle, the spray mixture is broken into droplets of various sizes. Droplets less than 150 microns are highly susceptible to drift but even larger droplets can become drift prone if reduced in size by evaporation.

Droplet categories are shown in Figure 3 from extra fine to ultra coarse. Each of these categories encompasses a range of droplet sizes as indicated by the accompanying lines from small droplets up to larger droplets. The 50 per cent cumulative volume point indicates volume mediam diameter (VMD) of all droplets. What this means is that spray quality of very coarse to extra coarse with a VMD of 500 micron produces 50 per cent of volume in many small droplets, down to about 200 micron and 50 per cent up to about 850 micron in ideal conditions.

If operating practices are not optimal and/or weather conditions are windy, hot or dry it is possible to lose a much larger volume of spray to the atmosphere than spray quality indicates.

Figure 3: A reference graph showing spray nozzle classifications by droplet spectra.



🟧 Droplets less than 200µm are quite drift-prone, especially in summer when evaporation can rapidly reduce their diameter and weight. Generally 100µm droplets are highly drift-prone.

Source: Adapted with permission from Asabe Standard s572: Spray nozzle classification by droplet spectra (www.asabe.org/standards/images.aspx). St. Joseph, Mich.: American Society of Agricultural and Biological Engineers

Figure 4: Several smoke plumes rising, combining and spreading horizontally across the landscape in stable conditions. There will likely be widespread deposition of the smoke particles at some later time.

Photo: Teresa Aberkane

Widespread damaging effects

Patterns of drift damage are dictated, in part, by receptor vulnerability, and also by the formulation and concentration of the plume.

Direct drift damage generally has a clear connection to the source or sources. Without direct links, it can be difficult to determine the source(s). Widespread damaging drift with no clear gradients suggests that drifting pesticides have:

- fanned out across the landscape within stably stratified layers (inversions);
- returned to the surface by way of widespread dry or wet deposition; or
- been incorporated into mist or fog that settles out over the landscape.

Drifting pesticides are known to contaminate the broader environment. Pesticides that originate from remote sources at a distance of many hundreds or even thousands of kilometres will show very steady or gradual trends in air and precipitation over time and across regions. Alternatively, such a pattern may result from a very slow, prolonged release of pesticides from residues in the soil (Dijk et al. 1999) or other surfaces.

Dijk et al. (1999) note that "it's obvious that pesticides can travel over tens to hundreds of kilometres. Some may travel further. Quite surprisingly, this includes compounds which are hardly volatile, such as the acid forms of 2, 4-D and Dicamba, or photo-chemically unstable, such as Trifluralin".

Only recently has it been recognised that widespread damaging drift can impact regions rather than just the next paddock or two.

Vertically contained plumes of drifting pesticides that meander (Figure 4) or fan out may result in widespread and uniform damage rather than localised damage. Bish et al. (2019) use the term 'landscape effect' to describe widespread and uniform damaging events.

Figure 4 shows several smoke plumes rising from the surface. There are two reasons why this might be happening. The first is that a strong inversion exists from the surface upward but the smoke, being hot at its source, rises until it cools to an equilibrium temperature within the inversion and proceeds to flatten out and meander. The other is that the inversion has begun to erode from the ground upward and the smoke meanders and fans out beneath the resulting capping inversion (the capping inversion is not in contact with the surface – it halts upward motion and traps air pollutants below it). Either way, when inversions exist there are several smoke plumes rising and contributing to the concentration of the smoke. There is evidence too of other smoke plumes in the far distance, which may contribute to smoke concentrations.

Pesticides in the wider atmosphere

When the atmosphere is unstable, convective air currents can lift pesticides and mix them through the wider atmosphere. They reside in the wider atmosphere until they are washed out by rain, or slowly gravitate to the surface.

"Predictably, those chemicals found frequently in air are those used most extensively, have multiple emission sources, and resist degradation" (Woodrow, Gibson and Seiber 2019). Majewski and Capel (1995) note that "once pesticides are lifted into the atmosphere and remain for some time they are distributed between aqueous, particle and vapour phases". Some of these will be degraded or transformed, while others will be returned to the surface by:

1. wet deposition by fog, mist and rain. Vapours can be transferred to droplets, and pesticides bound to particles can become nuclei for droplet formation. When droplets fall they can intercept more pesticides. Effectively, droplets bring pesticides to the surface and also wash them out of the atmosphere. These processes are quite similar to dust being washed out of the atmosphere; and
2. dry deposition. This includes deposition to the Earth's surface of airborne pesticide vapours and particle-bound pesticides. Dry deposition is a continuous and slow process (Majewski and Capel 1995).

Tips to minimise spray drift

Drift mitigation relies on operator knowledge and skills. Land owners also need the desire to change operating practices to combat adverse conditions and minimise drift. Label instructions offer vital guidance for successful application but they cannot possibly cover every factor that needs careful consideration. Most of the following tips are extracted from publications written by Bill Gordon.

Be aware of what drifts

- Droplets that drift are variously cited as those that are less than 100 to 200µm. However, it is not that simple. If vertical air currents, wake turbulence and droplet deformation extend how long larger droplets stay in the air (their airtime), they may evaporate, reducing their size and mass and increasing their susceptibility to drift.
- Particulates drift after the aqueous component of the droplet has evaporated away, leaving the active ingredient and some other residues airborne.
- Vapours can enter the atmosphere for hours or days after an application of volatile pesticides.

Be prepared

- Attend training sessions and keep certification up to date.
- Read the product label carefully and operate within the recommendations.
- Plan buffer zones.
- Have a plan to safely empty a tank if conditions deteriorate.

Be careful of surrounding areas

- Know the location of nearby sensitive crops, waterways, livestock and communities.
- Let neighbours know of your spraying plans.
- Maintain buffer zones and be prepared to leave some sections for another day.

Use the right equipment and method

- Make sure the equipment is well maintained and calibrated for the specific job.
- If needed, increase water volumes to get the product to the target in larger droplets.
- Boom height and stability are critical; use height control systems for wider booms or reduce the spraying speed to avoid boom bounce.
- Set the boom height to achieve double overlap of the spray patterns.
  - With a 110-degree nozzle using 50-centimetre nozzle spacing, the correct boom height is 50cm above the top of the stubble or crop canopy.
- Avoid high spraying speeds, particularly when ground cover is minimal.
  - Spraying speeds above 16 to 18 kilometres per hour with trailing rigs and above 20 to 22km/h with self-propelled sprayers greatly increase losses due to effects at the nozzle and the aerodynamics of the machine.
- Select the coarsest spray quality that will provide an acceptable level of control.
  - Be prepared to increase application volumes when coarser spray qualities are used, or when the Delta T value approaches 10 to 12.
  - Use water-sensitive paper and the SnapCard® app to assess the impact of coarser spray qualities on coverage at the target.
- Be prepared to leave unsprayed buffers when the label requires, or when the wind direction is towards sensitive areas.
  - Always refer to the spray drift restraints on the product label and follow all downwind buffer requirements.
  - If there are no spray drift restraints or guidance on the label then a suitable rule of thumb is: for ground application of non-volatile products using a coarse spray quality (or larger) and wind speeds between 3 and 20km/h, a 300-metre downwind buffer is generally sufficient. Smaller spray qualities will require larger buffers.

Carefully manage formulation and tank mixtures

- Tank mix including the active ingredient, the formulation type, the adjuvant used (a chemical addition to the tank to improve pesticide performance) and water quality need careful management. Product labels and other supportive technical literature provide key information on spray quality and coverage requirements, buffer (no-spray) zones and wind speed requirements.

Observe weather conditions

- Record wind speed and direction, temperature and Delta T before spraying and at tank refills.
- Do not spray when hazardous inversions exist.
- Ideal wind speeds for spraying during the day are 5 to 15km/h measured at 2m.

- Ideal wind speeds for spraying at night are difficult to determine but generally they need to be greater than 11km/h measured at 2m to avoid hazardous inversions.
- When spraying at night keep the boom low, spray slowly and use the coarsest spray quality possible.
- Use a spray configuration that keeps the wind flowing across the path of travel.
- Morning spraying should only begin after the sun has risen more than 20 degrees above the horizon and the wind speed has been above 7km/h for more than 30 minutes, with a clear direction away from sensitive areas.
- Avoid temperatures over 30°C; efficacy may be compromised.
- Avoid Delta T <2: Small droplets can float for hours and there is risk of drift incorporating into fog.
- Avoid Delta T >12: Rapid evaporation can increase drift volume.

The atmospheric boundary layer

The atmospheric boundary layer (ABL) can be imagined as the container into which pesticides are released. The character of its constituents and airflow in part determines the success of pesticide applications but more importantly has a major impact on the fate of drifting pesticides.

The ABL depth represents the depth through which pollutants, including drifting pesticides, released from the surface are eventually mixed (Arya 2001).

Deep ABLs associated with unstable atmospheres contain large volumes of clean air into which pollutants can readily dilute. Shallow ABLs associated with stable atmospheres and temperature inversions trap pollutants at high concentrations in shallow surface layers with minimal volumes of clean air.

During the day, the depth of the ABL roughly equals the height of thermal rise. That is about 1000 to 2000 metres deep over most Australian agricultural regions.

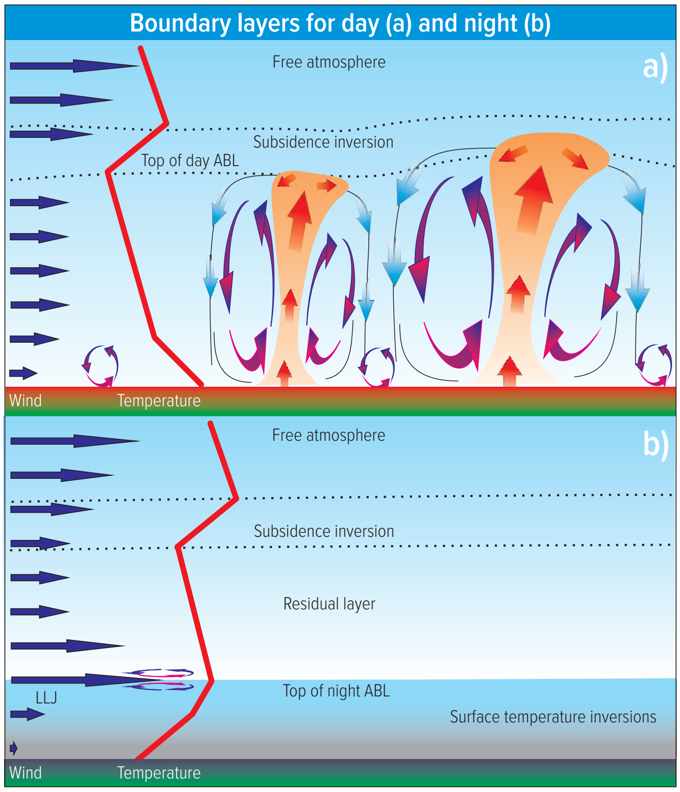
Thermal winds, being the upward arm of convective circulations, lift moisture, dust, salt particles and other aerosols, including pesticides, away from the surface up to the subsidence inversion – see Figure 5a.

Material lifted away from the surface and caught up in convective circulations mixes and disperses throughout the ABL (Arya 2001).

At night, the ABL is restricted to the depth of the temperature inversion (Figure 5b), which may only be a few metres to a few hundred metres deep. In this thin ABL, drifting pesticides spread horizontally across the landscape at high concentration.

Persistent air pollution episodes happen when emissions from the surface accumulate and do not disperse in the ABL beneath subsidence inversions (Figure 5a and b) for several days or longer in the presence of an anticyclone (high pressure system) and associated subsiding (sinking) and warming air. Typical subsidence inversions in Australia occur at an altitude of about 1000 to 2000m, well above surface inversions.

Figure 5: a) Idealised day ABL; b) idealised night ABL.



Turbulence and dispersion

Turbulence is the driver of dispersion. When active, turbulence efficiently mixes surface air and decreases the concentration of suspended material. Inactive or weak turbulence leads to the concentration of airborne material at the surface.

Turbulence is generated whenever airstreams of different speeds or directions interact. The interactions cause chaotic rotational eddies and sweeps in the airflow (Liu, Yan and Lu 2014) – see Figure 6.

The Primary Industries Standing Committee (2002) notes that "with increasing 'mechanical' turbulence intensity, the peak deposit is higher and closer to the source. Far downwind deposition levels, however, are higher at low turbulence intensities. This highlights the dangers of releasing small droplets in stable conditions". It also highlights the specific dangers of releasing driftable material into the weak turbulent conditions of hazardous inversions.

Although mechanical and thermal turbulence are the primary drivers of dispersion, wake turbulence, generated off the machine, can deform the spray sheet and increase the volume of drift-prone droplets. Wake eddies and sweeps elevate pesticides above the release height.

Mechanical turbulence

Mechanical turbulence occurs when air is slowed by surface and obstacles. It becomes more pronounced as wind speed and surface roughness increase. It occurs both during the day and at night.

At night, it is generally weaker than during the day and especially weak when hazardous inversions exist.

Mechanical turbulence may assist deposition of droplets to the surface through downward sweeps. However, because mechanical turbulence expands downwind in roughly a conical pattern, it also disperses material away from the surface into the wider atmosphere.

Vigorous mechanical turbulence, together with thermal turbulence, can rip particles of dust, soil, sand, spores and micro-organisms such as bacteria from the surface and raise them high into the atmosphere (Figure 7).

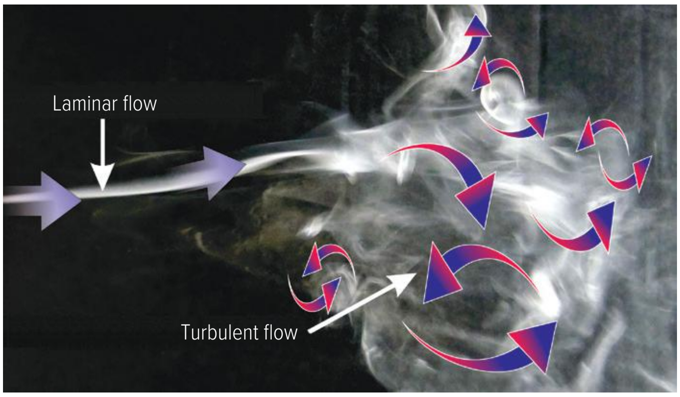
Thermal turbulence

Thermal turbulence occurs when there are upward motions of air – which range from the very minor to the very large and violent – followed by lesser downward motions. Water coming to the boil demonstrates the range of convective circulations that happen during thermal turbulence.

In the atmosphere, thermally induced uprising air is most vigorous. It is replaced by slower moving and more expansive sinking air which, on approaching the surface, is heated and rises. This causes convective circulations to be continuous.

Convective circulations commonly rise to the top of the ABL, which is several thousand metres deep by mid-afternoon, when the

Figure 6: Smoke defines wind flow conversion from laminar (non-turbulent) to turbulent. Rotational eddies ('closed circulations') and sweeps ('open circulations'), the drivers of dispersion, are evident.



Source: Graeme Tepper

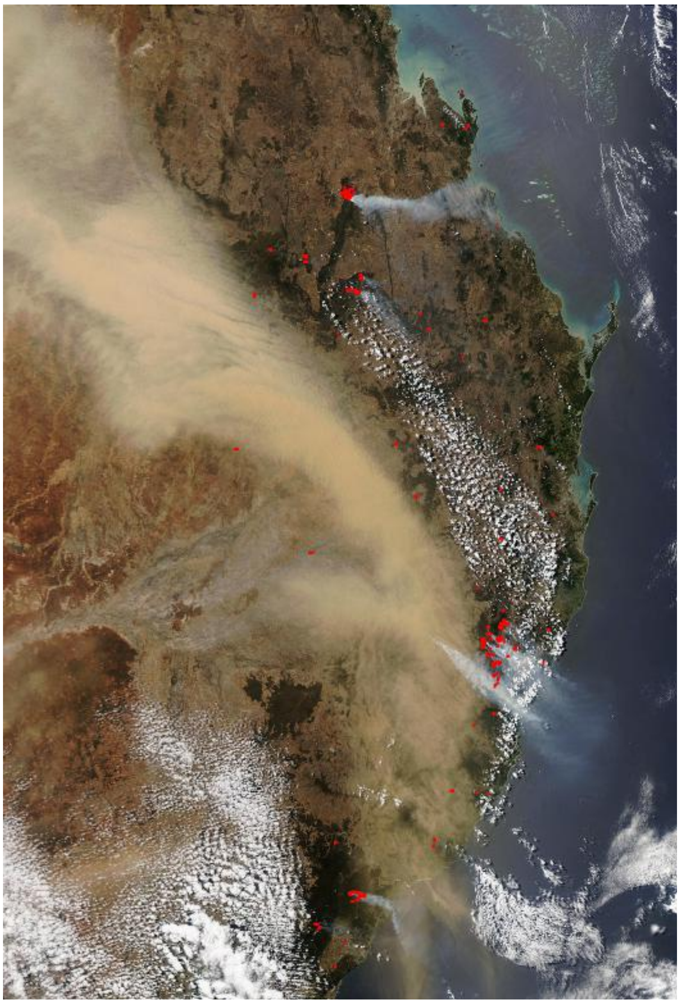


Figure 7: Extreme turbulence along a frontal surface rips soil from the surface.

Photo: BoM – satellite viewer

atmosphere is unstable. When the atmosphere is very unstable the circulations may rise to tens of thousands of metres, within convective storms.

Thermal turbulence, stretching up far above the surface, is very efficient at dispersing drifting pesticides and limiting, but not completely negating, downwind negative impacts.

Thermals are active during the day, no matter what the season, when the surface is warmer than the air just above. They are more noticeable in summer than winter because the surface is much hotter, the thermals are more vigorous and dust and other material is readily available to indicate strong upward motion.

The absence of thermals does not preclude vertical motion and cumulus cloud or thunderstorms developing. Many factors contribute to vertical motion, including topographic lifting, up-slide of air layers, latent heat release, frontal systems, wave motion, disparities in horizontal temperature and upper-air instabilities.

Wake turbulence

Although mechanical and thermal turbulence are the primary drivers of dispersion, wake turbulence, generated off the machine (groundrigs and airborne craft) can deform the spray sheet and increase the volume of drift-prone droplets. Wake eddies and sweeps elevate pesticides above the release height.

Wake turbulence is generated whenever the spray rig displaces air. Large bulky machines moving at high speed produce maximum wake turbulence, but small machines with poor aerodynamics also produce considerable wake turbulence.

Swaying and yawing of booms along with a machine's interactions with the ambient wind influence the intensity of wake turbulence.

Raised dust and droplets hanging in the air above boom height and wet boom infrastructure are indicators that wake turbulence is active; however, often there is no visual evidence.

The problem with wake turbulence is that spray sheets can be

Figure 8: Combinations of mechanical and thermal turbulence cause looping of a smoke plume as it traverses a paddock.

Photo: Frank Taylor

Figure 10: Droplets outline wake turbulence.

Photo: Creative Commons

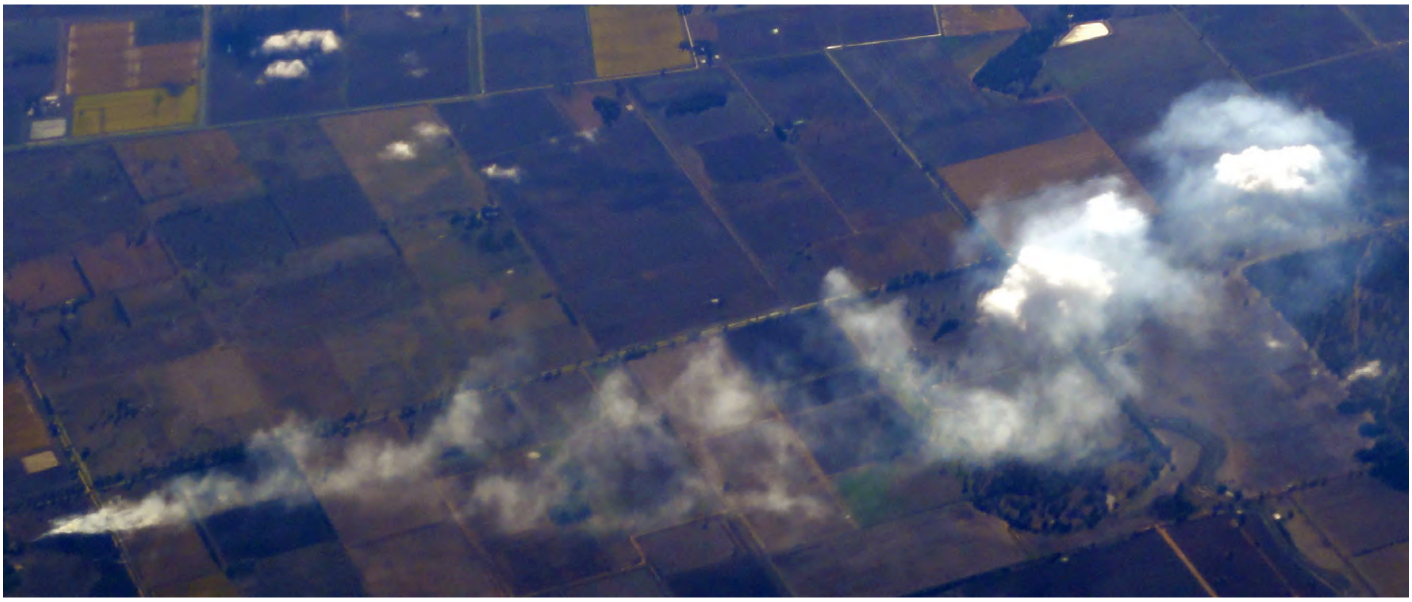


**Figure 9: A bird's eye view of smoke rising in an unstable atmosphere.
The chaotic, turbulent eddies are evident in the corkscrew pattern of rising and expanding smoke.
The smoke particles act as nuclei to form small clouds.**

Photo: Graeme Tepper

deformed and large and small droplets can be lifted away from their normal downward trajectory – see Figure 10.

All flying craft produce invisible wake, prop or rotor turbulence. To avoid powerful vortices interfering with the spray released, booms on fixed-wing aircraft do not extend to the end of the wings.

Helicopter wake may be significantly stronger than that caused by fixed-wing aircraft of the same weight and, as the Bureau of Meteorology (BoM) observes, “the strongest wake occurs when the helicopter is operating at slow speeds” (Meteorology – BoM).

Many types of drones, like the one shown in Figure 10, can be useful for pesticide application. However, challenges with using drones include limited payloads, low-water rates, finer sprays being caught in the air field flow of vortices (wake turbulence) and a potential for fine droplets to drift (Tom Wolf 2019). Tudi et al. equipped a commercial quadcopter with centrifugal nozzles and used it to spray while exposed to a range of different wind speeds. The researchers concluded, “flight speed and altitude have a significant effect on the distribution of the airflow field” (Tudi et al. 2021).

Each drone type and sprayer configuration needs to be assessed to determine the risk of drift over a range of meteorological conditions and operating conditions.

Fine-scale turbulence

Fine-scale turbulence promotes small droplet and particle suspension in thin layers. When humidity is very high and hazardous inversions exist, mist and fog make layering (stable stratification) visible, as in Figure 11.

Drift suspended in stable and saturated layers is likely to be incorporated into mist and fog.

Mysterious bursts of turbulent winds overnight are sometimes associated with top-down turbulence. Traditionally, turbulence at the surface has been regarded as originating at the surface (‘bottom-up’) but turbulence can intrude from aloft (‘top-down’) in intermittent bursts in strongly stable conditions (Mahrt 1999, 2014; Banta, Pichugina and Brewer 2006).

Figure 11: Fine-scale turbulent mixing can lead to layering within mist and fog when the atmosphere is stably stratified, and therefore when an inversion exists. Muschinski and Wode (1998) have referred to these layering events as ‘temperature and humidity sheets’.

Photo: Nicola Cottee

Atmospheric stability

Stability of the atmosphere promotes or suppresses vertical motion. It is the most critical factor determining concentrations and patterns of drift.

In fact, Miller et al. (2001) observe that the stability of the atmosphere is a primary factor controlling the time and space variability of drift.

Miller et al. (2001) highlight just how influential stability, or the lack of it, can be: “Small changes in the stability condition can produce very large and quite rapid changes in the concentration of airborne plumes and the amount depositing to the surface”.

Stability also impacts drift at various times. As Majewski and Capel (1995) note, “stability has significant effect on spray drift at the time of application, on post volatilization, and on the final concentration of deposits”. Stability also affects the volume of spray suspended in the atmosphere in the short term (hours) and long term (days to weeks).

Light winds in very unstable conditions may more readily disperse airborne material than stronger winds in very stable conditions.

Twin concepts of stability

When authors refer to ‘stability’ in the pesticide application literature, they are talking about dynamic stability, whereas when they refer to ‘inversions’, they are talking about static stability. Knowing the difference is critical to understanding why pesticides become airborne and what happens to them.

‘Static stability’ describes the potential for air parcels to be buoyant; that is, whether they will continue to rise or fall when displaced upwards or downwards. Knowing when the atmosphere is statically stable or unstable is useful for predicting how the weather might develop; for example, what types of clouds might form, whether there will be weather events such as thunderstorms and how severe these might be, and whether an inversion exists.

However, as useful as static stability is, it does not take into account the effects of wind conditions and turbulent mixing, which are critical factors controlling the dispersion of drifting pesticides.

‘Dynamic stability’ considers the effects of both static stability and wind effects – including mechanical and thermal turbulence – on the transport, dispersion and deposition of airborne pesticides.

The degree of dynamic stability affects spray drift at the time of application, post volatilisation, and the final concentration of deposits. Majewski and Capel (1995) note that “the concentration of the spray plume and the volume that deposits to the surface is dependent on atmospheric dispersion”.

The degree of dynamic stability is crucial in determining the concentrations of drifting pesticides and whether they will move vertically or horizontally. It needs to be assessed accurately in the field when attempting to critically assess drift, volumes depositing and vapour emissions.

Static stability

To understand the effects of atmospheric stability on spray drift it is useful to take an imaginary parcel of air and raise or lower it in three different atmospheric conditions: unstable, stable and neutral. Figure 12 shows what happens to the parcel of air, designated with the icon ‘15’, in each of these conditions. For simplicity, the parcel is moved vertically away from the temperature of the atmosphere – the environmental lapse rate (ELR).

Figure 12 shows that in unstable conditions, the ELR of the temperature decreases with height. A parcel of air displaced upward is warmer than the ELR; it is thus buoyant and continues to rise. When the parcel is displaced downward, it is colder than the ELR and therefore continues to fall. This unrestrained buoyancy supports convective turbulent mixing and dispersion.

In stable conditions, the ELR increases with height. A parcel of air displaced upward is colder than the ELR and will spring back to its original position. When it is displaced downward, the air parcel is warmer than the ELR and will similarly spring back to its original position. In stable conditions mixing, and therefore dispersion, are greatly suppressed.

Inversions are symptoms of stable conditions.

In neutral conditions, the ELR does not change with height. A parcel of air displaced either upward or downward stays put. In this situation, buoyancy alone has no effect on mixing. Usually the atmosphere is not exactly neutral. In the neutral case for mixing to occur it must be forced by mechanical turbulence.

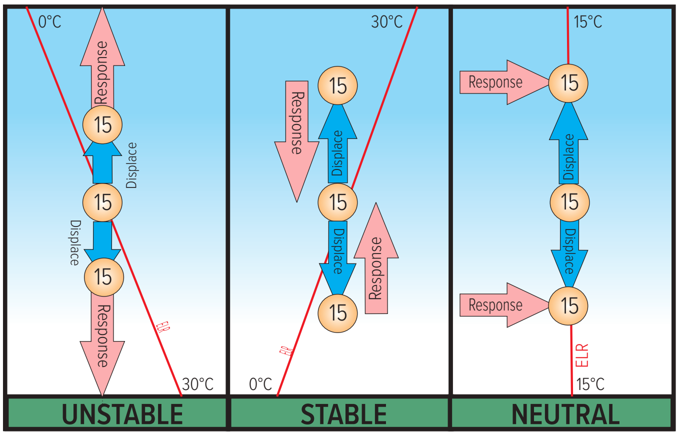


Figure 12: Static stability: the buoyancy of displaced air parcels in unstable, stable and neutral conditions.

Source: Graeme Tepper

Dynamic stability

As noted earlier, dynamic stability, which considers the combined effects of wind, turbulence and static stability, lends further clarity in determining the drift motion, pattern and dispersion of airborne material, including spray drift.

The three panels in Figure 13 profile how well identical volumes of drift composed of different droplet sizes reach the target in three atmospheric stability conditions: neutral, very unstable and strongly stable. Medium and coarse droplets (shown with purple and orange) reach the target and finer droplets, particles or vapours (shown with grey) suspend.

In particular, the atmospheric stability conditions affect the plume in the following ways:

- In neutral conditions, most of the plume intersects the surface but some is dispersed into the atmosphere.
- In very unstable conditions, the majority of the plume rises and is dispersed into the atmosphere.
- In strongly stable conditions, the plume is trapped in a layer at high concentration.

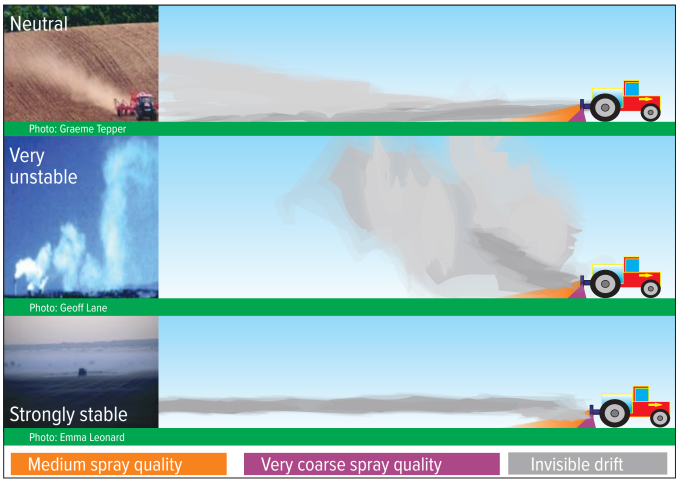


Figure 13: Three profiles of invisible drift. Source: Graeme Tepper

The APVMA publication *Spray drift management: Principles, strategies and supporting information* (Primary Industries Standing Committee 2002) advises that:

- wind speed should be between 4 and 15km/h for most spraying operations;
- spraying should not be undertaken if the wind is light and variable in strength or direction;
- spraying should not take place during highly unstable conditions; the dispersion of spray upwards may be high, increasing the amount of spray that enters the atmosphere; and
- spraying should not take place during highly (strongly) stable conditions or when surface temperature inversion exists. The dispersion rate of droplets may be low in strongly stable conditions, leading to high off-target deposition at ground level. Small droplets are capable of remaining airborne for long periods within the inversion layer and can cause severe damage several kilometres away from where the spraying takes place.

Spraying within stable conditions does not increase drift but it can certainly make it easier to detect near the surface. Stable conditions simply keep the volume drifting at high concentration rather than being dispersed by turbulence, as it is in unstable conditions.

Unstable atmospheres promote convective circulations, looping, fumigation to the surface and mixing of airborne material through the entire ABL. Figure 14 displays common motions and spread of smoke in the unstable daytime ABL.

Miller et al. (2001) observe that in unstable conditions, vertical motion is enhanced and airborne pesticides (including vapours) tend to mix upward, to weaker concentrations.

In fact, thermals can transport pesticides to remarkable heights (Thistle, Teske and Reardon 1998) and the circulations can mix them throughout the ABL, where they will remain until wet or the dry deposition process returns them to the surface. Crabbe, McCooeye and Mickle (1994) note that “vertical air currents and mixing associated with unstable conditions can loft spray particles into the overlying atmosphere and thereby reduce off-target deposits” directly downwind of the application. This means that the total mass of drifting material is often not captured by field experiments.

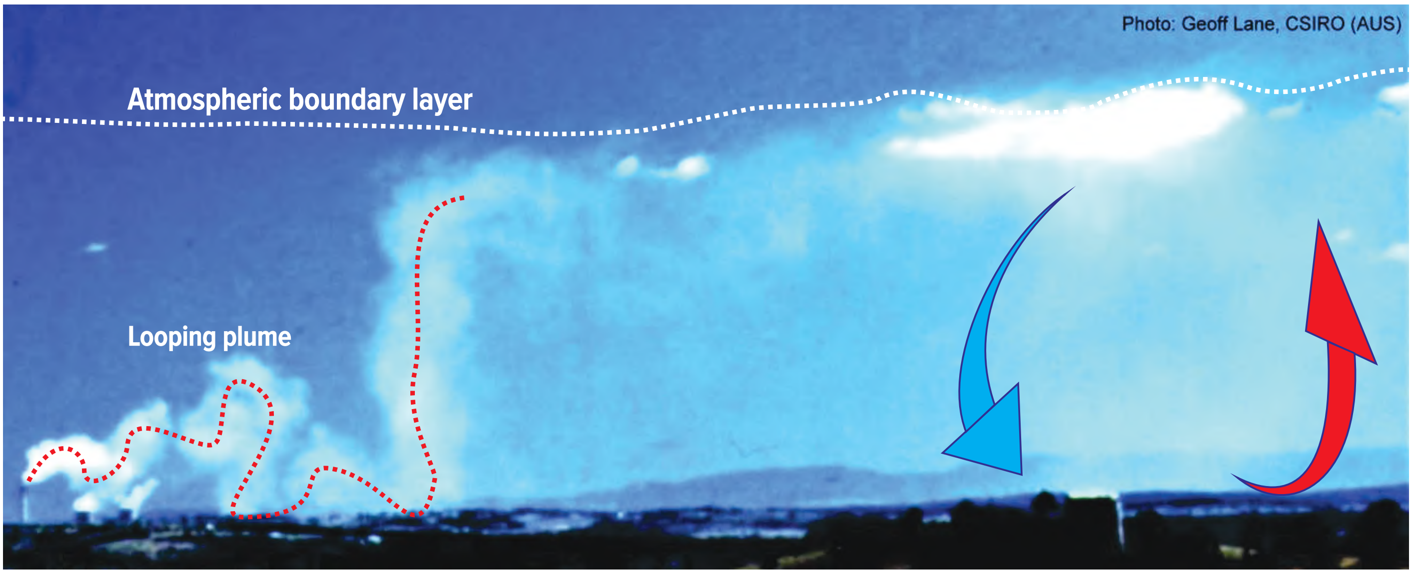


Figure 14: Dynamically strongly unstable conditions within the ABL. Here, the ABL is capped by a subsidence inversion.

Adapted by: Graeme Tepper

Figure 15: Dynamically very stable conditions in a shallow ABL. Observe in this image the various wind directions affecting the smoke plume as it rises before being carried away by laminar wind flow. Photo: Graeme Tepper

Strongly stable atmospheres promote restrictive layering and high concentrations of airborne material being transported away from the source – see Figures 15 and 16.

Miller et al. (2001) outline how the effects of strongly stable and unstable conditions on spray drift differ: "It has been found that in stable conditions, when vertical motion is suppressed, airborne pesticides don't disperse vertically but move horizontally at high concentrations near the ground. In unstable conditions, when vertical motion is enhanced, airborne pesticides tend to mix upward to weaker concentrations."

Seaman et al. (2008) elaborate on the behaviour of plumes in stable conditions, noting that in these circumstances, "plumes may remain quite highly concentrated over long distances downwind while exhibiting large changes in direction. The plume may even travel in a looping or nearly circular path".

On a regional basis, strongly stable conditions promote cold pool formation and localised stronger stability within the cold pools (Bodine et al. 2009).

How far smoke rises into an inversion depends on the heat of the fire and the initial temperature of the smoke parcels compared with the temperature of the air. Smoke parcels will continue to rise until their temperature cools to that of the air. At this equilibrium level, smoke will begin to spread sideways, as shown in Figures 15 and 16. Observe in Figure 14 that there are many levels of equilibrium for various smoke parcel temperatures lifting away from their source.

High humidity environments make it possible to observe how, in very stable conditions, various layers of mist and fog form, and to discern clearly demarcated layers of airborne material at various concentrations – see Figure 17.

Figure 17: Fog, mist and layering indicate very stable conditions. Photo: Nicola Cottee

Figure 16: Plumes of smoke at the surface and at 30m in very stable conditions drift horizontally in opposing directions without vertical dispersion. The undulations in the lower left portion of the image are assumed to be caused by slight thermal lift in the early morning. This plume extended far to the left. The plume in the upper right of the image evidently began to meander and spread horizontally into the far distance. Photo: G Ramsay

Surface temperature inversions

Pesticide applications during hazardous surface temperature inversions can lead to spray drift being transported at high concentrations and causing severe damage up to several kilometres off target. Current regulations prohibit spraying of agricultural chemicals when hazardous temperature inversions exist.

Surface temperature inversions are often referred to in pesticide application literature as ‘radiation temperature inversions’, ‘temperature inversions’, ‘surface inversions’ or, simply, ‘inversions’.

Hazardous inversion features that lead to long-distance and concentrated drift are not inherent in all inversions (Grace and Tepper 2021); however, Australian regulations prohibit spray application of certain agricultural chemicals when hazardous surface inversions do exist.

In these circumstances, drifting pesticides, although invisible, can converge and be transported by laminar wind flows to destinations not indicated by synoptic wind flows.

In Figure 18, which depicts a hazardous surface inversion in very stable conditions, the individual and combined smoke plumes mimic and trace out the convergence and transport of invisible drifting pesticides.

What is an inversion?

Inversions occur when temperature increases with height overnight – see Figure 19.

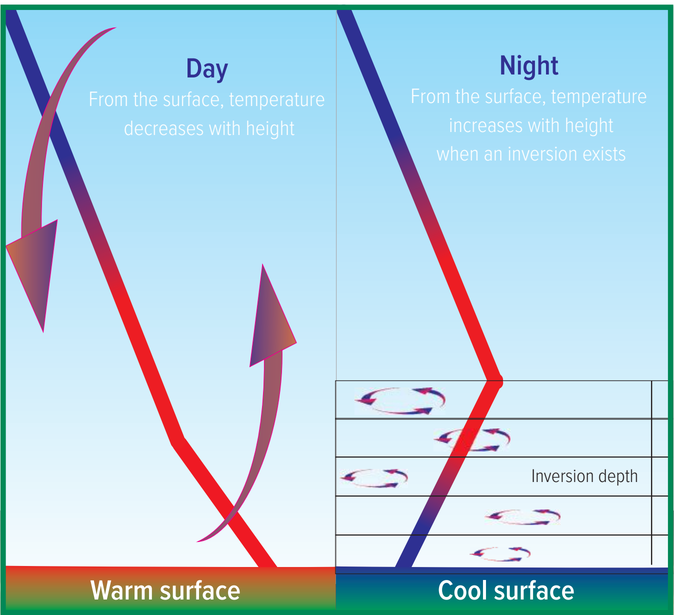


Figure 19: Typical vertical temperature profiles for day and night. Vertical mixing is strong during the day, when temperature decreases with height. At night, temperature increasing with height causes an inversion in which vertical mixing is suppressed.

Figure 18: Smoke plumes trapped in a strongly stable hazardous inversion and transported by laminar wind flow. Photo: Pete Nikolaison

Figure 20: Layering in hazardous inversion conditions with high humidity. Photo: Bill Gordon

Figure 21: Dust drifting close to the surface in a shallow layer is indicative of hazardous inversion conditions existing prior to sunset. Photo: Tom Luff

Figure 22: Inversion layering and the suspension of aerosols just above the surface. Photo: Frank Taylor

Figure 23: A shallow inversion layer acting as a duct for the transport of fog droplets generated from upstream moist surfaces. Photo: Nicola Cottee

Surface temperature inversions can be categorised as either non-hazardous (weakly stable) or hazardous (very stable).

In the case of a non-hazardous inversion, moderate to strong turbulence mixes and disperses drifting pesticides into a large volume of air and limits its downwind effects. Moderate to strong turbulent mixing is not supportive of long-distance high-concentration drift.

The intensity of turbulence in the non-hazardous regime is comparable with that observed in near-neutral conditions that are recommended under current guidelines as suitable for spraying (Grace and Tepper 2021).

In the case of a hazardous (very stable) inversion, weak turbulent mixing can support the transport of high concentrations of fine material over long distances.

Recent Australian research has designated that for an inversion to be considered hazardous, there needs to be standard deviation of vertical wind speed of less than 0.2 metres per second (Grace and Tepper 2021).

However, other authors allude to turbulence intensity as a critical factor in determining the amount of pesticide drift occurring near the surface.

MacCollom, Currier and Baumann (1986) write that “in very-stable conditions greater drift distances and amounts were observed under temperature inversion conditions than in their absence”, while Yates, Akesson and Cowden (1974) found that at 400m, the volume of downwind depositions was 13 times greater in very stable conditions.

Thistle, Teske and Reardon (1998) observe that “some of the more mysterious cases of off-target damage can be attributed to stability, or more specifically, a high concentration of fine droplets in a stable atmospheric layer”.

The APVMA directs operators not to spray when hazardous inversions exist, and adds this important clarification: “When application occurs in an area not covered by recognised inversion monitoring weather stations, all surface temperature inversion conditions are regarded as hazardous”.

Mist, fog and dust layering, as shown in Figures 20, 21, 22 and 23, act as a visual alert to hazardous inversions. Mahrt notes: “Mixing across a layer of stratified flow decreases the temperature at the top of the layer and increases the temperature at the bottom of the layer. If the flow is near saturation, then even a slight decrease of temperature may lead to condensation at the top of the thin mixing layer” (Mahrt 2014; see also Muschinski and Wood 1998; Balsley et al. 2006).

Inversion occurrence

Inversions occur over Australian agricultural regions most nights, when other weather conditions are suitable for spraying. Hazardous inversions occur less often than non-hazardous inversions – see Figure 24.

It should never be assumed that inversions only form when skies are clear and winds are very light. While clear skies and very light winds promote inversion formation, overcast skies and winds exceeding 20km/h may not prevent them.

It has long been assumed that inversions ‘strengthen’ overnight and ‘max out’ near sunrise. This is not always true. Australian data shows that the most hazardous inversions can occur during the first few hours of the evening; it depends on regional influences. The lower panels in Figure 24 indicate regional variations in hazardous inversion occurrence. The differences appear to depend on the development, persistence and strength of local wind flows.

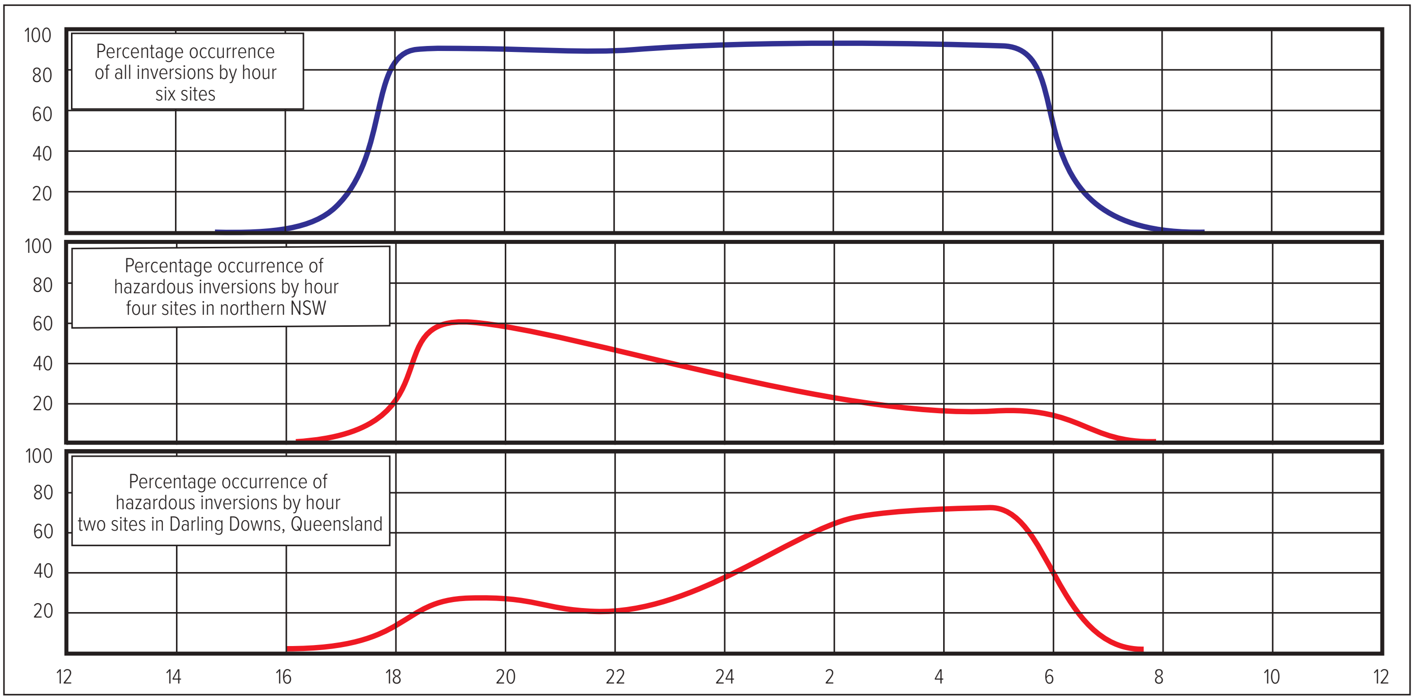


Figure 24: A three-year summer data analysis of percentage occurrence of inversions versus hazardous inversions for six sites in northern NSW and southern Queensland. The blue line includes all inversions. The red lines depict hazardous inversions. Of note is the variability of the maximum occurrence of hazardous inversions, which ranges from early evening in NSW to near sunset in Queensland for the sites investigated.

In both panels of Figure 24 indicating hazardous inversion, the rises and falls of occurrence across the night-time hours are mirrored by rises and falls in wind speed. The charts indicate the importance of developing regional climatologies specifically for pesticide application, as well as developing knowledge about inversion occurrence and associated wind flow regimes.

Generic spray guides – warning

The variability in the time of day that most hazardous inversions occur (Figure 24) and wind speeds that can be experienced around the times of inversion onset and cessation (Figure 27) provide evidence that generic 24-hour sprayer guidance needs to be used cautiously because it may not reflect regional or seasonal inversion variance.

There is a need for spray guidelines to be developed from robust data for the regions they are intending to support. It is likely that advice about the timing of inversion occurrence and indicators of when inversions will be most hazardous will vary seasonally and by region.

Hazardous inversion detection systems will provide robust datasets for the development of spatially accurate sprayer guidelines.

Inversion life cycle

While transitions in the atmospheric boundary layer (ABL) and inversion life cycles vary, the idealised life cycles depicted by Figure 25 provide realistic sequences of events. What the figure does not indicate are inversion events out of the ordinary that form long after sunset and cease long before sunrise, or occur fleetingly several times throughout a night.

Stage 1 of Figure 25 depicts a daytime unstable condition then, at stage 2, a shallow layer of cool air first forming at the surface cuts off thermal turbulence. The layer deepens during the night at stage 3. Turbulence (arrows) and wind speed increase over

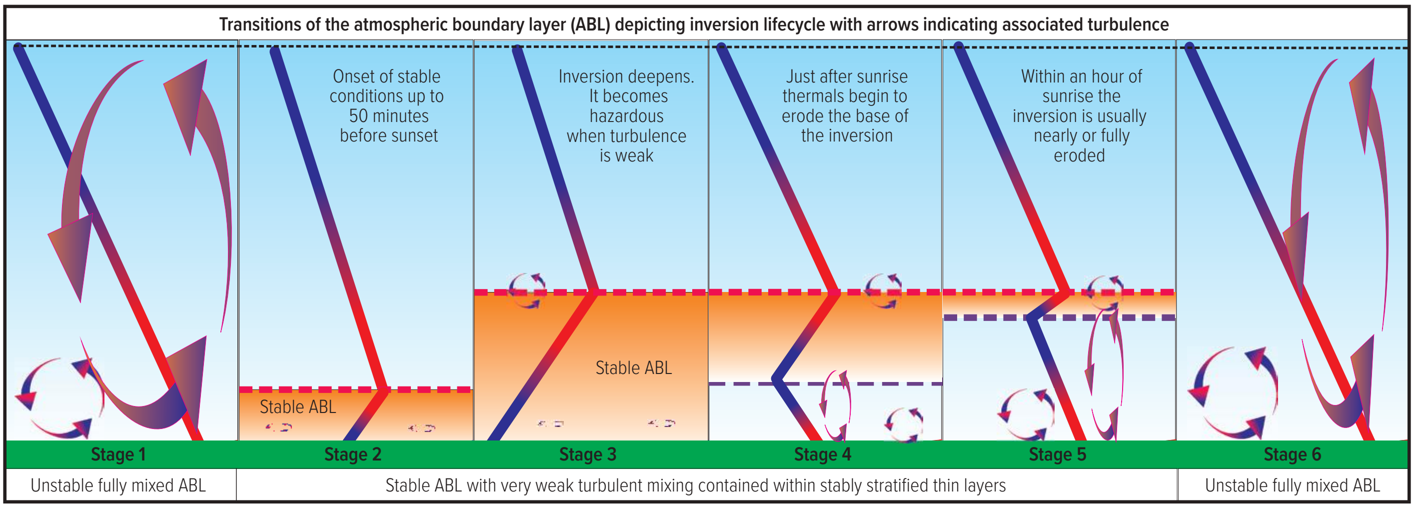


Figure 25: Idealised transitions in the atmospheric boundary layer (ABL) with inversion life cycle and turbulence.

the top of the inversion to counter the decrease within the inversion at stages 2, 3, 4 and 5. By stage 4, the lower levels of the inversion begin to be eroded by thermal activity from solar heating. At stage 5, inversion breakup is caused by thermal and wind shear turbulence.

Early cessation of inversions is likely to occur when the overhead wind shear turbulence becomes sufficiently strong that it breaks down the lower level stability before thermals are active. Late onset, early cessation and fleeting inversion events usually coincide with the clearance and onset of very cloudy skies and/or the weakening or strengthening of wind speed.

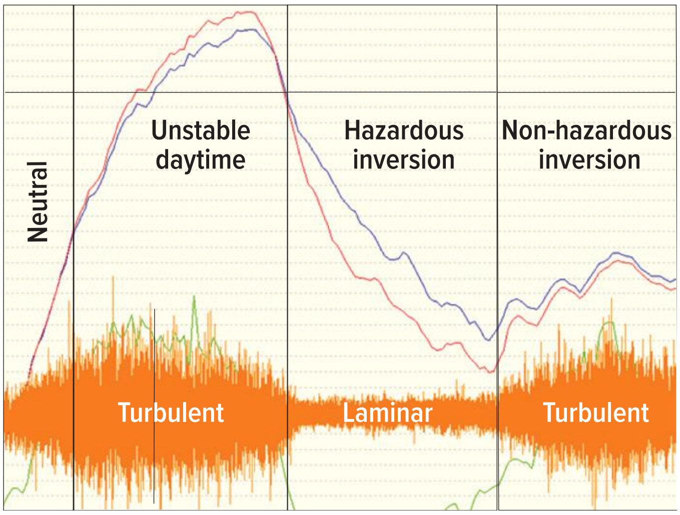


Figure 26: Turbulence compared with stability. Temperature at 1.25 and 10m is shown with red and blue lines, and the orange line shows the vertical wind speed. Large variations in vertical speed indicate maximum turbulence, while little variation indicates laminar wind flow.

Cloud cover when inversions exist

Clear skies are ideal for maximum overnight surface cooling but sufficient cooling can occur beneath overcast skies. How much cloud is too much is somewhat dependent on wind speed. Dense overcast clouds with weak winds are more favourable for inversion formation than dense clouds with strong winds. Thick transient clouds periodically cause temperatures to rise and fall, as does wind speed, leading to variations in vertical temperature difference (VTD), which in part determines the strength of inversions.

It has been observed that inversions can be temporarily destroyed by transient showers and storms.

Note that cumulus clouds producing showers and storms can occur when inversions exist. Such clouds are generated by upper-air instability. Upper-air instability can be associated with fronts, troughs, up-slide of air masses and topographic lifting of airflow as it crosses high terrain.

Inversion winds

Inversion winds, when strongly decoupled from the overriding atmosphere, can significantly contradict weather forecasts, which cannot resolve fine-scale topographic drivers of drainage and other locally driven winds. For this reason, operators must remain vigilant regarding locally driven winds and wind shifts if spraying at night, even if they believe a hazardous inversion does not exist.

Weak inversions can be difficult to detect when synoptic winds are only partially or intermittently decoupled from the surface. In such circumstances, moderate to strong intermittent or continuous turbulence occurs and disperses drifting pesticides into a large volume of air and limits its downwind effects (Grace and Tepper 2021).

Hazardous inversions commonly occur when the synoptic flow is completely decoupled from the surface. Complete decoupling

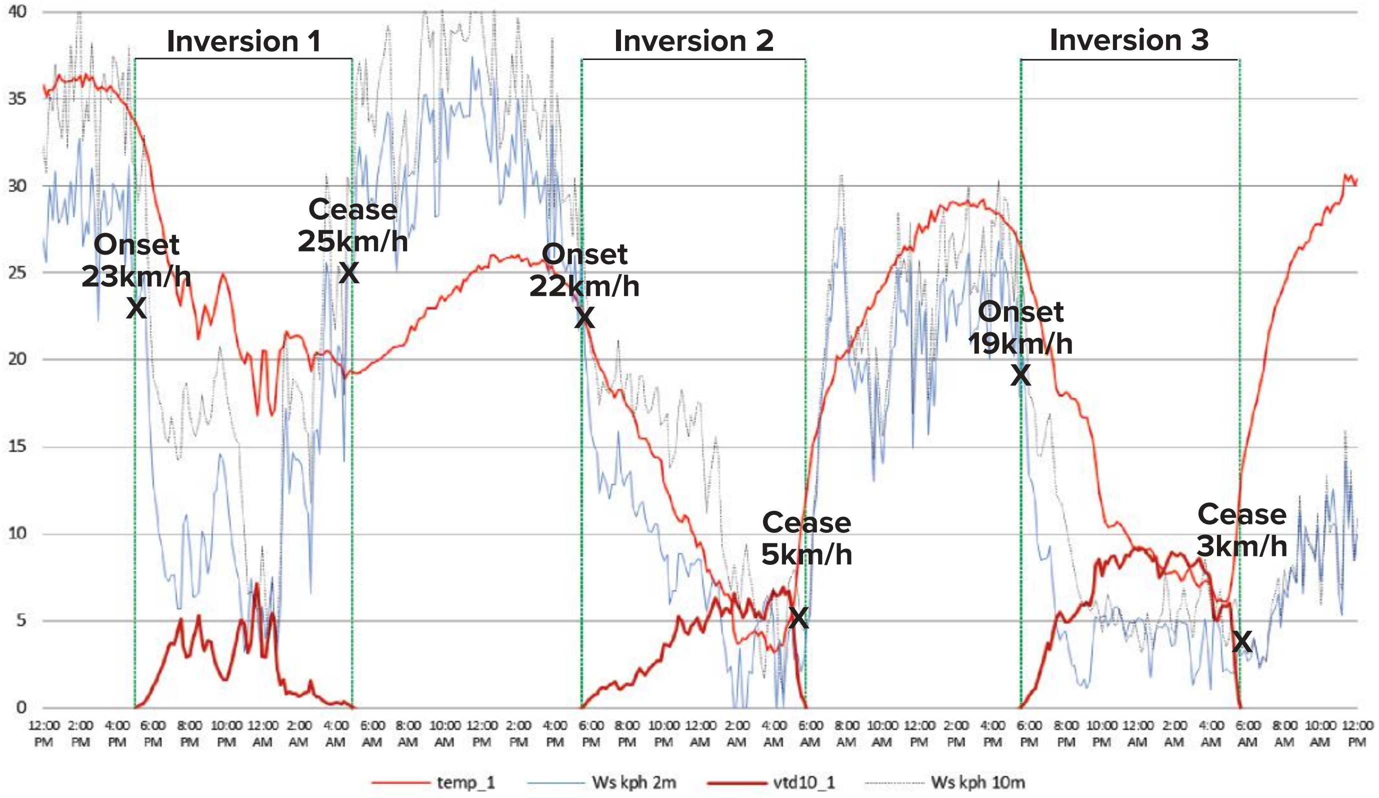


Figure 27: Three consecutive inversion nights at a site close to Dalby, Queensland, during November 2019. The three inversions occurred within an hour of sunset and ceased within an hour after sunrise. The tagged wind speeds refer to the 2m level.

promotes very stable stratification and the onset of local wind flows with very weak turbulence.

Decoupling can be likened to clutch disengagement; one part stops while the other, free of frictional drag, can freely accelerate.

Released from surface friction, winds accelerate above the inversion in a narrow band while surface winds often rapidly slow down or even become calm – see Figure 27. The surface winds initially slowed, but often speed up in response to the onset of local wind flows, including cool air drainage winds.

Unexpected, intermittent gustiness experienced during the night, remote from escarpments, might be explained by accelerated wind speeds from above the inversion, occasionally injecting turbulence to the surface.

Figure 26 depicts turbulence responses to changes in stability. Greater spikiness and spread represent turbulent conditions. Limited spread and spikiness represent the laminar wind flow expected when hazardous inversions exist.

Airflow speed and direction within hazardous inversions become complex when flows from numerous topographic sources collide. It is not all that unusual to find that the wind direction at 2m is different to that at 10m and even opposed, and that the wind speed is erratic. Wind speed variations are often mirrored by variations in the vertical temperature difference (VTD).

Wind speeds when inversions exist

It is remarkable how strong wind speeds can be when hazardous inversions exist. Australian studies over agricultural regions indicate that at 2m, average wind speeds are commonly up to 10km/h, and that speeds up to 15km/h are not unusual at 10m.

Even higher wind speeds are accommodated by non-hazardous (weak) inversions, as depicted by Figure 27.

Australian research found incidents of hazardous inversion conditions being accompanied by 18km/h winds at 10m while the VTD was as much as 6°C between 10 and 1.25m (Grace and Tepper 2021). A 6°C VTD can be considered to be extreme, and indicative of an intensely strong inversion in terms of static stability. The fact that wind speeds can be as much as 18km/h when such strong inversions exist should ring alarm bells for those who believe inversions can only exist when winds are light (light winds often being defined as those travelling at less than 5km/h).

The APVMA recommends that agricultural wind measurement for ground sprayer application be recorded at 2m above the surface, but the BoM observes and forecasts winds at 10m. Therefore, it is important to understand the differences between 2m and 10m wind speeds, especially at night when large disparities can occur, as shown in Figure 27.

Many people operating spraying equipment will be surprised to learn that it is not unusual for winds to exceed 20km/h during inversion onset and cessation transitional periods and that, on occasion, such strong winds periodically occur while inversions are well established. If spraying when hazardous inversions exist alongside such strong winds, large volumes of high-concentration drift may be transported long distances.

Examples of high wind speeds associated with inversions are depicted in Figure 27:

1. The dark red line indicates inversion occurrence: VTD of 10m minus 1.25m.
2. The light red line indicates the temperature at 1.25m.
3. The blue line indicates the 2m wind speed.
4. The grey line indicates the 10m wind speed.

Note the rapid wind speed reductions and the strength of winds at inversion onset (23, 20 and 18km/h). As noted earlier, these wind speeds are not traditionally recognised as being associated with inversion occurrence. Likewise, the high wind speeds during the hazardous periods of the inversion and at inversion cessation are not traditionally associated with inversions.

In the first inversion case shown in Figure 27, note the spiky responsiveness of temperature and VTD to wind speed. The second and third inversions similarly respond, but not so noticeably.

The stronger the wind speed with hazardous inversions, the greater the potential for high-concentration drift to travel far and wide, leading to extensive damage across the landscape.

Studies of wind speed for both non-hazardous and hazardous inversions across some Australian regions revealed that average wind speed is rarely calm when inversions exist, except for periods near onset and just prior to erosion. On average, winds within non-hazardous inversions are stronger than within hazardous inversions, especially those at 10m (compare Figures 28 and 29). It was also found that hazardous inversion winds at 2m travel on average at less than 11km/h – see Figures 29 and 30.

Individual site datasets need to be analysed to determine site and regional winds accompanying inversions to develop valuable spray guidelines.

Winds often travel between 4 and 10km/h when inversions exist.

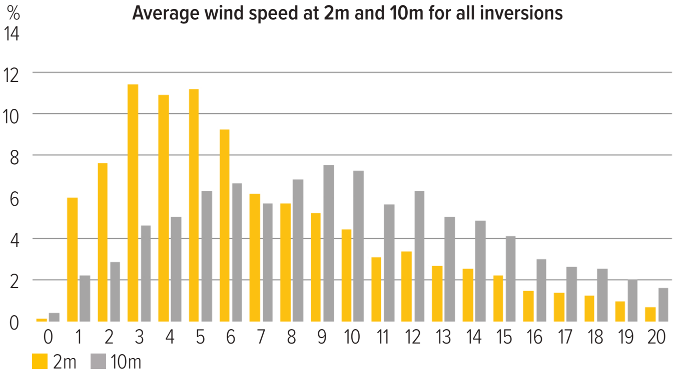


Figure 28: Wind speed percentage occurrences for all inversions.

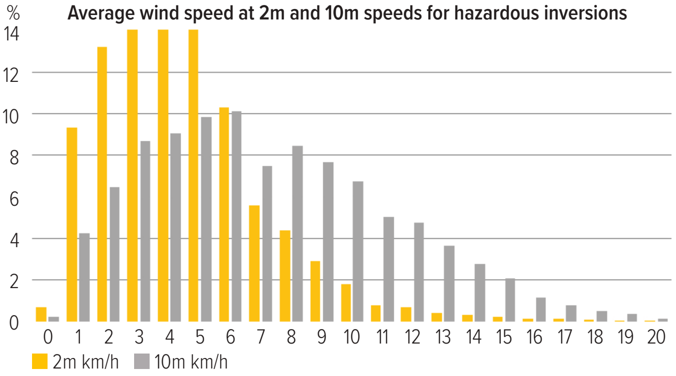


Figure 29: Wind speed percentage occurrences for hazardous inversions.

The impact of light breezes on drifting pesticides is well illustrated by the transport of suspended fog droplets within a hazardous inversion depicted in Figure 31. Observe that in Figure 31a, steam fog droplets do not appear to stray far from the source when winds are calm, but in Figure 31b, droplets are continuously fed into a cool, moist breeze that transports them at high concentration in a narrow streamer, well beyond the source. Such narrow streamers of fog emanating from dams can sometimes be observed from the air to extend tens of kilometres from the source. The lesson here is that airborne pesticides, although invisible, can be transported for kilometres in narrow bands under similar conditions.

Common inversion winds

The most common local winds occurring when inversions exist are cool air drainage flow winds (drainage flows). These are the winds often associated with extensive drift damage remote from the application. Drainage flows are shallow – just a few metres deep along slopes – but may be much deeper in valley systems or over low-lying regions, where the cool air can accumulate – see Figure 32.

Figure 30: Tabulated average wind speeds for non-hazardous (weakly stable) inversions and hazardous (very stable) inversions from 21 sites. Individual site statistics will differ.

Sample of averages in WA, SA, NSW and Queensland	Inversions			
	Non-hazardous		Hazardous	
	2m	10m	2m	10m
0–3km/h	25%	10%	40%	20%
4–10km/h	53%	45%	56%	59%
11–15km/h	14%	26%	2%	18%
16–20km/h	6%	12%	1%	3%
>20km/h	2%	7%	0%	0%

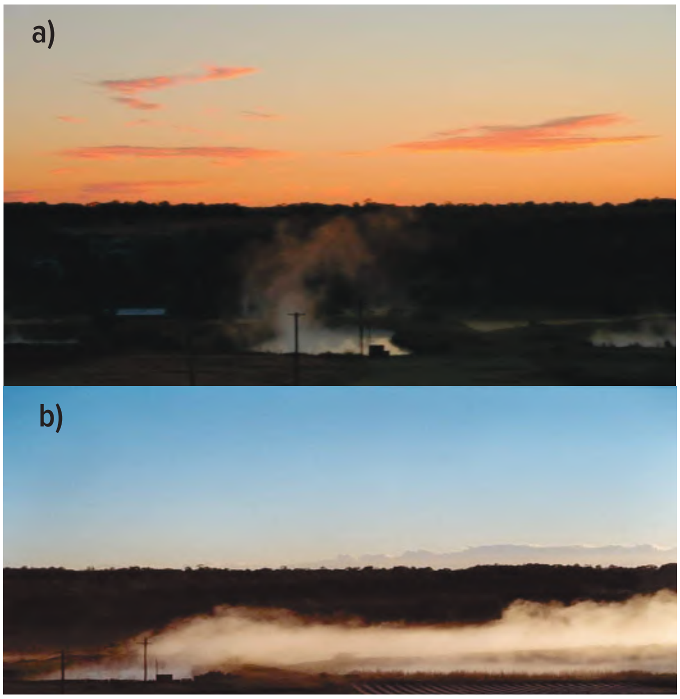


Figure 31: a) Steam fog forming in cool air over a warm water surface during calm conditions; b) steam fog continuously feeds into a cooling breeze that transports droplets away from the source in a ribbon or streamer.

Photo: Jimmy Deguara (http://australiasevereweather.com)

Drainage flows occur when cold, dense air starts to accelerate downslope by gravity in very stable conditions (Stull, 2000). These flows can only occur when the atmosphere is very stable in a shallow layer (Nauta 2013).

If they persist for some hours, they can shift pesticides away from application sites at high concentrations in directions more aligned with topographic slopes than suggested by the synoptic winds.

See more detail in the section on wind, page 24.

Pesticide residues in the air

Recent studies indicate that pesticides may be present in the atmosphere in any part of the world – even those regions far removed from pesticide applications.

It has become clear that pesticide residues are being continuously redistributed, and that these residues are sometimes redeposited far from the original sites of application (Jegier 2006).

As shown in Figure 33, stage 1, airborne pesticide residues can be mixed throughout the daytime atmospheric boundary layer (ABL) (see the red dots) and remain there overnight above inversions (stages 2 to 5). At night, drifting pesticides accumulate at high concentration within inversions (stages 2 to 4). When the inversion breaks (stage 5), drift and residues can combine. Some will be retained in the atmosphere to be swept away by high level winds, while some will deposit to the surface.

Predictably, chemicals found frequently in air are those that are used most extensively, that have multiple emission sources, and that resist degradation (Woodrow, Gibson and Seiber 2019).

Early morning spraying in cool and light-wind conditions may seem like a good idea, but if sprays are applied during the period of inversion erosion, any drifting material could be transported far from the point of application as the winds shift from locally generated to the synoptic flow.

Inversion detection

Inversion detection requires continuous and accurate measurement of the vertical temperature difference (VTD). “Small changes in the stability condition can produce very large and quite rapid changes in the concentration of airborne plumes and the amount depositing to the surface” (Miller et al. 2001).

Australian research has found that very small VTD can be associated with hazardous inversion conditions. For example, a VTD of only +0.7°C between 10m and 1.25m with a wind speed at 10m of 13km/h has been observed when a hazardous inversion existed.

Hazardous inversion detection requires continuous measurement of the standard deviation of vertical wind speed. This is done by 3D ultrasonic anemometers that measure the intensity of turbulence in the atmosphere four times per second. When turbulence is weak, hazardous inversions exist that are conducive to high concentrations of pesticides drifting near the surface over long distances. Stronger turbulence disperses drift.

Visual and other indicators may only become apparent hours after the onset of an inversion. Such indicators are last-resort tools for inversion detection. They should not be relied on for critical decisions.

NOTE: advisers and applicators should not equate mist, fog, dew or frost or the minimum temperature with the most hazardous times to spray. These indicators equate to temperatures falling, humidity rising and the occurrence of an inversion but not the level of hazard inversions pose.

Figure 32: Cool air drainage winds slipping downslope into a valley system.

Photo: Michael Bath

Some indicators of inversion are:

- rapid reduction in wind speed during the afternoon in fair weather conditions;
- mist, fog, dew or frost;
- smoke or dust hanging in the air just above the surface;
- cool off-slope breezes;
- distant sounds becoming clearer at night;
- aromas becoming more distinct (meaning that they are more concentrated near the surface);
- cumulus clouds dissipating in the evening (this only applies for fine weather cumulus clouds); and
- smoke, dust or fog descending to low-lying terrain.

Inversions can be avoided over Australian broadacre cropping regions by only spraying:

- up to 1.5 hours after sunrise; and
- up to 1 hour before sunset.

Obviously, this guidance places severe restrictions on summer spraying, but this may be warranted in regions that are not covered by a recognised inversion monitoring system. Additional precautions that can be taken by applicators include reducing ground speed, lowering boom height and using very coarse droplets. Taking such precautions may help ensure the protection of:

- human health – that of your family, neighbours and community;
- susceptible crops, which may be unintentionally damaged, causing economic damage;
- trade, by avoiding unacceptable residues on crops and pastures;
- farm vegetation, native vegetation, animal habitats and biodiversity;
- water quality, including water for human consumption, stock use and irrigation;
- aquatic organisms; and
- beneficial insects (predators and pollinators) and their refuges.

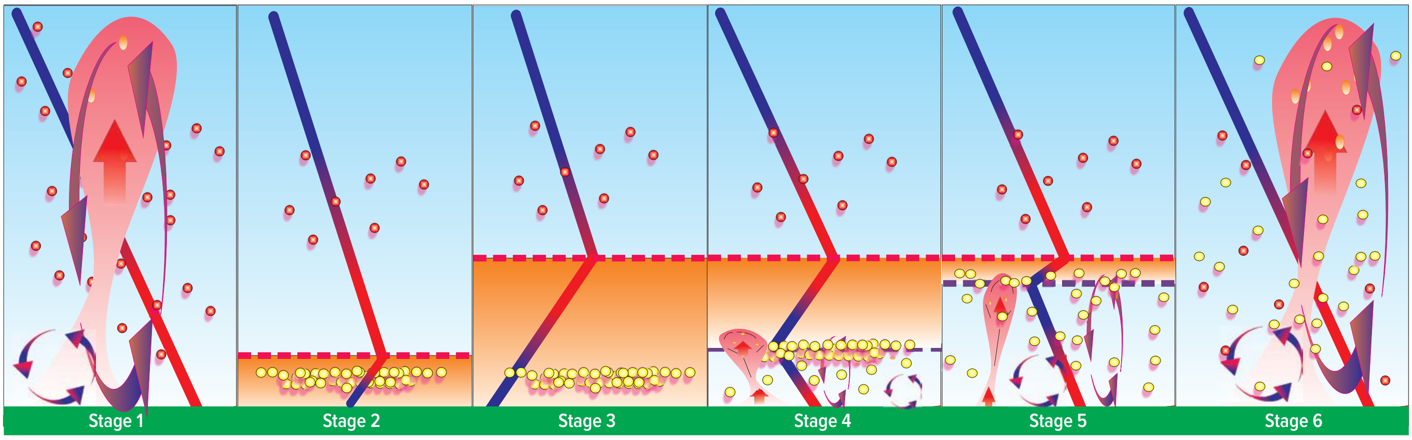


Figure 33: Pesticide residues can accumulate in the atmosphere for several days before being deposited on the surface far from the original sites of application.

Wind

Winds as forecast and reported by the Bureau of Meteorology (BoM) refer to those occurring 10m above the surface averaged over the past 10 minutes. The average wind reports conceal peaks and lows experienced over the 10 minutes prior to that.

The APVMA recommends that wind speed be measured at 2m above the ground in the paddock where pesticides are applied.

Gustiness in the wind flow

Wind is made up of gusts and lulls (see Figure 34) caused by surface friction and thermal activity interacting with the overriding airflow. Gustiness produces turbulence, which is suppressed when the atmosphere is stable and enhanced when unstable. Gusts and lulls at 10m will be typically 40 per cent higher and lower than the average on a fair weather day; they may be greater at lower levels closer to the surface. They can be much higher with the passage of fronts, showers and thunderstorms.

The examples of average wind speed compared with gustiness presented in Figure 34 show that the average 10m wind of 8.25km/h has gustiness of about 40 per cent. The 2m wind for the same time period indicates a little more gustiness than 40 per cent. This is expected from the lighter winds closer to the surface, as they are responding to greater friction effects.

When spray is applied near the upper limits of wind speed recommendations, gustiness could increase the potential for drift.

Wind variation with height

Near the surface, wind speed is slowed by surface friction. At night, when the atmosphere is strongly stratified, wind speed between 2m and 10m can vary greatly and the 2m wind speed is often about 50 per cent of the 10m wind speed or less (refer to Figure 28). During the day, on the other hand, the difference is not as pronounced: when the atmosphere is well mixed, the 2m wind speed is typically about 75 per cent of the speed at 10m.

Figure 35 graphs two inversion events between 27 and 29 July 2019 in the vicinity of Wee Waa, NSW. The intersection of the dotted yellow line with the X-axis indicates approximate sunrise and sunset. The dark red line indicates the positive vertical temperature difference (VTD) between 10m and 2m; that is, an inversion exists. Note that the day period of instability shows that the 2m wind speed is a substantial fraction of the 10m wind speed (about 80 per cent at times), indicating that thermal and mechanical turbulence are strongly mixing the air through the atmospheric boundary layer (ABL). Note also that the strong 10m wind speed at night is typical of the synoptic wind decoupling from the surface, with a compensating increase of wind speed above the surface.

In-paddock, wind measurements taken at 2m will provide good guidance on the airflow impacting the spray application, while measurements taken at 10m will best represent the general wind flow across a region.

Table 1: Wind scale – speed refers to winds at 10m.

Wind	Speed (km/h)	Observation
Calm	0–2	Smoke rises vertically. Note: initial rise may be due to heat of fire.
Light air	2–6	Direction of wind indicated by smoke and dust, but not wind vanes.
Slight breeze	7 –11	Wind felt on face, leaves rustle, wind vanes move, flags flap.
Gentle breeze	12–19	Leaves and small twigs in motion, wind extends light flag.
Moderate breeze	20–29	Wind raises dust, small branches move, flags flap.
Fresh breeze	30–39	Small trees with leaves begin to sway, flags ripple.
Strong wind	40–50	Large tree branches in motion, whistling heard from overhead wires, umbrellas used with difficulty, BoM issues strong wind warnings.
Near gale	51–61	Whole trees in motion; inconvenience in walking; flags extend.

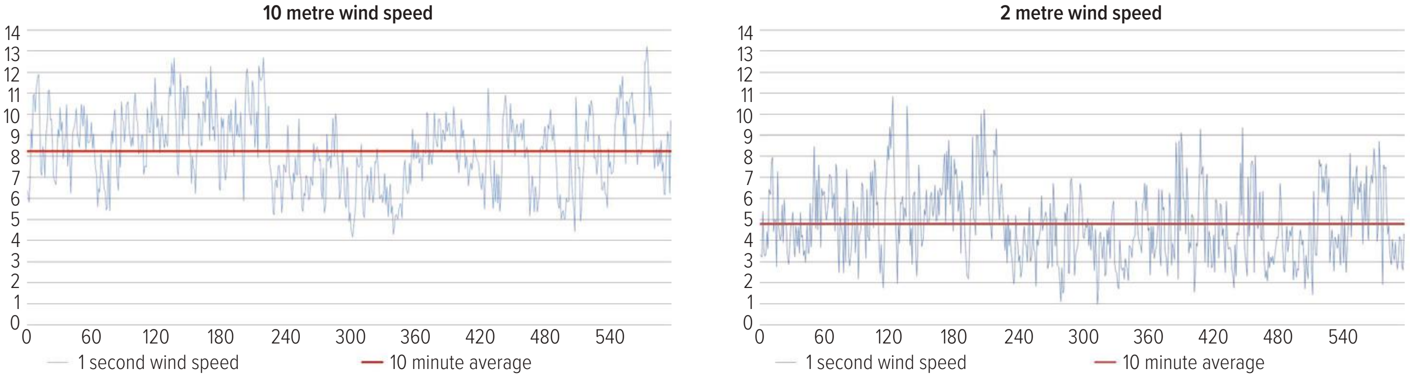


Figure 34: 10m and 2m gustiness around the average value reported at the end of a 10-minute period. The vertical axis is wind speed in km/h; the horizontal axis is time in seconds.

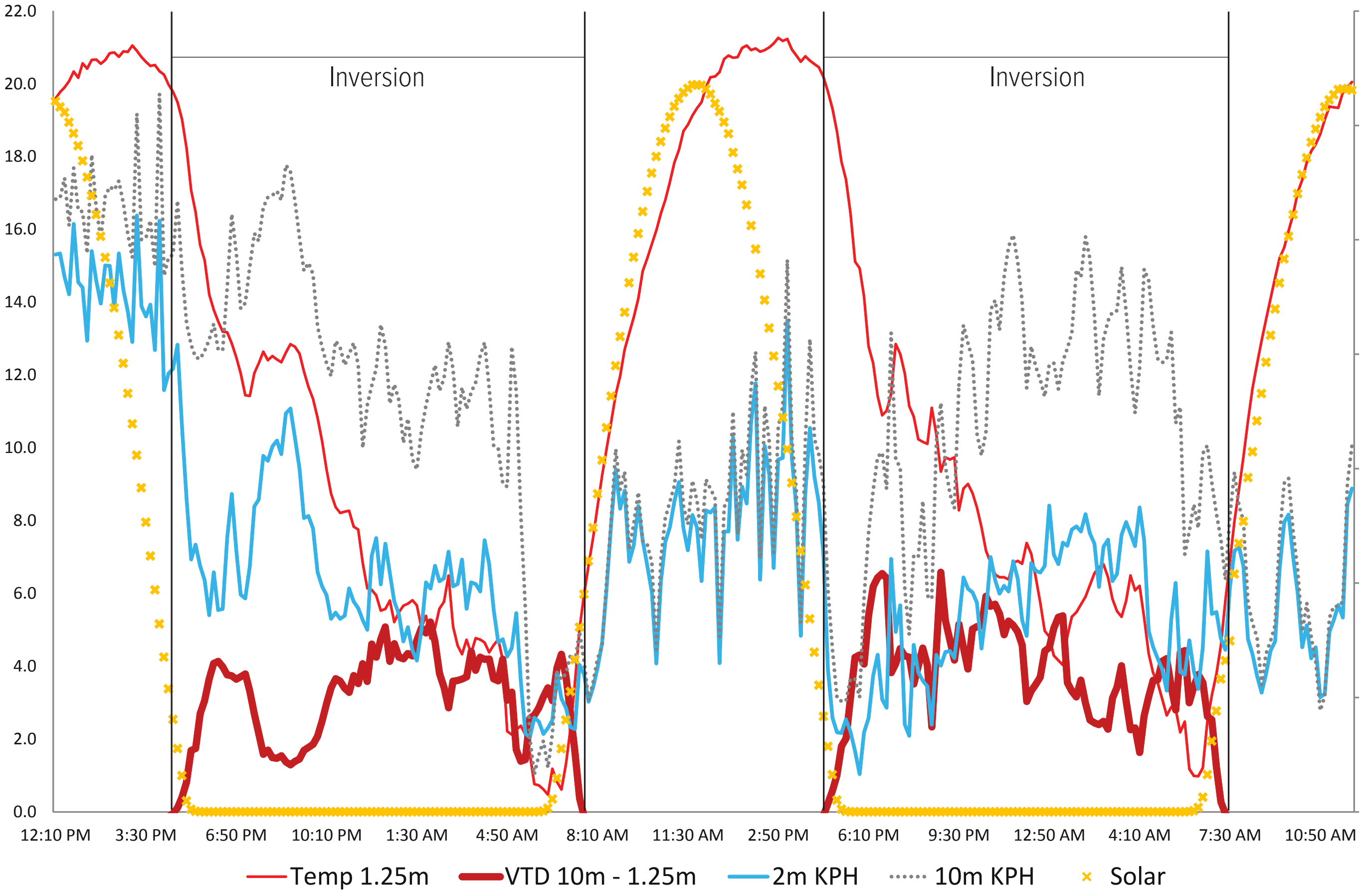


Figure 35: Two inversion events between 27 and 29 July 2019 in the vicinity of Wee Waa, NSW.

Source: Graeme Tepper

APVMA wind speed requirements

- The average wind speed at the application site during the time of application must not exceed the maximum given on the product label.
- The maximum wind speed (gusts) should not be more than one-third above the average wind speed.
- APVMA recommend that "Wind speed should be measured 2m above the ground at the application site. The point where the wind speed is measured should be representative of the application area and should be free of obstructions that may impact the measurement" (https://apvma.gov.au/node/51381).

Measurement of light winds

Unless cup-and-vane (CV) mechanical wind sensors are of scientific grade, many cup anemometers deployed in agricultural weather stations do not spin unless winds exceed 3km/h; thus, they report calm when in fact there is a light wind. They also tend to under-read light winds up to about 7 to 8km/h. Bowen (2007) found that mechanical sensors over a long-term average reported at the level of accuracy published in specifications, but also found that light winds were not well reported by mechanical sensors because of frictional and start speed restrictions. However, they did accurately report wind speeds greater than about 8km/h.

Wind vanes, unless they are of high quality and well maintained, often will not indicate the correct light wind direction because they will not line up with winds less than about 7km/h. Mechanical sensor 'errors' such as these need to be acknowledged and factored into spray decisions, especially when planning protective buffers for downwind receptors.

Ultrasonic anemometers are well proven to record low wind speeds accurately. They have no moving parts or start speed and require minimal maintenance. They are more expensive than CVs but in the long run should be considered for all agricultural wind observations.

The performance of a CV compared with that of an ultrasonic anemometer (US) is presented in Figure 36. The CV falsely reports calm conditions (19 per cent calm). The CV under-reads wind speed up to about 7km/h and thereafter syncs quite well. Note that the CV used in this comparison is a high-grade unit. Similar results were obtained from 15 other CV and US comparisons of the same types after being in the field for two years. These results are much the same as those reported by Bowen (2007).

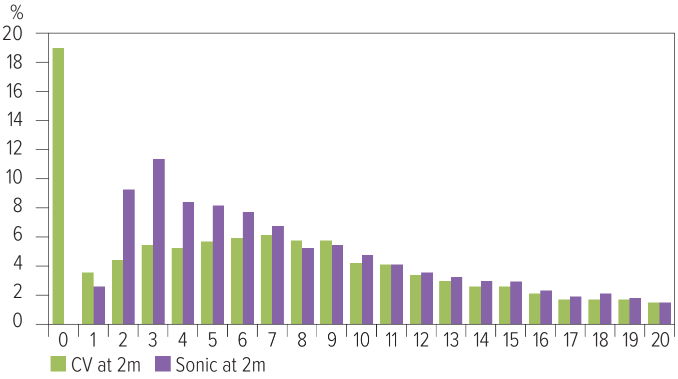


Figure 36: Cup-and-vane (CV) mechanical wind sensors compared with ultrasonic anemometer wind speed readings. The 19 per cent calm bar on the far left-hand side of the chart is a false measure of calm conditions caused by bearing retardation of the CV.

Source: Graeme Tepper

Figure 37: Wind shear described by smoke.

Photo: Graeme Tepper

Wind direction shear

Wind shear is generally not observable by eye but it can be made evident by clouds, smoke or dust changing course or speed with height. Drainage winds, land/sea breezes and inversions are frequently associated with wind shear.

An extreme example of smoke spiralling more than 360 degrees from the surface within an inversion layer is shown in Figure 37. This photo, published in 2011, was accompanied by the caption: "A pillar of black smoke rises from a chemical fire in the industrial suburb of Mitchell in Canberra, Friday, September 16, 2011. Emergency authorities have reduced the size of an exclusion zone around a fire as the threat of a toxic Phosgene smoke plume diminishes. (AAP: Alan Porritt)."

Figure 38 shows a different wind shear pattern. Note the meandering and spreading of the plume and how it blocks in front of the ranges and flows up into the valley, which provides the least resistant path for the smoke to flow.

The general (synoptic) wind

Figure 39 shows large-scale (synoptic) airflow. It begins in response to pressure gradient forces across high and low pressure systems. The closer the isobars are to each other, the faster the winds flow. Because of surface friction, winds do not blow directly from high to low pressure but cross the isobars at about 30 degrees, spiralling out of highs and into lows.

Figure 38: Smoke depicting wind shear, blocking and up-valley flow.

Source: Graeme Tepper

Locally generated winds

Local wind flows are not reliant on pressure gradients for their generation. Rather, local wind development depends on temperature differences between surfaces and/or air layers and topographic interactions. The most obvious of these are sea breezes, but others include lake, land, valley, anabatic, katabatic and cool air drainage breezes.

Locally generated winds may completely oppose the general synoptic wind flow. At night, in particular, there can be quite different wind directions and speeds at 10m compared with 2m.

Local wind flow during the day

In coastal regions, sea breeze fronts can bring quite rapid wind shifts with cooler conditions and carry pesticides far inland.

The sea breeze cool surge can penetrate hundreds of kilometres inland. Just a few locations that experience sea breeze incursions after sunset, long after the originating coastal sea breeze has expired, are Kalgoorlie in WA (345km from the originating breeze, which arrives around midnight), Renmark in SA (220km from the originating breeze), Emerald in Queensland (200km from the originating breeze, which arrives around 9pm) and Wagga Wagga in NSW (270km from the originating breeze).

In a summary paper of laboratory experiments on density currents, Simpson and Britter (1980) point out that no mixing takes place at the interface between the sea breeze inflow and the return flow above it (see Figure 40). This implies that emissions of pollutants (including, potentially, pesticides) into the sea breeze will be transported inland virtually undiluted, rise and mix with ambient air at the front, and head back towards the coast in the return flow. Furthermore, a 'clean' sea breeze will sweep polluted ambient air upwards and remove it seawards at higher levels while maintaining unpolluted air at the ground (Abbs and William 1992).

The inland infiltration occurs due to density gradients between the cooler sea breeze air and the original warmer land air. According to Abbs and William (1992), the inland incursion only ceases when the last cool air inflow, occurring near sunset, has travelled up to the head of the sea breeze. At that time the inland sea breeze is completely cut off from the coast and the circulation has ceased, but the gravity wave of cool dense air can continue travelling inland.

Sea breezes and drift

There are good reasons to be cautious when spraying in areas over which sea breezes flow because, as Abbs and William (1992) point out, “the stable sea-breeze air passing over the heated land can be responsible for enhanced surface concentrations of pollutants downwind of a coastal source”.

The concentration does not just happen in the immediate vicinity of the coast; it may go further inland.

Sea breezes are not always hindered by hills and mountain ranges, as Figure 40 indicates. They tend to flow around or over higher terrain and then into and along valleys, all the while transporting aerosols collected along the way and potentially depositing them into lower-lying terrain as the breeze ends.

In presentation to farmers in the Clare Valley region, SA, Graeme Tepper (2011) suggested that sea breezes from the gulf have the potential to rise over the ranges and descend into the valleys of the Clare Valley region and thereby may carry pesticides from the coastal plains up and over the seaward slopes before depositing drift into valley systems.

The deep inland penetration achieved by some sea breezes suggests that pollution (and possibly pesticides) from coastal regions may be transported large distances from the source. Such evidence has been found in a number of studies (Abbs and William 1992).

Weaker than sea breezes are lake breezes, which occur between land and water interfaces. Weak lake breezes can occur between wet marshes, irrigated fields, large dams and warmer land nearby. Associated circulations have the potential to carry drift from agricultural fields to lakes and marshlands.

Valley winds for both day and night

Valley systems modify the general synoptic wind flow by blocking and funnelling. They also generate complex katabatic flows overnight due to interaction of valley wall and floor slope winds (Tepper and Watson 1990). In the early morning and evening, katabatic winds can continue to flow while slopes are in shadow; anabatic winds, on the other hand, may flow up slopes in full sunshine. These flows cease when solar heating predominates over the valley system, as shown in Figure 41.

Valley-induced drainage winds can flow beyond the valley or they may pond within the valley.

Figure 41 is a simple depiction of complex interactions of heating, cooling and winds across valley systems over a 24-hour period. Cool air drainage winds can develop well before sunset if valley walls are shaded from the sun.

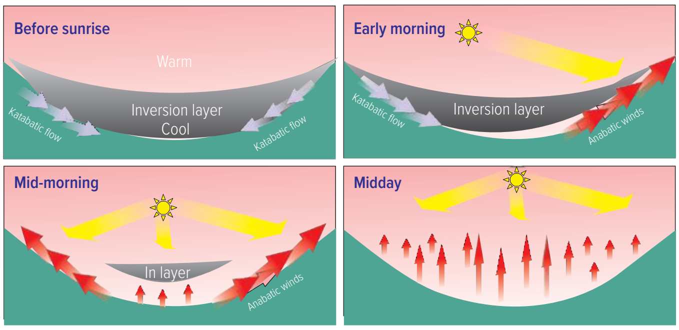


Figure 41: Diurnal valley winds.

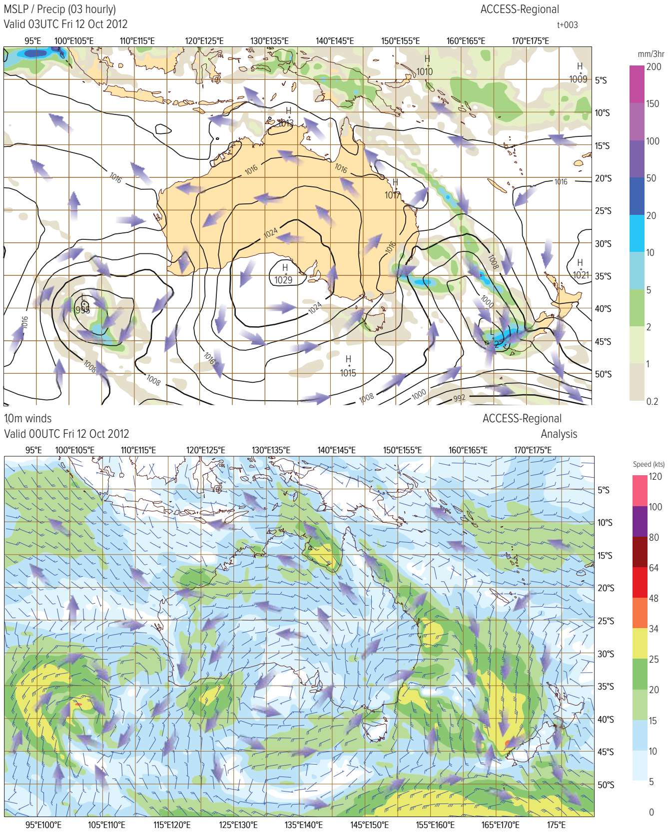


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Figure 39: The top chart shows a typical synoptic pressure chart with wind arrows added. The lower chart is for the same time period, with a streamline analysis of the wind field with circulations out of high pressure and into low pressure.

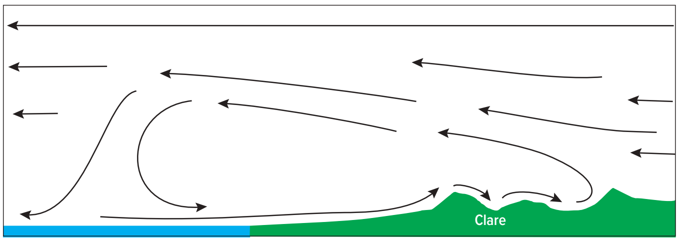


Figure 40: Sea breezes extending inland over ranges and into valleys.

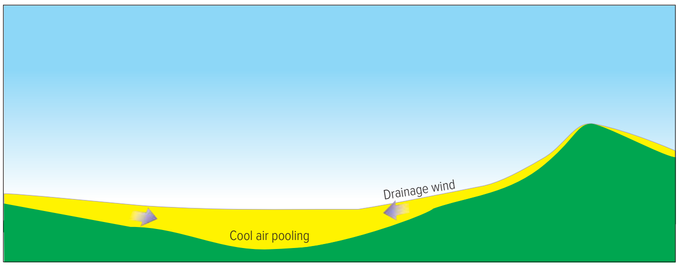


Figure 42: A simple cross-section of drainage wind flow and pooling of cool air. Note that drainage winds are very shallow over the high terrain.

Figure 43: Smoke descends into a drainage wind flow and concentrates into low-lying areas while an inversion exists.

Photo: Bill Campbell

Local wind flow at night

Apart from when frontal activity is dominant, winds experienced in paddocks overnight are often not related directly to the synoptic situation; rather, they are driven by regional topographic influences. They frequently drain off slopes and meander around obstacles, and they can flow towards low-lying areas or parallel to topographic contours. They can be locally generated winds such as land breezes, downslope winds and valley winds, any one of which can direct drifting pesticides to destinations not expected of the synoptic wind flow predicted in the synoptic charts.

Drainage winds may be the primary transporters of airborne pesticides at night. The precursor to drainage wind onset is the formation of an inversion along a slope – see Figure 42. Cool air drainage winds are common near the surface on clear nights due to radiative cooling over sloping terrain (Seaman et al. 2008).

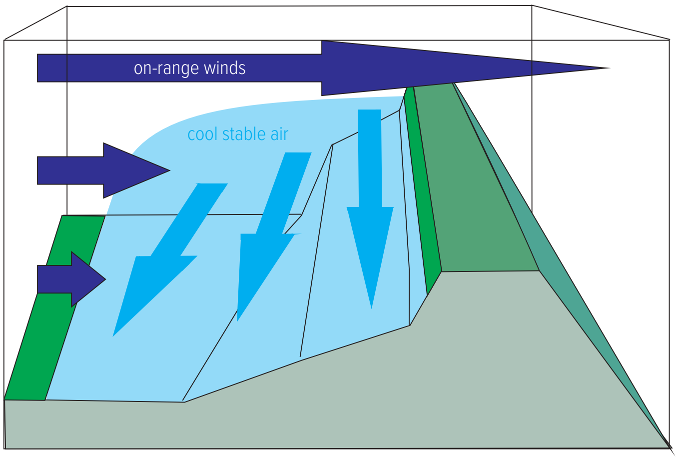


Figure 44: The basics of blocking and contour winds within cool stable air. Lower-level winds approaching the obstacle 'push' the cool air. Since vertical motion of the cool air is suppressed, the force causes horizontal flow. The direction of flow is dependent on the direction of least resistance, which is usually a gap in the obstacle.

Drainage winds generated by steep slopes become turbulent and periodically break up partially or altogether after only a short run. Gentle, long slopes are ideal for the formation and maintenance of long-lived drainage winds. Drainage winds can be maintained for hours over a gentle slope while an inversion exists.

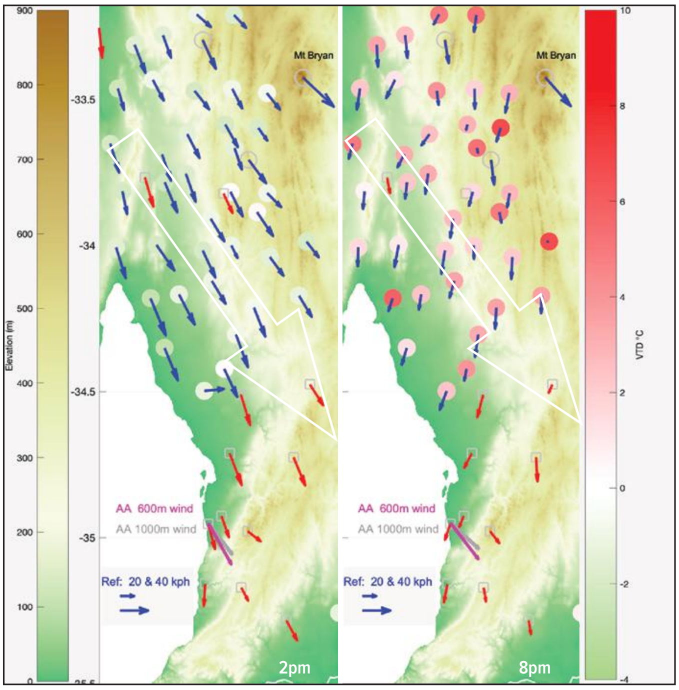


Figure 45: Wind flowing freely over an obstacle followed by blocking with contour wind flow. In conjunction with the onset of an inversion, contour flow began 30 minutes before sunset (at 6.03pm), continued throughout the night and ended two hours after sunrise (at 6.23am) with the cessation of the inversion. The north to north-easterly contour flow occurred beneath the north-west synoptic wind flow represented by the large white arrow. The winds remained steadily from the north-west at Mt Bryan (929m), at other high elevations, and over Adelaide at 600m and 1000m for a 24-hour period, inclusive of the contour flow event. The westerly wind in the first panel represents a sea breeze.

Source: Compiled by Warwick Grace in 2022 based on data from the company Conditions Over the Landscape (CotL). Blue arrows represent CotL winds, red arrows represent BoM winds.

Even extremely weak slopes (see Figure 43) can generate intermittent drainage wind, which in turn generates turbulence near the surface – sometimes spasmodically (Mahrt 2014). Mechanical turbulence is most predominant at the leading edge of drainage winds. Once established, drainage winds will tend to be laminar and able to transport drift at high concentrations for long distances into frost hollows, river valleys and other lower-lying areas. Drainage winds can flow off slopes and fan out over quite flat terrain, in much the same way as water running off slopes can continue to flow across plains.

Drainage wind that flows down slopes of about 2 degrees can maintain laminar wind speeds of 4 to 7km/h (Tepper and Watson 1990). Considering such speeds, it is conceivable that laminar drainage wind could move drifting pesticides many kilometres across the surface overnight. It is also possible that drainage winds may fill wide, open valleys and river valleys to depths much greater than the original depth of the drainage flow, resulting in pesticide drift being more concentrated within these areas than it is along a slope.

Agricultural regions with many varied slopes will experience multiple drainage events, which may merge and continue to flow towards low-lying regions carrying concentrated pesticides. Drainage winds, being cool, dense and heavy, are often blocked and redirected by obstacles interrupting their downslope trajectory. Such redirection can cause airborne pesticides to move to unexpected destinations.

Drainage winds may be incorporated or reinforced with overnight land breezes flowing towards lakes and other water surfaces – see the 3am panel in Figure 59. Ramifications for spray drift in such regions include the transport of pesticides over water surfaces. Some air pollution studies show that land-generated contaminants can be caught up in the land-to-water breeze circulation and return to recontaminate the land surface.

Blocking and contour wind flow

Contour winds, sometimes known as terrain winds, have the capacity to carry high concentrations of pesticides parallel to topographic contours for tens of kilometres. Such winds have been instrumental in causing strip damage in wine-growing regions and herbicide damage has been reported in areas remote from cropping regions (Tepper – studies unpublished).

- Winds occurring during the day have a strong tendency to flow up and over obstacles, especially when the atmosphere is unstable. Unstable atmospheres assist vertical motion.

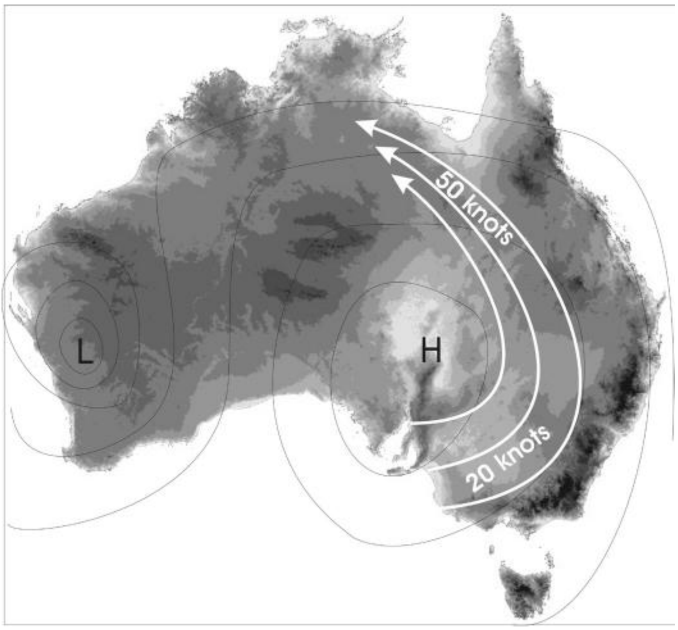


Figure 47: Low-level jet streams (LLJs) below 1000m over the eastern states of Australia. 50 knots is about 100km/h. Turbulent gusts originating from wind shear across the jet stream may intermittently descend to the surface and interrupt normal wind flows. Source: Graeme Tepper

- At night, when the atmosphere is very stable, the wind flow either becomes blocked and stagnant in front of obstacles or proceeds to flow around or parallel to them. The stable atmosphere resists vertical motion.

Contour winds are common but often not recognised when they are light and exist only overnight. High and long obstacles generate the most pronounced contour winds. However, contour winds can exist along small obstacles such as levy and dam banks, thick stands of trees and buildings.

Contour winds are often observed in specific geographic areas; for example, whenever winds approach the Mount Lofty Ranges in SA from the south-west to north-west and when inversions are established over the upstream plains.

Although Figure 45 depicts an example of contour wind occurring beneath a north-westerly airstream, similar contour winds often occur beneath south-west winds; this is especially the case in winter, when the upstream air is stable (Tepper and Watson 1990).

Figure 46: Smoke being blocked by raised terrain. The arrow points to smoke moving in a stably stratified environment.

Source: Graeme Tepper

Contour flows have been observed to extend across the whole of the Adelaide plains and out over the gulf waters and to move from as far north as Port Augusta, through Adelaide and beyond to Cape Jervis. Over Adelaide, the average speed of these winds at 10m is between 7 and 15km/h (Tepper and Watson 1990) but can be more than 20km/h.

Figure 46 shows how smoke moving from the left to right in a laminar wind flow while a hazardous inversion exists is blocked and trapped in front of some hills. There, it stagnates, concentrates, touches the obstacle and most probably falls out over an upwind zone. The smoke originated about 15km to the left of the hill.

Blocking by the Great Dividing Range

When it occurs in front of mountain ranges, the increase of wind speed over the top of an inversion can at times be extreme, as depicted in Figure 47. In this scenario, low-level jet streams (LLJs) can form across the top of an inversion, upwind of raised terrain. Speeds can exceed 100km/h, usually between 200 and 400m above the surface, while the surface winds may be only 10km/h. LLJs most probably contribute to the inversion erosion, especially as the capping inversion is raised by thermals.

The significance of these jet streams to pesticide application is that they may intermittently inject turbulence to the surface. These downward turbulent bursts can interrupt the normal night-time flows from time to time, causing short-lived shifts in wind speed and direction.

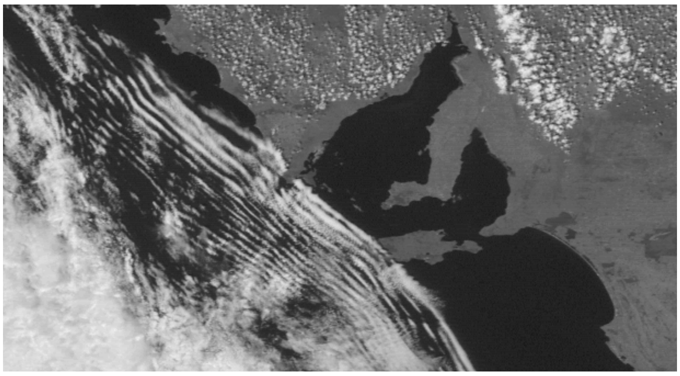


Figure 48: Low-level gravity waves approaching the south-east coast of SA.

Figure 49: Low-level gravity waves outlined by low stratus cloud. Notice the disturbance reaching the surface below the crest of the waves, where gusty winds would be expected.

Photo: Bill Campbell

Downslope winds

When spraying downwind and within a few kilometres of raised terrain, especially where the downwind slopes are steep, gusty winds that rapidly change in speed and direction can be experienced. These downslope winds can be likened to water spilling over a high dam wall: at end of the fall, there can be jumps in the flow as well as very turbulent eddies and gravity waves that move downstream for some distance before resuming a quieter and more consistent flow.

In Australia, hills and ridges as low as 250m have been shown to produce significant periodic fluctuations in wind speed and direction (Holton 1995) up to several kilometres downstream, with the most pronounced gusts close to the foothills.

Tepper 2021 (unpublished) observed downslope gusty winds with reverse flows about 8km north-west of the ridge between Coolanbilla Mountain and Colly Mountain west of Spring Ridge, NSW, when the general airstream was from the south-east. The ridge is approximately 200m above the surrounding plains and lies (very approximately) north to south.

The downslope winds are often recognisable as very gusty winds close to the foothills at night. As Grace and Holton (1990) remark, “the effect of downwind moving jumps is usually a rapid increase in wind strength with a marked directional shift”. From the foothills, rotors can progress several kilometres as illustrated by Figure 54 (an interpretation of diagrams from Grace 1995). The rotors cause rapid and periodic switching of the surface wind direction and speed.

If spraying at night near significant ridges during the summer months, assess whether the general airflow direction is across a ridge. If so, expect downwind wind shifts and use the coarsest spray quality, low booms and slow speeds.

Gravity waves

Gravity waves cause sudden and short-lived interruptions to wind flow. They are similar to swell waves moving through the ocean or ripples from a stone dropped in a pond. They can propagate far away from their source and impact spraying operations.

In some regions, such as inland of the Gulf of Carpentaria, they are a common feature. They can accompany the leading edge of inland sea breeze incursions for hundreds of kilometres inland and be generated by downslope winds and thunderstorm outflows; roll clouds sometimes spectacularly announce their arrival with very gusty winds. More gentle gravity waves are present at the leading edge of cool air drainage wind flows.

In regions where gravity waves are known to exist, it would be wise for spray applicators to gain local knowledge of the precursors and timing of gravity waves.

Some applicators are known to wait until sea breeze gravity waves move through a region before proceeding to spray in settled conditions (verbal communication from a spray applicator near Emerald, Queensland).

Gravity wave effects on wind flow can be minor but sometimes quite dramatic. In 1999, an event of thunderstorm-induced gravity waves was reported at Lucindale, SA. It was first noticed as a roaring sound accompanied with winds gusting to about 40km/h at the surface and estimated to be about 100km/h at tree top height. Winds were light ahead of and behind the event (Tepper 1999, unpublished account). The wave had propagated from cold air downbursts falling from thunderstorms some hundreds of kilometres away. The event coincided with the first band of cloud observed, which crossed over Lucindale – see Figure 48.

Figure 50: Smoke lifting away from several fires before meandering left and right across the landscape. A hazardous inversion leads to widespread fanning of the plume, which remains at high concentration.

Photo: Teresa Aberkane

A very well-known gravity wave accompanies morning glory clouds over the Queensland gulf country. "They move rapidly across the sky at speeds of 36 to 54km/h, the most usual direction being toward the south-west, although cloud lines orientated approximately east-west and moving from the south are sometimes observed. The passage of each cloud overhead is usually accompanied by the onset of a sudden wind squall which, although normally of short duration (perhaps 5 to 10 minutes), have wind speeds comparable to the speed of the cloud" (https://www.meteo.physik.uni-muenchen.de/~roger/AustralianProjects/TheMorningGlory/TheMorningGlory.html).

The incursion of sea breezes far inland is accompanied by a gravity wave that can cause subtle wind shifts.

Meandering

Meandering, as shown in Figure 50, contributes to widespread landscape drift events. It occurs in very stable (hazardous inversion) conditions. In such cases, plumes may remain highly concentrated over long distances while exhibiting large changes in direction (Seaman et al. 2008).

Hiscox, Miller and Nappo (2010) found in a field campaign that plume meander, driven by small scale wind motions, was responsible for most of the total horizontal plume spread in weak and variable winds and strong stability. This proportion was reduced in high wind (>15km/h) in weakly stable conditions but remained the dominant dispersion mechanism.

Local winds summary

The wind arrows in Figure 59 show temperatures and topographic features in the Melbourne vicinity. Note the 3am converging winds over Port Phillip Bay, the diverging winds at 9am and the swamping of local winds by the much stronger Bass Strait sea breeze at 3pm. Note also the convergent wind flow over narrow necks of land around the bay at 9am.

Wind changes such as those shown in Figure 59 are generated by local variations in heating. While the variations are quite dramatic in coastal regions, inland winds also vary in response to heat differentials. Knowing the local environment and the potential for such wind shifts would assist pesticide applicators in making decisions, especially about how to keep drift away from susceptible crops and environments.

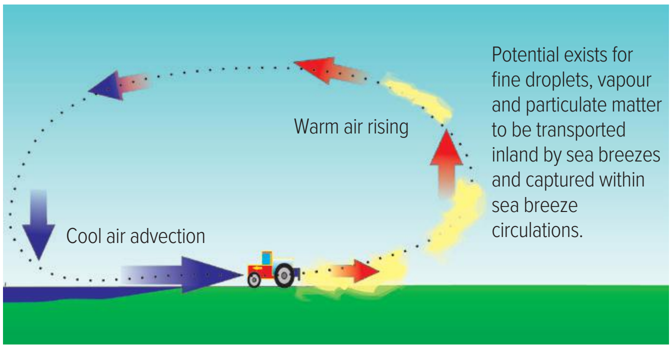


Figure 51: Sea and lake breezes. Sea breezes can be local and can occasionally penetrate well inland (for example to Renmark, SA, and Kalgoorlie, WA). These inland incursions can affect applications by inducing rapid changes in wind speed and wind direction. Lake breezes are gentle breezes not penetrating far inland but associated wind shifts, which in fair weather would occur at similar times from one day to the next. Such wind shifts need to be factored into spray plans to prevent drift being transported to sensitive crops and other receptors.

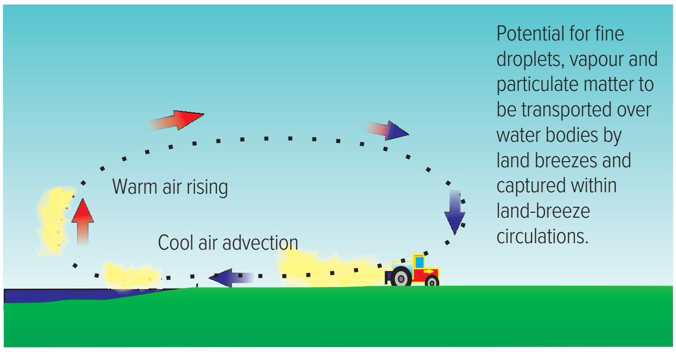


Figure 52: Land breezes. These are gentler than sea breezes and typically occur at night. They have the potential to carry concentrated airborne pesticides over water surfaces.

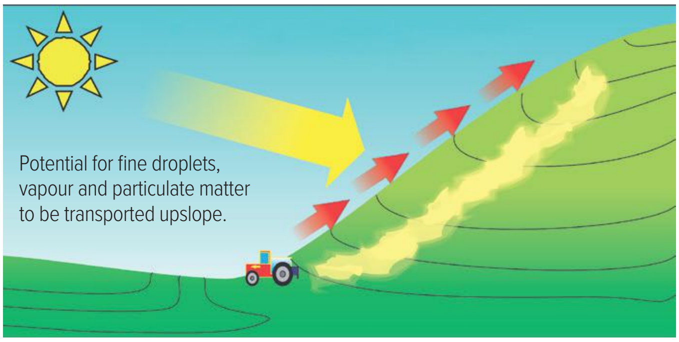


Figure 53: Anabatic (upslope) winds. These flow parallel to steep slopes in response to heating of the surface. They are most pronounced in the early morning and sometimes in the evening when the sun shines strongly on the slope. Pesticides can be carried up the slope.

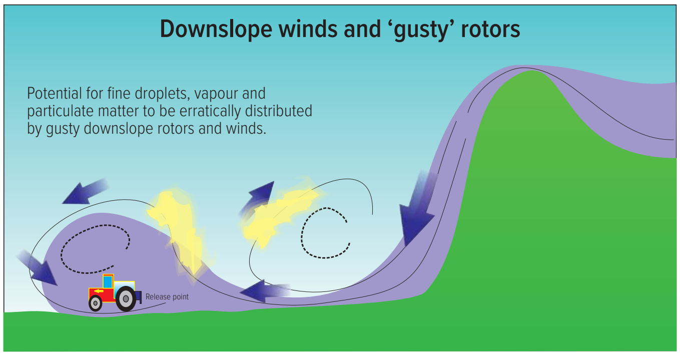


Figure 54: Downslope winds. These cascade down steep knolls, bluffs and hills. Gusty turbulent rotors roll away from the foothills, causing erratic winds to move back and forth from the foothills.

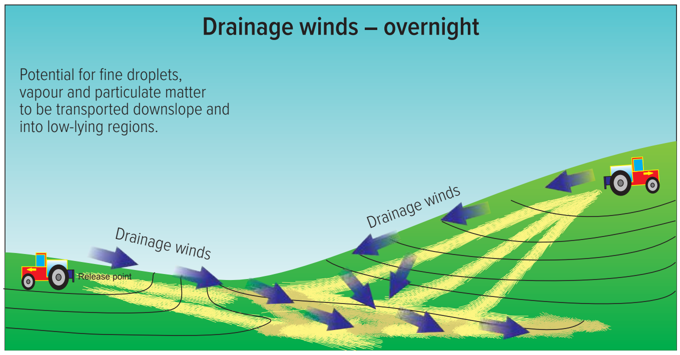


Figure 55: Drainage winds. These occur when inversions exist over slopes, and can develop over the slightest of slopes. They can carry concentrated airborne pesticides long distances.

Figure 56: Blocked winds. These occur when the atmosphere is stable. They flow strongly and consistently when winds approaching an obstacle are prevented from rising by strongly stable conditions.

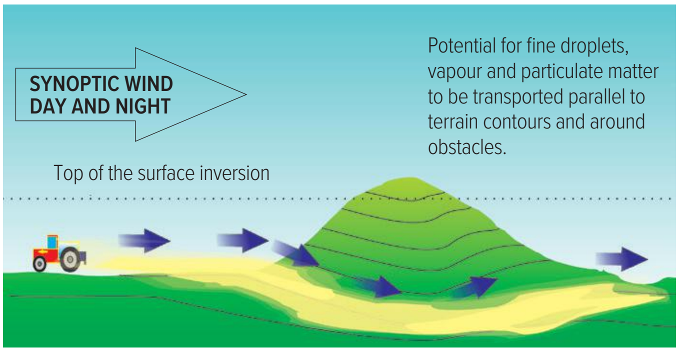


Figure 57: Blocked winds. These occur when the atmosphere is stable. They flow strongly and consistently when winds approaching an obstacle are prevented from rising by strongly stable conditions.

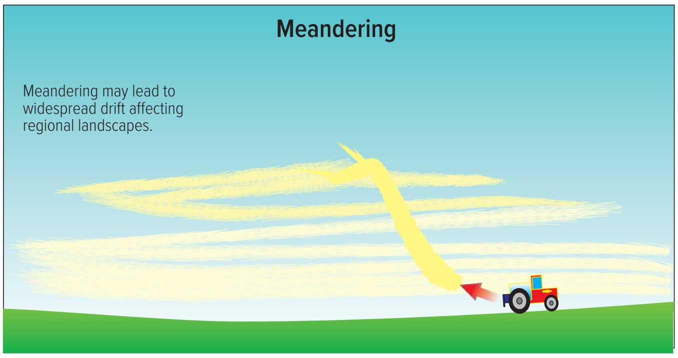


Figure 58: Meandering winds. Can cause drift to spread horizontally without much dispersion and thereby increase the potential for widespread damaging drift.

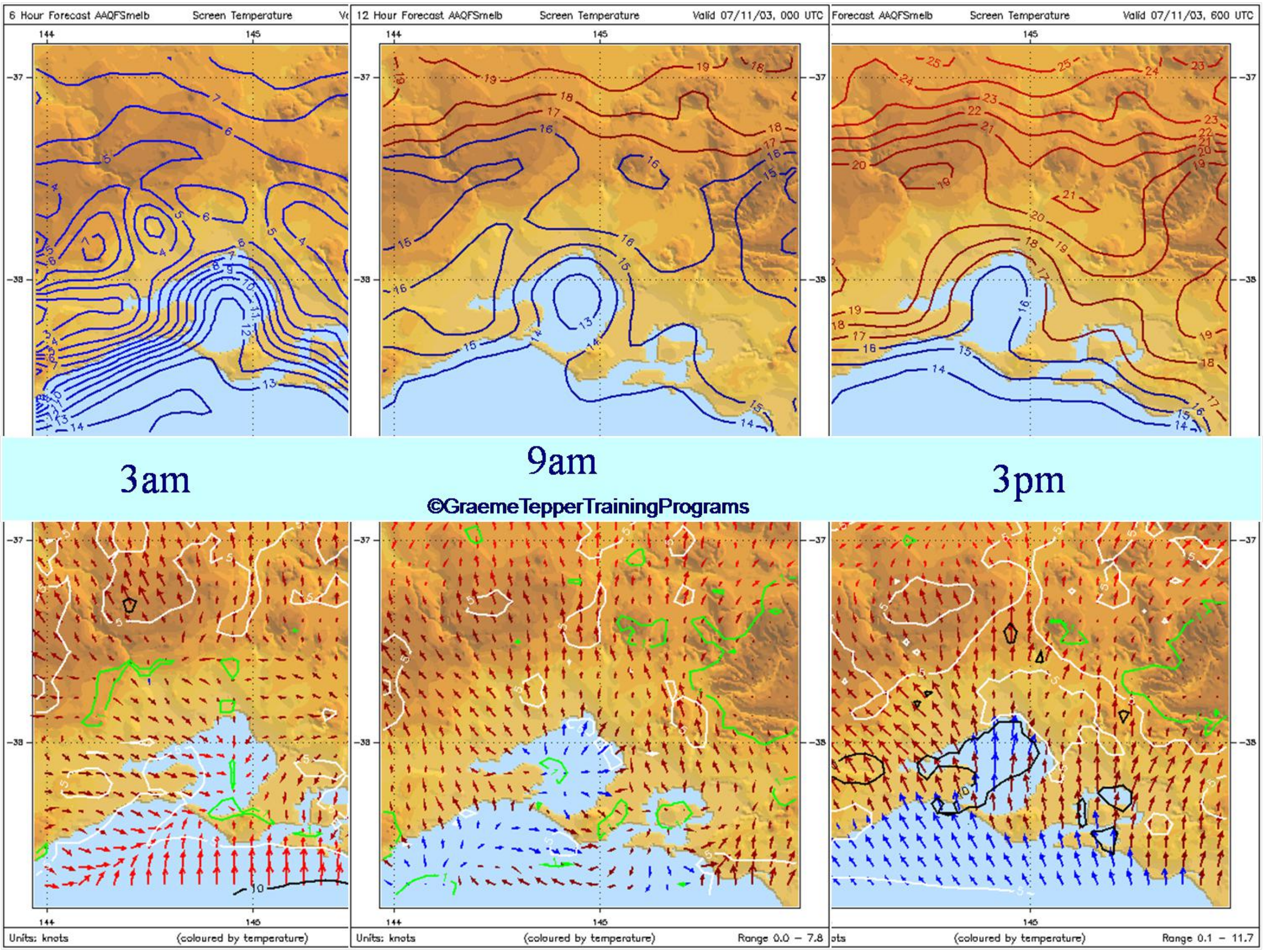


Figure 59: Charts from the BoM illustrate diurnal variations of winds in the vicinity of Port Phillip Bay, Victoria. From 3am to 3pm, the synoptic wind comes more or less from the south. At 3am, drainage winds and land breezes combine to drive air from the land towards the centre of the bay, where it converges and rises. By 9am, bay sea breezes dominate, and by 3pm, the Bass Strait sea breeze dominates.

Source: BoM

Temperature

Standard air temperature is measured at 1.25m above the surface and represents a mixture of heat radiated from upstream surfaces. Differences between surface and air temperatures influence the stability of the atmosphere, local wind flows, the generation of turbulence and the dispersion of drifting pesticides as well as rates of evaporation and volatilisation.

When the surface temperature is higher than the air temperature, thermal turbulence is generated. When the surface is cooler than the air above, inversions exist.

Differences between surface and air temperature can be extreme, as illustrated by Figure 60. This shows that bare ground is more than 20°C hotter by day, which points to extreme vertical thermal motion with vigorous turbulence in the airflow, and at night it is 4°C cooler than the air temperature at 1.25m, which indicates a strong inversion with weak turbulence.

Ground cover significantly impacts soil surface temperature, as depicted by Figure 61.

The following factors influence temperature.

- Soil colour: Dark-coloured soils absorb more solar heat and are therefore warmer than light-coloured soils.
- Soil composition and texture: Clay heats slowly compared with sand with equal water content. Sandy soils lose heat quickly at night because of their open texture.
- Consistency: Packed soils are able to absorb more heat than recently cultivated soils.
- Terrain exposure: Maximum absorption of heat from the sun occurs when the sun is at right angles to the surface. During the morning and afternoon, east and west-facing slopes receive their maximum solar contribution, while flat terrains receive theirs at noon.
- Soil mulch: Mulch shades the surface, inhibits evaporation and thereby reduces the temperature of the soil surface.
- Vegetative cover: A bare soil more readily absorbs heat than that insulated by vegetation.
- Organic matter content: Organic matter increases the water-holding capacity of the soil, thereby increasing soil temperature.
- Soil moisture: Wet soil conducts heat more efficiently, and distributes it more deeply, than dry soil.

Extreme surface temperatures are depicted in Figure 62. Note that soil temperature 4cm below the surface does not change much compared with the surface temperature.

When spraying paddocks with a high proportion of bare ground, efficacy may be compromised and drift will more readily rise – see Figure 63.

Increasing surface temperatures can lead to:

- droplets evaporating faster, for the same mass of water, because warmer air absorbs more moisture than cooler air;
- turbulence intensity increasing, because the atmosphere becomes more unstable;
- volatile pesticides on soil and plant surfaces vaporising faster, because vapour pressure increases as temperature increases; and
- thermals lifting more airborne pesticides into the atmosphere, because increasing the temperature increases the vigour and height to which thermals rise.

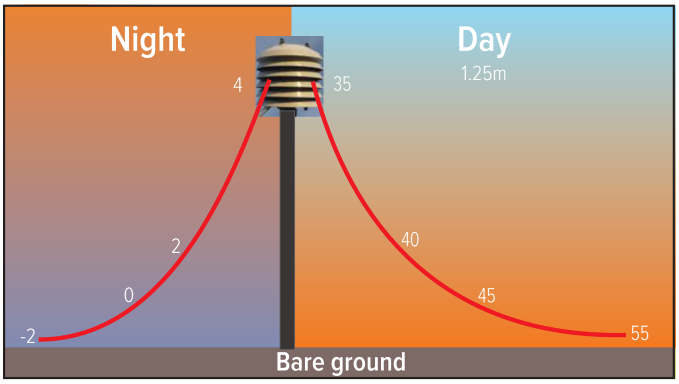


Figure 60: Extreme skin temperature compared with air temperature.

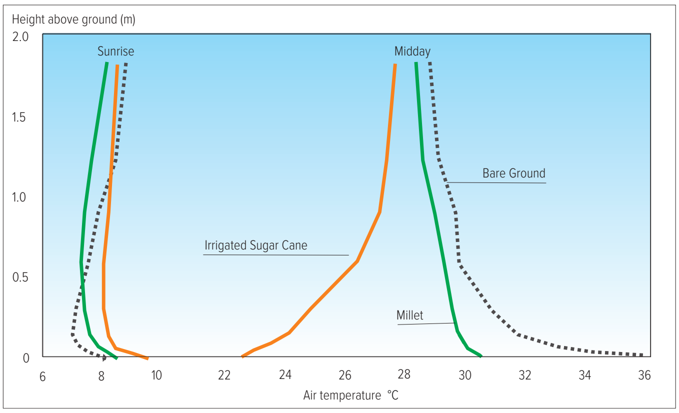


Figure 61: Temperature over bare ground, a millet field and an irrigated sugar cane field.

Source: Adapted by Graeme Tepper, after Ramdas and Atmanathan 1932

Droplet evaporation

Since nozzles produce a wide range of droplet sizes around the volume medium diameter (VDM) and since there are many more small droplets than larger ones, it is difficult to exactly quantify the volume able to drift immediately and the volume that will shrink and drift in 'real world' paddock conditions compared with conditions in experiments, which are highly controlled.

Small droplets are expected to drift but under some circumstances even large droplets end up drifting if they remain in the air for too long.

The volume initially drifting depends on the initial droplet size, formulation, airtime and atmospheric conditions, including turbulent motions, temperature and humidity.

Airtime is influenced by the sprayer ground speed, droplet velocity, vertical motion in the airflow and wind speed.

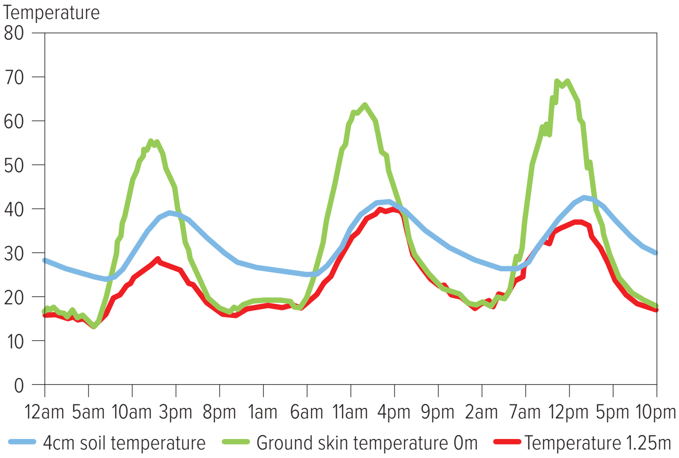


Figure 62: Temperatures at 4cm deep, at soil skin (0m) and at 1.25m above the surface near Katanning, WA. Source: Graeme Tepper

Turbulence around the machine with up motions lifting droplets, unstable booms 'throwing' droplets out of the normal downward trend and vertical winds can all extend airtime and lead to excessive evaporation of larger droplets.

It is not too difficult to find images of droplets being lifted away from the intended target by wake turbulence and thermal updrafts or remaining suspended then 'disappearing' behind an application. Some applicators and bystanders will have been surprised by the volume of droplets they see lifted away from the surface or remaining suspended when conditions are moderately warm.

The combined conditions that cause such lifting in general are known but very difficult to quantify, in part because the variable heat of underlying surfaces and atmospheric stability impact the volume of product remaining suspended or lifted away.

Small droplets evaporate faster than larger ones because the ratio of exposed surface area to total volume is much greater.

No evaporation of the carrier droplets (the medium, usually water, into which concentrated chemicals are dissolved into) leads to large droplets depositing to the desired target. However, small droplets not reaching the target may remain airborne for hours, and be incorporate into mists, fogs or clouds and transported far off target.

Partial evaporation of the carrier leads to shrinking droplets and increasing chemical concentration.

Total evaporation of the aqueous component leads to airborne particulates and vapours of the active chemical plus impurities and additives drifting. When droplets totally evaporate, small particles of concentrated chemical or vapours remain, which can drift over long distances by air currents and contaminate the environment (Matthews 2008).

To minimise evaporative loss of product between release and target it is essential to seek expert advice and operate with as coarse a droplet VMD as possible. *GroundCover^{TM} Supplement* 105 offers the following advice.

Figure 63: A paddock with a high proportion of bare ground. Photo: Graeme Tepper

"As a simple rule of thumb, each time you move to a coarser spray quality, you halve the drift potential. For example:

- fine spray quality will release more than 40 per cent of the chemical volume as droplets that can evaporate or move with the wind;
- medium spray quality reduces this to about 20 per cent; and
- coarse spray quality produces fewer than 10 per cent of droplets capable of moving away from the site of application.

Coarse spray quality (or larger) can provide very good results with fully translocated chemicals (those that enter and then circulate throughout an organism), particularly when spraying in difficult summer conditions, while a medium droplet spectrum is often best for surface-active chemicals and good spraying conditions (wind speed 3 to 15km/h)."

Selecting coarse spray quality will be most effective if travel speeds are within label, boom height and stability are optimal, weather conditions are optimal and surface temperatures are not so hot that they cause unacceptable evaporation and uplift of product.

Relative humidity

Relative humidity (RH) is a measure of how much water vapour is in the air compared with the maximum amount possible. The air's capacity to hold water vapour increases as its temperature increases. The simple illustration in Figure 64 indicates that if a fully saturated air parcel at 10°C were heated to 30°C, it could hold 72 per cent more water vapour. For this example, droplets will not evaporate at 100 per cent RH but will rapidly evaporate at 28 per cent RH.

As useful as RH is, it is not the best indicator of droplet evaporation because the same RH at different temperatures results in different rates of evaporation. For the purposes of determining pesticide droplet evaporation potential, Delta T has replaced the traditional RH.

Delta T

Delta T is defined as the dry bulb temperature minus the wet bulb temperature. Higher Delta T means the air is dry and low Delta T indicates that the air is moist. The same Delta T regardless of temperature indicates the same potential for evaporation.

The normal perception that rapid evaporation is correlated to hot conditions is not correct. For example, the evaporation is about the same for:

- 15°C and 28 per cent RH and a Delta T of 8; and
- 30°C and 50 per cent RH and a Delta T of 8.

As spray droplets reduce to less than about 150µm in diameter, they become highly susceptible to drift and can be transported over long distances by air currents before being deposited (Unsworth et al. 2000).

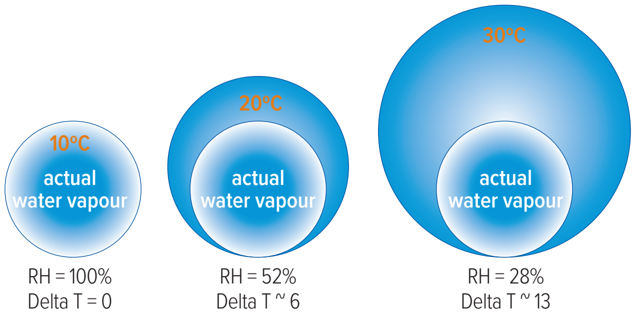
If large droplets are released far above the target or are lifted by vertical air currents, their extended airtime and exposure to evaporation may well cause them to drift.

Whether Delta T is too high or low for successful spray applications in regard to both efficacy and drift depends on the spray quality and on operating practices. Anything less than a coarse spray should be restricted to between Delta T of 2 and 8. Coarser sprays can be sprayed to Delta T of 12. Pushing a little beyond 12 would demand perfect operational practices and perfect delivery of the expected spray quality to the target. Low, slow booms and perfect control of spray quality would be essential.

DID YOU KNOW?

- Small droplets not immediately falling to the surface tend not to evaporate and may act as nuclei for fog droplets.
- Molecules of volatile herbicides can be absorbed into tiny water droplets or attached to particles, which may later settle to the surface.
- Chemical reactions in fog can result in compounds sometimes more toxic than the original pesticide. Glotfelty, Seiber and Liljedahl (1987) found that "a variety of pesticides and their toxic alteration products are present in fog, and … they occasionally reach high concentrations relative to reported rainwater concentrations".
- Settling of contaminated fog droplets bound with pesticides may fall out over wide areas.

Figure 64: A depiction of the varying RH for the same amount of water vapour at different temperatures.



Source: Graeme Tepper

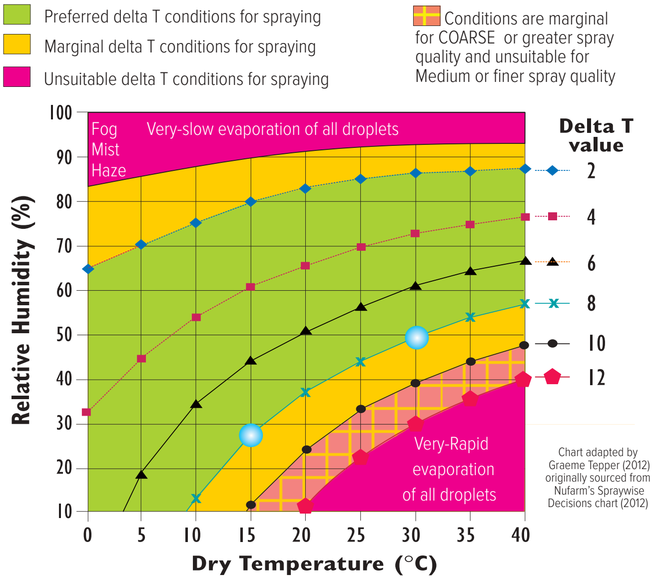


Chart adapted by Graeme Tepper (2012) originally sourced from Nufarm's Spraywise Decisions chart (2012)

For the estimation of evaporation potential of the aqueous component of pesticide droplets the rate can be considered to be constant for a given Delta T.

Figure 65: For a Delta T value there is a wide range of temperature and humidity combinations for which the potential for evaporation is the same. The blue dots represent different temperature and humidity levels having the same evaporation rates at the same Delta T of 8.

Figure 66: Spraying into a high humidity (Delta T >2) environment can lead to pesticides being incorporated into fog and mist.

Photo: Emma Leonard

When Delta T is too high:

- water evaporates rapidly away from droplets, the droplets shrink and the concentrations of actives and adjuvants increase;
- even large droplets can evaporate down to smaller droplets and particles are able to drift; and
- droplets can dry fast on the target and thereby slow the uptake of the active, which may reduce herbicide efficacy.

And remember, rapid evaporation increases the invisibility of drift but does not decrease its potential for damage.

When Delta T is too low:

- smaller droplets with high concentrations of active can remain suspended for many hours;
- potent droplets can be incorporated into mists and fogs;
- particles can act as condensation nuclei, attract water and re-activate while drifting;
- droplets can scavenge water vapour, grow and gain sufficient weight to settle to the surface; and
- chemical reactions in fog can result in compounds sometimes more toxic than the original pesticide (Glotfelty, Seiber and Liljedahl 1987).

Volatilisation as secondary drift

Volatilisation is the conversion of solids or liquids to vapour. It should not be neglected in estimating the exposure and environmental impact of pesticides leaving the site of application (Zivan, Bohbot-Raviv and Dubowski 2017).

Volatilisation over days poses unique challenges to applicators, given labels require that they are not to permit vapour to contact or damage off-target receptors.

In fine weather conditions it could be expected that vapours released during the day will disperse by mixing into the overlying atmosphere to weak concentrations. At night, when the atmosphere is very stable, vapours will move at high concentration across the surface, potentially in laminar drainage wind flows that descend down slopes.

Pesticides able to volatilise over days will encounter multiple states of stability leading to dispersion by day and concentration by night. This suggests that application of volatile formulations needs to be undertaken with acute awareness of the variety of stability conditions possible over some hours or days following an application.

Conditions conducive to widespread vapour drift include:

- shallow night-time atmospheric boundary layers (ABLs), hazardous inversions and laminar wind flow;
- meandering winds, ideal for transporting vapours long distances at high concentrations over expansive landscapes;
- drainage winds, transporters of vapours down gentle slopes to valley systems and across expansive low-lying regions;
- blocked winds and terrain contour flow, ideal for causing widespread damage upwind and damage along contour strips;
- multiple nights of stable stratification and multiple ‘brush stroking’ (applying multiple coats of pesticides residues at different times) over sensitive receptors; and
- laminar wind flows, on average to 11km/h when hazardous inversions exist, transporting vapours within narrow layers across the surfaces.

Paddocks having a high proportion of bare ground (as shown in Figure 63) or crops with open rows are likely to promote strong intermittent and variable winds with strong convective mixing during the day, leading to low concentrations of vapours being detected during the day. During the night, such surfaces will promote the establishment of hazardous inversions and high concentrations of vapours in laminar wind flows.

Weather monitoring

Only robust and well-maintained weather stations will provide long-term high-quality data to support optimal outcomes for pesticide application.

Legally, accurate records must be kept of application methods, wind speed and direction, temperature and humidity (Delta T) at the site of application.

There are numerous ways operators can monitor weather effectively.

Permanent fixed weather stations, when networked to other close-by stations, should be configured to provide time/spatial snapshots of local area conditions. From the snapshots, operators should gauge the progress of various elements, such as wind changes and inversion onset or cessation, and anticipate changes in a paddock of application. When such information is incorporated into long-term climatologies, the best times to spray or stop will become evident.

Handheld sensors are useful but operators must allow them to adapt to the environmental conditions before taking a reading. Portable weather stations set up at site and transmitting to a spray applicator would be ideal.

On-board weather stations with GPS for wind direction and compensation for machine motion provide useful information direct to the operator. All sensors must be placed in free airflow, away from the effects of exhaust heat, dust, turbulence and too much vibration. The requirements for measuring temperature and humidity should be easy enough to meet but measuring wind, on a bulky machine in motion, could be very challenging. To avoid modified wind flow over the cab and wake turbulence, the wind sensor would best be placed out in front of the machine. The recorded information must be modified to account for the machine's speed and the angle at which the wind flows across the sensor; both vertically and horizontally.

Wind sensors need to be exposed to free-flowing air representative of the application area. Record the average wind speed and direction at 2m above the ground as recommended by the APVMA. Be aware that forecast and observed winds from the BoM are for 10m. Ultrasonic anemometers are recommended to ensure accurate wind measurement.

Temperature and Delta T sensors should be placed at 1.25m above the surface within radiation shields. Handheld devices need to be acclimatised to paddock conditions and not exposed to full sunshine before recording.

For hazardous inversion detection (quantification of very stable dynamic stability) as described by Grace and Tepper 2021, 3D ultrasonic anemometers are required to measure the standard deviation of vertical wind speed sampled at 4 hertz or better. Raw data needs to be corrected for the surrounding terrain and the wind's angle of attack on the sensor. Additionally, thermocouples, housed within radiation shields between 1.25 and 10m, are required to determine vertical temperature difference (VTD).

It is anticipated that systems with the ability to detect, in real time, and forecast hazardous inversions will be established across some Australian high-value agricultural districts within the next few years.

Inversion detection

All inversions must be considered hazardous when utilising these methods, which aim to quantify statically stable conditions. Two methods for measuring VTD are as follows:

1. Method 1 (preferred): Deploy E Type thermocouples made from exactly the same batch of wire and all having exactly the same length wire (excess wire must be coiled, not cut).
   a. These sensors must be housed in radiation shields. It is recommended that they are placed at 1.25 and 10m to ensure a representative sampling of paddock conditions.
   b. The method of setting up the thermocouples and calculating the VTD requires some simple manipulation – consult the manufacturer for advice. There should be no need for calibration of the thermocouples.
2. Method 2: Deploy matched calibrated sensors with an accuracy of +/-0.1°C (implying a VTD accuracy of +/-0.2°C). These sensors must be housed in radiation shields. It is highly recommended that they are placed at 1.25 and 10m to ensure a representative sampling of paddock conditions.

Less accurate sensors will lead to false alarms and missed events. Matched calibrated sensors are likely to require yearly recalibration; check with the manufacturer.

References

Abbs, D. J. and L. William. 1992. Sea-breeze observations and modelling: a review. *Sea* 50: 95s.

Arya, S. Pal. 2001. *Introduction to Micrometeorology*. 2nd ed. Academic Press.

Australian Pesticides and Veterinary Medicines Authority (AVPMA). 2008. *Operating Principles in Relation to Spray Drift Risk*. APVMA.

Balsley, B. B., R. G. Frehlich, M. L. Jensen and Y. Meillier. 2006. High-resolution in situ profiling through the stable boundary layer: Examination of the SBL top in terms of minimum shear, maximum stratification, and turbulence decrease. *Journal of the Atmospheric Sciences* 63(4): 1291–1307. https://doi.org/10.1175/jas3671.1.

Banta, R. M., Y. L. Pichugina and W. Alan Brewer. 2006. Turbulent velocity-variance profiles in the stable boundary layer generated by a nocturnal low-level jet. *Journal of the Atmospheric Sciences* 63(11): 2700–2719. https://doi.org/10.1175/jas3776.1.

Bedos, C., P. Cellier, R. Calvet, E. Barriuso and B. Gabrielle. 2002. Mass transfer of pesticides into the atmosphere by volatilization from soils and plants: Overview. *Agronomie* 22(1): 21–33. https://doi.org/10.1051/agro:2001003.

Bish, M. D., S. T. Farrell, R. N. Lerch and K. W. Bradley. 2019. Dicamba losses to air after applications to soybean under stable and nonstable atmospheric conditions. *Journal of Environmental Quality* 48(6): 1675–1682. https://doi.org/10.2134/jeq2019.05.0197.

Bodine, D., P. M. Klein, S. C. Arms, and A. Shapiro. 2009. Variability of Surface Air Temperature over Gently Sloped Terrain. *Journal of Applied Meteorology and Climatology* 48(6): 1117–1141. https://doi.org/10.1175/2009jamc1933.1.

Bowen, B. 2007. *Improved Wind and Turbulence Measurements Using a Low-cost 3-D Sonic Anemometer at a Low-wind site*. University of North Texas Libraries, UNT Digital Library. https://digital.library.unt.edu.

Bureau of Meteorology. 2007. *Manual of Aviation Meteorology*. Australian Government.

Crabbe, R. S., M. McCooeye and R. E. Mickle. 1994. The influence of atmospheric stability on wind drift from ultra-low-volume aerial forest spray applications. *Journal of Applied Meteorology* 33(4): 500–507.

Dijk, H. V., W. Pul and P. Voogt. 1999. Fate of pesticides in the atmosphere: Implications for environmental risk assessment. Proceedings of a workshop organised by the Health Council of the Netherlands, Driebergen, The Netherlands, April 22–24, 1998.

Glotfelty, D. E., J. N. Seiber and L. A. Liljedahl. 1987. Pesticides in fog. *Nature* 325 (6105): 602–5. https://doi.org/10.1038/325602a0.

Gordon, B. 2017. *Spray Application Manual. Module 4: Drift management strategies: Minimising and managing spray drift risk*. GRDC Grownotes. https://grdc.com.au/resources-and-publications/grownotes/technical-manuals/spray-application-manual/4grdcsm4drift-management-strategies.pdf.

Grace, W. 1995. *Downslope Winds*. AGPS.

Grace, W., and I. Holton. 1990. Hydraulic jump signatures associated with Adelaide downslope winds. *Aus. Met. Mag*. Australian Bureau of Meteorology.

Grace, W., and G. Tepper. 2021. Micrometeorological aspects of spraying within a surface inversion. *Journal of Applied Meteorology and Climatology*. September, 1231–1244. https://doi.org/10.1175/jamc-d-20-0239.1.

Hiscox, A. L., D. R. Miller and C. J. Nappo. 2010. Plume meander and dispersion in a stable boundary layer. *Journal of Geophysical Research: Atmospheres* 115 (D21). https://doi.org/10.1029/2010JD014102.

Holton, I. 1995. Nocturnal boundary-layer flow over a long low ridge in central Australia. *Aust. Met. Mag.*: Australian Bureau of Meteorology.

Jegier, Z. 2006. Pesticide residues in the atmosphere. *Annals of the New York Academy of Sciences* 160: 143–154. https://doi.org/10.1111/j.1749-6632.1969.tb15835.x.

Liu, C., Y. Yan and P. Lu. 2014. Physics of turbulence generation and sustenance in a boundary layer. *Computers & Fluids* 102: 353–384. https://doi.org/10.1016/j.compfluid.2014.06.032.

MacCollom, G. B., W. W. Currier and G. L. Baumann. 1986. Drift comparisons between aerial and ground orchard application. *Journal of Economic Entomology* 79(2): 459–464.

Mahrt, L. 1999. Stratified atmospheric boundary layers. *Boundary-Layer Meteorology* 90(3): 375–396. https://doi.org/10.1023/A:1001765727956.

Mahrt, L. 2014. Stably stratified atmospheric boundary layers. *Annual Review of Fluid Mechanics* 46(1): 23–45. https://doi.org/10.1146/annurev-fluid-010313-141354.

Majewski, M. S. and P. D. Capel. 1995. *Pesticides in the atmosphere: Distribution, trends, and governing factors.* Chelsea, Mich.: Ann Arbor Press.

Matthews, G. 2008. *Pesticide application methods.* John Wiley & Sons.

Miller, D. R., T. E. Stoughton, W. E. Steinke, E. W. Huddleston and J. B. Ross. 2001. Atmospheric stability effects on pesticide drift. http://www.prairieswine.com/pdf/2983.pdf.

Muschinski, A. and C. Wode. 1998. First in situ evidence for coexisting submeter temperature and humidity sheets in the lower free troposphere. *Journal of the Atmospheric Sciences* 55(18): 2893–2906. https://doi.org/10.1175/1520-0469(1998)055<2893:fisefc>2.0.co;2.

Nauta, L. 2013. Shallow drainage flows over light sloping terrain during BLLAST 2011: Two case studies. Master's thesis, Meteorology and air quality group at the Wageningen University, supervised by Dr Ir. Oscar Hartogenesis.

Primary Industries Standing Committee. 2002. *Spray drift management: Principles, strategies and supporting information.* Vol. 82: CSIRO Publishing.

Ramdas, L. A. and S. Atmanathan. 1932. The vertical distribution of air temperature near the ground at night. *Beit.Geophys* 37: 116–117.

Sarigiannis, D. A., P. Kontoroupis, E. S. Solomou, S. Nikolaki and A. J. Karabelas. 2013. Inventory of pesticide emissions into the air in Europe. *Atmospheric Environment* 75: 6–14.

Seaman, N., B. Gaudet, A. Deng, S. Richardson, D. Stauffer and J. Wyngaard. 2008. J3.1 Evaluation of meander-like wind variance in high-resolution WRF model simulations of the stable nocturnal boundary layer. https://www.researchgate.net/publication/228510880_J_3_1_Evaluation_of_meander-like_wind_variance_in_high-resolution_WRF_model_simulations_of_the_stable_nocturnal_boundary_layer.

Seiber, J. N. and J. E. Woodrow. 2000. Transport and fate of pesticides in fog in California's Central Valley. In *Agrochemical Fate and Movement*, ACS Symposium Series, American Chemical Society, 323–346.

Simpson, J. E. and R. E. Britter. 1980. A laboratory model of an atmospheric mesofront. *Quarterly Journal of the Royal Meteorological Society* 106(449): 485–500. https://doi.org/10.1002/qj.49710644907.

Stull, R. B. 2000. *Meteorology for Scientists and Engineers: A technical companion book with Ahrens' Meteorology Today*. Brooks/Cole.

Tepper, G. 2011. Presentation to farmers in the Clare Valley region, SA.

Tepper, G. and A. Watson. 1990. The wintertime nocturnal northeasterly wind of Adelaide, South Australia: An example of topographic blocking in a stably stratified air mass. *Aus. Met. Mag.* 38, 281–291.

Thistle, H. W., M. E. Teske and R. C. Reardon. 1998. Weather effects on drift meteorological factors and spray drift: An overview. Proceedings of the North American Conference on Pesticide Spray Drift Management, March.

Tudi, M., H. Daniel Ruan, L. Wang, J. Lyu, R. Sadler, D. Connell, C. Chu and D. T. Phung. 2021. Agriculture development, pesticide application and its impact on the environment. *Int J Environ Res Public Health* 18(3). https://doi.org/10.3390/ijerph18031112.

Unsworth, J., R. D. Wauchope, A. W. Klein, E. Dorn, B. Zeeh, S. Yeh and K. D. Racke. 2000. Significance of the long range transport of pesticides in the atmosphere. *Pest Management Science* 58. https://doi.org/10.1351/pac199971071359.

Waite, D. T., P. Bailey, J. F. Sproull, D. V. Quiring, D. F. Chau, J. Bailey and A. J. Cessna. 2005. Atmospheric concentrations and dry and wet deposits of some herbicides currently used on the Canadian Prairies. *Chemosphere* 58(6): 693–703. https://doi.org/10.1016/j.chemosphere.2004.09.105.

Wolf, T. 2019. The challenges of spraying by drone. *Sprayers 101*. https://sprayers101.com/challenges-drone.

Woodrow, J. E., K. A. Gibson and J. N. Seiber. 2019. Pesticides and related toxicants in the atmosphere. *Rev Environ Contam Toxicol* 247: 147–196. https://doi.org/10.1007/398_2018_19.

Yates, W. E., N. B. Akesson, and R. E. Cowden. 1974. Criteria for minimizing drift residues on crops downwind from aerial applications [of pesticide sprays on alfalfa and sugarbeets]. *Transactions of the ASAE* 17 (4): 627–632.

Zivan, O., Y. Bohbot-Raviv and Y. Dubowski. 2017. Primary and secondary pesticide drift profiles from a peach orchard. *Chemosphere* 177: 303–310. https://doi.org/10.1016/j.chemosphere.2017.03.014.

Useful resources

Hazardous Inversion Fact Sheet, grdc.com.au/hazardous-inversion

Weather essentials for pesticide application, grdc.com.au/GRDC-Booklet-WeatherEssentials

Graeme Tepper (2022). *Spray drift hazard warning system*. GRDC Update Paper. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/07/spray-drift-hazard-warning-system

Weather and Networked DATA (WAND), wand.com.au

Conditions Over the Landscape (COtL), cotl.com.au

Notes

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