Meteorological Concepts in the Drift of Pesticide

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Abstract

The role of meteorology in pesticide drift is discussed. It is well known that the wind speed is a critical factor. The interaction of meteorological variables such as humidity and vertical temperature structure with airborne droplets is less well understood in the applicator community. A brief discussion of the relevant meteorological variables and the effect of these variables on drift is presented here.

Introduction

Meteorology plays an important role in determining the movement of spray droplets in the atmosphere as well as where these droplets land. Describing the exact movements of these droplets challenges the predictive capability of modern science. However, in a mean sense, the effect of meteorology on drift is understood and can be calculated.

Recent work confirms that the three primary factors in drift are droplet size, release height and meteorology (Hewitt et al., 2002). Immediately, it is apparent that two of these are not meteorological factors. Upon further thought, it is clear that the story is not as simple as it may at first appear. Droplet size is critical because as smaller droplets are considered, the role of gravity is lessened and the role of the ambient wind field is increased. As the release height increases, droplets will spend longer in the atmosphere and the ambient wind field will have a longer time to displace them laterally away from the target. Thus, when the interdependencies between variables are considered, it is clear that, in a sense, meteorology is responsible for drift. The role of meteorology in the determination of the position of deposition is generally proportional to the amount of time the droplet is in the atmosphere. Thus in low boom ground sprayer applications where nozzles are pointed downward, the vast majority of the spray material is not resident in the atmosphere for a long period and therefore is not much influenced by meteorology. Note that even in this scenario, there is a small fraction of the total mass of the spray material in very fine drops that does not reach the surface. This material is available to drift. The interdependency of the application parameters is apparent and lends itself to computer modeling. The role of meteorology will be illustrated here using modeled results. The model simulates aerial application but the points made are relevant to all application scenarios. It is interesting that of the three dozen or so variables that are used by the model to calculate drift, those that are generally least controllable by the applicator are variables describing the meteorology and variables describing the foliar canopy. Of these two, only meteorology is constantly varying in time and space.

This paper then addresses the role of meteorology in pesticide drift. Specifically the mechanisms of transport in the atmosphere that influence primary movement of spray material. Variance of meteorological variables is also discussed as well as the implication of this variance to off-target movement. Measurement of these variables as well as interpretation of data is addressed in a separate talk. It is obvious that only a very perfunctory discussion of the relevant meteorology is possible in this small space. For readers that would like additional information see Stull (1988), Panofsky and Dutton (1984), and Rosenberg(1974). These texts are introductions to the various aspects of meteorology important to this subject.

Wind Speed and Direction

Wind speed and direction are the primary meteorological determinants of the amount of material that is moved off-target as well as the direction that the material moves. Though wind direction is not discussed in relation to the magnitude of drift from an application, if the consideration is to prevent drift to a specific location that is considered sensitive, then wind direction is the critical variable as the direction of air movement determines the direction in which material will drift. The fluctuation in wind direction can also be used as an indicator of the amount of atmospheric turbulence and, therefore, the amount of dilution of a cloud of fine droplets.

Wind speed guidance is now given on many pesticide labels in the United States. However, even with the attention that wind speed has received, the regulatory and applicator community struggles with the concepts involved in the transport of spray droplets in a three dimensional turbulent fluid such as the Earth's surface layer atmosphere.

A simple case study is developed to illuminate the role of wind speed in drift. AGDISP 8.08 (Teske et al., 2003) does a reasonable job of simulating the position of deposition of droplets released in aerial spraying. A strength of the model is in its basic (thoughsimplified) physical correctness and its ability to correctly portray trends and interactions among variables in a mean sense. The method selected a base case (Teske et al., 1993) that is a typical operational scenario (J. Creighton, International Paper, personal communication), in this case it is an aerial herbiciding scenario of a young (short) pine plantation. The output compares the deposition between 50 and 250m downwind of the last swath edge. A summary of the base case is given in Table 1.

Table 1. Sensitivity Parameters

Aircraft	Bell 206B Jet Ranger
Release Height	9.14 m
Wind Speed	3.13 ms^{-1}
Number of Nozzles	47
Spray Volume Rate	93.5 Lha^{-1}
Non-Volatile Fraction	.5
Active Fraction	.075
Temperature	21.1°C
Relative Humidity	75%
VMD	852µm
Swaths	20

Ambient wind accomplishes the horizontal movement of the droplets as the aircraft wake vortices weaken. It can be seen from Figure 1 that there are over two orders of magnitude more drift in the high wind speed case than the low. Notice that in the low wind speed case, the deposition at 250m is very low (single $\mu g/m^{-2}$) even though the application rate is 93.5 Lha^{-1}. Generally, wind speed at application will be limited by label restriction to less than 4.5 ms^{-1}. Interestingly, it has been proposed to add low wind speed restrictions to labels with the contention that low wind speeds are associated with atmospheric inversions and are characterized by variable direction.

Humidity

The base case of Table 1. is used to investigate the role of humidity. The primary influence of humidity is to reduce the size of droplets through evaporation thus reducing droplet settling velocity and increasing the influence of ambient air movement. It can be seen from Figure 2 that deposition at 250m varies by a factor of two between the low humidity and the high humidity cases. Low humidity conditions increase drift by reducing the size of droplets after they are sprayed through increased evaporation. The amount of potential evaporation is a direct function of the volatility of the sprayed material. In the base case though only .075 of the spray material is active, the non-volatile fraction is specified as .5 simulating the inclusion of an anti-evaporant or non-volatile inerts. If the mix was .075 non-volatile AI mixed with .925 water, evaporation would be much higher. Rapid evaporation of material is more commonly a problem at high temperatures or in dry climates. It is often a controlling factor in the very dry climates of parts of the western United States

Figure 1. Wind Speed Dependence. This graph shows the modeled results of deposition downwind of the spray block for four wind speed scenarios. The solid line is the base case, the wind speeds progressing from finer dash to coarser are 4.47ms^{-1}, 1.79ms^{-1} and .45ms^{-1} respectively.

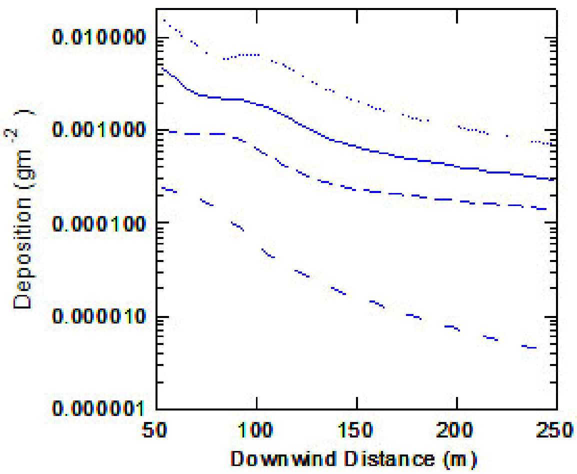
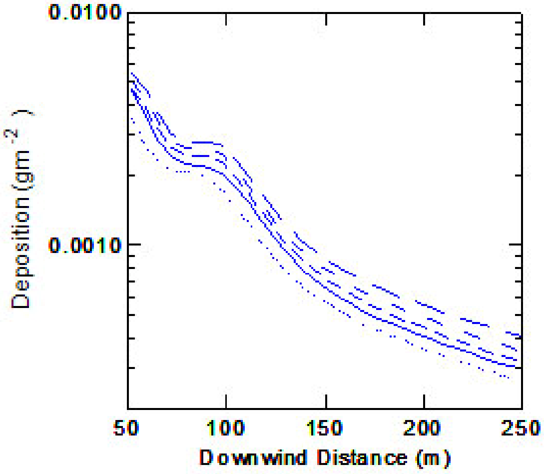


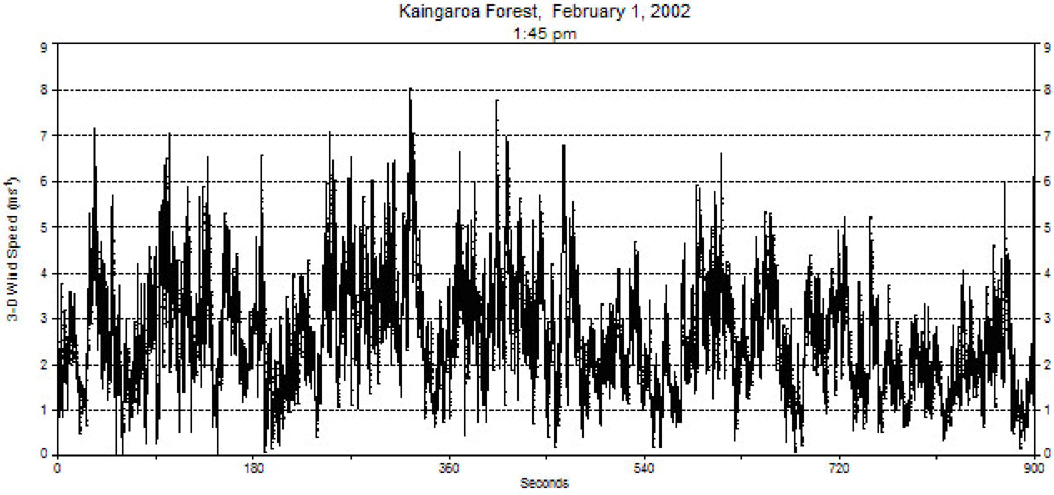
Figure 2. Humidity Dependence. This graph shows the dependence of downwind deposition on humidity (modeled as relative humidity). The base case is the solid line. The modeled humidity varies from coarser dash to finer as 15%, 35%, 55% and 95% respectively.



Variance

As the role of specific meteorological variables in off-target drift is discussed, it is necessary to discuss the implication of averaging and the meaning of a statement such as 'wind speed should be less than 5 mph'. Figure 3 is a trace of wind speed taken at 10Hz. It is immediately obvious that the wind speed is extremely variable, even when measured ten times per second. How does this variation effect the transport of a droplet? The first consideration is that fluid motion should not be treated as a scalar quantity. It is a vector with magnitude (speed) and direction in three-dimensions. Thus each measurement at 10Hz will have a different direction and speed of movement

Figure 3. Trace of wind speed measured at 1:30 pm, Feb. 1, 2002 in Kaingaroa Forest, NZ. Measured over a young Radiata pine canopy. (From Thistle et al., 2004.)



of the transporting fluid (the wind). Note that when a standard cup anemometer is used and a 15 minute average wind speed is stated, this is a scalar average. If the quick calculation is done that a neutrally buoyant droplet in a 5 ms^{-1}, 15 minute averaged wind speed will move 4500 m downwind in 15 minutes (5 ms^{-1} x 900 s) the answer arrived at is too large. Though it is the correct answer to the question 'How far did the droplet travel?' it is not the correct answer to the question 'How far did the droplet move in the mean downwind direction?' The answer to that question must consider the amount of variance in the wind direction and ultimately requires a vector resultant of the speeds and directions in the series. This distance will always be less than the distance based on the scalar averaged wind speed.

The reason that substantial variance is seen even at high frequency in these time series is that the mean state of the atmosphere changes spatially and these spatial gradients are large in the vertical direction. The surface layer atmosphere is almost always in a highly turbulent state (large Reynold's Number). In a turbulent fluid, the mean motion is composed of roughly circular eddies translating in a direction parallel to the mean pressure gradient. In the surface boundary layer where most pesticide application occurs, the ground surface exerts drag on the fluid above and forms what modelers call a no-slip boundary. This implies that the fluid at the surface has zero velocity while the fluid in the layer immediately above is moving much more quickly. When the circular eddies move in this vertical plane they constantly downwash higher velocity fluid from above and lift slower moving fluid from below. This serves to mix the atmosphere, and when monitored from a point, the variance in the time series of the wind can be related to the size of the eddies. Larger eddies move fluid from further away vertically, and therefore from a region of much higher velocity, this shows up as a gust in the series. The discussion of variance in this context is important because the amount of variance can be used as a measure of mixing in the atmosphere. Larger eddies will manifest as larger fluctuations in a time series of velocity. Larger eddies will also manifest themselves in the time series of wind direction. Thus both the magnitude of variance in the time series of wind as well as the magnitude of variance of the wind direction can be used to indicate the level of mixing in the atmosphere. The concept of mixing is introduced because a release of pesticide can be thought of as populating a volume of the atmosphere with droplets. If mixing is high (large eddies), material is mixed through a large volume of atmosphere but is relatively dilute. If mixing is low, the material is mixed through a small volume of atmosphere but is more concentrated. The condition of the atmosphere that determines the mixing volume is stability and is discussed below.

Solar Radiation and Energy Budgets

A fundamental point that is frequently overlooked is that the local meteorology is often dictated by local surface conditions and the interaction of the surface with the incident solar radiation. The sun emits radiation in high frequency waves that, in large part pass through the atmosphere with the important exception of a considerable segment reflected from cloud tops. This shortwave energy is intercepted at the surface and either reflected or absorbed. The surface then heats up and emits radiation at a much longer wavelength. This long wavelength energy is more susceptible to being absorbed by components in the atmosphere. Thus, the atmosphere is heated from below. The process reverses itself at night and the surface loses heat by radiation proportionally to the temperature of what the surface 'sees'. This is the idea of a view factor. If there is solid cloud cover, what the surface sees is the cloud base that is likely somewhat colder than the surface but not dramatically so, so the surface radiates heat to the clouds but substantial heat is radiated back as well. If it is a clear night, the surface sees outer space and radiates heat to space with very little energy radiating back. Thus on clear nights, the surface cools rapidly and becomes colder than the air above it.

Energy intercepted by the Earth's surface is partitioned into sensible heat (H) and latent heat (LE, other more minor components of the energy budget are not considered here). H is the heat that we feel as the atmosphere heats. LE is the heat energy that is stored in the phase change of water (evaporation) and is not available for heating. If there is available water, incident solar energy will be used for evaporation. Over a free water surface, the ratio H/LE which is known as the Bowen ratio, will be around .1. In a very arid setting the Bowen Ratio will approach 1. The relevance to this discussion is that wet surfaces will be cooler. Irrigated fields will have surface temperatures lower than nearby non-irrigated fields. A detailed discussion of this topic is beyond the scope of this brief treatment but two points need to be made. First, the atmosphere is cooler over a free water or wet surface when evaporation is occurring. Second, the atmosphere is more humid near water or over a wet surface. Both of these facts have implications for spray drift.

Atmospheric Stability and Turbulence

Atmospheric stability can be simply described by the change of temperature with height in the atmosphere. As one gains elevation in the atmosphere, there is less atmosphere above you so the pressure of the overlying atmosphere on a surface drops. Temperature in a fluid is related to pressure so the temperature drops as well. This effect is always present and results in a temperature drop of about .065 ºC/10 m vertically on average (Whiteman, 2000). To simplify our discussion here we will ignore this effect as it is small in the layer of interest and define a stable atmosphere as one in which the temperature increases with height, an unstable atmosphere as one in which the temperature decreases with height and a neutral atmosphere as one which doesn't change temperature with height.

The reason that stability is important in dispersion of fine droplets is through its role in suppressing or enhancing the ambient turbulence. In a stable atmosphere, warm air overlies cold air. If the air in this layer is displaced lower it is warmer than the layer it enters and it rises, if it is raised above its layer of origin it is colder than the air it moves into and it sinks. If air in this stable layer is displaced vertically, it returns to its vertical level of origin. Thus if pesticide is released into this layer, the drops that do not deposit with gravity stay in a narrow layer of the atmosphere and do not mix because the air is not mixing.

Conversely, in an unstable atmosphere, warm, less dense air is underneath cold air. If this air moves vertically it rises into colder air and keeps on rising as it is less dense than the layer it moves into. If it drops, it drops into warmer air and keeps dropping because it is heavier than the air below it. So, no matter which direction it is displaced it keeps on moving away from its level of origin. Hence, the layer is unstable as a slight perturbation sets the layer into vertical motion and enhances turbulence. The displaced air can keep rising in many cases because of this mechanism and can end up far away from its level of origin. Thus, the boundary layer can be deep and pesticide released at the surface may mix through this deep volume. The pesticide in this well mixed layer is likely very dilute but individual small droplets could travel far.

It needs to be emphasized that both strongly stable and strongly unstable layers generally do not exist in high winds, as the vertical layering is mixed and becomes uniform through mechanical mixing as wind speed increases. Cloud cover prevents the basic mechanism of strong surface heating and cooling from happening as it inhibits radiative exchange.

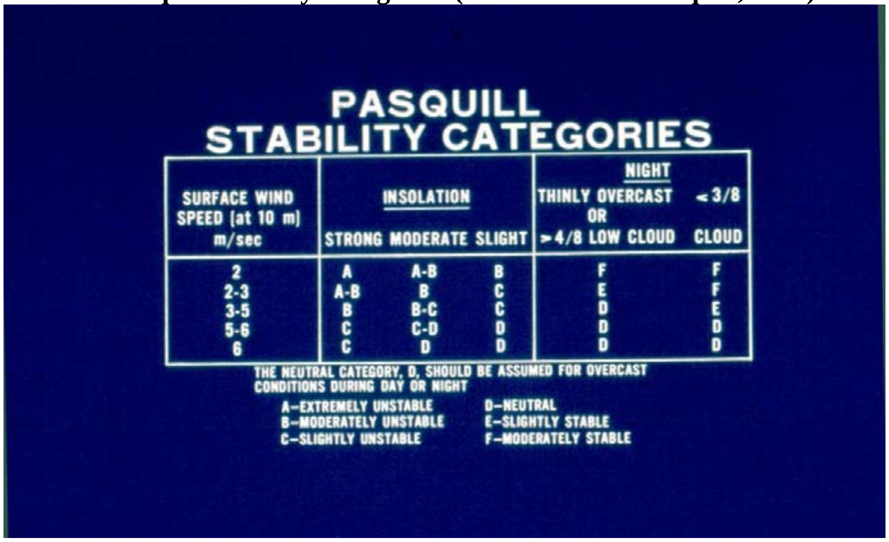
The influence of stability on a given application scenario depends on the size of the droplets being sprayed. The fact that strongly stable and strongly unstable conditions are typically characterized by low wind speeds means that larger droplets will settle out close to the point of release. The influence of stability will increase as the droplet diameter decreases. It may be said that stability is the third most important variable in the movement of gaseous quantities in the atmosphere (after wind speed and wind direction). This is not the case in applications where large droplets are sprayed and the deposition is largely gravity driven. The role of stability may also be obscured by the influence of the aircraft wake in aerial application and the influence of downward jetting from the nozzles in ground spraying. In these cases, impaction energy is mechanically imparted to the droplets and they may deposit before they are influenced by atmospheric turbulence. Also, in the case of very low ground sprayer applications, the droplets are initially inserted into a low velocity layer near the surface. For instance, in a vector control adulticiding application where aerosol size droplets are desired and they are released at heights over 40m, stability will play a critical role in the landing position of these droplets. Conversely, herbicide application from a low boom ground sprayer with spray VMD over 500µm will have a small percentage of the total mass that will be significantly affected by stability.

How to Recognize Inversion Conditions

Stable conditions are often referred to as ‘inversions’. It is inversion conditions that are of most interest to applicators. Because of the low dispersion conditions in stable atmospheres, pesticide droplets may remain concentrated and drift off target but remain concentrated. This scenario can result in a concentrated cloud of pesticide droplets landing downwind and possibly causing damage to non-targets. Applicators often have a difficult time recognizing inversion conditions because this is not a meteorological quantity that is often discussed in the mass media even though, in larger basins such as the Central Valley of California and the Salt Lake Basin (as well as smaller, populated valleys), inversion conditions are now discussed in air quality reporting.

Inversion conditions can in many cases be recognized through basic observation. The scheme presented in Table 2. is very useful in determining stability. Nighttime stability can only be either neutral or stable. It is the transitions in the morning and evening that are more difficult. If it is a clear dawn with low wind, it is a high probability the observer is in an inversion. After the sun rises, the surface begins to warm and the inversion will rapidly break up over surfaces receiving direct sunlight. Initially, (until two to three hours after sunrise or so) the inversion may still exist but it is elevated. This elevated inversion can be important in aerial application as the surface atmosphere is not stable, but at the elevation the spray is being released it may be stable. Eventually, as the day progresses, it is expected that the entire surface layer will be unstable if the sun is shining on the surface. As the sun sets, the surface is no longer being heated by solar radiation and begins to cool. The surface layer then shifts to stable again. The breakup of the morning inversion tends to be abrupt, while the evening transition from unstable to stable tends to be gradual. Keep in mind that under cloud cover or in higher winds, the atmosphere is neutral so stability is not a concern.

Table 2. Pasquill Stability Categories (Modified from Pasquill, 1974).



PASQUILL
STABILITY CATEGORIES

SURFACE WIND SPEED (at 10 m) m/sec	INSOLATION			NIGHT	
	STRONG	MODERATE	SLIGHT	THINLY OVERCAST OR >4/8 LOW CLOUD	<3/8 CLOUD
2	A	A-B	B	F	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
6	C	D	D	D	D

THE NEUTRAL CATEGORY, D, SHOULD BE ASSUMED FOR OVERCAST CONDITIONS DURING DAY OR NIGHT

A–EXTREMELY UNSTABLE
B–MODERATELY UNSTABLE
C–SLIGHTLY UNSTABLE
D–NEUTRAL
E–SLIGHTLY STABLE
F–MODERATELY STABLE

Conclusions

Meteorology is critical to pesticide drift. A basic discussion of meteorological concepts demonstrates the role of wind speed and direction, humidity and atmospheric stability. Variability of meteorological data is also discussed in terms of drift. A basic understanding of the role of meteorology will aid applicators in avoiding pesticide drift.

Bibliography

Hewitt, A. J., D. R. Johnson, J. D. Fish, C. G. Hermansky, and D. L. Valcore. 2002. Development of the spray drift task force database for aerial applications. *Environmental Toxicology and Chemistry* 21(3):648-658.

Panofsky, H.A. and J.A. Dutton. 1984. Atmospheric Turbulence: Models and Methods for Engineering Applications. New York, John Wiley and Sons.

Pasquill, F. 1974. Atmospheric Diffusion. New York. John Wiley and Sons.

Rosenberg, N.J. 1974. Micro-Climate: The Biological Environment. John Wiley and Sons, New York.

Stull, R.B. 1988. An Introduction to Boundary Layer Meteorology. Boston MA, Kluwer Academic Publishers.

Teske M. E. and J. W. Barry. 1993. Parametric sensitivity in aerial application. Transactions of the ASAE. 36: 27–33.

Teske M.E., H.W. Thistle and G.G. Ice. 2003. ‘Technical Advances in Modeling Aerially Applied Sprays’. *Transactions of the American Society of Agricultural Engineers.* Vol. 46 #4 pp. 985-996.

Thistle H.W., M.E. Teske and B. Richardson. 2004. Spray Droplet Trajectory Length in Ambient Vortices. ASAE Technical Paper #041088, St. Joseph, MI.

Whiteman C.D. 2000. Mountain Meteorology: Fundamentals and Applications. New York,_Oxford University Press.