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Measurement and Analysis of Atmospheric Stability in Two Texas Regions

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Abstract. Drift from aerial application of crop protection and production materials is influenced by many factors for which the applicator is responsible for considering and adjusting, where applicable, to reduce as much as possible, the potential for drift. In an effort to study the uncontrollable factors, this study monitored and documented atmospheric conditions over the course of several months at two locations in Texas. The measured meteorological data was used to assess how atmospheric stability varied as a function of time of day, location, and other meteorological conditions. Additionally, inversion periods were examined for strength, time of occurrence, and duration. Stable and very stable atmospheric conditions, which would tend to produce the most drift, primarily occurred between the hours of 6 p.m. and 6 a.m., with a few occurrences between 6 a.m. and 6 p.m. Between the hours of 6 a.m. and 6 p.m. unstable atmospheric conditions tended to dominate. Of the days monitored, almost half experienced inversion periods between the hours of 6 a.m. and 6:30 p.m., with more than half of these inversion periods being after 4 p.m. and having durations an order of magnitude greater than periods of inversions seen between 6 a.m. and 4 p.m. Generally, these late afternoon periods are of most concern as the probability of experiencing increasingly stable conditions or long inversion periods increases.

Keywords. Atmospheric stability, spray drift, deposition, aerial application, agricultural aviation

Introduction

Drift from aerial application of crop protection and production materials is influenced by many factors, both controllable (boom length, nozzle type and orientation, spray pressure, etc…) and uncontrollable (wind speed, wind direction, atmospheric stability). It is the applicator's responsibility to insure that all factors are considered and/or adjusted, where applicable, to reduce the potential for drift. The atmosphere is the most uncontrollable factor, and must be adjusted for based on real time observations and/or past experience. Many product labels provide limited guidance on optimal spray conditions; however many provide guidance on meteorological conditions. A number of studies have indicated that the more stable the atmosphere, the greater the potential for drift. It is therefore important to have an understanding of atmospheric stability as related to other meteorological parameters and how stability changes with the daily cycle.

This goal of this study was to monitor and document atmospheric conditions over the course of several months at two locations in Texas. The measured meteorological data was used to assess how atmospheric stability varied as a function of time of day, location, and other meteorological conditions. In addition, preliminary results from a field deposition and drift study are presented.

Atmospheric Stability

Lapse Rate and Atmospheric Stability

One of the main driving forces of atmospheric stability is the relationship of temperature with height. The rate at which the temperature varies height is called the lapse rate. Lapse rate significantly impacts the vertical movement of air. The mechanism by which air is displaced vertically is tied to the concept of the adiabatic lapse rate. Consider a mass of air that can deform with vertical movement. This is referred to as an air parcel (Seinfeld and Pandis, 1998). This air parcel will expand adiabatically (no heat exchange with surrounding air) as it rises in the atmosphere. Using the first law of thermodynamics and the ideal gas law, a relationship for the variation in temperature with height for a parcel of dry air rising adiabatically can be determined (Seinfeld and Pandis, 1998). This value is called the dry adiabatic lapse rate, and is equal to about 1° C per 100 meters of height.

The actual lapse rate will tend to be something other than the dry adiabatic rate due to surface heating or other localized weather. Were the actual lapse rate and the dry adiabatic lapse rate equal, a parcel of air that is displaced (either up or down) would have the same temperature as the surrounding air, thus the same density, and would be in equilibrium. This is called neutral stability. Consider a parcel of warm air in an environment where the actual lapse rate is greater than the dry adiabatic lapse rate. As this parcel rises, its temperature is greater than that of the surrounding air, thus its density is less and it will continue to rise. As the parcel rises, the temperature difference increases and parcel rise accelerates. This is an unstable atmosphere as vertical motion is enhanced. Now consider the same parcel of warm air in an environment where the actual lapse rate is less than the dry adiabatic lapse rate. As the parcel rises, its temperature is less than the surrounding air therefore its density is greater and the parcel will descend to the point where its temperature is the same as that of the surrounding air. This is a stable atmosphere as vertical motion is opposed. (Seinfeld and Pandis, 1998)

Temperature can also increase with height and is referred to as an inversion. Inversions can be caused by radiation cooling at the ground or horizontal movement of an air mass from above a warm (ground) surface to a cooler surface (water) (Seinfeld and Pandis, 1998). Inversions are associated with minimal mixing thus generating the highest downwind concentrations from an effluent source (Thistle, 2000). A temperature inversion essentially suppresses vertical mixing by forming a ceiling. In the air pollution dispersion modeling arena, this ceiling is known as the mixing height (Beychok, 1994). Seinfeld and Pandis (1998) illustrate how atmospheric stability varies with the actual lapse rate, as shown in Figure 1.

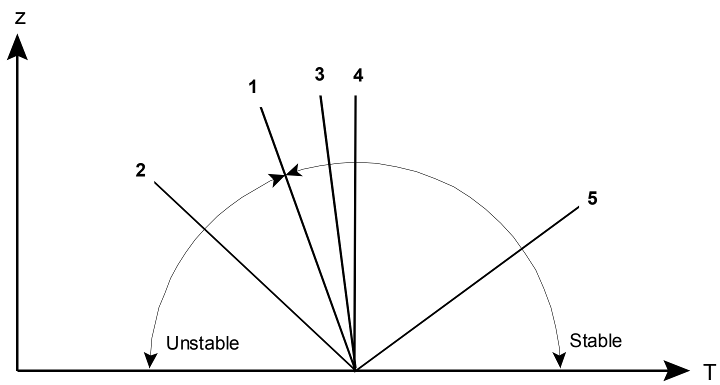

Figure 1. Temperature profiles in the atmosphere. (1) Adiabatic lapse rate (neutral stability, about 1°C per 100 m) T decreases with height such that any vertical movement imparted to an air parcel will result in the parcel maintaining the same T or density as the surrounding air. (2) Superadiabatic (unstable): a rising parcel is cooler than its surroundings so it becomes less buoyant and subsides. (4) Isothermal (stable): temperature is constant with height. (5) Inversion (extremely stable): temperature increases with height. (Seinfeld and Pandis, 1998).

Stability Ratio

For field studies measuring spray drift deposition, both the Environmental Protection Agency (US-EPA, 1998) and the American Society of Agricultural Engineers (ASAE, 1983) note that average wind speed and direction, variations in wind speed and direction, relative humidity, atmospheric pressure, and atmospheric stability should be collected. Atmospheric stability is expressed by the stability ratio (Equation 1). Munn (1966) states that the stability ratio is a simplified (for the purpose of measurement) estimate of the Richardson number, which has long been used as an estimate of stability. The stability ratio is a function of the actual lapse rate and can be used as an indicator of atmospheric stability.

$$SR = \frac{T_{z_2} - T_{z_1}}{u^2} \cdot 10^5 \qquad \text{(Munn, 1966)} \qquad (1)$$

T_{z1} and T_{z2} are temperatures (°C) at heights z_1 and z_2 and u^2 is the wind speed (cm/sec) measured at a height equidistant from z_1 and z_2 on a log scale. Yates et al. (1974) used heights of 8 and 32 feet for z_1 and z_2, respectively, and a wind speed measurement height of 16 feet. The ASAE standard (ASAE 1983) recommends z_1 and z_2 heights of 2.5 and 10 meters, with wind speed measurement height set at 5 meters. Yates et al. (1974) denote four separate classes of atmospheric stability with corresponding ranges for the Stability Ratio (SR in Equation 1), as shown in Table 1.

Table 1. Yates et al (1974) Atmospheric Stability Conditions as a Function of Stability Ratio Ranges.

Atmospheric Stability Condition	Stability Ratio Range
Unstable	-1.7 to -0.1
Neutral	-0.1 to 0.1
Stable	0.1 to 1.2
Very Stable	1.2 to 4.9

Effects of Atmospheric Stability

Yates et al. (1966) conducted a series of field drift studies for which a variety of parameters, including stability ratio, were collected. Generally they observed that tests conducted under more stable conditions resulted in significantly higher deposits than those conducted under unstable conditions. Yates et al. (1967) reported test results that indicated over three times the deposition under very stable conditions as that from unstable conditions. Miller et al. (2000) in a review of research on locally measured meteorological effects on spray drift stated that "...the general consensus identifies increased wind speed and intensification of "stable" conditions as important factors in higher drift amounts". They further stated that much of the previous work tends to agree with the results of Yates et al (1967) which found that in the near field, wind speeds are dominate parameters in describing the amount of drift deposition; while in the far field, atmospheric stability is more dominate (Miller, 2000). MacCollom et al. (1986) also found that greater drift distances and amounts were observed under temperature inversions than in the absence thereof. Hoffman and Salyani (1996) reported that depositions were higher for nighttime application versus daytime application. In addition the Pasquill atmospheric stability classes indicate that the most stable atmospheric conditions occur at nighttime (Pasquill and Smith, 1983). Based on these classes, the study by Hoffman and Salyani (1996) supported the previously mentioned findings. Miller et al. (2000) in a study addressing the effects of atmospheric stability on drift into an adjacent field from an orchard sprayer, found two to six times the amount of drift in stable conditions as compared to unstable conditions. Bird (1995) compiled a database of 42 separate field trials studying off-site deposition. These field trials, under all types of atmospheric stability conditions, came from a number of different studies, including several of the previously mentioned works. Bird (1995) showed that the highest drift deposits were from tests with relatively high wind speeds coupled with a temperature inversion and spray in the small droplet spectra (about 200 μ VMD).

One of the major components lacking from these studies is documentation of time and duration of the different atmospheric stability conditions. Beychok (1994) stated that temperature inversions most often occur during nighttime surface cooling and last until early morning surface heating. Pasquill's stability classifications differentiate between unstable to neutral type conditions (daytime or cloudy) and stable conditions (nighttime) with different levels of strength for each (Pasquill and Smith, 1983). Barratt (2001) presents a table of the Pasquill stability categories with a percentage of occurrences for each in central England. Other information on time and duration of atmospheric stability is limited to general trend observations. This lack of documented atmospheric stability recorded led to the initial focus of this research.

Monitoring and Documentation of Atmospheric Stability

Meteorological Monitoring Tower

The initial focus of this research is the monitoring and documentation of atmospheric stability by strength, duration, time of day, and location. A set of meteorological monitoring towers were constructed to measure and record atmospheric temperature and wind speed profiles from ground level to 10 meters. Shielded thermistors (Campbell Scientific 107 Temperature Probe) designed for air temperature measurements were housed in mechanically aspirated hoods to prevent radiant heating. Each set of five thermistors were match calibrated to within 0.05 °C of each other using a stirred ice bath. Temperature measurements were taken at 0.5, 2.5, 5, 7.5, and 10 meters. Wind speed measurements were taken using 3-cup anemometers (R.M. Young Wind Sentry Anemometer) at 2.5 and 10 meters. Wind direction (R.M. Young Wind Sentry Vane) and net solar radiation (Campbell Scientific LI200X Pyranometer) measurements were taken at 2.5 meters. Each monitoring station was controlled using a Campbell Scientific 10X datalogger along with Campbell Scientific PC208W operating software. The logging interval was set to every 60 seconds in order to match the thermistors response time. Data was collected beginning the first week of May 2003 through the end of October 2003. The station erected near College Station, TX is denoted as station 1 and the station erected near Wharton, TX is denoted as station 2.

Data Reduction and Analysis

The recorded meteorological data was reduced and analyzed for several factors using a series of FORTRAN programs. The following parameters were calculated as part of the initial raw data reduction process. Statistics for each hour of collected meteorological data were calculated and used in the analysis processes.

Wind Speed and Direction Statistics

Wind speed and direction averages and standard deviations were derived using vector computations as outlined in the US-EPA's meteorological monitoring guidance document (US-EPA, 2000).

Stability Ratio

The stability ratio was calculated using Equation 1. This calculation requires a value for wind speed at 5 meters. The monitoring tower did not record wind speed at 5 meters, but it can be extrapolated using the wind speed values at 2.5 and 10 meters using the wind speed logarithmic fit shown in Equation 2 (Cooper and Alley, 1994). The value of the exponent, p, was determined by solving Equation 2 for p and calculating its values using wind speed values (u_1 and u_2) at elevations z_1 and z_2 equal to 2.5 and 10 meters, respectively. With p determined, the wind speed at 5 meters can be calculated using either of the measured wind speed values. The stability ratio was calculated based on the wind speed at 5 meters and temperature at 2.5 and 10 meters.

$$\frac{u_2}{u_1} = \left(\frac{z_2}{z_1}\right)^p \qquad (2)$$

where:

z_1, z_2 = elevation 1 and 2

u_1, u_2 = wind speeds at z_1 and z_2

p = exponent

Atmospheric Stability Classification

Atmospheric stability classification was determined using two methods; one based on the stability ratio as suggested by Yates (1974) (Table 1). Additionally, atmospheric stability was categorized using the Pasquill stability classification system (Pasquill and Smith, 1983). A brief summary of these classifications is provided in Table 2.

Table 2: Summary of Pasquill Stability Classifications. (Pasquill and Smith, 1983)

	Insolation			Night	
Surface Wind Speed (m/s)	Strong	Moderate	Slight	Thinly overcast or $ 4/8 low cloud	# 3/8 cloud
<2	A	A-B	B	--	--
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

(For A-B, take the average of values for A and B, etc.)

US-EPA (2000) offers a more rigid method for estimating the Pasquill stability classification using collected meteorological data. The method used (Solar Radiation/ΔT method) relates daytime stability to wind speed and solar radiation and the nighttime stability to wind speed and temperature profile.

Data Analysis

Various analysis routines were employed to examine the data collected from both meteorological monitoring station locations. The wind speed statistics were calculated for each of the Yates stability groups. This provides a general "rule of thumb" for estimating atmospheric stability. A relationship between time of day and probability of atmospheric stability type was developed based on the total data collected from each station. This provides an overview of when each of the atmospheric stability classes is likely to occur. Additionally, the data was examined for inversion periods. This included time of occurrence, duration and strength. Finally, the data was grouped according to the Pasquill stability classes and the corresponding stability ratio statistics were determined for each class.

Results

The wind speed statistics for the Yates et al. (1974) atmospheric stability classes for each meteorological station are shown in Tables 3 and 4.

Table 3: Wind Seed Statistics by Atmospheric Stability Class for Meteorological Station 1.

	Yates et al. (1974) Atmospheric Stability Classes			
Wind Speed – mph (m/s)	Unstable	Neutral	Stable	Very Stable
Average	7.6 (3.4)	11.6 (5.2)	5.8 (2.6)	2.7 (1.2)
Standard Deviation	4.0 (1.8)	4.3 (1.9)	2.0 (0.9)	1.6 (0.7)

Table 4: Wind Speed Statistics by Atmospheric Stability Class for Meteorological Station 2.

	Yates et al. (1974) Atmospheric Stability Classes			
Wind Speed – mph (m/s)	Unstable	Neutral	Stable	Very Stable
Average	7.8 (3.5)	11.6 (5.2)	6.5 (2.9)	3.1 (1.4)
Standard Deviation	4.3 (1.9)	4.7 (2.1)	2.0 (0.9)	1.6 (0.7)

The wind speed statistics were nearly identical for both locations. Based on the data shown in Tables 3 and 4 a general rule of thumb is that wind speeds (at 10 meters) above 6 mph (2.7 m/s) indicate either unstable of neutral conditions, while wind speeds below 3 mph (1.3 m/s) indicate very stable or inversion type conditions. Looking at all inversion periods from each meteorological station, on average the wind speed (at 10 meters) is 4.9 mph (2.2 m/s) (standard deviation of 3.6 mph (1.6 m/s)) and 5.1 mph (2.3 m/s) (standard deviation of 3.4 mph (1.5 m/s)) for stations 1 and 2 respectively.

The probability distributions by time of day and location for each of the Yates atmospheric stability classes are shown in Figures 2 and 3. The results from these graphs tend to agree with conventional wisdom as to when the different stability conditions occur. Daytime hours (about 7 a.m. to 5 p.m.) tend to be dominated by primarily unstable conditions with some neutral conditions. There are occasional occurrences of both stable and very stable conditions during this time period. Nighttime hours (about 6 or 7 p.m. to 6 a.m.) tend to be dominated by very stable conditions followed by stable and neutral conditions. During these hours there were some occurrences of unstable conditions. Of particular interest are the transitional hours where conditions change from either the unstable daytime trend to more stable nighttime hours (6 p.m. for both stations) or from the stable morning trend to the unstable daytime hours (7 a.m. for both stations). These time frames offer the most potential for spraying during very stable or inversion conditions, and thereby have the greatest potential for possible drift.

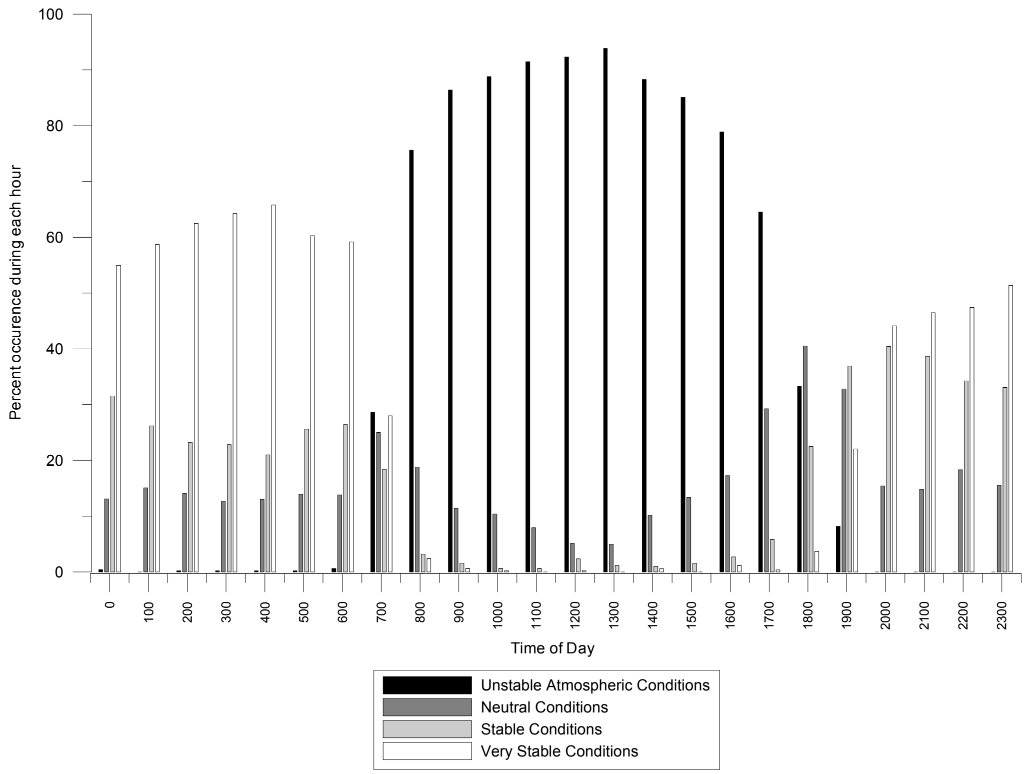

Figure 2: Probability distribution of Yates et al. (1974) atmospheric stability classes by time of day for meteorological station 1.

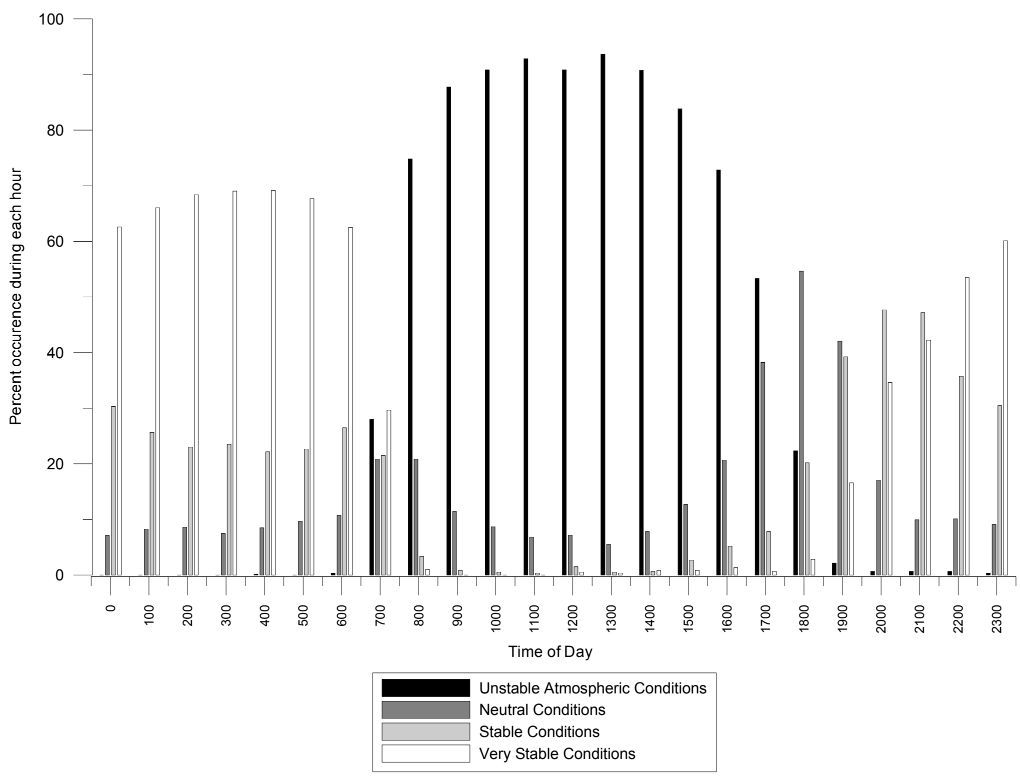

Figure 3: Probability distribution of Yates et al. (1974) atmospheric stability classes by time of day for meteorological station 2.

The data was filtered by time of day, based on inversion periods. Only inversions that occurred between 6:00 a.m. (CST) and 6:30 p.m. (CST) were considered in the analysis. This filtering process removed the extended nighttime inversion periods from the data set, allowing for analysis of the inversion events that occur during hours where spraying may occur. The inversion data was separated into three separate time periods, morning (6 a.m. to 11 a.m.), mid-day (11 a.m. to 4 p.m.) and evening (4 p.m. to 6:30 p.m.). Overall 78 days of the 136 days monitored (57%) by station 1 had periods of inversions during the specified time period. Similarly, 101 days of the 155 (65%) monitored by station 2 had periods of inversions during the specified time period. Summary statistics for inversion occurrences during each of the three time periods is shown in Table 5.

Table 5: Summary Statistics of Days Experiencing Inversion Conditions Between the Hours of 6:00 a.m. – 6:30 p.m. (CST) for Meteorological Monitoring Stations 1 and 2.

	Meteorological Station 1 Total of 136 Days Monitored			**Meteorological Station 2** Total of 155 Days Monitored		
		Percent of Total Days Monitored			**Percent of Total Days Monitored**	
Number of Days One or More Inversion Events Occurred	78	57%	**Percent of Total Inversion Days**	101	65%	**Percent of Total Inversion Days**
Number of Morning Inversion Events	20	15%	26%	34	22%	34%
Number of Mid-day Inversion Events	26	19%	33%	36	23%	36%
Number of Evening Inversion Events	61	45%	78%	77	50%	76%

Station 1 recorded 78 days where inversions occurred in the specified time periods, 20 days (15% of the total days monitored and 26% of the days with inversions) had inversions between 6 a.m. and 11 a.m., 26 days (19% of the total days monitored and 33% of the days with inversions) had inversions between 11 a.m. and 4 p.m., and 61 days (45% of the total days monitored and 78% of the days with inversions) had inversions between 4 p.m. and 6:30 p.m. Similarly, for meteorological station 2 there were 101 days where inversions occurred during the specified time periods, 34 days (22% of the total days monitored and 34% of the days with inversions) had inversions between 6 a.m. and 11 a.m., 36 days (23% of the total days monitored and 36% of the days with inversions) had inversions between 11 a.m. and 4 p.m., and 77 days (50% of the total days monitored and 76% of the days with inversions) had inversions between 4 p.m. and 6:30 p.m.

Each of these inversion periods was further examined for the strength and duration of the inversion incidences. For each time period, the average time of occurrence, duration, and strength as well as standard deviations were determined.

Table 6: Characteristics of Daytime Inversion Periods for Meteorological Station 1.

		Start Time	Duration (min)	Strength* (ΔT °C)
Morning	Average	8:27 a.m.	35	0.17
	Standard Deviation	n/a	57	0.10
Mid-day	Average	2:39 p.m.	27	0.16
	Standard Deviation	n/a	27	0.17
Evening	Average	6:04 p.m.	376	0.30
	Standard Deviation	n/a	392	0.29

*Measured difference between 2.5 m and 10 m

Table 7: Characteristics of Daytime Inversion Periods for Meteorological Station 2.

		Start Time	Duration (min)	Strength* (ΔT °C)
Morning	Average	8:22 a.m.	17	0.09
	Standard Deviation	n/a	20	0.05
Mid-day	Average	1:24 p.m.	32	0.15
	Standard Deviation	n/a	52	0.14
Evening	Average	6:11 p.m.	236	0.24
	Standard Deviation	n/a	355	0.28

*Measured difference between 2.5 m and 10 m

Based on the information shown in Tables 6 and 7, it is obvious that the evening inversions are of greatest concern as they tend to be the longest in duration and strongest in terms of temperature gradient. The reason for this is that inversions occurring during morning and mid-day periods tend to be fleeting due to increased atmospheric mixing from solar heating, while the evening periods occur as the sun sets and the ground losses heat (by radiation) faster than the air above (by convection). The duration of inversions occurring in the evening is also affected by the fact that these inversions tend to endure until the following morning, or if not tend to be followed by other periods of inversion.

The final analysis performed was to group the data by Pasquill stability classes and summarize the stability ratio values for these classes. The average stability ratio values for each of the Pasquill stability classes for each station are shown in Table 8.

Table 8: Stability Ratio Statistics for the Pasquill Stability Classes.

		Pasquill Stability Classification					
		A	B	C	D	E	F
Station 1	Average	-0.41	-0.14	-0.08	0.02	0.10	2.09
	Standard Deviation	1.31	0.36	0.24	0.39	0.381	8.71
Station 2	Average	-1.48	-0.33	-0.18	0.06	0.72	5.48
	Standard Deviation	3.97	0.48	0.29	0.47	1.06	10.04

These data are of most interest when modeling spray drift as the Pasquill stability classification system is an integral part of the Gaussian modeling scheme used in models such as AgDrift or AgDisp. These values can be compared to the Yates atmospheric stability classes (Table 1) by comparing the Pasquill A and B class to the Yates Unstable and similarly C to Neutral, D and E to Stable and F to Very Stable. The stability ratios corresponding to the Pasquill classes are very similar to the corresponding Yates stability classes.

Preliminary Results of Field Study

A series of field studies were conducted to measure spray drift and deposition under a variety of atmospheric conditions. Two treatments (a fine spray and a medium spray) were used. Sampling included mylar cards for deposition and monofilament samples for drift. The initial goal was to obtain as many samples as possible during very stable to stable conditions. Analysis of collected meteorological data indicated that between the hours of 6 a.m. and 7 a.m. very stable and stable conditions had a high probability of occurrence, thus testing began as soon after 6 a.m. as possible. Over the course of three days, 10 replications for each treatment were completed. Initial analysis of the collected meteorological data showed a range of stability ratios from greater than 10 to less than -10. Some were quite large (positive and negative) due to extremely calm wind speeds. Generally the first half of the test each day was classified stable or very stable with the remainder being unstable.

Initial analysis showed that the fine spray samples tended to have more material suspended that travel further downwind than the medium spray samples. This is illustrated in a plot of the suspended concentrations (monofilament samples) versus downwind distance for each treatment (Figure 4). Also, the medium spray samples tended to have greater ground deposition in the near field and less in the far field than the fine spray samples. The ground deposition concentrations (mylar samples) versus downwind distance for each treatment are shown in Figure 5. The fine spray samples tended to have greater concentrations at elevation than do the medium spray samples, as illustrated by the tower deposition data shown in Figure 6.

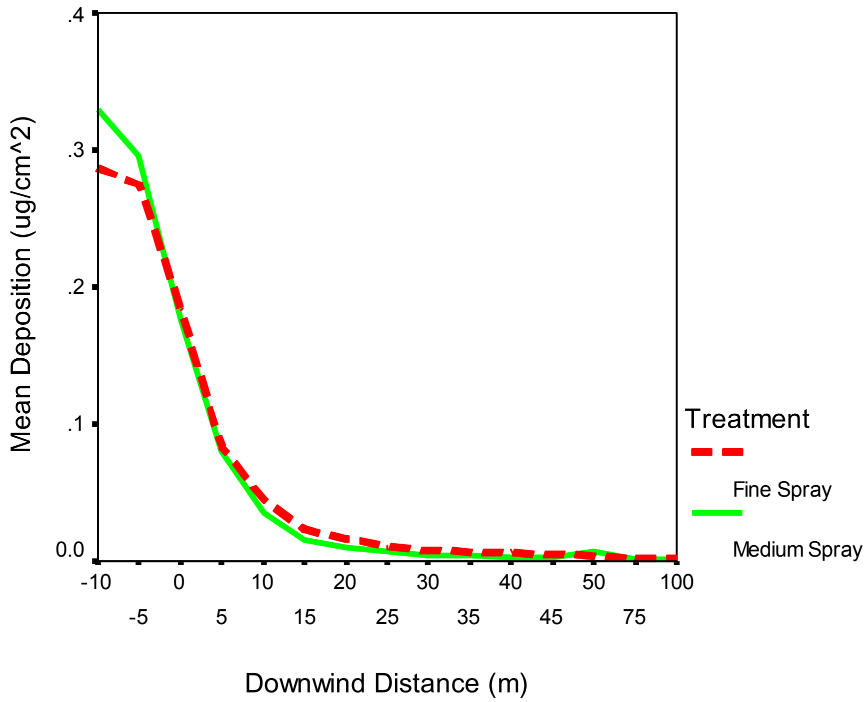

Figure 4: Ground deposition (mylar card samples) of fine and medium spray samples versus downwind distance.

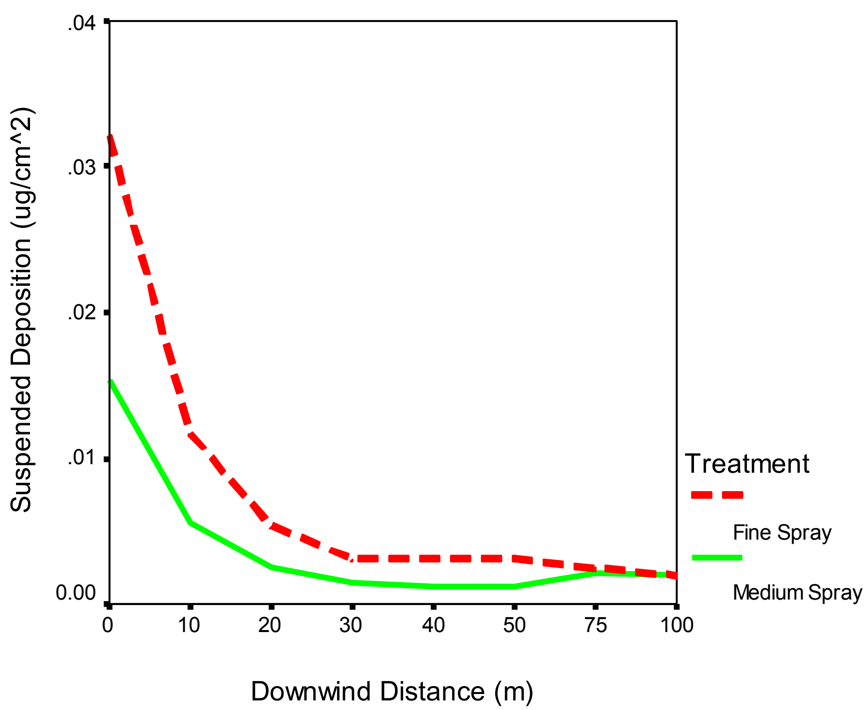

Figure 5: Suspended deposition (suspended monofilament samples) of fine and medium spray samples versus downwind distance.

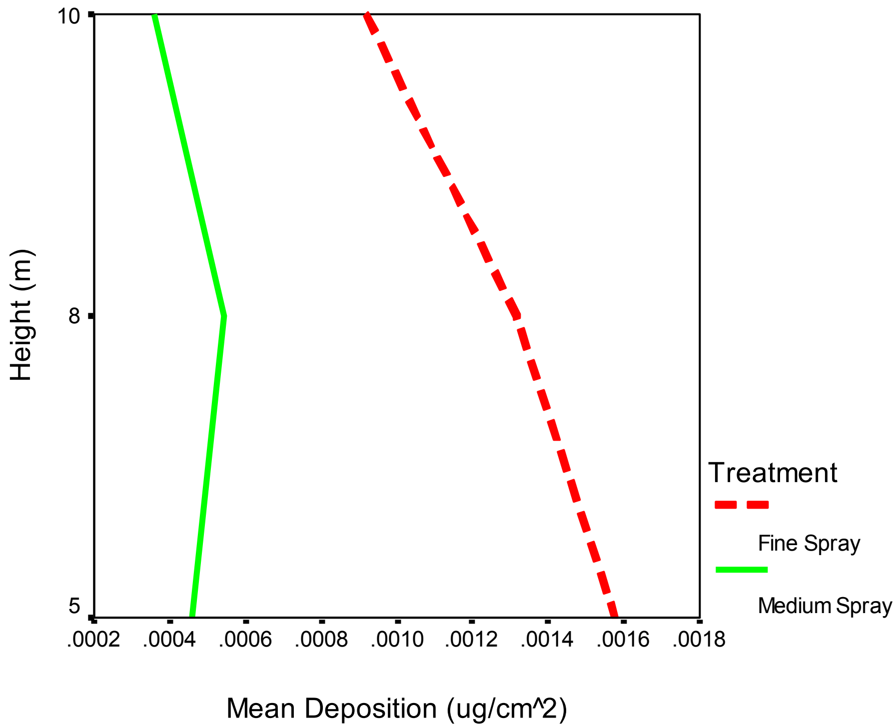

Figure 6: Elevated deposition at 50 meters downwind (tower monofilament samples) of fine and medium spray samples versus height.

Analysis of the effects of atmospheric stability on spray drift and deposition are complicated by other factors such horizontal and vertical wind speed. For example, replications 3 and 10 for treatment 2 both occurred during unstable conditions. Replication 3 had a horizontal wind speed of 0.1 mph along the sampling line and 1.6 mph upward, while replication 10 had a horizontal wind speed of 4.1 mph along the sampling line and 0.1 mph downward. Figure 7 is a plot of the deposition on the string samples by distance for each replication.

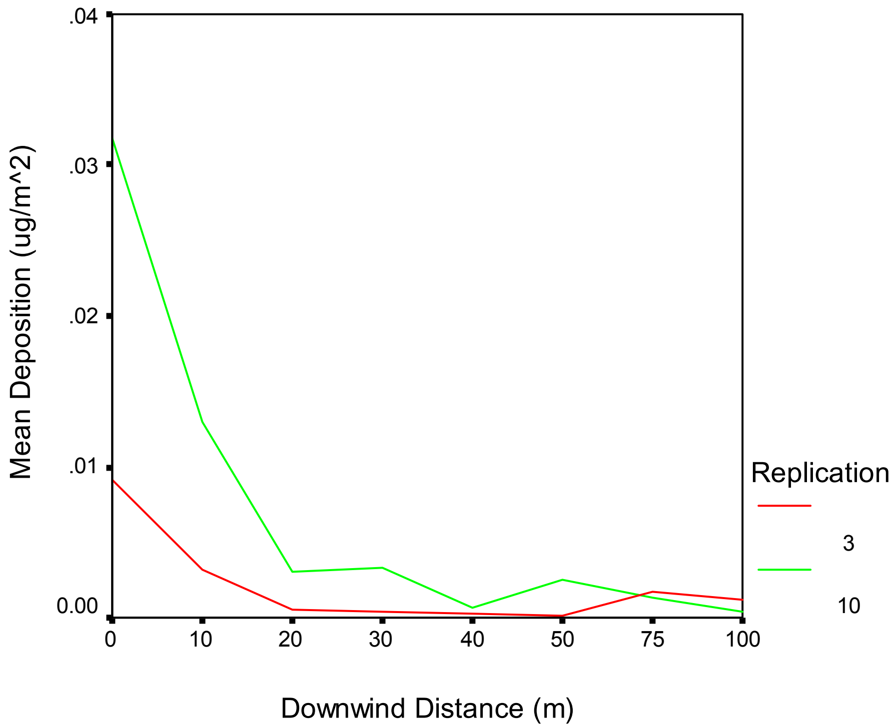

Figure 5: Suspended deposition (suspended string samples) of replications 3 and 10 under unstable conditions.

Most replications during the first day of testing had wind speeds that were very low and in a direction other than along the sampling line. Graphical analysis of both drift and deposition as a function of atmospheric stability does not result in any conclusive results. Further statistical analysis will be performed to determine the effects of atmospheric stability on both ground deposition and drift.

Conclusion

Results from this study showed that for the two regions monitored, the majority of stable to very stable atmospheric conditions and periods of temperature inversions occur between the hours of 6 p.m. and 6 a.m. Between the hours of 6 a.m. and 6 p.m. atmospheric stability tends to be unstable with a few occurrences of neutral conditions and even fewer cases of stable or inversion conditions. For location 1 only 57% of the days monitored had inversion conditions between the hours of 6 a.m. and 6:30 p.m. Similarly, only 65% of the days monitored at location 2 had inversion periods during these hours. For both locations almost half of the inversion periods recorded during these hours occurred after 4 p.m. The duration of these afternoon inversion periods was an order of magnitude greater than the duration of inversions in the morning and mid-day periods. In general, evening spraying would have the greatest probability of being influence by stable to very stable or inversion conditions.

Further Research

Future research efforts will include additional field studies similar to those mentioned previously in an effort to asses the effect of atmospheric stability on spray deposition and drift. The previous field work demonstrated the difficulty of planning samples during morning inversion or very stable periods. Any further field studies will likely be planned for late evening, as appropriate conditions tend to be more predominate during this time. Field trials will also be performed during unstable conditions to provide comparison data.

Additional research efforts will also include field testing of a recently obtained Aventech in-flight wind and temperature measurement system. This system was designed to measure wind speed and direction as well as temperature profile to provide an estimate of the stability ratio. Initial testing will consist of multiple trial flights over meteorological station 1 and comparison of measurements.

References

Agricultural Engineers Yearbook of Standards. 1983. S387.1. Test procedure for measuring deposits and airborne spray from ground swath sprayers. St. Joseph, Mich.: ASAE.

Barratt, R. 2001. *Atmospheric Dispersion Modeling – An Introduction to Practical Applications*. Sterling, VA. Earthscan Publications Limited.

Beychok, M. R. 1994. *Fundamentals of Stack Gas Dispersion*. 3rd Edition Newport Beach, CA. Milton R. Beychok.

Bird, S. L. 1995. A compilation of aerial spray drift field study data for low-flight agricultural application of pesticides. In *Environmental Fate of Agrochemicals: A Modern Perspective*. ed. M. L. Leng, E. M. K Loevey, and P. L. Zubkoff. Lewis Publishers, Chelsea, MI.

Cooper, C. D. and F. C. Alley. 1994. *Air Pollution Control: A Design Approach*. 2nd Edition. Prospect Heights, Illinois: Waveland Press, Inc.

Hoffmann, W. C. and Salyani, M. Spray deposition on citrus canopies under different meteorological conditions. Trans. ASAE 39 (1): 17-22. 1996.

MacCollom, G. B., W. W. Currier, and G. L. Baumann. 1986. *Journal of Economic Entomology* 79(2): 459-464.

Miller, D. R., T. E. Stoughton, W. E. Steinke, E. W. Huddleston, and J. B. Ross. 2000. Atmospheric stability effects on pesticide drift from and irrigated orchard. *Transactions of the ASAE* 43(5): 1057-1066.

Munn, R.E. 1966. *Descriptive Meteorology – Advances in Geophysics Supplement 1*. New York: Academic Press.

Pasquill, F. and F. B. Smith. 1983. *Atmospheric Diffusion: A Study of the Dispersion of Windborne Material from Industrial and Other Sources*. 3rd Edition. Chichester, West Sussex, England: Ellis Horwood Limited.

Seinfeld, J. H. and S. N. Pandis. 1998. *Atmospheric Chemistry and Physics – From Air Pollution to Climate Change*. New York: John Wiley & Sons, Inc.

Thistle, H. W. 2000. The role of stability in fine pesticide droplet dispersion in the atmosphere: a review of physical concepts. *Transactions of the ASAE* 43(6): 1409-1413.

United States Environmental Protection Agency Office of Air Quality Planning and Standards. 2000. Meteorological Monitoring Guidance for Regulatory Modeling Applications. EPA-454/R-99-005. Research Triangle Park, North Carolina.

United States Environmental Protection Agency Office of Prevention, Pesticides and Toxic Substances (OPPTS). 1998. Spray drift test guidelines – Spray drift field deposition. OPPTS 840.1200. EPA 712-C-98-112. March 1998.

Yates, W. E., N. B. Akesson, and R. E. Cowden. 1974. Criteria for minimizing drift residues on crops downwind from aerial applications. *Transactions of the ASAE* 17(4): 637-632.

Yates, W. E., N. B. Akesson, and H. H. Coutts. 1967. Drift hazards related to ultra-low-volume and diluted sprays applied by agricultural aircraft. *Transactions of the ASAE* 10(5): 628-632, 638.

Yates, W. E., N. B. Akesson, and H. H. Coutts. 1966. Evaluation of drift residues from aerial applications. *Transactions of the ASAE* 9(3): 389-393, 397.