Low-Level Atmospheric Temperature Inversions and Atmospheric Stability: Characteristics and Impacts on Agricultural Applications

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ABSTRACT

Drift from aerial application of crop protection and production materials is influenced by many factors. The applicator is responsible for considering these factors and adjusting application techniques, where applicable, to reduce the potential for drift as much as possible. In an effort to study the uncontrollable factors and provide guidance for agricultural applicators, this study monitored and documented atmospheric conditions at two locations. 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, however, almost half experienced inversion periods between the hours of 6 a.m. and 6 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. Based on these results, agricultural applicators should take caution when spraying in the morning or, most particularly, evenings, especially when wind speeds are below 2 m/s.

Keywords: Temperature inversion, spray drift, aerial application, agricultural aviation, atmospheric stability, USA

1. 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) and uncontrollable (wind speed, wind direction, atmospheric stability). It is the applicator's responsibility to consider and account for these factors to reduce the potential for drift. The atmosphere is the most uncontrollable factor requiring the applicator to make adjustment in real time based on observed conditions and past experience. Many product labels provide recommendations regarding meteorological conditions during application. Due to increased drift potential, many of these labels advise or require avoiding application during a temperature inversion (for example: BidrinXP, EPA Reg. No. 5481-552 and Roundup Original, EPA Reg.

No. 524-445). Applicators also have guidance in the form of county, state or national application manuals many of which (e.g. Kansas State and University of MN extension manuals) advise or require applicators to avoid applications during temperature inversions. Determining if a temperature inversion is present is usually accomplished through visual observation of low lying fog or smoke released from the aircraft. Typically, these methods are not sufficient to detect inversions or the presence of a very stable environment, especially for new or inexperienced applicators, thus the reason for this work which provides basic information and rule-of-thumb guidance with respect to temperature inversions and atmospheric stability. This study monitored and documented atmospheric conditions over a six month period at two locations in Texas. The measured meteorological data was used to relate low-level temperature inversion with respect to time of day, duration, and other associated meteorological conditions.

2. LITERATURE REVIEW

2.1 Temperature Inversions and Spray Drift

A temperature inversion occurs when temperature increases with height from the ground and can be caused by radiation cooling at the ground or horizontal movement of an air mass from a warm (ground) surface to a cooler surface (water) (Seinfeld and Pandis, 1998). Inversions are associated with minimal air mixing, or more stable atmospheric conditions, and thus generate the highest downwind concentrations from an effluent source (Thistle, 2000).

The body of research in this area, Yates et al. (1966 and 1967), MacCollom et al. (1986), Hoffmann and Salyani (1996), Miller et al. (2000), and Bird (1995), to name a few, support the idea of increased spray movement (i.e. drift) under temperature inversions and more stable environments. One of the major components lacking from these studies is documentation of time and duration of the measured stable and unstable temperature profiles. 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).

2.2 Stability Ratio and Temperature Profile

For field measurements of 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 recorded. The ASAE standard recommended using stability ratio (Equation 1), which is a function of the temperature profile and wind speed, as an indicator of atmospheric stability. As the majority of the literature linking spray drift to stability or inversions use the stability ratio, it is used in this work to group the measured stability data.

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

T_{z1} and T_{z2} are temperatures (°C) at heights z_1 and z_2 and u is the wind speed (cm/s) measured at a height equidistant from z_1 and z_2 on a log scale. Yates et al. (1974) used heights of 2.4 and 9.8 m (8 and 32 feet) for z_1 and z_2, respectively, and a wind speed measurement height of 4.9 m (16 feet). The ASAE standard (ASAE 1983) recommends z_1 and z_2 heights of 2.5 and 10 m, with wind speed measurement height set at 5 m.

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. Notice that positive stability ratio values correspond to higher temperature at higher altitude (i.e. an inversion) and are associated with stable and very stable conditions.

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

3. OBJECTIVE

The objective of this work was to monitor low level inversions along with other meteorological data to provide applicators with a basic understanding of their diurnal behavior and ‘rules-of-thumb’ for determining their presence.

4. METHODOLOGY

4.1 Meteorological Monitoring Equipment

Meteorological towers were equipped and positioned to monitor and document the meteorological conditions at two separate geographical locations. A set of meteorological monitoring towers were constructed to measure and record atmospheric temperature and wind speed profiles from ground level to 10 m. Shielded thermistors (Campbell Scientific 107 Temperature Probe, Logan, Utah) 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 0.1 °C of each other using a stirred ice bath. Temperature measurements were taken at 0.5, 2.5, 5, 7.5, and 10 m. Wind speed measurements were taken using 3-cup anemometers (R.M. Young Wind Sentry Anemometer, Traverse City, MI) at 2.5 and 10 m. A reading at 5 m was not taken as only 2 anemometers, per tower, were available. Wind direction (R.M. Young Wind Sentry Vane, Traverse City, MI) and net solar radiation (Campbell Scientific LI200X Pyranometer, Logan, Utah) measurements were taken at 2.5 m. Each monitoring station was controlled using a Campbell Scientific 10X datalogger along with Campbell Scientific PC208W operating software. The recorded data was logged every 60 s. Data was collected beginning the first week of May 2003 through the end of October 2003. The station erected near College Station, TX (30° 31’ 24.25” N, 96° 23’ 57.88” W; Elevation 67 m) is denoted as Station 1 and the station erected near Wharton, TX (29° 19’ 2.10” N, 96° 13’ 20.39” W; Elevation 33 m) is denoted as Station 2. The stations are approximately 137 km apart with station 2 being representative of a coastal location, subject to on and off shore flow while Station 1 is an interior location.

4.2 Data Reduction and Analysis

The following parameters were calculated as part of the initial raw data reduction process. Statistics were calculated for each hour of collected meteorological data and used in the analysis processes.

4.2.1 Wind Speed Statistics

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

4.2.2 Stability Ratio

The stability ratio was calculated based on the wind speed at 5 m and temperature at 2.5 and 10 m using Equation 1. This calculation required a value for wind speed at 5 m. As wind speed was not measured at 5 m, it was extrapolated using the wind speed values at 2.5 and 10 m and 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 m, respectively. With p determined, the wind speed at 5 m can be calculated using either of the measured wind speed values. .

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

where:

z_1, z_2 = elevation 1 and 2, m
u_1, u_2 = wind speeds at z_1 and z_2, m/s
p = exponent, unitless

4.2.3 Atmospheric Stability Classification

Atmospheric stability classification was determined using the classification system based on the stability ratio as suggested by Yates et al. (1974) (Table 1).

4.2.4 Data Analysis

The determination of the Yates stability classification groups provided a general "rule of thumb" for estimating atmospheric stability. A relationship between time of day and probability of atmospheric stability class was developed for each station. For the analysis of daytime inversions, the data from each station was filtered by time of day. Only inversions that occurred between 6:00 a.m. Central Standard Time (CST) and 6:30 p.m. (CST) were considered in the analysis. This filtering process removed the extended nighttime inversions from the data set, allowing for analysis of the inversion events that occurred during typical hours when spraying would normally occur. The inversion data were 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.). The 6 a.m. and 6:30 p.m. times were chosen based on the time when the measured solar radiation levels either exceeded or was less than zero, respectively.

This provided an overview of when each of the atmospheric stability classes was likely to occur. Additionally, the data was examined for inversion periods that occurred during daylight hours.

For each inversion period indentified, the time of occurrence, duration and strength (magnitude of temperature gradient) were recorded.

5. RESULTS

The wind speed statistics for the Yates et al. (1974) atmospheric stability classes for each station are shown in Table 2.

Table 2. Wind Speed at 2.5 m height (mean ± standard deviation) for each station.

	Yates et al. (1974) Atmospheric Stability Classes			
Wind Speed at 2.5 m (m/s)	Unstable	Neutral	Stable	Very Stable
Station 1 Mean ± SD	2.4 ± 1.2	3.9 ± 1.5	1.9 ± 0.7	0.7 ± 0.4
Station 2 Mean ± SD	2.8 ± 1.5	4.1 ± 1.7	2.0 ± 0.8	0.7 ± 0.5

The wind speed statistics were nearly identical for both locations. Based on the data shown in Table 2 a general rule of thumb is that wind speeds at 2.5 m above 2 m/s indicate either unstable or neutral conditions, while wind speeds below 2 m/s indicate very stable (or inversion) type conditions. Grouping all inversions by station, regardless of stability class, on average the wind speed is 1.7 ± 0.9 m/s and 1.6 ± 0.8 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 1 and 2. The results from these graphs 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 conditions (inversions), and thereby have the greatest potential for possible drift.

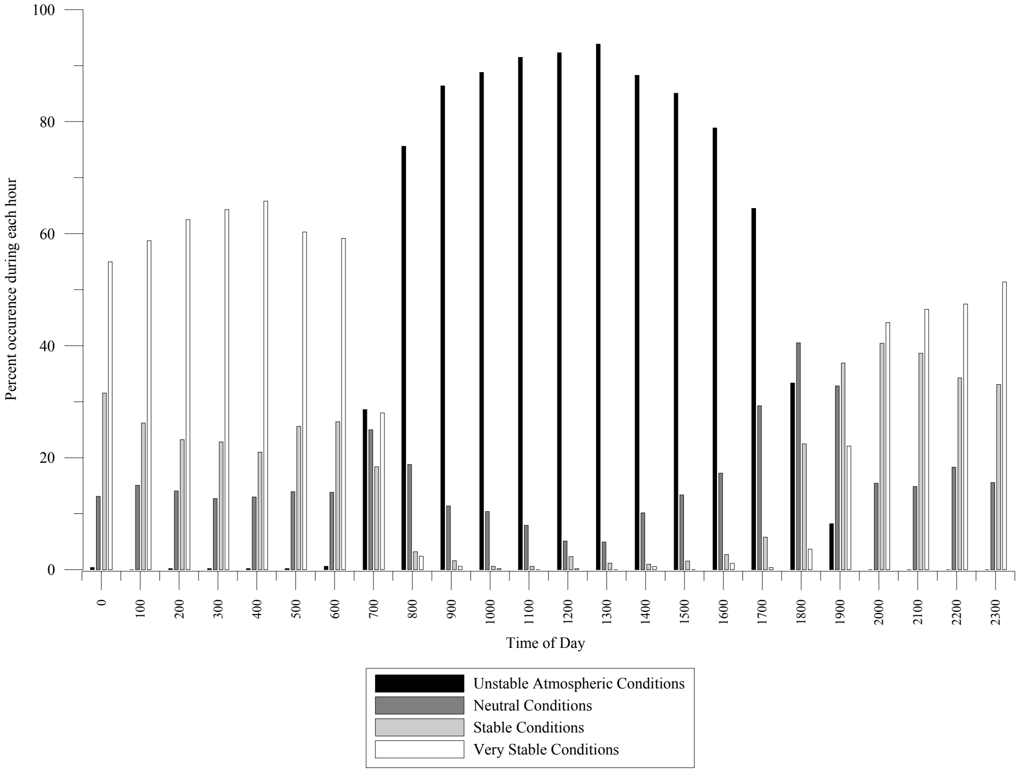

Figure 1. Probability distribution of Yates et al. (1974) atmospheric stability classes by time of day for Station 1.

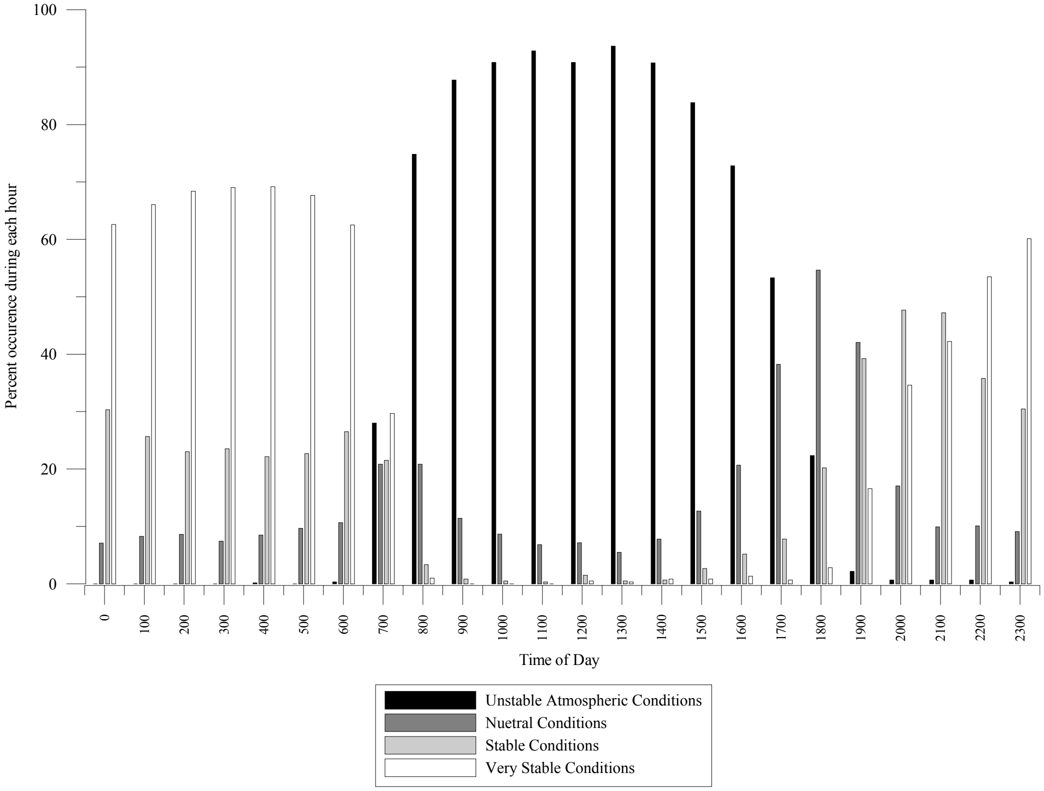

Figure 2. Probability distribution of Yates et al. (1974) atmospheric stability classes by time of day for Station 2.

Overall, 78 (57%) of the 136 days monitored by Station 1 had periods of inversion during one of the specified time periods. Similarly, 101 days (65%) of the 155 monitored by Station 2 had periods of inversion during one of the specified time periods. Summary statistics for inversion periods occurring during each of the three time periods, by station, are shown in Table 3.

Table 3. Summary statistics of days experiencing inversion conditions between the hours of 6:00 a.m. – 6:30 p.m. (CST) for Stations 1 and 2.

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

Station 1 recorded 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 Station 2, 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.

Inversions occurring in each of these time periods were further examined for the strength and duration of the inversion event. For each time period, the average time of occurrence, duration, and strength (magnitude of the temperature difference) as well as standard deviations were determined (Tables 4 and 5).

Table 4. Characteristics of daytime inversions by time period for Station 1.

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

*Measured difference between 2.5 m and 10 m

Table 5. Characteristics of daytime inversions by time period for Station 2.

Time period	Average Start Time	Duration (min) (mean ± s.d.)	Strength* (ΔT °C) (mean ± s.d.)
Morning	8:22 a.m.	17 ± 20	0.10 ± 0.05
Mid-day	1:24 p.m.	32 ± 52	0.15 ± 0.15
Evening	6:11 p.m.	236 ± 355	0.24 ± 0.28

*Measured difference between 2.5 m and 10 m

Based on the data shown in Tables 4 and 5, 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 loses 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 later by other inversions. This is reflected by the duration times for the evening inversions. These times, as presented in Tables 4 and 5, exceed the time window of the evening period as they reflect the total duration of the inversion event, which in many cases extended well into the nighttime hours.

6. CONCLUSIONS

For the two locations monitored during this study, 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 very stable (inversion) conditions. For Station 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 Station 2 had inversion conditions during these hours. For both locations almost half of the inversions recorded during these hours occurred after 4 p.m. The duration of these afternoon inversions was an order of magnitude greater than the duration of inversions in the morning and mid-day periods. At station 1, 96% of the inversions had mean wind speeds bellows 2 m/s and at station 2, 88% of the inversions had mean wind speeds below 2 m/s. Though there was no significant difference in the occurrence of inversions between the two stations, it is likely that the coastal nature (i.e. more constant and sustained coastal breeze) of station 2 was responsible for the greater percentage of inversion events with wind speeds greater than 2 m/s. In general, evening spraying would have the greatest probability of being influenced by stable to very stable or inversion conditions. Based on these results, agricultural applicators should take caution when spraying in the morning or, most particularly, the evenings, especially when wind speeds are below 2 m/s.

7. DISCLAIMER

Mention of a commercial or proprietary product does not constitute an endorsement for its use by the U. S. Department of Agriculture.

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