Atmospheric Stability Intervals Influencing the Potential for Off-Target Movement of Spray in Aerial Application

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Abstract

A tower was equipped with temperature and wind-speed sensors at different heights to monitor weather conditions needed to quantify atmospheric stability throughout the day. Data presented in this study showed consistent patterns of atmospheric stability occurring primarily between the hours of 18:00 and 06:00 hrs during summer months on clear days. Further, our results verified correctness of the three-degree rule in Arkansas when spraying on clear days in the summer months. This study is informative for pilots and farm managers to schedule aerial application assuring that spraying will not occur under stable atmospheric conditions to avoid off-target drift.

Keywords

Aerial Application; Spray Drift; Temperature Inversion; Atmospheric Stability; Stability Ratio; Crop Protection

Introduction

Crop protection materials and harvesting aids applied from both aircraft and ground sprayers can drift off-target due to many factors such as nozzle type and orientation, spray pressure, and application height. Droplet size, which is influenced by nozzle and spray formulation interaction, is a significant factor for near-field off-target drift (Ozkan, 1998). Uncontrollable weather factors must also be considered, and it is incumbent on the applicator to schedule application during periods that do not exacerbate off-target drift or off-target movement of spray. For good environmental stewardship from aerial application of crop protection materials, it is essential that the applicator avoid application under 'stable' atmospheric conditions when a temperature inversion is likely to occur. Spraying must not occur where a temperature inversion prevents the spray cloud settling within the treated area (FAO, 2001). The detrimental effects on cotton of spraying 2, 4-D to rice or pastures under conditions of a temperature inversion have been documented (Bennett, 2006). Based on field and extension reports the increased number of drift complaints in East Arkansas were most likely the result of multiple applications of 2,4-D under stable atmospheric conditions. Under those conditions, a parcel of air cannot rise and disperse, but it can move laterally in the light variable winds typical of a surface inversion (Ramsey, 2001). The plumes of small droplets remaining suspended in air is dispersed through the atmospheric boundary layer in much the same manner as other air pollutants (Stoughton et al., 1997). A spray layer applied under stable conditions is thus "ready to move" off target when the wind picks up (Bennett, 2006). Basic studies have been performed to quantify the mechanisms and to model increase in wind speed due to morning heating of the atmospheric boundary layer (Lapworth, 2006). Although not indicated as an example application, these relationships also have a direct effect on when it is safe to spray crop protection materials. Mahrt et al. (1998) attempted to characterize weakly stable, transition-stable, and very stable nocturnal boundary layer regimes in a heavily instrumented set of experiments as a function of several

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factors including wind. Although aerial spraying does not typically occur at night, these relationships could be useful in examining spray cloud movement from nocturnal ground spraying. Miller and Stoughton (1999) actually tracked plumes of small droplets as a function of atmospheric stability. As expected, the time that it took for droplet dispersal was primarily controlled by atmospheric stability.

Surface temperature inversions occur during night-time surface cooling and until morning surface heating (Beychock, 1994; Ramsey, 2001). These conditions usually occur at sunset to just after sunrise, under windless to low wind conditions, and under clear to partly cloudy skies. Other indicators are the presence of ground fog (if sufficient humidity exists), dust hanging over a roadway, smoke from a chimney forming a layer, and dew or frost (also if sufficient humidity exists). However, many of these indicators illustrate the 'potential' for temperature inversions and duration of these events can be highly variable. For the latitude of College Station, TX, Fritz et al. (2008) indicated that stable atmospheric conditions (unfavorable for spraying) occurred when wind speeds were 2.0 m s-1 or below. The authors also documented that daytime (06:00 to 18:30) temperature inversions occurred between 57 and 65% of the monitored days.

Some States in the US where aerial application is prevalent have adopted guidelines for management of spray drift from ground and aerial applications, but recommendations vary widely and in scope regarding spray application under conditions favorable for temperature inversion or stable atmosphere. Section 219.06 of Mississippi applicators licensing rule (MDAC, 2016) states "Smoke and/or other suitable means shall be used to detect inversion conditions and determine wind direction and speed." This refers to the direction of smoke as an indicator of whether it is safe to spray. A guideline from Australia (CSIRO, 2002) indicates that the presence of an inversion can also be indicated by driving a vehicle along a dusty track and observing movement of dust, and the EPA has proposed a pesticide applicators rule that requires applicators show proficiency in use of smoke generators for determining off target movement of spray (Wiggins, 2015).

Because of concerns such as those outlined by Bennett (2006), guidelines in Arkansas have been revised to include quite specific language concerning conditions to avoid spraying during an atmospheric temperature inversion. A rule from the Arkansas State Plant Board (ASPB, 2008), states that "Herbicide applications may not be made under conditions where the spray may possibly be entrained in an inversion layer." The regulation goes on to state "As an indicator that an inversion is unlikely to exist, the applicator shall record the ambient temperature measured at the field of application for each application. Inversions are much less likely to exist if the temperature has increased three (3) degrees Fahrenheit from the morning low at the time of application for applications made before noon or has not decreased more than three (3) degrees Fahrenheit from the afternoon high for applications made after noon." It is not clear however, where information to develop these guidelines originated, and no seasonal dependency was implied for the recommendation. It would thus be useful and instructive to document the time and duration of stable atmosphere and temperature profiles on a seasonal basis to present better guidelines for agricultural pilots. By using an instrumented tall tower, temperature and wind profiles that indicate both the presence of surface and aloft temperature inversions and ultimately, atmospheric stability known to influence off-target movement of spray, could be determined. This study presents data from towers used to calculate stability ratios. These data can help facilitate recommendations on times of day that are likely to be of concern when spraying crop protection materials.

Objectives

Objectives of this study were

1.To measure weather variables on an instrumented tower and use these data to determine temporal atmospheric stability.

2.To use atmospheric stability criteria from example periods representing a range of conditions to determine times of day and weather conditions favorable for a stable atmosphere.

3.Using stability criteria, develop guidelines for aerial applicators on times of day, wind conditions, air temperatures, and times of year to avoid spraying under stable atmospheric conditions

Materials and Methods

A tall tower was set up at the USDA ARS CPSRU Mechanization Research Farms, Stoneville, MS (Figure 1). The tower was equipped with Omega 44000 series precision thermistors of 0.1% interchangeability to measure air temperatures, Qualimetrics model 2030 anemometers to measure wind speed, and a Met-One 024A wind direction sensor. The temperature sensors were placed at 4.6, 9, 14, 18.3, 23, and 27.4 m for temperature; 4.6, 12, 20, and 27.4 m for monitoring wind speeds.

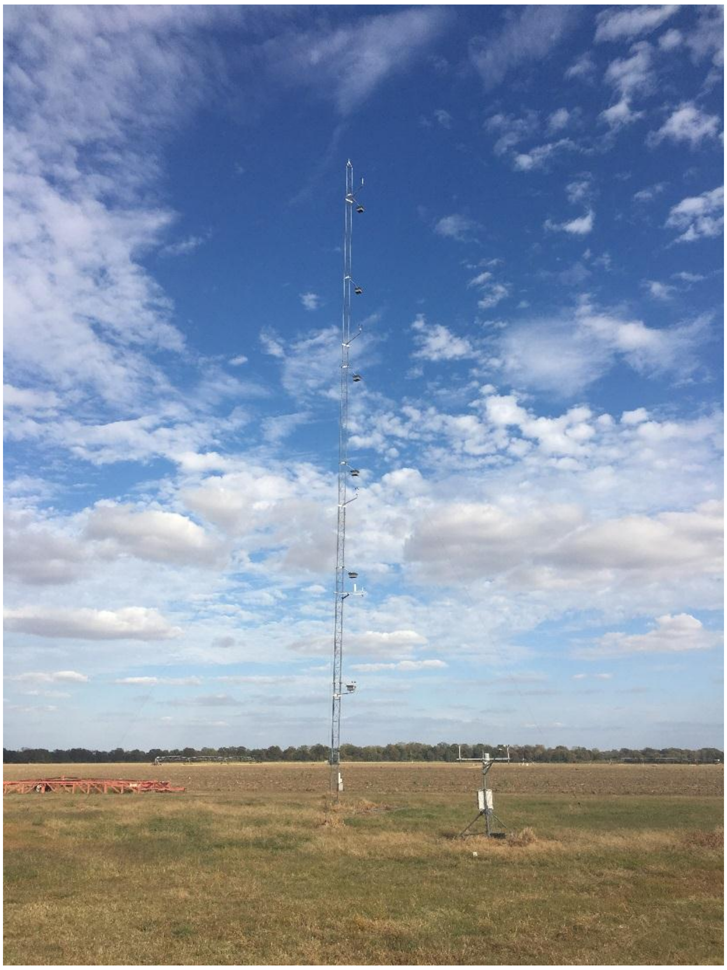


FIGURE 1. TALL WEATHER TOWER FOR DATA ACQUISITION.

A Campbell CR-21X micrologger was used for data acquisition and was setup in pulse counting mode for the wind speed sensors. The CR-21X was programmed in a half-bridge mode with precision completion resistors to measure output from the thermistors using 5000 mv excitation. The wind direction sensor also utilized the precise excitation voltage. Weather data were obtained from April through October 2004 and read every five minutes. These data were periodically downloaded from data cans for further processing using a custom-designed program written in SAS 8.2 (SAS Institute, Cary, NC, USA). This program created a spreadsheet file from raw data for each block of downloaded data, and data files for each month were created. Data read every five minutes were averaged over a one hour period and a resulting spreadsheet file was regenerated using a custom routine programmed in Matlab® R2010a (Mathworks, Natick, MS USA).

Using the collected meteorological data, the Stability Ratio (SR) (Munn, 1966) was calculated as:

$$SR = \frac{T_{z_2} - T_{z_1}}{WS_{z_3}^2} \cdot 10^5 \tag{1}$$

where T_{Z_1} and T_{Z_2} are temperature (oC) at height z1 and z2 and WS_{Z_3} the wind speed (cm/sec) measured at a height of z3 between z1 and z2,, which is the measured equidistant between z1 and z2 on a log scale. Yates et al. (1974) used heights of 2.4 and 9.8 m for z1 and z2, respectively, and a wind speed measurement height of 4.9 m.

To calculate SR, temperatures were measured at 4.6 m and 9 m for T_{Z_1} and T_{Z_2} . Wind speed WS_{Z_3} was measured at 4.6 m. This height was not equidistant between the two temperature levels for strict application of Equation (1), but this discrepancy will be addressed later. Diurnal atmospheric stability can be determined based atmospheric stability classes as illustrated Table 1 for calculation of stability ratio.

TABLE 1. ATMOSPHERIC STABILITY CATEGORIES AS A FUNCTION OF STABILITY RATIO (SR) RANGES (YATES ET AL., 1974)

Atmospheric Stability Category	SR 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

Results and Discussion

Before evaluating ASPB (2008) criteria for daytime spraying at transition times between stable and unstable states, it is instructive to determine the likelihood that safe spraying could occur during night-time hours. Night spraying is sometimes desirable for ground spraying, although aerial spraying at night is primarily conducted in the Southwest U.S. deserts, far from neighboring areas. Data presented in the study presented herein showed consistent patterns of atmospheric stability primarily between the hours of 1800 and 0600 in the summer months, which is also consistent with a study in College Station, TX (Fritz et al., 2008). Figure 1 illustrates a 63% average probability of either stable or strongly stable conditions occurring between 1900 and 0600 over the period of 14 April 2004 to 6 November 2004. Neutral conditions occurred 23% of the time and unstable conditions occurred 14% of the time. Probability of either stable or strongly stable conditions over the logging period was 63%, which compares well with 57 % and 65% of days monitored in Texas over two different stations. Enough wind at night can cause sufficient mixing and create unstable atmospheric conditions suitable for spraying. It is cautioned, however, that ground spraying during high winds can exacerbate off–target near-field drift.

Figures 3 through 7 illustrate weather data and stability ratios representing a range of atmospheric combinations over a single season. As Equation (1) is mechanistic and simply requires combinations of wind and temperature values to determine atmospheric stability, five days over the cropping season were chosen to illustrate a range of conditions that would be encountered by aerial applicators to make decisions on whether to spray based on results obtained from Equation (1). Diurnal changes that influence atmospheric stability were clearly illustrated within these periods. Table 2 shows transitional periods and stability ratios for the five selected dates. For 15 April 2004 (Figure 2), the transition point from stable conditions (unfavorable for aerial application) to unstable conditions in the morning hours occurred between about 06:00 and 07:00. This response characterizes a typically smooth transition between states as categorized in Table 1. It is interesting to note that stable or very stable conditions were still prevalent at relatively high wind speeds (between 1.25 to 1.60 m s-1). In the evening, stable conditions began to occur after about 18:00 (6:00 PM) at very low wind speed (0.23 m s-1) and 4.6 m height.

The plot of 15 July (Figure 2) indicates more variable wind, although diurnal temperature cycles followed a similar smooth pattern as did the 15 April plot. Within the morning hours normally indicating stable conditions, fluctuations between stable and unstable conditions inversely tracked wind speed fluctuations, as would be expected. Evening hours showed transition to stable conditions after 18:00 as in the 15 April plot, and stable conditions were clearly in place when wind speed decreased to 0.67 m s-1. The 16 August plot (Figure 5) shows a similar trend to the July plot except that the ‘strength’ of late afternoon stability at 19:00 was not as great. Wind speed was higher (1.52 m s-1) as compared with 1.51 m s-1 in July. The atmosphere was still classified as ‘stable’ at a wind speed of 1.52 m s-1 on 16 August.

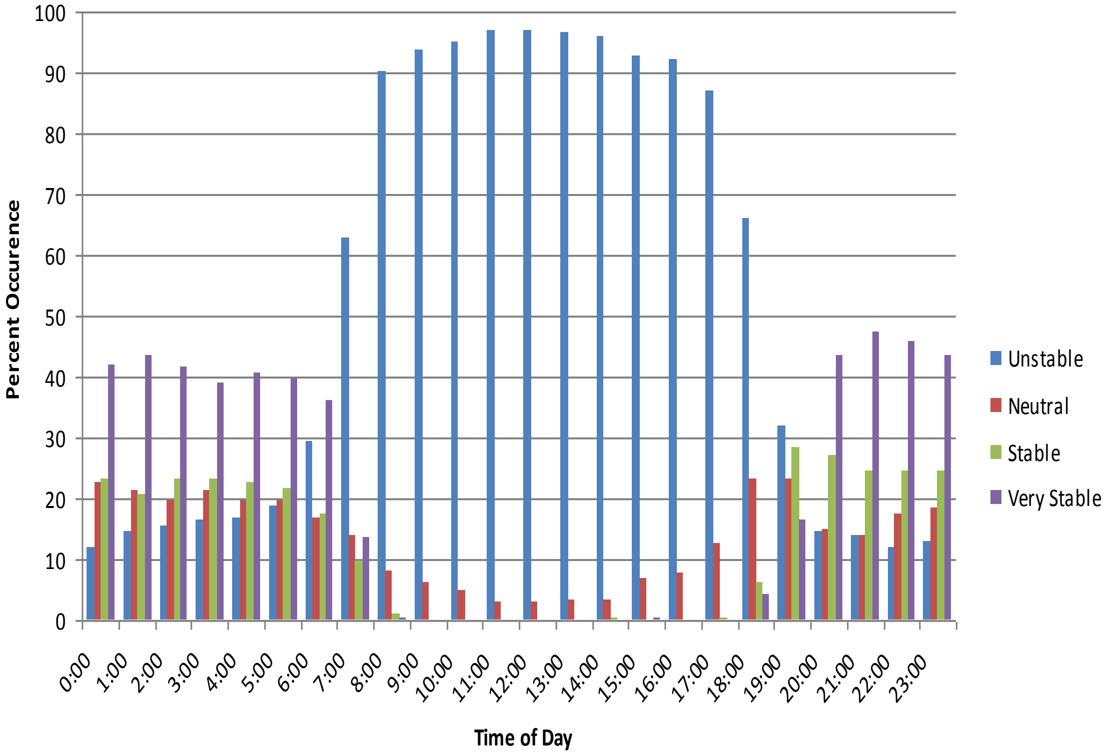


FIGURE 2. PROBABILITY DISTRIBUTION OF ATMOSPHERIC STABILITY CLASSIFICATION BY TIME OF THE DAY BETWEEN 14 APRIL, 2004 AND 6 NOVEMBER, 2004.

Not until 08:00 were neutral conditions established (Table 2) for either 15 September or 15 October (Figures 6 and 7, respectively). Figure 7 illustrates weakly stable conditions during the early morning hours after midnight because of higher wind speeds hovering in the 1.11 m s-1 range until 08:00. The transition to stable conditions in the evening occurred after 1800 as the wind speed measured at 4.6 m dipped to 0.89 ms-1. The 15 September plot indicated high winds continuing until midnight and corresponding neutral conditions. Stable conditions became apparent as the wind speed slowed at night.

Table 2 indicates that the criteria for unstable or neutral conditions suitable for spraying were satisfied at 07:00 on both 15 July and 16 August. Criteria for neutral or unstable conditions were not satisfied until 08:00 in April, September, or October. As indicated herein, a rule written for Arkansas (ASPB, 2008) indicates a required 1.67 º C temperature rise in the morning hours before aerial spraying can occur safely (in neutral or unstable atmosphere). Temperature rise as specified by the ASPB rule to achieve these conditions was exceeded on all example days except 15 April. This could be a significant finding as aerial spraying for burn-down herbicide customarily occurs in the late winter and early spring, so pilots may thus need to delay spraying in the morning during the cooler months. Stable or very stable conditions returned by 1900 in July and August and by 18:00 in April and October. The values for September are not shown because higher winds kept conditions unstable during this period (Figure 6). The ASPB rule of stopping spray before a 1.67 º C temperature decrease appeared to be exceeded for all example dates shown in Table 2 except April. However, an unstable condition was still indicated on 15 July when this value was exceeded indicating that a 1.67 º C reduction was rather conservative. Likewise, the temperature reduction result almost matched a 1.67 º C for 15 August while unstable conditions still prevailed. For July and August however, the ratio indicating instability was rather weak (-0.40 and -0.41 respectively) at 18:00. In April, wind was very calm in the afternoon and atmosphere became very stable rapidly before air temperature measured at 4.6 m decreased appreciably. The transition from stable to very stable conditions thus indicated high sensitivity to small temperature inversions after 17:00.

TABLE 2. ATMOSPHERIC STABILITY RATIOS FOR FIVE SELECTED DATES USING AIR TEMPERATURES MEASURED AT 4.6M AND 9.8M. TEMPERATURE CHANGE INDICATED IN BOLD DUE TO CHANGE OF STATE CAN BE COMPARED WITH GUIDELINES FOR REQUIRED 1.67 º C TEMPERATURE DIFFERENCE (INCREASE IN MORNING; DECREASE AT NIGHT) TO ASSURE UNSTABLE CONDITIONS (ASPB, 2008).

Julian Day	**Date**	**Time**	**Time offset from sunrise/sunset (min)**	**Stability Classification**	**Stability Ratio**	**Wind Speed (m/s)**	**Air Temperature (º C), 4.6m**	**Temperature Change (º C)**	**ASPB Criteria Met?**
106	15-Apr	06:00	-33	V-stable	3.67	1.23	9.50	0.40	
		07:00	27	Stable	0.76	1.64	11.20	2.10	
		08:00	87	Neutral	-0.08	2.73	13.70	**4.60**	Yes
		17:00	-155	Unstable	-1.70	0.23	24.20	-0.05	
		18:00	-95	V-stable	4.90	0.23	23.30	**-0.92**	No
197	15-Jul	06:00	-5	V-stable	4.90	0.39	24.70	0.33	
		07:00	55	Unstable	-0.39	1.13	27.00	**2.69**	Yes
		18:00	-134	Unstable	-0.40	1.98	34.00	-1.94	
		19:00	-74	V-stable	4.90	0.67	31.60	**-4.34**	Yes
229	16-Aug	06:00	-27	V-stable	4.90	0.23	14.90	0.03	
		07:00	33	Unstable	-1.70	0.23	17.20	**2.30**	Yes
		08:00	93	Unstable	-1.70	1.22	22.00	7.14	
		18:00	-108	Unstable	-0.41	2.26	29.00	-1.62	
		19:00	-48	Stable	1.06	1.52	26.30	**-4.34**	Yes
259	15-Sep	07:00	13	V-stable	2.66	0.97	21.50	0.83	
		08:00	73	Neutral	-0.08	3.76	24.40	**3.51**	Yes
289	15-Oct	07:00	-8	Stable	0.63	1.93	7.82	0.44	
		08:00	52	Neutral	0.03	2.11	10.11	**2.72**	Yes
		17:00	-89	Neutral	-0.05	2.86	21.91	0.51	
		18:00	-29	Stable	0.99	1.29	19.49	**-2.66**	Yes

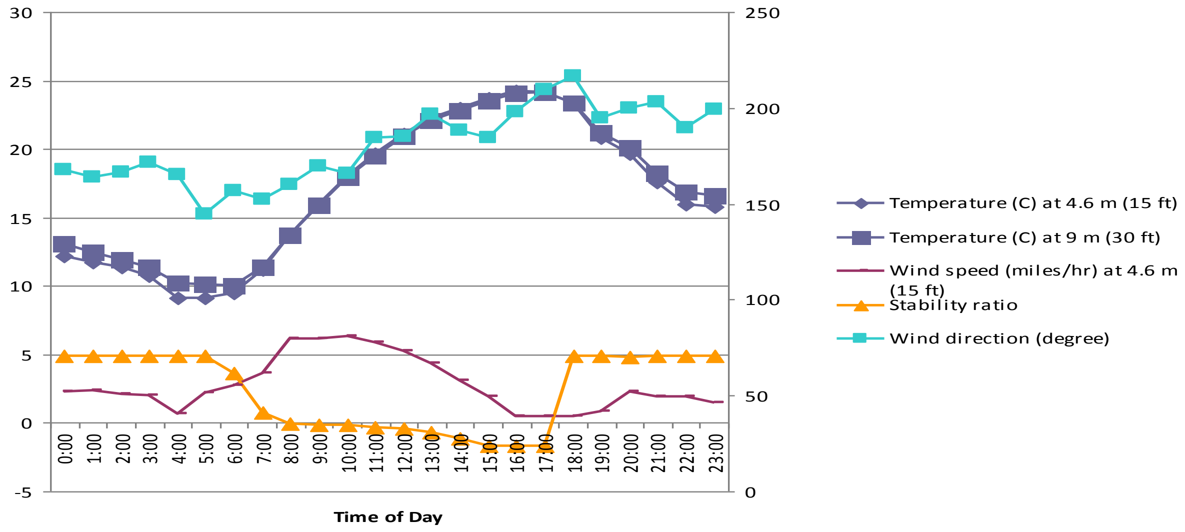


FIGURE 3. STABILITY RATIOS, TEMPERATURES, AND WIND FOR 15 APRIL, 2004. RIGHT AXIS IS THE SCALE FOR WIND DIRECTION (1 MILE/HR = 0.447 M/S).

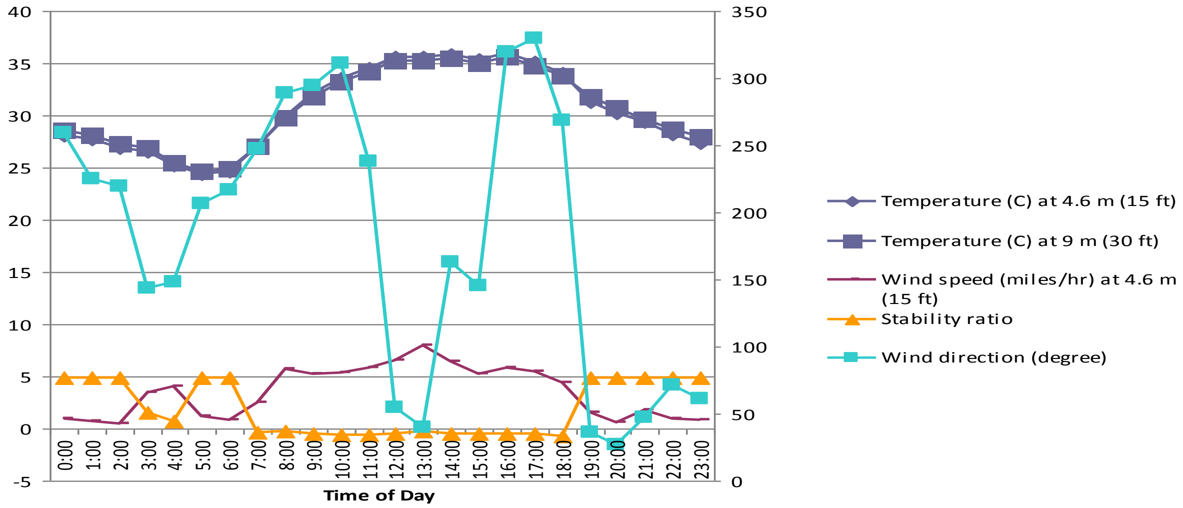


FIGURE 4. STABILITY RATIOS, TEMPERATURES, AND WIND FOR 15 JULY, 2004. RIGHT AXIS IS THE SCALE FOR WIND DIRECTION (1 MILE/HR = 0.447 M/S).

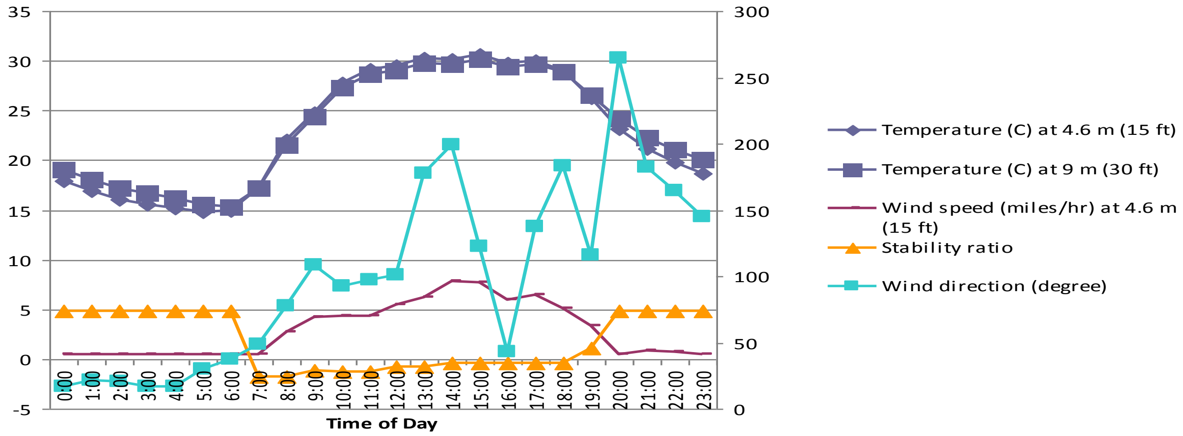


FIGURE 5. STABILITY RATIOS, TEMPERATURES, AND WIND FOR 16 AUGUST 2004. RIGHT AXIS IS THE SCALE FOR WIND DIRECTION (1 MILE/HR = 0.447 M/S).

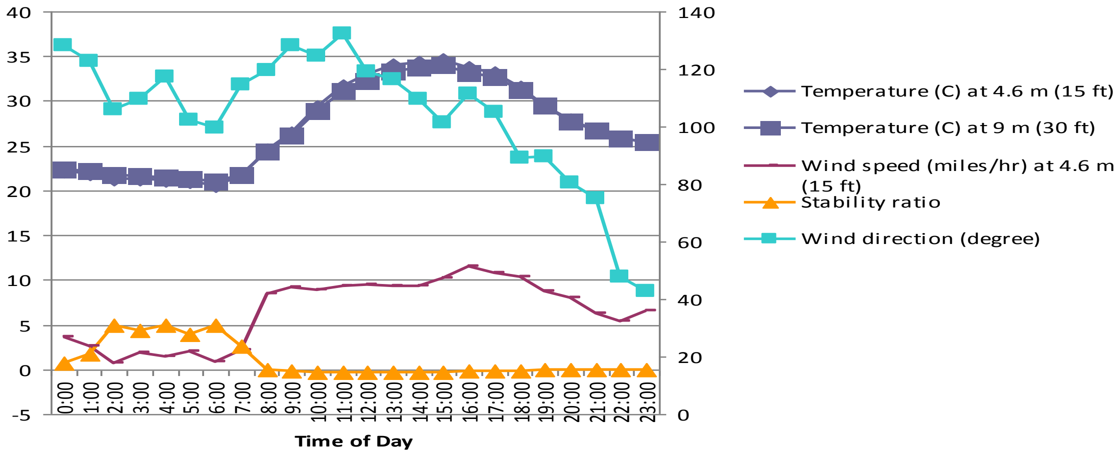


FIGURE 6. STABILITY RATIOS, TEMPERATURES, AND WIND FOR 15 SEPTEMBER, 2004. RIGHT AXIS IS THE SCALE FOR WIND DIRECTION (1 MILE/HR = 0.447 M/S).

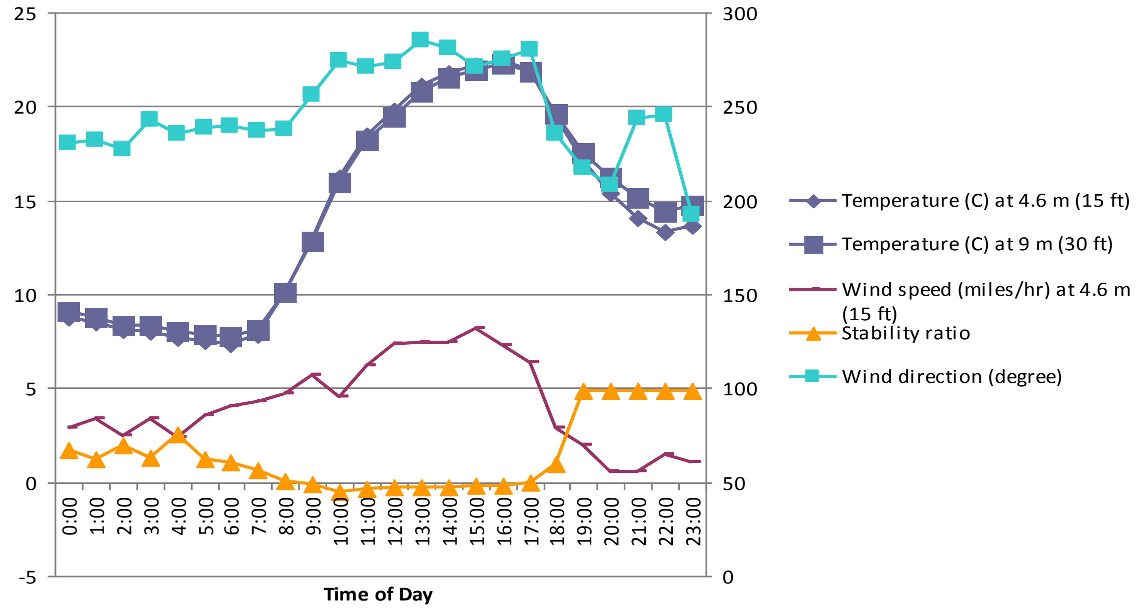


FIGURE 7. STABILITY RATIOS, TEMPERATURES, AND WIND FOR 15 OCTOBER, 2004. RIGHT AXIS IS THE SCALE FOR WIND DIRECTION (1 MILE/HR = 0.447 M/S).

Weather Considerations and Strict Application of the Stability Equation

There was somewhat of a discrepancy between wind speeds indicating stable atmosphere from Stoneville and College Station, TX. At the Stoneville location (and as discussed), wind speeds measured at the 4.6 m height in the morning typically ranged from 1.25 to 1.60 m s-1 during the transition from stable to unstable conditions (the former being unfavorable conditions for spraying). The College Station study indicated higher wind speed (2.0 ms-1), but this value was interpolated at 5.0 m based on wind speeds measured at 2.5 and 10 m heights. This was done to assure that Equation (1) would be used as intended (with wind speed measured at a height between the two temperatures). The equation used to interpolate that value (Fritz et al., 2008) is presented by Cooper and Alley (1994) as a logarithmic interpolation:

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

where

z_1, z_2 = elevations 1 and 2 (m)

u_1, u_2 = wind speeds at z_1 and z_2, m s^{-1}

p = exponent, unitless

To determine relative accuracy of this equation, data from the weather tower obtained at two heights and the interpolation equation (Equation (2)) were used to find wind speed at the intermediate height for comparison with measured values.

An example set of readings and calculations for two pairs are illustrated in Table 3. For each pair, the exponent p was determined and then used to calculate the wind speed at intermediate heights using wind speed at both the lower height (Z1) and the higher height (Z2). Results illustrate that results differed depending on which height was used in the log interpolation equation, but in no case did the interpolated value exceed the measured value by more than 6.3%. This indicates that the interpolated wind speed below which stable conditions unfavorable for spraying occurred (Fritz et al., 2008) at College Station TX (2.0 m s-1 vs. 1.25 - 1.60 m s-1 at Stoneville) was probably not too high an estimate for that location.

TABLE 3. WIND SPEEDS INTERPOLATED FROM TOWER DATA USING LOG FUNCTION (COOPER AND ALLEY, 1994). CALCULATED VALUES ARE IN BOLD.

U_1	1.2	2.0
U_2	2.5	3.4
Ratio of U	2.1	1.7
Z_1	4.6	12.2
Z_2	19.8	27.4
Ratio of Z	4.33	2.25
P	0.50	0.62
Interpolation of wind speed at intermediate height		
Desired height from which to obtain wind speed (m)	12.2	19.8
Actual (target) wind speed (m s^{-1})	2.02	2.56
Interpolated wind speed using wind speed at Z_1	**1.57**	**2.47**
Interpolated wind speed using wind speed at Z_2	**2.01**	**2.73**
% difference from actual wind speed (using Z_1)	28.7	3.5
% difference from actual wind speed (using Z_2)	0.5	-6.3

The study presented herein measured wind speed within 0.4 m of the specified height (4.6 m) but the air temperature at the lower height for application of Equation (1) was measured at the same height as wind speed. Strict application of Equation (1) requires that wind speed be measured between the two temperatures, so the interpolation procedure of Equation (2) could also be used here (Fritz et al., 2008). However, because temperature at the lower height was measured at 4.6 m instead of 2.4 m, stability factors would be calculated based on temperature combinations slightly above the atmospheric layer within which spraying occurs. So, we chose instead to extrapolate the temperature to 2.5 m based on temperature trends at other heights. This would allows strict application of Equation (1) within the correct layer (Yates et al., 1974), and data could be compared to determine if Equation (1) still gave acceptable results using data acquisition heights in our study.

To extrapolate temperature at the 2.5 m height, curve fits for air temperature vs. height were developed around transitions illustrated in Figs. 2 through 6 between unstable and stable conditions. Figures 8 through 12 illustrate trends in air temperature as a function of height, and the air temperature at the 2.5 m height could be obtained from the curve fit for each graph. We were careful to consider 'expected' trends when choosing a curve fit. Monotonic functions were used wherever possible, as these can also give accurate information on the inflection point (for example to find the height at which an inversion switches to non-inversion at a given time) as indicated by the first derivative. As an example, Figure 13 illustrates the first derivative of the Hoerl model used to fit temperature data at 0700 on 15 April (Figure 8 (a)) indicating a zero slope at 10.63 m height. A plot is also shown of the first derivative of a polynomial fit of the same data, which does not give an accurate result, consistent with issues raised by Tao and Watson (1987) regarding data fitting procedure. It is thus important to understand limitations of using polynomial fits if derivatives of the response function are desired.

Table 4 illustrates stability classifications at the same transition points as Table 1 but recalculated using curve fit-extrapolated air temperatures at 2.5 m. Although there were a few cases where stability classifications differed (ie. very stable vs. stable), in no case did the transition between stable and unstable/neutral conditions differ between the two situations. This indicates that temperature measurements obtained at the 4.6 and 9.8 m heights specified stability conditions accurately enough within one hour intervals.

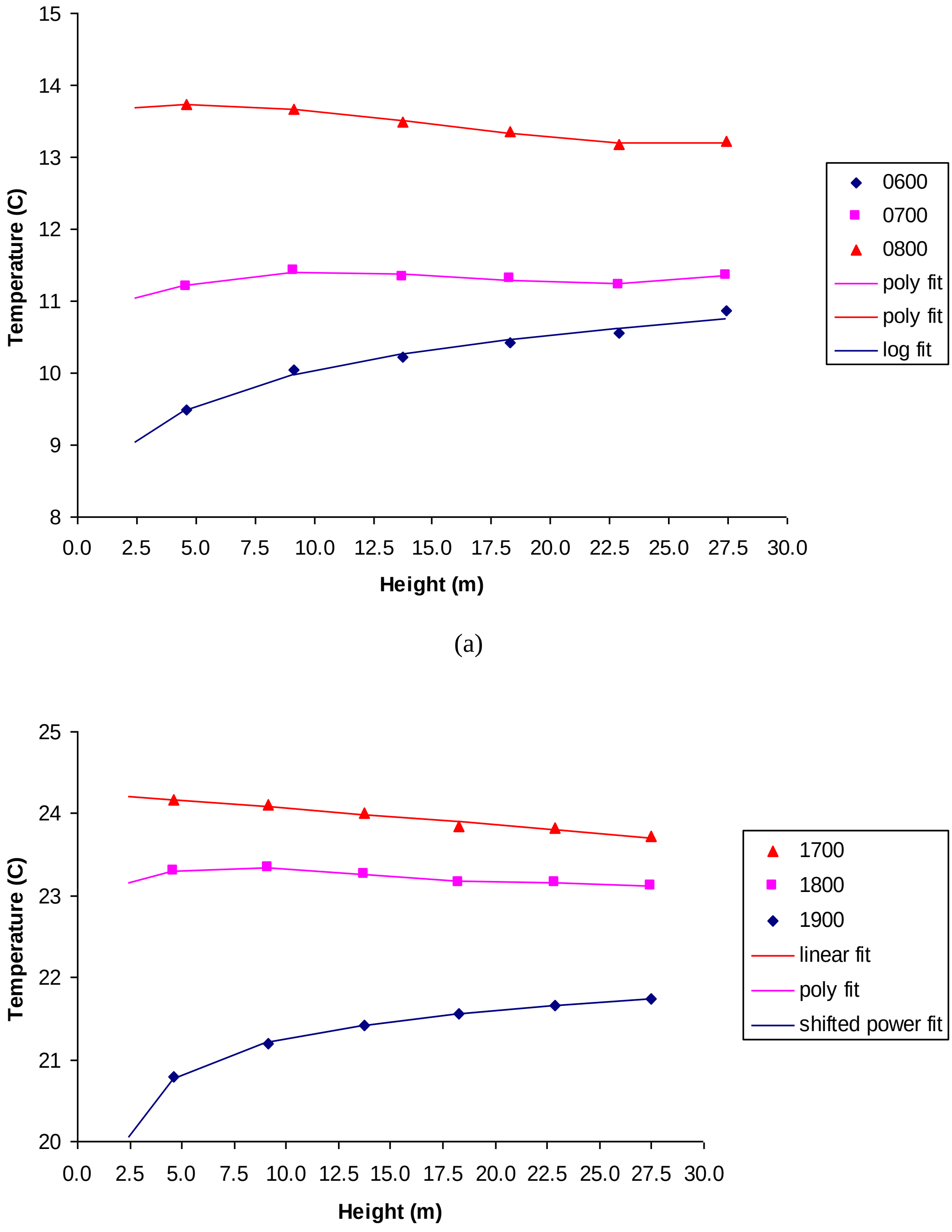
Table 4. Atmospheric stability ratios for five selected dates using air temperature extrapolated to 2.5m and temperature measured at 9.8m in the stability equation.

Julian Day	Date	Time	Stability Classification	Stability Ratio	Wind Speed (m/s)	Air Temperature (C) extrapolated to 2.5m
106	15-Apr	0600	V-stable	4.90	1.23	9.04
		0700	V-stable	1.42	1.64	11.03
		0800	Neutral	0.00	2.73	13.70
		1700	Unstable	-1.70	0.23	24.22
		1800	V-stable	4.90	0.23	23.15
197	15-Jul	0600	V-stable	4.90	0.39	24.65
		0700	Unstable	-1.69	1.13	27.21
		1800	Unstable	-0.72	1.98	34.09
		1900	V-stable	4.90	0.67	31.30
229	16-Aug	0600	V-stable	4.90	0.23	14.72
		0700	Unstable	-1.70	0.23	17.18
		0800	Unstable	-1.70	1.22	22.56
		1800	Unstable	-0.71	2.26	29.20
		1900	V-stable	2.73	1.52	25.94
259	15-Sep	0700	V-stable	3.77	0.97	21.43
		0800	Unstable	-0.31	3.76	24.78
289	15-Oct	0700	Stable	1.05	1.93	7.67
		0800	Neutral	0.00	2.11	10.13
		1700	Unstable/neutral	-0.11	2.86	21.96
		1800	V-stable	1.79	3.76	19.35

Vertical Temperature Gradients and the Inversion Layer

Figures 8 through 12 illustrate vertical temperature gradients that indicate the presence of inversions. The 15 April plot (Figure 8) shows interesting differences between temperature trends at lower altitudes vs. higher altitudes. Very stable conditions still prevailed at 07:00 and figure 8 shows the inversion layer up to about 9.8 m above which neutral or unstable conditions appeared to exist. However spraying customarily occurs well below the 9.8 m altitude, so this finding would not be of practical benefit with regard to spraying (ie. spraying is still not warranted at 07:00). Likewise between 17:00 and 18:00, spraying should be stopped as the 18:00 curve also shows inversion to 9.8m but unstable conditions above that level. This is also consistent with very stable conditions at 18:00 as indicated in Figure 5.

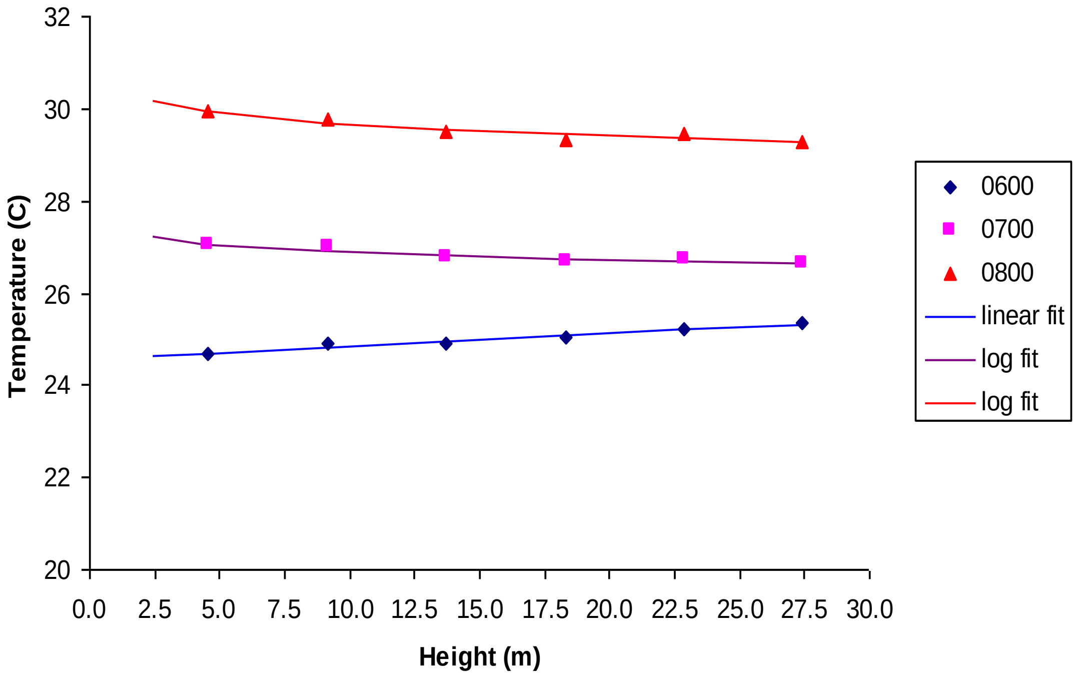
Figure 9 illustrates the 15 July plot. By contrast with the 15 April plot, inversions are not indicated at 07:00 or 18:00, and the curves follow a consistent pattern as a function of altitude (except for an anomaly at 22.9m). The 16 August plot (Figure 10) shows a similar trend as the July plot, but an almost flat (but still negative) temperature difference with altitude. [$T_{Z_2} - T_{Z_1}$] only equaled -0.02 C and [T_{Z_2} - extrapolated T_{Z_1}] = -0.04 º C. Temperatures were very close to each other not indicating an inversion, and Table 4 indicates unstable conditions at 07:00 for 16 August. The behavior of Equation (1) can be illustrated with regard to wind speed. Wind was almost calm at 07:00 (0.23 ms-1) and then jumped to 1.22 ms-1 by 08:00. If wind speed is low but inversion conditions are not detected, then unstable conditions will prevail. Higher wind speeds imply more mixing, but the trend is towards neutral if temperature differences are very small. Like the 15 April plot, the 16 September plot (Figure 11 (a)) indicated a temperature inversion and very stable conditions at 07:00. Air temperatures were much higher than in April, but a check of prevailing conditions (Weather Underground, 2016) indicated morning cloudiness until about 08:30. This would delay heating of the ground surface much as cooler air temperatures would. Wind speeds were high throughout the day and into the evening indicating neutral or unstable conditions into the evening (Figure 5; Table 4). The October plot (Figure 12 (a)) shows a similar inversion near the surface as in the April plot at 07:00; conditions were sunny and cool.



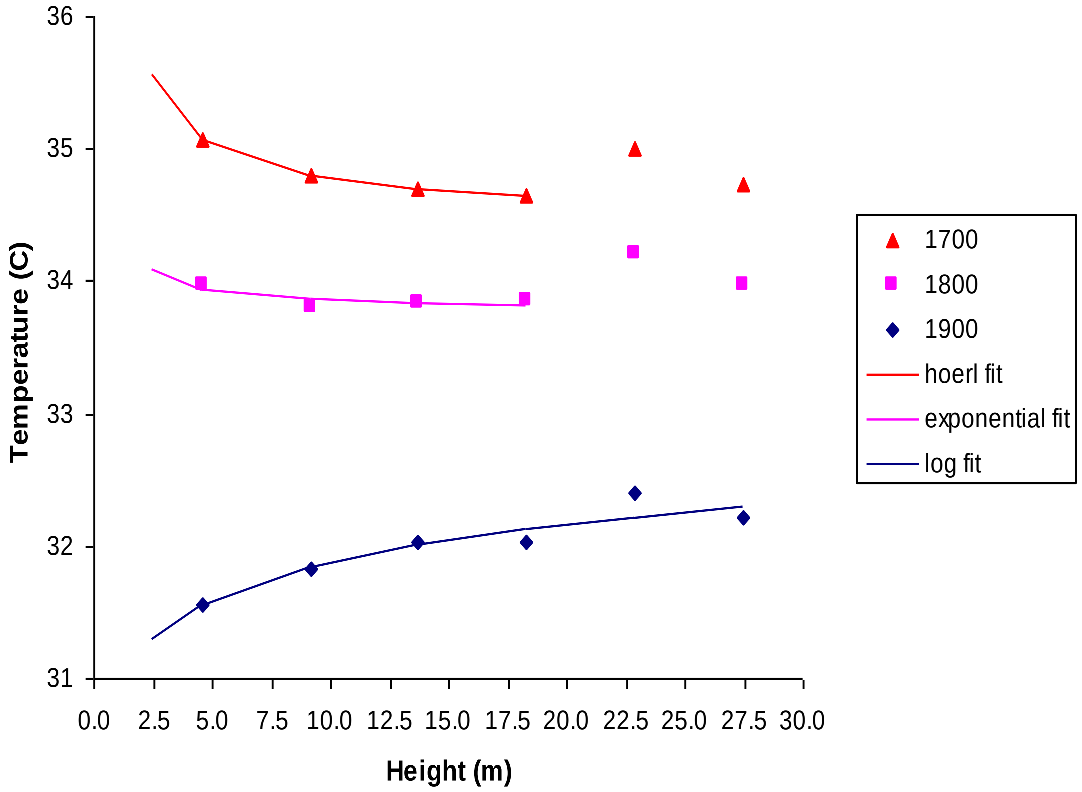
(a)

(b)

FIGURE 8. AIR TEMPERATURE AS A FUNCTION OF HEIGHT INDICATING MODEL EXTRAPOLATIONS FOR THE 2.5M HEIGHT OF TEMPERATURE ACQUISITION: (A) MORNING READINGS; (B) LATE AFTERNOON READINGS; 15 APRIL 2004).

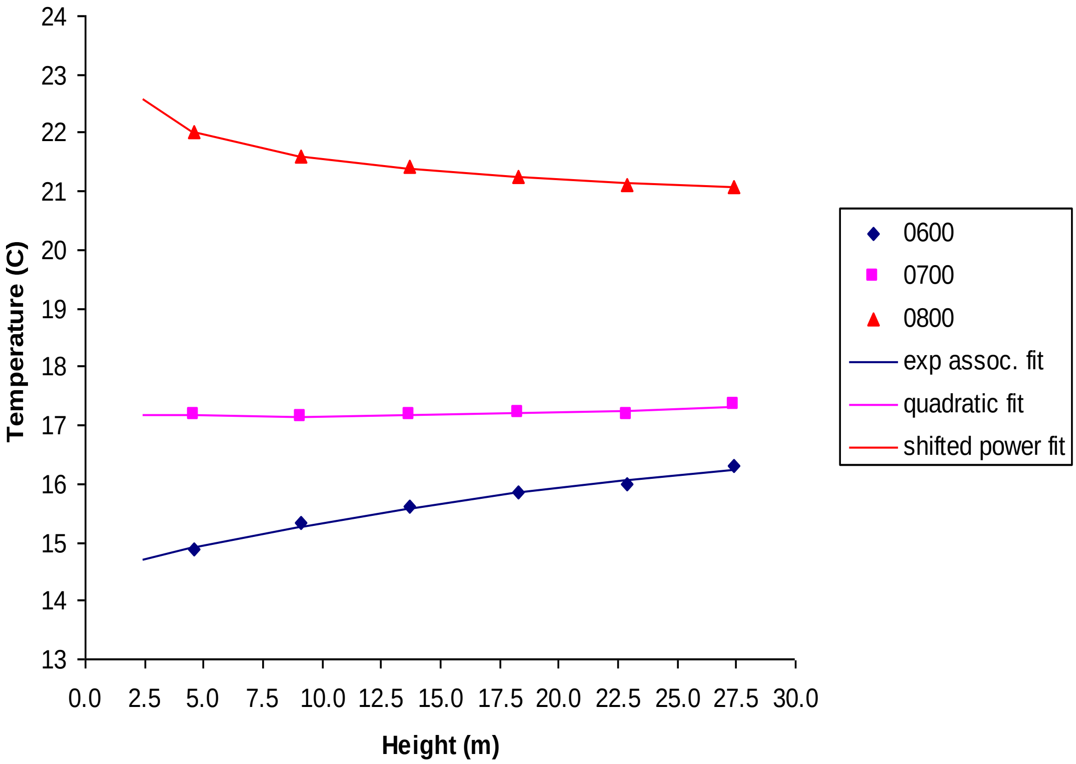


(a)

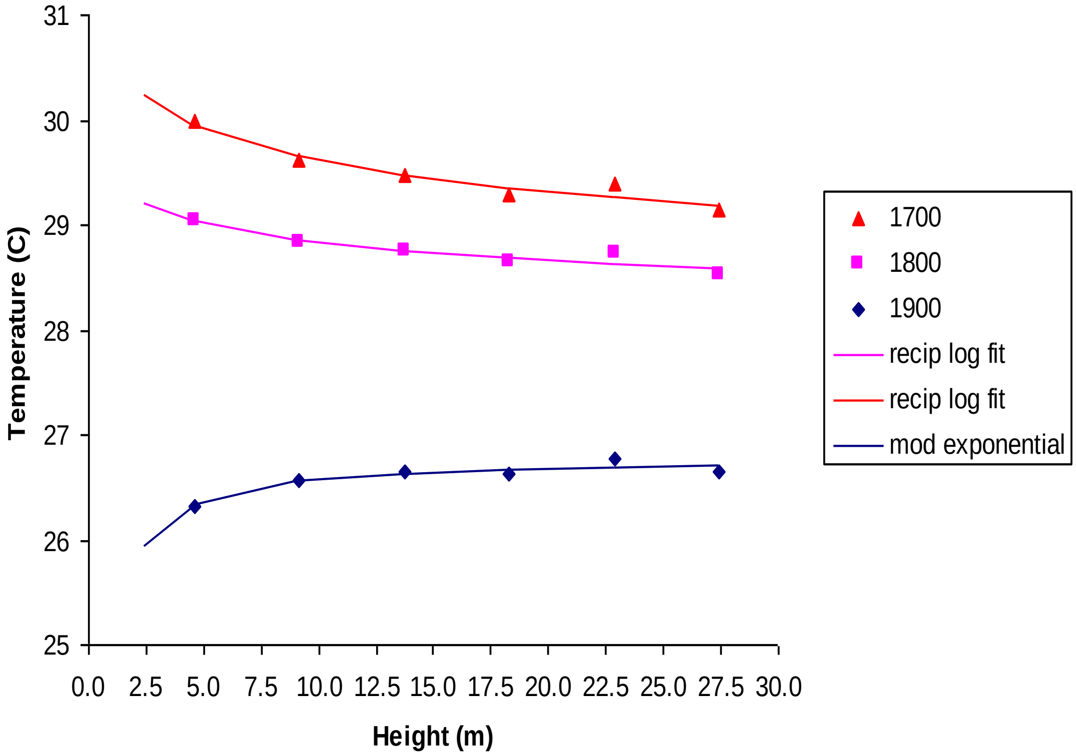


(b)

FIGURE 9. AIR TEMPERATURE AS A FUNCTION OF HEIGHT INDICATING MODEL EXTRAPOLATIONS FOR THE 2.5M HEIGHT OF TEMPERATURE ACQUISITION: (A) MORNING READINGS; (B) LATE AFTERNOON READINGS; 15 JULY 2004).

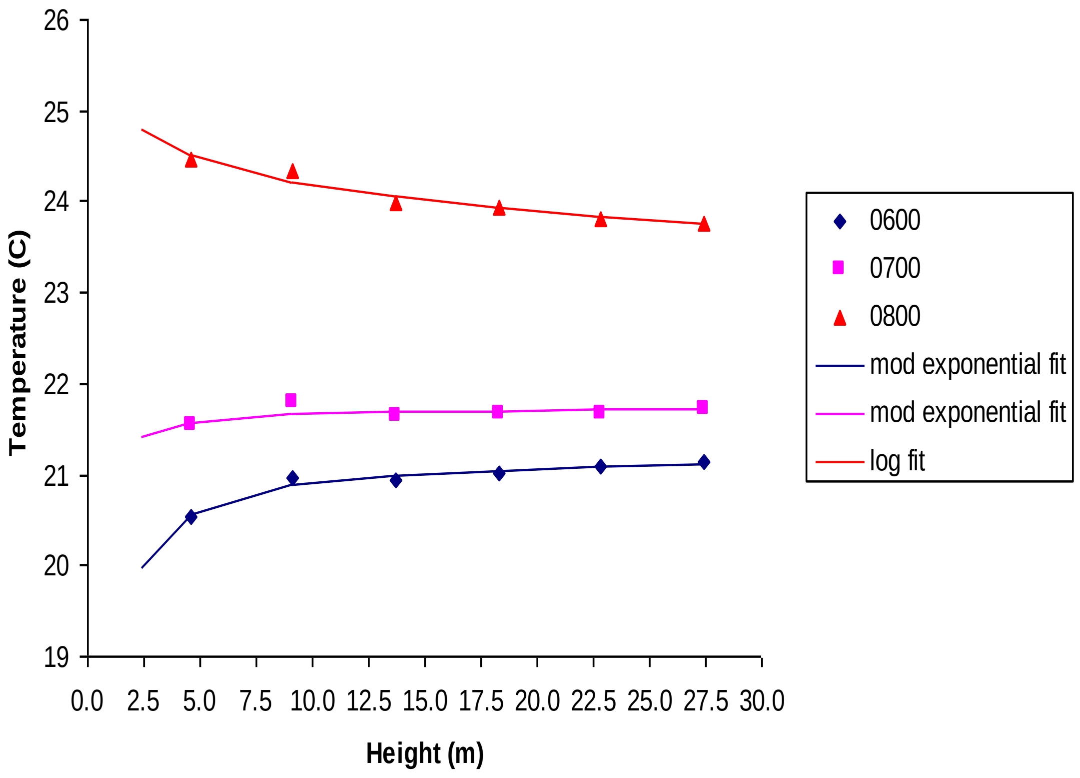


(a)

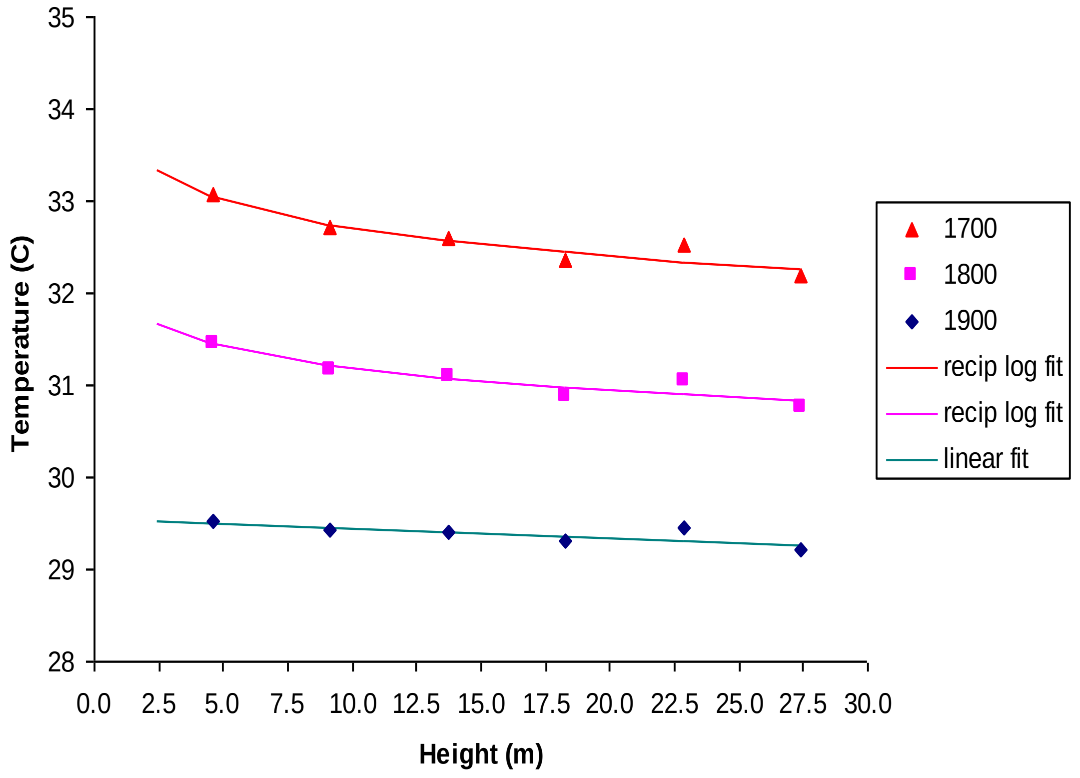


(b)

FIGURE 10. AIR TEMPERATURE AS A FUNCTION OF HEIGHT INDICATING MODEL EXTRAPOLATIONS FOR THE 2.5M HEIGHT OF TEMPERATURE ACQUISITION: (A) MORNING READINGS; (B) LATE AFTERNOON READINGS 16 AUG 2004).

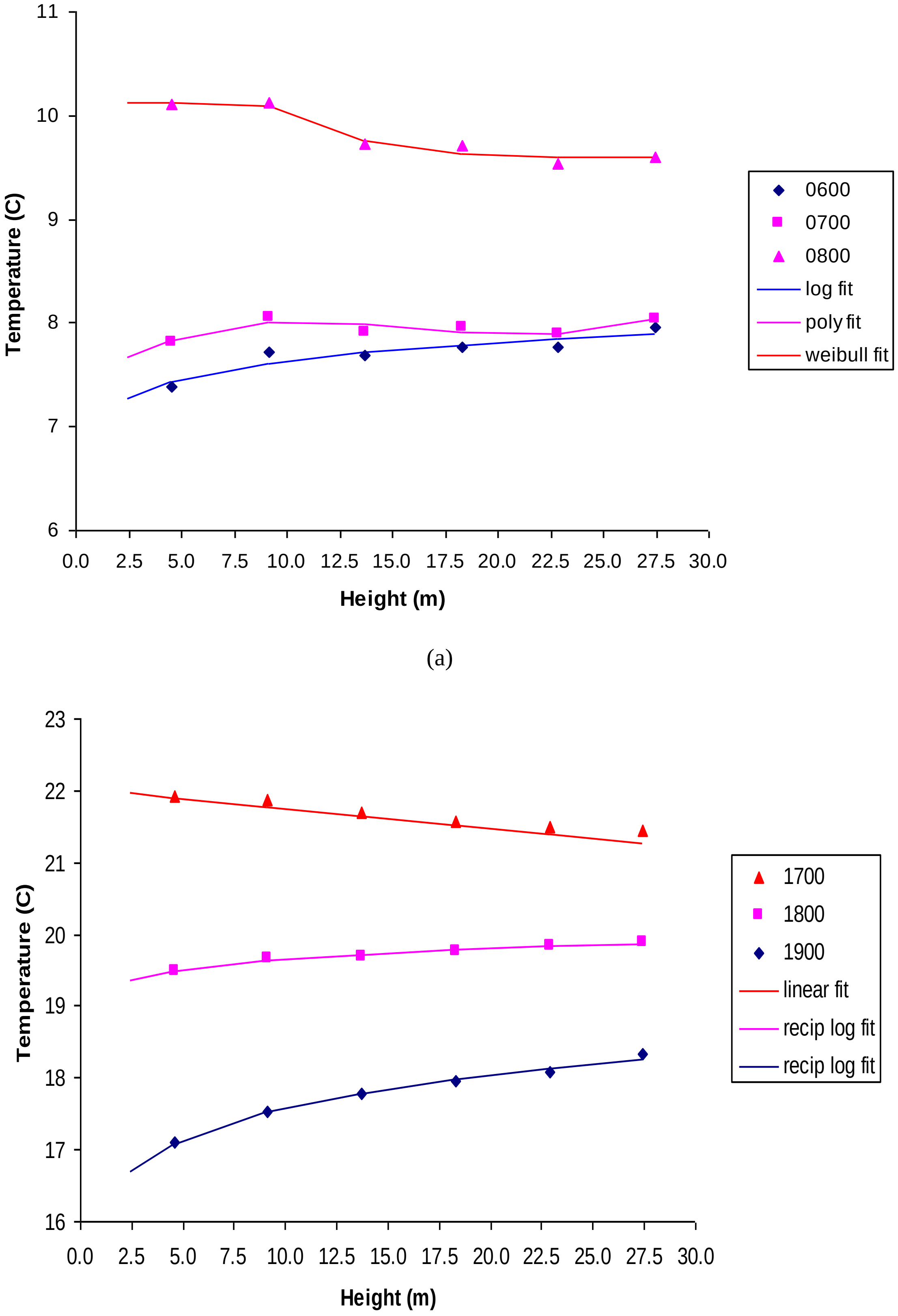


(a)



(b)

FIGURE 11. AIR TEMPERATURE AS A FUNCTION OF HEIGHT INDICATING MODEL EXTRAPOLATIONS FOR THE 2.5M HEIGHT OF TEMPERATURE ACQUISITION: (A) MORNING READINGS; (B) LATE AFTERNOON READINGS 15 SEP 2004).



(a)

(b)

FIGURE 12. AIR TEMPERATURE AS A FUNCTION OF HEIGHT INDICATING MODEL EXTRAPOLATIONS FOR THE 2.5M HEIGHT OF TEMPERATURE ACQUISITION: (A) MORNING READINGS; (B) LATE AFTERNOON READINGS 15 OCT 2004).

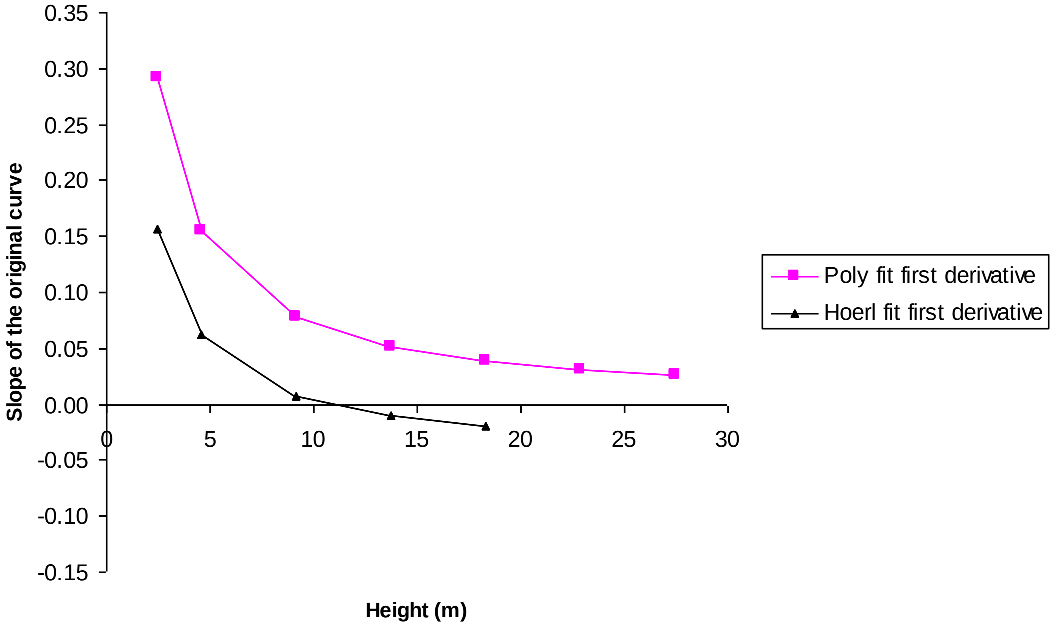


FIGURE 13. FIRST DERIVATIVE OF MODEL FITS TO AIR TEMPERATURE VS. HEIGHT DATA FOR 15 APRIL, 2004 ON FIGURE 8 (A).

Summary and Conclusions

Air temperature and wind speed data were taken at several heights to determine conditions necessary for stable atmosphere under which to avoid aerial spraying. These data confirm that solid recommendations can be made to pilots on times of day to watch for stable atmospheric conditions unfavorable for spraying. Cool or cloudy conditions delayed the time where spraying was permissable in the morning (to 0800 by our hourly analysis). An applicator should use judgment to find a balance between conditions that are so stable that spray does not disperse (with potential to move off-site), and conditions that are so unstable and windy that spray is quickly dispersed and moved off-site without reaching the target.

Results of this study suggest that guidelines on times of day and wind speeds below which spraying should be avoided can be identified. Results also evaluated guidelines developed for Arkansas that specify air temperature changes required during the morning and evening hours to avoid spraying under stable atmospheric conditions. When temperature criteria were satisfied, unstable conditions were achieved in all months indicated except for one month in the Spring. Stable atmospheric conditions persisted longer during the morning hours and began sooner in the evening under clear condiitons in cooler months of the scenarios indicated. It should be noted that during the daily cycle of atmospheric conditions, inversions occuring late in the afternoon are likely to persist through the remainder of the day. For a study such as this, high accuracy instrumentation was necessary to successfully determine temperature inversions, as vertical temperature gradients were very small in many cases.

Based on results, the following conclusions can be made:

- Temperature inversions were indicated before 07:00 and between 18:00 and 19:00 on days where ambient temperatures were high and conditions were clear.
- Cool or cloudy conditions delayed the time spray could take place safely by about one hour in the morning and moved back the time when spray should be halted by one hour in the late afternoon.
- Wind speed influenced the degree of atmospheric stability in concert with vertical temperature gradients. However, wind speed was not a good indicator of stable atmosphere by itself in narrow ranges of low to medium wind speed.
- Criteria for aerial applicators indicating stable, neutral, or unstable atmosphere were best indicated by

temperature differences with height. Recommendations made by the ASPB (2008) on temperature differences by which to gauge the likelihood of atmospheric stability were validated by our data at one hour intervals.

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