2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation
DOI: 10.13031/aim.20162461726
Paper Number: 162461726

Measuring Sub-Second Wind Velocity Changes at One Meter above the Ground

Matthew W. Schramm, H. Mark Hanna, Matt J. Darr, Steven J. Hoff, and Brian L. Steward
Agricultural and Biosystems Engineering Department, Iowa State University, Ames, IA

Written for presentation at the
2016 ASABE Annual International Meeting
Sponsored by ASABE
Orlando, Florida
July 17-20, 2016

ABSTRACT. *Agricultural spray drift is affected by many factors including current weather conditions, topography of the surrounding area, fluid properties at the nozzle, and the height at which the spray is released. During the late spring/summer spray seasons of 2014 and 2015, wind direction, speed, and solar radiation (2014 only) were measured at 10 Hz, one meter above the ground to simulate conditions that are present for a droplet. Measurements of wind velocity as the wind passed from an upwind sensor to a downwind sensor were used to evaluate under what conditions wind may be most likely to have a significant direction or speed change which affects droplet trajectory. For two individual datasets in which the average wind speed was 3.6 m/s and 1.5 m/s, it was found that there existed little linear correlation of wind speed or wind direction between an upwind and downwind anemometer separated by 30.5 meters (100 ft). The highest observed correlation, resulting from a 12 second lag between the upwind and downwind datasets, was 0.29 where the average wind speed was 3.6 m/s. Correlations were only found for wind speeds exceeding 3 m/s. Using this lag time, it was observed that the wind direction 30 seconds into the future had a 30% chance to be different by more than 20 degrees from current conditions. While a wind speed difference of more than 1 m/s from current conditions (mean wind speed was 3.6 m/s) happened about 50% of the time. Looking at 2014 and 2015 spray season data, it was found that the most variability occurred with wind speeds below 2 m/s.*

Keywords. *Sprayers, spray drift, data collection, wind effects, turbulence, simulation parameters.*

Introduction

Agricultural sprayers are used to provide agricultural chemicals that protect and improve crop plant health. However, off-site drift of these chemicals can be detrimental to adjacent crops or other forms of life. Many factors affect spray drift ranging from the topography of the land, current weather conditions, droplet size distribution, and the height at which the droplets are released. The EPA defines spray drift as follows, “Pesticide spray drift is the physical movement of a pesticide through air at the time of application or soon thereafter, to any site other than that intended for application” (EPA, 2014). Spray technology includes capabilities to mitigate spray drift by affecting droplet size for wind conditions (Nordby & Skuterud, 1974; Smith, Harris, & Goering, 1982). Boom height, air temperature, relative humidity, droplet size, droplet release pressure, air pressure, and wind conditions are just some of the factors that control spray drift with droplet size being the biggest contributing factor (Spray Drift Task Force, 1997). The sprayer can control only some of these factors. Instrumentation placed on a sprayer may be used to control droplet size dependent upon current weather conditions giving extra control over spray drift, but this strategy may be defeated by unforeseen changes in wind direction or speed after the droplet has left the nozzle.

To better understand how spray drift propagates down wind, simulation models have been developed. Popular methods include Lagrangian, Gaussian, Random Walk, Regression, and CFD models (Holterman, Van de Zande, Porskamp, & Huijsmans, 1997; Baetens, et al., 2007; Teske, et al., 2002; Tsai, et al., 2005; Frederic, Verstraete, Schiffers, & Destain, 2009; Smith, Harris, & Goering, 1982). Through the use of such models, applicators gain knowledge of when drift potential is high and can adjust buffer zones to minimize the risk for spray drift (Craig, 2004; Brown, Carter, & Stephenson, 2004). Attention is given to the development and progression of the droplets, but less attention is devoted to the random nature of weather surrounding the droplet, such as the distribution of wind speed and direction with which the droplet interacts. The models include wind turbulence interactions by either using real data collected at one physical location that is used for the entire range of the simulation (Tsai, et al., 2005; Frederic, Verstraete, Schiffers, & Destain, 2009), or by using the averaged wind velocity and updating the velocity at every time step with a random fluctuation to simulate the turbulent nature of wind (Holterman, Van de Zande, Porskamp, & Huijsmans, 1997).

Previous research has attempted to incorporate the random nature of wind speed and wind direction, but little work was found seeking to characterize the wind conditions that a droplet experiences from release to deposition. Data recorded for short-term wind velocity changes near the ground’s surface are needed to better understand their effects on spray droplet trajectories.

Objectives

The objective of this research were to:

- Understand changes in transient wind velocity (direction and speed) at a typical ground sprayer boom height off the field surface, and
- Evaluate under what conditions wind may be most likely to have a significant velocity change or be more turbulent.

Methods and Materials

Experimental Design and Apparatus

Field measurements of wind speed and direction were collected during the late spring/summer spraying season of 2014 and throughout the 2015 season using instrumentation set into a field of growing oats. The fields were located at the Iowa State University Research Farm’s Bruner Farm fields F1 and F3 (respectively for 2014 and 2015) near Ames, Iowa (Figure 1). The field dimensions were 268 m long (north to south) by 105 m wide (east to west) (880 by 348 ft) for field F1 and 107 m long by 201 m wide (350 by 660 ft) for field F3.

Wind speed and solar radiation measurements were acquired at 10 samples per second using ultrasonic anemometers (model: WindMaster 3d, Gill Instruments, Lymington, Hampshire, UK) and a pyranometer (model: SP-212, Apogee Instruments, Logan, UT). The anemometers measured the wind speed in the north-south, east-west, and vertical directions (Figure 2). Open source microcontrollers equipped with a GPS module (model: Arduino Uno, Arduino Inc; Ultimate GPS Shield, Adafruit, New York, USA) were used to log data to micro SD data cards. Using the GPS’s PPS (Pulse per Second) output, time correction was able to be done to ensure time synchronization of the wind velocity measurements among the microcontrollers. To reduce influences to wind speed, the microcontrollers and power supplies were located separate from the anemometers at a distance of approximately 2-3 meters away. Sensors were placed in a cross pattern with 15.2 m (50 ft) spacing from a center point (Figure 3). Sensor 5 was only used for the 2015 season. Anemometers were placed one meter above the ground’s surface to collect wind measurements. The pyranometer was placed on the west most sensor’s (Sensor 1) charging station near the anemometer.

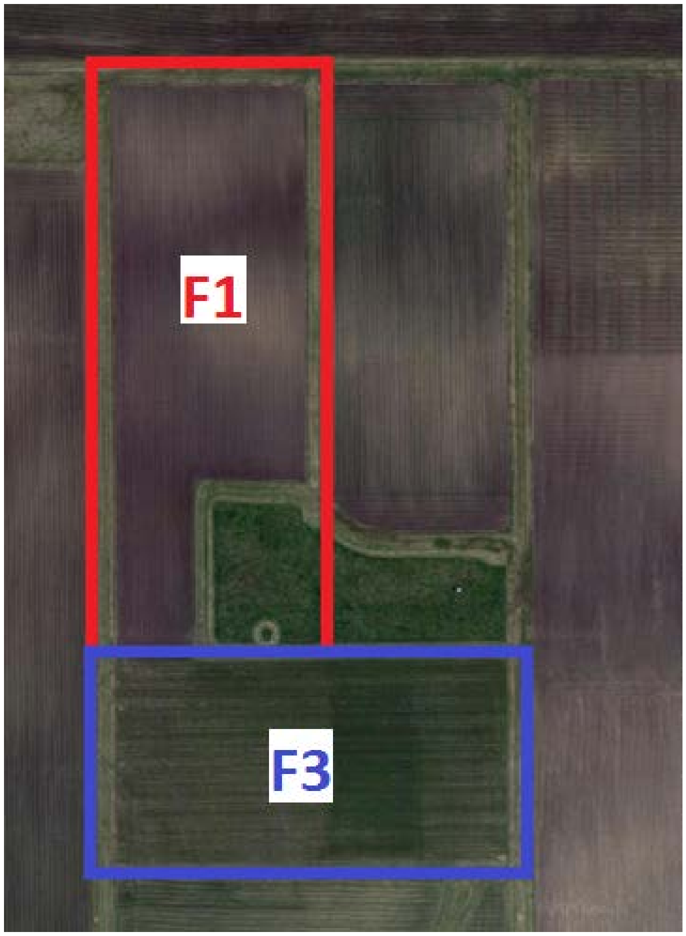


Figure 1: Bruner Farm filed F1 and F3 (42.015N 93.731W) (Google, 2015)

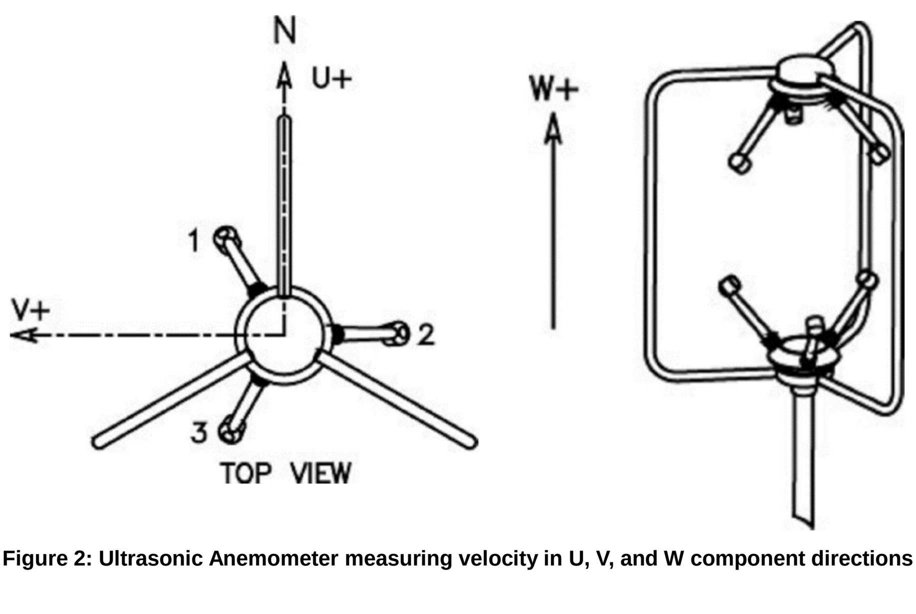


Figure 2: Ultrasonic Anemometer measuring velocity in U, V, and W component directions

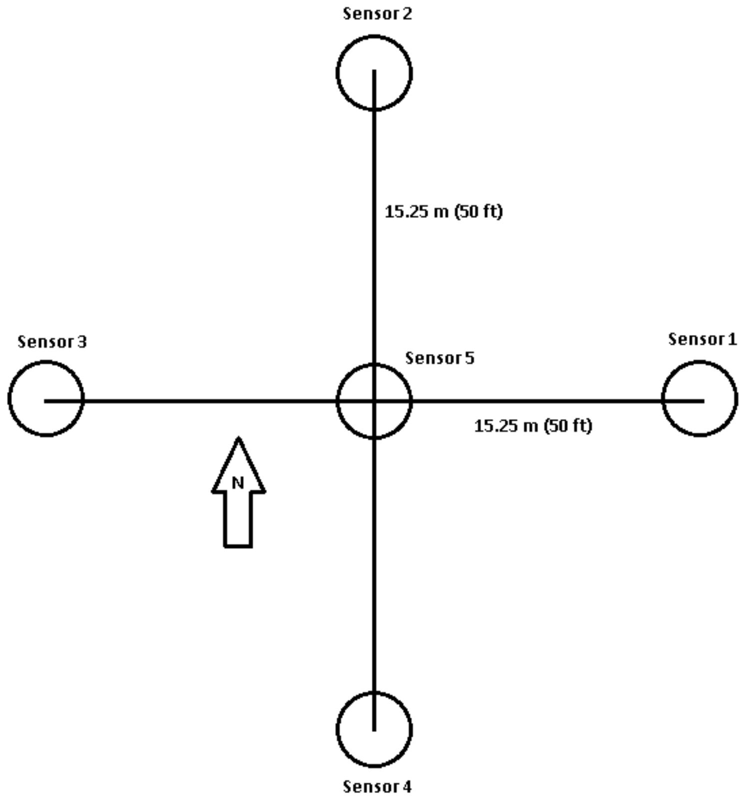


Figure 3: Sensor Positioning

Data Analysis

Wind speed was converted to wind direction using trigonometric relationships. A wraparound method was used to produce a semi-continuous wind direction data set. Wraparound refers to the convention of allowing the wind direction to go above 359 degrees and below 0 degrees, i.e. 12 degrees = 372 degrees.

Because of small amounts of drift in the actual recording time of wind velocity at each sensor location, a form of interpolation was used to estimate wind velocity at points between 10 Hz collection times. This need comes from the data recorders not staying exactly in sync with one another. MATLAB (Version 8.3 (R2014a), MathWorks), used for analysis in this project, offered many different schemes for interpolation ranging from discontinuous to second derivative continuity (C^2). MATLAB's cubic spline offered the smoothest fit to the data, however the assumption that wind speed and direction have continuous first and second derivatives cannot be confirmed. For this reason MATLAB's pchip (Piecewise Cubic Hermite Interpolating Polynomial) was also not used due to its C^1 (first derivative) continuity. Ultimately, a piecewise linear polynomial was chosen. For linear interpolation, no assumption was needed on the derivatives of the data (Faires, 2011).

To find if wind measurements recorded at an upwind sensor were correlated to measurements at a downwind sensor, shorter length datasets were taken in which the wind direction, on average, would move a particle over multiple sensors. The first dataset from 2014 consists of a 5 hour period (7:30 am to 12:30 pm) in which the average wind speed was 3.6 m/s (8 mi/h). The second dataset from 2015 is from a 1.5 hour long period (12:50 pm to 2:20 pm) with a mean wind speed of 1.5 m/s (3.4 mi/h). The entire recorded dataset was then used to determine conditions more likely to be present during significant wind directional changes. This analysis was divided into 2014 and 2015 datasets.

Results and Discussion

Linear correlation

Relationship at individual 0.1 s intervals between sensors over 5 hour period (2014)

Initial analysis checked for a linear correlation between the upwind and downwind sensors. Figure 4 shows the data collected. The average wind speed during this time was 3.6 m/s (8 mi/h). Due to the large number of points, it is unclear graphically if there is a correlation (Figure 4) but the linear correlation of individual 10 Hz measurements between the sensors, for the five hour period, was 0.29 and 0.27 for wind direction and speed, respectively.

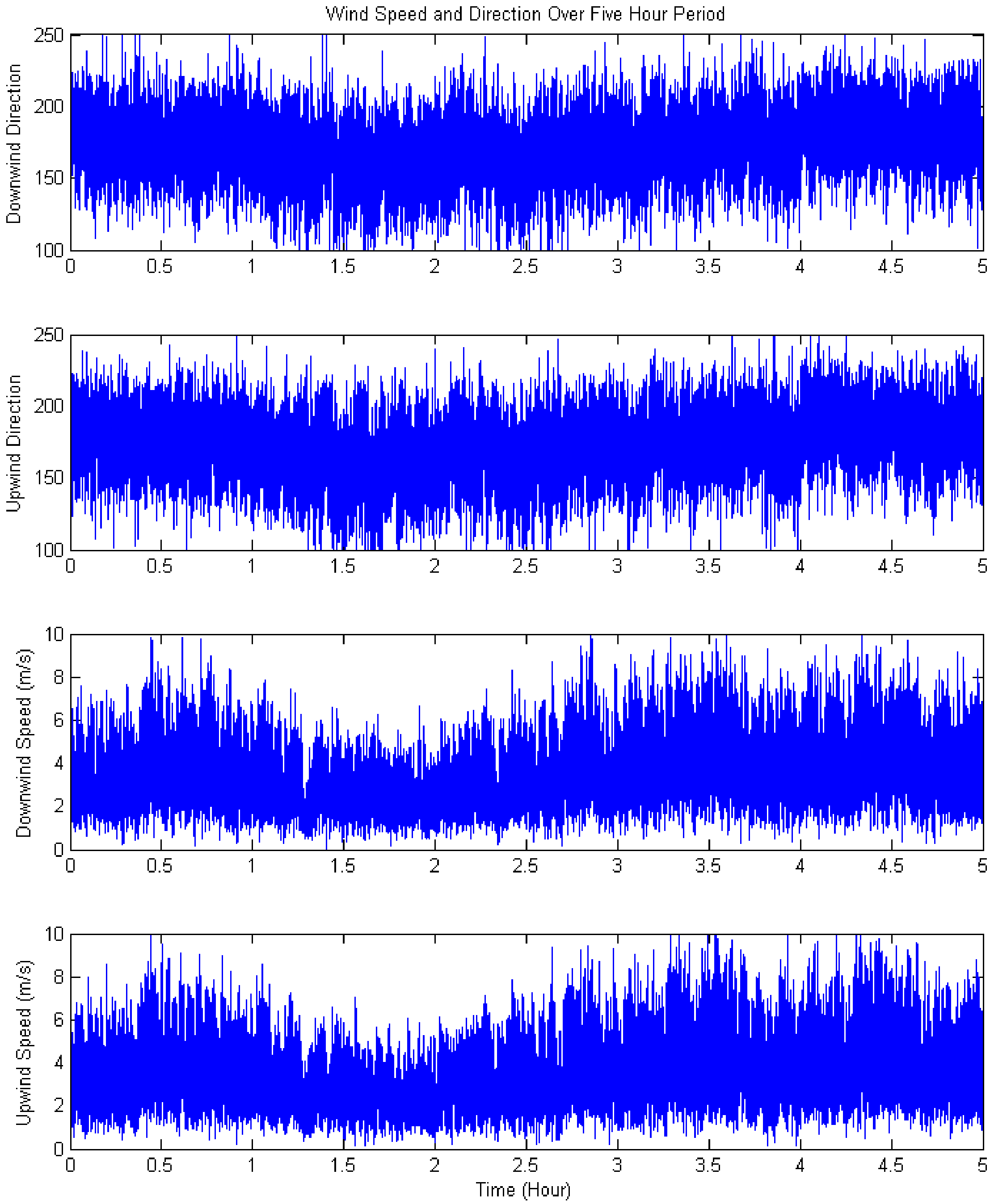


Figure 4: Five hour period of upwind/downwind sensors for both wind speed and wind direction

To graphically see the structure of the data better, two-dimensional natural logarithmic histograms were used (Figure 5). This was done by creating a two-dimensional mesh of cells of all possible combinations of upwind and downwind sensor data values and then counting the number of data points occurring within each cell of the mesh. Using the natural logarithm of counts inside the mesh reduced the wide range of individual counts in each cell and was done to see smaller structures in the data. To accommodate cell locations with a count of one (natural log of one equals zero), one was added to the value of all cells after the natural log transformation. This step allowed differentiation between cells with an original count of one and cells with no observed (zero) values. The bar graph to the right of the graphs show the shading equivalents to the natural log values. Data grouped around the mean with no apparent linear dependency structure.

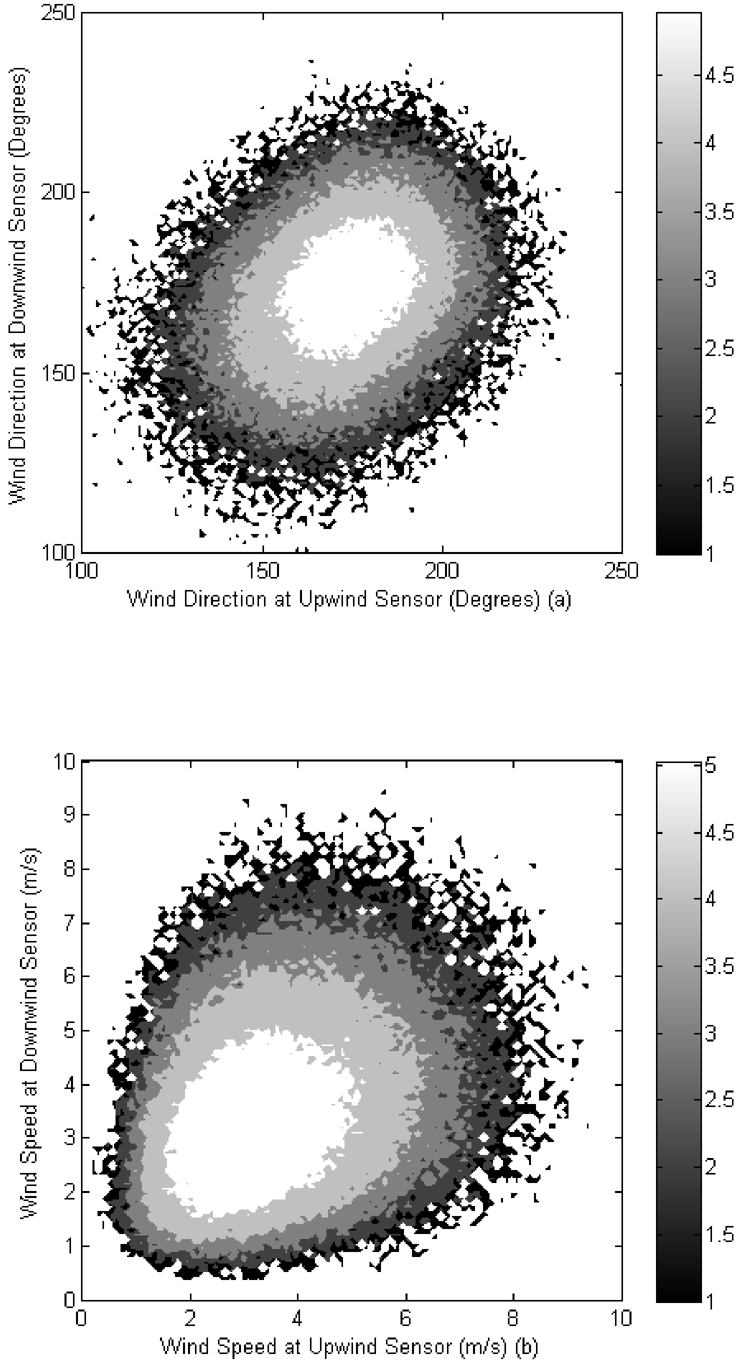


Figure 5: Density plots of point grouping for downwind direction (a) and downwind speed (b) as a function of upwind conditions. The range was divided into sectors (e.g., for wind direction, grid spacing of 1x1 degree were used) and the number of points were then counted for each sector. The natural log was then applied to the counts to show underlying structure. Since ln(1) = 0, a value of 1 was added to all sectors that originally had a value of at least one.

Relationship at individual 0.1 second intervals between sensors over 1.5 hour period (2015)

This analysis was also done for a data sample with average wind speed of 1.5 m/s (3.4 mi/h) from 12:50 to 2:20 p.m. during which wind generally came from the south and passed over the southern, central, and northern sensors (Figure 6). The correlation coefficients for wind direction and wind speed for all combinations of two of the three sensors were all below 0.03. Figure 7 shows the logarithmic histograms for the central and northern sensors. Similar figures were attained at the other sensors. An absence of change in general wind direction and speed during the shorter time period in 2015 resulted in the area of highest frequency of values in the histograms being more circular (less elliptically elongated) than in 2014.

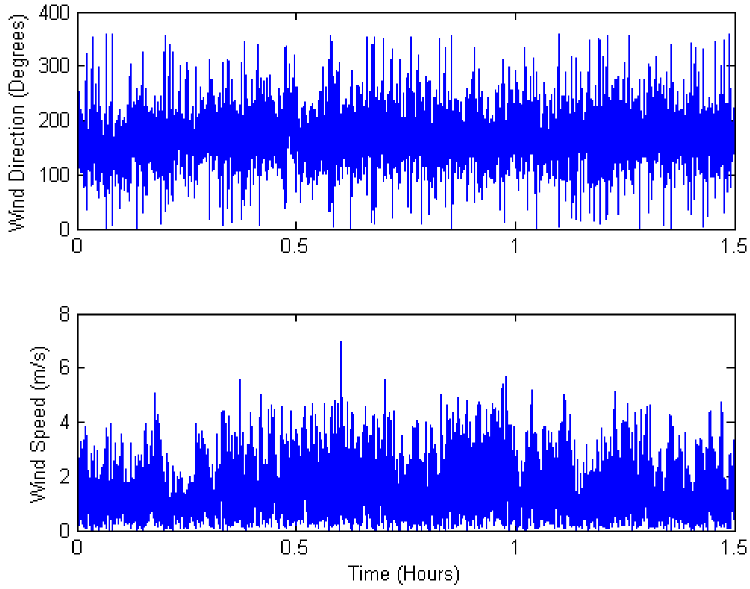


Figure 6: One and a half hour period of wind speed and wind direction at the center sensor

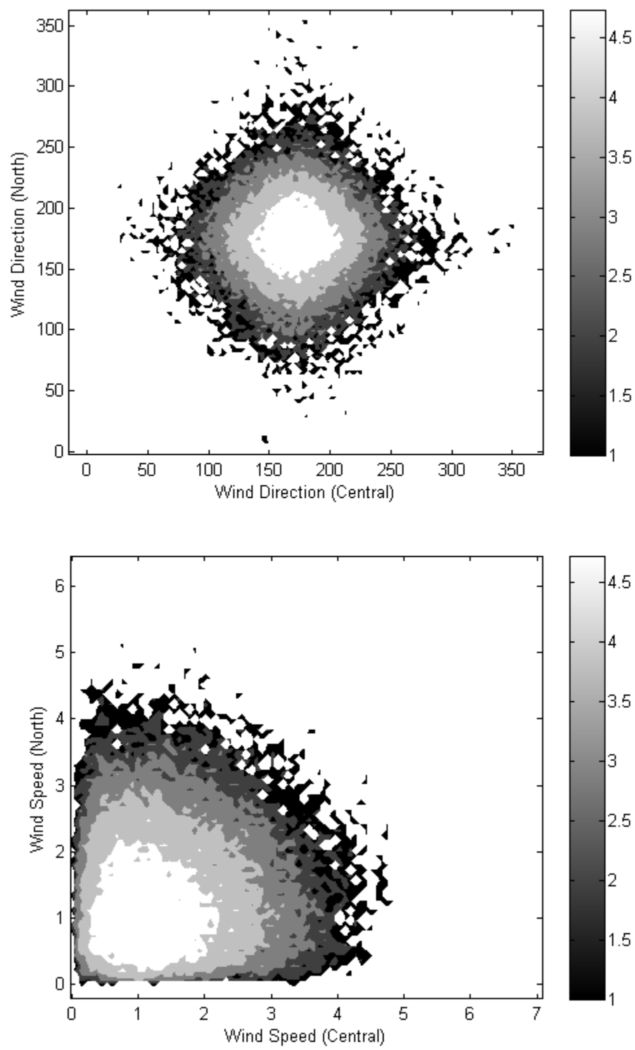


Figure 7: Histograms of wind direction and wind speed at the central and northern sensors

Short Term Relationships during one minute intervals (2014)

Significant flight path changes of small, drift-prone spray droplets take place over much shorter time periods, on the order of a minute rather than five hours. The five hour period was broken into shorter, one minute long data sets. Linear correlation coefficients were then calculated for each one minute period in the five hour (300 minute) long data set using the 10 Hz data. Averaging these 300 linear correlation coefficients yielded adjusted correlation coefficient values to compare velocity relationships between upwind and downwind sensors during one-minute time periods. For wind direction and wind speed, the adjusted average correlation coefficients were 0.01 and 0.02 respectively. This result gives insight of the highly variable nature of wind during short term measurements. When the correlation was calculated for the entire five hour period, there was time for the wind speed and direction to shift sufficiently to show long term correlation. This is not the case during short time periods when the droplet is in the air.

Short Term Relationships during one minute intervals (2015)

The one and a half hour period was split into multiple one minute long data sets. The linear correlation coefficients were then calculated as before. To reduce confusion, when discussing interactions between two sensors, the first letter of the sensor location is used with the second letter denoting the upwind sensor. For example, if discussing a process at the central sensor that came from the south sensor, this process would be given the name CS. The linear correlation coefficient for wind speed for NC was 0.02, and the coefficient for CS was 0.01. The wind direction linear correlation coefficients for NC and CS were 0.003 and 0.005 respectively.

Max Correlation using lag adjustment

Using smaller one-minute segments of data, the time it takes for the wind change to travel to the next sensor can be included. During the five hour period, there was a 3.6 m/s (8 mi/h) average wind speed and the sensors were spaced 30.5 m (100 ft) apart. Average wind speed implies a lag of about 8.5 seconds, (taking the distance separated by the sensors and dividing by the average wind speed), before similar conditions would be observed downwind if the wind moved smoothly over the field. However, maximum correlation occurs at 12 seconds (Figure 8). This could be caused by turbulent interactions across the top of the oat crop canopy.

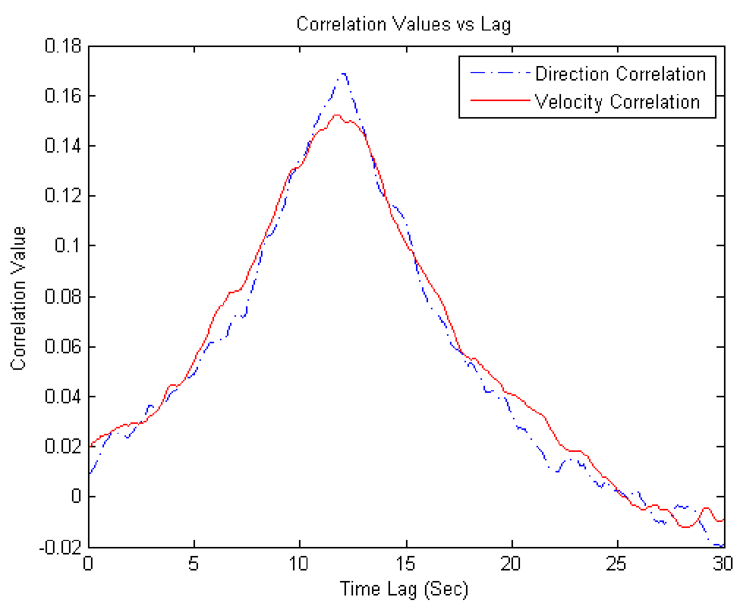


Figure 8: Correlation plot as a function of lag between the sensors for wind direction and wind speed (2014)

From investigating the five hour segment of data, wind direction and wind speed cannot be considered to remain constant at a downwind location after leaving the upwind sensor. Taylors Hypothesis of Frozen Turbulence states that turbulence can be considered "frozen" as eddies (turbulent motion of wind) advects pass a sensor(s) (Stull, 2009). The lack of correlation between upwind and downwind sensors, even after adjusting for lag in wind conditions shown in Figure 8 implies that turbulence is not frozen on these small length and time scales.

Lag was also checked for the 2015 data. There was no set lag time that gave the highest correlation value unlike the 2014 data. Mean wind speed of 2015 data was slower than 2014 data, and the inability to identify a lag period may have been related to the light and variable nature of slower wind speeds (Figure 9).

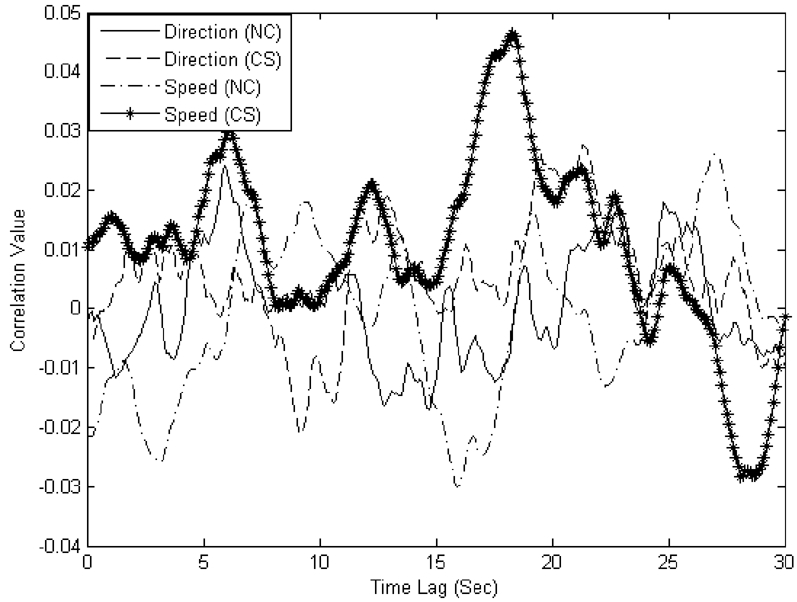
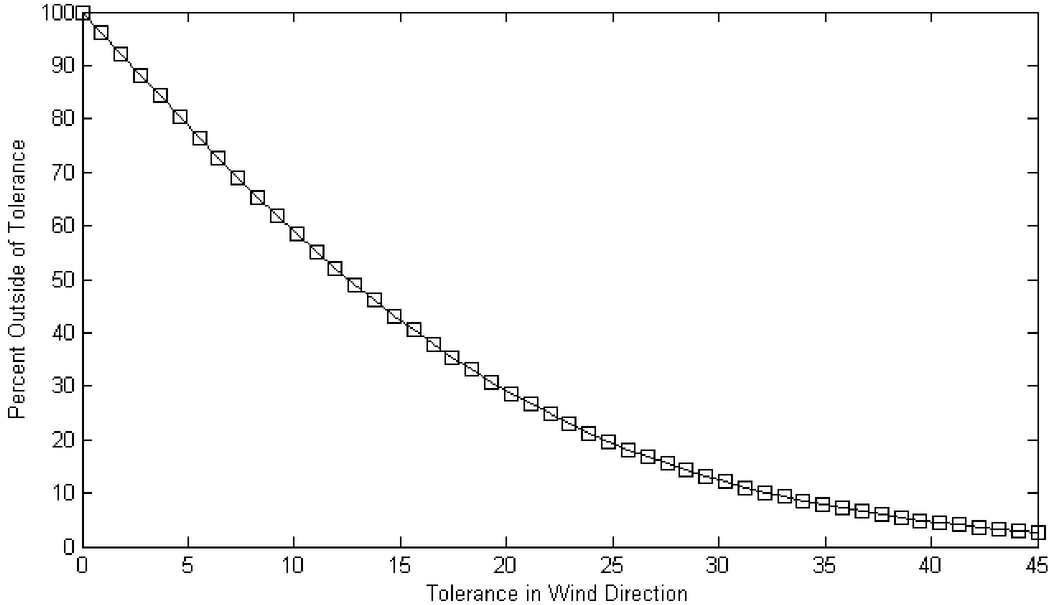


Figure 9: Correlation plot as a function of lag between the different sensors for wind direction and wind speed (2015)

Probability that downwind velocity is within range of upwind velocity

To anticipate an unexpected change in wind direction or speed after spray is released from the nozzle, it would be desirable to know what the probability is of the downwind sensor being within a given tolerance range of an upwind sensor. Multiple sensors were used again utilizing the higher wind speed dataset. From Figure 8, an adjusted lag value of 12 seconds was used in this analysis of the 10 Hz data. The percentage of time that the downwind sensor is outside a given tolerance of the upwind sensor is shown in Figure 10. This probability analysis was done by comparing the difference between the upwind and downwind sensors and counting how many data points fell outside of a tolerance. This count was then divided by the total number of points. For example, if the speed tolerance was set to $\pm$ 1 m/s, then about 50% of the time the absolute value of the difference between the upwind and downwind sensor would be greater than 1 m/s. If the directional tolerance was set at $\pm$ 20 degrees, then about 30% of the time the absolute value of the difference between the sensors would be greater than the set tolerance. Figure 10 gives insight on the probability of random finite fluctuations in both wind velocity and direction.

Figurer 11 shows this analysis for the low wind speed dataset for wind direction and wind speed. The wind speed was scaled to 1 m/s to better match the scaling of the 2015 data. Due to the lack of a peak lag for all sensors, no lag time was used in figure 11. Figure 11 shows that the sensors followed similar curves with one another. This result shows that the probability that a downwind measurement will be within an upwind measurement is similar within at least 30 meters of the upwind sensor. Due to the low wind speed and the lack of a group lag time, the variability at downwind sensors is higher leading to higher degrees of uncertainty. As an example, if a tolerance of 20 degrees was set, the downwind sensor would be outside of the tolerance about 65% of the time.



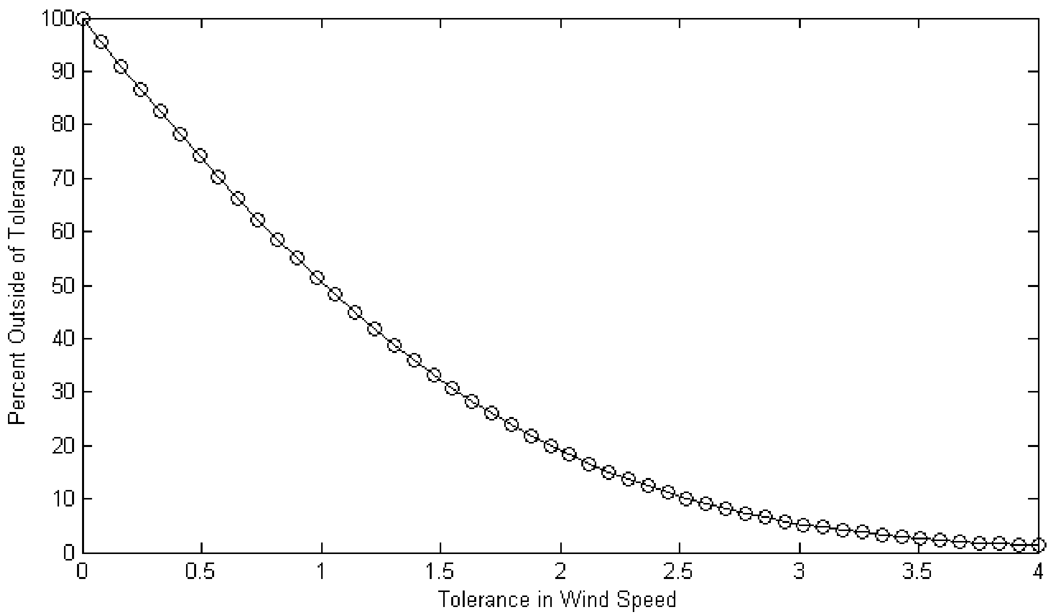


Figure 10: Probability that the downwind sensor will be outside a given tolerance to the upwind sensor for wind direction and wind speed

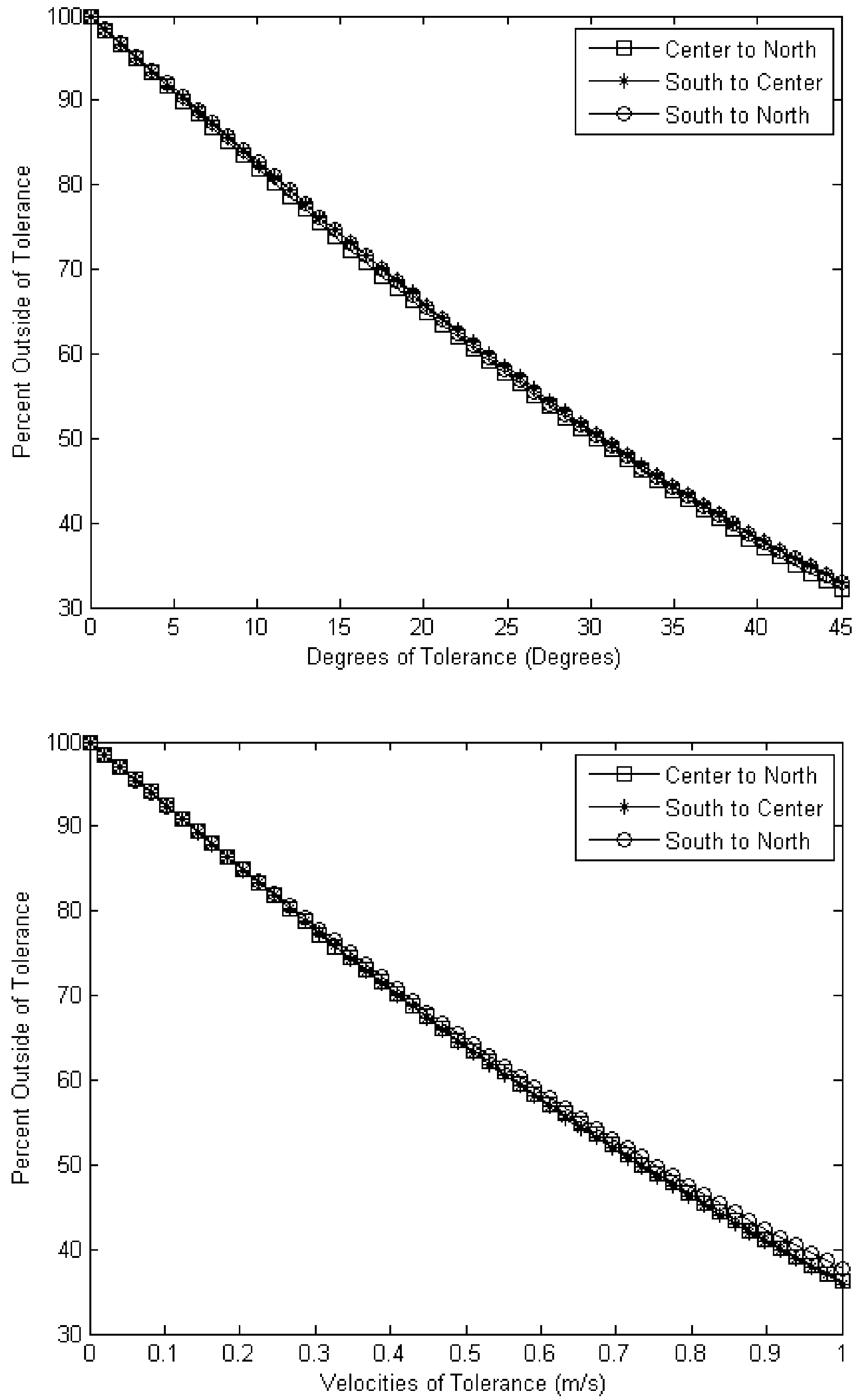


Figure 11: Probability that the downwind sensor is within a tolerance of an upwind sensor for wind speed and wind direction

Parameters related to wind changes

To gain greater insight as to what meteorological weather conditions are present when transient wind velocity changes occur that may affect trajectory after the droplet has left the spray boom, data collected over a range of 36 days (greater than 100 million data points) in the late spring/summer spraying seasons of 2014 and 2015 were analyzed to see when it was more likely to see a change in the wind direction 30 seconds into the future. As data were processed, if the value for wind direction at a sensor, thirty seconds into the future, was greater than a given tolerance (45, 25, or 5 degrees), the current wind direction, speed, solar radiation, and time of day were recorded. Figures 12, 13, and 14 show the percentage of occurrences when wind direction changed by more than 45, 25, or 5 degrees for each individual finite segment of solar radiation, time of day, and wind speed, respectively, when comparing wind direction at a specific time and 30 seconds later at individual wind sensors. For example, at a tolerance of 45 degrees, out of the total time in which the day was between the hours of 1:30 am and 4:30 am, about 5% of that time had a large wind change that was greater than the allowed tolerance.

The figures 12, 13, and 14 show how wind change events are distributed. As the sun heats the earth, increasing the surface energy, the weather becomes turbulent (Stull, 2009) as is seen in Figure 12. As the tolerance is tightened, to 25 degrees and 5 degrees in Figures 13 and 14 the distributions for Time of Day and Solar Radiation become more uniform. However, the tendency for wind directional shifts to occur more frequently at lower wind speeds remains relatively unchanged as tolerance is reduced from 45 degrees to 25 degrees. This shows that most unstable events occur below 1 m/s (2.2 mi/h) winds. Application at low wind speeds is often recommended and may limit the distance of off-target drift even if the likelihood of unforeseen wind directional shift is greater.

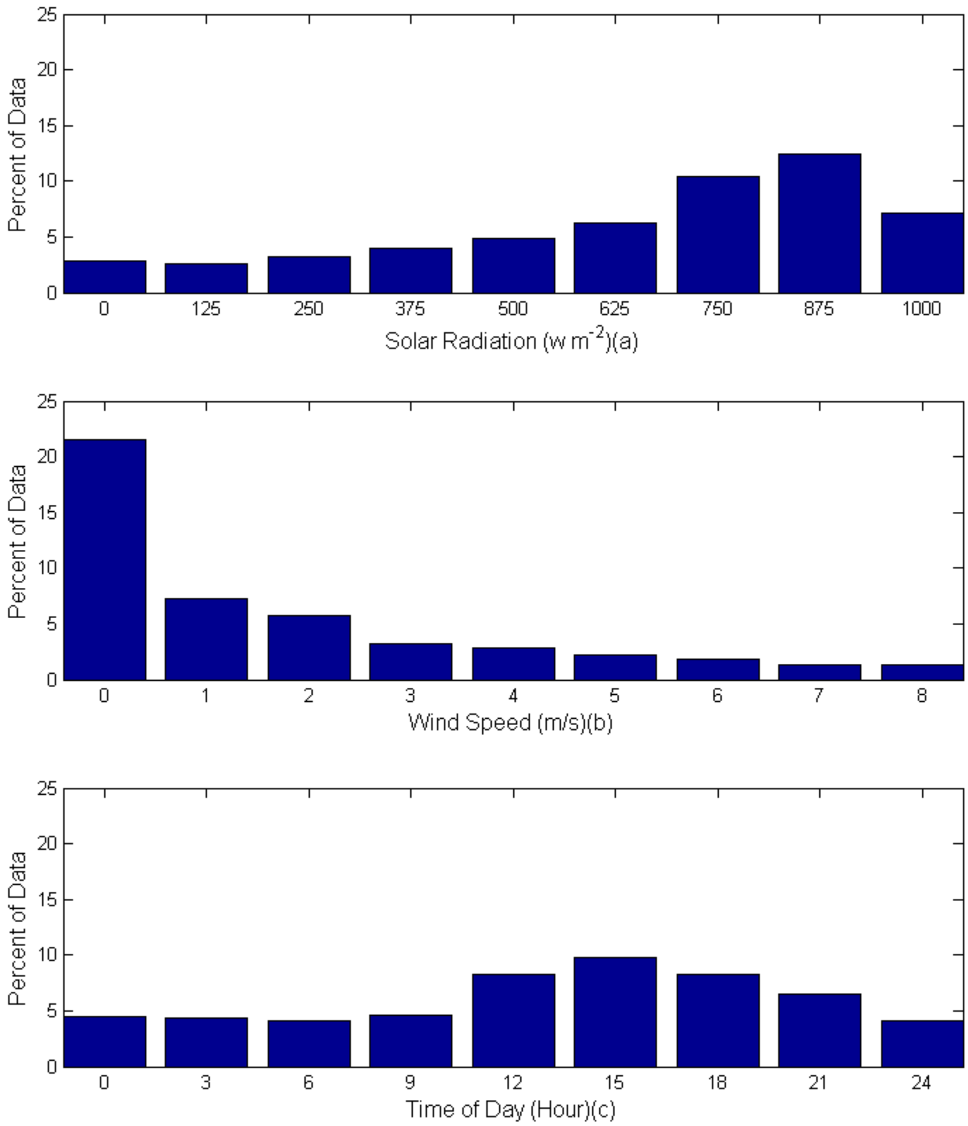


Figure 12: Percentage of data within a certain range in which a wind change 30 seconds in the future was greater than 45 degrees

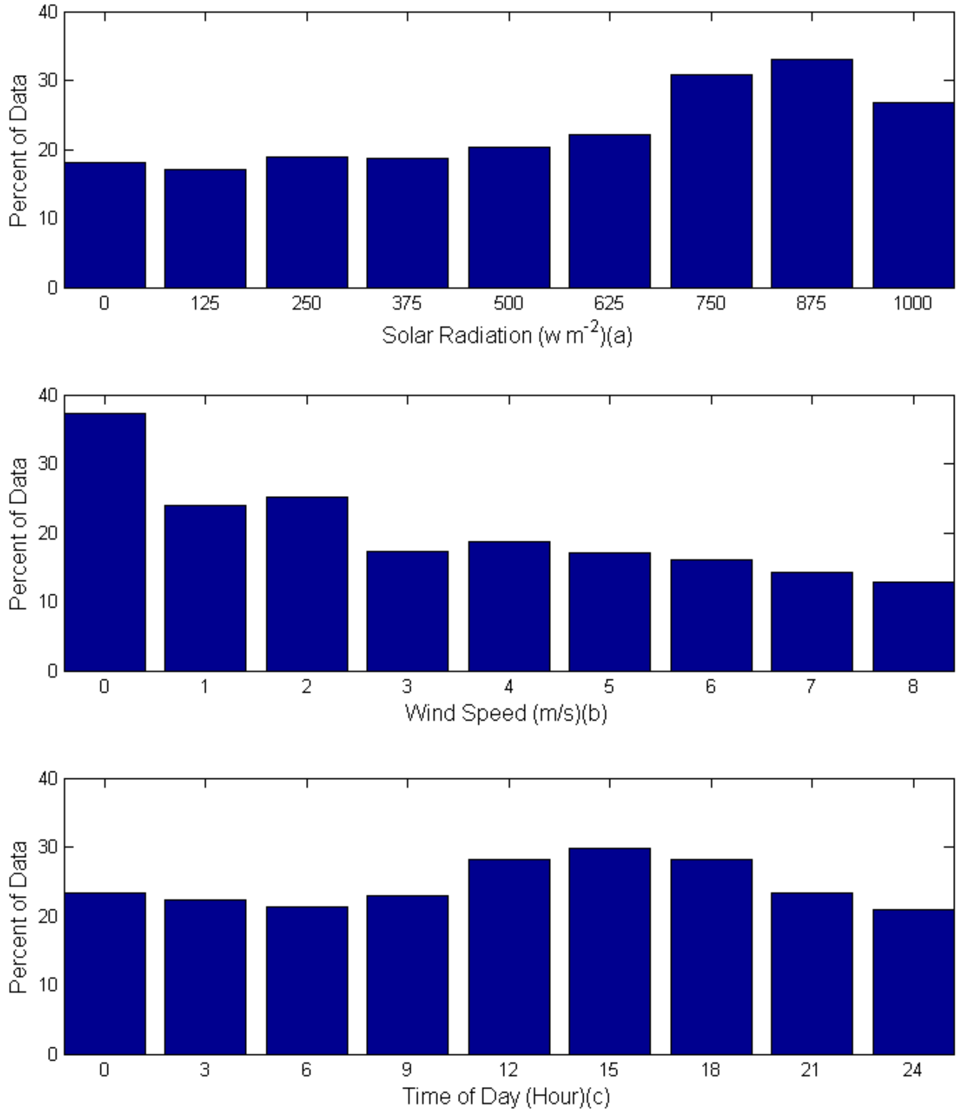


Figure 13: Percentage of data within a certain range in which a wind change 30 seconds in the future was greater than 25 degrees

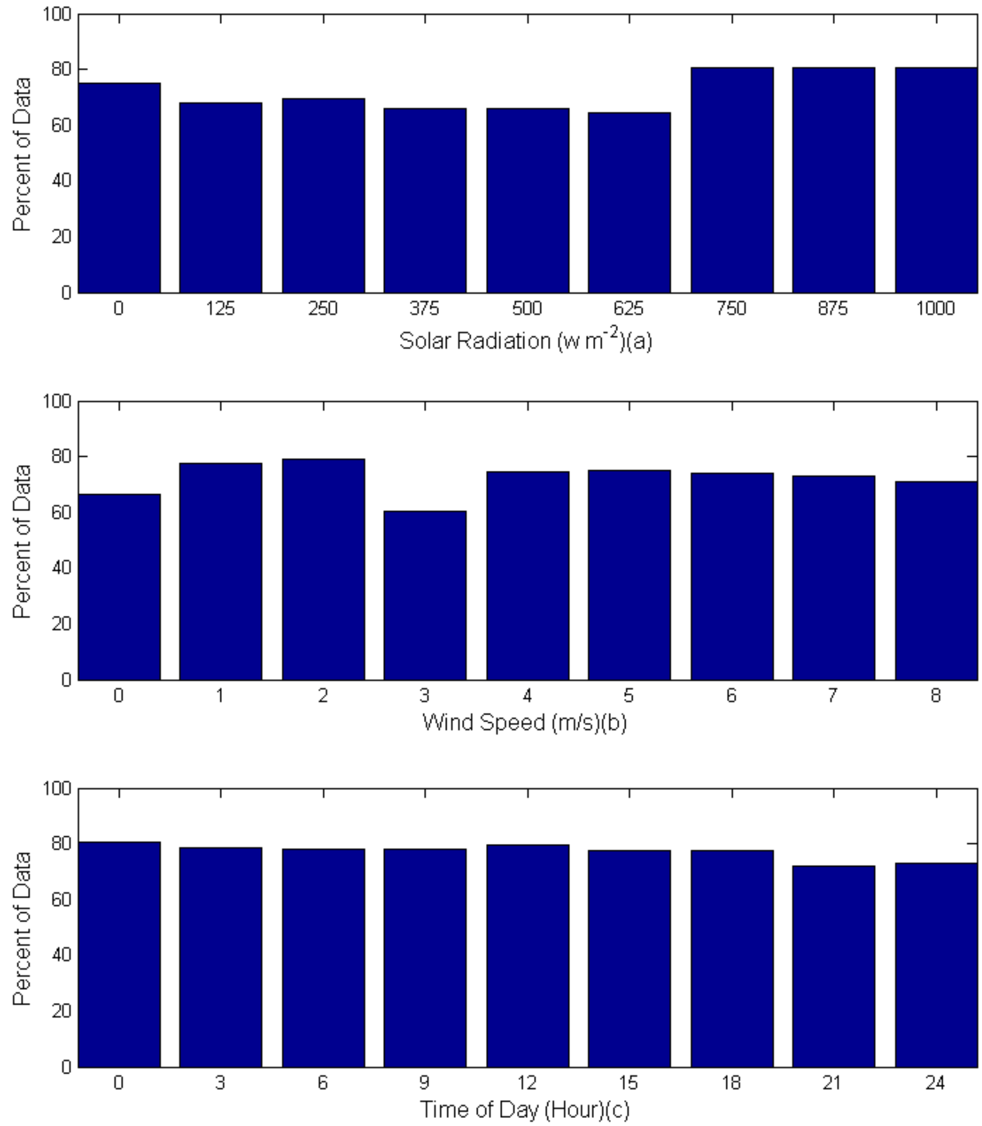


Figure 14: Percentage of data within a certain range in which a wind change 30 seconds in the future was greater than 5 degrees

Conclusion

Wind velocity data taken during late spring/summer conditions that are suitable for ground based spraying support the following conclusions:

- During a five hour period (7:30 am to 12:30 pm) with an average wind speed of 3.6 m/s (8 mi/h) and general wind direction of due north
  - Random fluctuation of wind direction and speed at upwind and downwind sensors, 30 m (100 ft) apart, had correlation coefficients of 0.29 and 0.27
  - Correlation was less during shorter one-minute periods in which a spray droplet may travel, but improved to a coefficient of 0.15 if a lag time was used between the two sensors
  - Using a lag time, downwind direction was greater than 20 degrees different than the upwind sensor 30% of the time while wind speed was greater than 1 m/s (about a quarter of the mean wind speed) different than the upwind speed about 50% of the time
- During a 1.5 hour period (12:50 pm to 2:20 pm) with an average wind speed of 1.5 m/s (3.3 mi/h) and general wind direction of due north
  - Correlation coefficients between the downwind and upwind sensors either 15 or 30 m (50 or 100 ft) apart had lower values < 0.03
  - Downwind direction was greater than 20 degrees different than the upwind direction 65% of the time, while the downwind speed was greater than 0.25 m/s (about a quarter of the mean wind speed) different

than the upwind speed 80% of the time

- Across a range of late spring/summer days in which suitable conditions for ground spraying were present, significant change in wind direction 30 seconds later was more likely to occur during wind speeds in the range of 0-2 m/s (0-4.5 mi/h) with all tolerances
- Solar radiation and time of day seemed to have a greater effect on wind changes when investigating tolerances of 45 degrees, as the tolerance tightened to 5 degrees, solar radiation and time of day became more uniformly distributed

References

Baetens, K., Nuyttens, D., Verboven, P., Schampheleire, M. D., Nicolai, B., & Ramon, H. (2007). Predicting drift from field spraying by means of a 3D computational fluid dynamics model. *ScienceDirect*, 161-173.

Brown, R. B., Carter, M. H., & Stephenson, G. R. (2004, November). Buffer Zone and Windbreak Effects on Spray Drift Deposition in a Simulated Wetland. *Best Management Science, 60*(11), 1085-1090.

Craig, I. P. (2004, June). The GDS Model - A Rapid Computational Technique for the Calculation of Aircraft Spray Drift Buffer Distances. *Computers and Electronics in Agriculture, 43*(3), 235-250.

EPA. (2014, 02 04). *Glossary.* Retrieved from U.S. Enbironmental Protection Agency: http://www.epa.gov/pesticides/regulating/labels/pest-label-training/glossary/

Faires, R. L. (2011). *Numerical Analysis.* Cengage Learning.

Frederic, L., Verstraete, A., Schiffers, B., & Destain, M. (2009). Evaluation of Reatime Spray Drift Using RTDrift Gaussian Advection-Diffusion Model. *Commun. Agric. Biol. Sci., 74*(1), 11-24.

Holterman, H., Van de Zande, J., Porskamp, H., & Huijsmans, J. (1997, December). Modeling Spray Drift from Boom Sprayers. *Computers and Electronics in Agriculture, 19*(1), 1-22.

Nordby, A., & Skuterud, R. (1974). The effects of boom height, working pressure and wind speed on spray drift. *Weed Research, 14*(6), 385-395. doi:10.1111/j.1365-3180.1974.tb01080.x

Smith, D. B., Harris, F. D., & Goering, C. E. (1982). Variables affecting drift from ground boom sprayers. *Transactions of the ASAE, 25*(6), 1499-1523.

Spray Drift Task Force. (1997). *A Summary of Ground Application Studies.* Macon, MO: Agricultural Research Services Inc.

Stull, R. (2009). *An Introduction to Boundary layer Meteorology* (13 ed.). Springer.

Teske, M., Bird, S., Esterly, D., Curbishley, T., Ray, S., & Perry, S. (2002). AgDrift: A Model for estimating near-field spray drift from aerial applications. *Environmental Toxicology and Chemistry, 21*(3), 659-671.

Tsai, M., Elgethun, K., Ramaprasad, J., Yost, M., Felsot, A., Hebert, V., & Fenske, R. (2005). The Washington aerial spray drift study: Modeling pesticide spray drift deposition from an aerrial application. *Science Direct*, 6194-6203.