2013

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Recommended Citation

Tollefson, William, "Effect of atmospheric boundary layer conditions on agricultural spray drift" (2013). *LSU Master's Theses*. 2667.
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EFFECT OF ATMOSPHERIC BOUNDARY LAYER CONDITIONS ON AGRICULTURAL SPRAY DRIFT

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Geography and Anthropology

by
William C. Tollefson
B.S., Mississippi State University, 2011
December 2013

ACKNOWLEDGEMENTS

I would like to acknowledge and thank those who have supported and aided me in my education, research, and time here at Louisiana State University: my advisor Dr. Robert Rohli for all his guidance and support throughout this process; Drs. Roberto Barbosa and Billy Leonard of the LSU Department of Biological and Agricultural Engineering and the LSU AgCenter for their guidance and funding of this work; Jessica Parker, Shelby Williams, and Karla Emfinger for their assistance in conducting field work; Donna Elisar, Angela Singleton, and Thomas Mcclure for their assistance in my work at the Department of Biological and Agricultural Engineering; and Dr. Kristine DeLong for her assistance and for providing funding for my final semester.

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ABSTRACT

Drift of pesticides can be a significant health hazard, particularly in areas where agricultural land is adjacent to a school, retirement home, or other populated area. Off-target drift of pesticides depends on many atmospheric variables, both mechanical and thermal. While non-atmospheric variables, such as applicator nozzle size, height of application, and particle size, can be controlled by the applicator to reduce drift potential, understanding how atmospheric conditions set a framework for drift potential enables applicators to choose to spray when the weather conditions would minimize drift. Specifically, atmospheric stability plays an important role in the near-ground concentration of sprays downwind of the spray site; stable conditions confine spray near the surface if the application occurs near the surface. This project investigates the efficacy of using Pasquill stability classes as a simple way to estimate surface boundary layer stability conditions in the field. Wind speed and a qualitative insolation estimate (strong, moderate, or slight) are used to determine the Pasquill stability class. A series of case studies conducted under varying Pasquill stability classes near Winnsboro, Louisiana, provides data to test the efficacy of Pasquill stability classes as drift predictors. Results suggest that the Pasquill stability estimates give applicators a useful method for estimating downwind dispersion and drift under a wide range of atmospheric conditions, thereby improving their ability to make informed decisions to reduce the risk of off-target drift.

CHAPTER 1: INTRODUCTION

Pesticide and herbicide treatment of crops often benefits agricultural yields, but drift of agricultural sprays to off-target areas raises concerns about the environmental impacts of this practice (Holterman et al. 1997). The U.S. Environmental Protection Agency (EPA) cautions that spray drift not only leads to harmful direct exposures to farm workers, nearby population, and wildlife, but also contaminates nearby crops, domestic gardens, and wildlife habitats that might be vulnerable to treatment (EPA 1999). Even if not harmful, the pesticide residues may reach crops advertised as grown organically. The proximity of residents in rural agricultural communities to targeted spray areas increases their risk of exposure (Tsai et al. 2005). The 2010 U.S. census recorded that roughly 25 percent of Louisiana residents live in rural areas (USDA 2011); thus, many people in Louisiana have an elevated risk of exposure to agricultural spray drift.

Rachel Carson, the mother of the modern environmental movement who brought national attention to the problems of using extremely toxic pesticides, described drift in her testimony in a U.S. Senate hearing as, "The phenomenon that plagues every householder who receives contaminating spray from his neighbor across the street, or from his government's spray planes several miles away (Testimony of Rachel Carson to the Senate Hearing on Interagency Coordination of Environmenal Hazards 1964)." In her book *Silent Spring*, Carson gives an example of the worst case drift scenario where a boy, playing in his yard, died after spray drifted in from an adjoining field where his father was spraying an extremely toxic pesticide (Carson 1962).

In response to serious and sometimes deadly side effects of pesticide use, the EPA and many state agencies were tasked with pesticide regulation (EPA 1992). While that regulation has helped reduce the deadly consequences of pesticide use, drift still poses a risk to humans, animals, and plants in proximity to targeted spray areas. To address those risks, the Louisiana State University (LSU) AgCenter began a project in April 2011 under the direction of Dr. Roberto Barbosa (Department of Biological and Agricultural Engineering) and Dr. B. Rogers Leonard (Professor, Macon Ridge Research Station, LSU AgCenter) to investigate current application and drift reduction techniques, and then propose new techniques with guidelines to increase efficacy of pesticide/herbicide treatments and reduce drift. To attain those objectives, the project focuses on two drift related variables—equipment-related and weather-related—to find which conditions, equipment, and techniques minimize drift while maintaining spray efficacy. A review of relevant literature revealed that droplet size is the primary factor influencing the efficacy and drift potential of a pesticide. This means that smaller spray droplets increase the efficiency of coverage of target area while simultaneously increasing the risk of off-target drift by allowing the droplet to be more influenced by near-surface air motion (e.g., Bache and Johnstone 1992). Research previously conducted by the LSU AgCenter focused mainly on the equipment/mechanical-related variables affecting drift. This research focuses on the project's second objective of identifying weather/environmental-related variables affecting drift, and producing simple rules of thumb regarding what weather conditions are or are not suitable for spray operations.

There are two main drift reduction approaches: active and passive. Active approaches to reducing drift include mechanical spraying equipment and techniques for reducing the amount of drift-prone droplets, including nozzle types, application pressure, and shields (Felsot et al. 2011). Passive methods act to reduce the effects of drift or amount of drift particles and include buffer zones and wind breaks (Felsot et al. 2011). Another possible passive technique for reducing drift involves application of sprays during atmospheric conditions that will reduce drift probability, or at least avoiding application during conditions known to cause large drift events. Many models for the dispersion and drift of pesticides have been developed including: Forest Service, Cramer, Barry and Grim (FSCBG) model described by Teske et al. (1993), the Institute of Environmental and Agricultural Engineering's Program for Drift Evaluation from Field Sprayers by Computer Simulation (IDEFICS) model by Holterman et al. (1997), a spray transport model by Raupach et al. (2001), the Gaussian diffusion sedimentation (GDS) model by Craig (2004), a computational fluid dynamics (CFD) model by Baetens et al. (2007), the Oklahoma Dispersion Model by Carlson and Arndt (2008), a diffusion-advection model by Baetens et al. (2009), and a real time drift model (RTDrift) by Lebeau et al. (2011). Collectively, these models show that meteorological variables such as wind speed and direction, atmospheric stability, and relative humidity do affect drift; however, most of these models are computationally intense and require precise input data which would usually be unavailable for field applicators. This project investigates the possibility of using simple weather observations to estimate the drift risk posed by atmospheric conditions, that would allow applicators to make more informed choices to protect nearby areas from drift.

Pasquill (1961) derived relationships between simple observations on sun angle, cloud cover, and wind speed to estimate the general category of boundary layer atmospheric stability conditions. These categories (A-F) are known as Pasquill stability classes and allow certain reasonable assumptions to be made about drift risk under conditions within each category (Pasquill 1972). For this project, several case studies were conducted in which spray deposition was measured at certain distances from a spray path under different stability classes to determine the amount of pesticides moving beyond the desired application site.

Understanding the combination of mechanical and environmental conditions that maximize the efficiency of pesticide application and minimize off-target drift is of great importance to the agricultural community of Louisiana. In addition to providing environmental and health benefits reducing off-target drift reduces the volume of pesticides needed to be applied to an area, increasing efficiency of on-target deposition, which provides an economic incentive for responsible spraying practices (Stover et al. 2004). Maximizing spray efficiency and minimizing drift provides economic gain by reducing the risk of crop damage due to pests and weeds as well as damage to nearby, non-target crops from drift of an unnecessary or even deleterious pesticide.

While there is no perfect method of eliminating drift, a wide range of drift reduction equipment, techniques, and practices can be employed. A major component of reducing drift in real-world situations is education (Felsot et al. 2011, Stover et al. 2004). According to the U.S. EPA (1999), parties responsible for the application of pesticides and herbicides are responsible for using all available application practices for reducing spray drift, and must consider all factors, including meteorological conditions, before deciding to apply these products. Relaying knowledge to applicators and those working in the agricultural industry so they can make informed decisions about pesticide application and drift reduction should be a top priority of government agencies and university extension programs. The creation of a simple guide for minimizing drift, based solely on estimation of sun angle, wind velocity, and cloudiness, will give applicators a powerful new tool to reduce agricultural spray drift.

After providing a more detailed background on the atmospheric dispersion literature, Chapter 2 will articulate the specific objectives and detailed hypotheses of this research. Chapter 3 will describe the methods used in the field experiments to relate atmospheric conditions to spray drift over an agricultural field in northern Louisiana, with Chapter 4 presenting the results of those experiments, and Chapter 5 offering discussion on those results. Finally, Chapter 6 will offer conclusions and suggestions for further research on this topic.

CHAPTER 2: BACKGROUND

2.1 Pesticide Use and Risks

In developed nations 3-5 percent of the population produces the food consumed by the rest of the population with excess exported to other nations. The level of agricultural production and the high standard of living in the United States and much of the developed world would not be possible without the use of pesticides. Humans have been using natural compounds to fight pests—plants and animals that endanger crops or human health and/or comfort—since ancient Roman times. Chemical pesticides were in widespread use among U.S. farmers to protect their field crops from pests by the end of the 19th century (Delaplane 1996). Several highly-toxic, synthetic pesticides were developed during a research boom spurred by World-War II, and were put into use in the United States and other countries without the due process of risk assessment. “For a country consumed with fears of Soviet aggression, the Korean War, McCarthyism, polio, civil rights, Sputnik, and rock’n’roll, pesticide dangers hardly registered—at least not until in 1962 when Rachel Carson published *Silent Spring*” (Daniel 2005, p. 2). These new pesticides, which were inexpensive and effective, were seen as a miracle of science and were advertised as such to the agricultural community and the public at large (Daniel 2005). In his book *Toxic Drift*, Pete Daniel (2005) discussed how many pesticide-related health effects have arisen from widespread use of synthetic pesticides on farms, in yards, in and around buildings, and within urban areas in the last half of the 20th century. Much has been accomplished since the 1960’s to reduce the negative impacts of pesticide while maximizing their benefits, yet there is more work that needs to be done.

To understand the risks that pesticide drift poses to humans, one must first understand the possible negative health effects of pesticide exposure, and the processes that disperse pesticides causing drift. Pesticides, being toxic by design, have a wide range of negative health impacts in humans, ranging from simple skin or eye irritation to death (Hallenbeck and Cunningham 1985). The World Health Organization (WHO) estimated that 20,000 deaths and 3 million cases of acute poisoning annually are the result of pesticide use, principally in the rural agricultural communities of developing countries (WHO 1990).

Exposure to pesticides can occur in three forms—inhalation, dermal exposure, or oral ingestion, which can come from direct exposure, or through contaminated food or water (EPA 2007). Lee et al. (2011) collected data from 11 states for a period from 1998 to 2006 to identify acute illnesses thought to be caused by pesticide exposure. The authors found that 44 percent of the cases involved exposure to toxic pesticides at a private residence and in 37 percent of cases the individuals were exposed on a farm or nursery. They also found that incident reports of pesticide drift events cited applicator error or carelessness and unfavorable weather conditions as the main causes of drift exposure (Lee et al. 2011).

In the wake of environmental and health disasters and the public outcry brought about largely by *Silent Spring*, the U.S. government established the EPA to establish and enforce environmental protection standards (EPA 1992) including pesticide regulation. The EPA works with federal and state governments to regulate pesticides to ensure that their use does not pose unreasonable risks to human or environmental health (EPA 2007). The EPA uses the National Research Council’s (NRC 1983) four-step process for human health risk assessment: hazard identification, dose-response assessment, exposure assessment, and risk characterization. The first step, hazard identification, or toxicology, identifies potential health effects that may occur from exposure to a pesticide’s active ingredients. Dose-response assessments serve to observe what exposure levels lead to adverse effects in test animals; those levels are then scaled to determine ‘safe’ levels of exposure in humans. Exposure assessments test how pesticides enter the body and the effects of differing exposure levels and duration. Risk characterization combines the knowledge gained from the previous steps and describes the overall risk a pesticide poses to human health, with a general working equation stating that risk is equal to the toxicity of the compound multiplied by the possibility of exposure. Based on this risk assessment, the EPA determines whether there is reasonable certainty that, if used according to label directions, a pesticide will not harm a person’s health; if not they may prescribe additional protective measures to limit harmful exposure (EPA 2007). Once the EPA deems a pesticide safe, it can be sold and used. Even with the regulations enacted by the EPA to reduce the human and environmental health risks of pesticide use, the off-target drift of pesticides still poses a threat to human, animal, and plant populations in proximity to spray areas. The application of a pesticide to crops or other target areas cannot be completely contained within that target area due to the nature of droplet dispersion. It is inevitable that some droplets of that pesticide will drift in the air and settle outside the original target area (Felsot et al. 2011).

2.2 Causes of Off-Target Drift

The *Glossary of Terms Relating to Pesticides* (Stephenson et al. 2006) defines dispersion as the movement of particles or molecules from regions of higher concentration to areas of lower concentration, in accordance with the second law of thermodynamics, due to the random movement of particles or turbulent mixing over the gradient. In addition, the glossary defines spray drift as the movement of spray droplets beyond the intended application area. The dispersion of pesticides applied to agricultural fields depends on many factors, ranging from mechanical to meteorological, with droplet size being a key factor in how the spray moves in the environment. Properties that affect the size of droplets produced during pesticide spraying include physical properties of the spray and the mechanical properties of the sprayer such as, the type of sprayer nozzles, sprayer pressure, and speed of application vehicle (Felsot et al. 2011, Hilz and Vermeer 2013, Holterman et al. 1997, Matthews 2006). The size of the droplets produced during a pesticide application is important because it determines the effective coverage of the targeted plant or pest, with smaller droplets providing better coverage; however, droplet size plays a major role in the potential for off-target drift with smaller droplets (100-200 millionths of a meter or micrometers (μm), or smaller) creating a higher risk (Bache and Johnstone 1992, Matthews 2006).

The dispersion distance of any aerosol spray released near the surface depends on local atmospheric processes (Bache and Johnstone 1992). Many meteorological factors have been cited as influencing spray dispersion and drift: wind speeds, surface boundary layer (SBL) stability, turbulent flow, humidity characteristics, solar radiation, local lapse rates, and relative humidity (Bache and Johnstone 1992, Bird et al. 1996, Felsot et al. 2011, Fritz 2006, Miller et al. 2000, Miller 1993, Pasquill 1961, Yates et al. 1967). Unlike mechanical factors, meteorological factors cannot be controlled by the applicator to reduce off-target drift (Fritz 2006). By understanding their effects on dispersion and drift it is possible to know which conditions lead to a minimization of off-target drift. The three micrometeorological factors that influence pesticide dispersion the most are wind (speed, direction, and shear), SBL stability, and relative humidity (RH) (Miller et al. 2000).

Winds, stability, and RH are closely related in the SBL with complex interactions between the three having a large impact on spray dispersion and drift. Although RH does not directly influence the dispersion or drift of pesticides, along with temperature it is a surrogate for vapor pressure. Vapor pressure relates to the evaporation rate of liquids in the spray droplets, with the rate of evaporation increasing as humidity decreases. The RH and temperature can therefore be used to estimate how evaporation affects droplet size (Bache and Johnstone 1992, Holterman et al. 1997, Sundaram and Sundaram 1991). Relationships between RH and droplet size are well understood with the studies of Bache and Johnstone (1992) and Miller (1993) providing analytical calculations for those relationships. Droplet size in a spray cloud correlates to the residence time—the amount of time the droplet will remain suspended in the air before settling on a surface, thus the magnitude with which SBL stability affects drift (Bache and Johnstone 1992, Bird et al. 1996, Crabbe et al. 1994, Miller et al. 2000, Miller 1993). Several papers determine that wind speeds are the dominant factor determining the amount of spray deposited on near field sites (< 1000 m from target site) due to the gravitational settling of larger particles (Crabbe et al. 1994, Maybank et al. 1978, Yates et al. 1967). Winds and stability are closely related in the SBL; that relationship will be discussed in further detail later.

SBL stability is the extent to which convection is suppressed (in a stable atmosphere) or enhanced in an unstable atmosphere by local atmospheric conditions at a given time and place thus affecting spray dispersion and drift in several ways. Stability and the related concept of turbulent mixing directly influence the vertical spread of spray droplets; both are influenced by the strength of near-surface winds, resulting in the physical processes determining how spray droplets will move (Miller et al. 2000, Thistle 2000). The complex nature of SBL stability means that the physical processes governing stability must be well-understood before the relationship between dispersion and drift can be known. Atmospheric stability includes both thermal and mechanical turbulence. Turbulence is the process by which energy is transferred through the atmosphere via eddies (Arya 2001). Energy is transferred from larger eddies to smaller eddies until the subsequent eddies become too small to overcome the air's viscosity; then the energy is transformed into heat (Thistle 2000).

Thermal turbulence, also known as static stability, provides a measure of buoyant convection. Temperature and therefore pressure differences between parcels of air and the surrounding atmosphere are responsible for thermal turbulence (Fritz 2006). The temperature differences between parcels in the SBL are due to differential surface heating, which is a result of solar radiation interacting with different surface covers. The rising and sinking of parcels caused by thermal turbulence control the vertical extent of motions within a spray cloud, and therefore the amount of material staying near the ground downwind of the release site (Miller et al. 2000).

Mechanical turbulence, also known as dynamic stability, is turbulence caused by wind shear (Miller et al. 2000) and surface stresses, leading to disturbances in air flow (Bache and Johnstone 1992). Mechanical turbulence mixes air in the SBL, allowing better dispersion of the spray cloud, reducing concentrations downwind (Thistle 2000). However, the mixing caused by mechanical turbulence reduces the temperature differences responsible for thermal turbulence; in effect high mechanical turbulence decreases the effect of thermal turbulence (Miller et al. 2000). SBL stability is therefore closely related to wind speed and shear since those are the factors responsible for creating mechanical turbulence.

The following discussion summarizes the work of Miller et al. (2000) on the different mechanisms controlling the drift of spray clouds in different stability profiles. In an unstable atmosphere, the movement of the cloud is dependent on short-lived coherent turbulent events, which means that the cloud is dispersed in several directions with varying intensity, depending on turbulence patterns. In a stable atmosphere, the spray cloud is restricted near the ground and is more influenced by mechanical turbulence caused by surface stress. That study concluded that during unstable conditions the spray droplets mix well in the vertical direction due to the larger and stronger eddies, so little drift is recorded near the ground. In similar manner, the authors concluded that stable conditions, leading to small, weak eddies, which do not allow vertical mixing, causing the spray to migrate downwind with relatively little mixing (leading to high drift measurements).

In addition, the study of Thistle (2000) found that during stable atmospheric conditions eddies are suppressed and have a low amount of kinetic energy, which allows the spray cloud to remain intact, leading to a narrow concentrated plume near the surface far downwind. By contrast, in unstable atmospheric conditions turbulent eddies have a large amount of kinetic energy and can grow large in size, leading to a spray cloud that is dispersed quickly and effectively. That efficient dispersion leads to a broader downwind plume with much lower concentrations of spray droplets.

After pesticides are applied, the large droplets settle on the crop or surrounding ground within the target area while the smaller droplets with a sedimentation velocity—the droplet's velocity at which gravity can pull it to the ground — weaker than the turbulent motion of surrounding air will remain airborne and drift off the application site (Bache and Johnstone 1992, Davies 1966). To reduce the risk of direct exposure to bystanders and nearby environments, spraying conditions should be such that large droplets are able to easily settle on target, while smaller droplets are able to mix with surrounding air, horizontally and vertically, to reduce the concentration of the drift cloud. Having low to moderate wind speeds and moderate to high insolation rates provides such conditions that allow larger droplets to settle but smaller droplets to be mixed by SBL turbulence driven mainly by thermal instability (Miller et al. 2000, Thistle 2000).

Different researchers measure stability in different ways for studying its effects on dispersion and drift. Measurements of SBL stability should be based on the two types of turbulence, or stability; that is, they should take into account both winds and radiation. Many types of stability measurements including: the turbulent kinetic energy equation, the Richardson number, and other stability factors have been used to achieve this by examining temperature and wind speed.

The turbulent kinetic energy (TKE) equation (Stull 1988, Thistle 2000) – an overall measure of turbulence intensity – can be used to understand the stability of the SBL. The terms of the TKE describe the amount of turbulence created by mechanical forces (wind shear) or buoyant (thermal) forces:

$$\frac{\partial \bar{e}}{\partial t} = -\left(\overline{u'w'}\right)\left(\frac{\partial \bar{u}}{\partial z}\right) + \frac{g}{\bar{\theta}}\left(\overline{w'\theta'}\right) - \frac{1}{\rho}\frac{\partial}{\partial z}\left(\overline{w'p'}\right) - \frac{\partial}{\partial z}\left(\overline{ew'}\right) - \varepsilon$$

Where $\bar{e}$ is the mean TKE, *t* is time, *u* is west-to-east component of motion, *z* is height, *g* represents the acceleration due to gravity, *θ* is potential temperature (the temperature that an air parcel would have if it were moved dry adiabatically to the 1000 hPa level), *w* is down-to-up component of motion, *ρ* is density, *p* is pressure, and *ε* is the viscous dissipation of TKE to heat at the molecular level. The ∂ symbol refers to a partial derivative – the rate of change of the variable of interest (in the numerator) as the other variable (in the denominator) changes, while holding the effects of all other variables constant. The first, third, and fourth terms of the right side of the TKE equation – advection, pressure correlation, and vertical transport — are always positive, meaning that they contribute to TKE. The fifth term of the right side of the equation represents the turbulent energy that is converted to heat, and always detracts from TKE. Unlike the rest of the terms the second term, (buoyant flux) can be either positive or negative and therefore can contribute or detract from TKE, depending on the thermal structure of the SBL. If potential temperature is increasing with height, this term will be negative and buoyant flux will dampen turbulence; decreasing potential temperatures with height are associated with positive buoyant flux term and enhance turbulence (Stull 1988, Thistle 2000).

The gradient Richardson number (Ri) – the dimensionless ratio of thermal to mechanical turbulence – is commonly used to quantify atmospheric stability in the SBL (Anderson et al. 1992, Payne 1992). Ri utilizes temperatures and wind speeds from two heights within the SBL to provide a measure of the overall stability or turbulent characteristics of the SBL. The study of Stoughton and Miller (2002) found that Ri provides an adequate value for stability during turbulent conditions. However, during near-neutral and stable conditions Ri values were projected as being overly stable compared to other stability measures, including the stability parameter ζ used by Miller et al. (1996), Miller et al. (2000), and Stoughton et al. (1997). The ζ parameter is defined as $\zeta = \frac{z-d}{L}$, where *z* represents the measurement height (m), *d* is the height of zero plane displacement (m), and L represents the Obukov length ($L = \frac{\rho c_p T u_*^3}{kgH}$), where ρ represents density (kg m^{-3}), c_p is specific heat of air (J kg^{-1} K), *T* is virtual air temperature (K), u_* is friction velocity (m s^{-1}), *k* represents the dimensionless ratio of vertical turbulence of an eddy in statically-neutral conditions to the mixing length (or von Karman's constant (0.4)), *g* is the acceleration due to gravity (m s^{-2}), and *H* is the sensible heat flux (W m^{-2}).

The studies of Yeo and Thompson (1953) and Renne and Wolf (1979) used the stability factor denoted as "F" ($F = \frac{T_{2-T_1} - \Gamma \Delta H_{2-1}}{\bar{u}^2}$), which was derived as an effective and measurable replacement for Ri (Yeo and Thompson 1953) where Γ is the dry adiabatic lapse rate (9.8 K km^{-1}) and $\overline{u}$ is the average wind speed (m s^{-1}) measured at the two heights.

In a series of experiments in 1963 and 1964 Yates et al. (1967) created a stability ratio (SR) using the equation $SR = (\frac{T_2 - T_1}{u^2})10^5$, where T_2 and T_1 are temperatures at two different heights (°C) and u is the mean horizontal wind speed in cm s^{-1} at the geometric mean height between the heights of the temperature measurements. The study of Yates et al. (1974) then created a classification system for the stability ratio that included classes for unstable, neutral, stable, and very stable with corresponding SR values of -1.7 to -0.1, -.1 to .1, 0.1 to 1.2, and 1.2 to 4.9 respectively.

A wide range of results has been reported in field trials studying the atmospheric effects on drift due to the near impossibility of duplicating atmospheric conditions between studies (Maccollom et al. 1986, Thistle 2000). Results from most field trials and models show that SBL stability greatly contributes to dispersion patterns and drift of sprays. Increasing stability has been shown to correlate with increasing drift (Anderson et al. 1992, Bird et al. 1996, Crabbe et al. 1994, Maccollom et al. 1986, Miller and Stoughton 2000, Stoughton and Miller 2002, Thistle 2000).

The study of Crabbe et al. (1994) studied early morning aerial application, which was the favored practice for spraying pesticides in orchards due to the ease and safety of flight in low turbulence conditions and low surface wind speeds. They found that spray application early in the morning, often during temperature inversions, led to increased drift deposits on downwind surfaces, because the inversion hindered the vertical mixing of the spray cloud.

All of the authors mentioned above succeeded in using their respective stability measures to assess dispersion; however, all of the measures require input data too specific for an *in situ* field estimation of SBL stability. Although these stability measures are good for theoretical application, or intensive field research, they are impractical for pesticide applicators to use, due to the lack of specialized equipment for measuring the required input parameters. This chapter will therefore continue to investigate pesticide dispersion by representing SBL stability in terms of Pasquill stability classes which require only general measurements and inputs. The study of Pasquill (1961) developed a stability classification scheme based on wind speed and insolation rates of strong, moderate, or slight, discussed further in section 2.3.

2.3 Dispersion Modeling

In recognition of the importance of stability, the report of Pasquill (1972, p. 5) surmised that, it would be possible to define ‘normal’ values of plume spreading for given combinations of wind speeds and the amount of solar radiation reaching the ground. Using those categories would obviate the need for specialized meteorological data in the calculations of drift. To that end, the study of Pasquill (1961) developed a classification method – Pasquill Stability Classes – to distinguish atmospheric stability features within the SBL. Pasquill Stability Classes use wind speed and visually-based incoming solar radiation (insolation) estimates to categorize stability in the SBL, thereby circumventing the need for making more complicated measurements of vertical velocity and thermal gradients required by other stability indexes. The Pasquill classes range from A to F, with the stability ranking of each category shown in Table 2.1, and the criteria for classifying conditions into a Pasquill class are presented in Table 2.2. It should be noted that for classification strong insolation corresponds to a sun elevation angle of greater than 60° above the horizon, moderate insolation occurs when the sun elevation is between 35-60°, and slight insolation corresponds to times when the sun elevation angle is less than 30°. It should be noted that middle clouds with broken or overcast coverage reduce insolation from strong to moderate and similar coverage with low clouds reduces insolation from strong to slight (Eagleman 1991).

Table 2.1: Pasquill Classes and Associated Stability Conditions

Pasquill Class	Stability Conditions
A	Extremely Unstable
B	Moderately Unstable
C	Slightly Unstable
D	Neutral
E	Slightly Stable
F	Moderately Stable

Table 2.2: Determination of Pasquill Class

Wind Speed ($m\ s^{-1}$)	Strong Insolation	Moderate Insolation	Slight Insolation	Nighttime, >1/2 Cloudiness	Nighttime, <1/2 cloudiness
<2	A	A	B	E	F
2-2.99	A	B	C	E	F
3-3.99	B	B	C	E	F
4-4.99	B	C	D	D	E
5-6	C	C	D	D	D
>6	C	D	D	D	D

The study of Pasquill (1961) plotted the horizontal angular spreading of a plume at two distances downwind from a point source under the different stability classes. Using those plots he was able to determine corresponding equations which estimate the horizontal fluctuations of the wind over the time required for the plume to travel a certain distance. The study of Gifford (1960) converted the plume width and height into the parameters σ_y and σ_z , representing the standard deviation of the plume concentration, using a series of equations based on Pasquill's stability classes, called the Pasquill-Gifford dispersion parameters. The Pasquill-Gifford parameters simplified the use of Pasquill classes in Gaussian plume equations. Briggs (1973) developed a series of empirical equations (Table 2.3), from dispersion experiments run near St. Louis, Missouri, which estimate the values of σ_y and σ_z to further simplify Gaussian dispersion equation calculations using Pasquill stability classes.

Table 2.3: Briggs Equations for Pasquill-Gifford Parameters for Open Country Conditions

Pasquill Class	**σ_y**	**σ_z**
A	$0.22x*(1+0.0001x)^{-1/2}$	$0.20x$
B	$0.16x*(1+0.0001x)^{-1/2}$	$0.12x$
C	$0.11x*(1+0.0001x)^{-1/2}$	$0.08x*(1+0.0002x)^{-1/2}$
D	$0.08x*(1+0.0001x)^{-1/2}$	$0.006x*(1+0.0015x)^{-1/2}$
E	$0.06x*(1+0.0001x)^{-1/2}$	$0.03x*(1+0.0003x)^{-1}$
F	$0.04x*(1+0.0001x)^{-1/2}$	$0.016x*(1+0.0003x)^{-1}$

2.4 Drift Reduction Measures and Integrated Pest Management

Any spray-application of pesticides will result in some amount of drift due to the nature of the SBL, but equipment and spray practices exist that decrease the amount of drift observed (Felsot et al. 2011, Yarpuz-Bozdogan and Bozdogan 2009). Several methods have been suggested for reducing drift and its negative health impacts. Some groups argue that the negative effects on human health and the environment are too great to continue use of chemical pesticides, believing their use should be eliminated to ensure a more sustainable agriculture, putting food security, health, and the environment above the increased production that they could provide (Dinham 1993). That option may seem best from a purely environmental standpoint; however, entirely eliminating chemical pesticide use would come at a cost of decreased crop yield and seem like an unattainable goal.

Barring the elimination of chemical pesticides, the use of materials and techniques which reduce the amount of, or even the need for, those chemical pesticides provides the best way to reduce the risk of exposure thus related health and environmental problems. Integrated pest management (IPM) is a systematic approach wthat strives to provide a cost-effective and environmentally sound way of managing the health and productivity of crops (Damalas and Eleftherohorinos 2011). IPM has been discussed and used for about 50 years, and is defined by the Food and Agriculture Organization of the United Nations (UN) as "a pest management system that in the context of the associated environmental and population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest population at a level below those causing economic injury (Food and Agriculture Organization 1968)." If farmers are able to keep pest levels below damaging levels using IPM methods, which reduce the amount of pesticides needing to be applied, it will provide both environmental and economic benefits.

The study of Felsot et al. (2011) provides an in-depth review of current studies and methods focused on reducing drift from the technological or engineering viewpoint. Droplet size is the major mechanical factor determining drift, because smaller droplets have a longer residence time and can be carried farther off-target than larger droplets that settle quickly (Davies 1966, Felsot et al. 2011, Holterman et al. 1997, May and Clifford 1967). Several mechanical solutions for reducing drift are based on this principle. One technique centers on using nozzles designed to create fewer small droplets (Yarpuz-Bozdogan and Bozdogan 2009). Adding emulsifiers to the spray solution is another method used to create larger droplets that will have lower drift potential (Felsot et al. 2011, Stover et al. 2004).

Windbreaks and buffer zones which serve to reduce drift or its negative impacts are employed in the design of agricultural sites (Burn 2003, Felsot et al. 2011, Stover et al. 2004). Buffer zones do not actually impede the drift of pesticides, but provide a space for droplets to settle before entering a risk area (e.g. residence, playground, or water body). Buffer zones composed of bare ground, or sown in grass, or other short vegetation, which is better at absorbing the spray without negative effects, can protect sensitive areas or species from pesticide use in nearby areas (Burn 2003). Typically, buffer zones are prescribed at 3,6, or 8 meters beyond the edge of the treated areas to allow space for most spray droplets to settle (Burn 2003, Felsot et al. 2011), but larger buffers can be implemented in areas where drift poses a higher risk (Burn 2003). Windbreaks are rows of vegetation, cloth, webbing, mesh, or fences that reduce wind velocity, thus the drift of pesticides beyond the windbreak (Felsot et al. 2011). Windbreaks are commonly used in orchards and vineyards, and have been found to reduce by 83-97 percent the measured amount of spray droplets downwind, which depends on the height and density of the windbreak (Lazzaro et al. 2008).

One part of the IPM method is to determine when to apply a pesticide, if needed, to increase the efficiency of the application and to reduce the off-target drift. As discussed previously applying pesticides in weather conditions that will not enhance drift plays a major role in reducing off-target drift. This study, with the goal of finding a method for anticipating drift risk based on simple, *in situ* observations, fits well within the concept of IPM. This study seeks to find a method for pesticide application, which will reduce the negative environmental impacts.

2.5 Objectives

The objectives of this project are as follows:

1) Determine if dispersion and deposition patterns of agricultural sprays are significantly different under the different Pasquill classes. It is hypothesized that conditions classified under different Pasquill classes will have significantly different dispersion and deposition characteristics, thus making them a viable way to predict drift.
2) Determine the Pasquill classes under which agricultural sprays are most prone to drift. It is hypothesized that the more stable Pasquill classes will allow more drift as the spray cloud is able to move beyond the application site without entrainment and reduced concentration.
3) Produce a field guide to be used by pesticide applicators to determine drift risk based on simple SBL meteorological observations. It is hypothesized that by using this guide and their observations applicators could reduce drift hazards for nearby crops, wildlife, and populations.

CHAPTER 3: METHODS

The materials and methods used in the field studies and their analysis were modified from those used in initial drift measurement tests (Roberto Barbosa, personal communication, 2011), and are outlined below. Field trials were conducted at the Macon Ridge Research Station of the LSU AgCenter near Winnsboro, Louisiana, with the assistance of station staff. The chemical makeup and the method of applying the spray remained constant, to isolate the effects of meteorological factors on drift.

3.1 Case Studies

Case studies were conducted to gather data used to test the real world feasibility of using the Pasquill stability classes as indicators for drift risk. In each case study, the amount of agricultural spray that was deposited at various distances from an initial path of application under different stability classes was measured. Case studies were conducted on a mown grass field, with a vegetation height of approximately 0.075 m (3 in), on 13 September and 18 October 2012, and 5 February and 13 March 2013. The field was bounded on one side by a stand of trees but was open on other sides, with the spray applied so that the trees were not upwind of the path. Total fetch was about 200 meters.

To collect experimental (observed) data, a water-based spray containing 5 g l^{-1} of tartrazine – a food colorant, chemical formula: $C_{16}H_9N_4Na_3O_9S_2$ was used as a tracer dye released along a linear path. Tartrazine was chosen for the tracer due to its stable, nonvolatile nature in the environment, and because it has little sensitivity to sunlight, with a photolysis half-life of approximately 300 days (US National Library of Medicine 2012). Tartrazine has been used effectively as a tracer dye in spray deposit and drift tests in the studies of Richardson et al. (1989) and Pergher et al. (1997), and was found to be the best dye for colorimetric analysis by the study of Pergher (2001) due to its low rate of photodegradation and lack of toxicity. The spray mixture was applied using a John Deere 6000 series, 3 wheeled, high-cycle spray rig (Figure 3.1). The rig was outfitted with Tee Jet TX-8 hollow cone brass nozzles at 0.508 m (20 in) spacing, set to apply 93.5 l ha^{-1} (10 gal/acre), at a height of 1.06 m (42 in) (Figure 3.1). Tee Jet TX-8 hollow cone brass nozzles were used, because they produce finer droplets that are more prone to drift (Nuyttens et al. 2007).

Stands with various collection surfaces were placed at distances of 10, 25, and 50 meters downwind of the spray path. To capture a full range of spray droplet sizes, three different collection surfaces were used. The first type of collection surface consisted of solid plastic spheres—table tennis balls—with an average radius of 0.019 m, with 3 spheres suspended on a wire, with two wires extending from a wooden stand at 0.30 m (1 ft) intervals (Figure 3.2). The second type of collection surface was composed of two 3.05 m (10 ft) monofilament strands—fishing line—with a diameter of 0.59 mm stretched horizontally between wooden stands, with one monofilament at a height of 0.30 m (1 ft) above field surface and the other at a height of 1.22 m (4 ft) above field surface (Figure 3.2). The monofilament was run through a wash chamber made of PVC pipe with a rubber stopper at the lower end through which the line was pulled, to remove any spray deposited on the line. The third type of collector was microscope slides positioned on 'Leading Edge' rotorods—rods extending off a central point which spins on battery power.

During each study the meteorological elements observed included: ten-minute mean wind velocity (Hanna et al. 1982), fraction of sky covered by cloud, and estimated sun angle (Pasquill 1961).

Figure 3.1: Spraying Equipment
Left: John Deere 6000 Series, three-wheeled, high-cycle sprayer used to apply spray mixture during the case studies. Right: Tee Jet TX-8 hollow cone brass spray nozzles used in case studies.

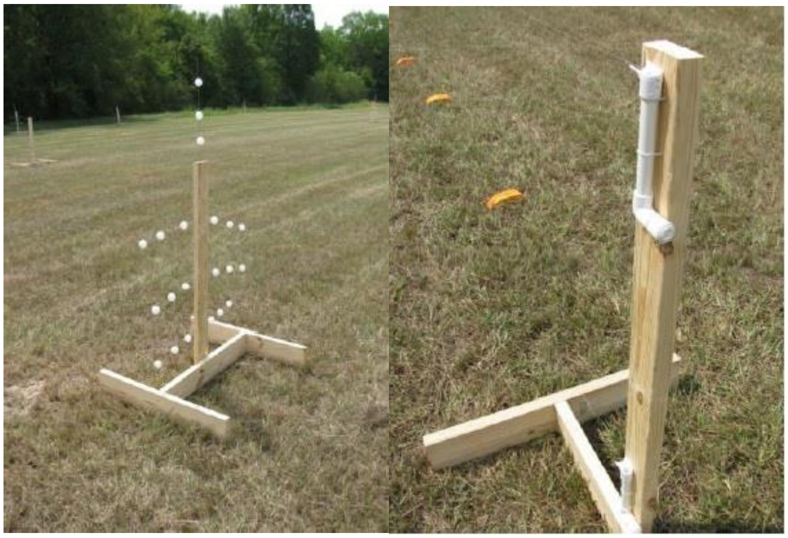

Figure 3.2: Collector Stands
LEFT: spherical collection surfaces, with a diameter of 0.019 m, were placed on wires extending from wooden stands at 0.30, 0.61, 0.91, and 1.22 m. RIGHT: 3.05 m monofilament strand was suspended between two wooden posts at 0.30 and 1.0 m and running through PVC wash chamber.

The Pasquill class was determined by using the classification technique presented by Pasquill (1961), which used wind speed and insolation levels — slight, moderate, or strong — determined by approximate sun angle and then modified by the cloud cover conditions. Sun angle and temperatures were reported to provide temporal estimates for when those conditions would be seen in a typical growing season. The time and date were of each study were recorded to allow the calculation of the exact sun angle to ensure that the observer’s estimate was accurate. Fifteen minutes after spraying, the spheres from each wire and microscope slides from each rotorod were collected in a labeled bag, and the monofilaments were washed in the PVC wash chamber using 60 ml of deionized water with the resulting wash being placed into a labeled mason jar to be taken back to a Louisiana State University Biological and Agricultural Engineering Department laboratory for analysis.

3.2 Laboratory Procedures

A visual analysis was performed on the microscope slides to determine the droplet size at distances from the spray path. The analysis of the amount of spray on the spheres was performed by washing the spheres in 10 ml of deionized water for 30 seconds to transfer Tartrazine from the spheres to the 10 ml of water. A 4 ml aliquot of the wash solution of each sphere and monofilament was then loaded into cuvettes to be analyzed in a Thermo-Genesys 20 spectrophotometer using the wavelength of 425 nm—the peak absorbance wavelength for tartrazine (Jain et al. 2003, Pergher 2001). The spectrophotometer sends a light beam at a specified wavelength through the sample, and then reports how much energy was absorbed by the sample (Lebeau et al. 2011). Results from that analysis enabled the calculation of the concentration (g ml^{-1}) of dye in the wash solution by comparing the absorbance reading from that sample to a standard dilution curve of the tartrazine dye. The dilution curve was created in an experiment where a known amount of dye was added to a known amount of water, and a set of serial dilution samples were created to analyze in the spectrophotometer. For this standardization experiment eleven samples were created and a trend line representing the dilution curve was fit using ordinary least squares (OLS) regression (Figure 3.3). The dilution curve is represented by the function $y = 2.49E^{-5}x + 3.72E^{-7}$ in the format of $y = mx + b$, where the dependent variable y is the concentration of tartrazine in the dye (g ml^{-1}), the independent variable x is the absorbance reading of a sample, m is the slope, and b is the y-intercept. This regression function had an R^2 value (a goodness of fit measure) of 0.997, meaning the regression provides a good fit to the samples, and a standard error of 5.85E^{-7}.

The concentration of dye in the wash (g ml^{-1}) was then multiplied by the amount of water in the wash (10 ml for spheres and 70 ml for monofilament) to determine the total mass of dye in the wash (g), which was then divided by the collection surface area (m^2).

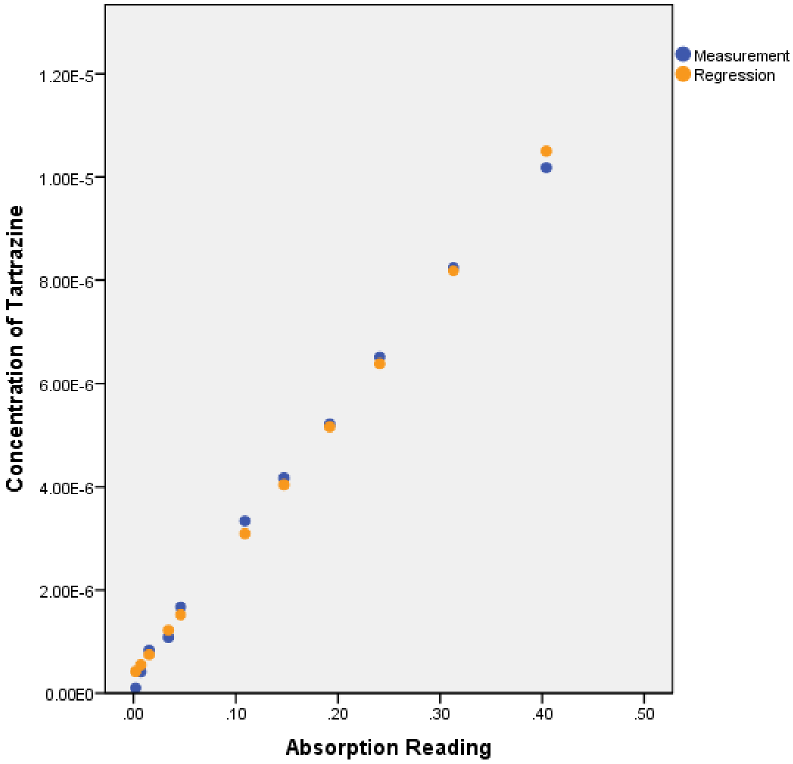

Figure 3.3: Tartrazine Dilution Standard

The collection area was assumed to be one-half of the total surface area of the collector as the top and front of the collector would be directly exposed to the spray droplets, while the bottom and back would not. The calculated collection area of each sphere was equal to 0.00226 m^2, and that of each monofilament was 0.00283 m^2.

3.3 Statistical Analysis of Case Study Samples

Once the deposition amount (mg m^{-2}) was determined for each sample, the results were grouped based on different study parameters, including collector type, Pasquill Class, wind speed, insolation level, distance from spray path, and height above ground. All data analyses were conducted separately for the spherical and monofilament collectors, as they have different collection efficiencies—a measure of their ability to capture spray droplets usually presented as a percentage of the amount of droplets collected to the total number of droplets that would have passed through the projected area of the collector had it not been present (May and Clifford 1967). The collection efficiency E can be determined for an object using a dimensionless impaction parameter P as defined by (Parkin and Merritt 1988) as $P = \frac{V_s u}{gl}$ where v_s is the droplet settling velocity, u is the horizontal wind speed, g is the acceleration due to gravity, and l is the characteristic length of the object, taken to be its diameter. V_s is determined by Stokes equation $V_s = \frac{g\rho d^2}{18\eta}$ where g is the acceleration of gravity, ρ is the density of the droplet (with water-based sprays $\rho \approx 1$ can be assumed (Quantick 1985)), d is the diameter of the droplet, and η is the viscosity of air. The setting velocity for droplets with a range of sizes slightly larger than those as observed in the study of Barbosa (2011) using a similar nozzle were taken from Quantick (1985) to calculate P for the spherical and monofilament collectors. From those values of P the collector efficiencies were determined using the figures of experimentally derived E for spheres and cylinders found in the study of May and Clifford (1967).

To test the hypothesis that deposition differs significantly between the Pasquill classes, therefore allowing Pasquill class to be a valid way to estimate drift risk, a one-way analysis of variance (ANOVA) test was conducted. The ANOVA statistical tool is used to test the null hypothesis that samples in multiple groups are drawn from populations with the same mean values; if group means are pulled from populations with the same mean values, the variance between the groups should be lower than the variance of the samples (von Storch and Zwiers 1999). In this case, a one-way ANOVA was run on the deposition data, with respect to PC, with the expectation that the null hypothesis would be rejected, and that samples from different PCs would be found to significantly differ. The assumptions of ANOVA are that the response variable is normally distributed within each group, the samples are independent, and that there is homoscedasticity or homogeneity of variance across all values of the independent variable (Cox 1987). A Shapiro-Wilk's test was conducted to test the assumption of sample normality (Shapiro and Wilk 1965); a chi-squared test was used to test sample independence; a nonparametric Levene's test was used to test for homogeneity among variances (Levene 1960, Nordstokke and Zumbo 2010).

If the results of the ANOVA reveal significant differences between treatments, a *post hoc* test known as Scheffé's Simultaneous Confidence Interval test was used to determine which treatments differ significantly from the others. The advantage of Scheffé's test over simply conducting multiple t-tests for difference of two means is that the repeated implementation of the t-tests increases the probability of introducing a Type I error, an erroneous conclusion of rejecting a true hypothesis (Cox 1987, Scheffé 1999).

To determine under which Pasquill class the spray was most prone to drift, the means, variance, and standard deviations of samples in different groups were calculated and plotted using IBM’s SPSS 21 for comparisons. OLS correlation analysis was performed, where the correlation of several variables was tested in relation to the observed deposition on spherical collectors to determine which physical factors most influenced deposition. The independent variables tested were those observed during the case studies and cited as being important factors that affect drift; these include wind speed ($m\ s^{-1}$), sun elevation angle (degrees above horizon), sample distance from spray path (m), sample height above the ground surface (m), and relative humidity.

The results of these experiments will be presented in Chapter 4.

CHAPTER 4: RESULTS

The purpose of this chapter is to describe the results of the experiments which took place from fall 2012 through spring 2013 in Winnsboro, Louisiana. All explanations, implications, and suggestions for future research involving these results will be presented in Chapter 5.

A series of eight case studies were analyzed throughout fall 2012 and spring 2013. The results from these studies are presented here ordered by the context in which those conditions would typically be seen during a day in a growing season, or throughout the growing season such that lower sun angles and cooler conditions are typically observed early in a day or early in the growing season with higher sun angles and warmer temperatures observed later in a day or later in the season. The meteorological conditions and the resulting Pasquill Class (PC) under which the case studies took place are shown in Table 4.1, which details the observed conditions from each of the case studies.

Table 4.1: Atmospheric Conditions during Case Studies

Case Study	**Date/Time (CST)**	**Pasquill Class**	**Average Wind (m/s)**	**Sun Angle (˚)**	**Cloud Cover**	**Insolation**	**Temperature (˚C)**	**RH (%)**
1	2/5/13 10:50	D	0.09	37	1	slight	15.5	71.6
2	2/5/13 10:00	D	0.49	32	1	slight	17.2	68.8
3	3/13/13 09:00	B	1.39	32	0	slight	10.8	45.8
4	9/13/12 09:50	B	1.23	57	0.7	slight	29.4	52
5	3/13/13 09:50	B	2.19	41	0	moderate	14.4	37.6
6	10/18/12 10:30	A	1.76	44	0	moderate	26.8	53.5
7	9/13/12 09:30	A	0.88	44	0.4	moderate	27.2	68.5
8	10/18/12 12:20	A	1.88	47	0.2	moderate	32.3	48.6

As stated in Chapter 3, the deposition on spherical and monofilament collectors were analyzed independently due to their differing collection efficiencies. The results of collection efficiency estimates revealed that, both spherical and monofilament collection efficiencies increased with wind speed and droplet size. However, the spherical collectors had much lower overall collection efficiencies, which were more dependent on droplet size than monofilament collectors. It was found that the monofilament collectors had high collection efficiencies with E > 90 percent for most droplet sizes and wind speed combinations seen during the case studies, with the lowest E being 65 percent. Values for the collection efficiencies of spherical collectors ranged from <10 percent for the slowest wind speed to 40-75 percent for larger droplets and higher wind speeds.

The results of the deposition analysis for the spherical collectors from the eight case studies are presented in Table 4.2. The samples are labeled such that the first number corresponds the case study number (1-8), the middle letter corresponds to the sampler distance from the spray path (A= 10 m, B= 25 m and C= 50 m from spray path), and the last number corresponds to the position of the sphere on the sampler stand (1 and 2 are 0.30 m above the ground surface, 3 and 4 are at 0.61 m, 5 and 6 are at 0.91 m, and 7 has a mean height of 1.22 m).

The monofilament samplers were unavailable for the two case studies conducted on the first day of field work, reported as case studies four and seven. Table 4.3 shows the overall results from the remaining case studies of the deposition analysis with the samples labeled such that the first number represents the case study number, the following letter represents the samples distance from the spray path (A = 10 m, B = 25 m, and C = 50 m), and the last letter represents the height of the line (L = 0.30 m, and U = 1.22 m).

Table 4.2: Deposition (mg m^{-2}) on Spheres

Sample	Deposition	Sample	Deposition	Sample	Deposition	Sample	Deposition	Sample	Deposition	Sample	Deposition	Sample	Deposition	Sample	Deposition
1A1	0.84	2A1	0.77	3A1	0.99	4A1	1.10	5A1	0.91	6A1	1.50	7A1	1.28	8A1	2.38
1A2	0.62	2A2	0.73	3A2	0.80	4A2	1.57	5A2	0.91	6A2	1.43	7A2	1.02	8A2	3.22
1A3	0.95	2A3	0.80	3A3	0.99	4A3	1.02	5A3	1.13	6A3	1.32	7A3	0.95	8A3	0.98
1A4	0.84	2A4	0.95	3A4	0.91	4A4	1.68	5A4	0.84	6A4	1.61	7A4	1.06	8A4	3.44
1A5	0.69	2A5	1.02	3A5	1.06	4A5	1.54	5A5	0.88	6A5	1.79	7A5	1.21	8A5	3.78
1A6	0.73	2A6	0.73	3A6	0.99	4A6	2.56	5A6	1.13	6A6	1.76	7A6	1.10	8A6	2.12
1A7	0.62	2A7	0.80	3A7	0.91	4A7	1.39	5A7	1.17	6A7	1.13	7A7	1.21	8A7	3.63
1B1	0.99	2B1	0.80	3B1	0.80	4B1	0.73	5B1	1.13	6B1	2.78	7B1	1.76	8B1	1.28
1B2	1.17	2B2	0.73	3B2	0.91	4B2	1.39	5B2	0.84	6B2	1.43	7B2	1.68	8B2	1.79
1B3	1.21	2B3	0.80	3B3	0.88	4B3	1.54	5B3	0.80	6B3	1.10	7B3	1.13	8B3	1.10
1B4	1.06	2B4	0.84	3B4	0.88	4B4	1.13	5B4	0.95	6B4	1.17	7B4	1.17	8B4	1.13
1B5	1.17	2B5	1.06	3B5	0.84	4B5	0.95	5B5	0.88	6B5	1.10	7B5	1.13	8B5	2.45
1B6	1.06	2B6	0.84	3B6	0.77	4B6	0.66	5B6	0.95	6B6	1.35	7B6	1.10	8B6	1.76
1B7	1.17	2B7	0.69	3B7	0.80	4B7	0.58	5B7	1.06	6B7	1.13	7B7	1.10	8B7	1.87
1C1	0.62	2C1	1.10	3C1	0.55	4C1	2.09	5C1	0.80	6C1	0.99	7C1	0.99	8C1	1.98
1C2	0.84	2C2	0.84	3C2	0.66	4C2	1.50	5C2	0.88	6C2	1.06	7C2	0.84	8C2	1.76
1C3	0.69	2C3	0.80	3C3	0.62	4C3	1.13	5C3	0.80	6C3	1.06	7C3	0.84	8C3	1.21
1C4	0.66	2C4	1.02	3C4	0.62	4C4	0.95	5C4	0.77	6C4	1.21	7C4	1.21	8C4	1.39
1C5	0.73	2C5	1.02	3C5	0.62	4C5	1.61	5C5	0.99	6C5	1.13	7C5	0.88	8C5	1.68
1C6	0.73	2C6	0.84	3C6	0.66	4C6	1.35	5C6	0.84	6C6	0.88	7C6	0.95	8C6	1.65
1C7	0.80	2C7	0.88	3C7	0.69	4C7	1.28	5C7	0.91	6C7	0.91	7C7	0.58	8C7	1.65

Table 4.3: Deposition (mg m^{-2}) on Monofilaments

Sample	Deposition	Sample	Deposition	Sample	Deposition	Sample	Deposition	Sample	Deposition	Sample	Deposition
1AL	15.360	2AL	N/A	3AL	12.281	5AL	15.976	6AL	33.222	8AL	28.910
1AU	10.433	2AU	11.665	3AU	27.063	5AU	19.672	6AU	17.208	AU	19.672
1BL	11.665	2BL	12.897	3BL	16.592	5BL	17.208	6BL	21.519	8BL	15.976
1BU	14.129	2BU	11.049	3BU	12.281	5BU	15.360	6BU	28.910	8BU	31.990
1CL	12.897	2CL	10.433	3CL	12.281	5CL	15.360	6CL	19.672	8CL	12.897
1CU	11.665	2CU	11.049	3CU	12.281	5CU	15.976	6CU	19.672	8CU	15.360

4.1: Results of Analysis of Variance

The results from testing the assumptions of the one-way ANOVA tests are presented here. First, the assumption that the samples within each group have a normal distribution was tested.

The Shapiro and Wilk (1965) test for normality is a powerful and frequently used test for normality that can be used for data with a large range of sample sizes (Thode 2002). If the significance of the Shapiro-Wilk's test is > 0.05, the data can be said to be normally distributed at the 95 percent confidence interval; if the significance is < 0.05 it can be said that the data significantly deviate from the normal distribution. For the spherical and monofilament collectors, the Shapiro-Wilk's tests revealed that only samples of deposition on monofilaments from PC A and D had normal distributions (Tables 4.4 and 4.5). However, Kirk (1995) suggests that ANOVAs are robust and adequately powerful even if the normality assumption is not met, and are often still used.

Table 4.4: Shapiro-Wilk's Test for Normality for Spherical Collectors

	Pasquill Class	Shapiro-Wilk		
		Statistic	Degrees of Freedom	Sig.
Deposition	A	0.78	63	0.00
	B	0.84	63	0.00
	D	0.94	42	0.03

Table 4.5: As in Table 4.4, but for Monofilament Collectors

	Pasquill Class	Shapiro-Wilk		
		Statistic	Degrees of Freedom	Sig.
Deposition	A	0.90	12	0.16
	B	0.80	12	0.01
	D	0.89	11	0.15

A chi-square test was used to examine whether the samples within each PC were independent (Cox 1987). A one-sample chi-square test of both spherical and monofilament data suggests that the null hypothesis that categories of PC occur with equal probability is retained, thus the data are assumed to be independent.

Levene's (1960) test and the Brown–Forsythe (1974) test are commonly used to test for homoscedasticity and use the same procedure as a one-way ANOVA, except with the absolute value of the difference between values and the mean or median for their group/treatment, respectively. However, these tests operate on the assumption that the samples are normally distributed and are of equal size, but the data from these experiments are not all normally distributed and of unequal sizes. Since the results for each PC are not normally distributed and have unequal sample sizes, a non-parametric Laverne's test is conducted (Nordstokke and Zumbo 2010). This is done by ranking the total population of deposition samples across all PCs, then determining the mean rank for each PC. Then the difference between each sample and its group mean is calculated, and the absolute value is taken. It is with those data that a one-way ANOVA is run and the results indicate whether the variance differs significantly between PCs (Nordstokke and Zumbo 2010). For the data from both spherical collectors and monofilament collectors the variances were found to be homogeneous (Tables 4.6 and 4.7).

Table 4.6: Nonparametric Levene's Test for Deposition on Spheres

	Sum of Squares	Degrees of Freedom	Mean Square	F	Sig.
Between Groups	1180	2	588	1.315	0.271
Within Groups	73800	165	447		
Total	74500	167			

Table 4.7: As in Table 4.6, but for Monofilament Collectors

	Sum of Squares	Degrees of Freedom	Mean Square	F	Sig.
Between Groups	11.2	2	5.62	0.445	0.645
Within Groups	404	32	12.6		
Total	415	34			

After testing the assumptions, it was determined that a one-way ANOVA could be run on the data to determine if they had different means. The one-way ANOVA for deposition on spheres (Table 4.8) produced an F-value of 31.52, which was above the .05 critical F-value 3.07 determined from the F distribution table for an F with 2 and 165 degrees of freedom, so the null hypothesis was rejected. Since the null hypothesis of the one-way ANOVA was rejected, a Scheffé's Simultaneous Confidence Interval test was conducted for those samples (Table 4.9), and the test revealed that the deposition on spheres from case studies within each PC significantly differed from samples in both other PCs. The one-way ANOVA for deposition on monofilaments (Table 4.10) produced an F-value of 12.59, which was above the .05 critical F-value of 3.22 for an F with 2 and 32 degrees of freedom, so the null hypothesis of the one-way ANOVA was rejected. The Scheffé's Simultaneous Confidence Interval test (Table 4.11) revealed that for deposition on monofilaments, samples from PC A differed significantly with the other two PCs, but PC B and PC D did not differ significantly from each other at the 95 percent confidence interval.

Table 4.8: ANOVA of Deposition on Spheres

	Sum of Squares	Degrees of Freedom	Mean Square	F
Between PC	14.9	2	7.46	31.524
Within PC	39.0	165	0.237	
Total	53.9	167		

Table 4.9: Scheffé's Test on Spheres

(I) Pasquill Class	(J) Pasquill Class	Mean Difference (I-J)	Std. Error	Sig.
A	B	0.460*	0.087	0.000
	C	0.741*	0.097	0.000
B	A	-0.460*	0.087	0.000
	C	0.282*	0.097	0.016
C	A	-0.742*	0.097	0.000
	B	-0.282*	0.097	0.016

*. The mean difference is significant at the 0.05 level.

Table 4.10: As in Table 4.8, but for Monofilament Collectors

	Sum of Squares	Degrees of Freedom	Mean Square	F
Between PC	584	2	292	12.586
Within PC	742	32	23.2	
Total	1326	34		

Table 4.11: As in Table 4.9, but for Monofilament Collectors

(I) Pasquill Class	(J) Pasquill Class	Mean Difference (I-J)	Std. Error	Sig.
A	B	6.06*	1.96	0.016
	D	9.97*	2.01	0.000
B	A	-6.06*	1.96	0.016
	D	3.91	2.01	0.167
D	A	-9.97*	2.01	0.000
	B	-3.91	2.01	0.167

*. The mean difference is significant at the 0.05 level.

4.2 Results of Aggregated Spherical Collectors

The mean deposition on all spherical collectors from case studies representing PC A, B, and D (Figure 4.1) decreases from 1.48 mg m^{-2} for samples in PC A to 1.02 mg m^{-2} for samples in PC B to 0.863 mg m^{-2} for samples in PC D, which are surrogates for surface boundary layer (SBL) static stabilities: highly unstable, moderately unstable, and neutral. In addition, Figure 4.1 shows that the variance around the mean decreases from 0.463 in PC A to 0.132 in PC B to 0.028 in PC D— decreasing variance is shown in the figure by the error bars representing one standard deviation from the mean.

As was presented in Chapter 2, PC is determined based on both insolation and wind speed. To isolate the effects of insolation and wind speed, mean deposition was plotted against both individually (Figures 4.2 and 4.3). The eight case studies were divided evenly in regard to insolation, with four studies conducted under both slight and moderate insolation. Each case study had a unique mean wind speed value. Figure 4.2 shows that the mean deposition measured on all spherical collectors during case studies with moderate insolation exceeded the measured deposition during slight insolation.

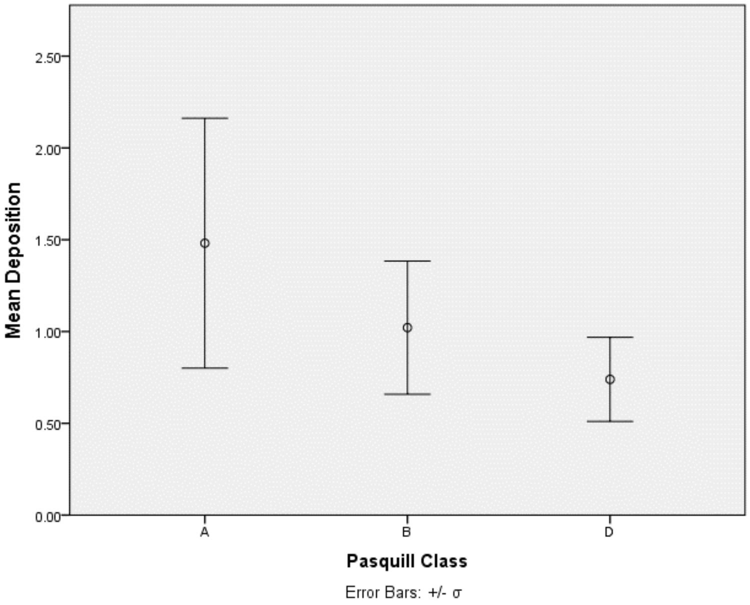

Figure 4.1: Mean Deposition (mg m^{-2}) on Spheres by Pasquill Class

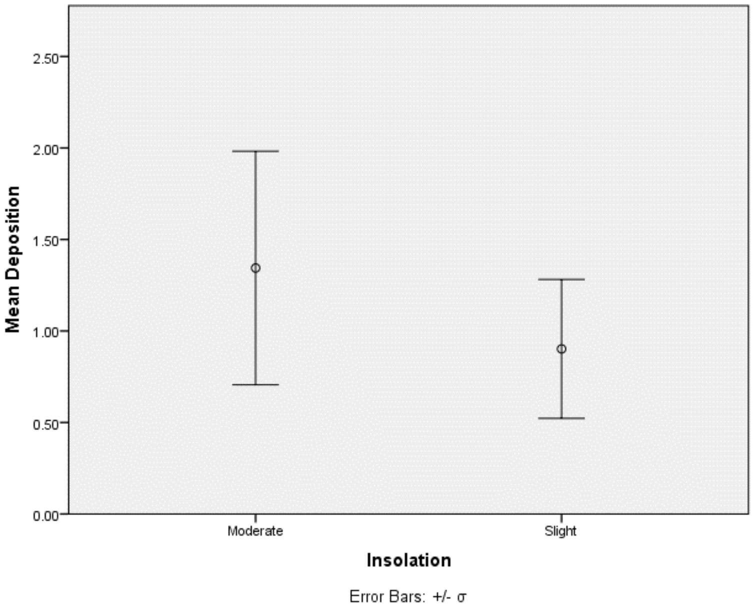

Figure 4.2: Mean Deposition (mg m^{-2}) on Spheres by Insolation

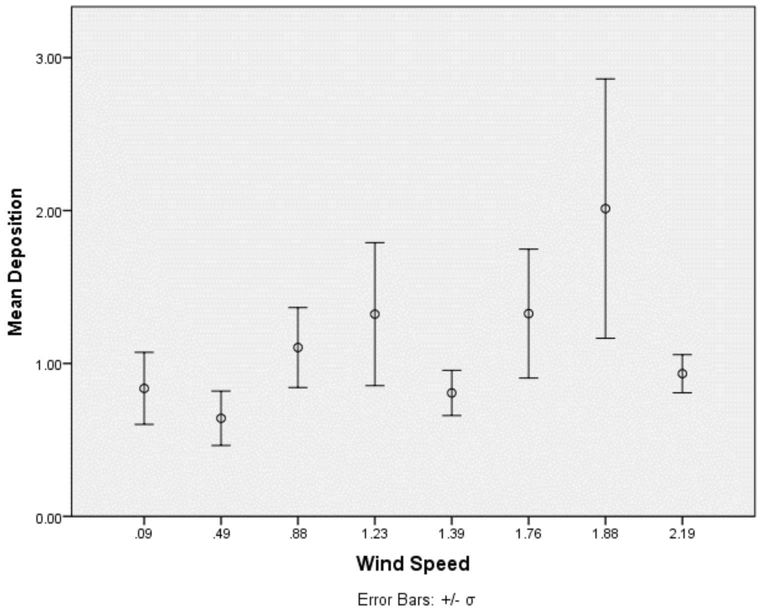

Figure 4.3: Mean Deposition (mg m^{-2}) on Spheres by Mean Wind Speed

Figure 4.3 shows a general increase in mean deposition with wind speed, except for case studies 3 and 5, which had small measured deposition values despite having relatively higher wind speeds as well as small variance around the mean deposition. As seen in Figure 4.1 the variance around the mean deposition decreased from PC A to B to D.

To better visualize that variance, Figure 4.4 shows each measured deposition value for all spherical collectors from case studies with PC A, B, or D conditions. There were three case studies conducted under PC A and B, and two under PC D conditions. The range of measured deposition values was greater in PC A studies, with a few notable high measures. PC B had a slightly smaller range with a few outlying values. PC D had the smallest range and no outlying values.

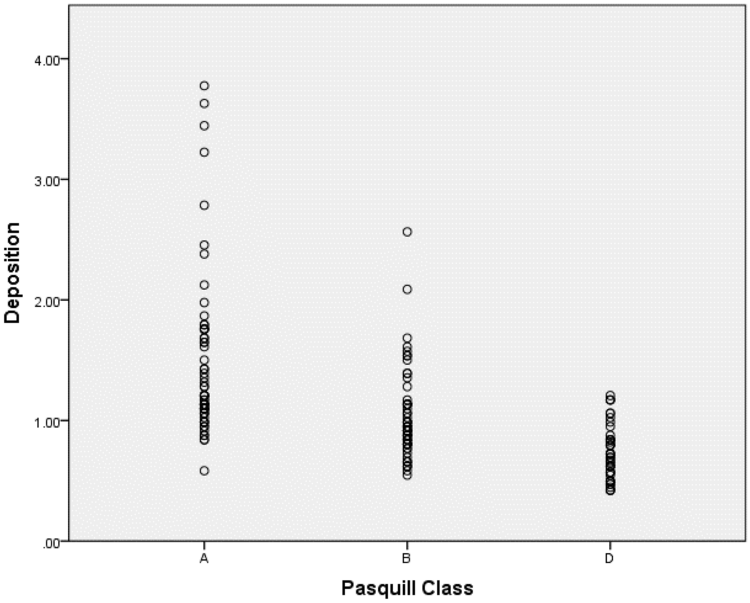

Figure 4.4: Measured Sphere Deposition Values (mg m^{-2})

4.3 Results from Specific Distances and Heights of Spherical Collectors

Figures 4.1 to 4.4 show measured deposition values on spherical collectors aggregated from various locations within the dispersion field and across multiple case studies. More detailed information can be found by analyzing deposition at each collector distance (A = 10 m, B = 25 m, and C = 50 m) and height (0.30 m, 0.61 m, 0.91 m, and 1.22 m) during the different PC conditions (Figures 4.5 and 4.6).

Figure 4.5 shows the mean deposition on spheres from collectors as set distances, it should be noted that this value is the mean for collector across all heights, but the mean collector heights between distances and PC are equal. Figure 4.5 reveals that samplers at 10 m from the spray path are responsible the most of the variance in PC A case studies, but that there is less variance in deposition rates at 10 m in PCs B and D. A decreasing trend in deposition can be seen at 10 m as PC increases in stability. During case studies with PC A conditions, there is a clear decrease in deposition with distance from the spray path. During case studies with PC B conditions, the deposition decreases beyond 10 m, but at 25 m and 50 m the mean of deposition measurements fall within one standard deviation of each other, meaning that they cannot be treated as different from a statistical perspective. During case studies with PC D conditions, the deposition rates are less than with PC A or B, but as the cloud moves farther from the spray path the deposition increases at 25 m, and then decreases at 50 m back to levels similar to those at 10 m.

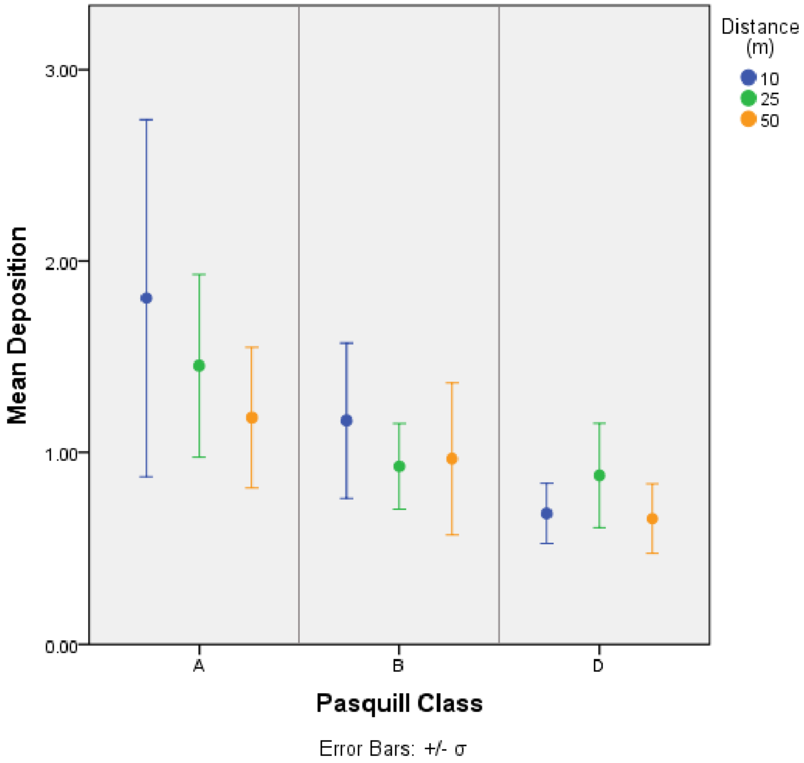

Figure 4.5: Mean Deposition (mg m^{-2}) on Spheres at Distances from Spray Path

Figure 4.6 shows the mean deposition on collectors grouped by collector height. Samples from case studies with PC A conditions had the greatest mean deposition at the 0.30 m height followed by 0.91 and 1.22 m samples, with the samples at 0.61 m having the lowest mean deposition. The means for the 0.30, 0.91, and 1.22 m samples were all within one standard deviation of each other, while the mean for samples at 0.61 m was just outside of the standard deviation for the 0.30 m samples, but not for the 0.91 or 1.22 m samples. Figure 4.5 shows that studies conducted under PC A conditions had the most variance around the mean, which agrees with the other assessments, suggesting that deposition is highly variable in PC A conditions. The mean of measured deposition for samples at a given height in studies with PC B and D conditions were both lower than those with PC A conditions, and they fall within one standard deviation of the other heights of the same PC; with a decrease in deposition from PC B to D.

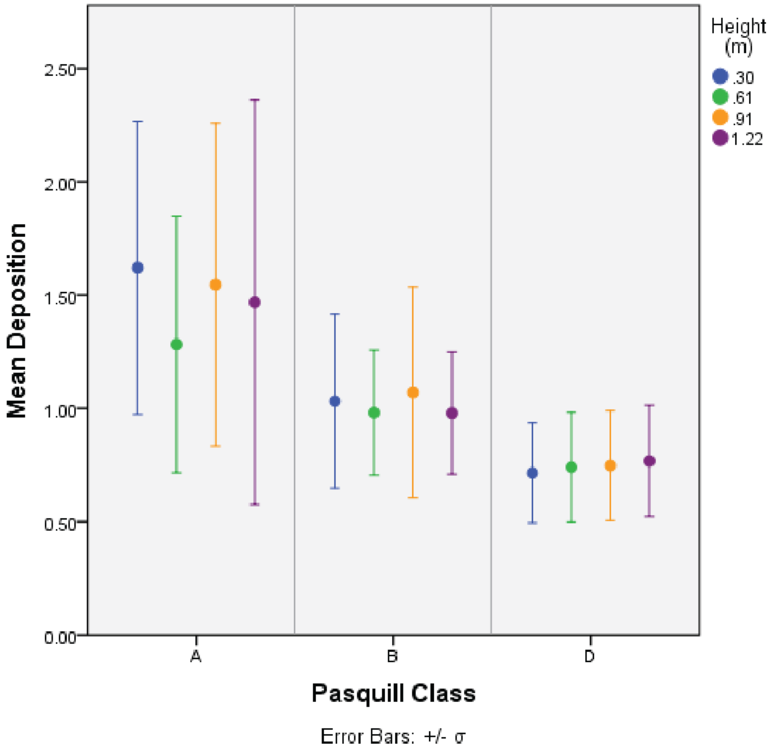

Figure 4.6: Mean Deposition (mg m^{-2}) on Spheres at Heights above Ground

Next, the case study samples were divided into groups by PC conditions and the mean deposition on collectors at each sample height were plotted for each collector distance (10, 25, and 50 m). Figure 4.7 shows the results of the deposition analysis for case studies with PC A conditions on the left, PC B conditions in the middle, and PC D conditions on the right. The case studies in PC A had more overall variance than those from PC B or PC D and that by 50 m there is decreasing mean deposition with height. The samples in PC B have more variability

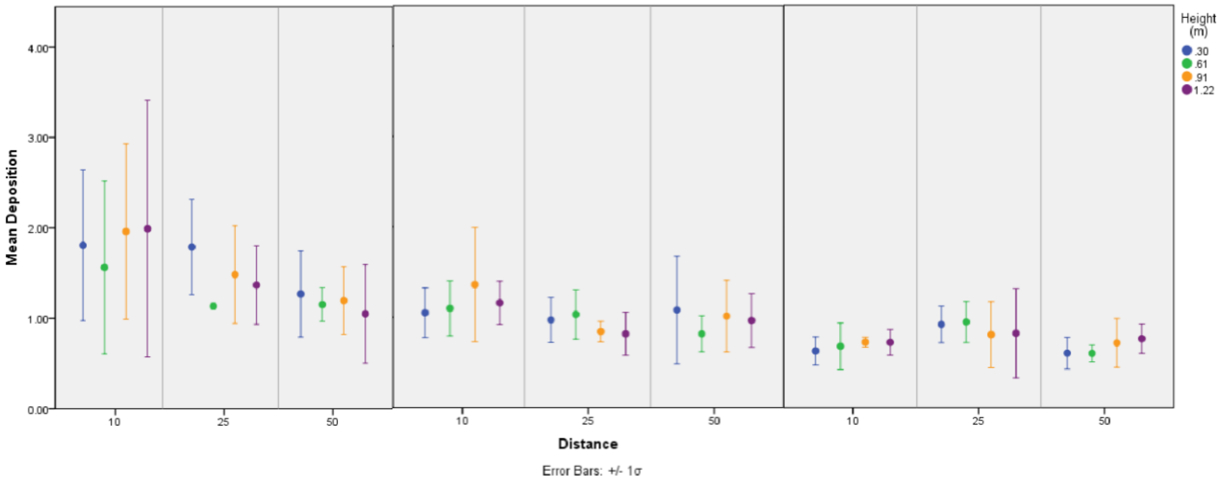

Figure 4.7 Mean deposition (mg m-2) on Spheres for Pasquill Classes A, B, and D

between mean deposition at different collector heights at the same distance, and a slight decrease in mean deposition beyond 10 m. As expected from previous analyses, this figure shows that case studies with PC D conditions had smaller mean deposition that were consistent at all collector heights and distances, with the means within one standard deviation of other group mean.

4.4 Results of Aggregated Monofilament Samples

Figure 4.8 shows the measured deposition values on monofilament collectors from the two case studies conducted in each PC. A similar pattern to the deposition on spheres can be observed, with greater and more varied deposition in PC A conditions and less and more similar values in PC B and D respectively. Similarly, Figure 4.9 shows the mean deposition values of samples from each PC, with the decreasing mean deposition and variance—signified by the standard deviation about the mean—from a mean of 22.01 mg m^{-2} with a standard deviation (σ) of 6.6 for samples in PC A to a mean of 16.03 mg m^{-2} with σ of 4.02 for samples in PC B to a mean of 12.11 and σ of 1.49 for samples in PC D.

Breaking down the component inputs for PC categorization, as discussed in Chapter 2, Figure 4.10 shows the mean deposition on samples grouped by insolation categories (moderate and slight) with a decrease from moderate to slight. Figure 4.11 shows the mean deposition on samples grouped by the mean wind speed observed during the case studies. This shows that as wind speed increases the deposition rates generally increase and become more varied; however, this is not a linear trend, with the peak in mean deposition occurring at a wind speed of 1.76 m s^{-1}.

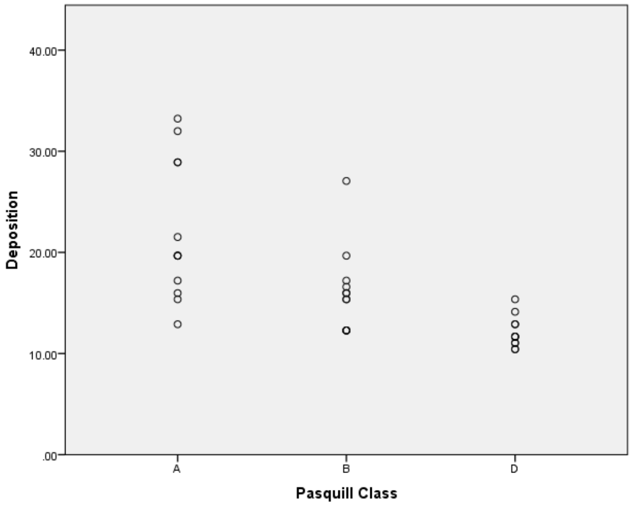

Figure 4.8: Measured Monofilament Deposition Values (mg m^{-2})

Figure 4.9: Mean Deposition (mg m^{-2}) on Monofilaments by Pasquill Class

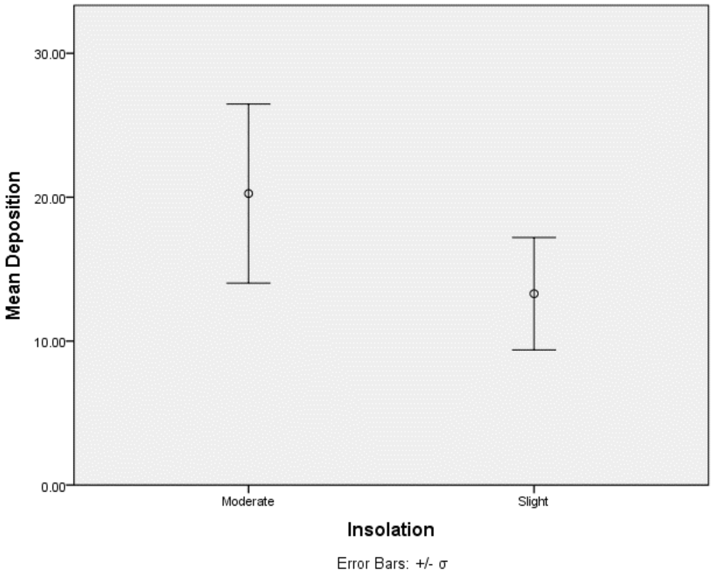

Figure 4.10: As in Table 4.9, but by Insolation

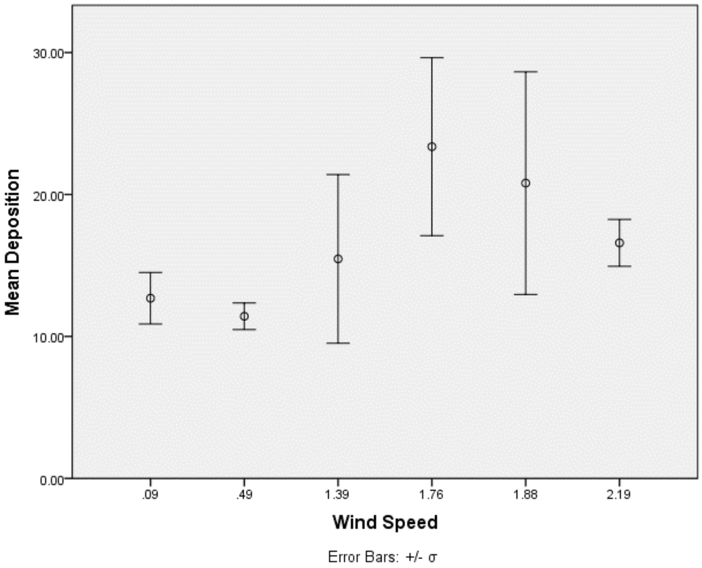

Figure 4.11: As in Table 4.9, but by Wind Speed

4.5 Results from Specific Distances and Heights on Monofilaments

Next, samples from each PC were separated into groups based on their distance from the spray application path (Figure 4.12). The mean deposition for samples in PC A shows virtually no change from 10 to 25 m with the mean deposition decreasing by only 0.15 mg m^{-2}. There is a drop in both mean and variance in samples from 25 m to 50 m, with a decrease in mean deposition from 24.60 to 16.9 mg m^{-2} and a decrease in σ from 6.27 to 2.91 mg m^{-2}. Samples from case studies during PC B show a decrease in mean deposition from 18.75 mg m^{-2} at 10 m to 15.36 mg m^{-2} at 25 m, and 13.97 mg m^{-2} at 50 m, with decreasing standard deviations from 5.47 to 1.90 mg m^{-2} and 1.17 mg m^{-2}, for 10 m, 25 m, and 50 m respectively. Samples from case studies with PC D show a small decrease in mean deposition (<1 mg m^{-2} difference from 10 m to 50 m) and variance with distances as well; however, the mean of samples at each distance is within one standard deviation of the other two distances.

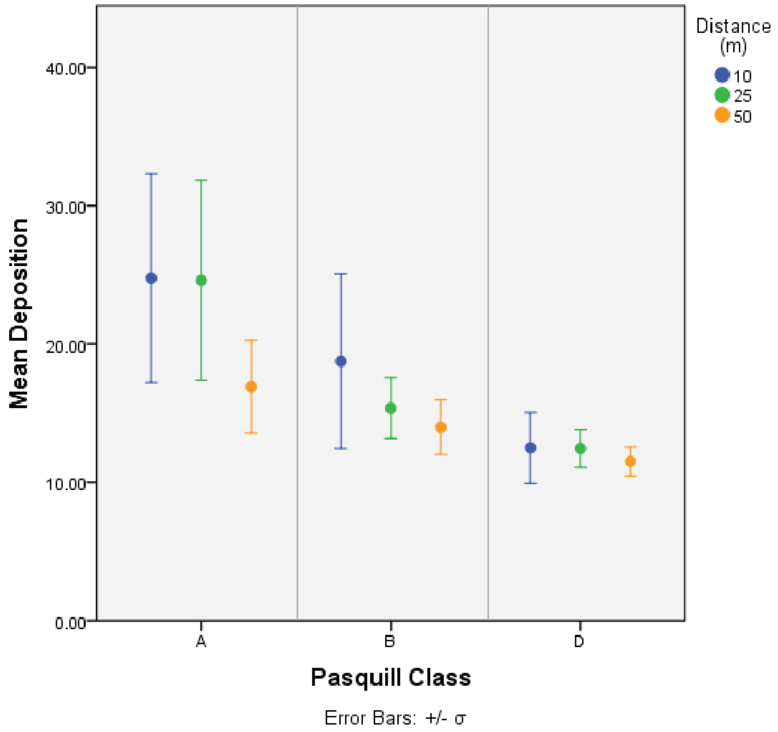

Figure 4.12: Mean Deposition (mg m^{-2}) on Monofilaments by Distances from Spray Path

Then the samples from each PC were grouped based on the height of the monofilaments, with the results presented in Figure 4.13. The mean deposition for the samples from case studies with PC A show an increase of mean deposition of 0.11 mg m^{-2} from the lower strand to the upper, while the standard deviation decreased from 7.05 to 6.13. The samples from case studies with PC B conditions show a larger increase in mean deposition from 14.95 to 17.11 mg m^{-2} and variance with standard deviation increasing from 1.97 to 5.11 from the lower strand to the upper. Samples from case studies with PC D show a small decrease in mean deposition with a 0.97 mg m^{-2} change and decreasing variance from a standard deviation of 1.63 to 1.18 from the lower to the upper strands.

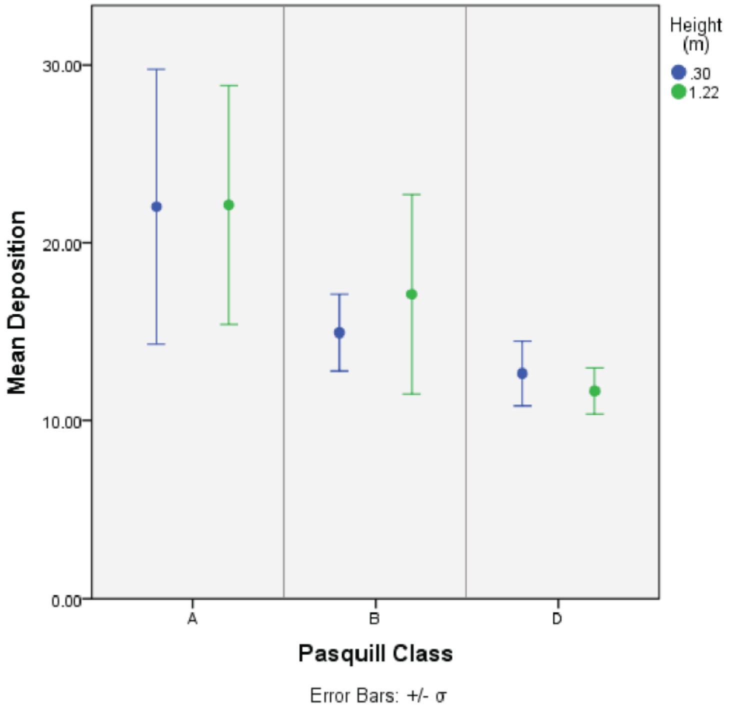

Figure 4.13: As in Figure 4.12, but by Heights above Ground

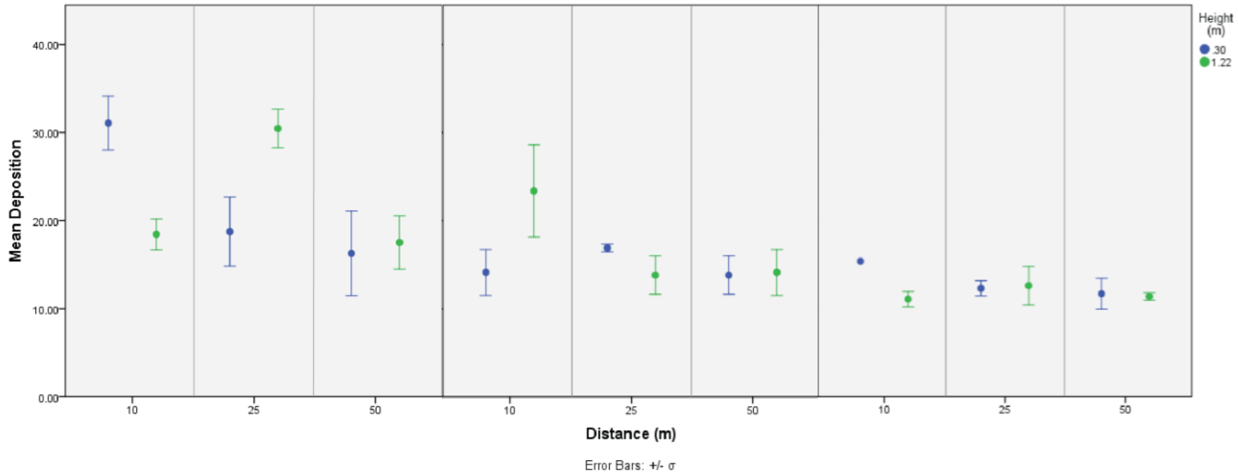

Figure 4.14: Mean Deposition (mg m^{-1}) on Monofilaments for Pasquill Classes A, B, and D

Figure 4.14 shows that deposition in case studies with PC B conditions (center panel) was lower than that in PC A conditions (left panel), but had a different pattern. During PC B conditions the 1.22 m strand showed a large decrease in mean deposition from 10 m to 25 m and then a slight increase from 25 m to 50 m. The 0.30 m strand showed an increase in mean deposition from 10 m to 25 m, but then dropping back at 50 m to levels similar to 10 m.

Figure 4.14 (right panel) shows that the deposition in case studies with PC D conditions was relatively stable between distances and heights, with samples from the 0.30 m strand showing a slight decrease with distance (a change of ~5 mg m^{-2}), and an even smaller increase in samples from the 1.22 m strand (with total change of approximately 2 mg m^{-2}).

4.6 Results of Rotorod Analysis

The microscope slides from the Rotorod collectors were examined with a microscope to determine droplet sizes captured during the case studies. A lack of specialized equipment and improper transportation, the exact droplet sizes were not able to be measured; however, a qualitative measure of droplet size was recorded. In case studies performed in PC A there was a mix of large and small droplets on samples from both 10 m and 25 m while samples from 50 m showed small droplets. In case studies with PC B conditions larger droplets were seen mainly on samples from 10m whereas small droplets were observed at all locations. In case studies performed in PC D conditions no obviously larger droplets were seen on any slides. With this information, and with the results of the work of Barbosa (2011) who performed drift experiments with a similar nozzle and found droplet sizes in the range of 120-80 μm at distances from approximately 5-25 m, droplets in a slightly larger range of 140-60 μm were assumed to have been present in these case studies and were used to calculate the range of collection efficiencies presented in Chapter 3.

4.7 Results of Correlation Analysis

The results of the OLS correlation analysis for spherical collectors presented in Table 4.12 (monofilament collectors in Table 4.13), the correlation coefficient shows a significant correlation beyond a 95% confidence level for all variables except height. Despite that correlation, the error of the slope for the trend line between the variables and deposition is greater than the slope for wind speed and height, meaning that changes in those

Table 4.12: OLS Regression for Spherical Collectors

Independent Variable	Trend Line Slope	Slope Error	Intercept	Intercept Error	Correlation	Goodness of Fit	N
Wind Speed	0.32	0.61	0.72	0.02	0.37	0.15	168
Sun Angle	0.04	0.00	0.34	0.00	0.50	0.26	168
Distance	-0.01	0.00	1.33	0.00	-0.22	0.04	168
Height	0.00	0.30	1.11	0.01	-0.01	0.00	168
Relative Humidity	-0.01	0.00	1.72	0.00	-0.33	0.06	168

4.13: As in Table 4.12, but for Monofilament Collectors

Independent Variable	Regression Slope	Slope Error	Intercept	Intercept Error	Correlation	Goodness of Fit	N
Wind Speed	4.59	56.35	10.91	6.19	0.50	0.27	35
Sun Angle	0.71	0.96	-10.45	1.32	0.56	0.34	35
Distance	-0.05	0.16	18.33	0.02	-0.16	0.02	35
Height	1.23	209.90	15.94	21.91	0.02	0.01	35
Relative Humidity	-0.22	0.24	28.65	0.13	-0.36	0.17	35

variables produce a range of changes in deposition that lies beyond the estimated relationship, so it cannot be said with confidence that the trend exists. This leaves sun angle, relative humidity, and distance as variables with which deposition trends and has a significant correlation—ordered by the correlation value. Relative humidity and distance have negative correlation values, so deposition decreases as these variables increase; so deposition on a collector decreases as the distance from the spray path increases or as the relative humidity increases. Deposition is positively correlated with sun angle, meaning that the closer the sun is to zenith the higher the measured deposit on collectors. The results of the OLS regression analysis for monofilament collectors revealed similar correlation and r^2-values to those from the spherical collectors; however, none of the trend line slopes were greater than the error associated with their calculation.

4.8 Summary of Results

This chapter described the results of the spray drift and deposition case studies. The six most important results were:

1. Deposition differed significantly between all PCs on spherical collectors, and between PC A and PC B/PC D on monofilament collectors.
2. Deposition rates decreased from PC A to B to D.
3. Deposition decreased with distance in PC A.
4. Deposition was similar with distance in PC D.
5. Variance in deposition amount was greater in PC A and smaller in PC D.
6. Significant trends were observed between deposition and the physical factors of sun angle, distance and relative humidity for spherical collectors.

CHAPTER 5: DISCUSSION

5.1 Significance of PC and Deposition Trends

The F statistic of the ANOVA, calculated at the ratio between the mean squares within the treatments (Pasquill Classes (PCs)) to the mean squares between the treatments, provides a test of the null-hypothesis that there are no treatment effects. If there were no treatment effects, the F statistic should be 1, and the greater the number above 1 the more unlikely it is that there are no treatment effects. A critical F-value (based on the degrees of freedom of between and within groups) can be found using an F distribution table for a given level of significance, and represents the threshold for rejecting the null hypothesis that the groups represent the same population (Cox 1987). The critical F-statistic value at 95% confidence interval was 3.07 for the spherical collectors and 3.32 for the monofilament collectors. The results of the ANOVA for both spherical and monofilament samples suggest that the null-hypothesis that the groups come from the same population, i.e. there are no treatment effects, must be rejected. Both F statistics were well above the critical values, suggesting that it is extremely unlikely that there are no treatment effects. This confirms that the samples collected in different PCs are not homogeneous.

The results of Scheffé's Simultaneous Confidence Interval test suggest that the means of the samples from each PC differ significantly from each other with respect to the spherical collectors, while on the monofilament collectors samples from PC A differed significantly from PC B and PC D, but PC B and PC D did not differ significantly from each other. These results indicate that Pasquill classes represent valid groups into which conditions that lead to different spray deposition, and thus drift patterns, may be separated. The rest of the discussion will proceed upon this notion.

5.2 Deposition and Pasquill Class

As shown in Chapter 4, the deposition on both spherical and monofilament collection surfaces decreased from PC A to B to D (Figures 4.1 and 4.13). Three possible explanations for the decrease in deposition are offered. The first is that rate of spray deposition, driven by the concentration of spray droplets settling to the surface, is greater in PC D than in PC B which is in turn greater than the rate in PC A, meaning that the amount of spray airborne as the cloud moves with the wind away from the application site decreases from PC D to B to A. The results indicate that during PC D conditions most of the spray droplets have settled to the surface before reaching the first collectors, whereas during PC B conditions more of the droplets remain airborne by the time they reach the collectors, and even more so during PC A conditions. If this explanation were correct there should be an observed decrease in deposition with distance in each PC. This trend should be especially evident in PC A conditions where most of the spray would be deposited in the area between collectors meters but still clearly visible in both PC B and D as well. There should also be a decreasing trend in deposition with height at each sample distance as more of the cloud droplets would be closer to the ground surface.

As depicted in Figure 4.5, there is indeed a clear decrease in deposition on spherical collectors in PC A. Samples from PC B show a decrease from 10m to 25 m, but an increase from 25 m to 50 m. Samples from PC D show increases between 10 m and 25 m but a decrease from 25 to 50 m. As seen in Figure 4.6 the spherical collection surfaces do not show a decreasing trend in deposition with height, but rather samples from PC A and PC B conditions show no discernible pattern while samples from PC D show an increase in deposition with height. As depicted in Figure 4.16, samples from the monofilament collectors do show a general decreasing trend with distance from the spray path, but it is least discernible during PC A with deposition at 10 m and 25 m virtually the same. Deposition on monofilament samples in PC A had a slight increase with height, with an even greater increase with height during PC B while PC did show a slight decrease with height, as shown in Figure 4.17. Therefore, these results do not match what would be expected if this explanation were adequate.

The second potential explanation of this observation is that less of the spray is depositing on the collection surfaces because more of the spray cloud remains aloft and drifts beyond the application site and the collectors in PC D than in PC B and PC A. If this explanation were adequate, the results would indicate that more of the spray would be deposited with a higher concentration on surfaces near the application site in PC A and B conditions, while more of the spray would remain above the surface and be deposited farther from the application site with reduced concentration but increased coverage in more stable PC D conditions. Thus, if this were the case there should be a decreasing trend in deposition with distance for PC A, less so for PC B, and even less so for PC D as the rate of deposition decreases, respectively, because more of the cloud is able to remain airborne. There should also be an increasing trend in deposition with increasing sample heights at each distance, especially in PC D as more of the cloud is maintained above the surface.

The first of those trends was depicted in Figure 4.5 with the samples from spherical collection surfaces, and there was a slight increase in mean deposition with height in PC D samples as seen in Figure 4.6, but not in the samples from the other PCs. The mean deposition on monofilament collection surfaces, as presented in Figures 4.16 and 4.17, shows the greatest decreasing trend in PC B, and not PC A, with a slight decrease in PC D. The monofilament data do show a slight increase in deposition with height during PC A and PC B conditions, but not in

PC D conditions. Again, the data do not match what would be expected if this explanation were adequate.

Neither of the previous hypotheses are completely supported by the data, that is because they assume that the spray cloud is made of droplets that will all react the same way to the surface boundary layer (SBL) conditions; however, in reality spray clouds consist of droplets with a range of diameters with larger droplets behaving one way and smaller droplets another (Bache and Johnstone 1992). The third explanation considers this idea and combines the previous two explanations by suggesting that larger droplets are suspended better in progressively more turbulent conditions of PC B and PC A and then settle out just beyond the application site (in the range of the sample collectors); thus allowing for larger deposition amounts on surfaces near the application site. Deposition from smaller droplets increases from PC A to B to D as conditions become more stable and the droplets are able to remain in a more defined cloud without entrainment and decreasing in concentration with distance from the application site, leading to more stable deposition rates with distance. According to this explanation, there should be increases in measured deposition during the more turbulent PCs as the larger droplets are supported by stronger vertical winds and will travel farther downwind carrying larger amounts of dye than smaller droplets; therefore fewer droplets would be required to cause equal measured deposits from larger droplets as from smaller droplets. There should also be an observed increase in the amount of large droplets from PC D to B to A at each collector distance, with large droplets observed more on lower collection surfaces than higher surfaces.

Exact measures of the droplet sizes at the different sample distances and heights would serve as the best evidence for the validity of this explanation. The rotorod samplers holding microscope slides were used with this intention in mind; however, they would only provide droplet sizes at distances but not each sample height. The researcher was not able to determine droplet size with a quantitative measure, as discussed in Chapter 4, as only qualitative measures of droplet size were recorded from these samples. The observed decrease in large droplets with distance in PC A, and from PC A to PC B supports this notion. In addition, data from case studies with PC D show fairly steady deposition rates on the monofilament strands—which have relatively high collection efficiencies for the whole range of expected droplet sizes—with distance from the spray path in PC D (Figure 4.16). In addition, the data show an the increase in deposition from 10 m to 25 m and then back to 10 m levels at 50 m on spherical collectors (Figure 4.5), which had higher collection efficiencies for larger droplets. These observations suggest that the smaller droplets are staying together without significantly mixing out, while most large droplets are deposited quickly, at short distances from the spray path. These results support the suppositions about droplet behavior in different stability conditions made by Miller et al. (2000) and Thistle (2000).

The decreasing spread of sample values, and variance around the mean from PC A to PC B to PC D as presented in Figures 4.1, 4.4, 4.12, and 4.13 suggest that Pasquill stability classes tend to represent different degrees of turbulence in the SBL. As explained in Chapter 2, PC A is termed extremely unstable, PC B is moderately unstable, and D is neutral. These results indicate that the greater the SBL turbulence, the more likely it is for heavy or light deposition to occur on an individual collector depending on its location in relation to eddies and the moving spray cloud (Miller et al. 2000). Furthermore, these results support the notion that more large droplets remain suspended during PC A than PC B and PC D, as larger droplets would be more likely to increase the deposition measure by adding large increases to the mass of dye deposited on a collection surface. As seen in Figure 4.10 there were five samples whose dye deposits were upper-end outliers—out of which one was significant—at 10 m, three upper-end outliers—two of which were significant—at 25 m, and only one upper-end outlier at 50 m. In addition to these outlying values, the upper quartiles of PC A field trials were very large, being 1-2 mg m^{-2} higher than the median deposit amount. These values could have been recorded because the sampler was positioned just so that a higher concentration section of the cloud was moved past the collectors within one of the eddies caused by the turbulent SBL conditions. The decrease in outliers from PC A to B to D further supports the explanation that Pasquill stability classes provide a fair estimate for SBL turbulence conditions.

CHAPTER 6: CONCLUSIONS

In conclusion, testing of the hypotheses from Chapter 2 led to the following conclusions:

1) The case studies revealed that deposition, and therefore the inferred dispersion pattern for agricultural sprays, differs significantly between Pasquill classes. This difference is based on the way that spray droplets are moved in the SBL, with unstable conditions producing more turbulent flow, in turn producing larger eddies to mix SBL air. This turbulent flow allows the larger droplets to remain suspended for a longer time, while allowing the smaller droplets, which usually are the main cause of drift (Bache and Johnstone 1992, Matthews 2006), to be mixed well in the horizontal and vertical directions, minimizing the concentration that a downwind location would receive. The observed differences between Pasquill classes suggest that the Pasquill classification system is a valid method for analyzing and possibly predicting drift dispersion features.

2) The studies revealed that within the first 50 m from the application site, deposition was greatest in Pasquill class A (extremely unstable), and then decreased in Pasquill class B (moderately unstable) and D (neutral). This suggests that for near-field drift concerns (<50 m) spraying is best done with neutral or slightly unstable conditions. The review of literature revealed that for drift concerns at larger distances (i.e. beyond 50-100 m), stable or neutral conditions are likely to increase drift by allowing smaller droplets to travel farther downwind without significant entrainment (Bache and Johnstone 1992, Davies 1966, Miller et al. 2000, Thistle 2000). This conclusion was further supported by the observed lack of decreasing deposition with distance in Pasquill class D.

3) Based on the review of literature and case studies, this study concludes that simple observation of relative insolation strength and wind speeds is sufficient for estimating the general dispersion characteristics of an agricultural spray, and therefore the potential drift risk, using the Pasquill class method described herein.

As in most scientific research, this project has raised more questions than it has answered. First, in future research more case studies should be conducted to validate the relationships identified here. In addition, future research must be done to assess the role of droplet size and nozzle type in drift-stability class relationships. The remoteness of the Macon Ridge station proved to be an obstacle to increasing the number case studies with varied atmospheric conditions. The travel required planning case studies several days in advance, and therefore hindered the collection of data in very different atmospheric conditions, and at different times of day. For future research, it would be preferable that if possible, case studies could be conducted at the Central LSU AgCenter research station in East Baton Rouge Parish. The proximity of the station to the LSU – Baton Rouge campus would facilitate increasing the number of case studies and capturing more varied atmospheric conditions. In addition the Central station would provide a larger fetch, and facilitate sampling at distances farther from the spray path, which would provide data for a more definitive description of drift in locations far (> 50 m) from the application site.

To produce a highly accurate and detailed guide for spray applicators to use *in situ* with confidence in a variety of conditions would require more case studies to verify the relationships observed in this project and case studies for all Pasquill classes. However, based on the results from this project, preliminary drift risk sheets or cards could be created that could be used by applicators to make more informed application decisions. Charts of drift risk for areas within approximately 150 ft (50 m) of field edge could be produced for spray applications under different meteorological conditions. A preliminary example is provided in Table 6.1. Table 6.1 could be accompanied with a brief overview of what strong, moderate, and slight sun conditions would be. “Strong sun” corresponds to high sun angles with few clouds; “moderate sun” corresponds to moderate sun angles (30-60° above horizon) with few clouds, or “strong sun” with mostly cloudy conditions; “slight sun” corresponds to low sun angles (15-30°) or “strong” or “moderate sun” with overcast conditions. “Nighttime conditions” are representative of all times when the sun is lower than 15° above the horizon. While this study could be considered successful in achieving the research goals, it should be noted that this study only represents a first step toward understanding dispersion conditions for one set of droplet and nozzle sizes and spray application style. Future research should be undertaken to provide more detailed analysis under a wider variety of atmospheric conditions, to ensure greater protection of life and property.

Table 6.1: Drift Risk Guide for Field Use

Average Wind Speed (mph)	**Strong Sun**	**Moderate Sun**	**Slight Sun**	**Nighttime, >1/2 Cloudiness**	**Nighttime, <1/2 cloudiness**
< 4	Low Risk	Low Risk	Low-Moderate Risk	Very High Risk	Extreme Risk
4-6	Low Risk	Low-Moderate Risk	Moderate-High Risk	Very High Risk	Extreme Risk
6-9	Low-Moderate Risk	Low-Moderate Risk	Moderate-High Risk	Very High Risk	Extreme Risk
9-11	Low-Moderate Risk	Moderate-High Risk	High Risk	High Risk	Very High Risk
11-13	Moderate-High Risk	Moderate-High Risk	High Risk	High Risk	High Risk
> 13	Moderate-High Risk	High Risk	High Risk	High Risk	High Risk

REFERENCES

Anderson, D. E., D. R. Miller, Y. S. Wang, W. G. Yendol, K. Mierzejewski and M. L. McManus (1992) Deposition of Aerially Applied BT in an Oak Forest and Its Prediction with the Fscbg Model. *Journal of Applied Meteorology,* 31, 1457-1466.

Arya, P. S. 2001. *Introduction to Meteorology,* San Diego, CA: Academic Press.

Bache, D. H. and D. R. Johnstone. 1992. *Mictoclimate and Spray Dispersion*. Chinchester, West Sussex, England: Ellis Horwood.

Baetens, K., Q. T. Ho, D. Nuyttens, M. De Schampheleire, A. M. Endalew, M. Hertog, B. Nicolai, H. Ramon and P. Verboven (2009) A Validated 2-D Diffusion-Advection Model for Prediction of Drift from Ground Boom Sprayers. *Atmospheric Environment,* 43, 1674-1682.

Baetens, K., D. Nuyttens, P. Verboven, M. De Schampheleire, B. Nicolai and H. Ramon (2007) Predicting Drift from Field Spraying by Means of a 3d Computational Fluid Dynamics Model. *Computers and Electronics in Agriculture,* 56, 161-173.

Barbosa, R. 2011. Pesticide Application Efficiency and Drift Potential from Aerial and Ground Sprayers. In *Soybean and Grain Research and Promotion Board Meeting*. Baton Rouge, LA.

Bird, S. L., D. M. Esterly and S. G. Perry (1996) Off-Target Deposition of Pesticides from Agricultural Aerial Spray Applications. *Journal of Environmental Quality,* 25, 1095-1104.

Briggs, G. A. 1973. Diffusion Estimation for Small Emissions. ed. Environmental Research Laboratory. Air Resources Atmospheric Turbulence and Diffusion Laboratory, NOAA. Oak Ridge, TN.

Brown, M. B. and A. B. Forsythe (1974) Robust Tests for Equality of Variances. *Journal of the American Statistical Association,* 69, 364-367.

Burn, A. (2003) Pesticide Buffer Zones for the Protection of Wildlife. *Pest Management Science,* 59, 583-590.

Carlson, J. D. and D. S. Arndt (2008) The Oklahoma Dispersion Model: Using the Gaussian Plume Model as an Operational Management Tool for Determining near-Surface Dispersion Conditions across Oklahoma. *Journal of Applied Meteorology and Climatology,* 47, 462-474.

Carson, R. 1962. *Silent Spring*. Houghton Mifflin.

Cox, C. P. 1987. *A Handbook of Introductory Statistical Methods*. New York: John Wiley and Sons.

Crabbe, R. S., M. McCooeye and R. E. Mickle (1994) The Influence of Atmospheric Stability on Wind Drift from Ultra-Low-Volume Aerial Forest Spray Applications. *Journal of Applied Meteorology,* 33, 500-507.

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

Damalas, C. A. and I. G. Eleftherohorinos (2011) Pesticide Exposure, Safety Issues, and Risk Assessment Indicators. *International Journal of Environmental Research and Public Health,* 8, 1402-1419.

Daniel, P. 2005. *Toxic Drift : Pesticides and Health in the Post-World War II South / Pete Daniel*. Baton Rouge ; Washington, DC : Louisiana State University Press in association with Smithsonian National Museum of American History.

Davies, N. C. 1966. Deposition from Moving Aerosols. In *Aerosol Science,* ed. C. N. Davies, 393-446. London, New York: Academic Press.

Delaplane, K. S. 1996. Pesticide Usage in the United States: History, Benefits, Risks, and Trends. Athens, GA: Cooperative Extension Service, University of Georgia.

Dinham, B. 1993. *The Pesticide Hazard : A Global Health and Environmental Audit / Compiled by Barbara Dinham ; with a Preface by Monica Moore*. London : Atlantic Highlands, NJ, USA. Zed Books, 1993.

Eagleman, J. R. 1991. *Air Pollution Meteorology*. Lenexa, KS Trimedia Publishing Company.

EPA. 1992. The Guardian: Origins of the EPA. ed. U. S. Evironmental Protection Agency. Washington D.C.

EPA. 1999. Spray Drift of Pesticides. ed. U. S. Environmental Protection Agency. Washington D.C.

EPA. 2007. Assessing Health Risks from Pesticides. ed. U. S. Environmental Protection Agency. Washington D.C.

Food and Agriculture Organization. 1968. Report on the Fist Session of the FAO Panel of Experts on Integrated Pest Control. Rome, Italy: Food and Agriculture Organization of the United Nations.

Felsot, A. S., J. B. Unsworth, J. Linders, G. Roberts, D. Rautman, C. Harris and E. Carazo (2011) Agrochemical Spray Drift; Assessment and Mitigation - a Review. *Journal of Environmental Science and Health Part B-Pesticides Food Contaminants and Agricultural Wastes,* 46, 1-23.

Fritz, B. K. (2006) Meteorological Effects on Deposition and Drift of Aerially Applied Sprays. *Transactions of the ASABE,* 49, 1295-1301.

Gifford, F. (1960) Atmospheric Dispersion Calculations Using the Generalized Gaussian Plume Model. *Nuclear Safety,* 2, 56-69.

Hallenbeck, W. H. and K. M. Cunningham. 1985. *Pesticides and Human Health / William H. Hallenbeck, Kathleen M. Cunningham-Burns*. New York : Springer-Verlag, c1985.

Hanna, S. R., G. A. Briggs and J. Rayford P. Hosker. 1982. Handbook on Atmospheric Diffusion. ed. U. S. Department of Energy, 25-35. Washington, DC : Technical Information Center.

Hilz, E. and A. W. P. Vermeer (2013) Spray Drift Review: The Extent to Which a Formulation Can Contribute to Spray Drift Reduction. *Crop Protection,* 44, 75-83.

Holterman, H. J., J. C. van de Zande, H. A. J. Porskamp and J. F. M. Huijsmans (1997) Modelling Spray Drift from Boom Sprayers. *Computers and Electronics in Agriculture,* 19, 1-22.

Jain, R., M. Bhargava and N. Sharma (2003) Electrochemical Studies on a Pharmaceutical Azo Dye: Tartrazine. *Industrial and Engineering Chemistry Research,* 42, 243-247.

Kirk, R. E. 1995. Fundamental Assumptions in Analysis of Variance. In *Experimental Design: Procedures for the Behavioral Sciences*, 72-112. Belmont, CA US: Thomson Brooks/Cole Publishing Co.

Lazzaro, L., S. Otto and G. Zanin (2008) Role of Hedgerows in Intercepting Spray Drift: Evaluation and Modelling of the Effects. *Agriculture Ecosystems and Environment,* 123, 317-327.

Lebeau, F., A. Verstraete, C. Stainier and M. F. Destain (2011) RTDrift: A Real Time Model for Estimating Spray Drift from Ground Applications. *Computers and Electronics in Agriculture,* 77, 161-174.

Lee, S. J., L. Mehler, J. Beckman, B. Diebolt-Brown, J. Prado, M. Lackovic, J. Waltz, P. Mulay, A. Schwartz, Y. Mitchell, S. Moraga-McHaley, R. Gergely and G. M. Calvert (2011) Acute Pesticide Illnesses Associated with Off-Target Pesticide Drift from Agricultural Applications: 11 States, 1998-2006. *Environmental Health Perspectives,* 119, 1162-1169.

Levene, H. 1960. Robust Tests for Equality of Variances. In *Contributions to Probability and Statistics; Essays in Honor of Harold Hotelling.* eds. I. Olkin,S. G. Ghurye,W. Hoeffding,W. G. Madow and H. B. Mann, 278-292. Stanford, California: Stanford University Press.

Maccollom, G. B., W. W. Currier and G. L. Baumann (1986) Drift Comparisons between Aerial and Ground Orchard Application. *Journal of Economic Entomology,* 79, 459-464.

Matthews, G. A. 2006. Spray Drift, Bystander, Resident and Worker Exposure. In *Pesticides : Health, Safety and the Environment*. Oxford, UK; Ames, Iowa, USA: Blackwell Publishers.

May, K. R. and R. Clifford (1967) The Impaction of Aerosol Particles on Cylinders, Spheres, Ribbons and Discs. *Annals of Occupational Hygiene* 10, 83-95.

Maybank, J., K. Yoshida and R. Grover (1978) Spray Drift from Agricultural Pesticide Applications. *Journal of the Air Pollution Control Association*, 28, 1009-1014.

Miller, D. R. and T. E. Stoughton (2000) Response of Spray Drift from Aerial Applications at a Forest Edge to Atmospheric Stability. *Agricultural and Forest Meteorology,* 100, 49-58.

Miller, D. R., T. E. Stoughton, W. E. Steinke, E. W. Huddleston and J. B. Ross (2000) Atmospheric Stability Effects on Pesticide Drift from an Irrigated Orchard. *Transactions of the ASAE,* 43, 1057-1066.

Miller, D. R., W. E. Yendol, K. M. Ducharme, S. Maczuga, R. C. Reardon and M. A. McManus (1996) Drift of Aerially Applied Diflubenzuron over an Oak Forest. *Agricultural and Forest Meteorology,* 80, 165-176.

Miller, P. C. H. 1993. Spray Drift and Its Measurement. In *Application Technology for Crop Protection,* eds. G. A. Matthews and E. C. Hislop, 101-102. Wallingford, CAB International.

Nordstokke, D. W. and B. D. Zumbo (2010) A New Nonparametric Levene Test for Equal Variances. *Psicologica,* 31, 401-430.

NRC. 1983. Risk Assessment in the Federal Government: Managing the Process. ed. Committee on the Institutional Means for Assessment of Risks to Public Health. Washington DC : National Academies Press.

Nuyttens, D., M. De Schampheleire, K. Baetens and B. Sonck (2007) The Influence of Operator-Controlled Variables on Spray Drift from Field Crop Sprayers. *Transactions of the ASABE,* 50, 1129-1140.

Parkin, C. S. and C. R. Merritt (1988) The Measurement and Prediction of Spray Drift. *Aspects of Applied Biology*, 351-361.

Pasquill, F. (1961) The Estimation of the Dispersion of Windborne Material *The Meteorological Magazine,* 90, 33-49.

Pasquill, F. (1972) Factors Determining Pollution from Local Sources in Industrial and Urban Areas. *Meteorological Magazine,* 101, 1-7.

Payne, N. J. (1992) Off-Target Glyphosate from Aerial Silvicultural Applications, and Buffer Zones Required around Sensitive Areas. *Pesticide Science,* 34, 1-8.

Pergher, G. (2001) Recovery Rate of Tracer Dyes Used for Spray Deposit Assessment. *Transactions of the ASAE,* 44, 787-794.

Pergher, G., R. Gubiani and G. Tonetto (1997) Foliar Deposition and Pesticide Losses from Three Air-Assisted Sprayers in a Hedgerow Vineyard. *Crop Protection,* 16, 25-33.

Quantick, H. R. 1985. Dynamics of Droplet and Particulate Dispersal. In *Aviation in Crop Protection, Pollution and Insect Control*, 140-174. London: Collins.

Raupach, M. R., P. R. Briggs, N. Ahmad and V. E. Edge (2001) Endosulfan Transport: Ii. Modeling Airborne Dispersal and Deposition by Spray and Vapor. *Journal of Environmental Quality,* 30, 729-740.

Renne, D. S. and M. A. Wolf (1979) Experimental Studies of 2, 4-D Herbicide Drift Characteristics. *Agricultural Meteorology*, 20, 7-24.

Richardson, B., J. Ray and A. Vanner. 1989. Evaluation of Techniques to Measure Aerial Spray Deposition. In *42nd New Zealand Weed and Pest Control Conference,* ed. A. Popay, 133-137. Palmerson North, New Zealand: New Zealand Weed and Pest Control Society.

Scheffé, H. 1999. The S-Method of Multiple Comparison, General Case. In *The Analysis of Variance,* 68-72. New York: Wiley-Interscience Publication.

Shapiro, S. S. and M. B. Wilk (1965) An Analysis of Variance Test for Normality (Complete Samples). *Biometrika,* 52, 591-611.

Stephenson, G. R., I. G. Ferris, P. T. Holland and M. Nordberg (2006) Glossary of Terms Relating to Pesticides - (Iupac Recommendations 2006). *Pure and Applied Chemistry,* 78, 2075-2154.

Stoughton, T. E. and D. R. Miller (2002) Vertical Dispersion in the Nocturnal, Stable Surface Layer above a Forest Canopy. *Atmospheric Environment,* 36, 3989-3997.

Stoughton, T. E., D. R. Miller, X. S. Yang and K. M. Ducharme (1997) A Comparison of Spray Drift Predictions to Lidar Data. *Agricultural and Forest Meteorology,* 88, 15-26.

Stover, E., C. Wilson, D. Scotto and M. Salyani (2004) Pesticide Spraying in Indian River Grapefruit: Iii. Opportunities for Improving Efficacy and Efficiency While Reducing Off-Target Deposition. *Horttechnology,* 14, 564-574.

Stull, R. B. 1988. Tubulence Kinetic Energy, Stability and Scaling. In *An Introduction to Bounary Layer Meteorology,* 151-189. Dordrecht, Boston: Kluwer Accademic Pbulishers

Sundaram, A. and K. M. S. Sundaram (1991) Role of Physical Factors on Pesticide Performance in Forestry - an Overview. *Journal of Environmental Science and Health Part B-Pesticides Food Contaminants and Agricultural Wastes,* 26, 115-146.

Teske, M. E., J. F. Bowers, J. E. Rafferty and J. W. Barry (1993) FSCBG - an Aerial Spray Dispersion Model for Predicting the Fate of Released Material Behind Aircraft. *Environmental Toxicology and Chemistry,* 12, 453-464.

Testimony of Rachel Carson to the Senate Hearing on "Interagency Coordination of Environmenal Hazards". 1964. In *Committee on Government Operations*. Washington D.C.: Government Printing Office.

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, 1409-1413.

Thode, H. C. 2002. *Testing for Normality*. New York: Marcel Dekker.

Tsai, M. Y., K. Elgethun, J. Ramaprasad, M. G. Yost, A. S. Felsot, V. R. Hebert and R. A. Fenske (2005) The Washington Aerial Spray Drift Study: Modeling Pesticide Spray Drift Deposition from an Aerial Application. *Atmospheric Environment*, 39, 6194-6203.

USDA. 2011. State Fact Sheets: Louisiana. U. S. Department of Agriculture.

US National Library of Medicine (2012)Tartrazine.

von Storch, H. and F. W. Zwiers. 1999. Analysis of Variance. In *Statistical Analysis in Climate Research*, 171-192. Cambridge, United Kingdom: Cambridge University Press.

WHO. 1990. Public Health Impacts of Pesticides Used in Agriculture. ed. World Health Organization. Geneva, Switzerland: World Health Organization.

Yarpuz-Bozdogan, N. and A. M. Bozdogan (2009) Assessment of Dermal Bystander Exposure in Pesticide Applications Using Different Types of Nozzles. *Journal of Food Agriculture and Environment*, 7, 678-682.

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, 628-632.

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, 627-632.

Yeo, D. and B. W. Thompson (1953) Deposition of a Coarse Aerosol Released from a Low-Flying Aircraft. *Nature*, 172, 168-169.

APPENDIX 1: ABSORPTION TO DEPOSITION

Table A1.1 Calculation of Deposition from Absorption Readings for Spheres:

Sample	Absorbance	Tartrazine Concentration (g ml^{-1})	Tartrazine Mass in Sample (g)	Deposition (g m^{-2})
1A1	0.008	5.71E-07	5.71E-06	0.84
1A2	0.002	4.22E-07	4.22E-06	0.62
1A3	0.011	6.46E-07	6.46E-06	0.95
1A4	0.008	5.71E-07	5.71E-06	0.84
1A5	0.004	4.72E-07	4.72E-06	0.69
1A6	0.005	4.97E-07	4.97E-06	0.73
1A7	0.002	4.22E-07	4.22E-06	0.62
1B1	0.012	6.71E-07	6.71E-06	0.99
1B2	0.017	7.96E-07	7.96E-06	1.17
1B3	0.018	8.21E-07	8.21E-06	1.21
1B4	0.014	7.21E-07	7.21E-06	1.06
1B5	0.017	7.96E-07	7.96E-06	1.17
1B6	0.014	7.21E-07	7.21E-06	1.06
1B7	0.017	7.96E-07	7.96E-06	1.17
1C1	0.002	4.22E-07	4.22E-06	0.62
1C2	0.008	5.71E-07	5.71E-06	0.84
1C3	0.004	4.72E-07	4.72E-06	0.69
1C4	0.003	4.47E-07	4.47E-06	0.66
1C5	0.005	4.97E-07	4.97E-06	0.73
1C6	0.005	4.97E-07	4.97E-06	0.73
1C7	0.007	5.46E-07	5.46E-06	0.80
2A1	0.006	5.22E-07	5.22E-06	0.77
2A2	0.005	4.97E-07	4.97E-06	0.73
2A3	0.007	5.46E-07	5.46E-06	0.80
2A4	0.011	6.46E-07	6.46E-06	0.95
2A5	0.013	6.96E-07	6.96E-06	1.02
2A6	0.005	4.97E-07	4.97E-06	0.73
2A7	0.007	5.46E-07	5.46E-06	0.80
2B1	0.007	5.46E-07	5.46E-06	0.80
2B2	0.005	4.97E-07	4.97E-06	0.73
2B3	0.007	5.46E-07	5.46E-06	0.80
2B4	0.008	5.71E-07	5.71E-06	0.84
2B5	0.014	7.21E-07	7.21E-06	1.06
2B6	0.008	5.71E-07	5.71E-06	0.84
2B7	0.004	4.72E-07	4.72E-06	0.69
2C1	0.015	7.46E-07	7.46E-06	1.10

(Table A1.1 Continued)

Sample	Absorbance	Tartrazine Concentration ($g\ ml^{-1}$)	Tartrazine Mass in Sample (g)	Deposition ($g\ m^{-2}$)
2C2	0.008	5.71E-07	5.71E-06	0.84
2C3	0.007	5.46E-07	5.46E-06	0.80
2C4	0.013	6.96E-07	6.96E-06	1.02
2C5	0.013	6.96E-07	6.96E-06	1.02
2C6	0.008	5.71E-07	5.71E-06	0.84
2C7	0.009	5.96E-07	5.96E-06	0.88
3A1	0.012	6.71E-07	6.71E-06	0.99
3A2	0.007	5.46E-07	5.46E-06	0.80
3A3	0.012	6.71E-07	6.71E-06	0.99
3A4	0.010	6.21E-07	6.21E-06	0.91
3A5	0.014	7.21E-07	7.21E-06	1.06
3A6	0.012	6.71E-07	6.71E-06	0.99
3A7	0.010	6.21E-07	6.21E-06	0.91
3B1	0.007	5.46E-07	5.46E-06	0.80
3B2	0.010	6.21E-07	6.21E-06	0.91
3B3	0.009	5.96E-07	5.96E-06	0.88
3B4	0.009	5.96E-07	5.96E-06	0.88
3B5	0.008	5.71E-07	5.71E-06	0.84
3B6	0.006	5.22E-07	5.22E-06	0.77
3B7	0.007	5.46E-07	5.46E-06	0.80
3C1	0.000	3.72E-07	3.72E-06	0.55
3C2	0.003	4.47E-07	4.47E-06	0.66
3C3	0.002	4.22E-07	4.22E-06	0.62
3C4	0.002	4.22E-07	4.22E-06	0.62
3C5	0.002	4.22E-07	4.22E-06	0.62
3C6	0.003	4.47E-07	4.47E-06	0.66
3C7	0.004	4.72E-07	4.72E-06	0.69
4A1	0.015	7.46E-07	7.46E-06	1.10
4A2	0.028	1.07E-06	1.07E-05	1.57
4A3	0.013	6.96E-07	6.96E-06	1.02
4A4	0.031	1.15E-06	1.15E-05	1.68
4A5	0.027	1.05E-06	1.05E-05	1.54
4A6	0.055	1.74E-06	1.74E-05	2.56
4A7	0.023	9.46E-07	9.46E-06	1.39
4B1	0.042	1.42E-06	1.42E-05	2.09
4B2	0.026	1.02E-06	1.02E-05	1.50
4B3	0.016	7.71E-07	7.71E-06	1.13
4B4	0.011	6.46E-07	6.46E-06	0.95
4B5	0.029	1.10E-06	1.10E-05	1.61

(Table A1.1 Continued)

Sample	Absorbance	Tartrazine Concentration (g ml^{-1})	Tartrazine Mass in Sample (g)	Deposition (g m^{-2})
4B6	0.022	9.21E-07	9.21E-06	1.35
4B7	0.020	8.71E-07	8.71E-06	1.28
4C1	0.005	4.97E-07	4.97E-06	0.73
4C2	0.023	9.46E-07	9.46E-06	1.39
4C3	0.027	1.05E-06	1.05E-05	1.54
4C4	0.016	7.71E-07	7.71E-06	1.13
4C5	0.011	6.46E-07	6.46E-06	0.95
4C6	0.003	4.47E-07	4.47E-06	0.66
4C7	0.001	3.97E-07	3.97E-06	0.58
5A1	0.010	6.21E-07	6.21E-06	0.91
5A2	0.010	6.21E-07	6.21E-06	0.91
5A3	0.016	7.71E-07	7.71E-06	1.13
5A4	0.008	5.71E-07	5.71E-06	0.84
5A5	0.009	5.96E-07	5.96E-06	0.88
5A6	0.016	7.71E-07	7.71E-06	1.13
5A7	0.017	7.96E-07	7.96E-06	1.17
5B1	0.016	7.71E-07	7.71E-06	1.13
5B2	0.008	5.71E-07	5.71E-06	0.84
5B3	0.007	5.46E-07	5.46E-06	0.80
5B4	0.011	6.46E-07	6.46E-06	0.95
5B5	0.009	5.96E-07	5.96E-06	0.88
5B6	0.011	6.46E-07	6.46E-06	0.95
5B7	0.014	7.21E-07	7.21E-06	1.06
5C1	0.007	5.46E-07	5.46E-06	0.80
5C2	0.009	5.96E-07	5.96E-06	0.88
5C3	0.007	5.46E-07	5.46E-06	0.80
5C4	0.006	5.22E-07	5.22E-06	0.77
5C5	0.012	6.71E-07	6.71E-06	0.99
5C6	0.008	5.71E-07	5.71E-06	0.84
5C7	0.010	6.21E-07	6.21E-06	0.91
6A1	0.026	1.02E-06	1.02E-05	1.50
6A2	0.024	9.71E-07	9.71E-06	1.43
6A3	0.021	8.96E-07	8.96E-06	1.32
6A4	0.029	1.10E-06	1.10E-05	1.61
6A5	0.034	1.22E-06	1.22E-05	1.79
6A6	0.033	1.20E-06	1.20E-05	1.76
6A7	0.016	7.71E-07	7.71E-06	1.13
6B1	0.061	1.89E-06	1.89E-05	2.78
6B2	0.024	9.71E-07	9.71E-06	1.43

(Table A1.1 Continued)

Sample	Absorbance	Tartrazine Concentration (g ml^{-1})	Tartrazine Mass in Sample (g)	Deposition (g m^{-2})
6B3	0.015	7.46E-07	7.46E-06	1.10
6B4	0.017	7.96E-07	7.96E-06	1.17
6B5	0.015	7.46E-07	7.46E-06	1.10
6B6	0.022	9.21E-07	9.21E-06	1.35
6B7	0.016	7.71E-07	7.71E-06	1.13
6C1	0.012	6.71E-07	6.71E-06	0.99
6C2	0.014	7.21E-07	7.21E-06	1.06
6C3	0.014	7.21E-07	7.21E-06	1.06
6C4	0.018	8.21E-07	8.21E-06	1.21
6C5	0.016	7.71E-07	7.71E-06	1.13
6C6	0.009	5.96E-07	5.96E-06	0.88
6C7	0.010	6.21E-07	6.21E-06	0.91
7A1	0.020	8.71E-07	8.71E-06	1.28
7A2	0.013	6.96E-07	6.96E-06	1.02
7A3	0.011	6.46E-07	6.46E-06	0.95
7A4	0.014	7.21E-07	7.21E-06	1.06
7A5	0.018	8.21E-07	8.21E-06	1.21
7A6	0.015	7.46E-07	7.46E-06	1.10
7A7	0.018	8.21E-07	8.21E-06	1.21
7B1	0.012	6.71E-07	6.71E-06	0.99
7B2	0.008	5.71E-07	5.71E-06	0.84
7B3	0.008	5.71E-07	5.71E-06	0.84
7B4	0.018	8.21E-07	8.21E-06	1.21
7B5	0.009	5.96E-07	5.96E-06	0.88
7B6	0.011	6.46E-07	6.46E-06	0.95
7B7	0.001	3.97E-07	3.97E-06	0.58
7C1	0.033	1.20E-06	1.20E-05	1.76
7C2	0.031	1.15E-06	1.15E-05	1.68
7C3	0.016	7.71E-07	7.71E-06	1.13
7C4	0.017	7.96E-07	7.96E-06	1.17
7C5	0.016	7.71E-07	7.71E-06	1.13
7C6	0.015	7.46E-07	7.46E-06	1.10
7C7	0.015	7.46E-07	7.46E-06	1.10
8A1	0.050	1.62E-06	1.62E-05	2.38
8A2	0.073	2.19E-06	2.19E-05	3.23
8A3	0.012	6.71E-07	6.71E-06	0.99
8A4	0.079	2.34E-06	2.34E-05	3.45
8A5	0.088	2.57E-06	2.57E-05	3.78
8A6	0.043	1.44E-06	1.44E-05	2.12

(Table A1.1 Continued)

Sample	Absorbance	Tartrazine Concentration (g ml^{-1})	Tartrazine Mass in Sample (g)	Deposition (g m^{-2})
8A7	0.084	2.47E-06	2.47E-05	3.63
8B1	0.020	8.71E-07	8.71E-06	1.28
8B2	0.034	1.22E-06	1.22E-05	1.79
8B3	0.015	7.46E-07	7.46E-06	1.10
8B4	0.016	7.71E-07	7.71E-06	1.13
8B5	0.052	1.67E-06	1.67E-05	2.45
8B6	0.033	1.20E-06	1.20E-05	1.76
8B7	0.036	1.27E-06	1.27E-05	1.87
8C1	0.039	1.34E-06	1.34E-05	1.98
8C2	0.033	1.20E-06	1.20E-05	1.76
8C3	0.018	8.21E-07	8.21E-06	1.21
8C4	0.023	9.46E-07	9.46E-06	1.39
8C5	0.031	1.15E-06	1.15E-05	1.68
8C6	0.030	1.12E-06	1.12E-05	1.65
8C7	0.023	9.46E-07	9.46E-06	1.39

Table A1.2: As in Table A1.1, but for Monofilament Collectors

Sample	Absorbance	Tartrazine concentration (g ml^{-1})	Tartrazine Mass in Sample (g)	Deposition (mg m^{-2})
1AL	0.010	6.21E-07	4.35E-05	15.36
1AU	0.002	4.22E-07	2.95E-05	10.43
1BL	0.004	4.72E-07	3.30E-05	11.67
1BU	0.008	5.71E-07	4.00E-05	14.13
1CL	0.006	5.21E-07	3.65E-05	12.90
1CU	0.004	4.72E-07	3.30E-05	11.67
2AL	--	--	--	--
2AU	0.004	4.72E-07	3.30E-05	11.67
2BL	0.006	5.21E-07	3.65E-05	12.90
2BU	0.003	4.47E-07	3.13E-05	11.05
2CL	0.002	4.22E-07	2.95E-05	10.43
2CU	0.003	4.47E-07	3.13E-05	11.05
3AL	0.005	4.97E-07	3.48E-05	12.28
3AU	0.029	1.09E-06	7.66E-05	27.06
3BL	0.012	6.71E-07	4.70E-05	16.59
3BU	0.005	4.97E-07	3.48E-05	12.28
3CL	0.005	4.97E-07	3.48E-05	12.28
3CU	0.005	4.97E-07	3.48E-05	12.28
5AL	0.011	6.46E-07	4.52E-05	15.98

(Table A1.2 Continued)

Sample	Absorbance	Tartrazine concentration (g ml^{-1})	Tartrazine Mass in Sample (g)	Deposition (mg m^{-2})
5AU	0.017	7.95E-07	5.57E-05	19.67
5BL	0.013	6.96E-07	4.87E-05	17.21
5BU	0.010	6.21E-07	4.35E-05	15.36
5CL	0.010	6.21E-07	4.35E-05	15.36
5CU	0.011	6.46E-07	4.52E-05	15.98
6AL	0.039	1.34E-06	9.40E-05	33.22
6AU	0.013	6.96E-07	4.87E-05	17.21
6BL	0.020	8.70E-07	6.09E-05	21.52
6BU	0.032	1.17E-06	8.18E-05	28.91
6CL	0.017	7.95E-07	5.57E-05	19.67
6CU	0.017	7.95E-07	5.57E-05	19.67
8AL	0.032	1.17E-06	8.18E-05	28.91
8AU	0.017	7.95E-07	5.57E-05	19.67
8BL	0.011	6.46E-07	4.52E-05	15.98
8BU	0.037	1.29E-06	9.05E-05	31.99
8CL	0.006	5.21E-07	3.65E-05	12.90
8CU	0.010	6.21E-07	4.35E-05	15.36

APPENDIX 2: MEANS, STANDARD DEVIATIONS, AND SAMPLE SIZES

Table A2.1 Means, Standard Deviations, and Sample Sizes for Deposition on Spherical Collectors

Sample Set	Mean	Standard Deviation	Sample Size	Figure Number
PC A Samples	1.48	0.68	63	4.1
PC B Samples	1.02	0.36	63	4.1
PC D Samples	0.86	0.17	42	4.1
Slight Insolation	0.96	0.34	84	4.2
Moderate Insolation	1.34	0.81	84	4.2
Case Study 1	0.87	0.20	21	4.3
Case Study 2	0.86	0.12	21	4.3
Case Study 3	0.81	0.15	21	4.3
Case Study 4	1.32	0.47	21	4.3
Case Study 5	0.93	0.12	21	4.3
Case Study 6	1.33	0.42	21	4.3
Case Study 7	1.10	0.26	21	4.3
Case Study 8	2.01	0.85	21	4.3
PC A, 10 m	1.81	0.93	21	4.5
PC A, 25 m	1.45	0.48	21	4.5
PC A, 50 m	1.18	0.37	21	4.5
PC B, 10 m	1.17	0.41	21	4.5
PC B, 25 m	0.93	0.23	21	4.5
PC B, 50 m	0.97	0.40	21	4.5
PC D, 10 m	0.79	0.12	14	4.5
PC D, 25 m	0.97	0.18	14	4.5
PC D, 50 m	0.83	0.14	14	4.5
PC A, 0.30 m	1.62	0.65	6	4.6
PC A, 0.61 m	1.28	0.57	6	4.6
PC A, 0.91 m	1.55	0.71	6	4.6
PC A, 1.22 m	1.47	0.89	3	4.6
PC B, 0.30 m	1.03	0.38	6	4.6
PC B, 0.61 m	0.98	0.28	6	4.6
PC B, 0.91 m	1.07	0.47	6	4.6
PC B, 1.22 m	0.98	0.27	3	4.6
PC D, 0.30 m	0.84	0.17	6	4.6
PC D, 0.61 m	0.89	0.16	6	4.6
PC D, 0.91 m	0.89	0.17	6	4.6
PC D, 1.22 m	0.83	0.19	3	4.6
PC A, 10, 0.30	1.81	0.83	6	4.9

(Table A2.1 Continued)

Sample Set	Mean	Standard Deviation	Sample Size	Figure Number
PC A, 10, 0.61	1.56	0.96	6	4.9
PC A, 10, 0.91	1.96	0.97	6	4.9
PC A, 10, 1.22	1.99	1.42	3	4.9
PC A, 25, 0.30	1.79	0.53	6	4.9
PC A, 25, 0.61	1.13	0.03	6	4.9
PC A, 25, 0.91	1.48	0.54	6	4.9
PC A, 25, 1.22	1.37	0.43	3	4.9
PC A, 50, 0.30	1.27	0.47	6	4.9
PC A, 50, 0.61	1.15	0.19	6	4.9
PC A, 50, 0.91	1.19	0.38	6	4.9
PC A, 50, 1.22	1.05	0.54	3	4.9
PC B, 10, 0.30	1.05	0.28	6	4.8
PC B, 10, 0.61	1.10	0.30	6	4.8
PC B, 10, 0.91	1.36	0.63	6	4.8
PC B, 10, 1.22	1.16	0.24	3	4.8
PC B, 25, 0.30	0.97	0.25	6	4.8
PC B, 25, 0.61	1.03	0.27	6	4.8
PC B, 25, 0.91	0.84	0.11	6	4.8
PC B, 25, 1.22	0.82	0.24	3	4.8
PC B, 50, 0.30	1.08	0.60	6	4.8
PC B, 50, 0.61	0.82	0.20	6	4.8
PC B, 50, 0.91	1.01	0.40	6	4.8
PC B, 50, 1.22	0.96	0.30	3	4.8
PC D, 10, 0.30	0.74	0.09	4	4.7
PC D, 10, 0.61	0.89	0.08	4	4.7
PC D, 10, 0.91	0.79	0.15	4	4.7
PC D, 10, 1.22	0.71	0.13	2	4.7
PC D, 25, 0.30	0.92	0.20	4	4.7
PC D, 25, 0.61	0.98	0.19	4	4.7
PC D, 25, 0.91	1.03	0.14	4	4.7
PC D, 25, 1.22	0.93	0.34	2	4.7
PC D, 50, 0.30	0.85	0.20	4	4.7
PC D, 50, 0.61	0.79	0.17	4	4.7
PC D, 50, 0.91	0.83	0.14	4	4.7
PC D, 50, 1.22	0.84	0.05	2	4.7

Table A2.2 As in Table A2.1, but for Monofilament Collectors

Sample Set	Mean	Standard Deviation	Sample Size	Figure Number
PC A	22.08	6.61	12	
PC B	16.03	4.02	12	
PC D	12.11	1.49	11	
Slight Insolation	13.30	3.91	17	
Moderate Insolation	20.25	6.22	18	
Case Study 1	12.69	1.66	6	
Case Study 2	11.42	0.84	5	
Case Study 3	15.46	5.42	6	
Case Study 5	16.59	1.51	6	
Case Study 6	23.37	5.72	6	
Case Study 8	20.80	7.16	6	
PC A, 10 m	24.75	7.57	4	
PC A, 25 m	24.60	7.24	4	
PC A, 50 m	16.90	3.35	4	
PC B, 10 m	18.75	6.31	4	
PC B, 25 m	15.36	2.19	4	
PC B, 50 m	13.97	1.97	4	
PC D, 10 m	12.49	2.56	3	
PC D, 25 m	12.43	1.37	4	
PC D, 50 m	11.51	1.05	4	
PC A, 0.30 m	22.03	7.73	6	
PC A, 1.22 m	22.14	6.71	6	
PC B, 0.30 m	14.95	1.97	6	
PC B, 1.22 m	17.11	5.11	6	
PC D, 0.30 m	12.65	1.63	5	
PC D, 1.22 m	11.67	1.18	6	
PC A, 10 m, 0.30 m	31.07	3.05	2	
PC A, 10 m, 1.22 m	18.44	1.74	2	
PC A, 25 m, 0.30 m	18.75	3.92	2	
PC A, 25 m, 1.22 m	30.45	2.18	2	
PC A, 50 m, 0.30 m	16.28	4.79	2	
PC A, 50 m, 1.22 m	17.52	3.05	2	
PC B, 10 m, 0.30 m	14.13	2.61	2	
PC B, 10 m, 1.22 m	23.37	5.23	2	
PC B, 25 m, 0.30 m	16.90	0.44	2	
PC B, 25 m, 1.22 m	13.82	2.18	2	
PC B, 50 m, 0.30 m	13.82	2.18	2	
PC B, 50 m, 1.22 m	14.13	2.61	2	
PC D, 10 m, 0.30 m	15.36	--	1	

(Table A2.2 Continued)

Sample Set	Mean	Standard Deviation	Sample Size	Figure Number
PC D, 10 m, 1.22 m	11.05	0.87	2	
PC D, 25 m, 0.30 m	12.28	0.87	2	
PC D, 25 m, 1.22 m	12.59	2.18	2	
PC D, 50 m, 0.30 m	11.67	1.74	2	
PC D, 50 m, 1.22 m	11.36	0.44	2	

VITA

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