Analysis of Prospective Systems for Fog Warnings

FDOT Contract Number BDK83 977-19

FINAL REPORT

Peter S. Ray. Ph.D.
Xizhen Du, Ph.D.
Justin Rivard

Florida State University
Department of Earth, Ocean, and Atmospheric Science
Meteorology Program
Tallahassee, Florida 32306

July, 2013

Disclaimer

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Analysis of Prospective Systems for Fog Warnings.		5. Report Date July 2013 6. Performing Organization Code
7. Author(s) Dr. Peter S. Ray Dr. Xizhen Du Mr. Justin Rivard		8. Performing Organization Report No.
9. Performing Organization Name and Address		10. Work Unit No. (TRAIS) 11. Contract or Grant No. FDOT BDK83 977-19
12. Sponsoring Agency Name and Address Florida State University Tallahassee, Florida 32306		13. Type of Report and Period Covered 5/8/2012 – 7/13/2013 14. Sponsoring Agency Code
15. Supplementary Notes Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, Florida		

16. Abstract

On November 22, 2012, at about 8:35 a.m., thick fog resulted in a 140 vehicle accident near Beaumont, Texas. Remarkably, only two people died and 80 people were injured and required hospital care. On January 29, 2012, about 4:00 a.m., amidst thick fog and smoke on I-75 south of Gainesville, Florida, 11 people were killed and 18 hospitalized in a multi-vehicle crash. Nationally, there are about 38,000 fog related vehicle accidents each year resulting in about 620 fatalities. In Florida, between 2002 and 2009, 299 people died in vehicle crashes related to fog and smoke conditions on Florida highways. This is more than those who died from hurricanes and lightning in Florida over the same time period. Fog is a cloud on the ground. All types of fog require ubiquitous cloud condensation nuclei (CCN) and can form with a relative humidity less than 100%. The opaqueness (heaviness or thickness) of fog may be substantially increased by the presence of smoke, due to the increase of CCN. Fog is both spatially and temporally variable. With observation equipment widely dispersed, the challenge is how to forecast the occurrence of fog from observation far removed from the location of fog occurrence.

With the available data from 2002 to 2009, the location and frequency of fog was determined, thus forming a fog climatology. Using the data from that study, researchers evaluated fog-prediction techniques and made recommendation to improve fog-warning systems along Florida's highways.

17. Key Word Fog Smoke Visibility Crashes	18. Distribution Statement No restrictions

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 78	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Executive Summary

The Problem

On November 22, 2012, at about 8:35 a.m., thick fog resulted in a 140-vehicle accident near Beaumont, Texas. Remarkably, only two people died and 80 people were injured and required hospital care. On January 29, 2012, about 4:00 a.m., amidst thick fog and smoke on I-75 south of Gainesville, Florida, 11 people were killed and 18 hospitalized in a multi-vehicle crash. Nationally, there are about 38,000 fog related vehicle accidents each year resulting in about 620 fatalities. In Florida between 2002 and 2009, 299 people died in vehicle crashes related to fog and smoke conditions on Florida highways. This is more than those who died from hurricanes and lightning in Florida over the same time period.

Fog is a cloud on the ground. All types of fog require ubiquitous cloud condensation nuclei (CCN) and can form with a relative humidity less than 100%. The opaqueness (heaviness or thickness) of fog may be substantially increased by the presence of smoke, due to the increase of CCN. Fog is both spatially and temporally variable. With observation equipment widely dispersed, the challenge is how to forecast the occurrence of fog from observation far removed from the location of fog occurrence.

With the available data from 2002 to 2009, the location and frequency of fog was determined, thus forming a fog climatology. Using the data from that study, researchers evaluated fog-prediction techniques and made recommendation to improve fog-warning systems along Floridas highways.

The Solution

The challenge is to know in advance when and where fog will develop. The focus of this work is to use the available data on fog occurrence to indicate the frequency and location of fog formation in the state. This is correlated with accident reports where poor visibility is indicated as the underlying cause of the accident. Conditions at instrumented sites at the time of and before fog formation are examined to determine the meteorological conditions that preceded the formation of fog as well as the conditions when fog existed. Knowledge of conditions along roadways where poor visibility is known to be a significant problem is suggested to be critical in providing useful forecasts of fog formation.

Watches (Forecasts)

Watches refer to situations where forecasters believe that fog may develop along a highway and that with reduced visibility normal travel may not be possible. Condition may develop which would require reduced vehicle speed or the use of alternate routes. This cautionary information should be capable of being displayed in fog-prone areas when fog conditions are anticipated.

Warnings

Warning signs are to alert motorists that they are approaching a section of highway where visibility limiting fog is either existing or imminent. Waring signs would display information such as a reduced speed, anticipated range of visibility or perhaps directions for an alternate route or detour. Many states have signage which either posts a reduced speed limit or directs traffic to an alternate route (detour) around the region of a driving hazard. Some states and locations have permanent signs and warnings. Other places use signs activated only when the hazard exists, often with lights and other attention-getting displays. One would expect the latter signage to be the more effective. The University of Central Florida (UCF) examined the most needed sign locations based on the number of traffic accidents.

Table of Contents

List of Figures

List of Tables

Acronyms

AMS	American Meteorological Society
AP	Air Port
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
CCN	Cloud Condensation Nuclei
FAWN	Florida Automated Weather Network
FDOT	Florida Department of Transportation
FOG	Fog Operational Guidance
F/S	Fog and or Smoke
FSU	Florida State University
kt	Knots
MADIS	Meteorological Assimilation Data Ingest System
MOS	Model Output Statistics
NAS	Naval Air Station
NWP	Numerical Weather Prediction
NWS	National Weather Service
RH	Relative Humidity
SFWMD	South Florida Water Management District
UCF	University of Central Florida

Chapter 1

Introduction

As reported by the University of Central Florida (UCF), Florida nearly leads the nation in fatal vehicle crashes due to fog and smoke (F/S) conditions. Between 2002 and 2009, 299 persons died in vehicle crashes related to F/S conditions, more than died by hurricanes and lightning strikes combined. Often these crashes involve multiple vehicles, which compounds the tragedy. A warning of impending F/S conditions would allow FDOT to take appropriate steps more effectively to reroute or warn motorists of impending or possible driving hazards. Also, appropriate agencies could be on the alert to monitor a specific location or prepare for rerouting traffic. It may be possible to reduce the number of fatalities and crashes by an effective early warning system.

1.1 Problem

Many accidents occur each year in Florida where visibility, usually fog, is considered a contributing cause. Most often accidents occur at night when fog is more likely, and also where visibility is the poorest. Often these can become multi-vehicle disasters as limited visibility obscures an earlier collision down the road.

1.2 Objectives

The objective of this research is to provide a methodology to improve prediction of where and when fog or smoke-burdened fog would form that would interfere with normal driving conditions. Supporting objectives are to provide recommendations regarding instrumentation and models or procedures that would allow proactive warnings and actions that could prevent F/S-related accidents.

Achieving these objectives requires three phases of work: (1) Data and information gathering, (2) Synthesis of how the present system can be improved, what options exist and what is the most cost effective method. This involves the development of a model or procedure that would anticipate fog formation in fog-prone areas. Following that, (3) researchers will assess how well the available instrumentation systems perform and how well the models work, and what would be needed to improve performance.

The research has several objectives and activities that shall complement an on-going study being performed by UCF to develop and update historical data on past crashes due to F/S. Concurrently, FSU will identify sites where the potential exists, but no record currently exists, for F/S-related accidents. The research teams at FSU and UCF shall communicate and coordinate as appropriate to leverage the value of respective expertise and effort.

The UCF team is also examining various means of verifying fog, mostly by in situ instrumentation at known foggy locations. This study's objective of improving the knowledge of fog formation can inform the UCF efforts to determine (1) where fog is most likely and (2) where that relates to the greatest threat of crashes. The research team will first seek to use existing technology more effectively to minimize the need for procurement of additional instrumentation with the concurrent maintenance costs. After surveying available data and known fog prone locations, the research team shall work to improve the observation time and spatial location of the formation of fog.

Finally, the present state of the science of fog identification and prediction is given. An assessment of expected improvements in identification and prediction of fog with better instruments and wider deployment, as well as improved methods of analysis, is given.

1.3 Methodology

The research team had to ascertain when and where fog formed and then look at the surrounding meteorological data to see (1) if there is any way to forecast fog formation to provide useful fog watches, and (2) how close the data has to be to provide useful in situ-like data. Researchers needed to identify locations where fog was reported when it occurred. This data would form the backbone of our test and development cases. Researchers sought locations through inquiries to law enforcement agencies and other entities. It was FDOT's opinion that other agencies likely would not be responsive, and subsequent experience validates (unfortunately) that prediction. Next researchers sought locations from ASOS/AWOS stations, particularly at airports. The expectation is that they would report fog when it occurred and differentiate that from the days when it did not occur. The process would contain the following attributes:

- Identify locations where the research team could reliability determine each day whether fog formed and when, or if fog did not form;
- Use data from nearby stations to compute the correlations to determine what distance data might be useful to predict fog from an instrumented site;
- Use data in the forecast model to include elevation, wind speed, temperature, dew point temperature, maximum dew point temperature during the day, and whether it rained the previous day;
- Calculate statistics to determine how accurately the model predicts both the occurrence and the non-occurrence of fog.

Chapter 2

Fog

Fog is defined as a cloud on the ground that reduces visibility below one kilometer. According to Houghton (1985), fog generally occurs when water droplets are suspended in air that is within ten percent of saturation. Typically there are three primary physical processes that can make unsaturated air become saturated. These include cooling the air temperature, adding moisture, and mixing air parcels with different humidities and temperatures (Duynkerke, 1990). There are many other atmospheric and local factors that can exacerbate these mechanisms; including vegetation, horizontal and vertical winds, radiation fluxes, soil moisture, and topographic effects. However, once fog has formed, the primary mechanisms influencing further fog development and intensity are radiational cooling, gravitational droplet settling, fog microphysics, and cloud cover (Duynkerke, 1990).

2.1 Types of Fog

Synoptic, dynamic, and microphysical conditions will normally control what type of fog will generally form. Willett (1928) created an all-inclusive fog classification system, later revised by Byers (1959), which comprised 11 different types of fog, each of which was categorized by the physical processes involved and the atmospheric scenario in which the fog formed. Most of the fog types classified by Byers (1959), however, are merely derivatives of the four distinct types of fog as described by Stull (1999): advection fog, upslope fog, frontal fog, and radiation fog.

This project will focus primarily on radiation fog in the state of Florida. However, for the sake of completeness, the five different fog types are defined below.

2.1.1 Advection Fog

Advection fog occurs when a warm moist air mass moves over a cool surface (AMS, 1999). The warmer air mass loses heat through conduction to the cooler surface, thus lowering its temperature to its dew point temperature (Stull, 1999). The surfaces on which advection fog can form include: cold water, cold ground, and ground covered with snow or ice. Advection fog is typically found in marine environments such as coastal areas, as water sources provide the moisture and heat necessary to facilitate this fog type. However, the natural land-breeze thermal circulation that occurs in coastal regions during the early morning hours can limit the progress of advection fog. Therefore, overlying synoptic wind speeds and directions are critical in determining whether advection fog will form. According to the US Department of Transportation (1975), advection fog deepens as wind speed increases up to about 15 kt. Wind speeds much stronger than 15 kt will induce turbulence and mixing, leading to fog dissipation.

Sea fog is another form of advection fog where warm air advects over cooler ocean air. Through conduction, the warm air cools to its dew point (Baars et al., 2003). Sea fog typically occurs in regions of cold ocean currents to the west of continents, such as over the northeast Pacific Ocean off of the coast of California (Baars et al., 2009). Sea fog is most problematic for marine transportation, and only affects ground transportation when bridges or other roadways are over a sufficient amount of water. Both sea and land advection fogs are often more opaque and longer lasting than radiation fog (Toth et al., 2010). This contributes to the fact that advection fog, once formed, can experience radiational cooling on the top of the fog layer (Stull, 1999), exacerbating the rate of cooling in the warm-moist air mass, creating a more dense fog. The dissipation of advection fog is similar to that of most fogs. If the relatively cooler surface becomes warmer, saturation levels would not be sufficient for fog. Also, synoptic patterns, such as fronts, pressure systems, and wind direction can act to remove advection fog (Stull, 1999).

2.1.2 Upslope Fog

Upslope fog forms as a result of adiabatic expansion and cooling of the air as it is orographically lifted up the side of a hilly surface (Kolb and Goodmanson, 1945). The fog forms when the cooling is sufficient enough to lower the air temperature to its dew point. As is the case with advection fog, upslope fog can form with moderate to strong winds under cloudy skies (NWS, 2010). Under stable conditions this ground-level cloud will form when the air parcel reaches its lifted-condensation-level. If condensation nuclei are added into the airmass, from sources such as smoke or other continental particles, the fog will be more dense and longer lasting. The most important factors affecting the formation of upslope fog are: lapse rate of the parcel, moisture levels at the surface and on top of the hill, wind speed, and hill shape (Kolb and Goodmanson, 1945). Upslope fog will typically persist on the upslope side of the hill until the forcing at lower levels subsides, and/or there is a change in temperature or humidity levels.

2.1.3 Frontal Fog

Frontal fog, also known as precipitation fog, is usually divided into three types: warm-front prefrontal fog, cold-front post-frontal fog, and frontal-passage fog (Byers, 1944). Prefrontal fog occurs in the cool stable air mass ahead of a warm front when warm stratiform precipitation falls on the cool side of the front. As the rain falls, it evaporates and raises the dew point of the surrounding air (Gultepe, et al., 2008), making the nimbo-stratus cloud lower towards the surface. The northeastern US is most at risk for this type of fog, as mid-latitude cyclones occurring during the fall and winter bring the conditions necessary for prefrontal fog development. The mechanisms that form cold-front post-frontal fog are very similar to the aforementioned prefrontal fog, where evaporation from falling precipitation humidifies the air behind a cold front (Gultepe, et al., 2008). This type of fog is unlikely to be widespread due to the limited amount of precipitation that falls behind a cold front. However, stationary and cold fronts provide the ideal environment. Finally, frontal passage fog occurs when near-saturated air parcels from the warm and cold air masses mix together in calm wind environments (Gultepe, et al., 2008).

2.1.4 Radiation Fog

Radiation fog forms when radiative fluxes off the surface are sufficient to reduce the air temperature to its dew point (AMS, 1999). This fog type forms at night and typically requires clear skies and abundant low-level moisture. Clear skies are necessary in order for long-wave radiation to escape from the earth's surface, allowing temperatures to decrease rapidly. If dew point temperatures are sufficiently high enough, humidity levels can reach a critical point where fog will form. In addition, light winds, typically below $2.5\,\mathrm{ms}^{-1}$ (Taylor, 1917), are also necessary for radiation fog to occur. If wind speeds are too strong, turbulence within the boundary layer will result, and low-level moist air would mix with drier air aloft. However, if winds are too calm, gravity will force the suspended water droplets to settle on the ground, creating dew/frost. Other favorable conditions for radiative fog formation include a small dew point depression at sunset, low-lying areas or valleys, and large amounts of condensation nuclei.

Radiation fog forms upward from the ground as the night progresses and is usually deepest and most opaque around sunrise. Initially, the fog density decreases with height as temperatures at low-levels increase with height. However, as the fog continues to thicken at lower levels, it restricts the surface/ground from emitting long-wave radiation. When conditions reach this point, the maximum radiative cooling level moves upward toward the top of the fog layer. This results in denser fog at the top of the layer and initiates sinking cold thermals which act to turbulently mix the fog (Stull, 1999). Radiative cooling at the top of the fog can act to maintain and strengthen the fog intensity (Stull, 1999).

Radiation fog generally begins dissipating when the sun rises in the early morning hours, initiating mixing in the boundary layer. Through this method the surface warms quickly as it absorbs short-wave radiation and then warms the surrounding air. The water vapor droplets easily evaporate into the warmer air, resulting in dissipation of the fog. Radiation fog can also dissipate if there is a change in the overlying synoptic conditions, such as fronts or winds, or the dynamic forcing is altered.

In the southern United States, this type of fog is most problematic during the winter because the length of night is sufficiently long to drop the air temperature to the dew point. Interestingly, and as yet inexplicably, Tallahassee seems to be an exception to this, as it experiences more fog days during summer months.

2.2 The Fog Forecasting Problem

Advances in the understanding of fog formation have been made through many field and numerical experiments (Tardiff and Rasumessen, 2007). However, due to the variable and sudden nature of fog events, as well as the small scale on which fog tends to occur, the ability to forecast fog remains challenging. Herzegh et al. (2004) noted that fog forecasting is often done through observations; however, this has proven difficult, as remote sensing techniques involving satellite and radar tend to be ineffective. For example, fog often occurs at too low an elevation for conventional radar to identify it, and satellite imagery has difficulty in distinguishing fog from low-level stratus (Westcott, 2006), although some wavelength techniques may allow for identification of widespread fog events, e.g. Ellrod (2007) and Bendix et al. (2005).

Not only is fog difficult to identify with conventional sensing techniques, but fog is also highly variable in time and space: it may occur many times in many different areas or not at all (Ratzer, 1988). In addition, fog is dependent on many physical variables on different length scales within the boundary layer, including microphysical, dynamical, mesoscale conditions, and the overlying synoptic flow (Gultepe et al., 2006a or 2006b and

Westcott, 2006). As a result, fog is very difficult to forecast and model, particularly in regions of Florida, where radiation fluxes and advection can both determine whether fog will form. The fog-forecasting problem becomes exacerbated when the effects of control burns (smoke) are integrated into the forecast. The addition of smoke not only results in microphysical changes in condensation nuclei, but according to Achtemeier (2003), the burning of organic material leads to excess moisture in the atmosphere, which could result in fog forming faster and enduring longer.

Over the past half-century there have been numerous developments and methods attempting to solve the fog-forecasting problem (e.g., Leipper 1995, Gultepe 2006a or 2006b, Croft et al. 1997, Duynkerke 1990). However, most of the modeling and forecasting studies were only designed to be used in a specific location or region. Therefore, a fog model or forecasting method for one location may not apply to different locations, where topography, climate, and other environmental variables increase in complexity (Tardiff 2007). For example, fog has been studied extensively on the west coast of the United States by many authors, e.g., Leipper (1995) and Lewis (2003). Tardiff (2007) examined fog in the New York City area, and Croft (1997) conceived a conceptual model for fog forecasting in the Southern region of the United States.

The need, however, for a fog forecasting method remains for much of the United States, including Florida, which, as mentioned before, has had excessive fatalities from sudden, dense fog events. The objectives of this project include: researching what conditions generally lead to fog formation in the state of Florida; looking into how the current weather network across the state can be used to forecast fog on a short time scale; investigating the effects that smoke from control burns has on fog formation; and using forecasting and observational data to improve fog/smoke forecasting.

2.2.1 Numerical Weather Prediction Limitations

The NWS forecasts fog using a variety of tools, including model output statistics (MOS), conceptual models, and many other methods as described by Baker et al. (2002) and

Cox (2012). However, Ballard (1991) writes that forecasting fog tendencies, such as formation, intensity, and dissipation remains one the most difficult problems for a forecaster. Liepper (1995) regards fog forecasting as a difficult task which involves predicting the formation and dissipation of a cloud at a certain time and specific location in space. Croft (1997) attributes the fog forecasting problem to the fact that fog is a boundary layer phenomenon. Since the boundary layer is initially set-up by synoptic scale forces, and then later is also affected by dynamic mesoscale forces, the prediction of the interactions between these scales is not accomplished through current models. Also, microphysical processes further act to complicate the interactions.

Despite the fact that many years have passed and the models have continued to advance with time, the progress made with numerical weather prediction models, in terms of forecasting fog, has been slow (Zhou et al., 2007). One reason for this is that NWP model resolution is too coarse to model local scale fog. Additionally, NWP model cloud parameterization schemes only function well for clouds at high levels (Stoelinga and Warner 1999, and Miller et al. 2005). Also, in order to predict fog, NWP uses local solutions, aided by mesoscale models. Since the domain for these forecasts encompasses the entire continental US, the computer resources available are often insufficient (Zhou et al., 2007). Gultepe et al. (2006) confirms this when he notes that the NWP model coarse vertical resolution and oversimplified cloud physics result in an inability to resolve mesoscale processes affecting fog formation. Another problem with the NWP, as pointed out by Gultepe et al. (2006a), is that the model calculates visibility with relationships between liquid water content and visibility (Gultepe et al., 2006a). In other words, NWP needs the visibility in order to predict the possibility of fog. However, since surface observations are spatially insufficient in determining visibility (Ellrod, 2002), initiating the model with the observed visibility could give a bad representation of atmospheric conditions.

2.3 Fog Forecasting Techniques

Fog forecasts can either be dichotomous (i.e., fog/no fog) or probabilistic. The dichotomous forecast, when correct, is more useful, while the probabilistic forecast will be more accurate. We will examine both of these later.

Due to the inadequacies of NWP models, other methods have been developed to forecast fog. For example, Croft (1997) created a simple conceptual model for the southern region of the United States by employing well known physical fog formation principals to new forecasting techniques, and Baker et al. (2002) explained the UPS Airlines-developed conceptual model.

2.3.1 The Croft et al. Conceptual Model for the Southern U.S.

The conceptual model developed by Croft (1997) for the southern United States employs boundary layer characteristics such as air mass type, available cloud condensation nuclei, moisture availability, and dynamic forcing. The different variables that must be accounted for in the model represent the scale lengths and processes that affect fog formation; these include synoptic, mesoscale, microphysical, and dynamic effects. The model itself is comparable to a forecast decision tree, where the forecaster answers certain questions about atmospheric conditions, which then leads him/her to a guidance forecast. To use the model effectively, the forecaster would first judge the overall synoptic pattern to determine what type of air mass would be affecting the area of concern (Croft, 1997). The model's base surfaces range from maritime air masses to continental air masses and allow the forecaster to identify the concentrations of CCN and relevant drop sizes. This step helps provide information to the forecaster of how heavy/opaque the fog will be, as well as its duration.

When this step is completed, the forecaster would look at moisture availability in the area, as well as dynamic forcing, specifically looking for the development of a surface layer inversion. Dynamic forcing mechanisms are assessed according to base-state flow, local circulations, and thermodynamic lifting (Croft, 1997). From the dynamic forcing, the forecaster can determine the duration of the fog event as well as the extent of the occurrence. Moisture availability is determined according to how much moisture can be realized from condensation through cooling. This variable gives the forecaster an idea of the spatial extent of fog, and when combined with CCN and drop-size observations, can give a good idea of the fog intensity. The assessment of all these variables allow the forecaster to move within the bases of the model to determine how likely fog is to form, its intensity and duration (Croft, 1997). No comprehensive assessment of this labor-intensive approach is available.

2.3.2 UPS Airlines Conceptual Model and Forecast Methods

As discussed previously, fog can have severe economic consequences on the airline industry. For example, the United Postal Service Airlines Company, which ships packages across the world, is often affected by fog delays due to the high number of arrivals and shipments at sunrise (Baker, 2002). The fog forecasting problem motivated UPS airlines to develop a conceptual model using practical quantitative forecast tools.

The main idea behind this model is to account for vertical tendencies that affect the fog formation process. Baker (2002) noted that surface-based approaches to fog forecasting often fail to account for the very important changes that occur above and below the forecasted altitude. The UPS airlines fog forecasting model includes many of the variables which are typically ignored in the surface-based models, including the vertical distribution of humidity in the potential fog layer, the turbulent mixing potential of the lower boundary layer, and the surface temperature below the fog layer. The UPS forecasting method attempts to quantify these variables to better access vertical atmospheric changes and how they affect fog formation (Baker, 2002). And again, no comprehensive study of the efficacy of this approach is given.

2.3.3 Forecasting Using Model Output Statistics (MOS)

Model Output Statistics (MOS) is commonly used by the National Weather Service to objectively interpret numerical model output and produce site-specific guidance for a 6- to 84-hour period (NWS, 2008). MOS relates observed weather variables to different predictors with a statistical approach. The predictors that MOS uses include NWP model forecasts, past observations, geoclimatic data, and linear regressions from statistical output. MOS specializes in objectively interpreting NWP models based on historical data and predicting events forced by synoptic-scale systems. The MOS is also able to quantify uncertainty in NWP model's forecasts and can adjust for certain biases within the NWP model (NWS, 2003). The MOS is able to account for some local effects; however, it lacks the computing power necessary to consider every local effect, and it is also unable to predict based on mesoscale forces.

When forecasting fog, MOS uses probabilistic and categorical guidance for obstructions to vision. Typically, MOS will issue one of the five forecasts for the obstruction to visibility category. They are listed below:

1. No non-precipitating obstructions
2. Haze, smoke, or dust
3. Light fog or mist (fog with visibility of 5/8 mi or greater)
4. Dense fog or ground fog (fog with visibility of $< 5/8$ mi)
5. Blowing snow, dust or sand

To determine which components contribute most to an obstruction to visibility, MOS will correlate observations, such as ceiling and visibility to NWP model forecasts, and predict values of relative humidity, precipitable water, temperature, wind speed, etc. These will be used in making a percentage forecast. According to the WMO (1991), the predictors based on observations are the most important input in the model for giving an accurate short-range forecast.

Croft (1997) examined the statistical prediction of dense fog for the 24- and 6-hour MOS forecast for the cities of Jackson, Mississippi; Mobile, Alabama; and New Orleans, Louisiana. Croft (1997) found that the best statistical predictor for dense fog for the 24-hour forecast was the grid binary relative humidity, while the 6-hour MOS forecast's leading indicator was the latest observed visibility at the station during model initiation. The statistically significant predictors used for these models had nearly identical correlation coefficients to that of persistence nowcasting (Croft, 1997). This suggests that the MOS model studied had an inability to forecast fog better than a persistence method.

Although the resolution and accuracy of the MOS model has improved from when this article (Croft, 1997) was written, most of the inadequacies remain. For example, MOS is unable to account for extreme climatic conditions. This is a problem when smoke from forest fires occurs and alters the microphysical conditions affecting fog formation, or vertical profiles differ immensely from climatological means. The limitations of MOS extend further as it is unable to correct for NWP model physics, analysis schemes, or parameterizations (NWS, 2008). Also, as determined by Croft (1997) the best predictor for a 6-hour fog forecast is the observed visibility. However, if the weather observation network is spatially insufficient for recording observations, MOS will predict with more inaccuracy.

One critical piece of information for which there is no solution is high-resolution terrain data. Fog often forms in low-lying areas where the difference in elevation can be only a few feet.

2.3.4 Other Fog Forecasting Techniques

There have been many other attempts to develop fog forecasting techniques. Some are based on climatology, e.g., Johnson and Graschel (1992) and Jarvis et al. (2001), where past atmospheric conditions are evaluated during fog events, and then are used to forecast fog when similar conditions are forecasted to be present. Gurka (1978), Ellrod (1995), and Gultepe et al. (2009) employed remote sensing techniques, primarily using infrared imagery from the GOES satellite to detect fog location and depth. Others have focused on improving the microphysical parameters in numerical models. Gultepe et al. (2006a) suggested a new parameterization for fog visibility in numerical NWP models, where they noted that both droplet number concentration and liquid water content (LWC) are a better gauge in determining visibility within NWP models compared to the current scheme which only uses relationships between visibility and LWC (Gultepe et al., 2006a). Other fog forecasting methods, including statistical relationships, numerical modeling, operational modeling, and conceptual models, have all been used to solve the fog forecasting dilemma (Croft, 1997).

Unfortunately, many of these methods are incapable of forecasting or detecting fog in local areas. Many numerical models are incapable of forecasting fog due to excessive assumptions and poor resolution (Croft, 1997). Also, NWP depends on accurate initiation in order to forecast fog on a small scale; unfortunately, the current observational network is incapable of providing enough detail to support the NWP model initiation. Climatology techniques are incapable of handling any extreme conditions that may be present at any time. An example would include an influx of CCN from control burns or forest fires in a specific area. And finally, conceptual models act to give forecasters a good idea of whether there will be fog or not; however, they do not do a good job in determining localized fog, as these models depend on the data available and forecaster skill.

Chapter 3

Data

3.1 Mesonet stations

There are four institutional mesonet networks as well as a large number of private sites or networks. Some of the private mesonet sites are well maintained, and others have unknown maintenance status. Much of the data are archived at MADIS and other sites where all the incoming data are subjected to some quality control. Data generally arrive in 30-minute or 1-hour intervals, but some as often as 15-minute temporal resolution. All stations potentially available are shown in Fig. 3.1.

The most extensive sites with well-documented commitment to maintenance are the ASOS, AWOS, FAWN, and SFWMD networks. Although SFWMD is one of five Water Management Districts, it is the only district that maintains an extensive mesonet. These four networks are the primary mesonet stations that are used, as they are assured to be well-maintained, and they provide a total of 77 mesonet site locations. These are illustrated in Fig. 3.2

3.2 Elevation or topography

Florida is relatively flat with a ridge in the central peninsula. However, fog is much more likely to occur in lower elevations, often characterized by changes of only a few feet. In general, these small differences are not resolved in much of the topographical data, and are best known from the climatology of fog occurrence. Unfortunately, the data on fog

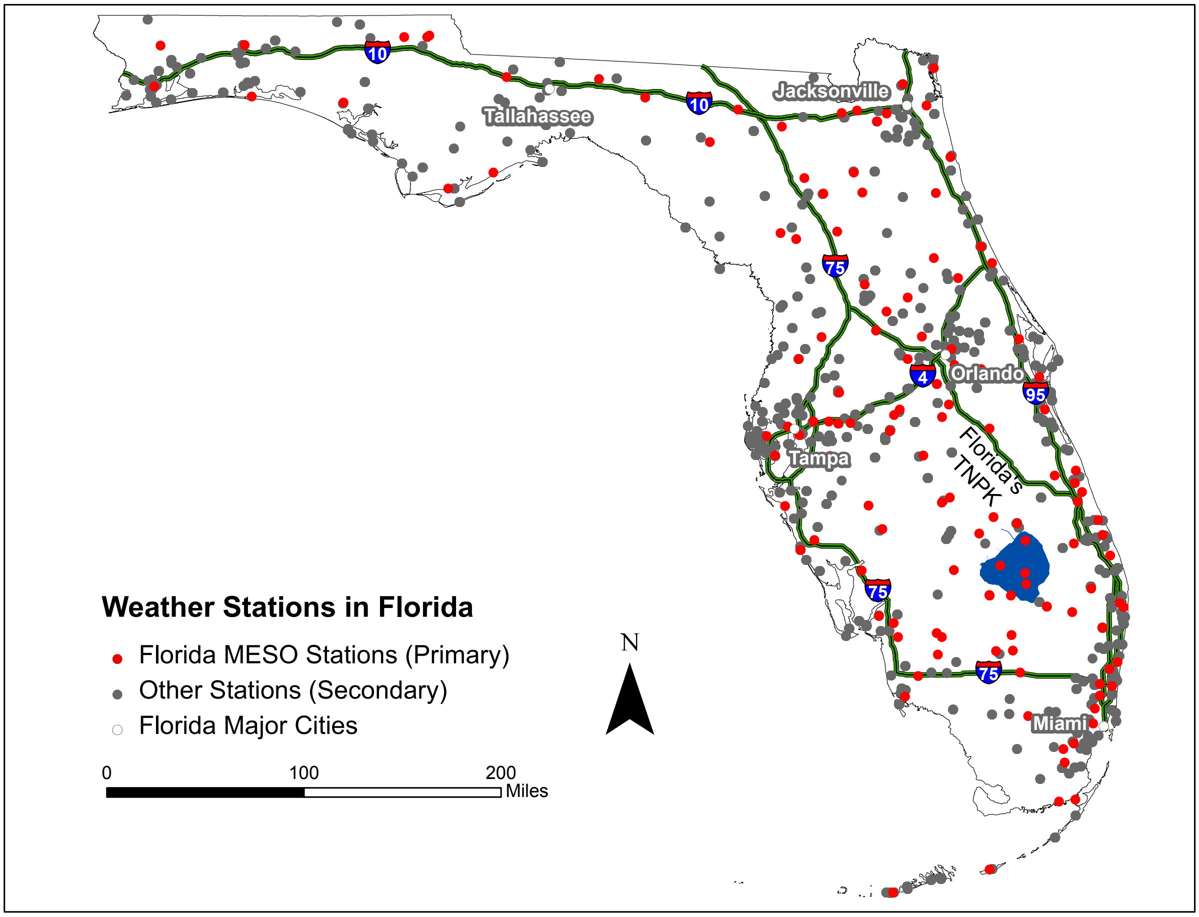

Figure 3.1: All Mesonet stations in Florida

occurrence is only very coarsely known. An illustration of the topographic features of Florida is given in Fig. 3.3

3.3 Fog data

Elevation measurements are available at the sites and in a few locations from laser measurements that are accurate to within inches. The data with full coverage of Florida, however, are on a scale of five-foot vertical resolution. This is clearly an issue where cold air drainage may favor specific locations.

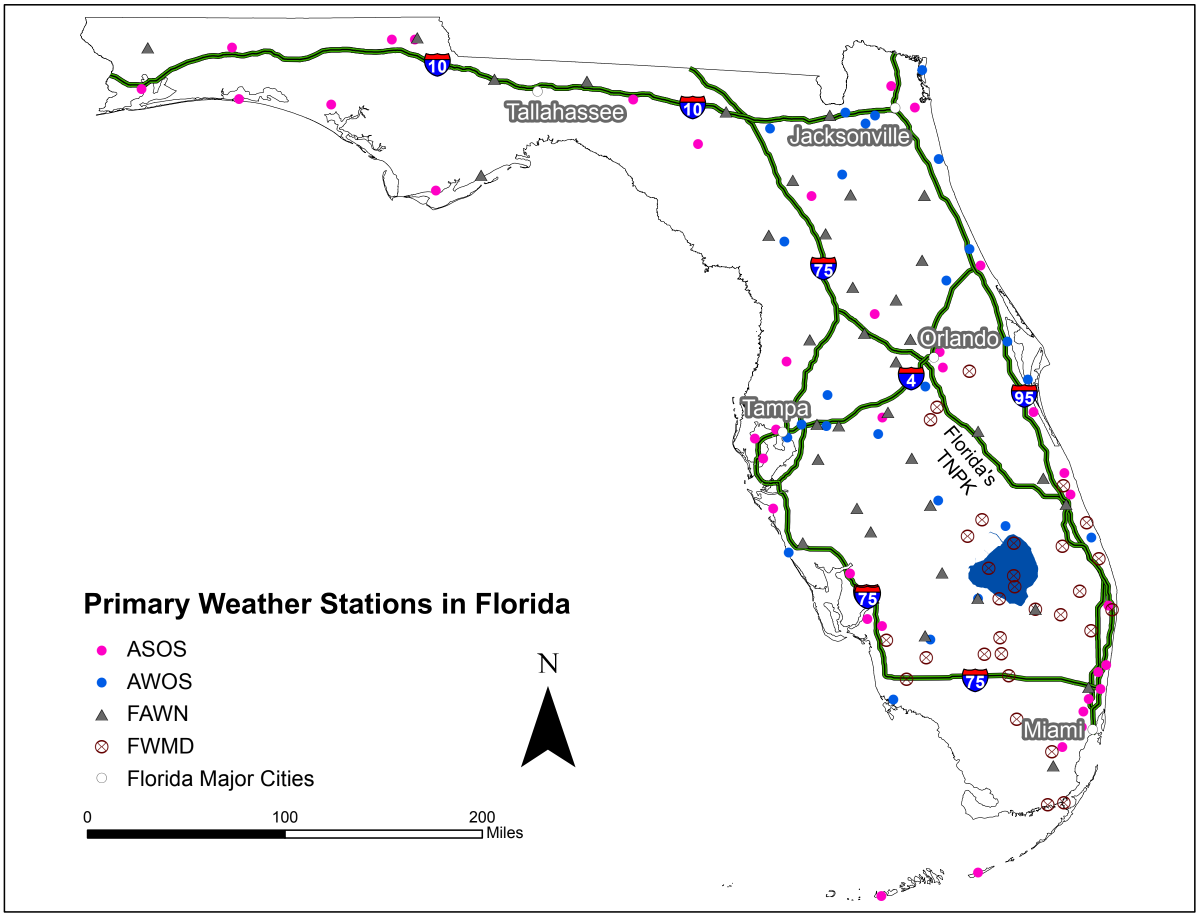

Figure 3.2: Primary Mesonet stations in Florida

3.4 Climatology of fog in Florida

Most of the fog in Florida is radiation fog. Unlike advection fog, radiation fog is most often found in "patches", even though those patches may extend over several miles. Just as often they may be well less than a mile in extent and can be found intermittently along the ground. Elevation often is an important factor where differences in a few feet (perhaps five feet) can be determinative in the location or formation of fog. Often there are "favorite" depressions where fog most frequently forms. The average number of days per year with fog in Florida is shown in Fig. 3.4.

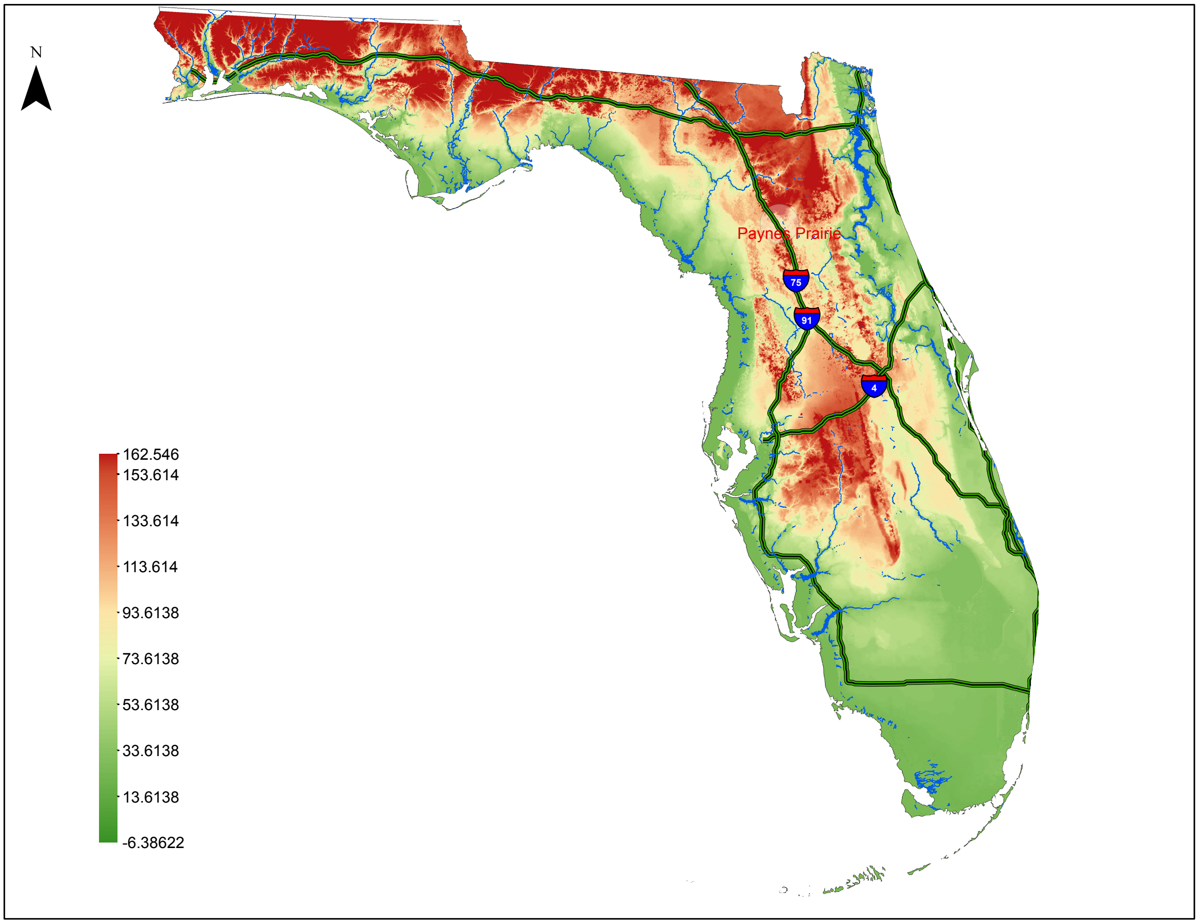

Figure 3.3: Topography of Florida

Note that fog is generally more prevalent in the panhandle than in peninsular Florida, yet most crashes are in the central peninsula. The visibility-related crashes are a product of the propensity of fog and the amount of vehicular traffic.

The maximum at Tallahassee is probably due to three factors. The first is the placement of the airport in a locally low area. Secondly, there is a synoptic condition in the summer that favors fog formation in the lower SE. Lastly, there is no other station within 100 miles, so the Tallahassee data extends over a large distance, unmoderated by other station data.

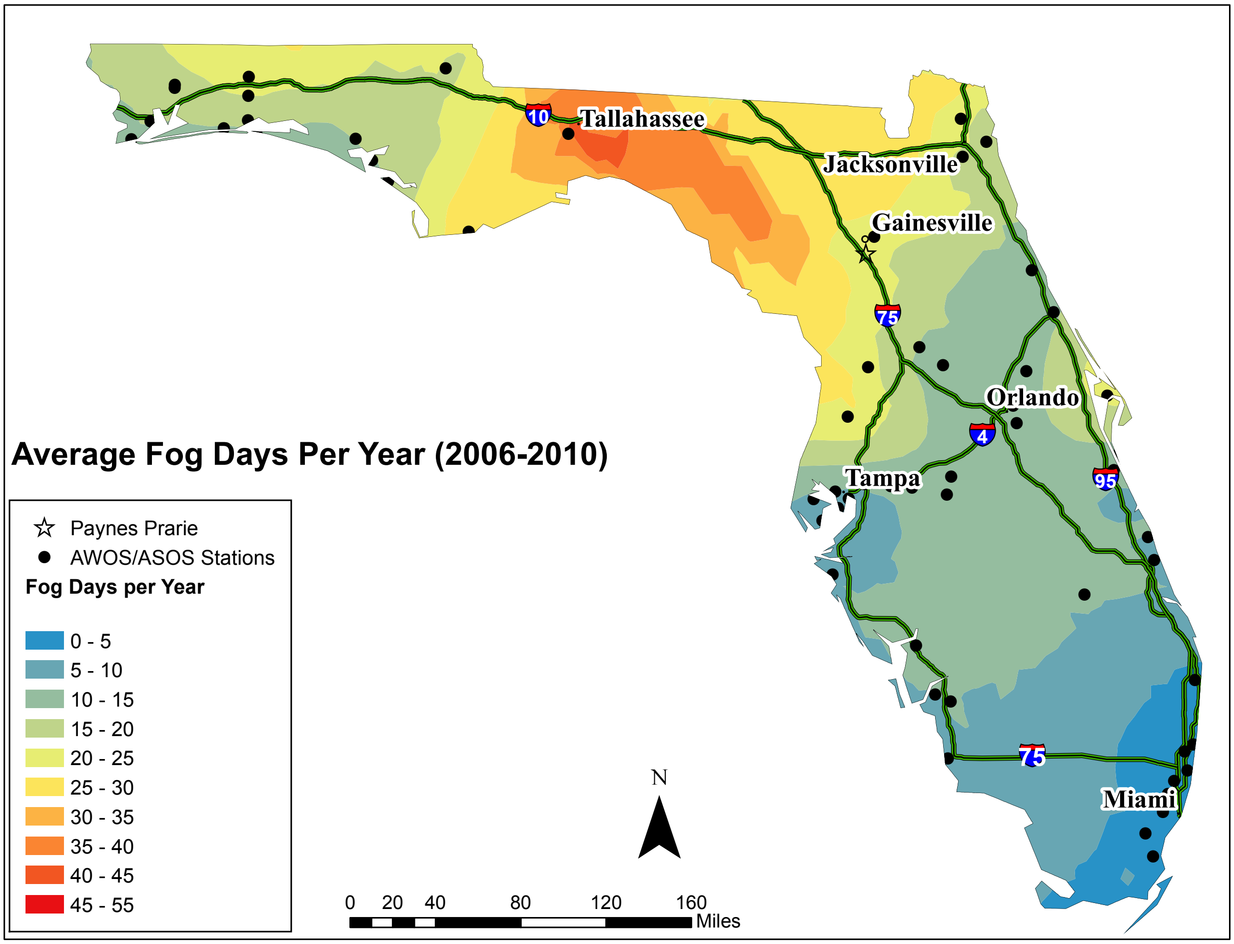

Figure 3.4: Climatological location and frequency of fog in Florida

As shown in Fig 3.5, fog is most frequent in the cold months and relatively infrequent during the warmest months. Again, Tallahassee is the exception with a maximum in the warm months. Fog is a nocturnal event as shown in Fig. 3.6. Fog occurs during the night-time hours, peaking just before dawn, and rare during day-time hours.

Fog usually forms when the temperature is at or near the dew point and the mixing ratio is relatively large; that is, there is sufficient moisture in the air. It is not a thermodynamic problem only: the physical terrain, soil moisture, and vegetation will all make a difference.

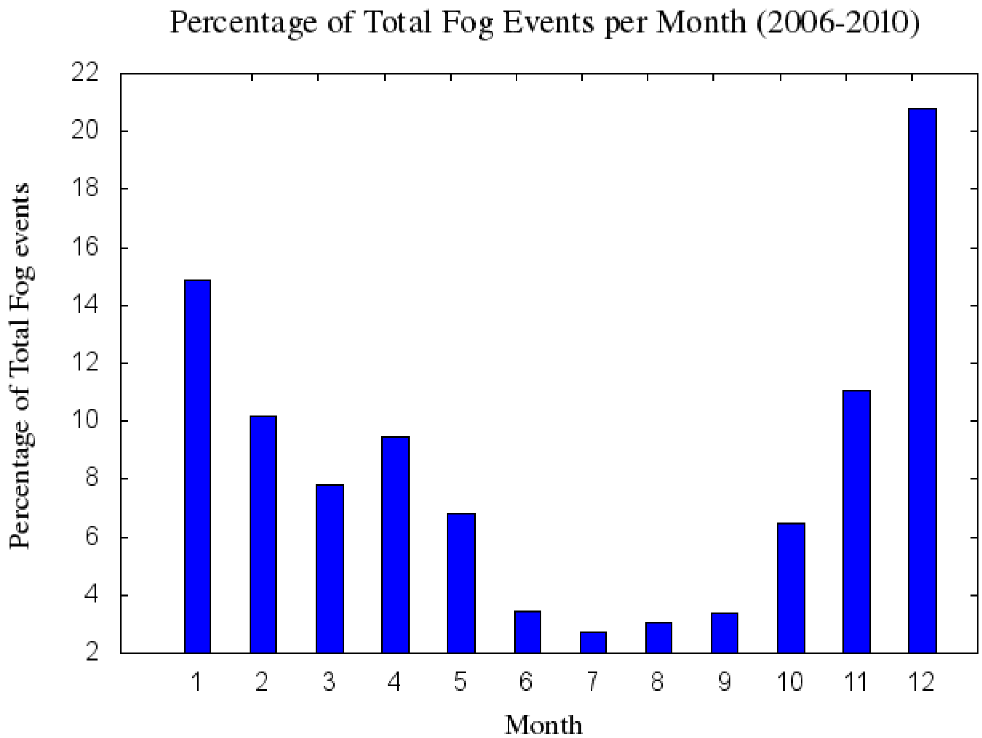

Figure 3.5: Percent of the total fog occurrence given by month of the year

Compounding the problem of determining where fog has formed is the lack of data of where and when fog has formed. Fog is reported by ASOS and AWOS suites that are often located at airports for obvious reasons. Thus in the Panhandle of Florida, for example, the ASOS site is at the Tallahassee airport (TLH), which happens to be conveniently located in a locally low area where fog forms more frequently. This location is not representative of the weather conditions over most of the area surrounding it, or even Tallahassee. As seen in Fig. 3.4 there are little data in the everglades and thus almost no reported fog events.

Perhaps there are two very important considerations in the climatology of fog. The first is simply what is considered fog, or fog that is dense enough to affect safe driving. The second is the local "spotty" nature of fog. Instruments are likely to be placed neither where fog most frequently forms, nor where fog is unlikely to form. Thus, data from any station only approximately represents the conditions of its surroundings. These are both

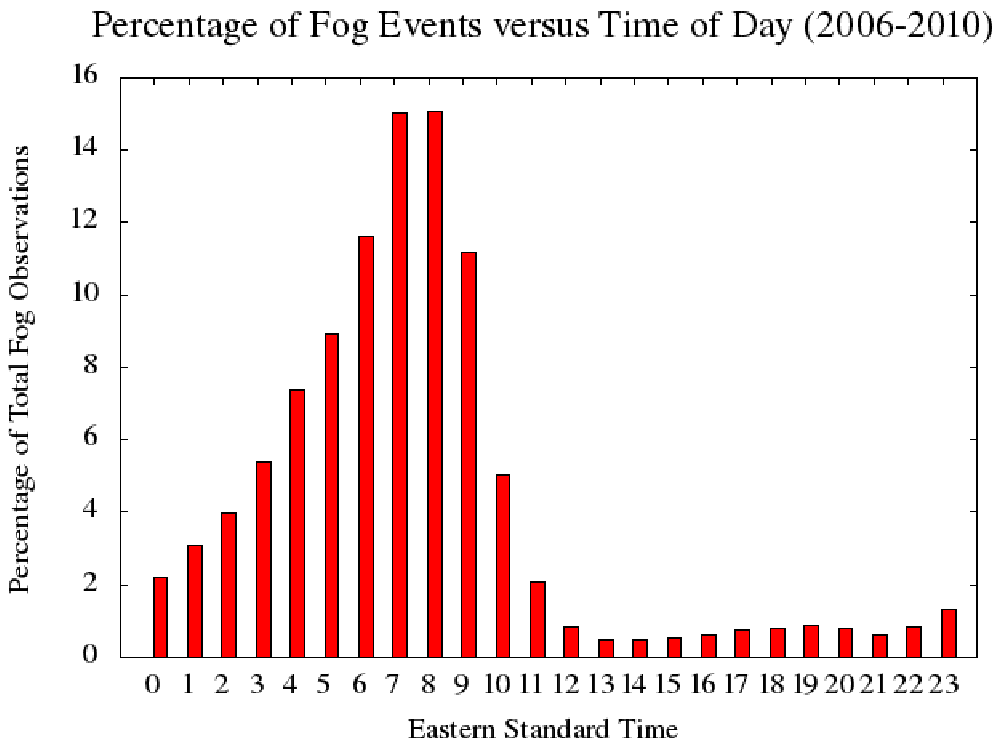

Figure 3.6: Percent of total fog occurrence given by the time of day

extremely important considerations when interpreting these results. In addition, **fog-related accidents do not necessarily occur where fog is most frequent, but where the product of the occurrence of fog and the density of traffic is the greatest.**

NOAA is engaged in a pilot program to improve the identification and the forecasting of fog over the next few years (which may extend to a decade or more, in reality). Pilot programs for the initial phase are in place, even in Florida. The NWS plans a multi-faceted and more sophisticated approach for the long term, but the outlook for that is in the 2015 time frame with the launch of a new GOES satellite. In the meantime, there are short-term advances that are available with the present system, but these need both study and a pilot implementation.

3.5 Fire

Fire contributes both moisture and, most importantly, CCN to the formation of fog. Although CCN are naturally ubiquitous, the more CCN, the more droplets will form, albeit perhaps smaller drops than with fewer CCN. However, the same total water content distributed among many more smaller drops will significantly decrease the visibility. Smoke produced by a fire close to a roadway form a "smoke fog" that can restrict visibility and produce an irritating acrid smell. The number of controlled burns far exceed the number of wild fires. It can be seen that the total number of fires in a given year is in the range of 200,000–500,000 a year, and the vast majority of number and acres burned being prescribed burns. The distribution of controlled and wild fires for the first half of the year are given for 2006, as an example, in Fig. 3.7 and for the last six months of the year in Fig. 3.8.

The total area burned during a six-year period for wild fires and controlledburns is given in Fig. 3.9. It is shown that during the course of these six years the vast majority of acreage burned was by controlledburns, not wild fines. It is also evident that the number of both controlledburns and wild fires decreased during this period, and seem to be "leveling off", as is also the number of acres burned.

To examine the possible impact of fire-generated CCN and their effects on the production of fog, researchers looked at the distance of a fog event to the closest fire that occurred within the past 24 hours. Fig. 3.10 shows that the median distance was 3 miles, but many events ranged from two to ten miles. What effect that actually had is not clear, except that fires are widespread enough and frequent enough to contribute CCN, if any were needed.

Fog events are only well-documented by (a) an ASOS or AWOS station or (b) a report of fog during a crash. The meteorological condition leading up to and during a fog even are only documented by an ASOS or and AWOS station. The cumulative frequency of fire events can be see in in Fig. 3.11.

3.6 Crash data

This project will attempt to show how the current Florida weather observation network can be utilized to forecast fog in the most problematic areas seen in Fig. 3.14. The project will also use MOS output, information on wild fires, and human observations of fog to compile a climatology of fog events.

The time and location of crashes from January 1, 2006 through the end of 2007 were examined. Only those crashes that were at least in part attributable to smoke, fog, or the combination are considered. For smoke the results are presented in Fig. 3.12. The individual crashes are represented by the dots and the density of crashes by the colored area overlaying the individual crash sites. If only crashes due only fog are considered, the result is shown in Fig. 3.13. Combining the two events, the results are shown in Fig. 3.14. In this figure, there is no distinction between the complicity of fog or smoke, or the more deadly combination.

There are those occasions, such as the well-known “Paynes Prairie” crash that occurred on January 30, 2012, when the fog was made much more opaque (“thick” or “heavy”) by the presence of a nearby controlled burn. The smoke-enhanced fog occasions are give in Fig. 3.14. The mechanism involved is that the fire, in addition to producing many visible particles (smoke), also produces many microscopic particles that enhance the number of CCN, and therefore the number of cloud drops, which increases the opacity.

The following is largely a recapitulation of the results found by Abdel-Aty et al. (2012). The research team confirmed their results and provided added support for all of the work that they did. The researches concurred with all the findings and methodologies employed. One point to make clear is that, in the process of computing the average number of crashes per year by the method they used called “kernel density analysis”, the granularity of the results depends upon a subjective choice of the area over which one averages. For example, with a radius of 50 km, there would be only one elongated area identified that started in St. Petersburg and ran east of Tampa. However, an averaging interval of 30 km would give two distinct areas, and many more of them across the state. Some of their plots showed an inconsistent use of radius, perhaps for different purposes.

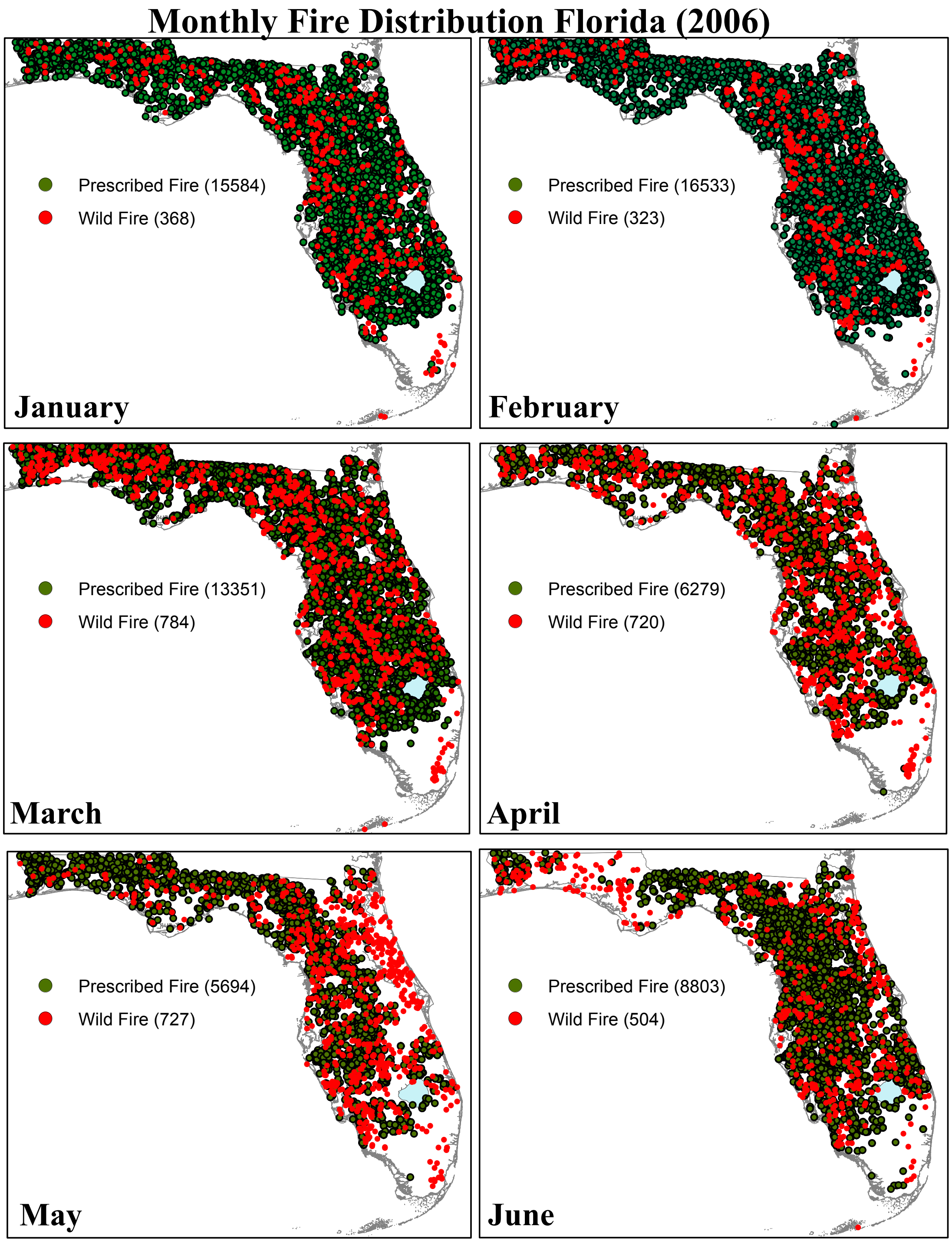

Figure 3.7: Controlled burns and wild fires during the first six months of 2006

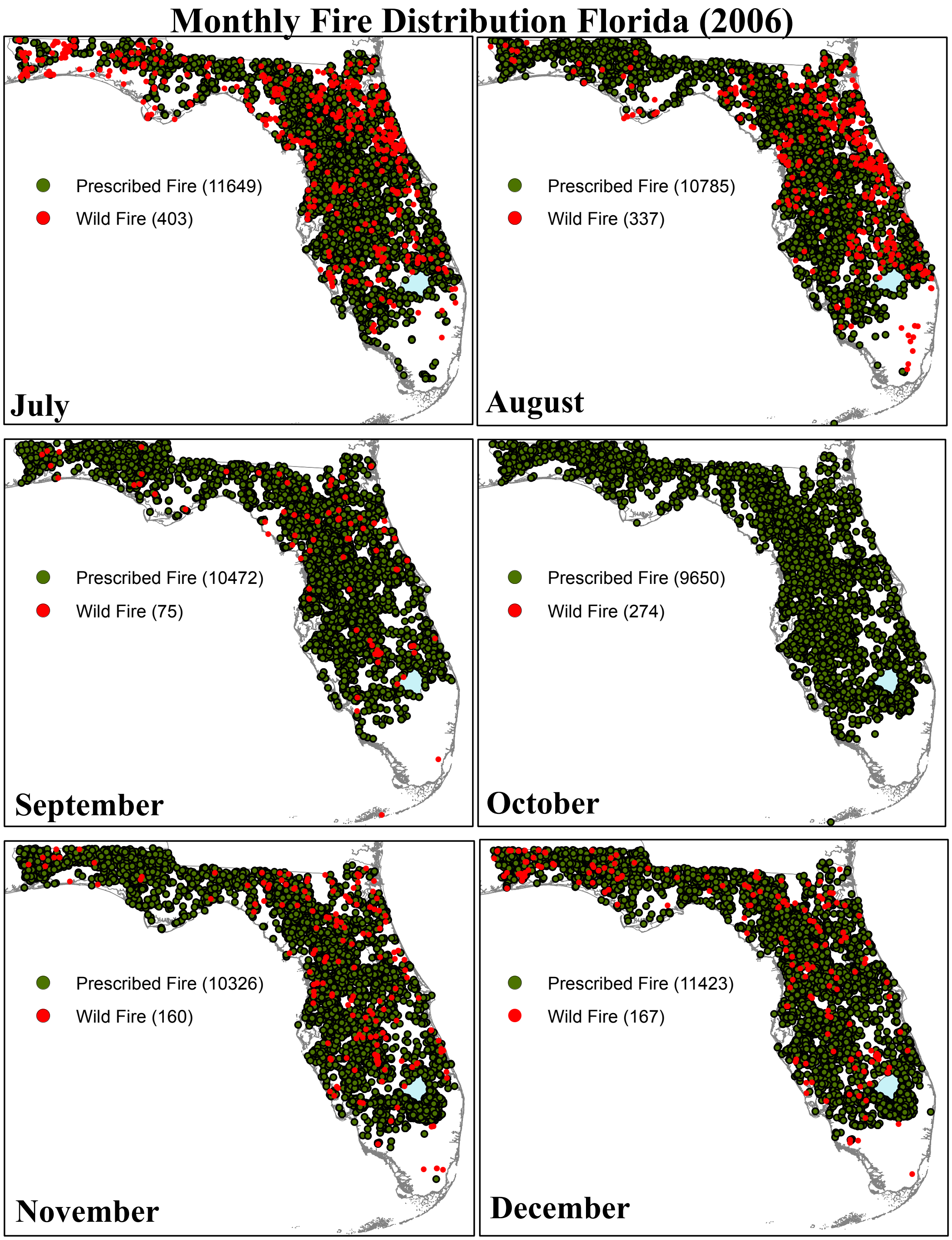

Figure 3.8: Controlled burns and wild fires during the last six months of 2006

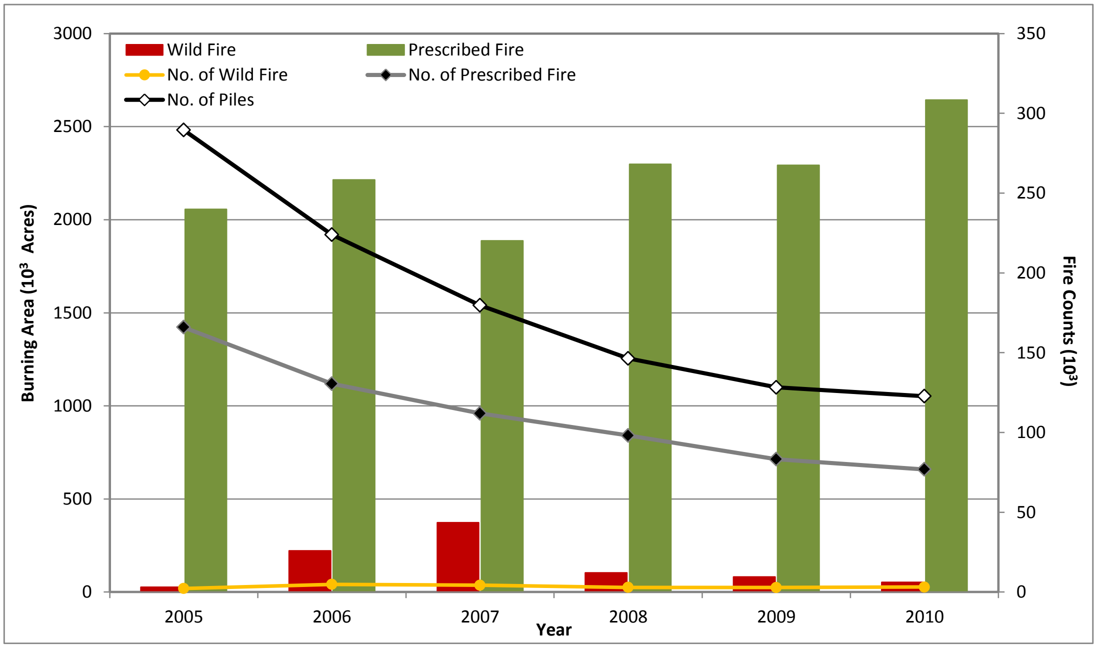

Figure 3.9: Fire counts and area burned during a 6-year period for wild fires and controlledburns

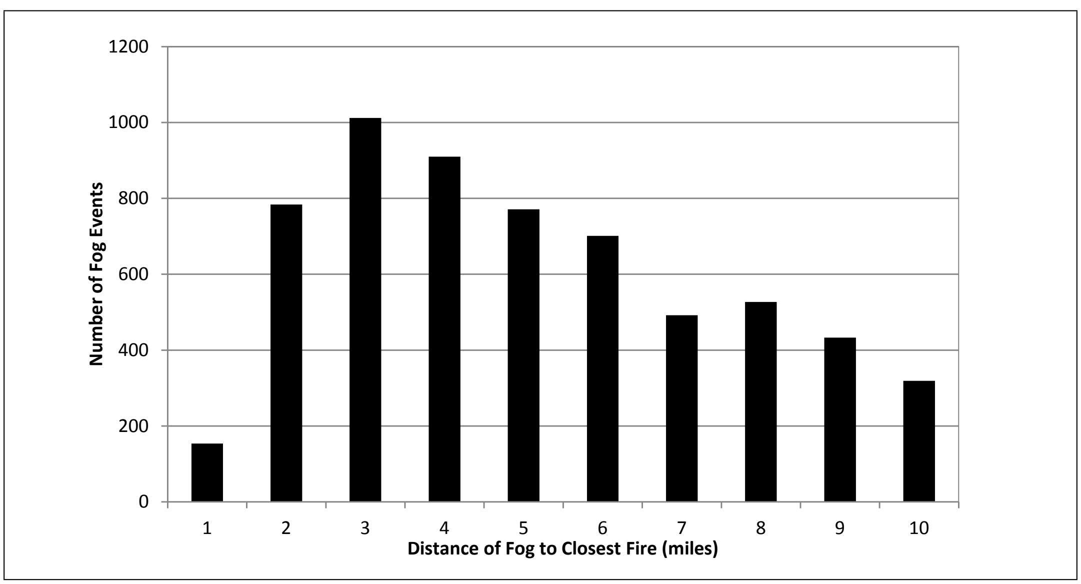

Figure 3.10: Distance in miles to the closest fire at the time of a fog-related crash

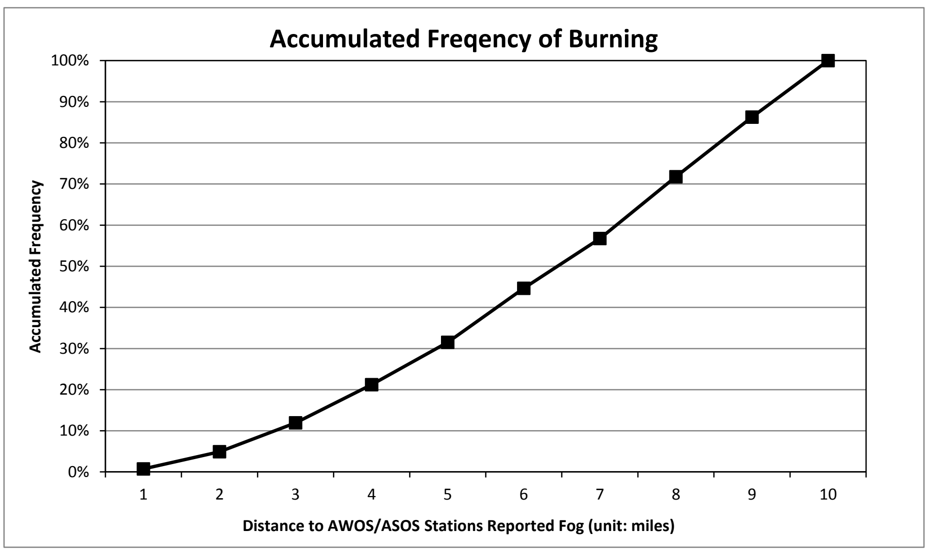

Figure 3.11: The cumulative fire distance to the closest ASOS station. For example, 70% of the fog events within 8 miles or less away from an ASOS or AWOS station

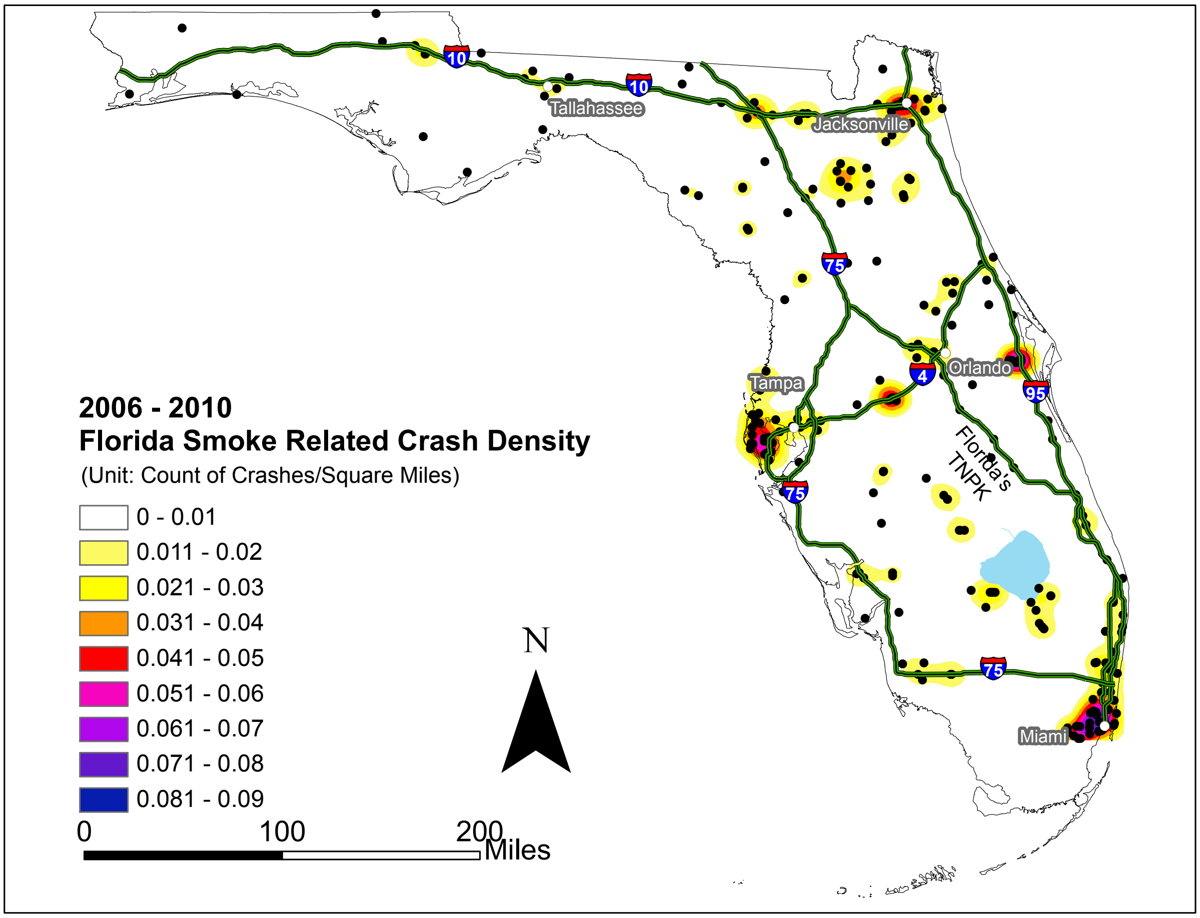

Figure 3.12: Crash density due only to smoke

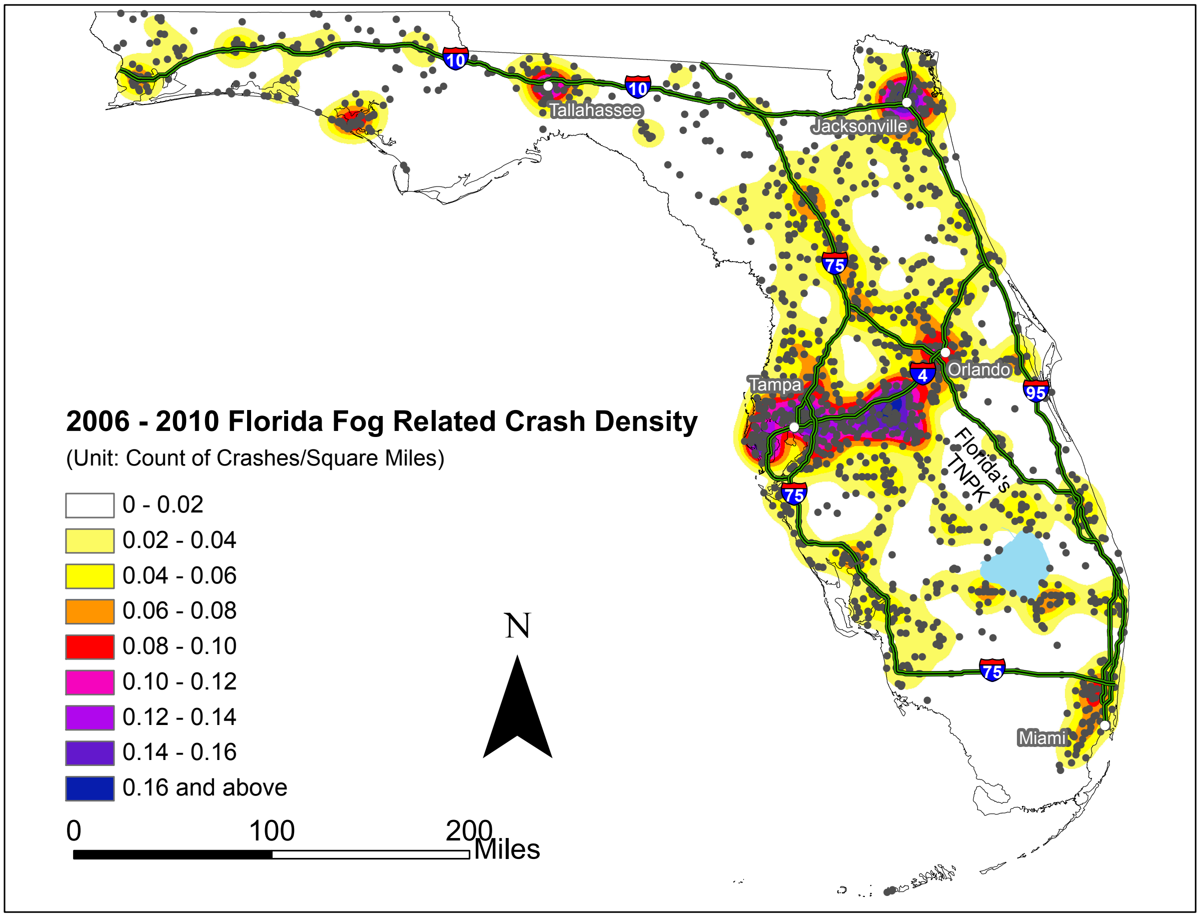

Figure 3.13: Crash density due only to fog.

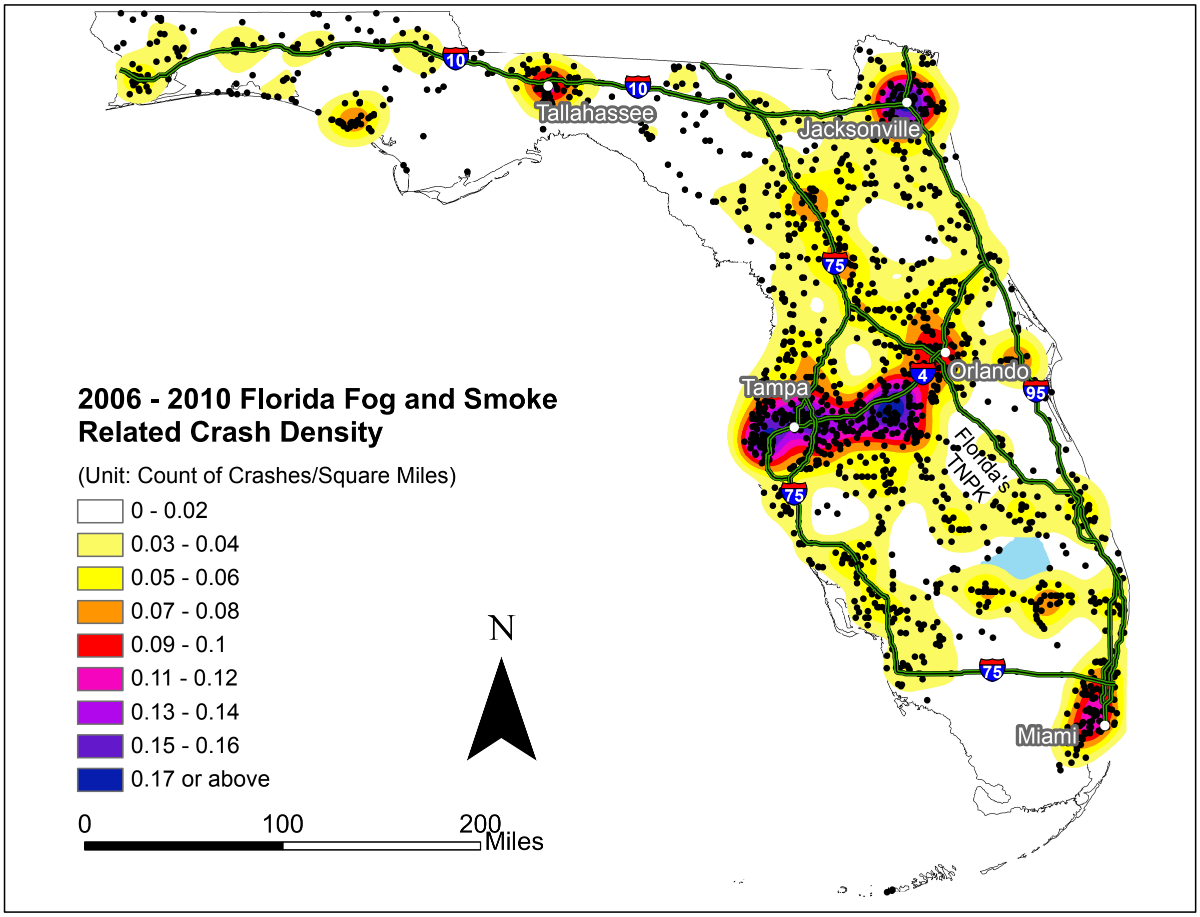

Figure 3.14: Location of all fog- and smoke-related crashes

Chapter 4

Forecasts

4.1 MOS

The National Weather Service's principal tool for fog forecast is the MOS visibility product. While useful as guidance, it is not site-specific. It represents the average probability over a fairly large area, with the probability of fog either under- or over-estimated for any specific location. The MOS visibility forecasts have value, but it is a goal of this effort to improve both on the accuracy and specificity of the MOS forecasts, which should be viewed as a vague guidance.

4.2 Mesonet data climatology

Their are several approaches that can be used to "sharpen" fog forecasts. Of prime importance is knowing where fog customarily forms. As explained in the fog climatology section, this is only well-known at selected locations, typically around airports. Out of necessity, the research team chose a regression-based probabilistic forecast method. Researchers examined several approaches. The assumptions employed include (1) researchers have climatological data available, and (2) the only other data researchers have is that which comes from sensors that report standard meteorological data at 15-minute intervals. For the algorithm development, researchers have restricted themselves to just the ASOS and AWOS because (1) they are reliable, and (2) they **alone** report visibility. Once the algorithm is developed, the research team can include the FAWN and SFWMD data and other networks to increase the accuracy and resolution of the forecasts. The data must come from MADIS or other data repositories.

ASOS and AWOS sites are never located at the point of the crash. It is useful to know how far to expect the data to be removed from the point of interest. The distance from the crash to the nearest ASOS/AWOS site is shown in Fig. 4.1. Fifty percent of the crashes were within 10 miles of an ASOS/AWOS site, and 70% were within 15 miles. Of course, if all sites were included, and not just the ASOS/AWOS sites, the distances will be much closer.

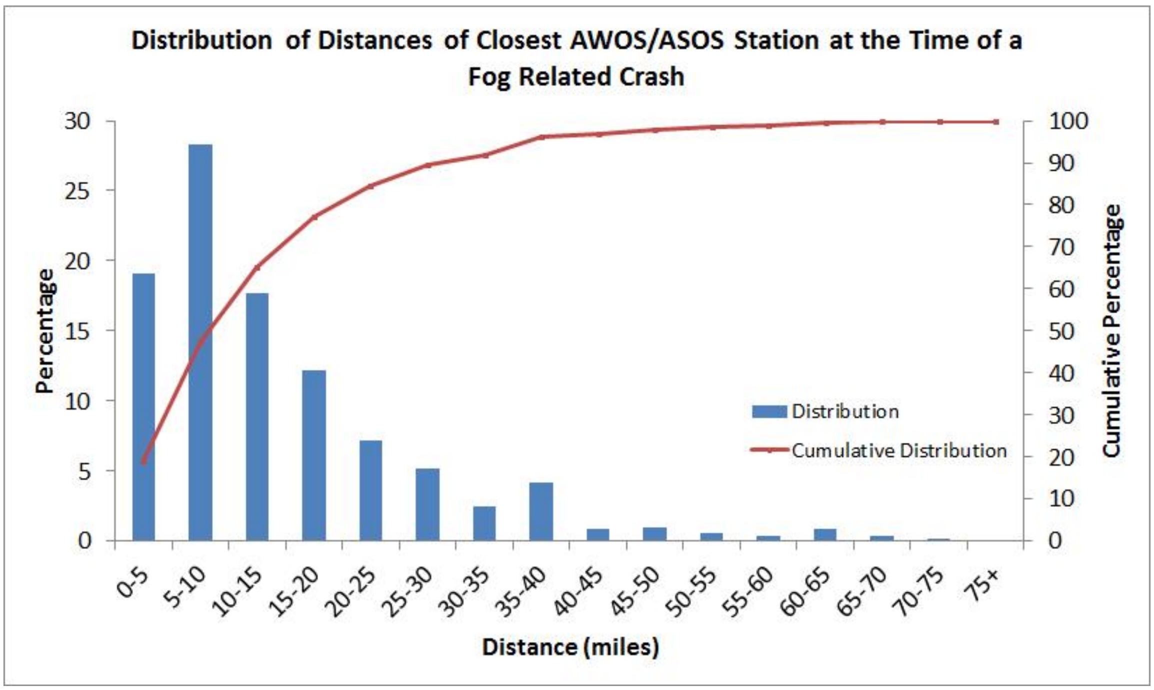

Figure 4.1: The distribution distance in miles from crash to the closest AWOS/ASOS station

4.3 Diagnosis

It is important both in this section and the following section to have a means of quantifiably evaluating a diagnosis or forecast and also have an objective function a means of measuring skill. Skill is often defined as how much better a forecast is over a reference forecast. Usually, the reference forecast is either persistence and/or as in this case, climatology.

There are several ways of scoring a forecast and the skill involved. Widely used for extreme events is the Contingency Table, shown in Fig. 4.2.

		Observed	
		Yes	No
Forecast	Yes	a	b
	No	c	d

a: an event is forecast and the event occurs
b: an event is forecast and the event does not occur
c: an event is not forecast and the event occurs
d: an event is not forecast and the event does not occur

$$\text{Percent Correct} = \frac{a+d}{a+b+c+d}$$
$$\text{Probability of Detection} = \frac{a}{a+c}$$
$$\text{False Alarm Rate} = \frac{b}{a+b}$$
$$\text{Critical Success Index} = \frac{a}{a+b+c}$$

Figure 4.2: Contingency Table

The Brier's score (Brier, 1050; Brier and Allen, 1952; and Brier, 1956) can be expressed as:

$$BS = \frac{1}{N}\sum(y_k - o_k)^2 \tag{4.1}$$

where y_k is the forecast (or the reference forecast) and o_k is the observation. A skill score can be developed which examines how much better the forecast is over some reference forecast, such as climatology.

The Briers skill score is represented as:

$$BSS = 1 - \frac{BS}{BS_{ref}} \tag{4.2}$$

A skill score attributed to Heidke (1926) also examines the improvement over (in this case) climatology

$$HSS = \frac{A - A_{ref}}{A_{pert} - A_{ref}} \times 100\% \tag{4.3}$$

where

A is a measure of accuracy,

A_{ref} is a measure of accuracy of the reference forecast,

A_{pert} is a measure of accuracy for a perfect forecast.

Initially 5 sites were selected, representing the geographic diversity as well as proximity to crash sites. For these sites, the percentage of the days of each month when there is fog is shown in Fig. 4.3.

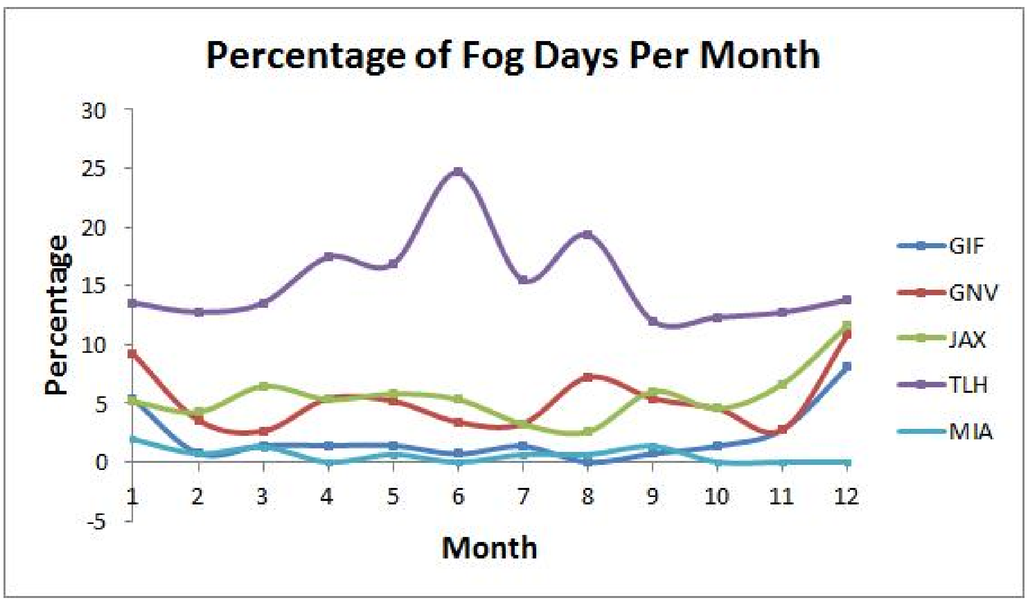

Figure 4.3: Percent of days with fog per month for selected locations

It is obvious that the distribution is fairly consistent over the months for all sites except Tallahassee, where, contrary to the average, the foggiest months are in the summer—just the reverse of all other stations. The reasons for this are both because of the fog reports and also due to placement in the state. For the preliminary analysis researchers focused on these sites. The distance between a reported crash site where visibility was listed as a contributing cause and the closest station has been shown in Fig. 3.10. Fig. B.1 (in the appendix) shows that a small value of dew-point depression is common to fog occurrence. This is also indicated in Fig. B.2. Examining the meteorological variables that are present when there is fog and when there is not fog (Fig. B.3 B.4), strongly suggests that the dew-point depression is almost always less than two degrees and wind speeds less than about 4 miles per hour. Even so, it is noted that when these and other favorable conditions exist, often there is no fog present. These conditions are not categorical, and there are exceptions to these “rules”. They capture about 70% of the occurrence of fog. However, they are are increasingly likely to capture the presence of fog the “thicker” or more dense the fog. These are the conditions that limit predictability.

As the dew point depression cut-off value is made larger, it will capture more cases of fog events, as well as more cases of no fog events. The Critical Success Index (CSI) is used as the objective function to find the optimum cut-off. Here it is suggested that a dew point depression of 2°F is an optimum balance between probability of detection and false alarm rate. This is evident for the 10-hour window (9 p.m. to 7 a.m.) during which conditions for fog formation were examined.in Fig. 4.6. Figure 4.7 restricts that window to just one hour. The difference is small.

4.3.1 Temporal forecast

The most reliable forecast is for zero hours, or a diagnosis. Without using a visibility sensor, researchers wanted to see how well meteorological stations can detect fog. The forecast problem is then how well can the conditions that are common to fog production be predicted 3, 6, or 9 hours in advance. First researchers looked at how feasible it is to forecast the presence of fog, possessing only the standard meteorological information available at all mesonet sites in Florida (hundreds of them). Two types of forecasts are examined—dichotomous (or fog/no fog forecasts), and probability of fog. The dichotomous forecast is examined first. A scoring metric that is is commonly used in meteorology, given below.

Table 4.1 figure shows the probability that a fog event will occur based on the dew-point depression ten and six hours before. The probabilities were calculated based on the climatological averages within the five year data set. It can be seen that as the forecast length decreases there is a higher certainty that a fog event will occur when the dew-point depression is less than 2°F.

The issue is how well can the cooling rate be predicted. In this case researchers restricted themselves to the winter months when most of the fog occurs. There could be seasonal and geographic adjustments which would no doubt increase the skill somewhat. For all stations examined the cooling rates and how the temperature might be forecast at the time of fog formation. This is shown for all stations during the winter months in Fig. 4.8.

This would suggest that it is best to focus our forecast to a 6-hour window, say from midnight, as this would avoid some of the more rapid cooling that occurs during the early evening, and our prediction would be more accurate. The forecast error in temperature perdition (for all the stations used in the regression) is give in Fig.4.9

This plot shows the skill scores for the 10-hour dichotomous forecasts, where fog is forecasted below a threshold forecast dew-point depression level. The highest level of success, as determined by the CSI and HSS, is when fog is predicted when the forecasted dew-point depression is less than one. As the forecasting time decreases, the skill scores increase by a small amount. Identical to the 10-hour forecast, the 6-hour forecast has the highest success rate when fog is forecasted when the forecasted dew-point depression is less than one. Figs. 4.12 to 4.14 show the highest skill score when fog is predicted when the forecasted dew-point depression is less than 1.5.

Table 4.1: Ten-hour fog probabilities for a given dewpoint depression

Dewpoint Depression	**Probability 10-hour**	**6 hour**
≤ 0	0.101	0.284
0–1	0.081	0.135
1–2	0.048	0.081
2–3	0.040	0.0185
3–4	0.027	0.016
4–5	0.038	0.016
> 5	0.014	0.002

4.3.2 Spatial forecast

It is difficult to estimate the area over which data from a station may be said to represent. It is intuitively accurate in that fog is known to be "patchy" and thus the conditions must not be wide spread. Yet, certain conditions from a remote site might portend conditions at a location that is favorable for fog formation. However, compounding that analysis is the meso- and micro-climate that embraces terrain, soil conditions, vegetation and other variables that make every place unique. It is true, that every station has an area of being representative. But it is also true that to know that requires a station-by-station analysis and for many areas, the data required to do such an analysis simply does not exist at present.

The research team focused on those areas where fog and accidents most commonly occur and develop the best forecasting strategies for those sites.

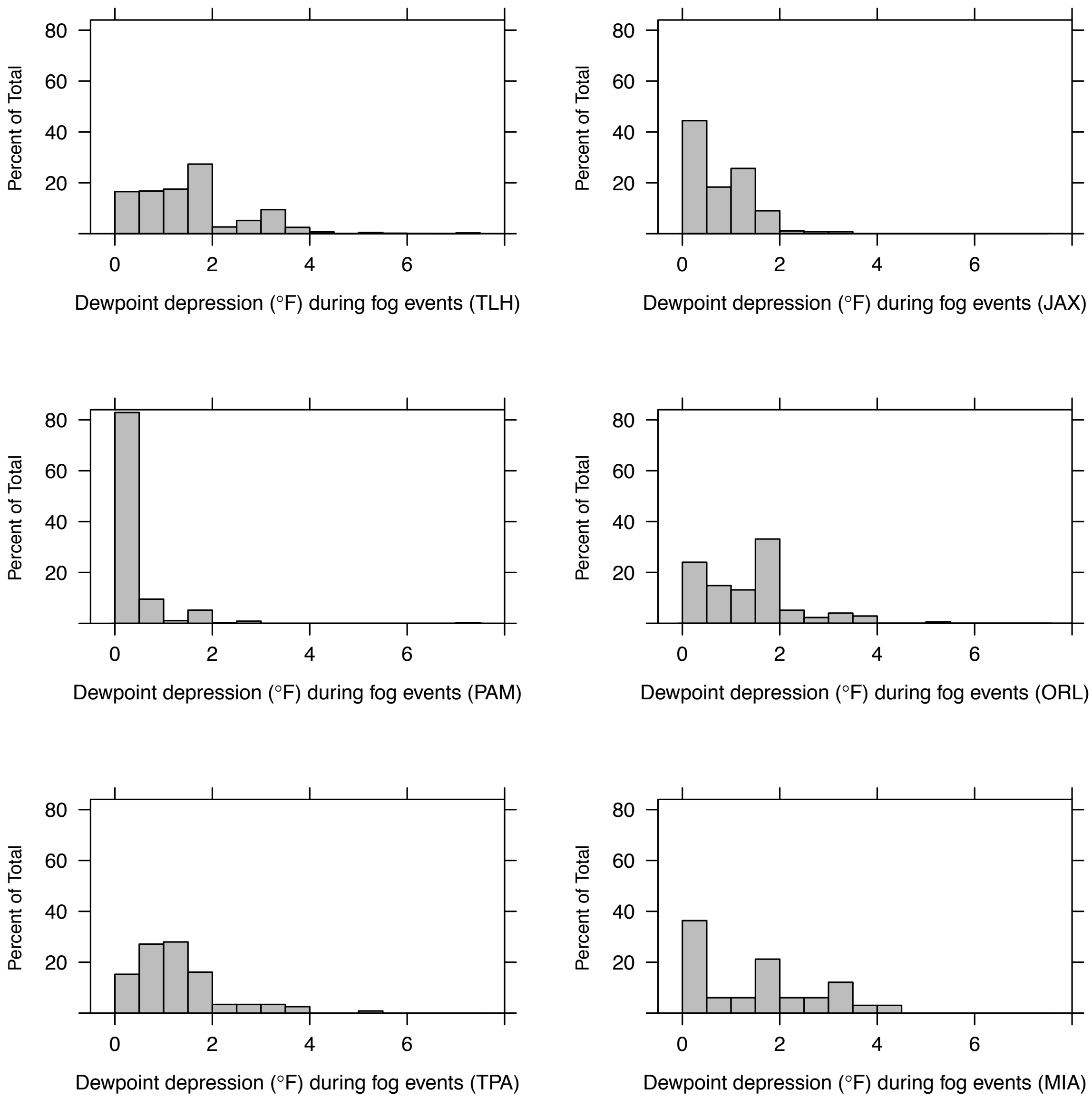

Figure 4.4: The dew-point depressions for selected sites when fog formed

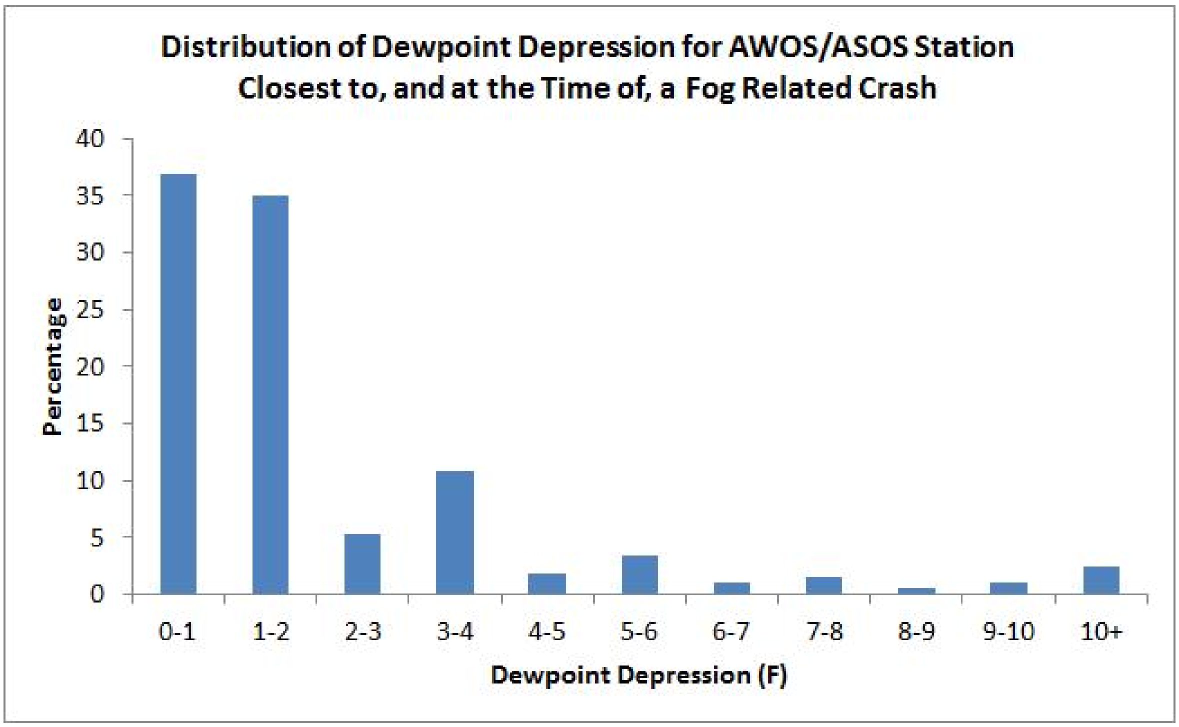

Figure 4.5: Distribution of dew-point depressions for AWOS/ASOS stations closest to and at the time of a fog-related crash

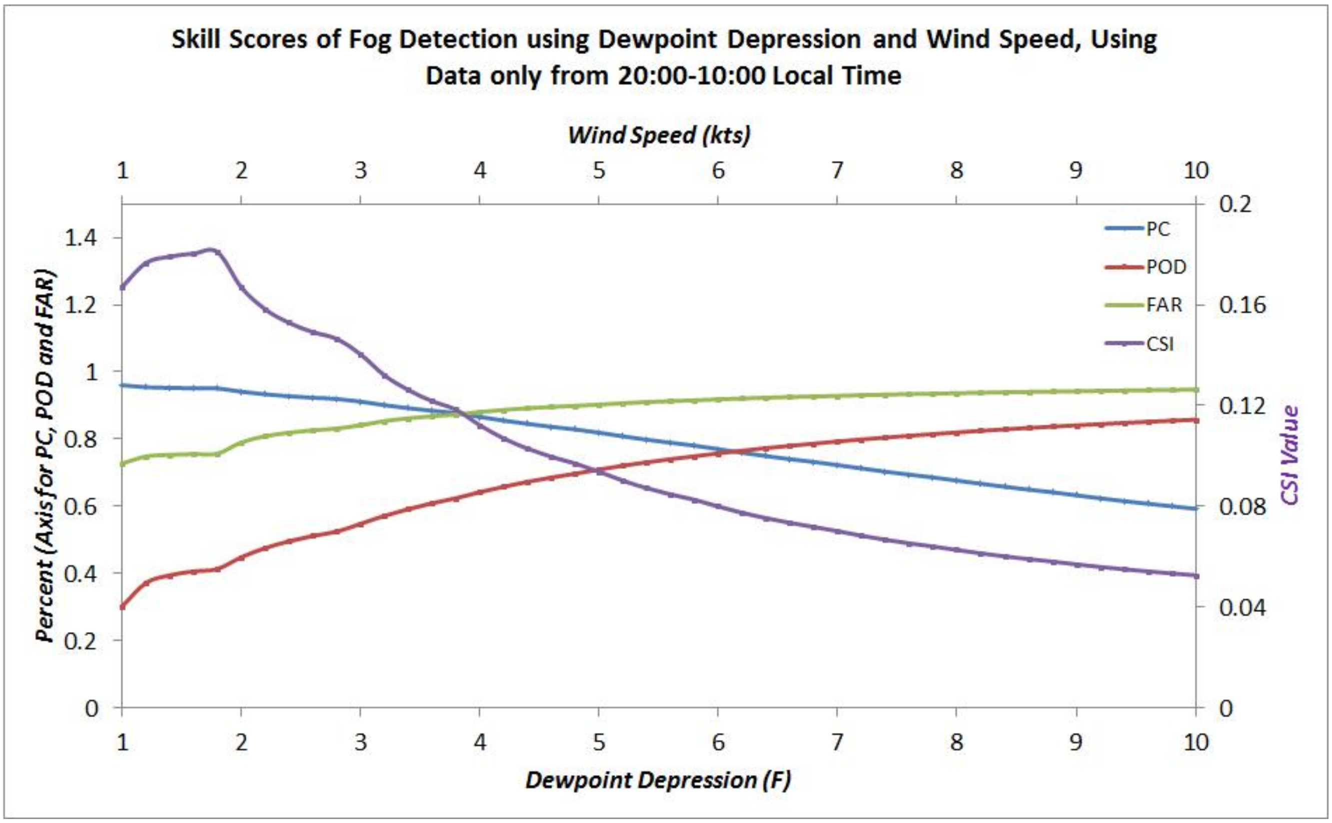

Figure 4.6: Skill scores of fog Detection using dew-point depression and wind speed from 20:00 p.m. – 10:00 a.m. local time

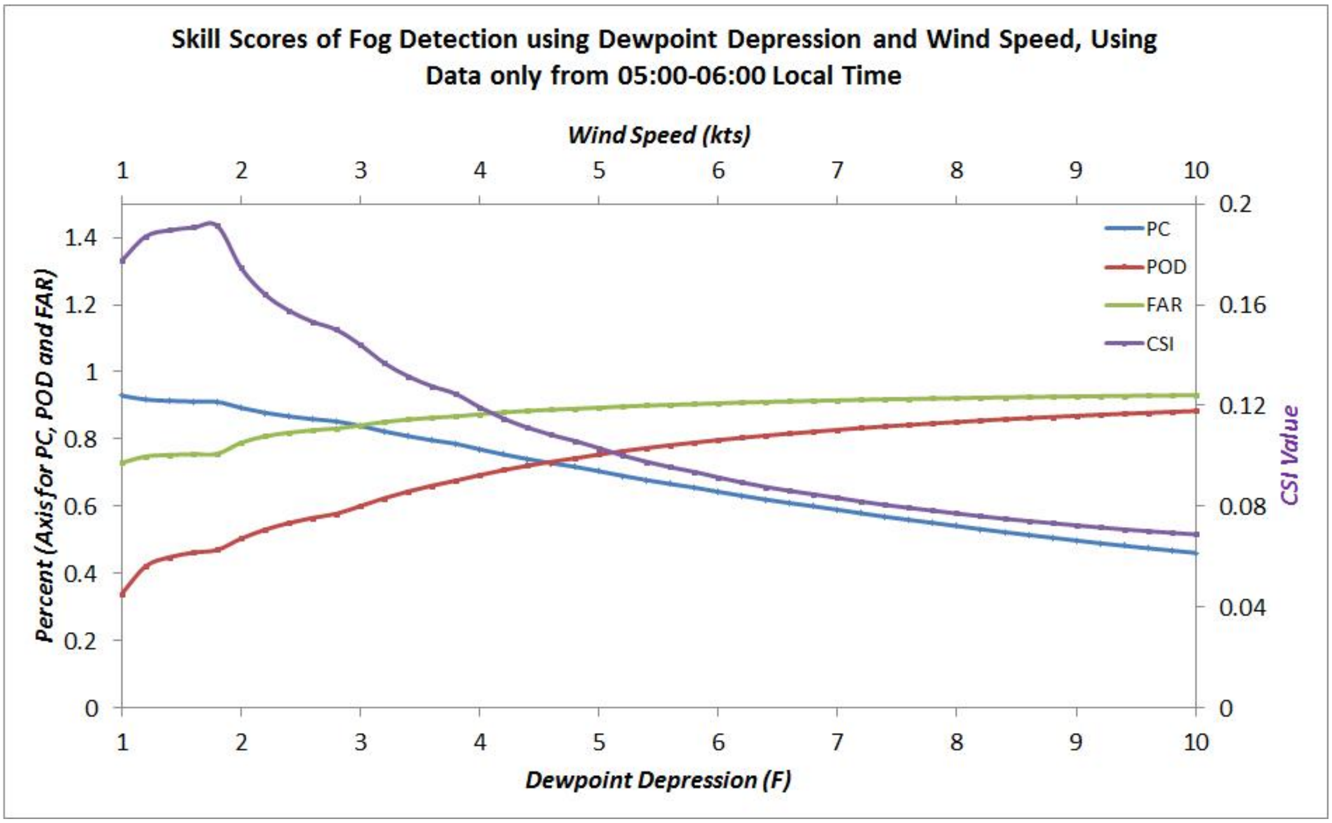

Figure 4.7: Skill scores of fog detection using dew-point depression and wind speed from 5:00 a.m. – 6:00 a.m. local time

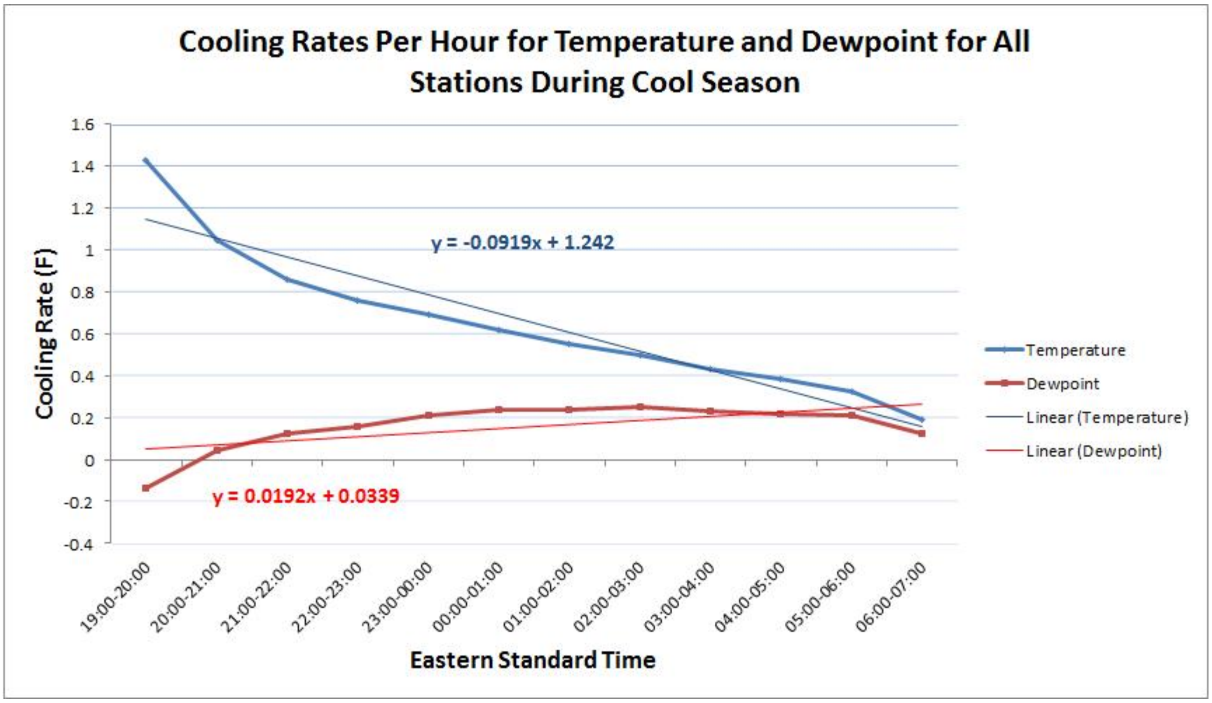

Figure 4.8: Rate of cooling of the temperature expected (averaged over all station and for five years during the cool months

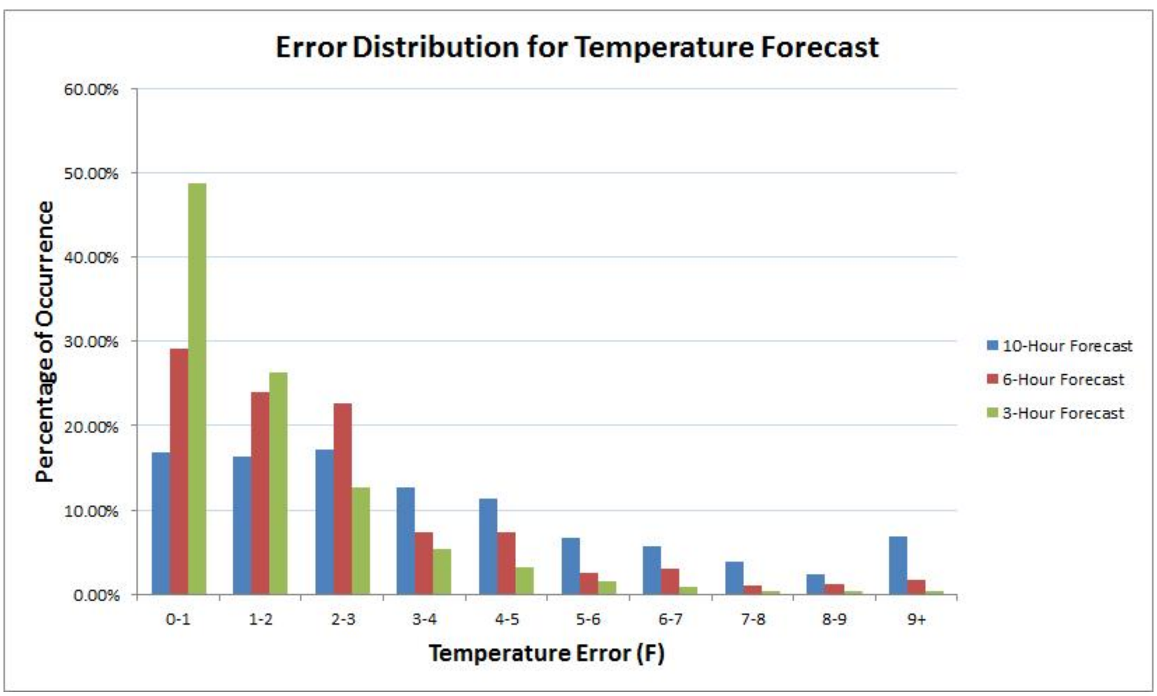

Figure 4.9: Forecast temperature error

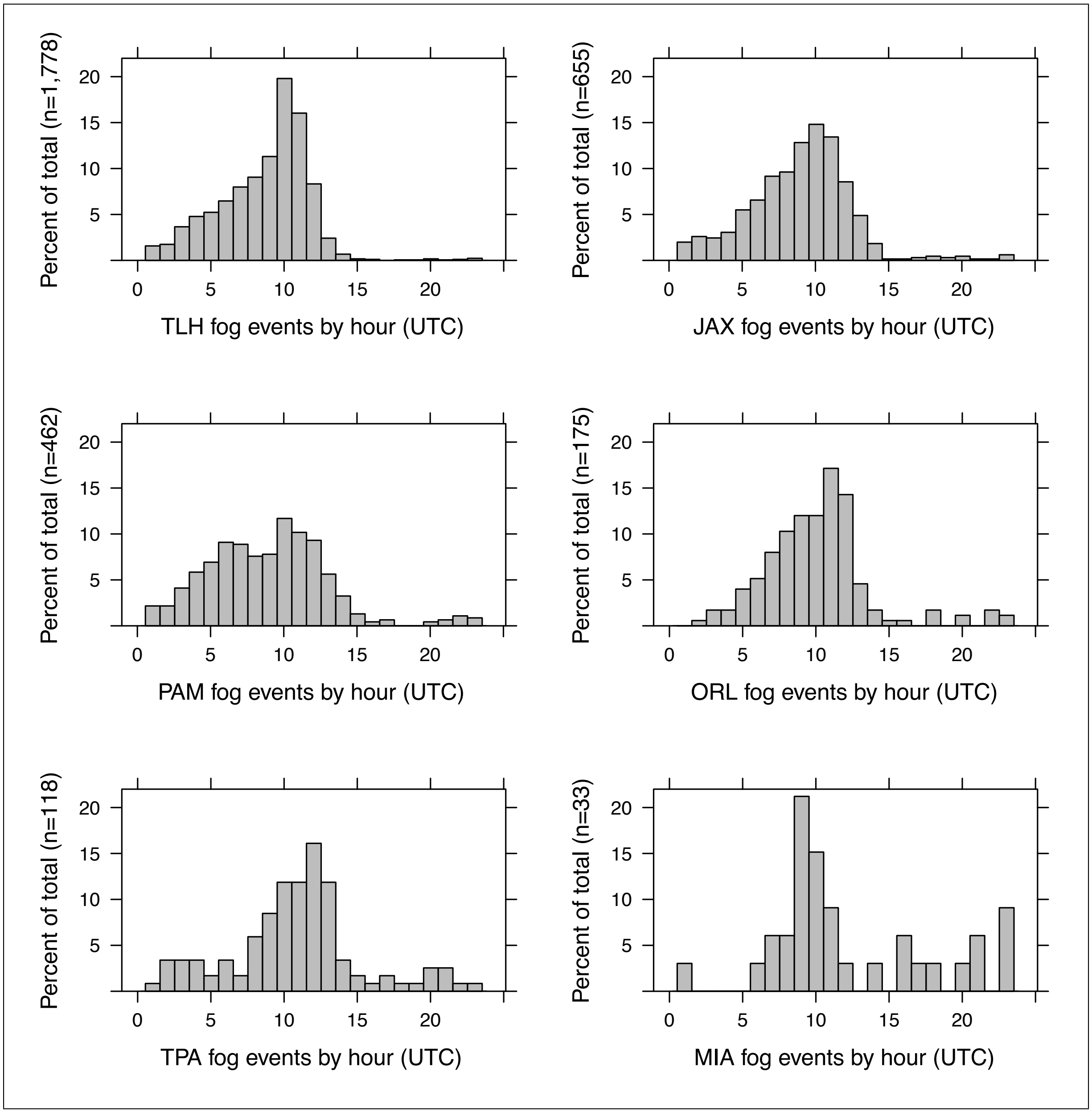

Figure 4.10: Fog occurrence by hour for selected site. EST=UTC-4 hours. EDT=UTC-5hours

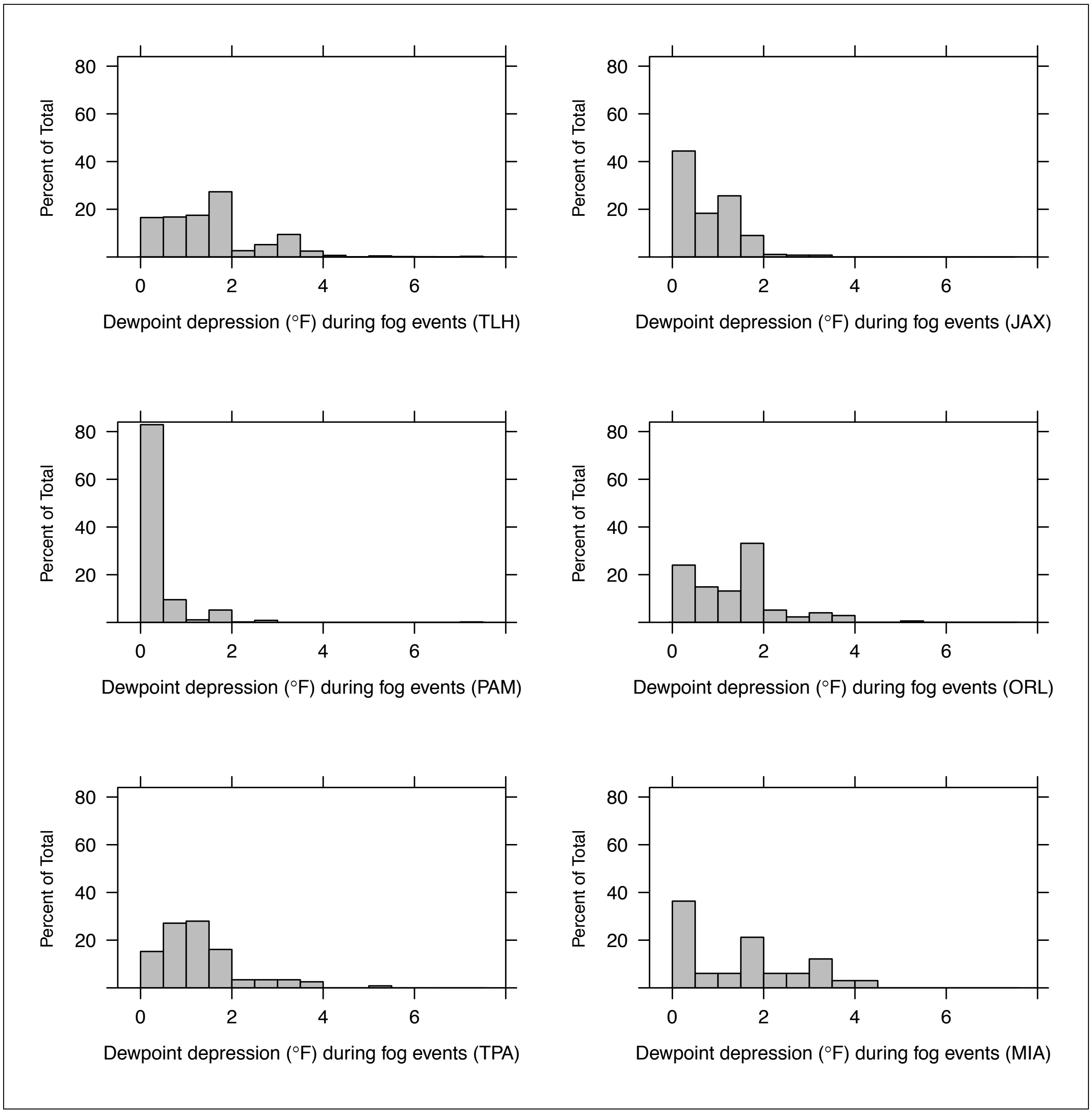

Figure 4.11: Fog dew point depression on nights when fog occurred (EST)

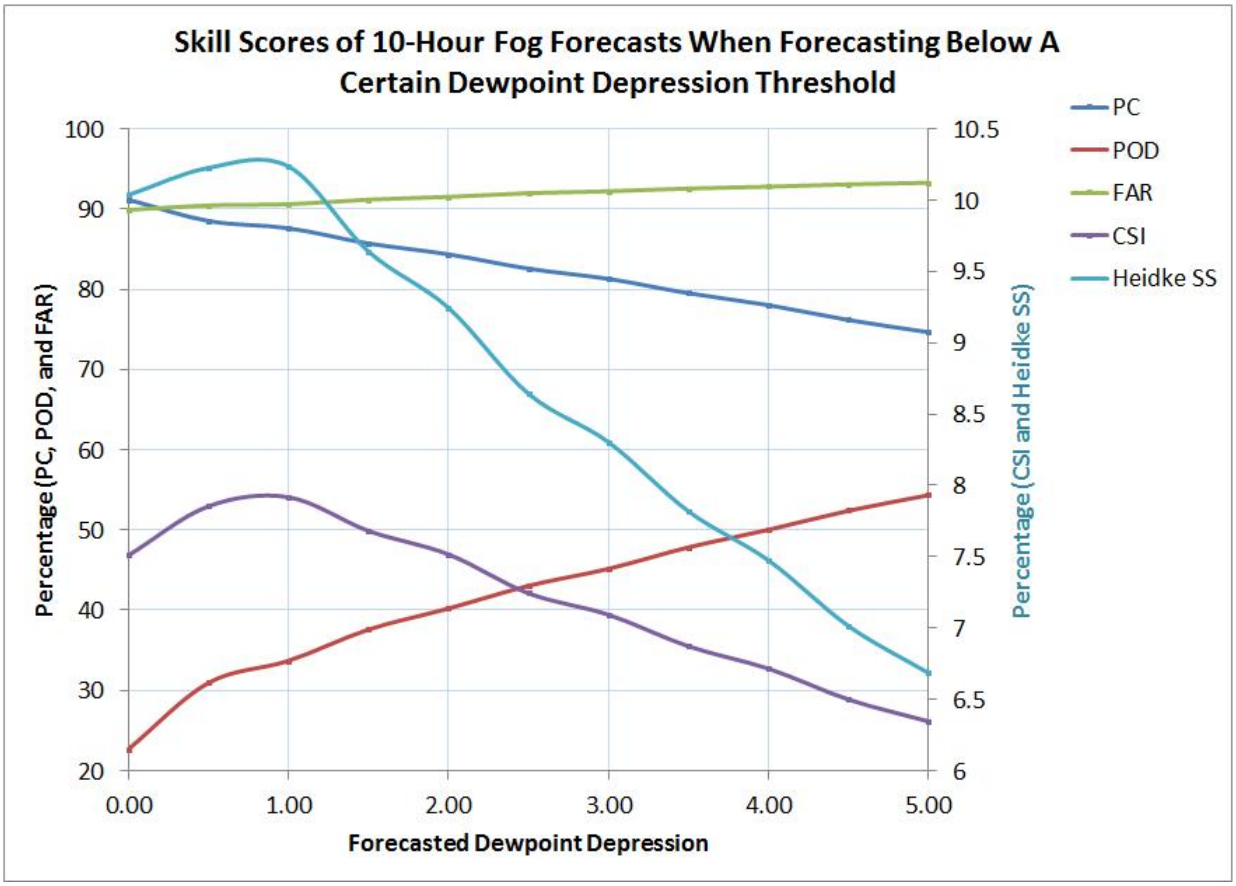

Figure 4.12: Ten-hour forecast skill score

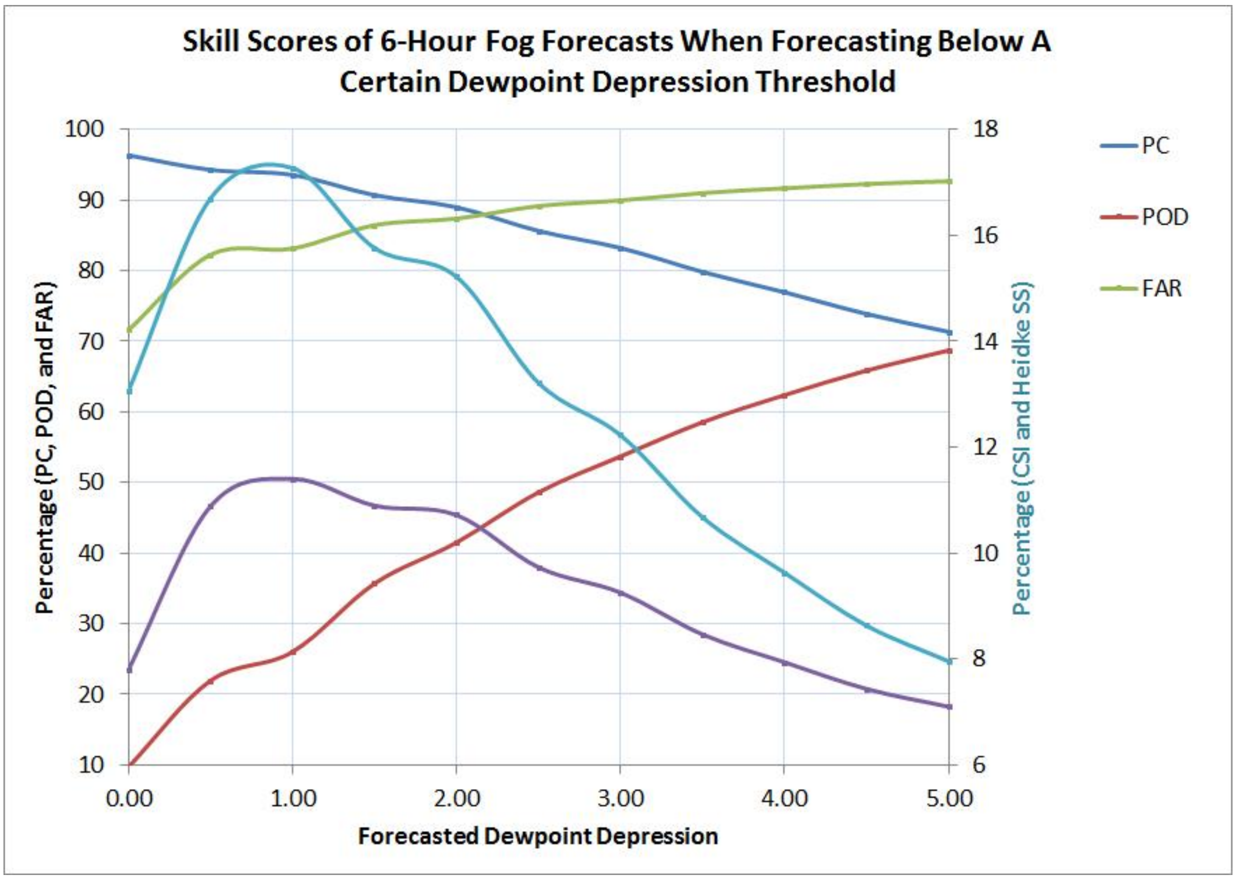

Figure 4.13: Six-hour forecast skill score

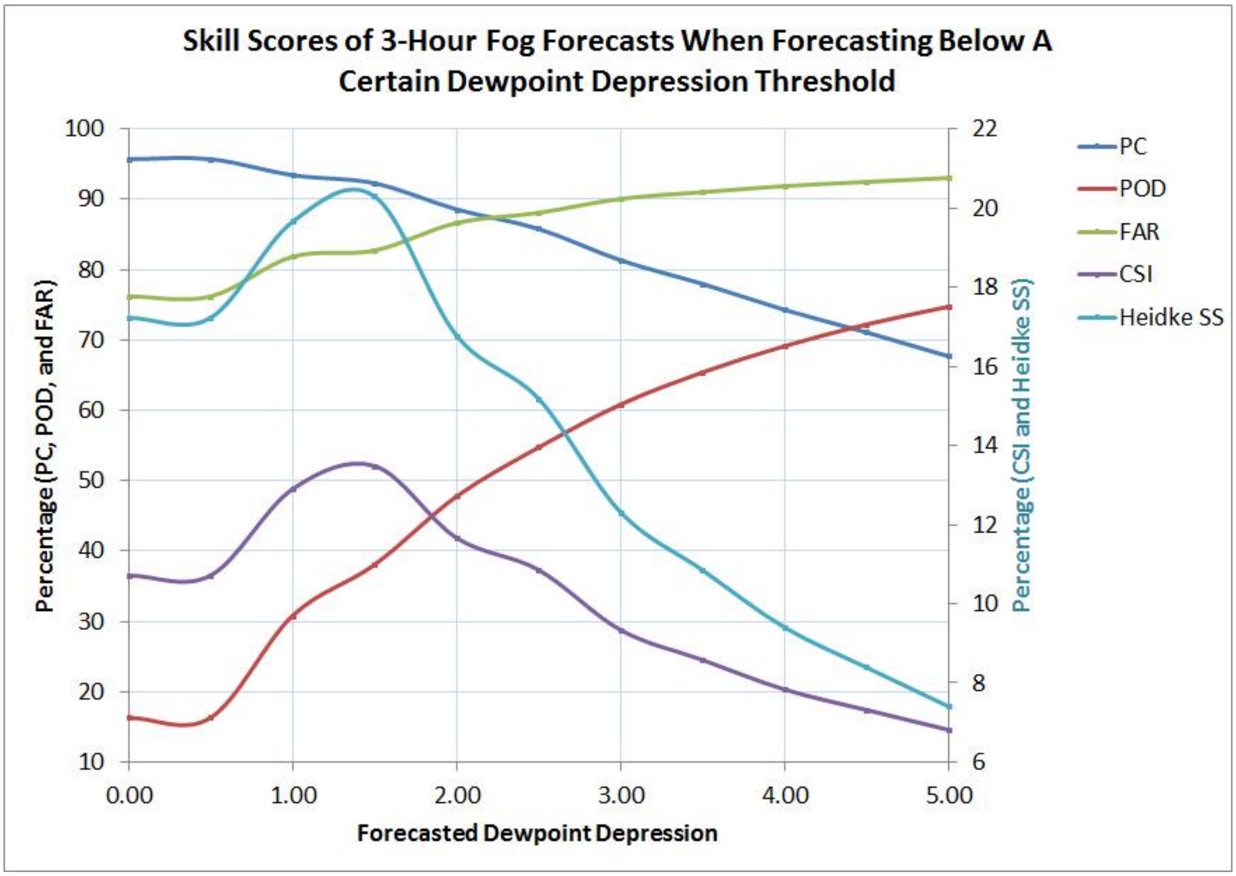

Figure 4.14: Three-hour forecast skill score

Chapter 5

Conclusions and Suggestions

5.1 Findings

1. **Climatology.** Fog is a small-scale event, largely a result of cooling by outgoing radiation during the night-time hours. There are only about 77 stations in Florida that measure visibility explicitly, and these were the only places where verification data were available. The results obtained would be more useful with data from the other networks, most notably the FAWN, the SFWMD, and FDOT. There are numerous private weather stations whose data are centrally archived, however, the quality control is much less assured, and given the sensitivity of fog formation, it is with risk that those data are of use without a verification study of their quality. Fog tends to form in the same locations. Knowledge of where and under what conditions fog formed is central to better forecasts. Existing knowledge of where fog forms is poor. A station might report no fog and yet there may be a place only a few miles away where fog forms frequently.

2. **Networks in Florida.** There are 77 ASOS and AWOS stations in Florida that explicitly measure visibility. FDOT has approximately 26 stations, and while SFWMD has 29, and FAWN 36 stations, none of them measure visibility. The FDOT sites do not presently report routinely to MADIS or the principal US data surface station repository.

3. **Equipment needed.** The present FDOT, AWOS/ASOS, FAWN or SFWMD equipment is adequate. What is needed beyond the basic meteorological variables

are (a) visibility sensors and (b) the data telemetered to MADIS or some central site where it can be retrieved. Any new sensors must be placed in a location where they will have the greatest impact in reducing crashes. Researchers have demonstrated that any forecast validity will degrade with distance. Thus, in crash-prone locations, additional equipment will improve both fog watches and warnings. Just as AWOS and many ASOS site are co-located at an airport to support terminal operations, instruments must be placed near affected roadways to best serve the interests of the vehicular traffic.

4. **Data availability.** Data are nationally collected and readily available from several sites within a hour or so from collection.

5. **Forecast capability.** Fog is difficult to forecast for the location where the data are collected and even more difficult for location distant from the observations.

5.2 Suggestions

1. **Test forecast methodologies in real time.** All of the recommendations support this recommendation. It is only through this real-time test that real evaluation can be performed and improvements can be made. There are significant logistical and administrative structures that must be addressed to cost-effectively provide the state-of-the-art evaluation and on-going development. Through this mechanism, competing methodologies can be evaluated. It is not only in generating forecasts, but also in decision-making and verification. All these are significant tasks. This is the over-arching goal, with elements of it listed below.

2. **Develop a much better fog climatology including satellite-based climatology.** As pointed out in section 3.5, in Florida, the climatology of fog is restricted to about 77 specific locations only. This leaves out most of Florida and its roadways. Analysis of satellite imagery taken over even one year would vastly improve

our knowledge of where fog is likely to form, when it does form. As new technology emerges and evolves over the next few years to identify fog in real time, it is strongly recommended that FDOT stay abreast of, and be involved in that emerging technology both in real-time detection and in improved forecasts.

3. **Install a station with a visibility sensor on Paynes Prairie.** Given the proclivity of fog to form at Paynes Prairie and the distance to the closest data station (Gainesville airport), it would be advantageous for FDOT or NOAA to supply a ASOS-type site at Paynes Prairie.

4. **Form a forecast distribution system.** Some mechanism must be developed within FDOT to transmit the likelihood of fog at specific locations to the proper authorities so they can anticipate the proper response to the proper authorities.

5. **Evaluate additional forecast methods.** Other techniques, including Baysian, linear and non-linear regression techniques, probabilistic, joint and conditional multivariate techniques, also hold promise, in principle. Many techniques would likely yield similar results (it is suspected), but there could be a technique which is superior to all others.

6. **Consider elevation effects.** It is well known that fog is more likely to form in low-lying areas. A careful study to include high-resolution height data may help refine forecasts.

7. **Place an ASOS-type instrumentation where fog is an issue.** This does not mean a mile away from where fog forms that affects driving conditions, but where that fog forms.

8. **Locate a visibility sensor at TLH.** Given the propensity of fog reported at TLH (more than anywhere else in the state), it would be an ideal test bed between a FDOT sensor and those used by ASOS/AWOS. There would be more days of fog to make such a comparison than any other place in Florida.

References

Abdel-Aty, M.A., M. Ahmed, J. L. Lee, Q. Shi, M. Abuzwidah, 2012: Synthesis of visibility detection systems. Final Report Contract from Florida DOT to UCF Orlando, Florida, Contract BDK78 -977-11. 134 pp.

Achtemeier, G. L., 2003: On the origins of "super fog" - a combination of smoke and water vapor that produces zero visibility over roadways. *Second International Wildfire Fire Ecology and Fire Management Congress and Fifth Symposium on Fire and Forest Meteorology*, Athens, GA J8.9.

American Meteorological Society., 2000: *Glossary of Meteorology*, **2** Allen Press. 638pp.

Baars, J. A., M. Witiw, and A. Al-Habash, 2009: Determining fog type in the Los Angeles basin using Historic surface observation data. *Poroc. 16th Conf. on Probability and Statistics in the Atoms. Sci.*, Long Beach, CA.

Baker, R. J. J. Cramer, and J. Peters, 2002: Radiation fog: UPS Airlines conceptual models and forecast methods. *10th Conf. on Aviation, Range and Aerospace Meteorology* Amer. Meteor. Soc. Portland, OR 154-159.

Ballard, S., B. Golding, and R Smith, 1991: Mesoscale model experimental forecasts of the air of northeast Scotland. *Mon. Wea. Rev.*, **119**, 2107-2123.

Bendix, J., B. Thies, J. Cermak, and Nauss, 2005: Ground fog detection from space based on Modis daytime data - a feasibility study. *Wea. and Forecasting*, **20** 989-1005.

Brier, G. W., 1950: Verification of forecasts expressed in terms of probability. *Mon. Wea. Rev.* **78**(1). 1-3.

Brier, G. W., 1957: Effect of errors in estimating probabilities on the usefulness of probability forecasts. *Bull. Amer. Meteor. Soc.*, **38**, 76-78.

Brier, G. W, and R. A. Allen, 1952: Verification of weather forecasts. Compendium of Meteorology. T.F. Malone, Ed. **Amer. Meteor. Soc.** 841-848.

Byers, H. B., 1944: *General Meteorology* 1st ed., McGraw-Hill, 645 pp.

Byers, H. B., 1959: *General Meteorology* 3rd ed., McGraw-Hill, 481 pp.

Cox, R. E., 2007: Applying fog forecasting techniques using AWIPS and the internet.

Croft, P. J., 1995: Forecasting significant fog in southern Alabama. *National Weather Digest* **19**. 10-16.

Croft, P. j., R. L. Pfost, J. M. Medlin, and G. A Johnson, 1997: Fog forecasting for the Southern Region: A conceptual model approach. *Wea. Forecasting* **12** 545-556.

Duynkerke, P.G., 1990: A comparison of model simulations with detailed observations. *Mon. Wea. Rev.* **119**, 119-324.

Ellrod, G. P., 2002: Estimation of low cloud base heights at night from satellite infrared and surface temperature data. *National Weather Digest* **26**, 39-44.

Ellrod, G.P., 2007: Event based climatology and typology of fog in the New York City region. *Wea. Forecasting.*,**10**, 606-619.

Gultepe, I., M. Muller, and Z. Boybeyi, 2006a: A new visibility parameter for warm-fog applications in numerical weather prediction models. *j. Appl. Meteor. Climatol.*, textbf45, 1469-1480.

Gultepe, I., M. Pagowski, and J. Reid, 2006b: A satellite-based fog detection scheme using screen air temperature. *Wea. Forecasting*, **22**, 444-456.

Gultepe, I., G. Pearson, J. a. Milbrandt, B. Hansen, S. Platnick, P. Taylor, M. Gordon, J.P. Oakley, and S. G. Cober, 2008: The fog remote sensing and modeling field project. *Bulletin American Meteor. Soc.*, **90**, 341-359.

Gurka, J. J., 1978: The use of enhanced visible imagery for predicting the time of fog dissipation. *Preprints, Conference on Weather Forecasting and Analysis and Aviation Meteorology*, St.Louis, MO Amer. Meteor. Soc. 54-57.

Heidke, P., 1926: Berechnung des Erfolges und der Güte der Windstärkevorhersagen im Sturmwarnungsdienst. Geor. Ann., Stockh. **8**, 310-349.

Herzegh, P. H., R. L. Bankert, B. K. Hansen, M. Tryhane, and G. Wiener, 2004: Recent progress in the development of automated analysis and forecast products for ceiling and visibility conditions. *20th Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology*, Seattle, WA.

Houghton, D. D., 1985: *Handbook of Meteorology*, 1st ed., John Wiley and Sons, 1461 pp.

Jarvis, M. R., H. E. Fuelberg, P. H. Ruscher and A. I . Watson, 2001: Improving forecasts of dense fog over north Florida. *18th Conf. Wea. Analysis and Forecasting*, Fort Lauderdale, FL. 218-222.

Johnson, G. a. and J. Grashel, 1992: Sea fog and stratus: A major aviation and marine hazard in the northern Gulf of Mexico *Preprints, Symp. on Weather Forecasting*, Atlanta, GA, 1992.

Kolb, L. L., and M. M. Goodmanson, 1945: Upslope weather along the inland Alaska air route. *J. of Meteor.* **1**, 98-108.

Leipper, D. L.,1995: Fog forecasting objectively in the California Coastal area using Libs. *Wea. and Forecasting*,**10**, 741-462

Lewis, J.m 2003: Sea fog off the California Coast: Viewed in the context of transient weather systems. *J. of Geo. Res.* **108**. D15.

Miller, M. D., M. Masbou, A Bott, and Z Janjic, 2005: Fog prediction in a 3d model with parameterized microphysics *Preprints, WWRP INt. Symp. on Nowcasting and very short range forecasting* Toulouse, France. Meteo-France page 6.26

Ratzer, M. A., 1988: *Middle Atmosphere Dynamics*, **2**, of Noaa Technical Service Publications NWS CR. Scientific Services Division. Central Region. U. S. Dept. of Commerce, National Oceanic and Atmospheric Administration. National Weather Service.

Stull, R. B., 1999: *Meteorology for Scientists and Engineers* 2nd ed., Brooks/Cole, 502 pp.

Tardiff, R and R. M. Rasmussen, 2007: Event based climatology and typology of fog in the New York City region. *Appl. Meteor. and Climo*, **46**, 1141-1168.

Taylor, G., 1917: The formation of fog and mist. *Royal Meteorological Society.* **43**, 241-268.

Westcott, N. E., 2006: Some aspects of dense fog in the midwestern United States. *Wea. and Forecasting*, **22**. 457-465.

Willett, H. C., 1928: Fog and haze, their causes, distribution and forecasting. *Mon. Wea. Rev.*, **56**, 457-468.

Zhou B., J. Du, B. Ferrier, J. McQueen, and G. Dimego, 2007: Numerical forecasts of fog - central solutions. *18th Conference on Numerical Weather Prediction*, Park City UT. Amer. Meteor. Soc.

Appendix A
Conversions

A.1 Approximate Conversion to SI Units

Length				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
mi	miles	1.61	kilometers	km

Area				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
in^2	square inches	645.16	sq millimeters	mm^2
ft^2	square feet	0.093	sq meters	m^2
mi^2	square miles	2.59	sq kilometers	km^2

Mass				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg

Temperature				
Symbol	**When You Know**	**Conversion**	**To Find**	**Symbol**
°F	Fahrenheit	$5 \times (°F - 32)/9$	Celsius	°C

A.2 Approximate Conversion from SI Units

Length				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
km	kilometers	0.621	miles	mi

Area				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
mm^2	square millimeters	0.0016	sq inches	in^2
m^2	square meters	10.764	sq feet	ft^2
km^2	square kilometers	0.386	sq miles	mi^2

Mass				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb

Temperature				
Symbol	**When You Know**	**Conversion**	**To Find**	**Symbol**
°C	Celsius	$(1.8 \times °C) + 32$	Fahrenheit	°F

Appendix B
Plots: Environmental Conditions Related to Fog Formation

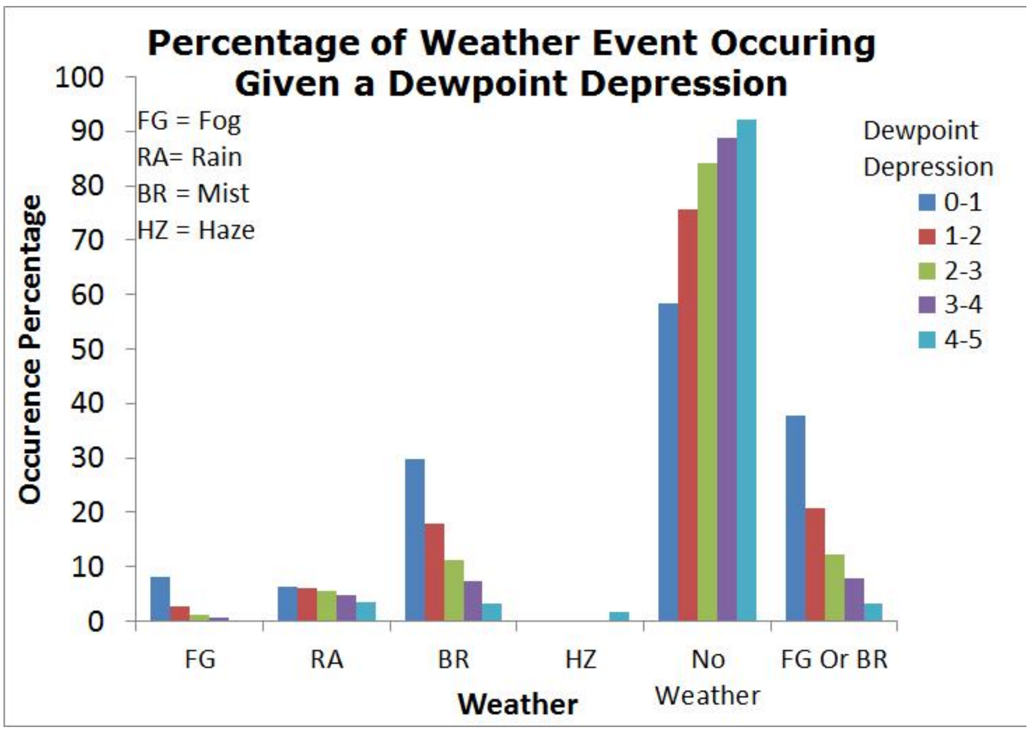

Figure B.1: Percent of type of weather event for specific dew-point depressions

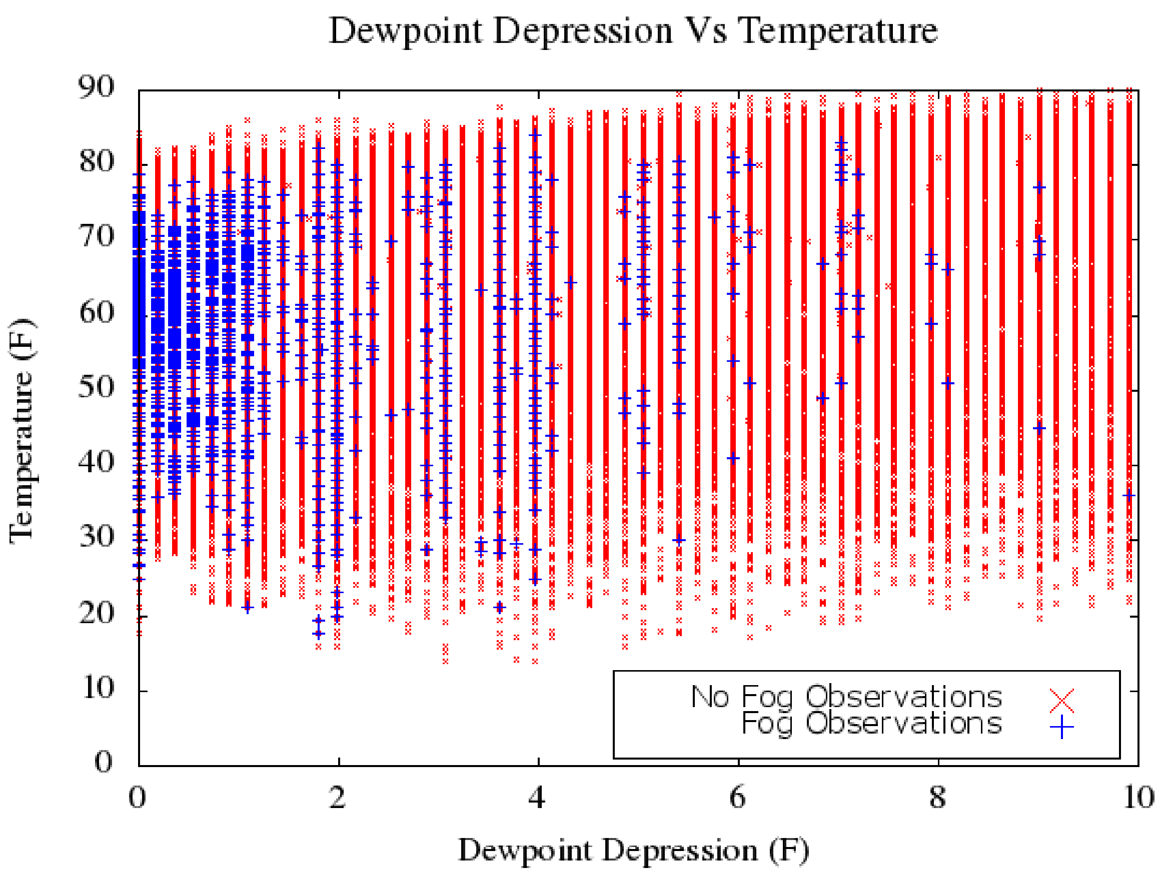

Figure B.2: Percent of type of weather event for specific dew-point depressions and temperature

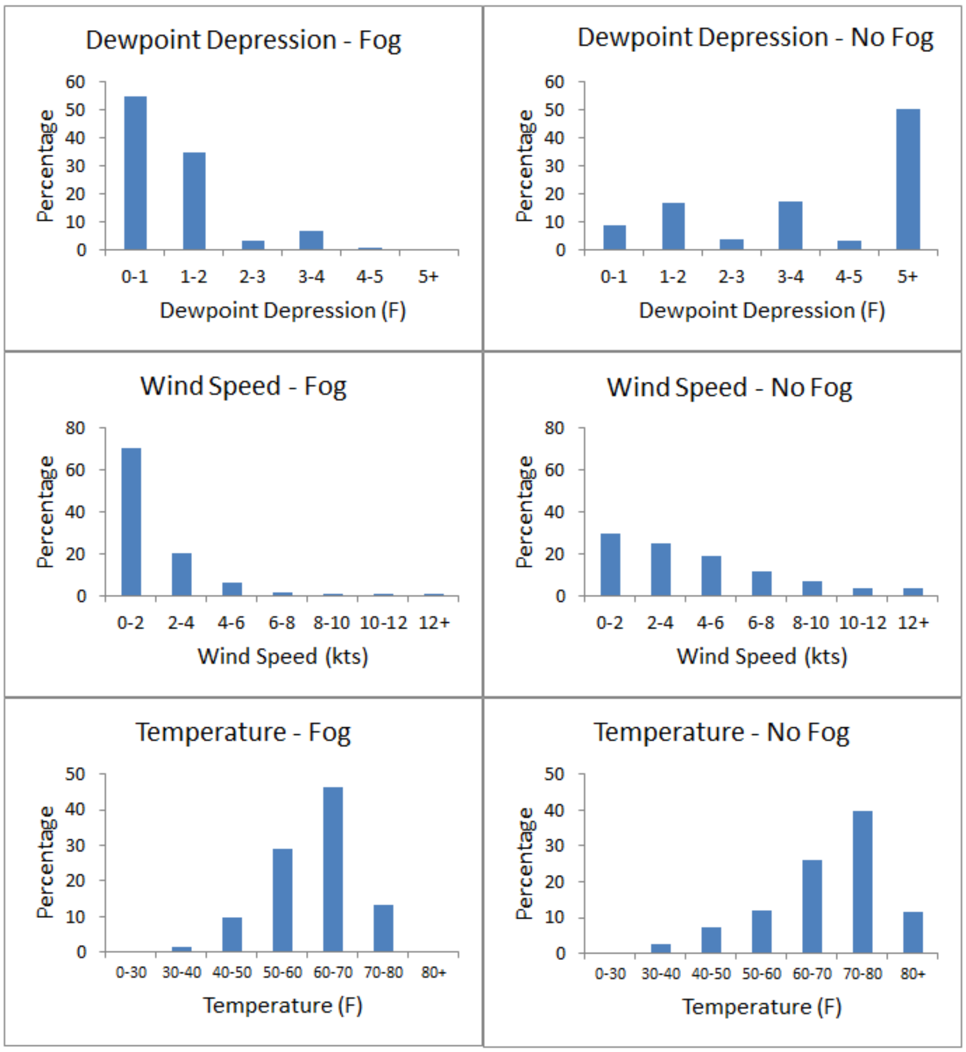

Figure B.3: Fog cover vs different measured variables

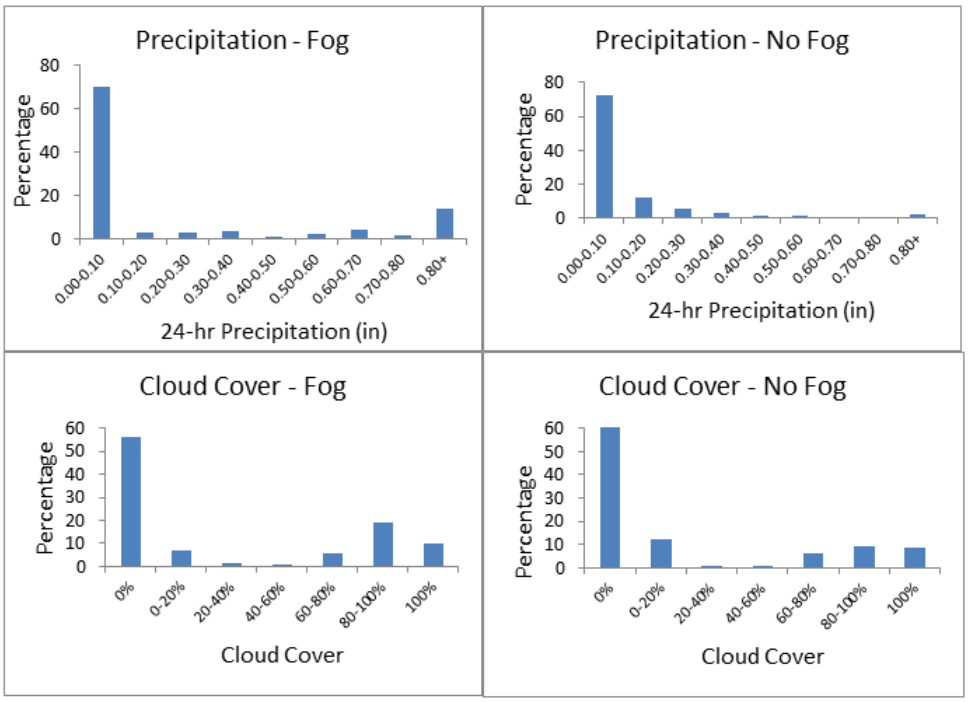

Figure B.4: Fog cover vs different measured variables continued

Appendix C
Location of Mesonet Sites

Table C.1: Location of Mesonet Sites

ID	Airport	Lat	Long
K40J	PERRY FOLEY	30.08	−83.57
KAAF	APALACHICOLA	29.73	−85.02
KAPF	NAPLES	26.15	−81.77
KBCT	BOCA RATION SP	26.38	−80.11
KBKV	BROOKESVILLE	28.47	−82.45
KCEW	CRESTVIEW	30.78	−86.52
KCTY	CROSS COTY	29.62	−83.10
KCOF	PATRICK AFB	28.23	−80.60
KCRG	CRAIG MUNICIPLE AP	30.33	−81.52
KDAB	DAYTONA BEACH	29.18	−81.05
KDTS	DESTIN	30.40	−86.47
KEYW	KEY WEST	24.55	−81.75
KLFLL	FORT LAUDERDALE	26.07	−80.15
KFMY	FORT MYERS	26.58	−81.86
KFPR	FORT PIERCE	27.50	−80.37
KFXE	FORT LAUDERDALE	26.20	−80.18
KGIF	WINTER HAVEN	28.07	−81.75
KGNV	GAINSVILLE	29.68	−82.27
KHRT	HURLBURT FILED	30.42	−86.68
KHST	HOMESTEAD AFB	25.48	−80.38
KISM	NORTH PERRY AP	26.00	−80.24
KISM	KISSIMMEE	28.29	−81.44
KJAX	JACKSONVILLE	30.5	−81.70
KLAL	LAKELAND AP	28.00	−82.05
KMCF	MADCILL AFB	27.85	−81.52
KMCO	ORLANDO INTL	28.43	−81.32

Table C.1: Location of Mesonet Sites (continued).

ID	Airport	Lat	Long
KLEE	LEESBURG	28.82	−81.81
KMAI	MARIANNA	30.83	−85.18
KMIA	MIAMI	25.82	−80.28
KMLB	MELBOURNE	28.10	−80.63
KMTH	MARATHONKEY AP	24.72	−81.08
KNIP	JACKSONVILLE NAS	30.23	−81.68
KNPA	PENSACOLA NAS	30.35	−87.32
KNRB	MAYPORT NAS	30.40	−81.42
KNSE	MILTON NAS	30.72	−87.02
KOCF	OCALA MUNICIPLE AP	29.17	−82.22
KORL	ORLANDO HERN AP	28.55	−81.34
KOPF	OPA LOCKA AP	25.9	−80.28
KPAM	TYNDALL AFFB	30.07	−85.58
KPBI	WEST PALM BEACH	26.68	−80.12
KPFN	PANAMA CITY	50.20	−85.68
KPGD	PUNTA GORDA	26.92	−82.00
KPIE	ST PETERSBURG	27.92	−82.68
KPMP	POMPANO BEACH	26.25	−80.11
KPNS	PENSACOLA	30.47	−87.23
KRSW	FT MYERS SW AP	26.53	−81.75
KSFB	SANFORD	28.78	−81.25
KSGJ	ST AUGUSTINE	29.97	−81.33
KSPG	SAINT PETERSBURG	27.77	−82.63
KSRQ	SARASOTA-BRADENTON	27.40	−82.55
KSUA	STURAT WITHAM FIELD	27.18	−80.22
KTLH	TALLAHASSEE	30.38	−84.37
KTMB	TAIAMI AP	25.65	−80.43
KTPA	TAMPA	27.97	−82.53
KTTS	NASA SHUTTLE FACILITY	28.62	−80.70
KLVDF	TAMPA/VANDENBURG	28.01	−82.35
KVPS	EGLIN AFB	30.48	−86.52
KVQQ	JACKSONVILLE NAS	30.22	−81.88
KVRB	VERO BEACH	27.65	−80.42
KVVG	THE VILLAGES	28.96	−81.97

Appendix D
Regression Statistics

Table D.1: Regression model of 11 UTC air temperature upon 8 UTC air temperature when 11 UTC fog was observed for TLH.

	Dependent variable:
	Air Temperature at 11 UTC
Air Temperature at 8 UTC	1.006^{***}
	(0.010)
(intercept)	-1.850^{***}
	(0.661)
Observations	342
R^2	0.967
Adjusted R^2	0.967
Residual Std. Error	$2.087 (df = 340)$
F statistic	$9,891.591^{***} (df = 1; 340)$
Note:	$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table D.2: Regression model of 11 UTC air temperature upon 5 UTC air temperature when 11 UTC fog was observed for TLH from 2006–2010.

	Dependent variable:
	Air Temperature at 11 UTC
Air Temperature at 8 UTC	1.005^{***}
	(0.016)
(intercept)	-4.142^{***}
	(1.077)
Observations	346
R^2	0.920
Adjusted R^2	0.920
Residual Std. Error	$3.232(df = 344)$
F statistic	$3,972.857^{***}(df = 1; 344)$
Note:	*p<0.1; **p<0.05; ***p<0.01

Table D.3: Regression model of 11 UTC air temperature upon 2 UTC air temperature when 11 UTC fog was observed for TLH.

	Dependent variable:
	Air Temperature at 11 UTC
Air Temperature at 8 UTC	1.015^{***}
	(0.026)
(intercept)	-8.924^{***}
	(1.822)
Observations	343
R^2	0.823
Adjusted R^2	0.822
Residual Std. Error	$4.829 (df = 341)$
F statistic	$1,582.661^{***} (df = 1; 341)$
Note:	*p<0.1; **p<0.05; ***p<0.01