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Defining Environmental Characteristics of Sea Breezes along the U.S. Gulf Coast

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Defining environmental characteristics of sea breezes along the U.S. Gulf Coast

By

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Defining environmental characteristics of sea breezes along the U.S. Gulf Coast

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Studies of sea breeze have been done on coastline locations worldwide, but only a few have focused on the U.S. Gulf Coast. This area is frequently influenced by sea breeze events; therefore, it is important for meteorologists to determine where and when these systems will occur. The objectives of this study are to quantify sea breeze frequency along the Gulf Coast and define the associated environmental characteristics. The study is based on sea breeze development during synoptically benign days. From 1991 to 2010 a total of 1,255 days were classified as synoptically benign, with 161 of those days identified as a sea breeze day through analysis of clouds from Geostationary Operational Environmental Satellite (GOES) imagery. The average surface temperature was significantly different between sea breeze and non sea breeze days, but the average surface wind speed and direction were not significantly different making them poor descriptors of sea breeze environments.

DEDICATION

This thesis is dedicated to my dear, sweet family for their support, prayers and motivation throughout these years. This is especially dedicated to my beloved dad Waldin Maldonado, my lovely mom Gloria Jaime, my adorable sister Wadeline, and my princesses, my nieces Stacy Lee and Coral Lee. I will always be grateful for all your love, prayers, encouragement, and caring. All of you are my inspiration! I love you all!

¡Lo logré!

ACKNOWLEDGEMENTS

I feel great satisfaction and happiness by being able to achieve this goal. I thank God, because only by His blessings and strength I was able finish this Thesis.

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CHAPTER I

INTRODUCTION

1.1 Definition of Sea Breeze

The sea breeze is an important meteorological phenomenon that affects coastlines and large bodies of water throughout the world, especially in areas with complex topography and coastline shape. Sea breezes are mesoscale thermodynamic systems that involve air–sea-land interactions. This system consists of wind flows due to thermal circulation along the coastline that brings air from the sea to land in the afternoon, whereas farther inland hot and still air is the general rule (Hsu, 1988).

The driving atmospheric mechanisms associated with sea breeze development begin with the differences in temperature between a warm land mass and colder water (Figure 1.1). The sea-breeze circulation (SBC) is a mesoscale cell, which develops a thermally-induced pressure gradient force that points from sea to land. During the day, the land heats up faster than the sea and develops a thermal-low over land (rising air), and a thermal-high above water (sinking air). This SBC is a convergence boundary that develops a line of cumulus (Cu) clouds along the coastline above the land surface. Eventually, this boundary creates a front, which defines an air mass over the ocean and another over the land. Huschke (1959) defined a sea- breeze front (SBF) as a horizontal discontinuity in temperature and humidity marking the leading edge of the intrusion of colder, marine air associated with the lower horizontal arm of sea breeze circulation patterns. Another component is the convective internal boundary layer (CIBL), an unstable region within the marine air mass, appearing on the coast and growing in depth with distance inland (Miller at al., 2003).

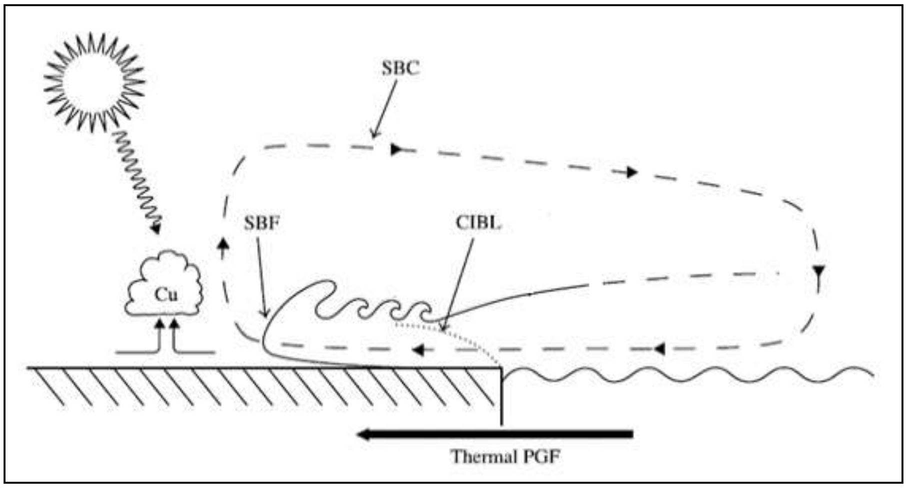


Figure 1.1 Sea-breeze circulation (SBC) and its principal components. (Adapted from Fig. 1 in Miller et al., 2003)

1.2 Problem Statement

The U.S. Gulf Coast is a very susceptible area for sea breeze development due to convergence of continental and maritime air masses. This area is influenced by the maritime tropical air mass (mT), which is characterized by warm and moist air and the continental tropical air mass (cT), which is represented by dry and warm air. Determining atmospheric characteristics in this area, such as when, where and how much precipitation will occur, can be complicated for weather forecasters when synoptic scale forcing is not present. Synoptic scale phenomena are weather systems that develop in the lower troposphere ranging in size from several hundred kilometers to several thousand kilometers (Glickmann, 2000). Midlatitudes cyclones (e.g. cold front, warm front) and tropical cyclones are examples of synoptic scale forcing.

Defining and predicting the environmental characteristics of a mesoscale system such as sea breeze is crucial for weather forecasters. The study and understanding of the sea breeze is important because a large part of the population lives in major cities in coastal areas (Miller et al., 2003). This phenomenon plays an important role in defining the atmospheric characteristics of coastal areas, such as air pollution transport, aviation safety (Watts, 1955), and location and initiation of convection (Gentry and Moore 1954; Pielke 1974; Blanchard and Lopez 1985; Nicholls et al. 1991). The understanding of this system is very important because it has a large impact on local coastal weather, as well as in many districts inland (Simpson, 1994).

1.3 Study Area

The Gulf Coast of the United States is a region where the southern states of this country, also known as the "Gulf States", border the ninth largest body of water of the Earth, the Gulf of Mexico. These Gulf States are Texas, Louisiana, Mississippi, Alabama and Florida. The U.S Gulf Coast spans 1,100 mi (1,770 km) from Texas to Florida (Encyclopedia Britannica, 2013).

The study area of this research covers the coasts of Louisiana, Mississippi, Alabama and northwest of Florida (Figure 1.2).

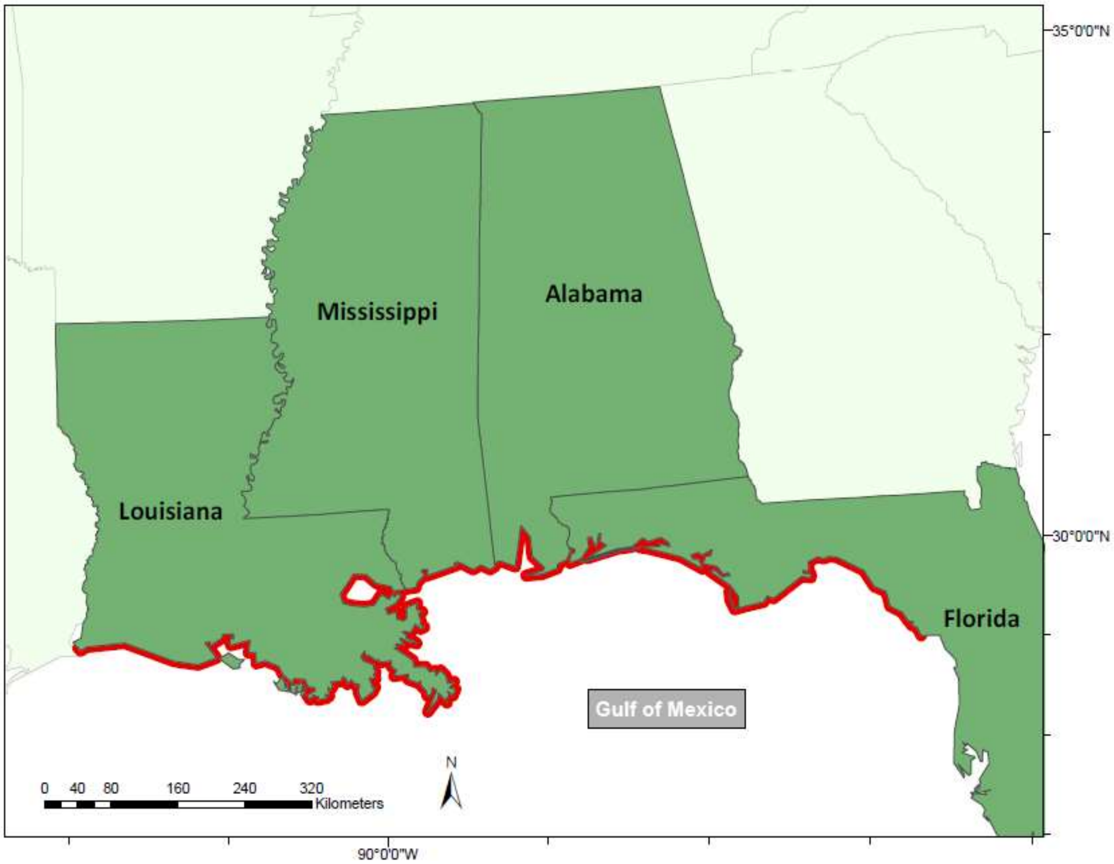


Figure 1.2 U.S. Gulf Coast from Louisiana to Florida panhandle.

The red outline is indicating the study area.

1.4 Objectives

Three objectives are accomplished in this study. The first objective is to quantify sea breeze frequency along the U.S. Gulf Coast during synoptically weak conditions. Then, to define surface environmental characteristics during a sea breeze day. Lastly, to compare the difference in the environmental characteristics between sea breeze and non-sea breeze days. The main reason is to develop strategies and to perform a useful platform for weather forecasters to determine areas at risk more quickly and accurately. The areas at risk are places that are more susceptible to floods (i.e., urban zones, coastlines, rivers) and areas highly populated. Sea breeze events are important because they incorporate physical and social impacts directly and indirectly. The direct physical impacts include rainfall accumulation, cloud cover, winds, temperature, relative humidity, etc., leading to indirect impacts such as flooding and wind erosion. Normally, the sea breeze develops during warm seasons; however, during a cold season it is difficult to forecast localized convection when there is weak synoptic forcing. Additionally, there are several important ports located throughout the Gulf Coast, a huge population that lives near the coastline, and an active tourism business that would like to enjoy the warm clime of the southern region.

CHAPTER II

LITERATURE REVIEW

2.1 Global Patterns of Sea Breezes

Sea breeze circulations occur in coastal locations throughout the world, especially in tropical and sub-tropical environments. This is one of the mesoscale phenomenon that has been comprehensively studied since the seventeenth century (Jehn, 1973). For years, scientists have studied the development, structure, and impacts of the sea breeze, mathematically and physically, using modeling and observations.

As a global pattern, this phenomenon has been analyzed in different regions covering a wide branch of components. Borne et al. (1998) studied the characteristics, onset and physical mechanisms of sea breezes in the archipelago area of south-western Sweden. They performed a platform to identify sea breezes developments based on previous knowledge of the physical processes of this system within the study area. The main criterion was to detect the change of surface wind direction within a 24-hour period at different locations along the West Coast of Sweden. In Israel, Lensky and Dayan (2012) detected and characterized the sea breeze in clear sky conditions during the summer, when the conditions for this mesoscale circulation system were most favorable. The method used in this study was primarily satellite and surface data (wind speed and wind direction). Banfield (1991) evaluated the frequency and surface characteristics of sea breezes at St. John's, Newfoundland, Canada. The first criterion of this study was to analyze the shift of the surface wind direction within a 24-hour period from an airport station to detect the sea breeze onset. The U.S. coastlines are also affected by this event. Gilliam et al. (2004) investigated the sea breeze by using surface observations and numerical simulations to examine the onshore penetration and intensity of the sea breeze during various large-scale flow regimes along the coastline of the Carolinas, U.S. Miller and Keim (2003) conducted research focused on the synoptic-scale surface environment in which the sea breeze develops by studying the physical behavior of the sea breeze on the central New England coast, including its inland extent, vertical depth, and frontal characteristics. These studies of sea breezes around Sweden, Israel, Newfoundland, New England and the Carolinas have a common objective: to evaluate its characteristics, structure and patterns according to its location.

Sea breezes in the Perth metropolitan coastline (western Australia) are characterized by one of the strongest and most consistent sea breeze systems in the world (Masselink and Pattiaratchi, 1998). An important feature of the sea breeze system is that it blows parallel to the shoreline, in contrast to the classic onshore sea breeze. The shore-parallel sea breeze system in Perth, and in fact along most of the western Australian coastline, is attributed to the interaction between the sea breeze system and synoptic weather patterns (Pattiaratchi et al., 1997). The development of this phenomenon produces gravity waves that increase the likelihood of deep convection along the coastline. In fact, Masselink and Pattiaratchi (1998) investigated the wind speed and direction along the Perth area by using three-hourly wind data collected from an airport station. On average, 197 sea breezes develop each year along on this area with a mean wind speed of 5.7 ms^{-1}. The wind direction is predominantly from west-southwest throughout the year.

Azorin-Molina et al. (2009) performed research regarding sea-breeze convergence zones along the Isle of Mallorca, Spain. They identified clear air boundaries and obtained a spatial distribution of convective areas associated with the sea breeze over the Iberian Mediterranean zone and the Isle of Mallorca. Results in this study indicate the differences between the boundary layer convergence zones during synoptic-scale flows and the prevailing wind speed at the leading edge of the sea breezes. Furthermore, Azorin-Molina et al. (2009) developed a climatology of sea breeze clouds in the southeast of the Iberian Peninsula at Alicante, Spain. In this study, they analyzed the impact of sea breezes on cloud types in the convective internal boundary layer and in the sea breeze convergence zone. Kottmeir et al. (2000) performed additional research in the southeast region of Spain, which evaluated the association between the daytime sea breeze and low level jets.

One of the most studied regions on the topic of sea breezes is the Florida panhandle and peninsula. Florida is located in a sub-tropical zone where there are usually warm temperatures that yield daytime convection along the coastline; therefore, a lot of the convection over the Florida panhandle and peninsula during summer is directly related to the SBC (Connell et al., 2001; Case et al., 2004). The sea breezes in western Australia, Spain and Florida can develop according to the air-land-sea interactions. While Australia and Spain are characterized by cold ocean currents and warm land, the coast of Florida is distinguished by relatively hot land and water. This leads to a considerable amount of moisture and heavy rainfall over the peninsula as a result of the sea breeze. In fact, sea breeze developments in south Florida are a result of the accumulation of synoptic-scale moisture in the convergence zones (Pielke, 1974). Another reason for a deep convection in this region is the interaction of energy and moisture fields at various spatial scales (Blanchard and López, 1985). Since most of the convection may occur due to synoptic-scale processes, Connell et al. (2001) incorporated research to evaluate the strength and development of the sea-breeze front under various synoptic winds and the effect on convective development.

There are studies of SBC throughout the world but only a few of them are focused on the U.S. Gulf Coast. DrMego et al. (1976) evaluated the frontal incursions by analyzing the frequency and mean conditions when it penetrates the Gulf of Mexico-Caribbean Sea region during warm and cold seasons. Smith et al. (2005) investigated the relation between synoptic-scale and mesoscale environments associated with the warm season lightning distribution over the northern Gulf of Mexico. This huge coastal area extending from Texas through western Florida is affected by sea breezes, but the study of frequency and patterns is limited. The Gulf of Mexico is located in a sub-tropical zone, interacting with the warm waters of the Caribbean Sea. Thus, the amount of moisture in combination with high temperatures creates considerable convection in this region. In fact, the study and understanding of sea breezes along the U.S. Gulf Coast is important because this is an area with complex topography, a large population living along the coastline, and several important commercial ports.

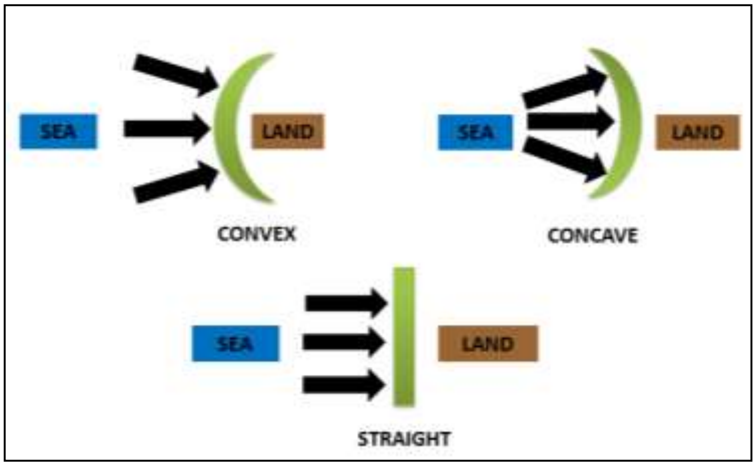


Figure 2.1 A schematic diagram depicting landward prevailing winds according to the shape of the land

The green color represents the shape of the surface.

2.2 Spatial Patterns of Sea Breezes

The general extent of the onshore sea breeze varies at different locations. One of the significant features of the inland penetration of the sea breeze is the wind speed and direction. Arritt (1993) investigated the effects and influences of the large-scale flows in the strength and landward penetration of the sea breeze by using a two-dimensional numerical model. Estoque (1962) explained the inland penetration of the sea breeze by large-scale winds. Dalu and Pielke (1989) studied the sea breeze intensity and its inland penetration as a function of latitude and friction. In general, Atkinson (1981) indicated that the horizontal extent could have a range between 30 and 300 km. Studies indicate a variation in the inland penetration of sea breezes according to the location. For example, the coast of Texas demonstrates a sea-breeze extent of 60 km (Hsu, 1970). Australia could experience an extent of 290 km (Clarke, 1955), while the SBC in southeastern Spain has a maximum extent of 150 km (Kottmeier et al., 2000). Calculating the inland penetration at the U.S. Gulf Coast, the Florida peninsula has recorded distances of 50 km

(Simpson, 1994). Given these results, it is possible to assume that the onshore wind along the Gulf Coast can reach a penetration between 50-150 km, approximately.

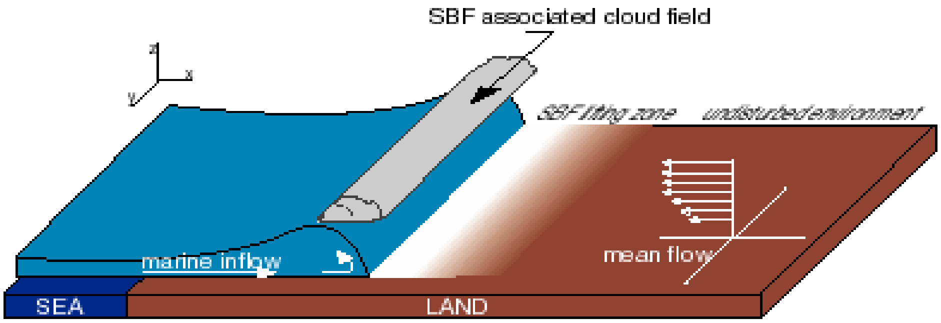
One of the factors for the strengthening and development of the sea breeze is the topography and shape of the landmasses. There is diversity in onshore characteristics throughout the coastline such as bays, mountains, valleys, and cliffs, such that the sea/land interface can be described as either a flat surface, convex or concave (Figure 2.1). Mahrer and Pielke (1977) studied the effect of topography on sea and land breezes, the mountain and valley winds and the combination of the sea, land and mountain winds. Gilliam et al. (2004) argued that the wind flow relative to the curvature of the coast has a significant effect on the sea-breeze evolution. The wind speed and direction can determine the entrance of this system landward. This system usually begins to move inland in a right angle with respect the landmass (Simpson, 1994). If the prevailing wind flows directly on a straight surface, the circulation will be uniform and a strengthened SBF is not expected. In a concave shape, there are diffluent flows that generate a weak SBF, while convex shapes create confluent flows that will allow the development of a strong SBF and deep convection. Indeed, Neumann (1951) indicated that curvature of the coastline is important for the diurnal variation of the frequency of thunderstorms.

A sea breeze front can occur and propagate in different forms with respect to the shape of the coastline. Complex landmasses can produce several sea breeze systems along different zones of the coastline (Miller et al., 2003). The effects of this phenomenon in headlands and peninsulas can aid in the development of a strong convergence zone due to a convex coastline, which develops a line of clouds (Simpson, 1994). The strength of a SBC over an island depends on its size. Sea breezes from a small island — of radius 26 km — produces much smaller vertical velocities than a large island — of radius 50 km — (Neumann and Mahrer, 1974; Simpson, 1994). McPherson (1970) applied a three-dimensional numerical model for the study of the sea breeze associated with coastal irregularities by using the Galveston Bay in Texas as a model. Results of this research revealed that the northeast and northwest areas of a bay develop and enhance convergence and uplift, which yields convective patterns. This is associated with coriolis and pressure gradient forces that act in opposite directions in the west and in the same directions on the east side of the bay. The period and strength of a sea breeze is also affected by the width of the landmasses. Xian and Pielke (1991) created a two-dimensional hydrostatic model to simulate SBC introduced by different-sized landmasses. When the width of a landmass is in a range of 100–150 km, the thermal forcing is sufficiently strong and may reach a height of 1–2 km and lead to a deep organized convective circulation. If the landmass width is less than 100 km, the thermal forcing is weak and the probability of deep convection is low.

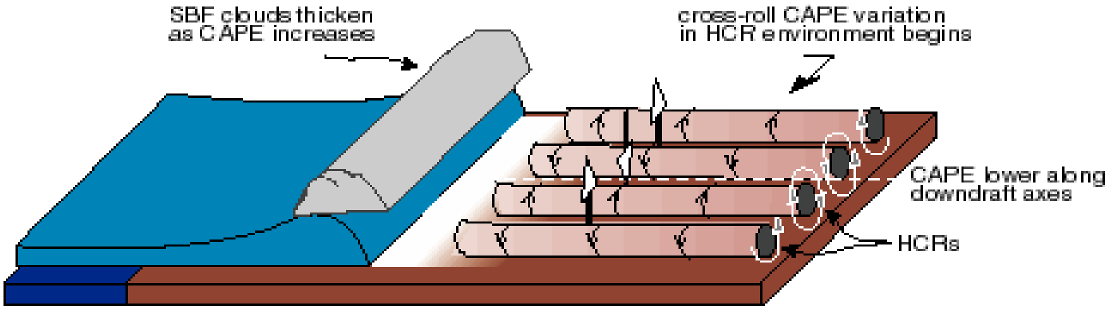
The topography and curvature of the U.S. Gulf Coast is diverse throughout the coastline. Although the coast is generally straight, it is complex in Mississippi and Louisiana. These places have large lakes and bays such as Lake Pontchartrain and Bay St. Louis that could enhance the formation of the sea breeze. In fact, those prominent factors are vital because they may impact the intensity, strengthening and direction of the sea breeze front.

Another criterion to consider in sea breeze circulation is the development of clouds and convection along the coast. The most predominant feature is the formation of towering cumulus clouds. Leopold (1949) indicated that towering cumulus clouds form along the sea-breeze front at discrete intervals. These intervals of clouds are formed by features known as horizontal convective rolls (HCRs). The HCRs are counter-rotating horizontal vortices that commonly occur within the planetary boundary layer (Glickman, 2000). The HCRs are characterized by updrafts and downdrafts, where the ascending zone of the roll circulations is the ideal area for the development of clouds (Markowski and Richardson, 2010). Wakimoto and Atkins (1994) argued that convective clouds in a sea breeze front are not always generated solely by HCRs. Instead, you will see cloud development along the front only at locations where these cloud streets intersect the boundary. In fact, Wakimoto and Atkins (1994) and Atkins et al. (1995) theorized that in areas where HCRs merged with the sea breeze front, enhanced cloud development could occur. Although the merge of these two mechanisms can result in strong cloud development, they argued that it is unclear if this mechanism alone is enough to produce a storm. Nevertheless, the interaction of these phenomena can lead to convection initiation.

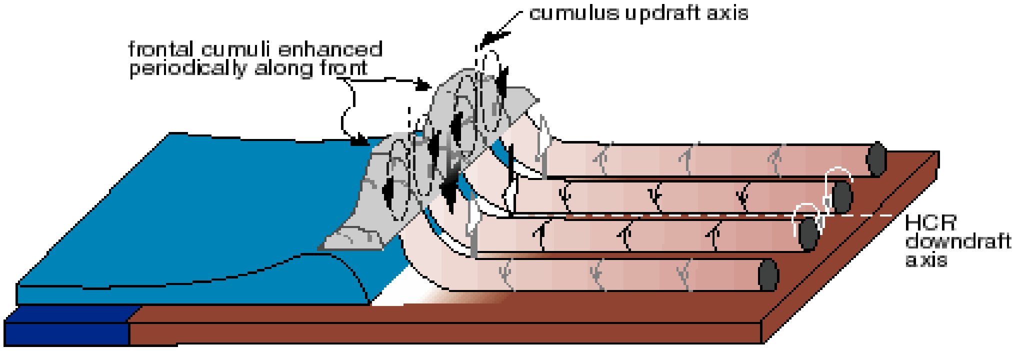
Dailey and Fovell (1999) developed a three dimensional numerical model to evaluate the interaction between the sea breeze front and the HCRs (Figure 2.2). In their study, when the HCRs updraft flows intersect the sea breeze front, the cloudiness associated with the sea breeze circulation is enhanced. This is a result of lifting associated with the HCRs updraft and the convective instability within the updrafts rolls.



A *Prior to development of the HCRs*



B *During development of the HCRs*



C *After interaction with the HCRs*

Figure 2.2 Schematic representation of the enhanced cloudiness development due to the interaction between the sea breeze front (SBF) with the horizontal convective rolls (HCRs)

(From Fig. 15 in Dailey and Fovell, 1999)

2.3 Temporal Patterns of Sea Breezes

The seasonal frequency and diurnal cycles of SBC have been studied and explained by various researchers (Clarke, 1984; Finkele et al., 1995; Simpson, 1996; Buckley and Kurzeja, 1997; Holmer and Haeger-Eugensson, 1999; Miller et al., 2003). The life cycle of a sea breeze is catalogued by three stages: immature, mature, and degenerate. Hsu (1988) explained the diurnal pattern of the sea breeze according to the observations on the coast of Texas. The first five patterns of this cycle are explained as follows: (1) 0900 LT: the land temperature is colder than the water, the land breeze is still prevailing, thus the atmosphere is in a baroclinic environment, i.e., where surfaces with constant pressure intersect the surfaces of constant density (temperature). (2) 1200 LT: the landmass is warmer than the water; there is a resulting onshore circulation due to a baroclinic field that is extended to 20 km inland. Because the land breeze is still prevailing farther inland, a convergence zone in the surface is created and scattered cumuli lines tend to form. Hsu (1988) indicated that in this period the temperature drops at approximately -15°C (5°F), relative humidity drops 7% and then rises 14%, and the surface wind direction shifts in a clockwise fashion, from northerly to southerly. The pattern continues; (3) 1500 LT: the air temperature difference between land and water reaches its maximum near noon; hence the sea breeze reaches the climax of its development stage at this time. In this period, cumulus clouds develop and precipitation is expected from 30–40 km inland for 1600–1700 LT. (4) 1800 LT: the land stays warmer than the water, the baroclinicity is weak but the sea breeze circulation is still prevailing, and there are few cumuli clouds from 30 km inland. (5) 2100 LT: the sea breeze circulation may remain but with less strength and speed.

The daily life-cycle of sea breezes following this pattern is more likely to begin between the late morning and local noon, when the landmass is relatively warm and the temperature gradient between the land and water is strong. Studies in Spain indicate a mean onset time at 0940 LT for the whole year; 0834 LT in the summer solstice and 1241 LT in winter solstice (Azorin-Molina et al., 2009). The period of interest is in general, from 1200 LT to 1800 LT (Atlas, 1960; Buckley and Kurzeja, 1997).

Sea breezes normally develop during the warm season — April through September — when synoptic-scale forcing is minimal and the land heats up rapidly. As a result, few studies have dealt specifically with sea breeze during the cold season. Azorin-Molina et al. (2009) conducted a study of the effect of sea breezes on cloudiness in Spain for warm and cold seasons; while DrMego et al. (1976) evaluated the frontal incursions into the Gulf of Mexico and Caribbean Sea for cold seasons. Despite a higher frequency of sea breeze initiation during the warm season, the U.S. Gulf Coast could be a good region for the development of deep convection during the cold season. This is due to its geographical position, which is located close to the tropical zone, which means the region is surrounded by a humid and warm air mass even during the colder months.

2.4 Impacts of the Sea Breeze

The sea- breeze circulation may cause physical impacts such as flooding and erosions near the coastline, as well as farther inland. When the thermal forcing is strong across the coastline, there will be upward motion over land associated with the thermal low. This uplift may initiate the presence of a sea breeze boundary. This is created by the convergence of the winds near the boundary, which often condenses and forms clouds (Simpson, 1994). This kind of upward motion creates cumulus clouds that are associated, in general, with precipitation. If there is a relatively unstable atmosphere, this vertical development can be intensified and may produce heavy rainfall, lightning and coastal flooding. These types of thunderstorms tend to be localized and can deliver abundant amounts of rainfall in a short time, producing flash flooding (Abbott, 2012). In fact, most of the flood-related deaths in this region are caused by flash floods.

The study of the sea breeze along the U.S. Gulf Coast is important for forecasters because it helps them to determine where and how much precipitation will develop in specific areas. Throughout the coastline zone there are dense populations and a lot of tourism and recreational activities; therefore, knowledge of rainfall timing and distribution is important for economic reasons. Additionally, when the sea breeze triggers heavy rainfall, it is important to produce a precise flash flood warning in these areas. Moreover, the Gulf Coast contains a number of ports that can handle conditional traffic and its volume of cargo, such as: Port of Houston, Texas, Port of New Orleans, Louisiana, Biloxi Port, Mississippi and Pensacola Port, Florida; therefore, it is important to consider the weather conditions in these areas since their operations are dependent on weather conditions.

CHAPTER III

DATA AND METHODOLOGY

To accomplish this investigation, it was necessary to perform a synoptic, mesoscale, and surface observation analysis from 1991 to 2010. The methodology of this study was divided into four steps: analysis of synoptically benign days, satellite data analysis, surface observation analysis and statistical analysis. The study period was based on the availability of data that coincided with the four steps.

3.1 Identifying Synoptically Benign Days

A significant thermal difference between land and water marks the onset and development of the sea breeze system. Because there is a thermal gradient, the wind speed and direction will shift during the afternoon. Lyons and Olsson (1972) and Banfield (1991) found the sea breeze onset is detected by an upper return flow or a rapid change in wind direction during a 24-hour period. It was necessary to perform an analysis of the wind speed, since it is very influential in the development of these systems. A sea breeze usually occurs when mid and upper-level wind speed is low and/or there are days with no synoptic forcing. The main criterion for this research was to determine synoptically benign days, i.e. when there are weak synoptic winds. Once the strong synoptic events were rejected, quantifying the sea breeze patterns and frequency was more straightforward.

An evaluation of the wind speed at different atmospheric levels was conducted to identify and remove days with the presence of a frontal system within the study period (1991-2010). This assessment was performed from atmospheric rawindsonde data taken from the National Weather Service offices at Slidell, LA and Tallahassee, FL. These sites were chosen due to the availability of sounding data and its location near the coastline. The wind speeds were quantified at 850 hPa and 500 hPa levels. These levels were taken because data from 850 hPa offer synoptic details above the planetary boundary layer and data from 500 hPa provide information from mid-level winds (Dyer, 2009). To determine the synoptically benign days, the median wind speed values were calculated. As a result, if the wind speed was lesser than 7.7 ms^{-1} (15 knots) and 14.4 $m s^{-1}$ (28 knots) at 850 hPa and 500 hPa, respectively, that day was classified as a synoptically weak or benign day. The values for wind speed must be lower than the criteria for 00Z and 12Z for a particular day, and for 00Z for the subsequent day.

3.2 Identifying Sea-Breeze Days

Once the days with weak synoptic conditions were classified, the next step was to define the existence of a sea breeze development based on the presence of cumulus clouds along the coastline in the study area. Infrared (IR) and visible satellite imagery from Geostationary Operational Environmental Satellites (GOES) were used to identify cloud features associated with a sea breeze. The thermal-IR sensor was used because it measures heat emitted from an object during the day and night. This sensor helps to identify cloud types where high and deep clouds are depicted by white color (brighter surfaces) because they tend to be cooler. Low warm clouds and cloud elements were properly identified using visible sensor.

The archived satellite data were taken from National Climatic Data Center (NCDC) GIBBS: Global ISCCP (International Satellite Cloud Climatology Project) B1 Browse System. This data provide satellite imagery from 1979 to the present, which covered the study period for this analysis. ISCCP B1 contains a spatial resolution of about 10 km at the Equator and a temporal resolution of 3 hours, providing eight observations per day (NCDC, 2013). The hourly observations taken to monitor sea breezes development were at 1500 UTC, 1800 UTC and 2100 UTC. The development and frequency of cloud structures were evaluated with a focus on towering cumulus clouds or the HCRs. In a day with no defined strong synoptic forcing, a formation of clouds can be visible when the sun starts to heat up the land. In general, clear sky over the water and cloudy over the land is the best indicator of a mesoscale sea-breeze front.

Examples of a sea-breeze development day are July 7, 1993 and July 19, 2002 (Figures 3.1–3.2). The infrared imagery demonstrated fair weather conditions with few or no clouds over the study area at 1445 UTC. The formation of cloud streets or the HCRs was more noticeable in the visible image. On the other hand, days such as May 31, 1993 and September 24, 1993 were rejected and classified as a non-sea breeze day because they did not show any coastline convection or a synoptic event through the study area (Figures 3.3–3.4). The sounding analysis performed in the first step had to remove the synoptically scale systems based on the wind speed. However, it was possible to have some of these systems along the study area. Therefore, this method served as a second step of quality control.

Performing this analysis led to certain limitations in spatial and temporal resolution. Data were only analyzed at 1500 UTC, 1800 UTC and 2100 UTC, therefore it was difficult to detect the development and strengthening of a sea breeze circulation with precision. 2009 was a year with a large number of missing data, and the transition from one satellite sensor to another led to missing data.

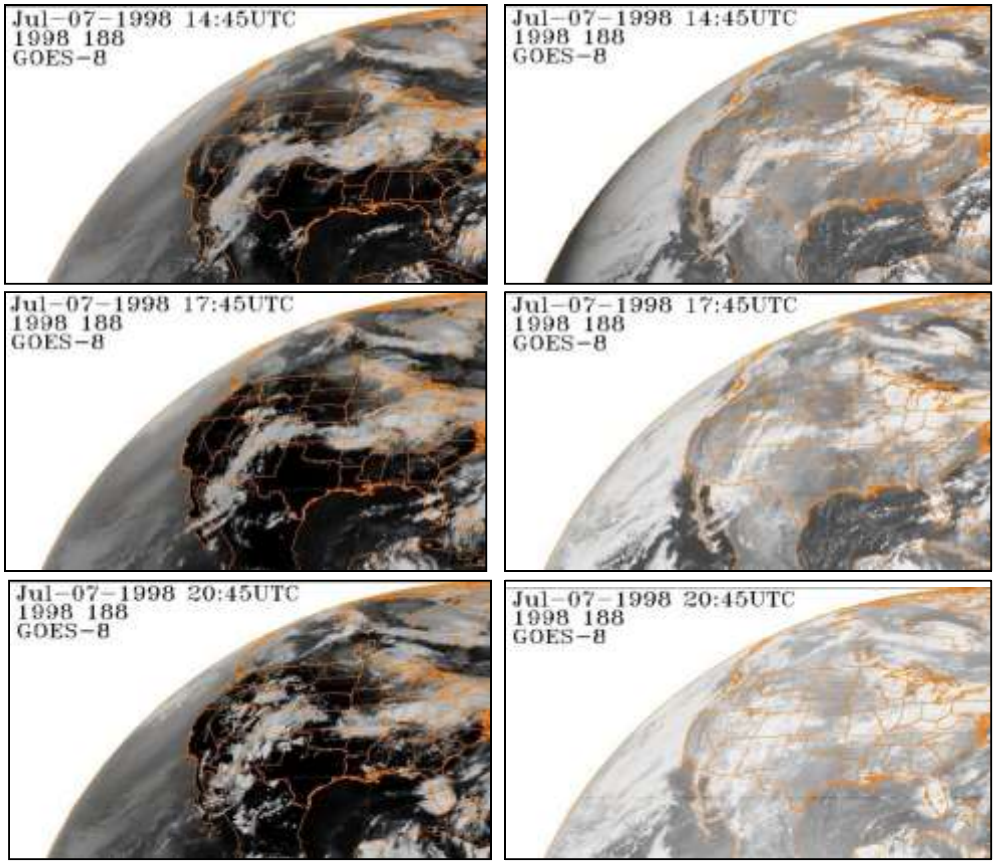


Figure 3.1 Example of sea breezes along the U.S. Gulf Coast for July 7, 1998 at 1445, 1745 and 2045 UTC

Infrared (Left) and visible (Right) satellite imagery.

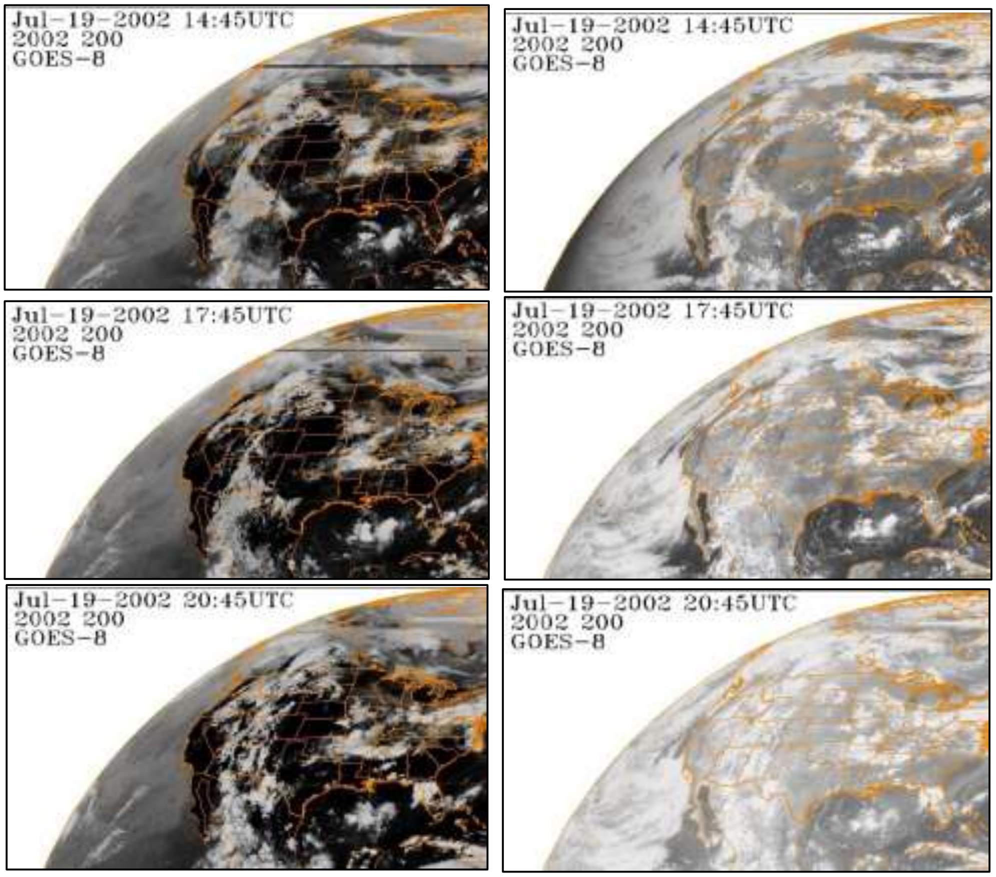


Figure 3.2 Example of sea breezes along the U.S. Gulf Coast for July 19, 2002 at 1445, 1745 and 2045 UTC

Infrared (Left) and visible (Right) satellite imagery.

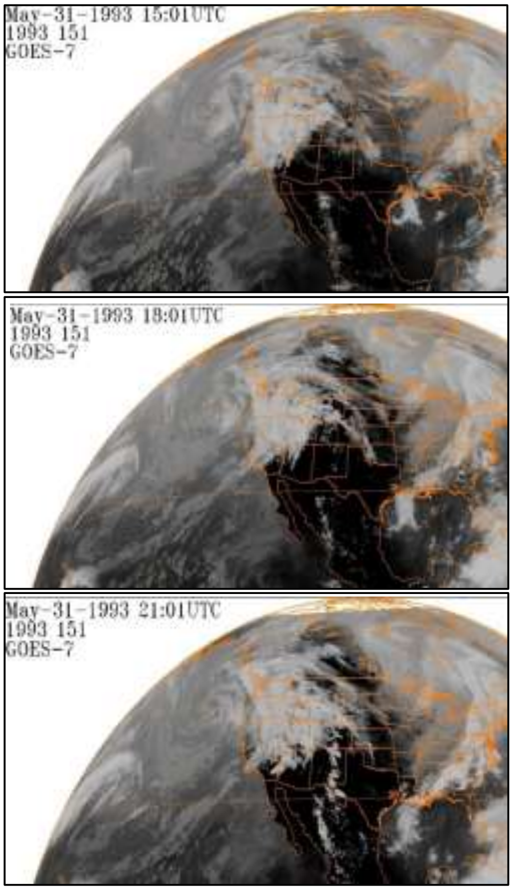


Figure 3.3 Example of a day not classified as a sea-breeze day

Infrared satellite imagery for May 31, 1993 at 1501, 1801 and 2101 UTC.

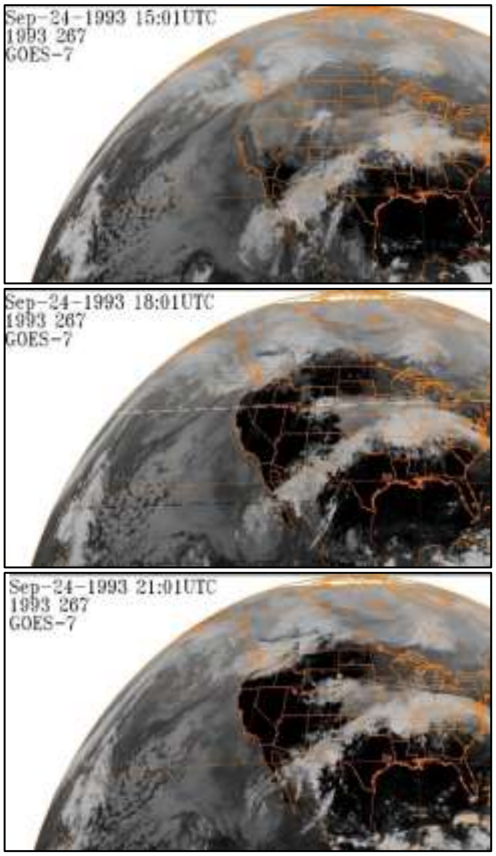


Figure 3.4 Example of a day not classified as a sea-breeze day

Infrared satellite imagery for September 24, 1993 at 1501, 1801 and 2101 UTC.

3.3 Surface Observation Analysis

After defining days when a sea breeze was present within the Gulf Coast study area, the environments in which these sea breezes developed was defined. This required an analysis of surface temperature, wind speed, and wind direction to recognize the onset of sea breezes during synoptically benign days.

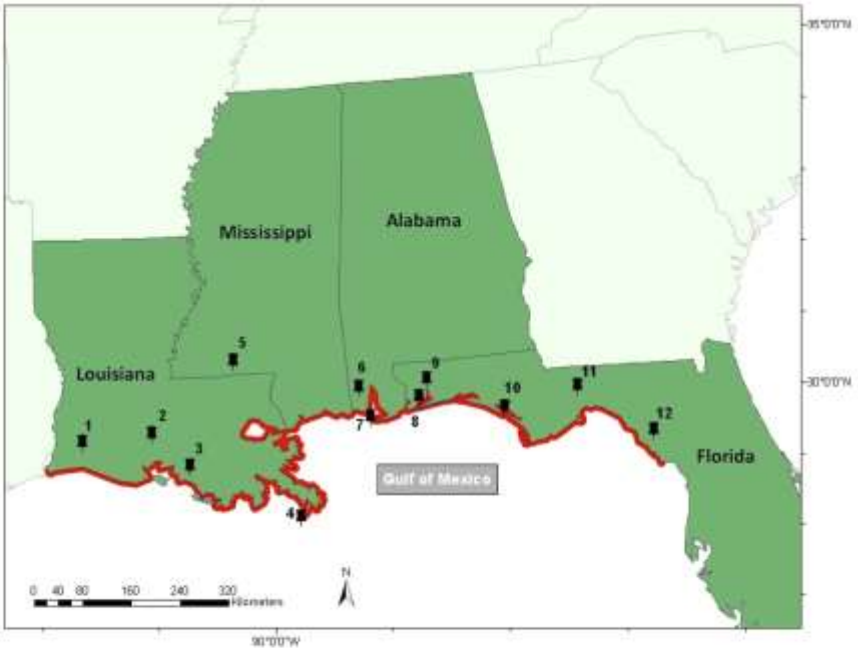


Figure 3.5 ASOS site locations used for this study

(1) Lake Charles, LA; (2) Lafayette, LA; (3) Harry P Williams, LA; (4) Southwest, LA; (5) McComb Pike, MS; (6) Mobile/Bates, AL; (7) Dauphin Island, AL; (8) Pensacola, FL; (9) Whiting, FL; (10) Panama City Bay, FL; (11) Tallahassee, FL; (12) Cross City, FL.

Data were collected from Automated Surface Observing System (ASOS) sites from the National Weather Service offices within the study area. ASOS data provide hourly values and continuous data essential for this study. There are twelve sites along the study area that are located close to the coastline (Figure 3.5). The identification and information for each station are detailed in Table 3.1. Fourteen stations were initially selected for this study; however, two stations were rejected due to lack of data (i.e. Hattiesburg, Mississippi (Station ID: 722348 99999), and Bob Sikes, Florida (Station ID: 722215 13884). Mississippi has only one station and it is located farther inland. McComb Pike station was the only station in Mississippi closer to the coast and with considerable amount of data. Even though it is located at roughly 145 km of distance from the coast, this station was selected because a sea breeze development can penetrate an inland distance up to 300 km.

A 24-hour (from 00 UTC to 2400 UTC) period was selected to evaluate the environments per hour and per day. From the 24-hour period, a selected time period from 0800 LST to 1400 LST (8:00 am to 2:00 pm) was chosen to define the environmental characteristics of sea breezes prior its onset. This period from the early morning to the onset of the sea breeze was designated to be consistent in time between the satellite imagery and the ASOS data. The variables of surface temperature, wind speed and wind direction were analyzed for each station and an average per hour was performed to obtain the 24-hour cycle for a specific station. This analysis was evaluated for those days with possible sea-breeze development obtained during the second step. The same method was performed for synoptically benign days with non-sea breeze development for comparison with the conditions associated with a sea-breeze development.

Table 3.1 Detailed information of the stations used for the surface observations

Station	ID Number	State	Latitude	Longitude
1. Lake Charles Muni	722400 03937	Louisiana	30.125°	-93.228°
2. Lafayette Regional	722405 13976	Louisiana	30.205°	-91.988°
3. Harry P Williams	722329 99999	Louisiana	29.717°	-91.333°
4. Southwest Pass	994010 99999	Louisiana	28.9°	-89.433°
5. McComb Pike Co Joh	722358 93919	Mississippi	31.183°	-90.471°
6. Mobile/Bates Field	722230 13894	Alabama	30.688°	-88.246°
7. Dauphin Island	994420 99999	Alabama	30.25°	-88.083°
8. Pensacola Regional	722223 13899	Florida	30.478°	-87.187°
9. Whiting Field Nas Nort	722226 93841	Florida	30.717°	-87.017°
10. Panama City Bay	722245 99999	Florida	30.212°	-85.683°
11. Tallahassee Municip	722140 93805	Florida	30.393°	-84.353°
12. Cross City	722120 12833	Florida	29.633°	-83.105°

Calculating the average of wind direction was different because this type of direction is based on a circular frame of reference (0° to 360°). Therefore, the directional mean for these values was calculated. The directional mean for wind direction (θ_R) is the arctangent of the absolute value of the sum of sine of each value divided by the sum of cosine (Equation 3.1).

$$\theta_R = \arctan\left|\frac{\sum_{i=1}^{n} \sin\theta_i}{\sum_{i=1}^{n} \cos\theta_i}\right| \tag{3.1}$$

In this study, 0° and 360° was defined as north, 90° was east, 180° was south and 270° was west. To determine the quadrant of the resultant, the absolute value of the ratio was used (Table 3.2).

Table 3.2 Method to determine the resultant bearing of the directional mean.

CONDITION	**QUADRANT**
$\sum_{i=1}^{n} sin\theta_i \geq 0$ and $\sum_{i=1}^{n} cos\theta_i \geq 0$	First: northeast θ_R can be used directly
$\sum_{i=1}^{n} sin\theta_i \geq 0$ and $\sum_{i=1}^{n} cos\theta_i < 0$	Second: southeast 180° - θ_R
$\sum_{i=1}^{n} sin\theta_i < 0$ and $\sum_{i=1}^{n} cos\theta_i < 0$	Third: southwest 180° + θ_R
$\sum_{i=1}^{n} sin\theta_i < 0$ and $\sum_{i=1}^{n} cos\theta_i \geq 0$	Fourth: northwest 360° - θ_R

An examination of the standard deviation per station and per variable was calculated to complete the first objective. With this test, the variability of the average temperature, wind speed and wind direction was analyzed to determine and define how these variables changes throughout a sea breeze day. The standard deviation was determined assuming a normal distribution for temperature and wind speed values. The variability for the wind direction data was performed different because this variable is a directional observation. Therefore, it was necessary to calculate the circular variance (Equation 3.2) because it is related to the length of the resultant vector (hourly directional mean).

$$\mathbf{OR} = [(\textstyle\sum_{i=1}^{n} sin\theta_i)^2 + (\textstyle\sum_{i=1}^{n} cos\theta_i)^2]^{1/2} \qquad (3.2)$$

3.4 Statistical Analysis

After completing the surface observations analysis, the environmental characteristics for a sea breeze day were defined. The next objective was to compare the difference between a sea breeze day and a non-sea breeze day. This analysis was completed by performing a statistical analysis, which compare the significance of the average temperature, wind speed and wind direction per station between a sea breeze day and a non-sea breeze day datasets.

The values of temperature are normally distributed but the values of wind speed are gamma distributed. Moreover, there were two samples (sea breeze and non-sea breeze day) with different sizes. Therefore, a nonparametric resampling tests, the permutation test means, were run by using a 95% confidence interval and a rejection level of $\alpha = 0.05$. Resampling tests build up a discrete approximation to the null distribution by repeatedly operating on the data set at hand (Wilks, 2011). A resampling of all data collected for both datasets (sea breeze and non-sea breeze days) was performed to obtain an estimation of the population distribution. The average daily values of temperature, wind speed and wind direction were sampled with replacement 1000 times until all possible scenarios were exhausted for all samples to obtain a p-value.

3.4.1 Hypothesis

Null hypothesis (H_0):

1. The values of the average surface temperature, average wind speed and average wind direction across the stations between sea breeze days and non sea breeze days are not significantly different.

Alternate hypothesis (H_A):

1. The values of the average surface temperature, average wind speed and average wind direction across the stations between sea breeze days and non- sea breeze days will be statistically significantly different.

The data are statistically significantly different when the *p-value* is less than 0.05; therefore, the null is rejected.

CHAPTER IV

RESULTS

4.1 Synoptically Benign Days

For the period of 1991 to 2010, a total of 6,508 days were evaluated using rawindsonde data from the Slidell, LA and Tallahassee, FL stations. From these days, only 1,255 met the criteria for a synoptically benign day (Figure 4.1). The largest frequency of synoptically benign days was found during the warm season with 1,094 days (Figure 4.2). This result was expected because synoptic forcings, such as midlatitudes cyclones, are usually north of the study area during the warm season.

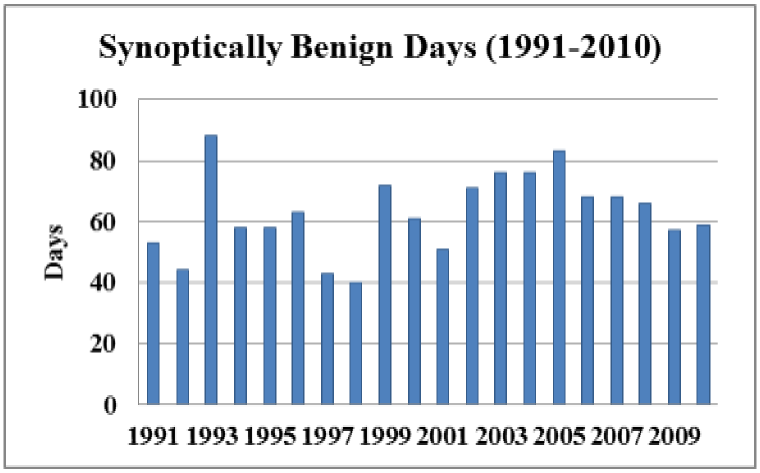


Figure 4.1 Annual distribution of synoptically benign days

A total of 1,255 synoptically benign days were identified from 1991 to 2010.

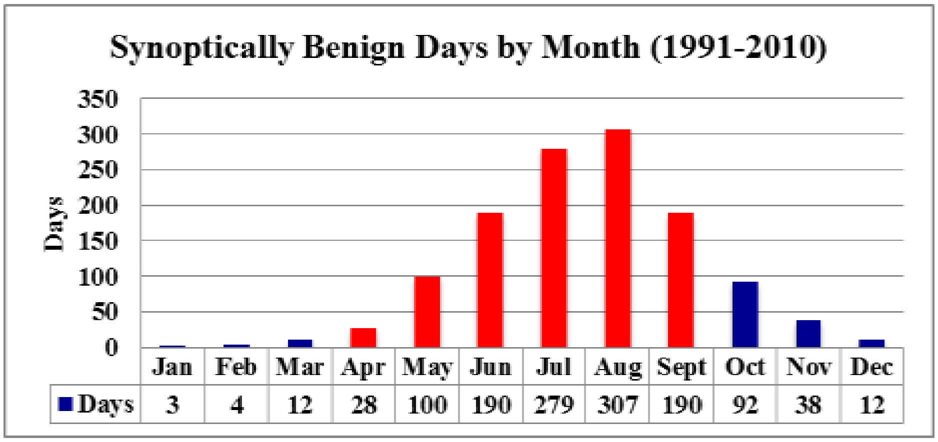


Figure 4.2 Synoptically benign days classified by month

Blue and red bars are depicting cold and warm seasons, respectively.

4.2 Sea breeze days

Only 161 of 1,255 synoptically benign days were identified as a sea breeze day (Figure 4.3). The development of sea breezes along the U.S. Gulf Coast were more evident during the warm season with a peak in August. The years that experienced more sea breezes were 1992 and 1993, both with 20 events, and 2005 with 18 events (Figure 4.4).

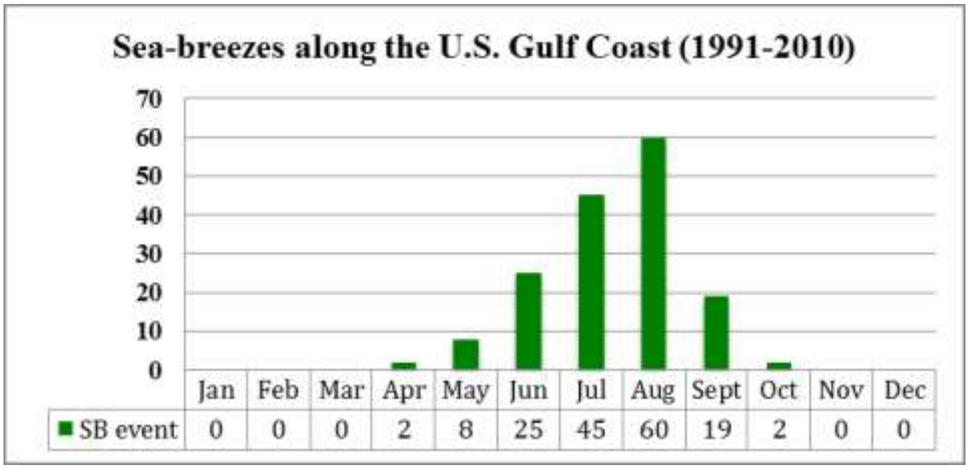


Figure 4.3 Monthly distribution of sea breezes along the U.S. Gulf Coast from 1991 to 2010.

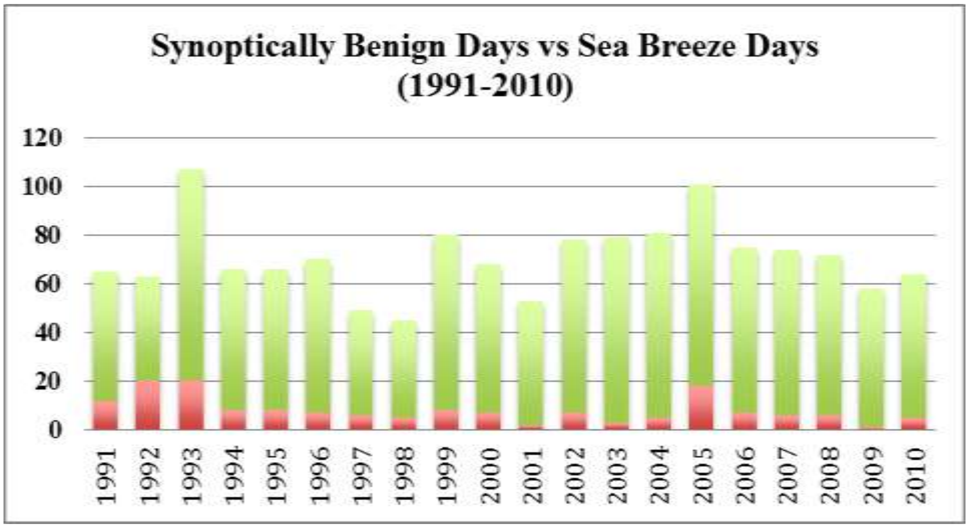


Figure 4.4 Annual Distribution of synoptically benign days (green bars) and sea breeze days (red bars)

4.3 Surface Environmental Characteristics

During a sea breeze day, the ranges in the average temperature for each state were: Louisiana from 27.1° to 28.4 °C, Mississippi with 26.5 °C, Alabama from 27.2° to

28.3 °C, and Florida from 27.1° to 28.5 °C (Figure 4.5–4.16). The largest range in temperature was found at McComb Pike station in Mississippi with a minimum value of 21.3 °C and a maximum value of 33.3 °C. This station is located in an estimated distance of 145 km from the Mississippi coastline with respect to the other stations; therefore it is less influenced by a potential sea breeze. For all stations, the variability in the average temperature was low in the morning but increased in the afternoon (starting around 1400 LST). All stations experienced variability in temperature of around -16.0 ºC (4.0 ºF) from 0800 LST to 1400 LST, except for Southwest Pass. This station obtained displayed a constant variability of -14.0 ºC (7.0 ºF) throughout the day. Overall, in a sea breeze day, the average temperature increased rapidly in the morning (after 8:00 am), and had a larger variability in the afternoon (after 2:00 pm approximately).

The average hourly wind speed varied from 0 ms^{-1} to 3.8 ms^{-1} for the twelve stations. During a sea breeze day, stations in Louisiana recorded average wind speeds values between 1.8–3.8 ms^{-1}, while Mississippi stations recorded an average wind speed of 1.5 ms^{-1}. The range in Alabama was from 2.3 ms^{-1} to 3.5 ms^{-1}, and the Dauphin Island station documented the highest wind speed value for this state. Florida stations had a range of 1.6 ms^{-1} to 2.7 ms^{-1}. Overall, the magnitude of the wind speed was dependent on the distance of the station from the coast where high values of wind speed occurred in stations near the land-water boundary. The variability in wind speed was high throughout the day for all stations.

Generally, during a sea breeze day the wind direction shifted between the morning and the afternoon for all stations. The wind direction in Lake Charles changed from east in the morning to south-southwest in the afternoon. The direction in Lafayette and Harry P Williams changed from north-east to south-southwest. The wind direction in Southwest Pass shifted from south at 7:00 am to north at 9:00am. In the afternoon, the wind direction came predominantly from south-east. In Mississippi, the wind came from the north-northwest in the morning, and from the south-southwest in the afternoon. The direction of the wind in Alabama came from north-west to south-west in Mobile/Bates, and from north in the morning to south in the afternoon for Dauphin Island. In Pensacola and Whiting stations at Florida, the wind direction came predominantly from north-west in the morning to south-west in the afternoon. Panama City, Tallahassee, and Cross City received, in general, the same direction of the wind, i.e. from north-east in the morning to south-west in the afternoon. Even though the shift in the wind direction was evident for all stations for a sea breeze day, the variability was different. Almost all stations had a low variability in the wind direction. Among all variables, wind direction had a lot of missing values, leading to a reduction in the sample size (Table 4.1 and 4.2). For this reason, the variability in wind direction was quite small. These results generated uncertainty in the reliability of these wind pattern consideration.

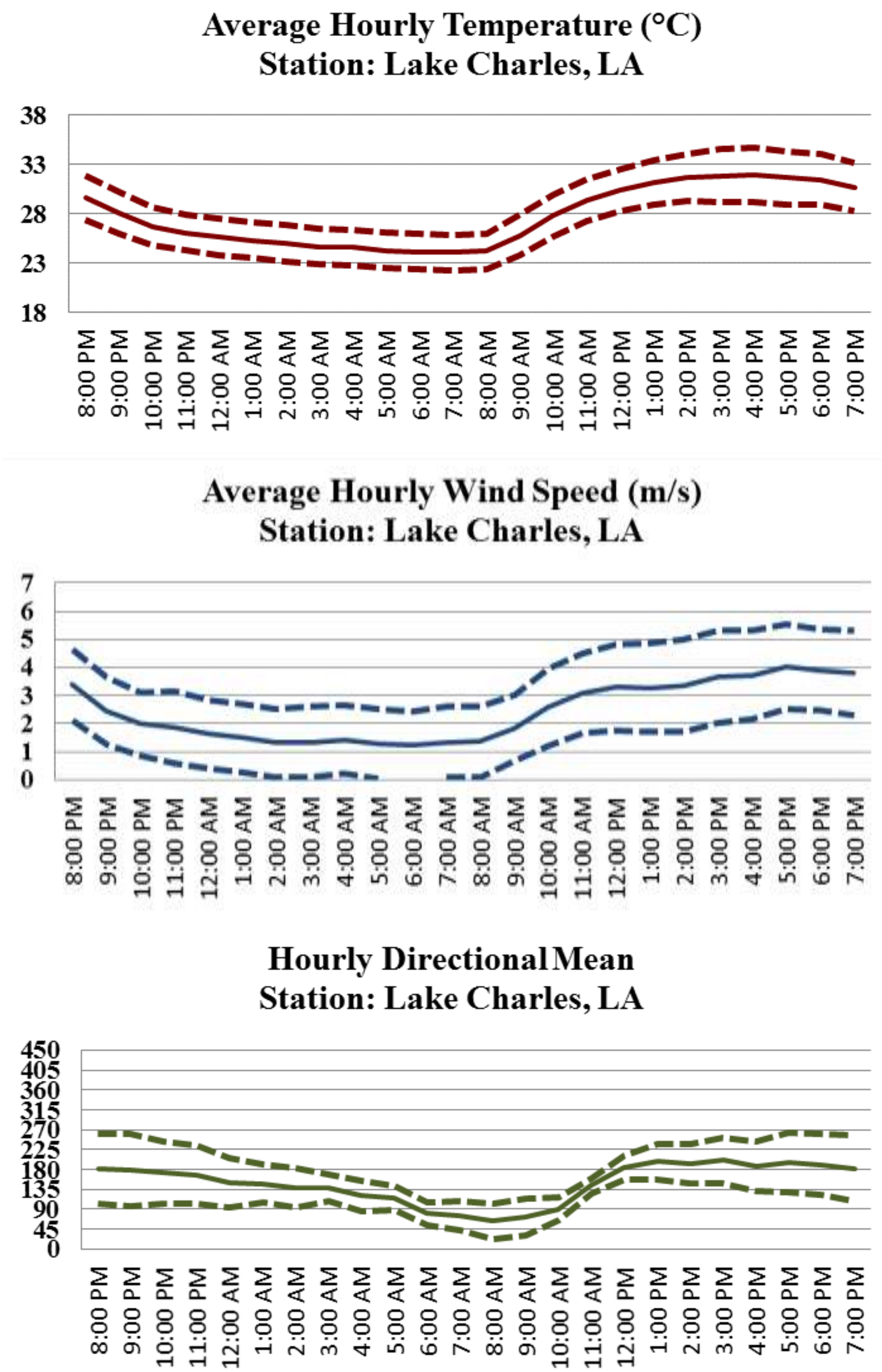


Figure 4.5 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Lake Charles station in a sea breeze day.

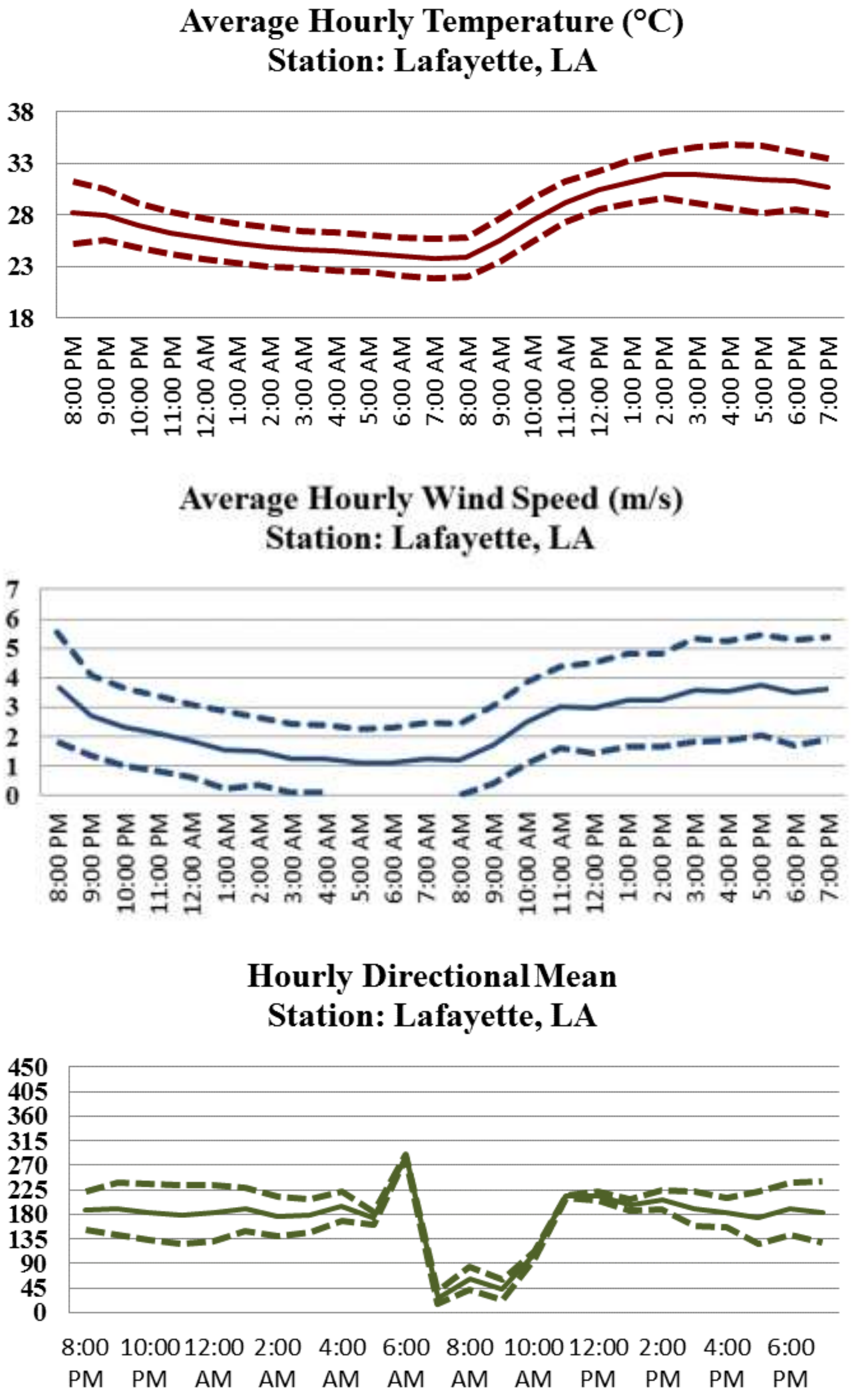
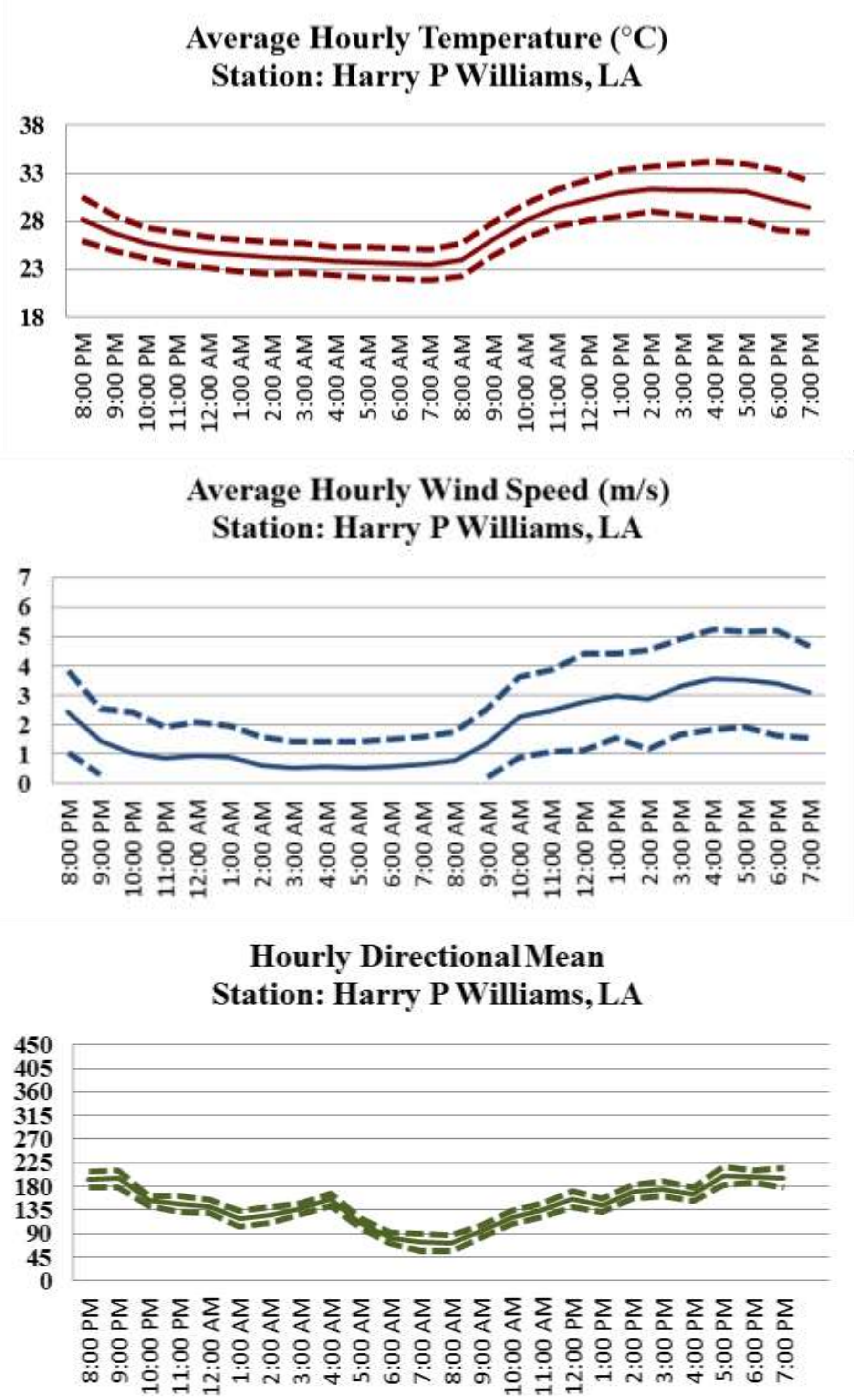


Figure 4.6 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Lafayette station in a sea breeze day.


Average Hourly Temperature (°C)
Station: Harry P Williams, LA

Average Hourly Wind Speed (m/s)
Station: Harry P Williams, LA

Hourly Directional Mean
Station: Harry P Williams, LA

Figure 4.7 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Harry P Williams station in a sea breeze day.

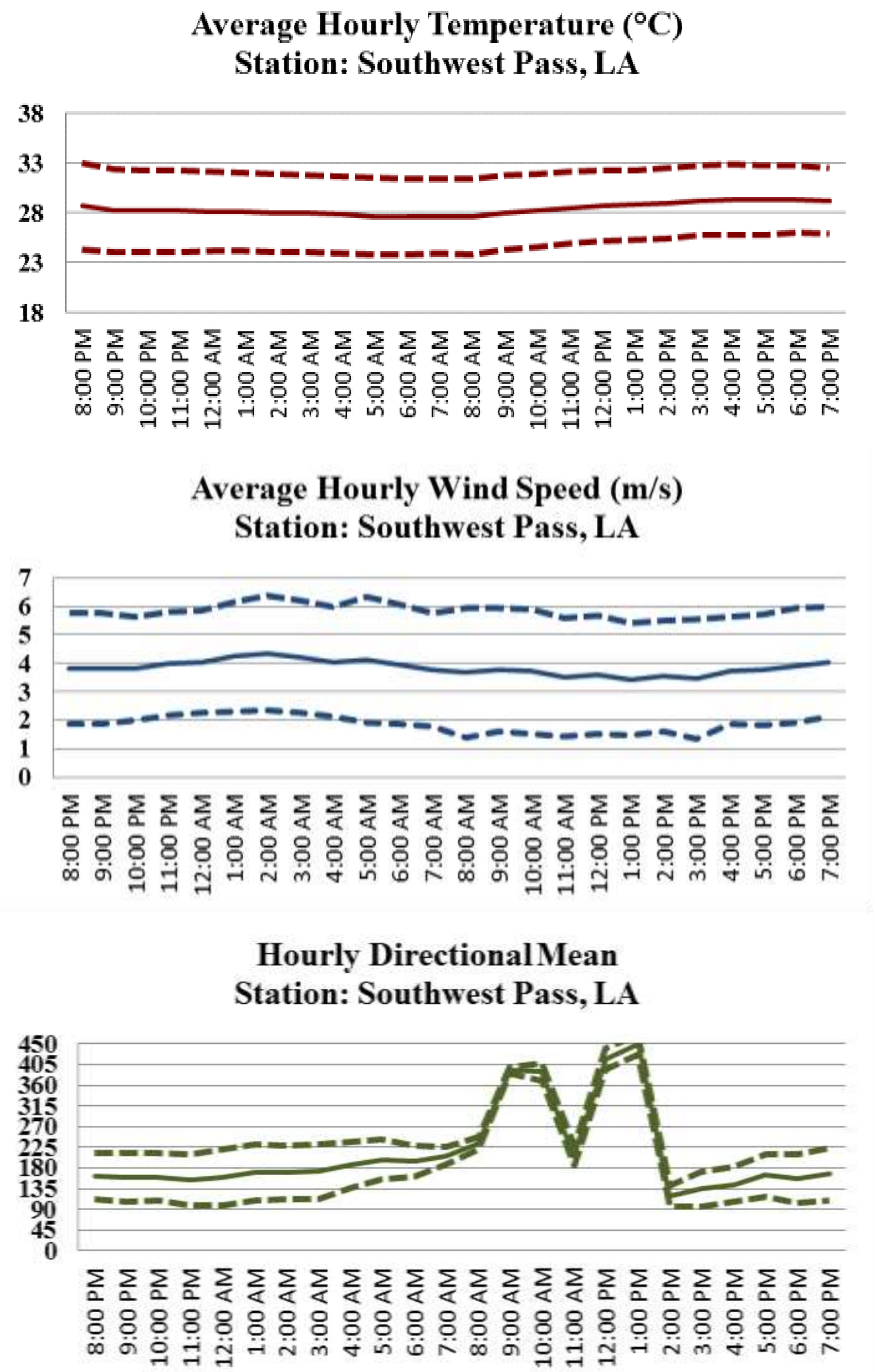


Figure 4.8 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Southwest Pass station in a sea breeze day.

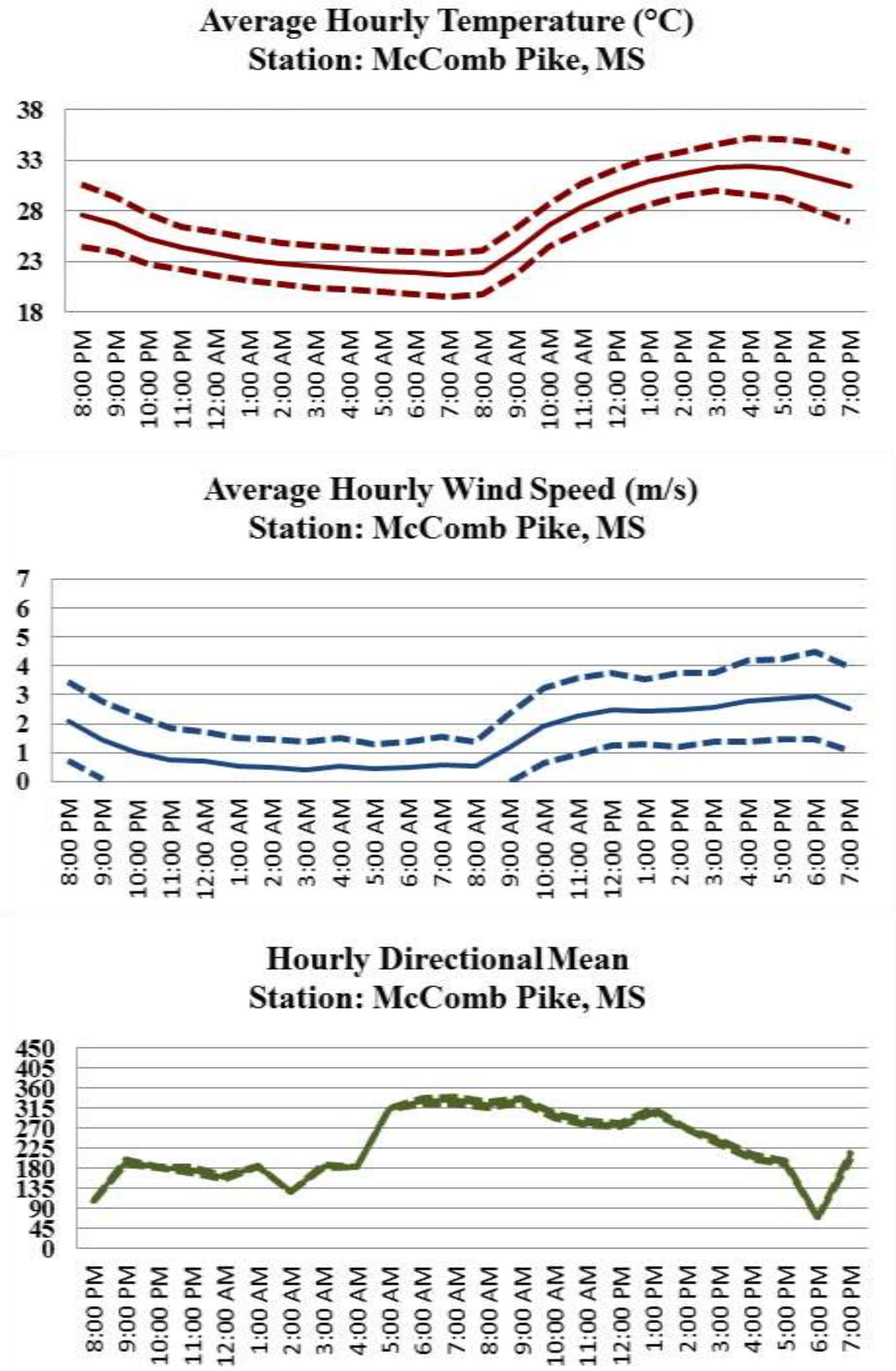


Figure 4.9 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for McComb Pike station in a sea breeze day.

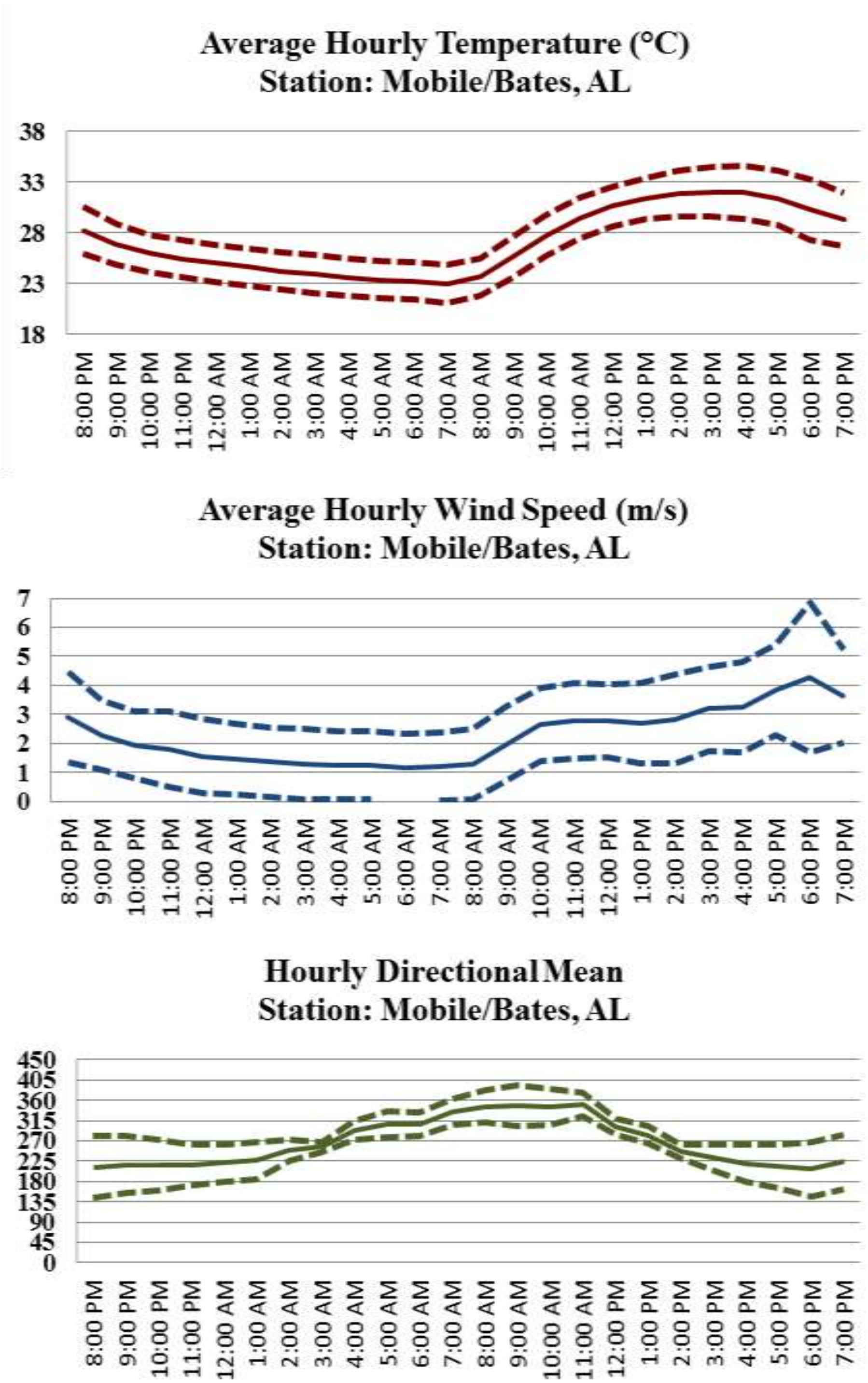


Figure 4.10 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Mobile/Bates station in a sea breeze day.

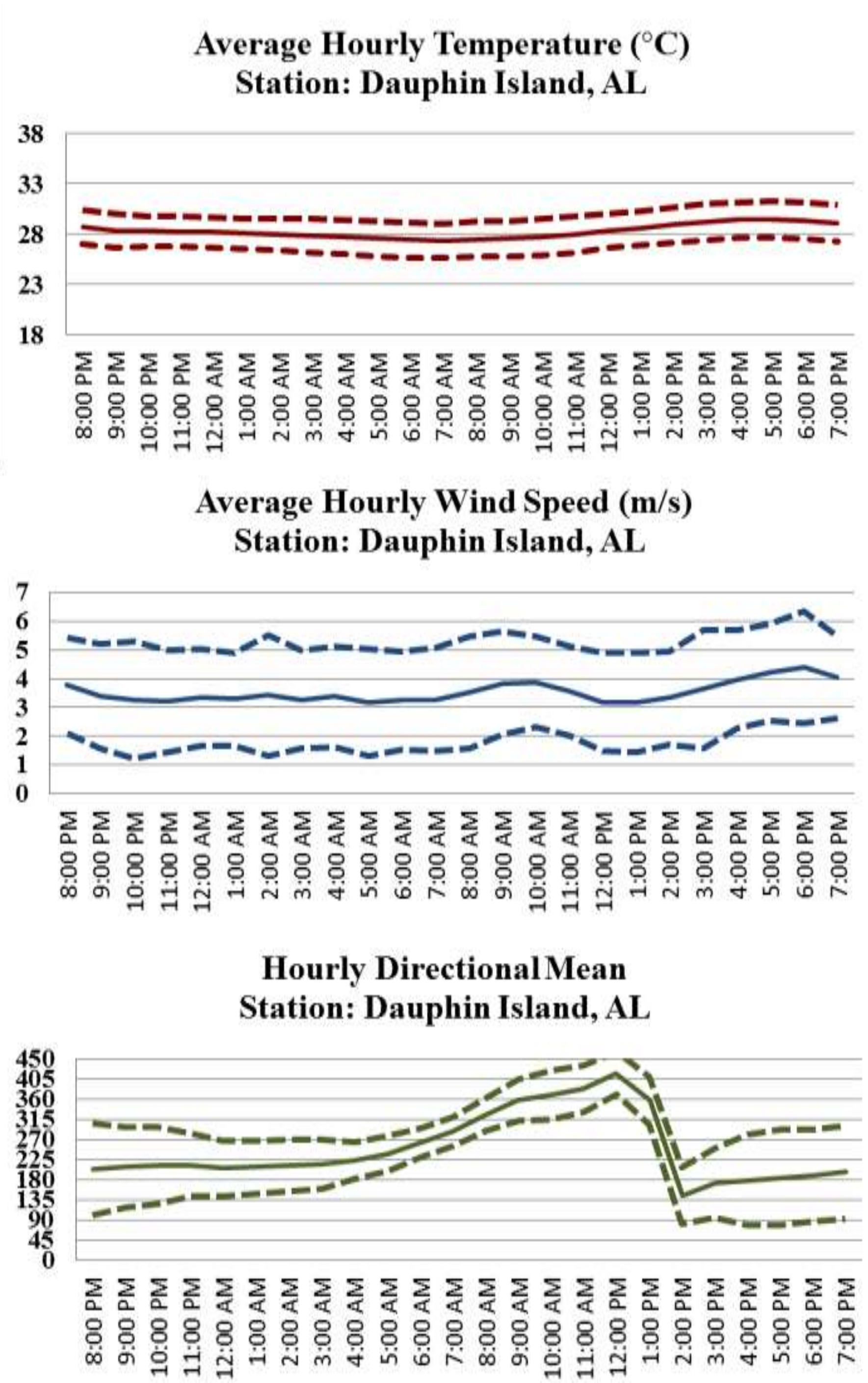
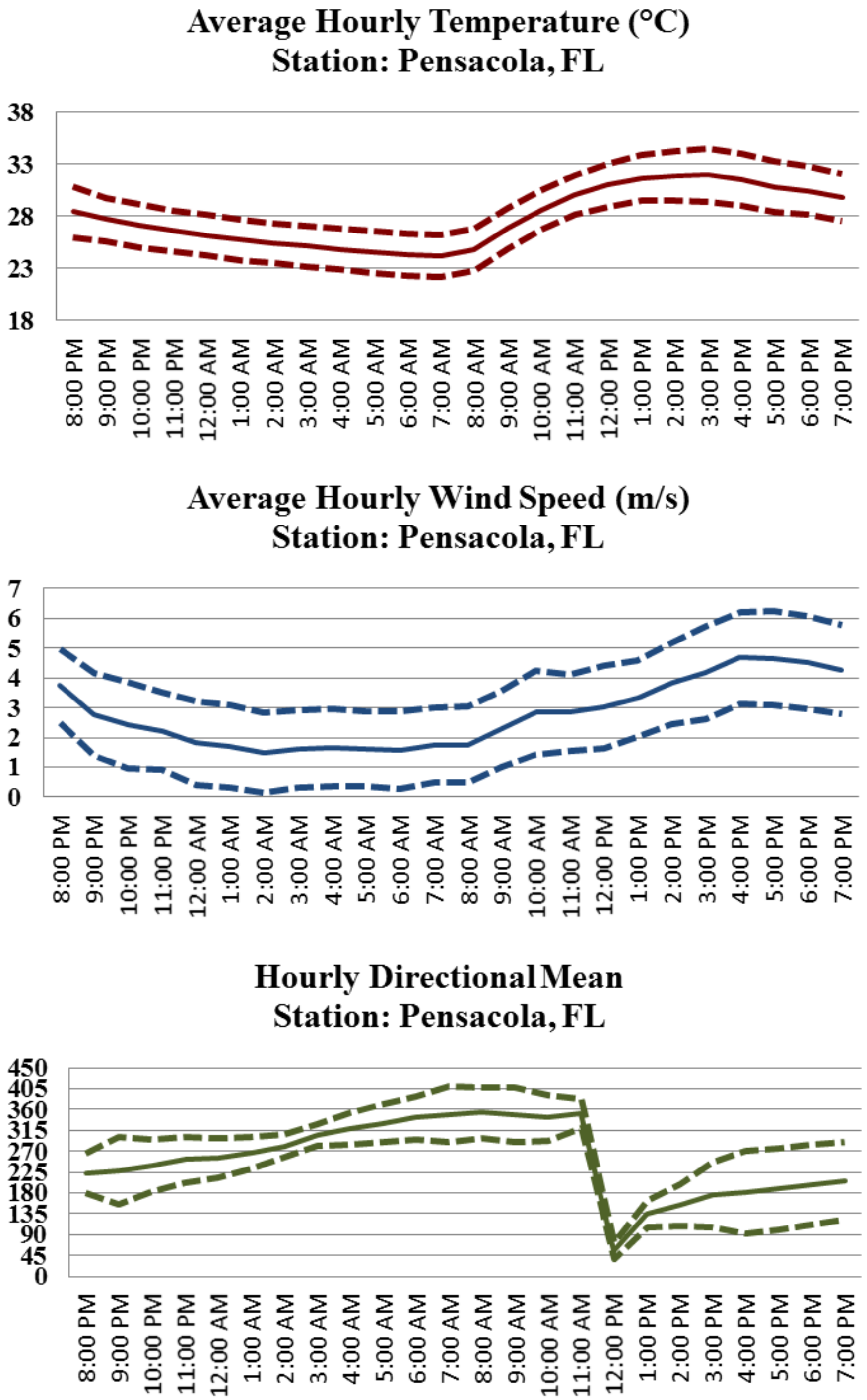


Figure 4.11 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Dauphin Island station in a sea breeze day.



Average Hourly Temperature (°C)
Station: Pensacola, FL

Average Hourly Wind Speed (m/s)
Station: Pensacola, FL

Hourly Directional Mean
Station: Pensacola, FL

Figure 4.12 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Pensacola station in a sea breeze day.

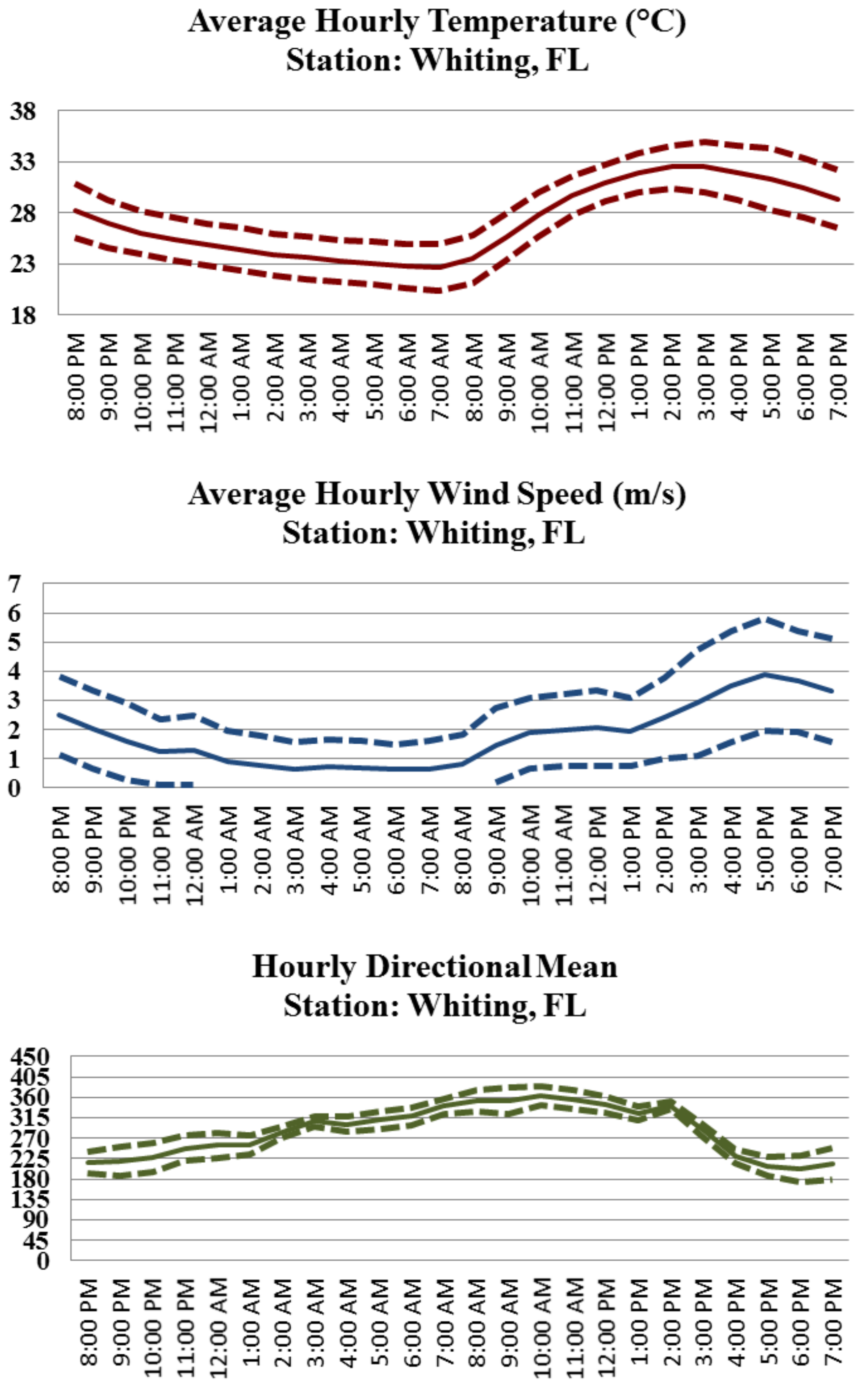


Figure 4.13 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Whiting station in a sea breeze day.

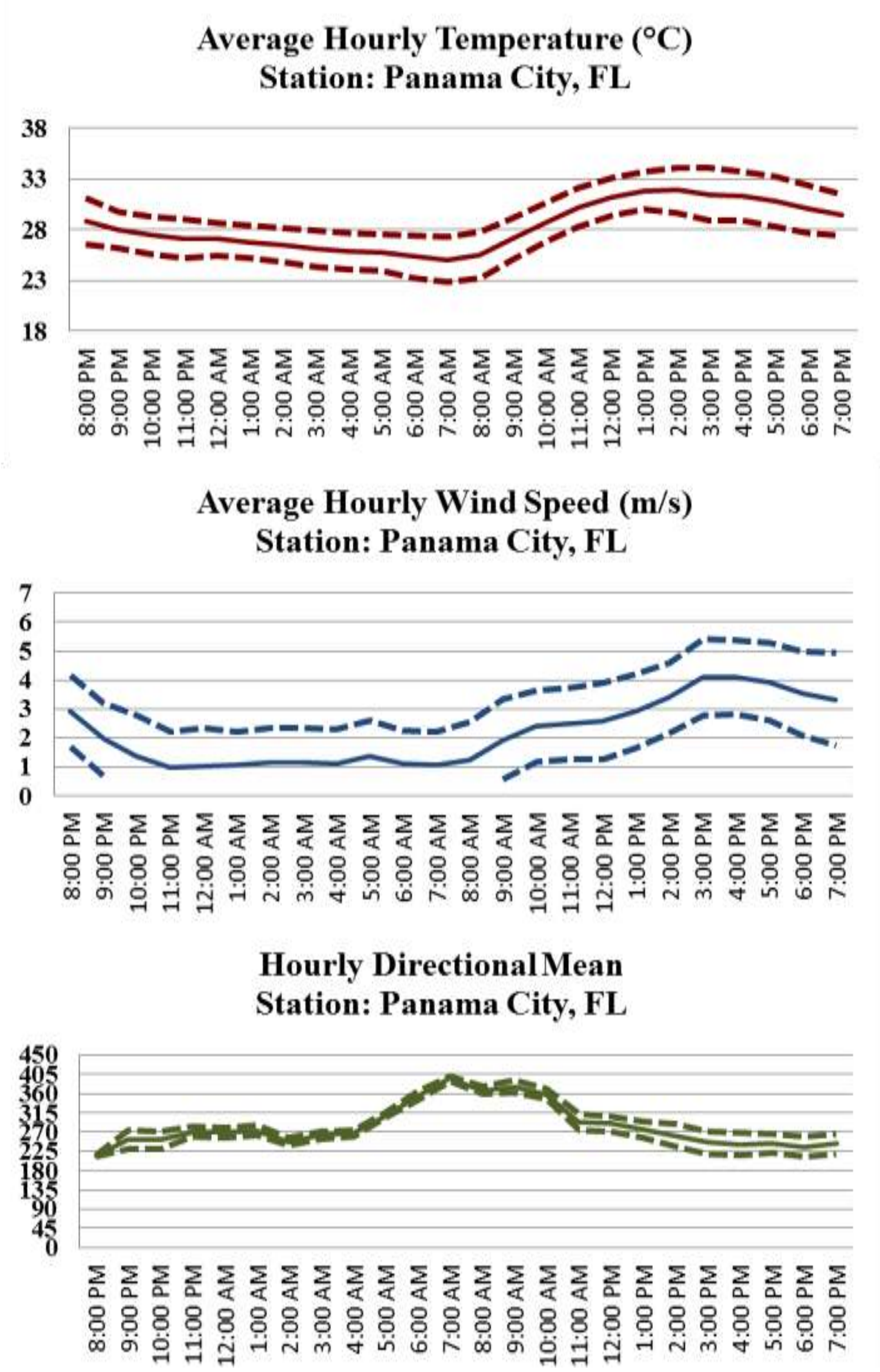
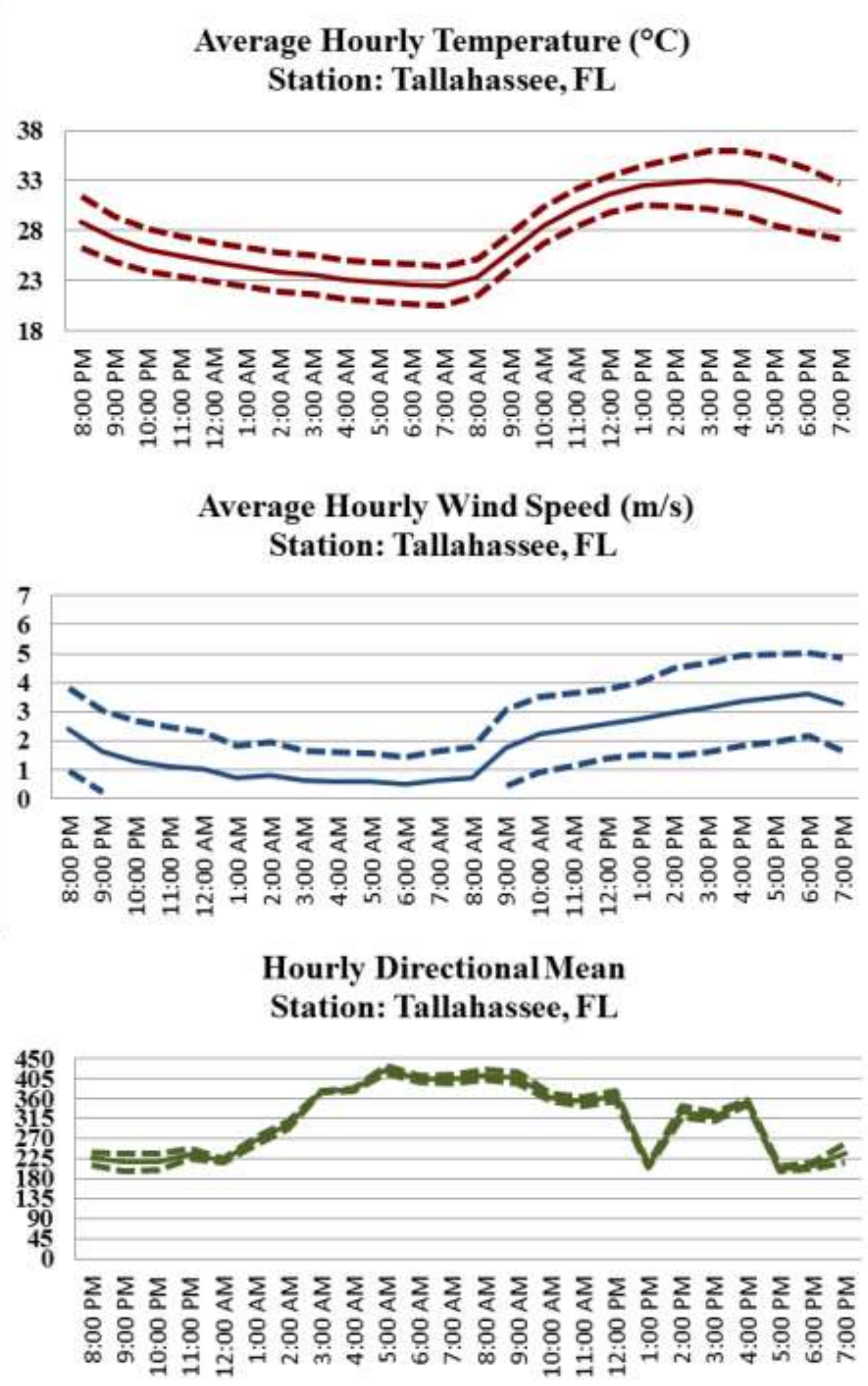


Figure 4.14 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Panama City station in a sea breeze day.



Average Hourly Temperature (°C)
Station: Tallahassee, FL

Average Hourly Wind Speed (m/s)
Station: Tallahassee, FL

Hourly Directional Mean
Station: Tallahassee, FL

Figure 4.15 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Tallahassee station in a sea breeze day.

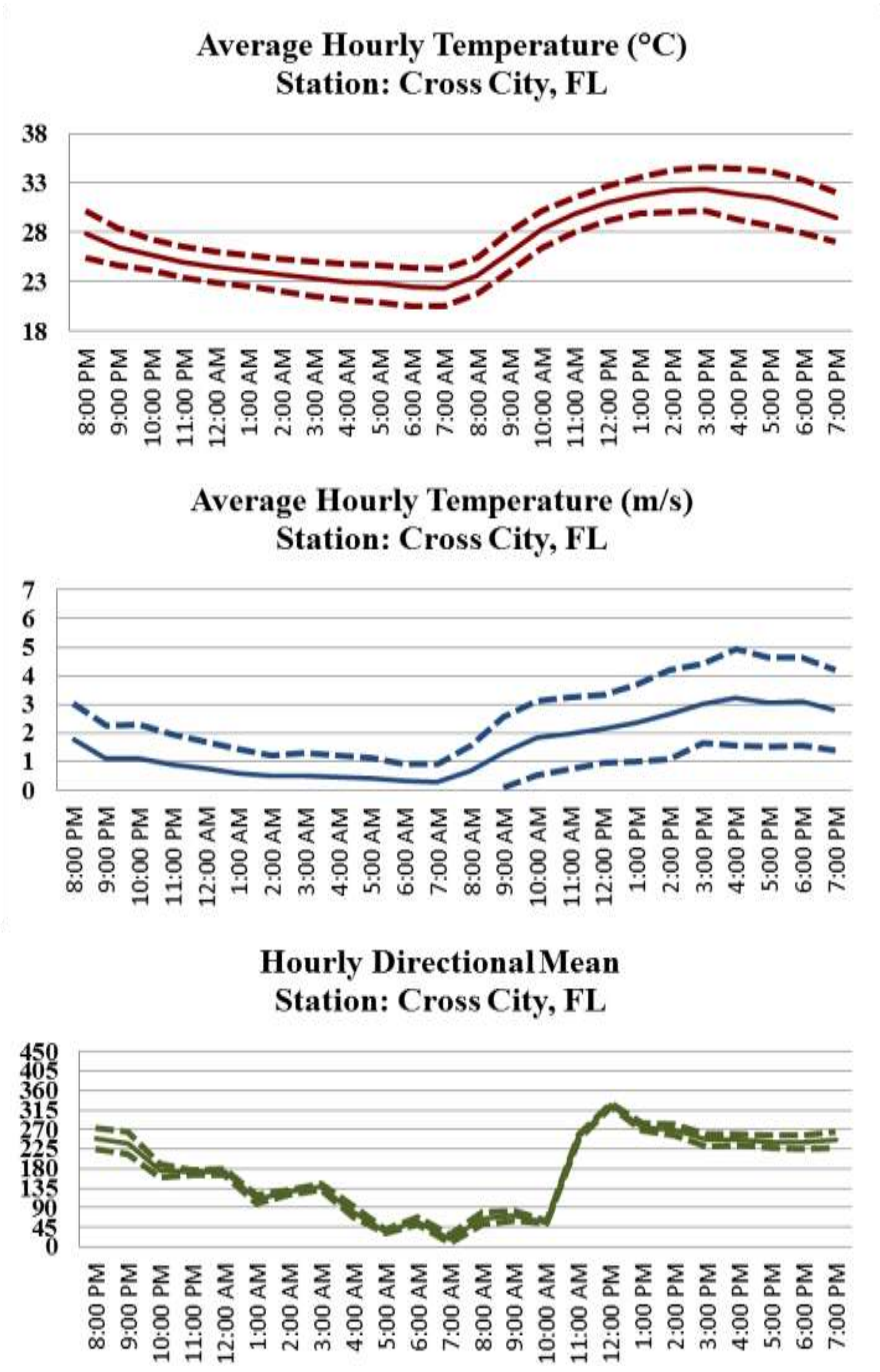


Figure 4.16 Average hourly surface observations (solid lines) and range of +/- one standard deviation (dashed lines) for Cross City station in a sea breeze day.

Table 4.1 Classification of total number of days with viable surface data (per station) for the sea breeze dataset.

Sea Breeze Days		
Station	**Total Number of Days**	**Total Number of Data Available**
Lake Charles	159	Temperature Data: 159
		Wind Speed Data: 159
		Wind Direction Data: 119
Lafayette	159	Temperature Data: 157
		Wind Speed Data: 110
		Wind Direction Data: 128
Harry P Williams	144	Temperature Data: 113
		Wind Speed Data: 118
		Wind Direction Data: 115
Southwest Pass	151	Temperature Data: 140
		Wind Speed Data: 140
		Wind Direction Data: 140
McComb Pike	161	Temperature Data: 153
		Wind Speed Data: 150
		Wind Direction Data: 30
Mobile/Bates	159	Temperature Data: 158
		Wind Speed Data: 117
		Wind Direction Data: 158
Dauphin	154	Temperature Data: 154
		Wind Speed Data: 154
		Wind Direction Data: 154
Pensacola	159	Temperature Data: 159
		Wind Speed Data: 159
		Wind Direction Data: 128
Whiting	152	Temperature Data: 128
		Wind Speed Data: 127
		Wind Direction Data: 63
Panama City	150	Temperature Data: 108
		Wind Speed Data: 104
		Wind Direction Data: 44
Tallahassee	159	Temperature Data: 157
		Wind Speed Data: 157
		Wind Direction Data: 64
Cross City	140	Temperature Data: 137
		Wind Speed Data: 127
		Wind Direction Data: 55

Table 4.2 Classification of total number of days with viable surface data (per station) for the non-sea breeze dataset.

Non-Sea Breeze Days		
Station	**Total Number of Days**	**Total Number of Data Available**
Lake Charles	1092	Temperature Data: 1087
		Wind Speed Data: 1087
		Wind Direction Data: 796
Lafayette	1098	Temperature Data: 1090
		Wind Speed Data: 1091
		Wind Direction Data: 731
Harry P Williams	964	Temperature Data: 844
		Wind Speed Data: 851
		Wind Direction Data: 530
Southwest Pass	939	Temperature Data: 869
		Wind Speed Data: 856
		Wind Direction Data: 851
McComb Pike	1105	Temperature Data: 1079
		Wind Speed Data: 174
		Wind Direction Data: 361
Mobile/Bates	1090	Temperature Data: 773
		Wind Speed Data: 1089
		Wind Direction Data: 841
Dauphin	1086	Temperature Data: 1076
		Wind Speed Data: 1077
		Wind Direction Data: 1070
Pensacola	1090	Temperature Data: 769
		Wind Speed Data: 1075
		Wind Direction Data: 881
Whiting	1060	Temperature Data: 768
		Wind Speed Data: 759
		Wind Direction Data: 487
Panama City	1034	Temperature Data: 823
		Wind Speed Data: 833
		Wind Direction Data: 487
Tallahassee	1090	Temperature Data: 1090
		Wind Speed Data: 1090
		Wind Direction Data: 503
Cross City	988	Temperature Data: 930
		Wind Speed Data: 946
		Wind Direction Data: 436

4.4 Statistical Analysis: Permutation Test

After conducting the permutation tests with a 95% confidence interval, results suggested that the average daily temperature was the only variable statistically different (p-value < 0.05) for all stations (Table 4.3). Therefore, the null hypothesis was rejected, which led to the conclusion that the average temperature between sea breeze days and non-sea breeze days was different for all stations. Regarding wind speed, results showed that there were statistically significant difference between sea breeze days and non-sea breeze days for Southwest Pass and Dauphin Island stations. The null hypothesis cannot be rejected for the rest of the stations. Results for wind direction demonstrated that the data were not statistically significantly different for any of the stations.

In addition, permutation tests were performed only for the period of 8:00 am to 2:00 pm (0800 LST to 1800 LST) (Table 4.4). This method helped to compare atmospheric characteristics during the sea breeze development phase by analyzing the significance of each variable during the late morning and early afternoon. The null hypothesis that the average surface temperature is the same for a sea breeze and a non-sea breeze day could be rejected. This was because the p-values showed a statistically significant difference in temperature for all stations. The average wind speed indicated p-values below the rejection level (0.05) for all stations, except for Lake Charles, Lafayette, Mobile/Bates. Thus, the null hypothesis that the wind speed for both datasets is the same could not be rejected for these three stations. Sea breeze days and non-sea breeze days were not statistically significantly different for wind direction at any of the stations ($p < 0.05$).

Table 4.3 P-values obtained for each station.

Station	Temperature p-value	Wind Speed p-value	Wind Direction p-value
1. Lake Charles, LA	*0.00*	0.99	0.21
2. Lafayette Regional, LA	*0.01*	0.98	0.49
3. Harry P Williams, LA	*0.00*	0.16	0.90
4. Southwest Pass, LA	*0.02*	*0.00*	0.89
5. McComb Pike Co Joh, MS	*0.00*	0.86	0.99
6. Mobile/Bates Field, AL	*0.00*	0.94	0.51
7. Dauphin Island, AL	*0.00*	*0.01*	0.29
8. Pensacola Regional, FL	*0.00*	0.98	0.43
9. Whiting Field Nas Nort, FL	*0.00*	0.10	0.30
10. Panama City Bay, FL	*0.00*	0.41	0.12
11. Tallahassee Municip, FL	*0.00*	0.85	0.66
12. Cross City, FL	*0.00*	0.46	0.64

Values in italics indicate statistical significance at the 95% confidence level ($p < 0.05$).

Table 4.4 P-values obtained for each station within the period of 800-1400 LST.

Station	Temperature p-value	Wind Speed p-value	Wind Direction p-value
1. Lake Charles, LA	*0.00*	0.42	0.86
2. Lafayette Regional, LA	*0.01*	0.41	0.91
3. Harry P Williams, LA	*0.00*	*0.01*	0.96
4. Southwest Pass, LA	*0.02*	*0.00*	0.91
5. McComb Pike Co Joh, MS	*0.00*	*0.02*	0.98
6. Mobile/Bates Field, AL	*0.00*	0.89	0.94
7. Dauphin Island, AL	*0.00*	*0.01*	0.97
8. Pensacola Regional, FL	*0.00*	*0.06*	0.97
9. Whiting Field Nas Nort, FL	*0.00*	*0.00*	0.98
10. Panama City Bay, FL	*0.00*	*0.00*	0.65
11. Tallahassee Municip, FL	*0.00*	*0.00*	0.88
12. Cross City, FL	*0.00*	*0.00*	0.97

Values in italics indicate statistical significance at the 95% confidence level ($p < 0.05$).

CHAPTER V

DISCUSSION

5.1 Sea-breeze frequency

When synoptic conditions along the U.S. Gulf Coast are weak, the likelihood of sea breeze development is increased because most of the convection is developed by the diurnal heating. Results showed that this phenomenon was more noticeable during the warm season, which is reasonable because the land warms up faster during this period and a thermal low is created on the land surface. Overall, 161 out of 1,255 synoptically weak days were identified as a sea breeze day during 1991 to 2010.

5.2 Defining the environmental characteristics of sea breeze

The environmental characteristics of sea breezes along the U.S. Gulf Coast were defined by average temperatures between 26.5° to 28.5 °C throughout the day with an increase in the variability in the afternoon. The average wind speed for all stations had a high but constant variability where the values ranged from almost 0 ms^{-1} to 3.8 ms^{-1}. Previous research on sea breezes around the world indicated different ranges of wind speed values during the morning of a sea breeze day. Masselink and Pattiaratchi (1998) argued that the average wind speed along the Perth coastline is 5.7 ms^{-1} at 1500 LT (11:00 am). On the west coast of Sweden, the wind speed at 1200 LT (8:00 am) might oscillate between 4–5 ms^{-1}(Borne et al.,1998). Conversely, studies in Israel showed that the diurnal wind speeds were weak and variable until the onset of the sea breeze at 12:00 LT (8:00 am) (Lensky and Dayan, 2012). On the U.S. Gulf Coast, results showed that the average wind speed value was low but sufficient to aid in the development of a sea breeze in some locations. These values of surface wind speed prior to the onset of a sea breeze helped in the strengthening and development of the systems in some locations. In fact, Azorin-Molina et al. (2009) hypothesized that strong winds at the surface reduce the low-level convergence, prohibiting the development of a sea breeze. On the other hand, there was evidence that the wind changed from one direction in the morning to almost the opposite direction in the afternoon in a sea breeze day. The direction of the wind varied according to the orientation of the station with respect to the coastline.

It is worth mentioning that ranges in the average hourly temperature, wind speed and wind direction in Dauphin Island and Southwest Pass stations were smaller when compared to other stations; however, the values of each variable were higher than other stations. In fact, these two stations recorded the highest average wind speed value, Southwest Pass: 3.8 ms^{-1} (8.6 mph) and Dauphin Island: 7.9 ms^{-1} (3.5 mph). In addition, these stations recorded the highest maximum value among all stations (Southwest Pass: 14.7 ms^{-1} and Dauphin Island: 14.2 ms^{-1}). These patterns might be because these two stations are closer to the coast than the rest of the stations; therefore, the thermal gradient produced by a sea breeze circulation is stronger near the land–water boundary than stations located more inland. This result is related to the Masselink and Pattiaratchi (1998) investigation at Australia, where they indicated that there is a difference between a site located on the coast (Ocean Reef) and a site situated about 20 km inland (Perth).

5.3 Comparison between sea breeze day and a non-sea breeze day

A permutation test was run for selected atmospheric characteristics associated with a sea breeze (temperature, wind speed, and wind direction) to determine the difference between a sea breeze and a non-sea breeze day. Tables 5.1, 5.2 and 5.3 present the differences in surface temperature, wind speed and wind direction between sea breeze and non-sea breeze day when the differences were significant ($p < 0.05$). This was a strategy to compare the environmental characteristics of sea breezes based on data from each station from the early morning through onset of sea breezes in the early afternoon (for 8:00 am, 11:00 am, and 2:00 pm). In fact, the only atmospheric variable statistically significantly different for all stations was the average temperature. Of the twelve stations included in this study, only Lake Charles, LA, Lafayette, LA, and Mobile/Bates, AL were not significant in the average wind speed. Additionally, no results can be drawn for the wind direction variable for all stations because the datasets were not statistically significantly different. This was largely due to low sample size for the stations due to missing data.

The results indicated a difference in the average temperature for all stations and in the wind speed in some stations between a sea breeze day and a non-sea breeze day. The significance in the variables in the permutation test was mainly because the study used surface data. Sea breezes are air-sea-land interactions, which start when the land warms up more rapidly than the sea and leads to a thermal gradient between the water and land. In addition, the wind speed in some stations and wind direction for all stations were not significantly different leading to the conclusion that the stations will be influenced by onshore flows even on a sea breeze day and a non-sea breeze day. This was mainly because the data were taken within the planetary boundary layer (PBL). Since surface friction has a strong influence on wind speeds in this level of the atmosphere, the development of surface wind speed and wind direction in the stations were not statistically significant, and are not useful in diagnosing the existence of the sea breeze. The friction in the PBL creates weak wind convergence at the surface leading to weak uplift and convection development, making both wind speed and direction poor descriptors of sea breeze. As a result, on the U.S. Gulf Coast during synoptically benign days, the surface temperature was significantly different between sea breeze and non-sea breeze days, but the surface wind speed and wind direction were generally not different. During synoptically benign conditions, the difference between a sea breeze day and a non-sea breeze day was most likely due to the increase in temperature over land, and eventually an increase in the thermal gradient, yielding to the onset of the sea breeze circulation.

In summary, temperatures were significantly different on a sea breeze day, wind speed was significantly different at some stations, and wind direction was not significantly different at any station; therefore, a forecaster should evaluate other atmospheric levels in order to diagnose the existence of a sea breeze according to the wind data. On a day with no strong synoptic forcing, if the temperature is higher than the previous day and it increases rapidly during the late morning (10:00 am– 12:00 pm), there is an increased probability for sea breeze development.

Overall, for the diagnosing of sea breezes along the study area, the temperature and the wind speed in only some stations might be analyzed at the surface. The wind direction can be easily analyzed at the surface; nevertheless, it is necessary to evaluate it at other levels such as 850 hpa (~1.5 km) to detect a possible sea breeze development. If a sea breeze is taking place, an upper return flow can be detected at this level.

Environmental characteristics of sea breezes along the U.S. Gulf Coast behave differently from other locations at the surface, such as wind speed and wind direction. The use of surface data was chosen because previous literature suggested that the temperature, wind speed and wind direction were the primary variables associated with sea breeze (Banfield, 1991; Borne et al., 1998; Masselink and Pattiaratchi, 1998; Gilliam et al. 2004; Lensky and Dayan, 2012). On the other hand, most of the studies of sea breezes used sea surface temperature (e.g. buoy data) to evaluate the difference in temperature between sea and land. However, this data could not be used in this study because there were not enough consistent data to compare with. For this reason, the hourly surface data from ASOS sites were taken because it provided consistent data at real-time. Lastly, even though the sea breezes can penetrate more than 100 km inland, this study analyzed the onshore stations but at different distances. This was because of two purposes: (1) geographic aspect: to obtain the differences in the environmental characteristics among stations; (2) the onset of sea breezes is more evident along the coast.

Table 5.1 A summary of the environmental characteristics of sea breezes per station.

Station	**Variable**	**Statistically Significant YES/NO**	**Period**	**Actual Value of SBD**	**Actual Value of NSBD**	**Differences between SBD and NSBD**
1. Lake Charles	Temperature: °C (°F)	YES	8:00 am	24.2 (75.5)	23.4 (74.0)	0.8 (1.5)
			11:00 am	29.3 (84.8)	28.0 (82.5)	1.3 (2.3)
			2:00 pm	31.7 (89.1)	30.0 (86.1)	1.7 (3.0)
	Wind Speed: m/s (mph)	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
2. Lafayette	Temperature: °C (°F)	YES	8:00 am	23.9 (75.1)	23.1 (73.5)	0.9 (1.6)
			11:00 am	29.2 (84.6)	28.0 (82.4)	1.2 (2.2)
			2:00 pm	31.9 (89.4)	30.0 (85.9)	1.9 (3.5)
	Wind Speed: m/s (mph)	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
3.Harry P Williams	Temperature: °C (°F)	YES	8:00 am	24.0 (75.2)	22.8 (73.0)	1.2 (2.2)
			11:00 am	29.4 (85.0)	27.6 (81.6)	1.9 (3.3)
			2:00 pm	31.4 (88.5)	29.2 (84.6)	2.2 (3.9)
	Wind Speed: m/s (mph)	YES	8:00 am	0.8 (1.7)	1.4 (3.1)	0.6 (1.4)
			11:00 am	2.5 (5.5)	3.0 (6.7)	0.5 (1.2)
			2:00 pm	2.8 (6.4)	3.3 (7.5)	0.5 (1.1)
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
4. Southwest	Temperature: °C (°F)	YES	8:00 am	27.6 (81.8)	26.4 (79.6)	1.2 (2.2)
			11:00 am	28.5 (83.3)	27.1 (80.7)	1.5 (2.6)
			2:00 pm	29.0 (84.2)	27.5 (81.5)	1.5 (2.6)
	Wind Speed: m/s (mph)	YES	8:00 am	3.6 (8.2)	4.7 (10.5)	1.0 (2.3)
			11:00 am	3.5 (7.9)	4.7 (10.7)	1.2 (2.8)
			2:00 pm	3.5 (7.9)	4.7 (10.6)	1.2 (2.7)
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---

Values of temperatures/wind speed occur when they are higher/lower than the normal temperatures (Non-sea breeze day). (LA stations)

*Environmental characteristics values for Louisiana station.

Table 5.2 A summary of the environmental characteristics of sea breezes per station.

Station	**Variable**	**Statistically Significant YES/NO**	**Period**	**Actual Value of SBD**	**Actual Value of NSBD**	**Differences between SBD and NSBD**
5. McComb Pike	Temperature: °C (°F)	YES	8:00 am	21.9 (71.4)	21.4 (70.5)	0.5 (0.9)
			11:00 am	28.4 (83.2)	27.1 (80.9)	1.3 (2.4)
			2:00 pm	31.7 (89.1)	29.7 (85.5)	2.0 (3.6)
	Wind Speed: m/s (mph)	YES	8:00 am	0.5 (1.2)	1.1 (2.6)	0.6 (1.4)
			11:00 am	2.3 (5.1)	2.5 (5.6)	0.3 (0.6)
			2:00 pm	2.5 (5.6)	2.8 (6.3)	0.3 (0.7)
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	
6. Mobile/Bates	Temperature: °C (°F)	YES	8:00 am	23.7 (74.6)	22.1 (71.9)	1.5 (2.7)
			11:00 am	29.4 (85.0)	27.3 (81.2)	2.1 (3.8)
			2:00 pm	31.9 (89.4)	29.4 (84.9)	2.5 (4.5)
	Wind Speed: m/s (mph)	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
7. Dauphin Island	Temperature: °C (°F)	YES	8:00 am	27.5 (81.5)	25.3 (77.6)	2.2 (3.9)
			11:00 am	28.0 (82.3)	25.7 (78.3)	2.2 (4.0)
			2:00 pm	28.9 (84.1)	26.7 (80.1)	2.2 (3.9)
	Wind Speed: m/s (mph)	YES	8:00 am	3.5 (7.9)	4.4 (9.8)	0.8 (1.9)
			11:00 am	3.5 (8.0)	4.3 (9.7)	0.8 (1.7)
			2:00 pm	3.3 (7.5)	4.2 (9.4)	0.9 (1.9)
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---

Values of temperatures/wind speed occur when they are higher/lower than the normal temperatures (Non-sea breeze day). (MS and AL stations)
*Environmental characteristics values for Mississippi and Alabama station.

Table 5.3 A summary of the environmental characteristics of sea breezes per station.

Station	Variable	Statistically Significant YES/NO	Period	Actual Value of SBD	Actual Value of NSBD	Differences b/w SBD and NSBD
8. Pensacola	Temperature: °C (°F)	YES	8:00 am	24.8 (76.7)	23.8 (74.8)	1.1 (1.9)
			11:00 am	30.1 (86.1)	28.1 (82.5)	2.0 (3.6)
			2:00 pm	31.8 (89.3)	29.4 (84.9)	2.5 (4.4)
	Wind Speed: m/s (mph)	YES	8:00 am	1.8 (3.9)	4.4 (9.8)	0.8 (1.9)
			11:00 am	2.8 (6.4)	3.1 (6.9)	0.3 (0.6)
			2:00 pm	3.8 (8.5)	4.0 (9.1)	0.2 (0.5)
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
9. Whiting	Temperature: °C (°F)	YES	8:00 am	23.5 (74.3)	22.3 (72.2)	1.2 (2.1)
			11:00 am	29.7 (85.4)	27.7 (81.8)	2.0 (3.6)
			2:00 pm	32.5 (90.5)	29.8 (85.7)	2.7 (4.8)
	Wind Speed: m/s (mph)	YES	8:00 am	0.8 (1.8)	1.4 (3.2)	0.6 (1.3)
			11:00 am	2.0 (4.4)	2.5 (5.6)	0.5 (1.2)
			2:00 pm	2.4 (5.4)	3.0 (6.8)	0.7 (1.5)
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
10. Panama City	Temperature: °C (°F)	YES	8:00 am	25.5 (77.9)	24.0 (75.1)	1.5 (2.7)
			11:00 am	30.2 (86.3)	28.4 (83.1)	1.8 (3.2)
			2:00 pm	31.9 (89.4)	29.8 (85.6)	2.1 (3.8)
	Wind Speed: m/s (mph)	YES	8:00 am	1.2 (2.8)	2.3 (5.2)	1.1 (2.4)
			11:00 am	2.5 (5.6)	3.0 (6.6)	0.5 (1.0)
			2:00 pm	3.4 (7.6)	3.7 (8.4)	0.4 (0.9)
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
11. Tallahassee	Temperature: °C (°F)	YES	8:00 am	23.3 (74.0)	22.7 (72.8)	0.7 (1.2)
			11:00 am	30.3 (86.5)	28.5 (83.4)	1.7 (3.1)
			2:00 pm	32.8 (91.0)	30.3 (86.5)	2.5 (4.5)
	Wind Speed: m/s (mph)	YES	8:00 am	0.7 (1.6)	1.5 (3.4)	0.8 (1.8)
			11:00 am	2.4 (5.3)	2.7 (6.2)	0.4 (0.8)
			2:00 pm	3.0 (6.7)	3.4 (7.6)	0.4 (0.9)
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---
12. Cross City	Temperature: °C (°F)	YES	8:00 am	23.6 (74.5)	23.0 (73.4)	0.6 (1.0)
			11:00 am	29.8 (85.7)	28.4 (83.2)	1.4 (2.5)
			2:00 pm	32.2 (90.0)	30.0 (85.9)	2.2 (4.0)
	Wind Speed: m/s (mph)	YES	8:00 am	0.7 (1.5)	1.5 (3.3)	0.8 (1.7)
			11:00 am	2.0 (4.5)	2.5 (5.7)	0.6 (1.2)
			2:00 pm	2.6 (5.9)	3.1 (6.9)	0.5 (1.0)
	Wind Direction: degree	NO	8:00 am	---	---	---
			11:00 am	---	---	---
			2:00 pm	---	---	---

Values of temperatures/wind speed occur when they are higher/lower than the normal temperatures (Non-sea breeze day). (FL stations)
*Environmental characteristics values for Florida station.

CHAPTER VI

CONCLUSIONS

The U.S. Gulf Coast is a favorable geographic area for sea breezes during the warm season and when synoptic forcings are not the predominant feature throughout the area. Sea breeze developments lead to unstable low-level atmospheric conditions that can produce short but intense rainfall and thunderstorms; therefore, defining the environmental characteristics of sea breezes is crucial for forecasters because they can use the information to help diagnose the onset of such systems. Despite the low frequency of sea breezes (161 days) along the U.S. Gulf Coast from 1991 to 2010, there is evidence that they exist and must be comprehensively studied.

The objectives of this study were to identify and define the environmental characteristics associated with sea breezes along the U.S. Gulf Coast. Then, a comparison between sea breeze day and non-sea breeze day was performed to determine which environmental characteristic was significant. Although sea breezes are mesoscale systems, this investigation was performed evaluating all possible sea breezes during synoptically benign conditions. The methodology used involved analysis of rawisonde data over the study area (Slidell, LA and Tallahassee, FL) to define synoptically benign days (days with a weak synoptic forcing), followed by analysis of GOES IR and visible satellite imagery to determine the existence of cloud structures associated with a sea breeze. Finally, the environmental characteristics of a sea breeze were defined by using surface observation analysis from ASOS sites during days with a noted sea breeze circulation.

According to the data evaluated, 19% of 6,508 days were classified as synoptically benign day along the U.S. Gulf Coast for the period of 1991 to 2010. Of these 19%, only 13% met the criteria of a sea breeze day. The difference in the average surface temperature between a sea breeze day and a non-sea breeze day was statistically significantly different for all stations. The average surface wind speed was statistically significant different for all stations except for Lake Charles, LA, Lafayette, LA, and Mobile/Bates, AL. The environmental characteristics of the wind direction may not be useful at surface because the data were not statistically significantly different. In presence of synoptically benign days, the environmental characteristics were defined as high average temperatures with a large variability in the afternoon.

Several limitations could have affected the obtained results in this investigation. The primary limitation was the lack of data (missing data) along the stations. Although there is quality control in the measurements, some instruments could produce errors. The detection of synoptically benign days during the first phase also had some limitations. For instance, the only sites chosen to evaluate sounding data within the study area were Slidell, LA and Tallahassee, FL; therefore, there is a gap in data in Mississippi and Alabama. The second phase was affected with some issues in the satellite resolutions. The selected satellite database had a low spatial resolution, which made it difficult to identify some cloud types along the study area. Another limitation in this phase was the transition of previous GOES sensors to newer versions, yielding a large amount of missed data for several days. An example of this limitation occurred in 1994 with the transition from GOES 7 to GOES 8.

Future research should focus on investigating other parameters such as: the amount of moisture in the atmosphere, the change of mean sea level pressure and temperature differences between sea and land by using the sea surface temperature. Future research should also include an analysis of surface winds and upper level winds (~850 hPa) to evaluate the development and progress of the sea-breeze circulation. An important element in a sea breeze development is the sea-breeze front. Research related to methods than can help detect and monitor the inland penetration of this front can help to determine areas more susceptible to sea breezes along the Gulf States. Another criteria to take into consideration are the analysis of physical impacts such as rainfall accumulation, and cloud cover to quantify precipitation depth and the extent of sea breezes. There are different methods to perform this investigation. This study was based on sea breezes but in a synoptic or large scale; therefore, future work should be addressed for specific areas based on coastline shape, topography, or other physical factors associated with surface heat fluxes and winds.

Other studies of sea breezes around the world use empirical knowledge of the environmental characteristics of this system. With these previous researches, more hypotheses can be rejected or not. Studies of sea breezes along the U.S. Gulf Coast are minimal, and this creates more questions to be answered in future projects. This investigation serves as a baseline to continue analyzing this mesoscale system along the study area.

REFERENCES

Abbott, P.L., 2012: *Natural Hazards*. 8th Ed. New York: Mc Graw Hill.

Arritt, R. W., 1993: Effects of large-scale flow on characteristic features of the sea breeze. *J. Appl. Meteor.,* **32**, 116–125.

Atkins N.T., R.M. Wakimoto, and T.M. Weckwerth, 1995: Observations of the Sea-Breeze Front during CaPE. Part II: Dual-Doppler, and aircraft analysis. *Mon. Wea. Rev.,* **123,** 944–969.

Atkinson, B.W., 1981:*Meso-scale Atmospheric Circulations*. Academic Press.495 pp.

Atlas, D., 1960: Radar detection of the sea breeze. *J. Meteor.*, **17**, 244–258.

Azorin-Molina, C., B.H. Connell, and R. Baena-Calatrava, 2009: Sea-breeze convergence zones from AVHRR over the Iberian Mediterranean area and the Isle of Mallorca, Spain. *J. Appl. Meteor. Climatol.,***48**, 2069–2085.

——, A. Sánchez-Lorenzo, and J. Calbo, 2009: A climatological study of sea breeze clouds in the southeast of the Iberian Peninsula (Alicante, Spain). *Atmosfera*.**22**, 33–49.

Banfield, C.E., 1991: The frequency and surface characteristics of sea breezes at St. Johns, Newfoundland. *Climatol*. *Bull*., **25**,3–20.

Blanchard, D. O., and R. E. López, 1985: Spatial patterns of convection in south Florida. *Mon. Wea. Rev.,* **113,** 1282–1299.

Borne, K., D. Chen, and M. Nunez, 1998: A method for finding sea breeze days under stable synoptic conditions and its application to the Swedish west coast.*Int. J. Climatol.*, **18**, 901–914.

Buckley, R.L., and R.J. Kurzeja, 1997: An observational and numerical study of the nocturnal sea breeze. Part I: Structure and circulation. *J. Appl. Meteor.*, **36**, 1577–1598.

Case, J.L., J. Manobianco, J.E. Lane, C.D. Immer, and F.J. Merceret, 2004: An objective technique for verifying sea breezes in high-resolution numerical weather prediction models. *Wea. Forecasting*, **19**, 690–705.

Clarke, R. H., 1955: Some observations and comments on the sea breeze. *Aust. Meteor. Mag.*, ***11***, 47–68.

Clarke, R. H., 1984: Colliding sea-breezes and the creation of internal atmospheric bore waves: Two-dimensional numerical studies. *Aust. Meteor. Mag.*, ***32***, 207–226.

Connell, B.H., K.J. Gould, and J.F.W. Purdom, 2001: High-Resolution GOES-8visible and infrared cloud frequency composites over northern Florida during the summers 1996–99. *Wea. Forecasting*, **16**, 713–724.

Dalu, G.A., and R.A. Pielke, 1989: An analytical study of the sea breeze. *J. Atmos. Sci.,* **46,** 1815–1825.

Dailey, P.S., and R. G. Fovell, 1999: Numerical Simulation of the Interaction between the Sea-Breeze Front and Horizontal Convective Rolls. Part I: Offshore Ambient Flow. *Mon. Wea. Rev ,***127,** 858–878.

DrMego, G.J., L.F. Bosart, and G.W. Endersen, 1976: An examination of the frequency and mean conditions surrounding frontal incursions into the Gulf of Mexico and Caribbean Sea. *Mon. Wea. Rev ,***104,** 709–718.

Dyer, J., 2009: Influences on land surface characteristics on precipitation over the lower Mississippi Alluvial Plain. *MS Water Resources Conference.,* 62–75.

Encyclopedia Britannica, cited 2013: Gulf of Mexico. [Available online at: http://www.britannica.com/EBchecked/topic/379348/Gulf-of-Mexico]

Estoque, M. A., 1962: The sea breeze as a function of the prevailing synoptic situation. *J. Atmos. Sci.,* **19,** 244–250.

Finkele, K., J. M. Hacker, H. Kraus, and R. A. D. Byron-Scott, 1995: A complete sea-breeze circulation cell derived from aircraft observations, *Bound.- Lay. Meteor.*, ***73***, 299–317.

Gentry, R.C., and P.L. Moore, 1954: Relation of local and general wind interaction near the sea coast to time and location of air-mass showers. *J. Meteor.*, **11**, 507–511.

Gilliam, R.C., S. Raman, and D.D.S. Niyogi, 2004: Observational and numerical study on the influence of large-scale flow direction and coastline shape on sea-breeze evolution. *Bound.-Lay. Meteor.*, **111**, 275–300.

Glickman, T.S., 2000: *Glossary of meteorology*. American Meteorological Society. 855 pp.

Holmer, B., and M. Haeger-Eugensson, 1999: Winter land breeze in a high latitude complex coastal area, *Phys. Geogr.*, ***20*** (2),152–172.

Hsu, S.A., 1988: Air–sea–land interaction. *Coastal Meteorology,* Academic Press, 140–149.

——, 1970: Coastal air-circulation system: observations and empirical model. Mon. Wea. Rev., **98**, 487–509.

Huschke, R.E., 1959: *Glossary of meteorology*. American Meteorological Society.638 pp.

Jehn, K.H., 1973: A sea breeze bibliography, 1664-1972. Report No. 37, Atmospheric Science Group, University of Texas at Austin, TX, 51 pp.

Kottmeier, C., P. Palacio-Sese, N. Kalthoff, U. Corsmeier, and F. Fiedler,2000: Sea breezes and coastal jets in southeastern Spain. *Int. J. Climatol.*, **20**, 1791–1808.

Lensky, I.M., and U. Dayan, 2012: Continuous detection and characterization of the sea breeze in clear sky conditions using Meteosat Second Generation. *Atmos. Chem. Phys*, **12**, 6505–6513.

Leopold, L.B., 1949: The interaction of trade wind and sea breeze, Hawaii. *J. Meteor.*, **6**, 312–320.

Lyons, W.A. and Olsson, L.E., 1972: The climatology and prediction of the Chicago lake breeze.*J. Appl. Meteor.*, **11**, 1254–1272.

Mahrer, Y., and R.A. Pielke, 1977: The effects of topography on sea and land breezes in a two-dimensional numerical model. *Mon. Wea. Rev.,* **105**, 1151–1162.

Markowski P., and Y. Richardson 2010: *Mesoscale Meteorology in Midlatitudes*. Wiley-Blackwell, 407 pp.

Masselink, G., and C.B. Pattiaratchi, 1998: Sea breeze climatology and nearshore processes along the Perth Metropolitan coastline, Western Australia. *Coast.Eng.,* 3165–3177.

McPherson, R.D., 1970: A numerical study of the effect of a coastal irregularity on the sea breeze. *J. Appl. Meteor.*, **9**, 767–777.

Miller, S.T.K., and B.D. Keim, 2003: Synoptic-scale controls on the sea breeze of the Central New England Coast. *Wea.Forecasting,* **18**,236–248.

——, ——, R.W. Talbot, and H. Mao, 2003: Sea breeze: structure, forecasting, and impacts. *Rev. Geophys*. 1–31.

National Climatic Data Center (NCDC), cited 2013: ISCCP B1 Data Rescue. [Available online at: http://www.ncdc.noaa.gov/oa/rsad/isccpb1/index.php?name=details]

Neumann, J., 1951: Land breezes and nocturnal thunderstorms. *J. Meteor.,* **8**, 60–67.

——, and Y. Mahrer, 1974: A theoretical study of the land and sea breezes of circular islands. *J. Atmos. Sci*., **31**, 2027–2039.

Nicholls, M.E., R.A. Pielke, and W.R. Cotton, 1991: A two dimensional numerical investigation of the interaction between sea breezes and deep convection over the Florida Peninsula. *Mon. Wea. Rev.,* **119,** 298–323.

Pattiaratchi, C., B. Hegge, J. Gould, and I. Eliot, 1997: Impact of sea-breeze activity on nearshore and foreshore processes in southwestern Australia. *Cont. Shelf. Res.,* **17**, 1539–1560.

Pielke, R.A., 1974: A three-dimensional numerical model of the sea breezes over south Florida. *Mon. Wea. Rev.,* **102**, 115–139.

Simpson, J.E., 1994: *Sea breeze and local winds*. Cambridge University Press., 234 pp.

——, 1996: Diurnal changes in sea-breeze direction. *J. Appl. Meteor.* **35**, 1166–1169.

Smith, J.R., H.E. Fuelberg, and A.I. Watson, 2005: Warm season lightning distributions over the northern Gulf of Mexico coast and their relation to synoptic-scale and mesoscale environments. *Wea. Forecasting*, **20**, 415–438.

Wakimoto, R.M. and N.T. Atkins, 1994: Observations of the Sea-Breeze Front during CaPE. Part I: Single-Doppler, Satellite, and Cloud Photogrammetry Analysis. *Mon. Wea. Rev.,* **122,** 1092–1114.

Watts, A., 1955: Sea breeze at Thorney Island. *Meteor. Mag*., **84**, 42–48.

Wilks, D.S., 2011: *Statistical methods in the atmospheric sciences.* 3rd ed. Academic Press, 676 pp.

Xian, Z., and R.A. Pielke, 1991: The effects of width of landmasses on the development of sea breezes. *J. Appl. Meteor.,* **30,** 1280–1304.

APPENDIX A

ENVIROMENTAL CHARACTERISTICS BETWEEN SEA BREEZE AND NON-SEA BREEZE DAYS

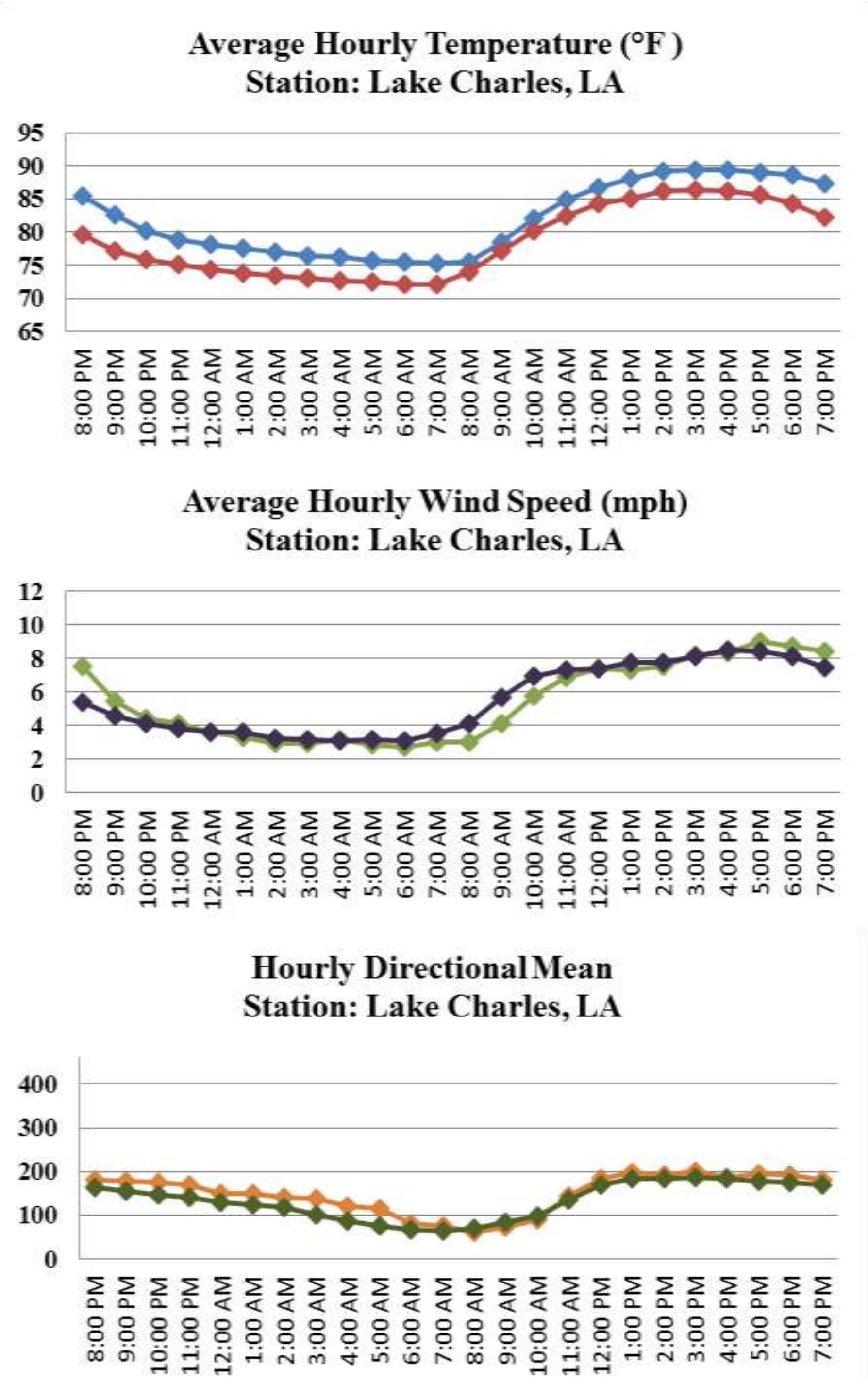


Figure A.1 Average hourly surface observations for Lake Charles station.

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.

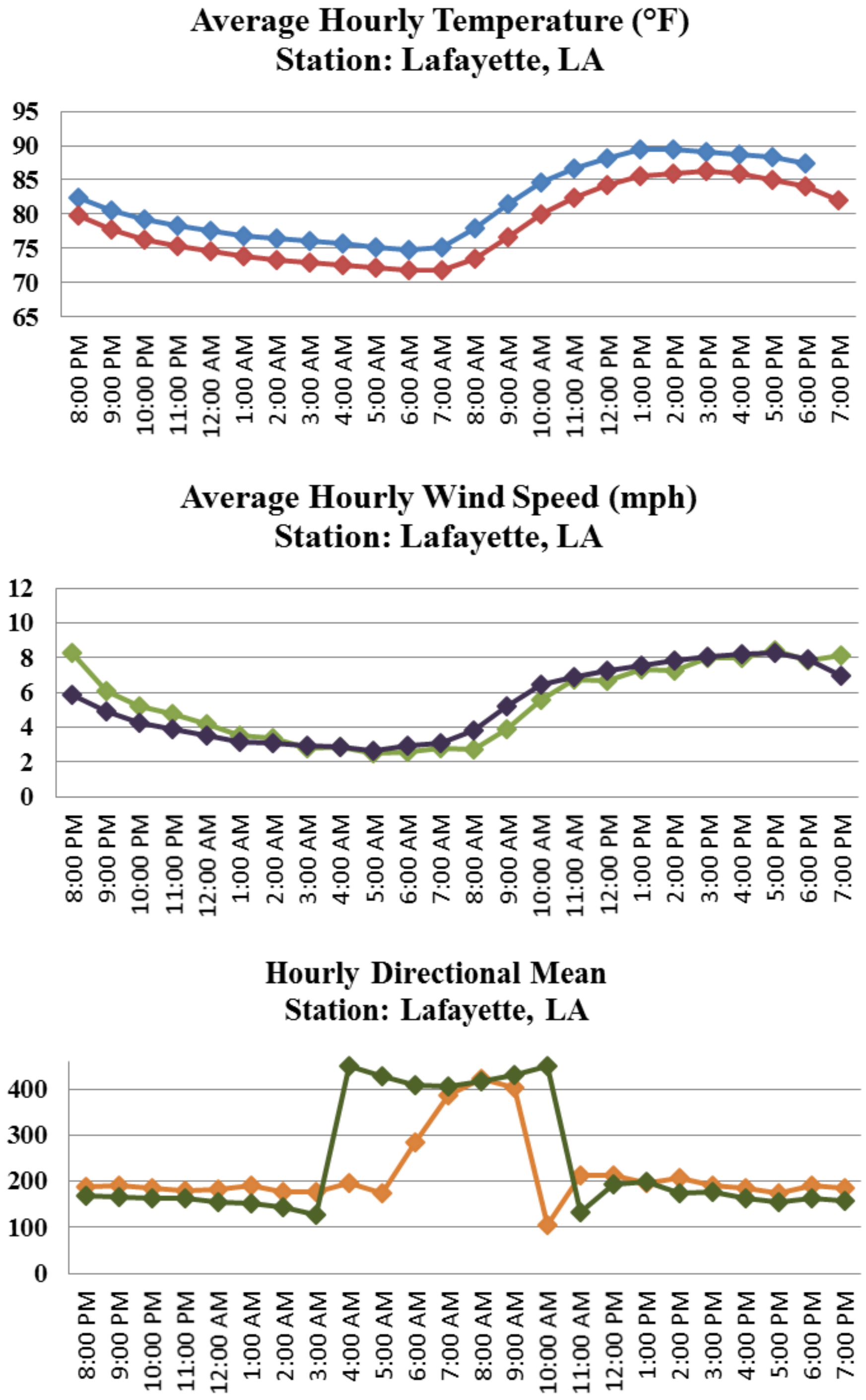


Figure A.2 Average hourly surface observations for Lafayette station.

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.

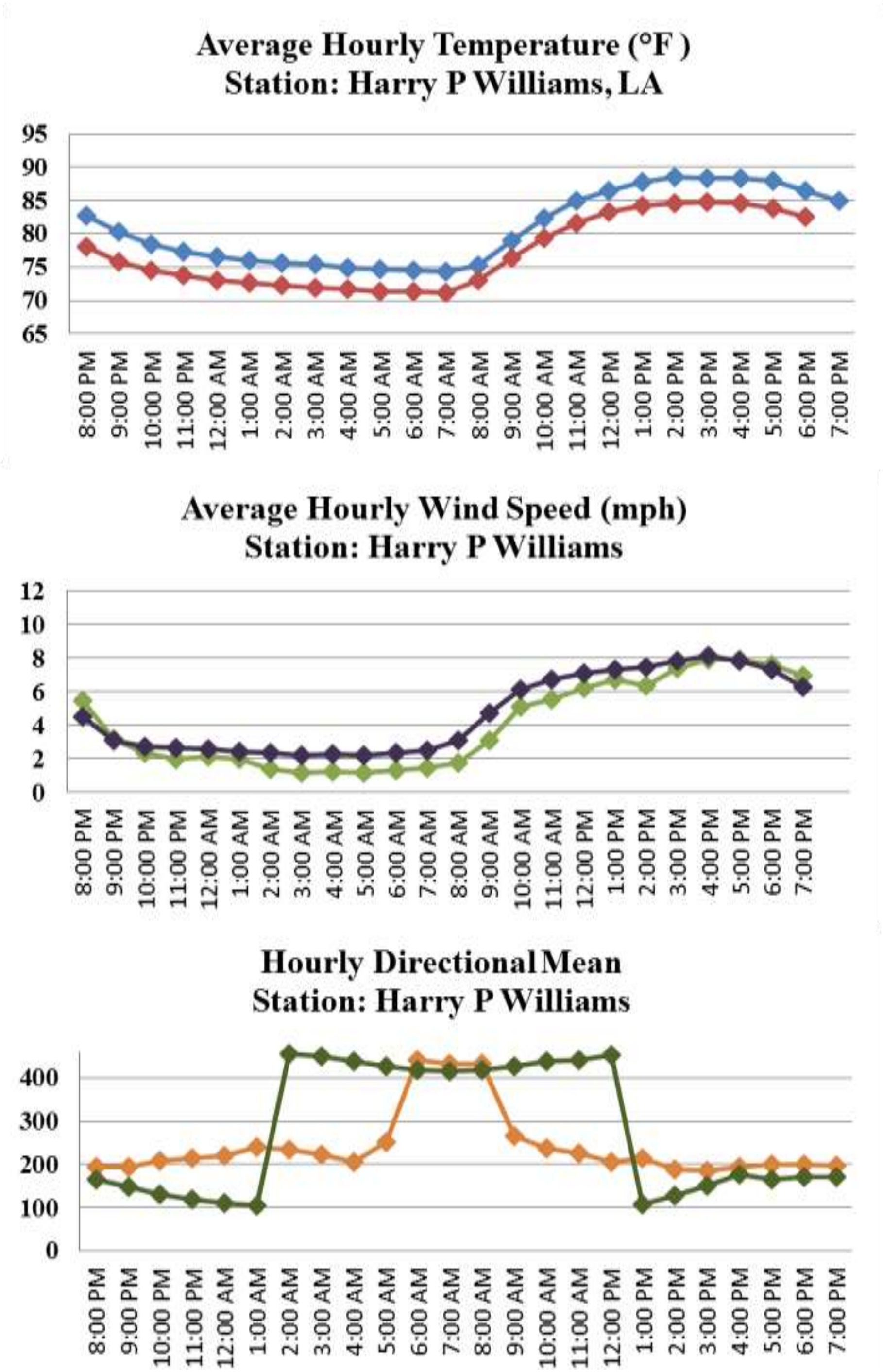
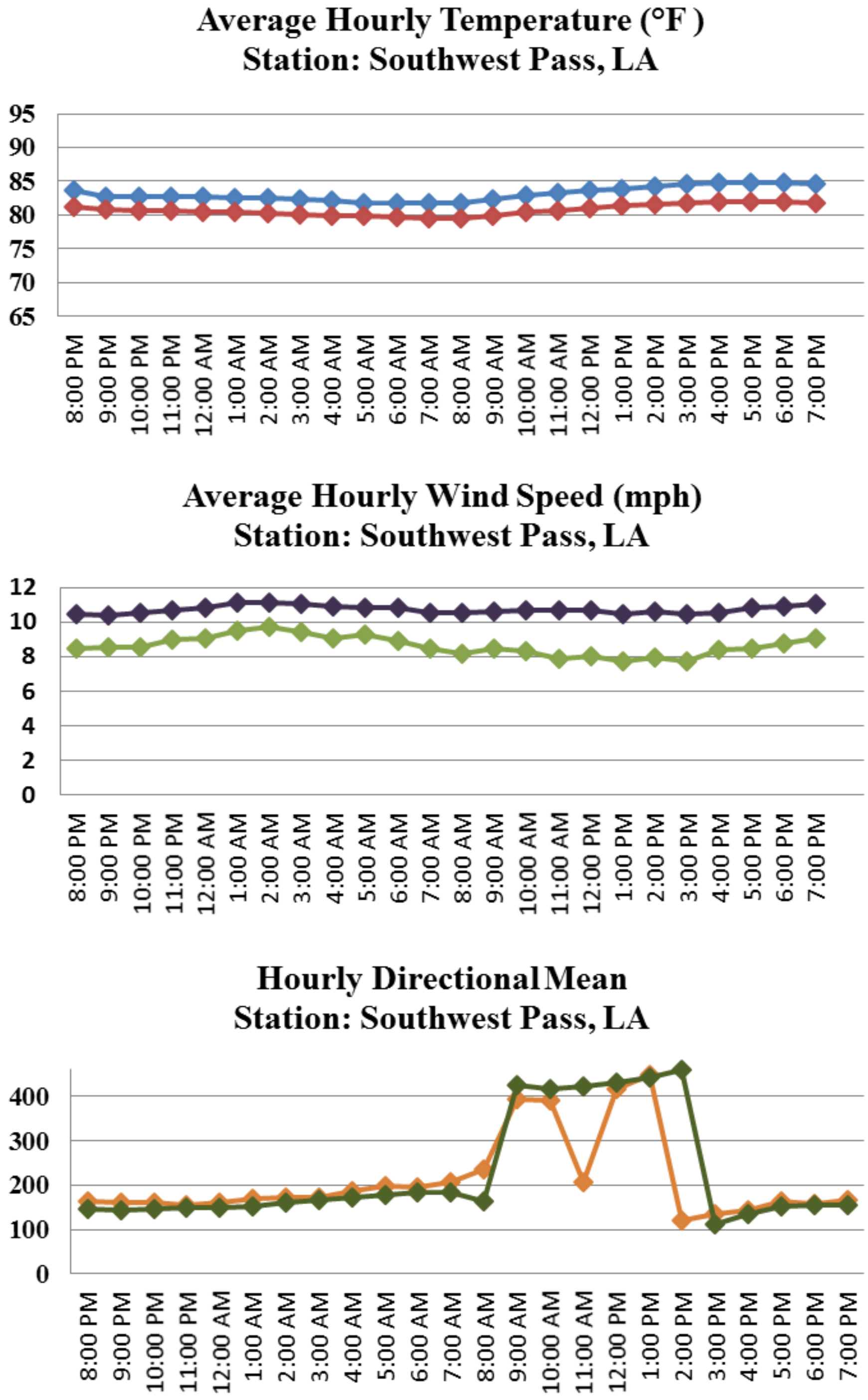


Figure A.3 Average hourly surface observations for Harry P Williams station

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.



Average Hourly Temperature (°F)
Station: Southwest Pass, LA

Average Hourly Wind Speed (mph)
Station: Southwest Pass, LA

Hourly Directional Mean
Station: Southwest Pass, LA

Figure A.4 Average hourly surface observations for Southwest Pass station

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.

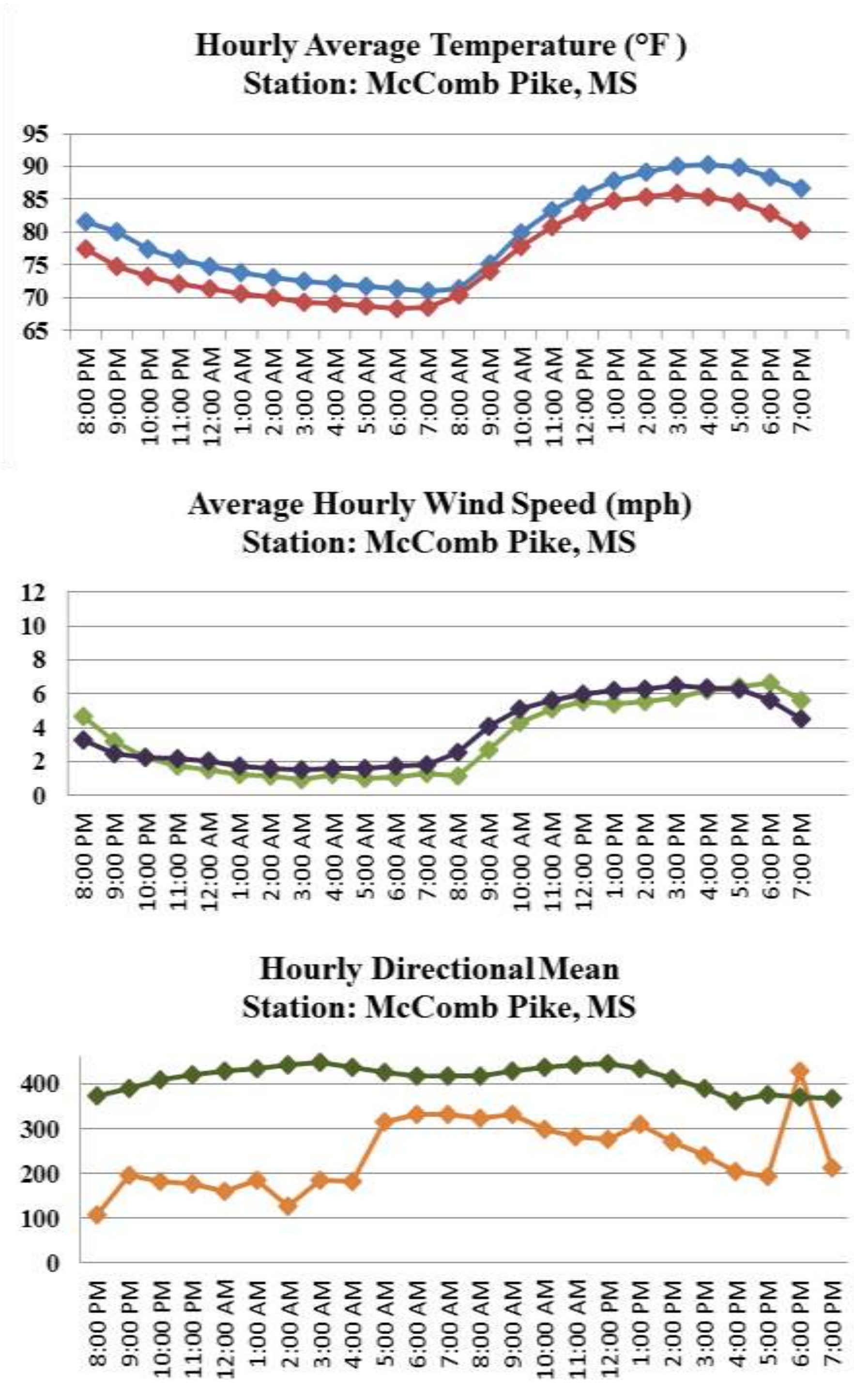


Figure A.5 Average hourly surface observations for McComb Pike station

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.

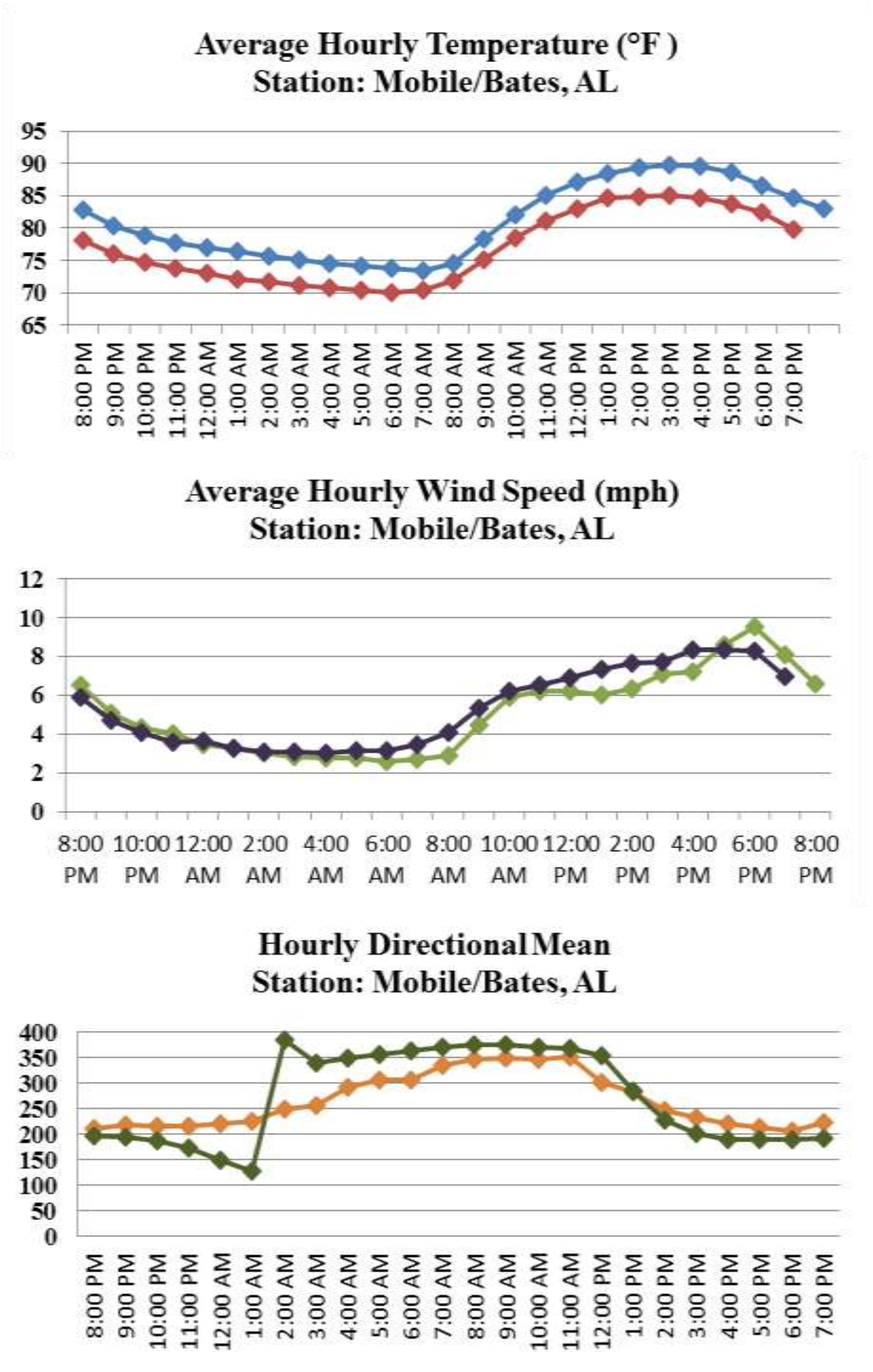


Figure A.6 Average hourly surface observations for Mobile/Bates station

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.

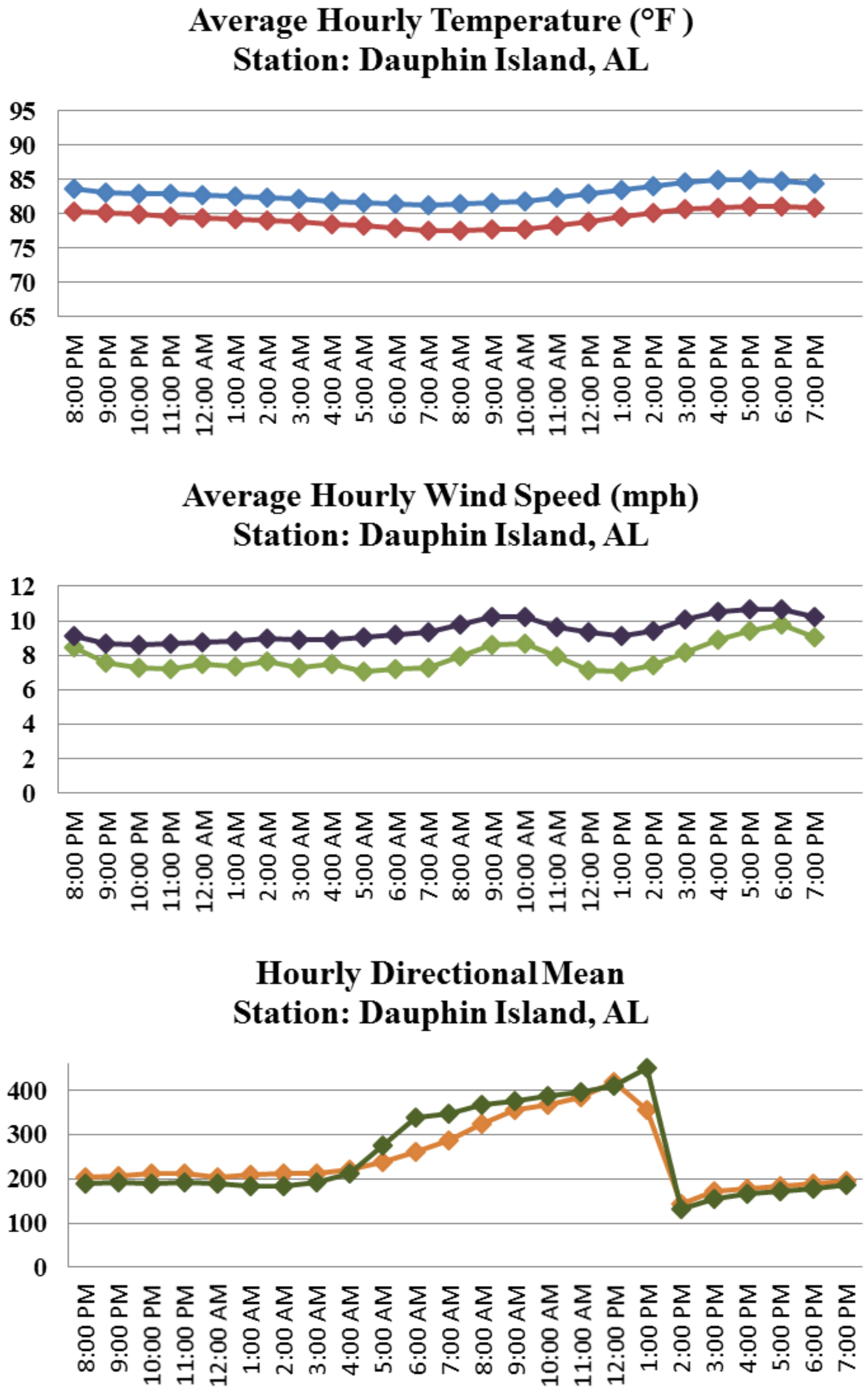


Figure A.7 Average hourly surface observations for Dauphin Island station

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.

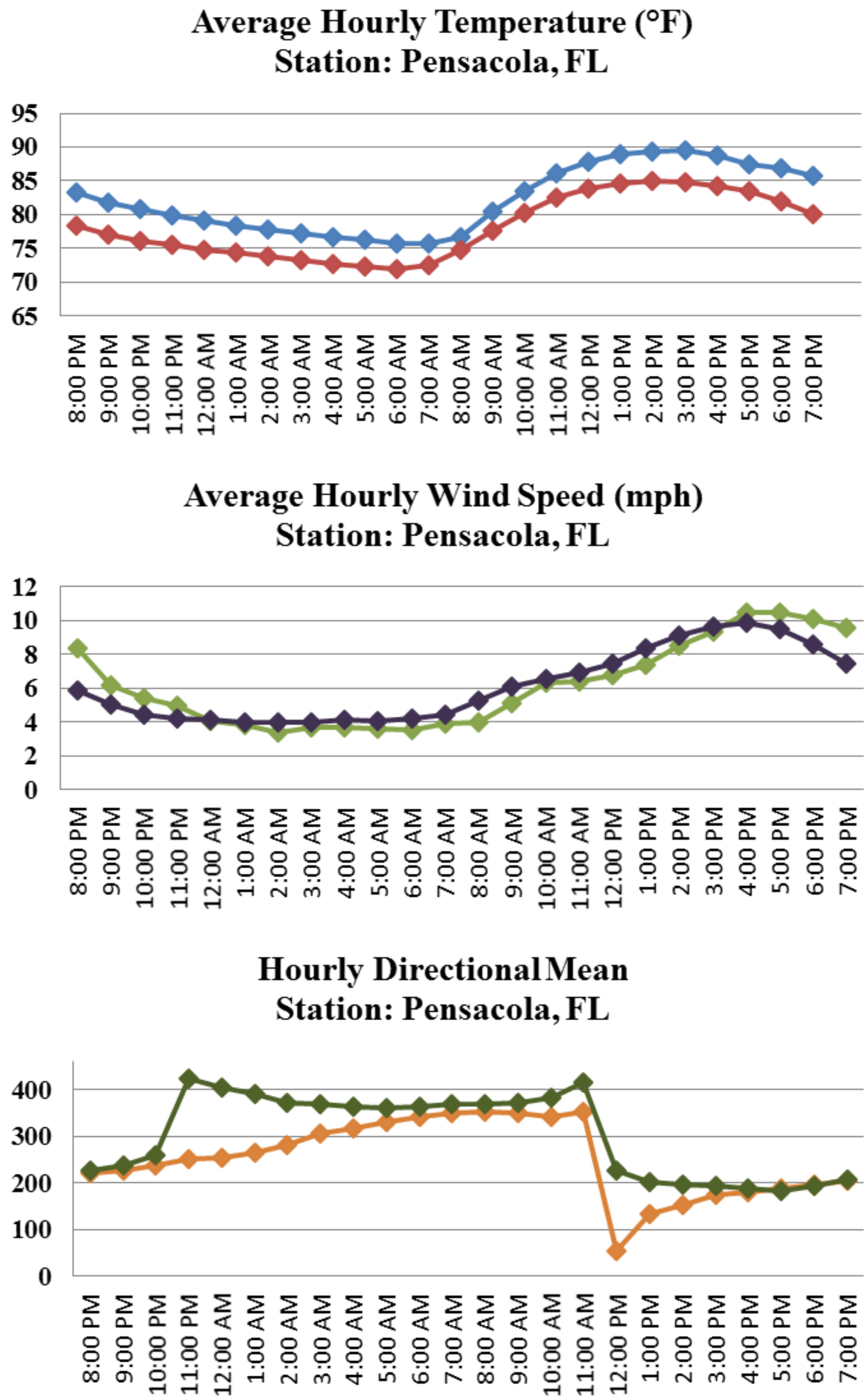
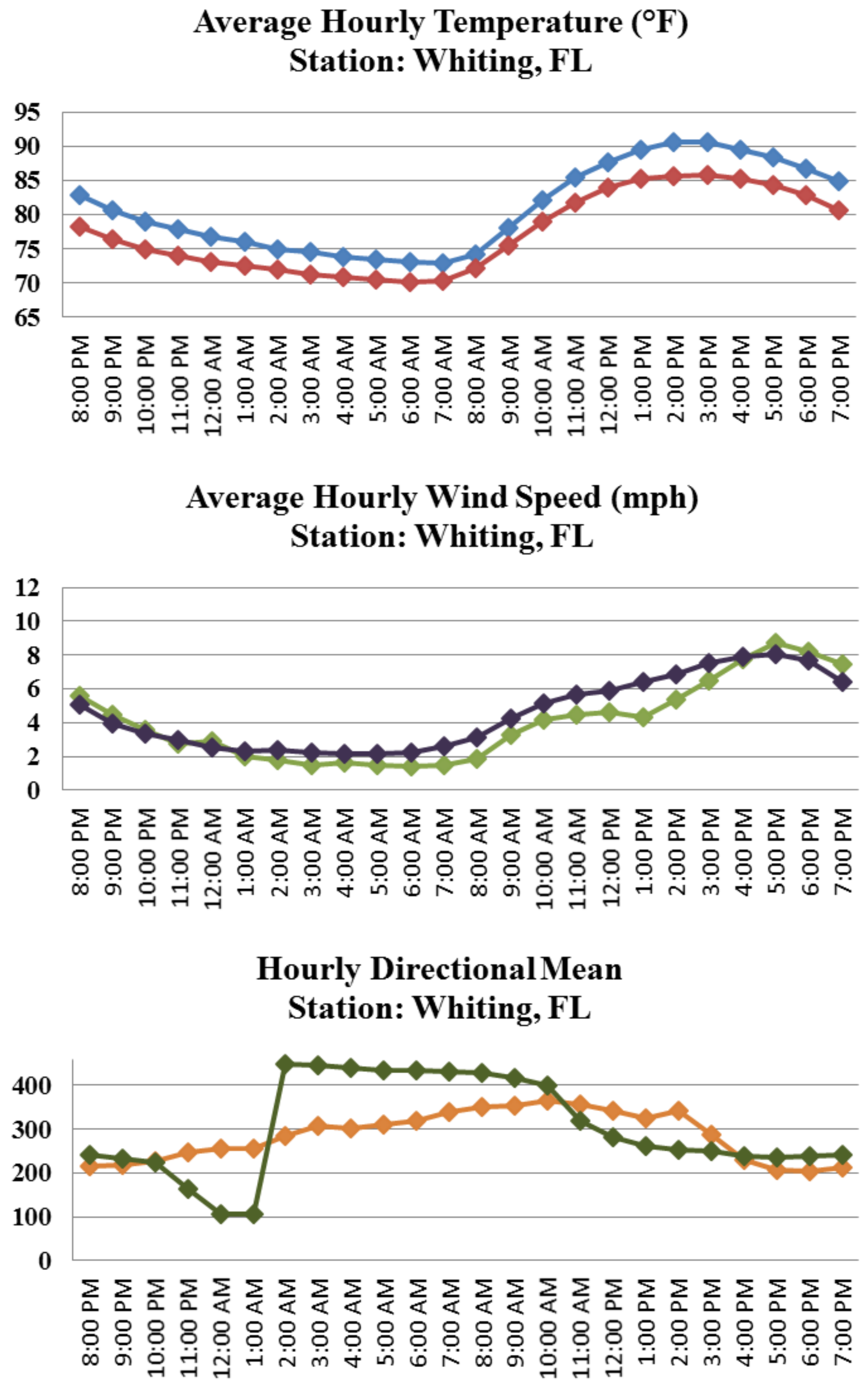


Figure A.8 Average hourly surface observations for Pensacola station

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.



Average Hourly Temperature (°F)
Station: Whiting, FL

Average Hourly Wind Speed (mph)
Station: Whiting, FL

Hourly Directional Mean
Station: Whiting, FL

Figure A.9 Average hourly surface observations for Whiting station

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.

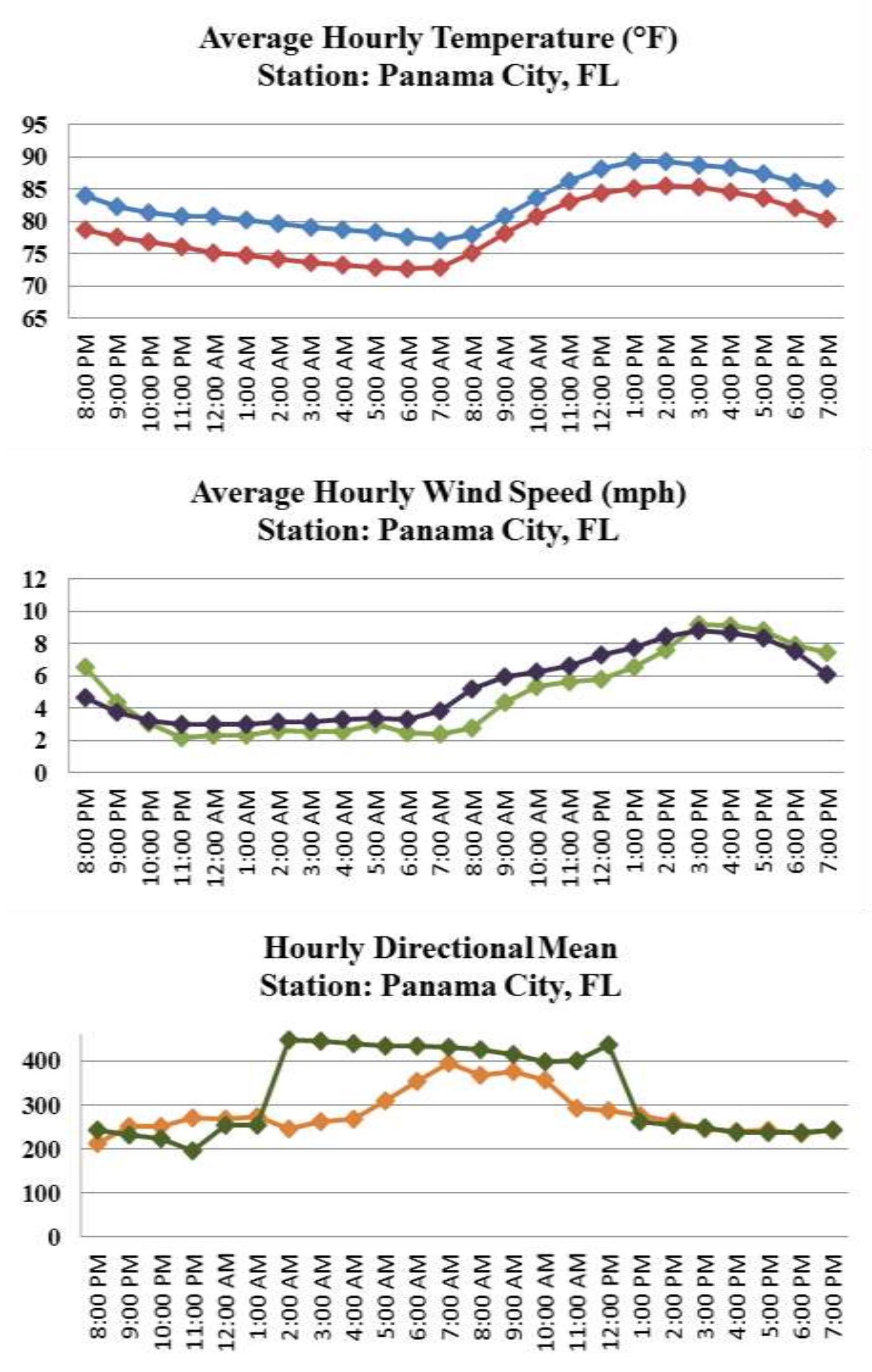


Figure A.10 Average hourly surface observations for Panama City station

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.

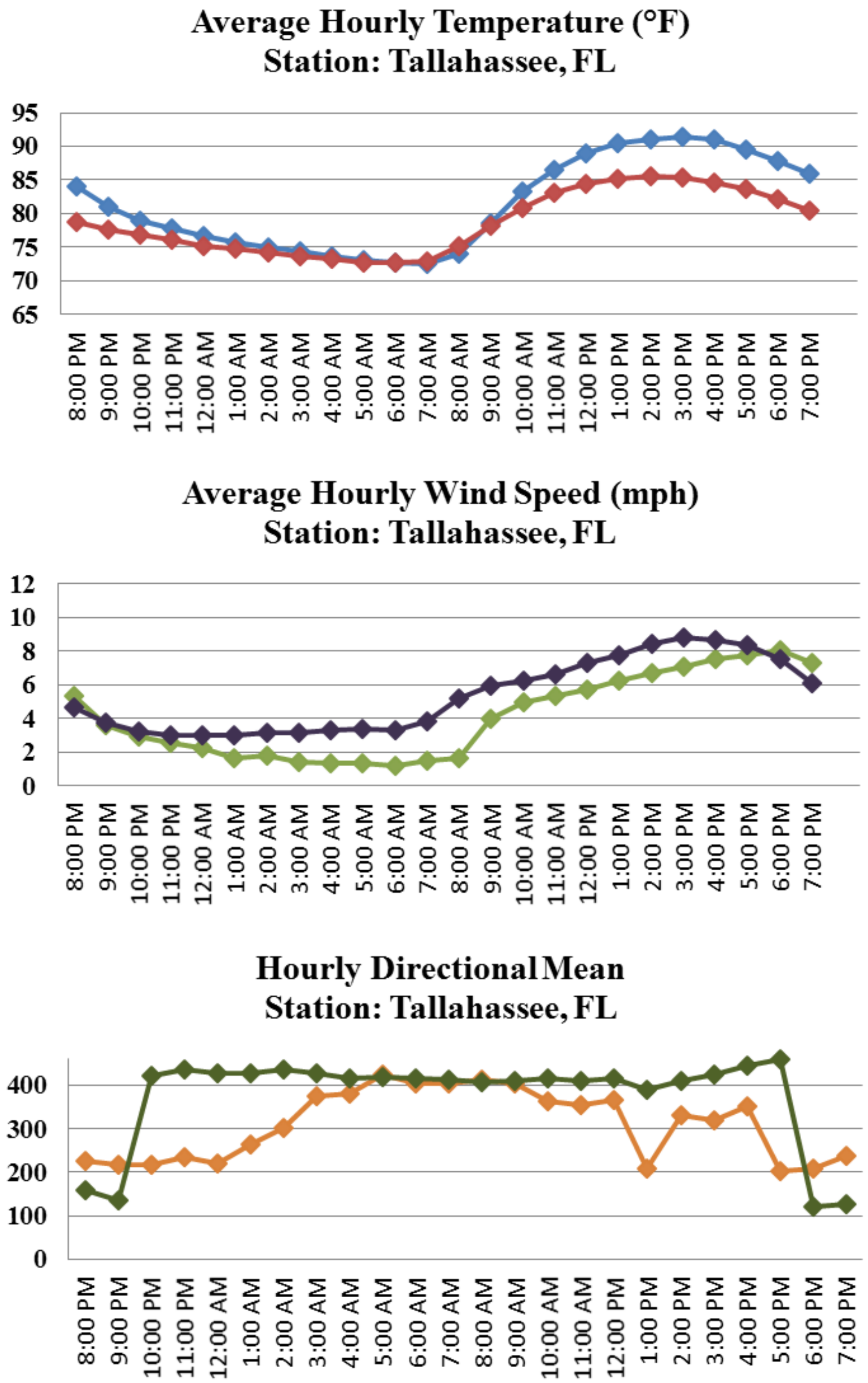
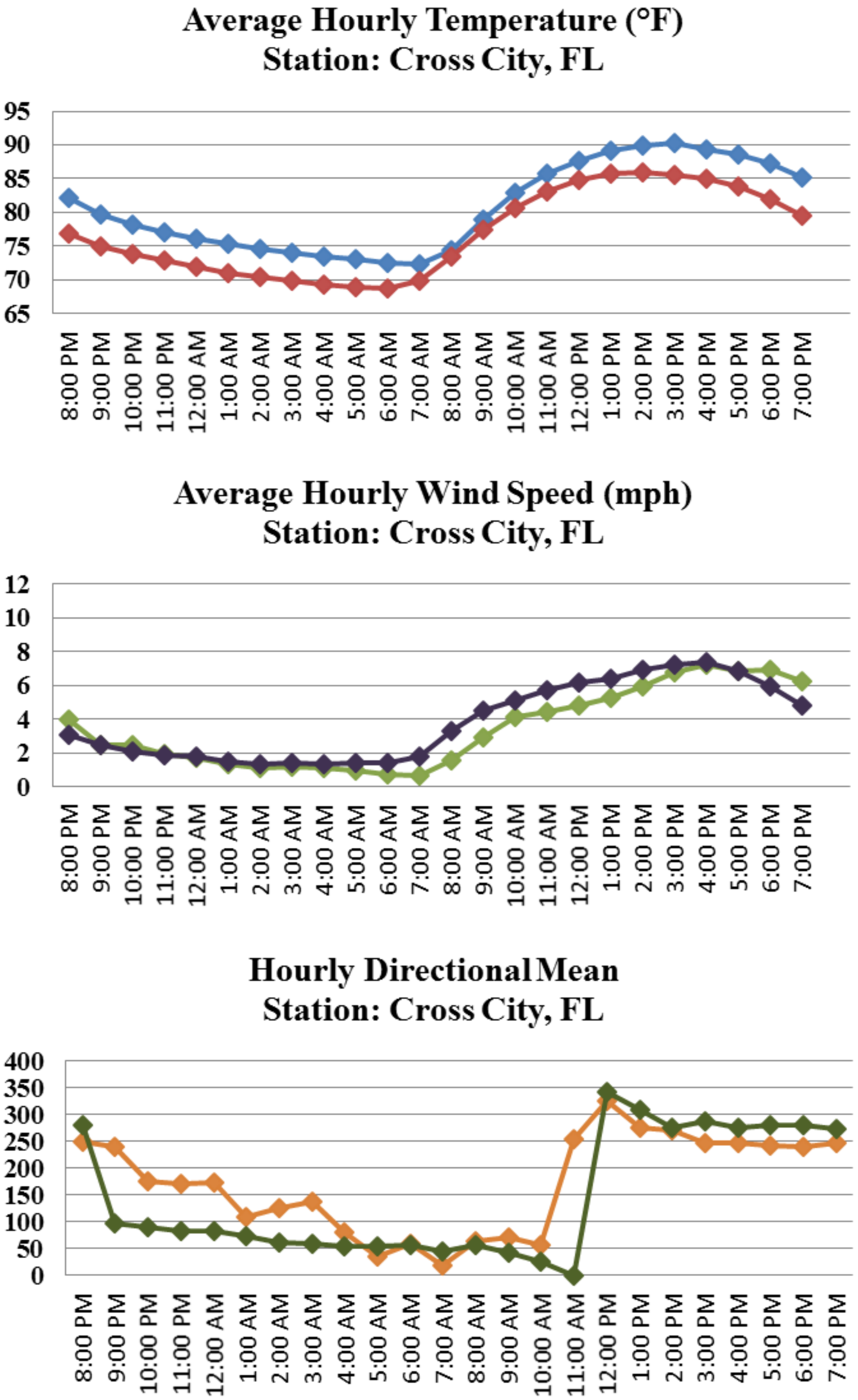


Figure A.11 Average hourly surface observations for Tallahassee station

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.



Average Hourly Temperature (°F)
Station: Cross City, FL

Average Hourly Wind Speed (mph)
Station: Cross City, FL

Hourly Directional Mean
Station: Cross City, FL

Figure A.12 Average hourly surface observations for Cross City station

Sea breeze day: colors blue, green, and orange, respectively. Non-sea breeze day: colors red, purple, and green, respectively.