THE CLIMATOLOGY OF THE DELAWARE BAY/SEA BREEZE

by

Christopher P. Hughes

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Marine Studies

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Approved: ____
Dana E. Veron, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: ____
Charles E. Epifanio, Ph.D.
Director of the School of Marine Science and Policy

Approved: ____
Nancy M. Targett, Ph.D.
Dean of the College of Earth, Ocean, and Environment

Approved: ____
Charles G. Riordan, Ph.D.
Vice Provost for Graduate and Professional Education

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This thesis is dedicated to:

My family for their unconditional love and support.

My wonderful fiancée Christine Benton, the love of my life, who has always been there for me every step of the way.

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ABSTRACT

The sea-breeze circulation is a coastal phenomenon that is of great importance to the Delaware community. The sea breeze is a mesoscale occurrence that is driven by the temperature difference of air over the land and the sea. A sea breeze front can cause drastic changes in wind direction, wind speed, and temperature which can have a significant effect on tourism, pollution, coastal ocean currents, and wind power potential.

The wind climatology over Delaware and its corresponding coastal regions is investigated using meteorological stations and output from the Weather Research and Forecasting Model (WRF). Significant summertime diurnal variations are found between coastal and inland areas in both observed and modeled data. Additional climatological wind variations are observed between stations over the Delaware Bay (BRND1) and nearby open ocean (Buoy #44009).

The climatology of the Delaware Bay/Sea Breeze is investigated using radar data, synoptic maps, meteorological stations, and WRF. Three sea breeze classifications are designated based on changes in dew point, temperature, and wind magnitude. A sea breeze detection algorithm was created which searches for classic sea breeze days with large temperature drops and estimates their time of occurrence. The large concentration of stations per area, along with radar animations, provides insight over the propagation shape of the sea breeze front. From this, it is shown that both the Delaware Bay Breeze and the Delaware Sea Breeze can act separately depending on varying synoptic conditions. A predictive algorithm was developed at a coastal station in Bethany Beach, DE that predicts the likelihood of a sea breeze based on conditions at 8 AM (EST). WRF has been employed to study the detailed structure of the sea breeze over land as well as over the bay and ocean where meteorological data is sparse. It is shown that the sea breeze circulation is a complicated phenomenon that occurs throughout the region and significantly impacts the summertime temperature and wind climatology of coastal Delaware.

Chapter 1

INTRODUCTION

1.1 Motivation

The genesis and behavior of atmospheric mesoscale systems are controlled by both prevalent synoptic conditions and local land surface properties. Small and large scale variability associated with land surface properties make mesoscale features difficult to predict. These features typically have a life cycle of hours to days and are often superimposed on the prevailing synoptic conditions. One such feature, the sea breeze, occurs frequently in the summertime along Delaware's coastline with the Atlantic Ocean and the Delaware Bay. The sea breeze circulation is important because it affects tourism, local temperature, and air quality. The sea breeze can increase wind speeds during hot summer days when power demand in Delaware is at its highest which may provide a boost to offshore wind turbines.

This research study is divided into two parts with a focus on improved understanding of the local winds over southern Delaware, the Delaware Bay, and the nearby Ocean. Thus far, studies have broadly classified the general wind climate for the region using only a few stations well inland or out to sea (Garvine and Kempton, 2008). However, this study will show that the local wind climate is far more complex. There are significant differences in the wind climatology between the above mentioned regions in part due to the influence of mesoscale systems like the sea breeze.

The first part of the study is an investigation of the wind climatology of the region using meteorological observations (Figure 1.1). Data from eight weather stations operated by the Delaware Environmental Observing System, the National Data Buoy Center, and WeatherBug have enough temporal coverage (over 4 years) to develop a detailed picture of wind directions in both the seasonal and diurnal timeframe. The extent of the data is not long enough to provide insight on inter-annual variability. Relationships between temperature, dew point, wind speed, and wind direction are quantified within and between stations. The Weather Research and Forecasting (WRF) model is employed for the year 2009 to examine the wind field developed in the model, which is evaluated with the meteorological stations.

The second part of the study focuses on the Delaware Bay/Sea Breeze which has significant impacts along Delaware's coastline. An analysis of radar images is used as an initial method for detecting a sea breeze front. An objective sea breeze detection scheme has been developed based on changes in the observed conditions. The Classic Sea Breeze category includes days with abrupt changes in temperature and wind direction over a short period of time. The Dew Sea Breeze category includes days with little to no temperature decrease but a sharp increase in dew point. Finally, the Weak Sea Breeze category includes days with a defined easterly wind regime at the test station while west winds are persistent at an inland reference station. A simplified detection scheme is developed for WRF output data based on wind and temperature conditions. Characterization of sea breeze by location, penetration distance, temperature drop, and time of onset are also investigated. A comparison of these modeled and observed variables and classifications lends insight into how a regional scale atmospheric model, WRF represents the sea breeze. The return flow and structure of the sea breeze at high spatial and temporal resolution are also investigated in WRF. The summertime Delaware sea breeze has been evaluated from 2000 to 2009.

1.2 Sea Breeze Formation and Structure

A sea breeze front usually originates along the coastline between land and a large body of water. The thermal properties of water allow incoming radiation to be absorbed in the water column primarily near the surface. This causes the surface temperature of a large bay or ocean to be minimally responsive to diurnal forcing. In direct contrast, most land surface types poorly disperse heat. In particular, urban surfaces have been observed to be heated to surface temperatures well in excess of the surrounding air temperature. In tandem, these processes create a temperature and pressure gradient from which a sea breeze circulation can develop (Figure 1.2).

The sea breeze front is located where advancing cool marine air meets warmer continental air. Typically the continental air mass is drier than the corresponding marine air but this is not always the case. Surface friction and opposing air flow forces some of the advancing sea air to be pushed upward and backward, which then mixes with the drier air. This forms the sea breeze head which lags behind the sea breeze front. More turbulence occurs behind the head and this can result in Kelvin-Helmholtz billows which form along the top of the sea breeze circulation. Surface friction also causes warm air to sink beneath the advancing sea breeze front. This air mixes with the sea breeze after the front passes and can form a series of lobes and clefts (Simpson, 1994). The height of the sea breeze is smallest at the front where it can be less than 500 meters thick. In the same study, the researchers showed that the height of the front is inversely proportional to the headwind (Simpson and Britter, 1980). However, throughout the length of the sea breeze, a typical frontal height is about 1 kilometer (Barry and Chorley, 1992).

The difference between air temperature over land and over the sea surface that is needed to develop a sea breeze can be as little as 1ºC (Watts, 1955). Generally, offshore wind has the effect of blocking the propagation of a sea breeze. However, this can be overcome if the temperature gradient is sufficient. For example, in England, it was shown that a sea breeze could form and propagate against 8 m/s prevailing winds if the temperature difference was greater than 11ºC (Watts, 1955). One would expect the highest propagation distances to occur in areas where there are large land-sea temperature gradients and relatively light synoptic winds. Northern Australia is a good example of this, with a sea breeze penetration distance of up to 200 kilometers (Barry and Chorley, 1992). Sea breezes are an almost daily occurrence in Florida, although the propagation distance is not as large (Atkins and Wakimoto, 1997). The distance of propagation of a sea breeze front was found to follow a logarithmic probability distribution in a twelve year study over England (Simpson, 1994). As the sea breeze propagates landward it also grows in a seaward direction. It is difficult to tell where the seaward circulation terminates because of a lack of a thermal boundary (Arritt, 1989).

1.3 Sea Breeze Observations

1.3.1 Radar Detection

There are many ways to study the progression of a sea breeze. Perhaps the most visually satisfying way is through the use of weather radar. It is easier to detect a front when the radar is in “clear air” mode as opposed to precipitation mode. This is a very sensitive setting that allows for the following types of echoes: birds, airborne insects, and dust. An early study showed that “there is a correspondence between the onset of a sea breeze and the passage on-shore of clear-air echoes” (Atlas, 1960). It is believed that the echo changes are probably caused by a combination of insects and changes in refractive index properties. The main radar site for this study is the NEXRAD station at the Air Force Base in Dover, Delaware (http://www.ncdc.noaa.gov/nexradinv/). The resolution of moving radar images in the Delaware region can be unpredictable but is typically 1 km by 1 degree. In dry air mode, this is usually high enough resolution to capture evidence of sea breeze fronts. This data is used to investigate typical shapes of the front and possible estimates of distance penetrated inland. Figure 1.3 shows the formation of a sea breeze over Delaware on July 8, 2007. Surprisingly, it appears that the front penetrated nearly to Delaware’s western border with Maryland before dissipating. An available animation with over 200 screen shots shows the development and propagation of the front (http://isadora.geog.udel.edu/~hughes/).

1.3.2 Satellite Data

Satellite imaging is another possible way of diagnosing a sea breeze front. The sea breeze front is the location where cool ocean air meets with warm land air at, and near, the surface. This causes uplift which leads to the possible production of cumulus clouds. When the front passes there is descending air which is cooler and typically more stable. This decreases the likelihood of cloud production. Air ahead of the front may also produce cumulus clouds, but usually less than at the front. These tendencies allow for the depiction of a sea breeze with standard satellite imaging as shown in Figure 1.4.

However, this method cannot be the primary way of detecting a sea breeze, as it requires high-resolution images taken at several times through the day. There is evidence that a sea breeze can pass through a coastal area without triggering the formation of clouds (Crouch, 2006). This may be due to the general stability of the atmosphere as well as the organization of the front. In some cases, especially with prevailing winds from the ocean, the front can be very poorly defined resulting in a slow drop in temperature and rise in dew point (Miller, 2003; Crouch, 2006). Due to the concerns described, the satellite-detection method is not employed in this study.

1.3.3 Meteorological Station Data

The main source for observing sea breezes as well as predicting them comes from meteorological weather stations. Databases from the National Data Buoy Center (NDBC) and Delaware Environmental Observing System (DEOS) are the two main sources of observational data in this study. From an observational standpoint, this allows for objective selection of parameters such as changes in wind speed, wind direction, temperature, and dew point that are associated with the passage of a sea breeze front. One concern is that a sea breeze, like many other weather features, is difficult to define. There is much interpretation over what defines a sea breeze (Crouch 2006). The proposed study will limit the definition of a sea breeze to the following: A wind flow from the ocean or bay towards land resulting in a reversal or change in magnitude of the prevailing synoptic winds which primarily is caused from the positive temperature gradient between the land and ocean surface. This interpretation attempts to isolate the sea breeze from winds that come solely from the water resulting from low pressure systems, back door synoptic fronts, and thunderstorm outflows. A methodology will be discussed in a later section that is similar to Crouch's classification of sea breeze days (Crouch 2006) which is based on observational temperatures, dew points, and wind directions and magnitudes. Dew point will be calculated from the relative humidity and temperature. The wind speeds will be interpolated to a height of ten meters for station and model comparison.

1.4 Importance

There are many reasons why a sea breeze is important to those living along the coast. The passage of a sea breeze front has a cooling effect which often moderates summer heat and can influence tourism. This is especially important to commercial businesses along Delaware's coastline whose tourist season occurs when sea breezes are most abundant. Additionally, air pollutants such as ozone and smog can get transported in a sea breeze circulation and can affect a location's air quality (Clappier and Alain, 2000). A sea breeze circulation can increase winds near the coast which could be a benefit to offshore wind turbines. Characterization of Delaware's sea and bay breezes can determine their impact on the local climate, such as overall impact on temperature. Understanding the low-level winds in this area will be useful in understanding how things may change in the future as local land-use and global climate changes.

1.4.1 Tourism

Sea breeze systems are most likely to develop in high temperature conditions with weak prevailing winds. An obvious effect of a sea breeze is that it brings cooler marine air inland. The temperature drop from the passage of a sea breeze front is typically on the order of 1ºC to 6ºC with part of this variation being related to the time of day when it passes. If a front passes early in the day it may suppress the natural daytime increase in temperature as opposed to causing a decrease in temperature. Contrastingly, if the front passes through late in the evening then it could be superimposed on the natural drop in temperature and can lead to a more substantial temperature change. The sea breeze's effect on tourism is difficult to measure because the influence is variable and encompasses all age groups, social classes, and personality types. A study using data from OECD (Organization for Economic Cooperation and Development) among other sources showed that worldwide, coastal areas receive a higher proportion of tourism than inland locations (Wietze & Tol, 2002). It was also shown that the optimal daily high temperature favored by American tourists is estimated to be 23.8ºC (74.8 F). Surprisingly, there was no optimal temperature found specifically for beach goers. It is suspected that this is due to the wide range of people who travel to the beach. The optimal temperature for many activities that bring in tourist dollars such as sightseeing, walking through town, and mini-golfing was found to be close to 24ºC (75 F). The passage of a sea breeze front typically has the effect of lowering the air temperature by several degrees. Since the average high temperature in Delaware in the summer is well above 80ºF it is suspected that the passage of the sea breeze front would increase tourist dollars spent. This is important because approximately 7.8 million visitors travel to Delaware annually (www.delaware.gov).

1.4.2 Pollution

Like many other states, Delaware has the potential for unhealthy air in the summer. In 2008 the National Ambient Air Quality Standards (NAAQS) estimated that there was 14 times where the healthy limit for ground ozone was surpassed in Delaware. In each of these cases there was more than 0.075 ppm of ozone recorded in at least one city in Delaware for at least 8 hours. A sea breeze has the effect of bringing in less polluted air from the ocean. It also pushes the polluted air towards new areas. However, once the sea breeze front has passed “the stable layer acts as a lid to the dispersion of smoke and other airborne pollutants” (Simpson, 1994). These pollutants can remain trapped in a small area and move towards the ocean overnight. There is evidence that the pollutants can remain intact offshore and move back towards land the next day if another sea breeze occurs. Vehicle exhaust is a major source of pollution along the Delaware coastline (Layton, 2006). Many tourists from out-of-state drive the length of Delaware to reach Delmarva beaches. Tourism peaks in the summer when sea breezes are more common. Vehicle pollution can undergo chemical changes in sunlight and form photochemical smog which tends to stay in the lower part of the atmosphere (Simpson, 1994). Understanding the climatology of the sea breeze is a critical step in ultimately understanding how pollution formed in Delaware’s coastal regions will behave.

1.4.3 Wind Power

The coast of Delaware is a favorable location for offshore wind power facilities. Figure 1.5 shows how the entire Delaware Bay and surrounding Atlantic Ocean are good wind resource locations. Many state governments are investigating offshore wind power. Specific locations have been researched in Delaware, Maryland, New Jersey, and Virginia (Figure 1.6).

Wind farms have an average life expectancy of at least twenty-five years. That is a long enough time-frame for the climatology of any region to shift especially in response to a modified land surface. Understanding the behavior of the winds along the Delaware Bay and neighboring areas is essential to increase the confidence that is needed for such a large investment. A slight increase or decrease in the mean winds can make a huge difference on the profit margins of these projects. This is because the power generated from a turbine is roughly proportional to the cube of the instantaneous wind speed (Figure 1.7). A sea breeze has an interesting effect on the output of wind turbines and depends very much on their distance from the coast. Sea breezes are most likely to occur on hot days with relatively weak prevailing winds. In Delaware, because there is a large influx of tourists during the summer months, power needs are increased. The power demand is increased further during hot and humid days. PJM, a regional transmission organization, typically experiences peak loads of electricity (~135,000 MW) during extreme heat waves (PJM). The sea breeze circulation originates at the coast and propagates in both directions. Therefore its climatological effect diminishes with distance away from the shore. This is the opposite of the general wind patterns which favor stronger winds away from the coastline where there is less surface friction. The backside of the sea breeze circulation (the portion over the water) may only reach 10 to 20 kilometers in length. Therefore it is anticipated that an increase in sea breeze days may increase power from offshore wind turbines that are close to shore during the peak demand of the summer season.

1.5 Literature Review

1.5.1 Theoretical Sea Breeze Model

There have been many studies that have focused on theoretically representing the structure of a sea breeze. While this study focuses on observations and numerical modeling, it is important to recognize the core physics of the sea breeze circulation and its interactions with other weather features. Walsh (1975) formulated a simple linear model of a sea breeze circulation. The Boussinesq approximation was used to simplify the effects of buoyancy-driven flow. This negates the effect of the difference in density of two air masses except in the calculation of the acceleration due to gravity. A typical Coriolis parameter was used and solar input was forced with a sinusoidal function. A hydrostatic and geostrophic solution was generated as a result of viscosity and conduction (Walsh, 1975). They noted that the non-hydrostatic solution did not significantly change the resulting velocities. The return flow was investigated with calm prevailing winds and was found to be half the speed but twice the thickness of the flow near the surface. This study helps to point out that additional variables including stability of the atmosphere and heat fluxes can influence the sea breeze circulation.

Another study looked at sea breeze circulation theory with respect to the generation of internal-inertial waves (Rotunno, 1983). They found that the circulation pattern depends on the Coriolis force and the prevailing wind. The Coriolis force has the effect of decelerating the circulation in the late afternoon. According to their model, the shape of the front does not depend on the land-sea temperature difference. More recently, Qian looked at how the structure of the sea breeze is affected by prevailing wind conditions (Qian 2009). The addition of background flow adds a component to the solution that is "broadly similar to flow past a stationary heat source (or equivalently to flow past topography)" (Qian, 2009). As expected, this effect is proportional to the speed of the background flow. This study provides insight into the larger scale response from the circulation but does miss smaller scale features.

1.5.2 New Jersey Sea Breeze

The closest region to Delaware that has had a study focusing on the sea breeze is New Jersey (Bowers, 2004). This study focuses on upwelling which is prevalent along both New Jersey and Delaware's coastline in the summer. The study concluded that increased upwelling, represented in the WRF model, increased the propagation of the sea breeze and causes winds at the front to be stronger. It is shown that a Delaware Bay breeze can form on the northwest side of the Bay and interact with the New Jersey sea breeze creating increased convergence in Cape May County. Through the WRF model it was shown in Bower's study that a 5°C to 6°C temperature differential between air over land and air over the ocean did not trigger a sea breeze while anything over that typically did. These conclusions are based on four test cases.

1.5.3 What Affects a Sea Breeze?

A figure by Crosman and Horel does an excellent job at visually capturing the environmental variables that influence a sea breeze (Figure 1.8). The land surface sensible heat flux is the primary driver of the sea breeze circulation. It is shown using WRF simulations that increasing the heat flux by increasing the temperature gradient results in an increase of the height of the sea breeze front and surface wind speed of the circulation (Steyn, 1998). The increases in wind speed and circulation height are shown to be proportional to the square root of the horizontal heat flux (Porson et al, 2007). Some of the strongest landward velocities occur on days with high air land/sea temperature gradients.

The geostrophic wind can prevent the formation of a sea breeze (Gilliam et al., 2004). If the flow is offshore it can counter the effects of the horizontal pressure gradient. If the flow is onshore it can remove the temperature gradient which fuels the sea breeze. Studies show that a geostrophic wind range of 6 m/s to 11 m/s includes the critical offshore wind speed needed to prevent a sea breeze (Biggs and Graves, 1962). Other studies indicate that a slightly slower wind speed will prevent the onshore propagation of the front (Grisogono et al., 1998). This is an outcome that is frequently seen across Delaware's coastline in radar and meteorological observations. Studies show that a 2 m/s to 4 m/s geostrophic onshore wind can prevent or mask the sea breeze (Arritt, 1993). Both weak onshore and offshore synoptic winds are suitable for large inland progression of the sea breeze front. This study looks at the effects of the background winds as measured by land stations placed more than twenty kilometers from the Delaware's shoreline. At times the synoptic winds can be strong enough to prevent the Delaware Bay/Sea Breeze even with land temperatures approaching 100°F.

The width of the water source has been shown to have an impact on the development of the sea breeze (Physick, 1976). This is partly because the width of the water body will limit the extent that the circulation can grow seaward. The Delaware Bay is oddly shaped but roughly has dimensions of 35 by 40 kilometers. Sea breezes can and often do develop on both the New Jersey and Delaware side of the Bay. These circulations compete for the available marine air over the Bay and studies in similar areas show that this competition will often limit the propagation of the front, effectively reducing the area available in which the circulation will develop (Physick, 1976). However, if the circulation has the right orientation, it can extend past the mouth of the Bay and out to sea. This impact is investigated with WRF simulations because there is a lack of observation stations immediately inland from the Delaware Bay. The shoreline across the western side of the Delaware Bay is concave. Studies have shown that a concave shoreline tends to weaken the landward component of the sea breeze (Gilliam, 2004).

In the northern hemisphere, the Coriolis force acts to shift the circulation clockwise. At the latitude of interest, this has been shown to be a dominant force several hours after the onset of the sea breeze (Yans and Anthes, 1987). It has been argued that at high latitudes the circulation at the front of the sea breeze can shift to have a seaward component overnight and thus be mistaken for or possibly increase the land breeze circulation (Rotunno, 1983).

1.5.4 Past Study of Delaware Winds

The wind climate over water has been analyzed for the Delaware Bay and the rest of the Mid-Atlantic Bight (Garvine & Kempton, 2008) using more than sixteen stations from the NDBC with record lengths from 1.7 to 19.6 years. Our study has several stations in common with this study including #44009, BRND1, LWSD1, SJSN4, and CMAN4. The mean wind speed in this region has a range of 6.83 m/s to 7.93 m/s at a height of 80 meters. The lower wind speeds are near the coast and the higher wind speeds are towards the mouth of the bay and out to sea. The analysis presented in this thesis will follow their study, but with the addition of many DEOS stations that span southern Delaware and with a higher temporal resolution. The Garvine and Kempton study shows that higher winds are observed in the winter months at Buoy #44009, with an increase in the mean wind speed of over 3 m/s (9.48 m/s and 6.37 m/s) which equates to over three times as much power density. Garvine and Kempton (2008) explored some of the diurnal changes in wind speed and direction and observed that the diurnal signal was more evident near coastal locations than well out to sea (>20 km). However, this purely observation based study does not investigate the location between the coastline and twenty kilometers seaward. The wind resource in the coastal mid-Atlantic region benefits from the low surface friction of open water but is also strongly influenced from the sea breeze circulation. The WRF model is used to analyze the general wind climatology and the effect of the sea breeze on this unique location.

Previously, the wind regime of the Delaware Bay has been included in studies that focus on the currents within the Delaware Bay. Münchow and Garvine (1993) showed that the wind forcing is often in competition with buoyancy forcing to control the Delaware Coastal Current. They showed that strong upwelling favorable winds can overpower the buoyancy forcing. This is most likely to occur in the late spring and summer seasons. They also showed that wind accounts for a large portion of the variance in the current for high frequencies. Wong (2002) studied the wind-induced exchange near the Indian River Bay. He showed that the coastal sea level fluctuation and currents were most responsive to two wind bands with directional headings of 40º and 90º. Other studies show the effects of wind forcing on surface currents and its effects on the transport of crab larvae (Epifanio, 1989). While studying the geomorphology of estuarine barriers in the Delaware Bay, Evelyn Maurmeyer (1978) looked at the winds from the Wilmington Airport between 1951 and 1960. There is a clear northwest signal in January and a slightly less pronounced dominant signal from the south in July. While this station is located in northern Delaware it still gives insight into the climatological winds of inland southern Delaware.

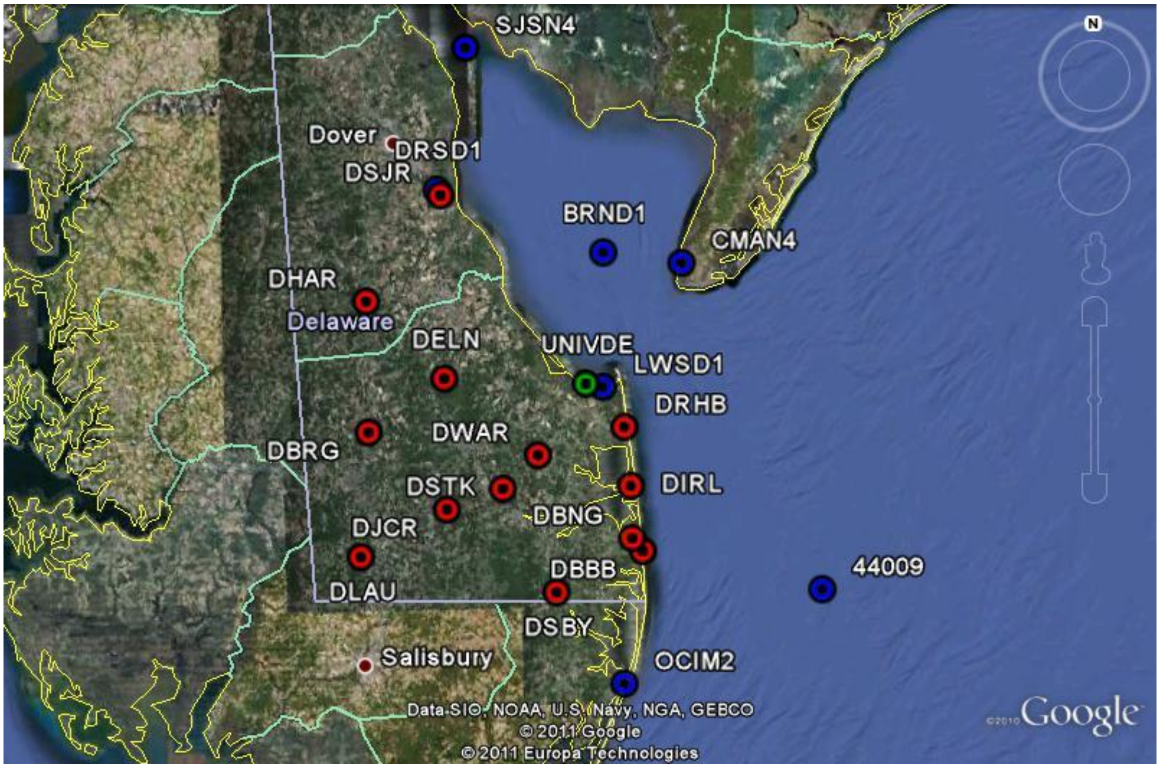
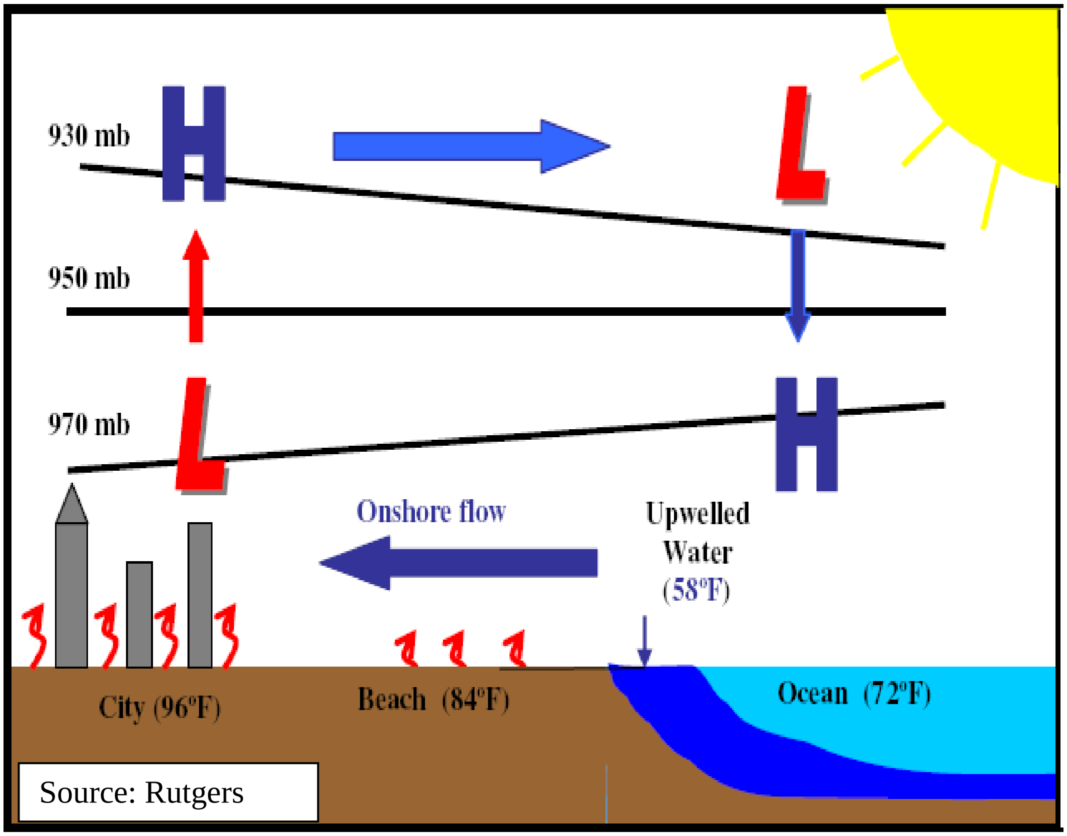


Figure 1.1: Meteorological stations of interest. There are twenty-one meteorological stations employed in this study. Thirteen (red) are from the Delaware Environmental Observing System (DEOS). Seven (blue) are from the National Data Buoy Center. A remaining station (green) is operated by the WeatherBug in the city of Lewes, DE.



Sea Breeze Circulation

Figure 1.2: **Representation of a sea breeze circulation. A sea breeze circulation is formed due to temperature differences between air over land and air over water. In the summer, the air over water is kept cooler due to the high specific heat of water. This causes a horizontal temperature and pressure gradient. An onshore flow develops from the ocean to the land. A return flow is caused by uplifting air over the land. This can lead to sinking air over the ocean. (Photo Courtesy of Rutgers University)**

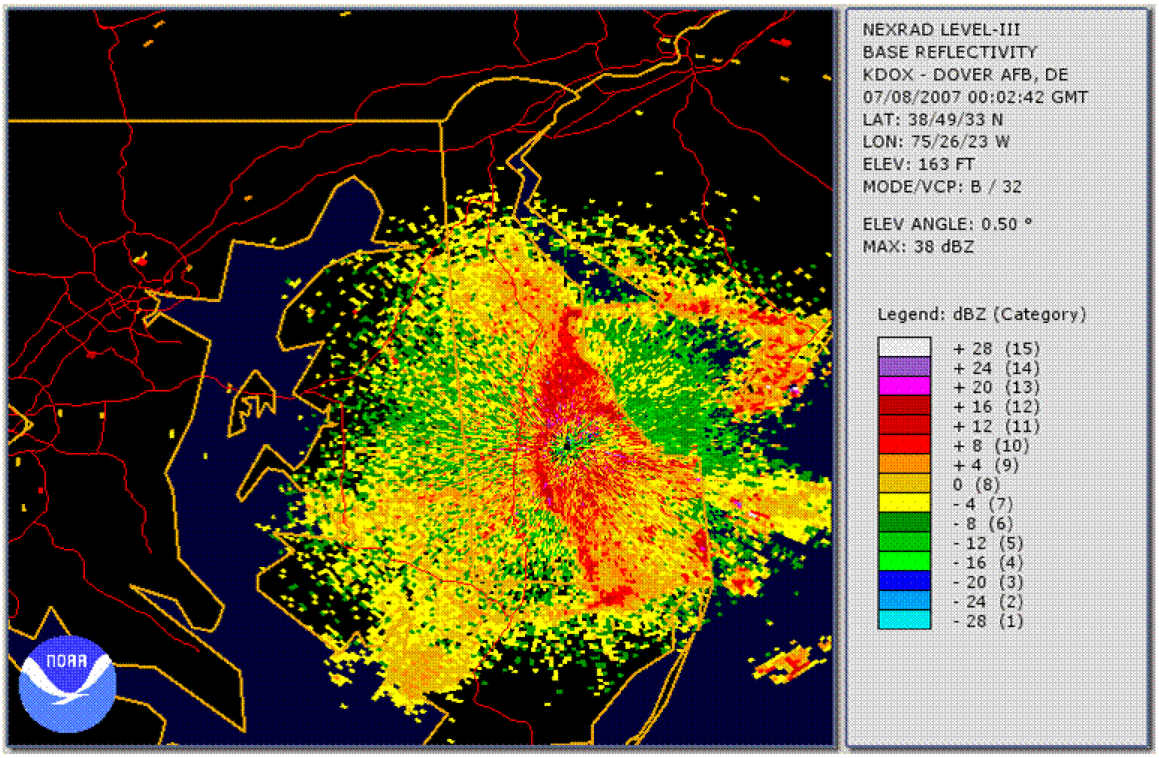


Figure 1.3: **NEXRAD Radar detected sea breeze front over Delaware (KDOV). This clear-air image shows differences in air density. The sea breeze front is represented by the darker orange and red colors.**

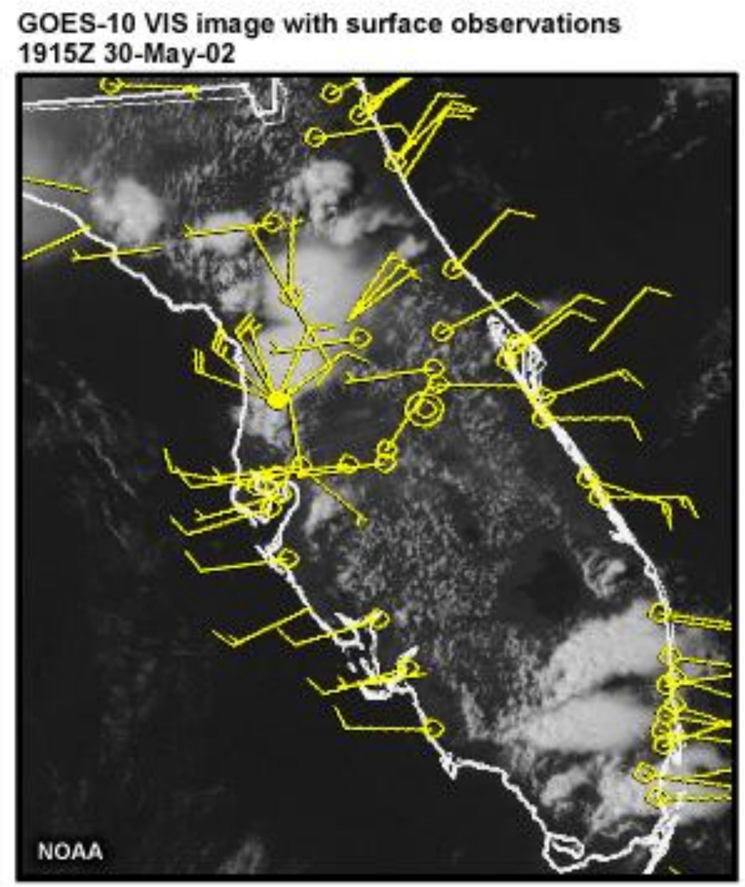


Figure 1.4: **NOAA satellite detected sea breeze front over Florida. This image shows multiple sea breeze fronts spanning Florida's coastline. The front is a favorable location for cumulus cloud development due to increased uplifting. The clear regions located near the coast are probably locations where the sea breeze front has passed and the atmosphere is more stable. The Lake Okeechobee breeze is also present in this figure.**

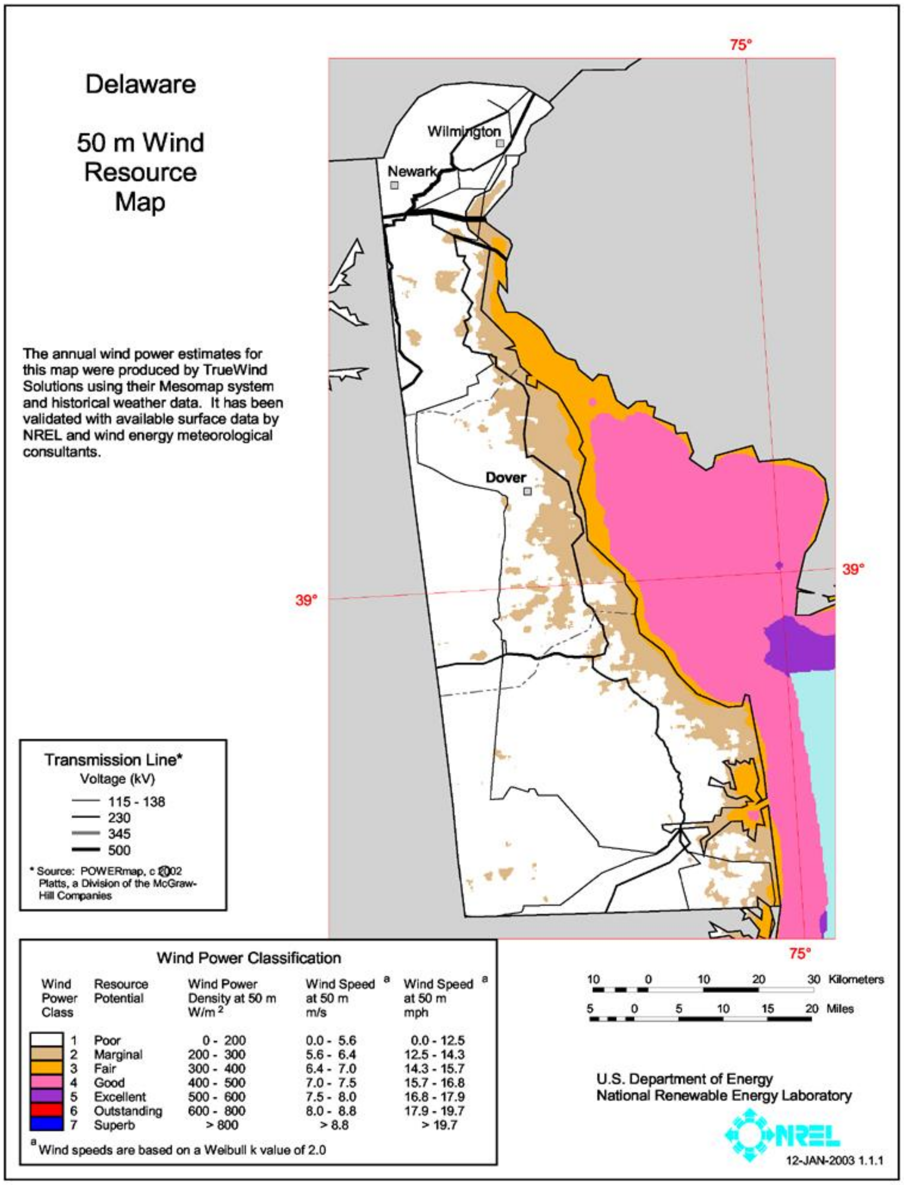


Figure 1.5: **NREL projection of Delaware's wind power resource. The immediate coastline of Delaware is a fair resource for wind energy while just offshore the ranking rises to good. This is an overall composite of the wind potential and does not take into account seasonal or diurnal mesoscale variations in wind strength.**

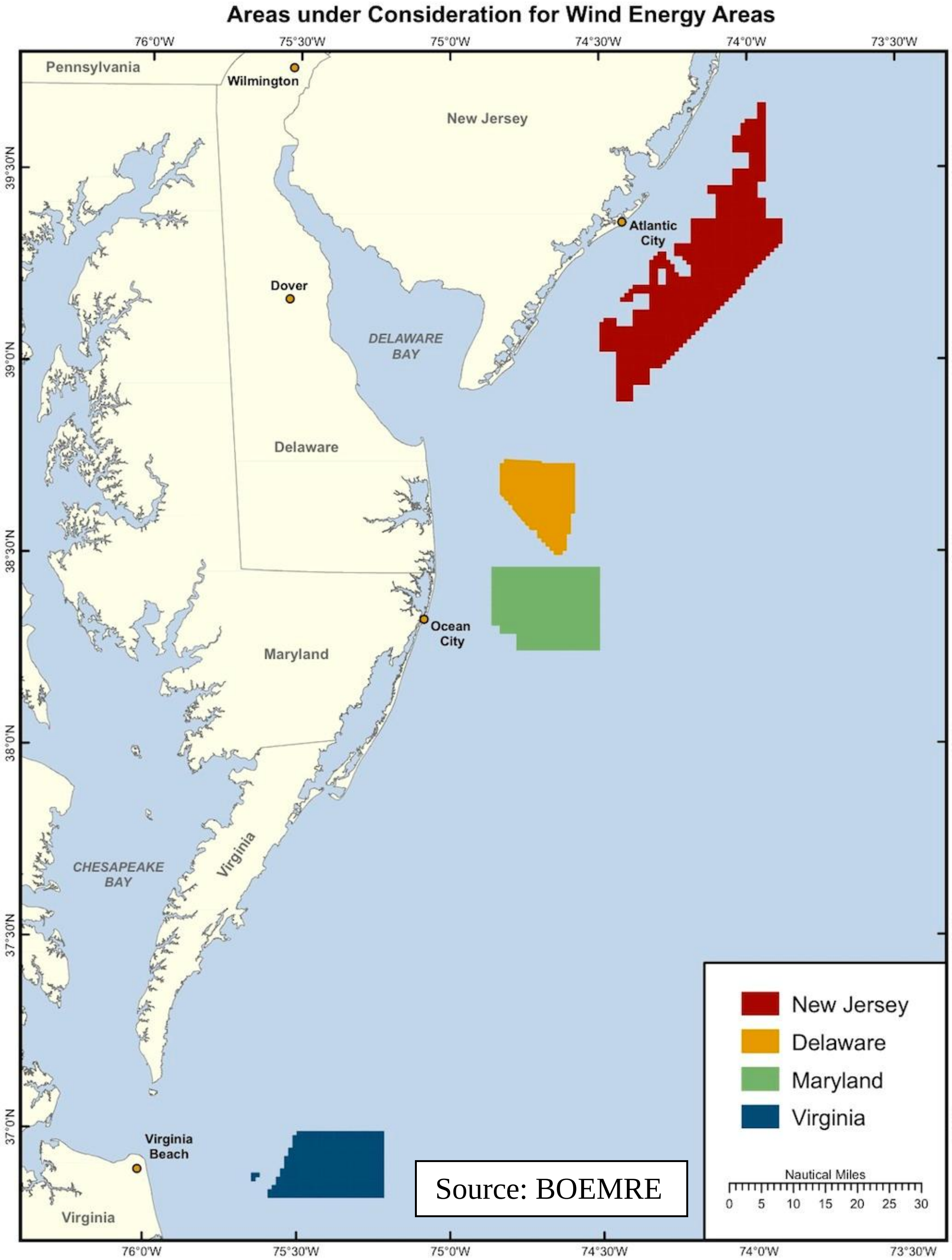


Figure 1.6: Offshore wind energy areas for possible development. Delaware and its neighboring coastal states have all investigated specific offshore locations that would be favorable for placing wind turbines. (Photo Courtesy of BOEMRE)

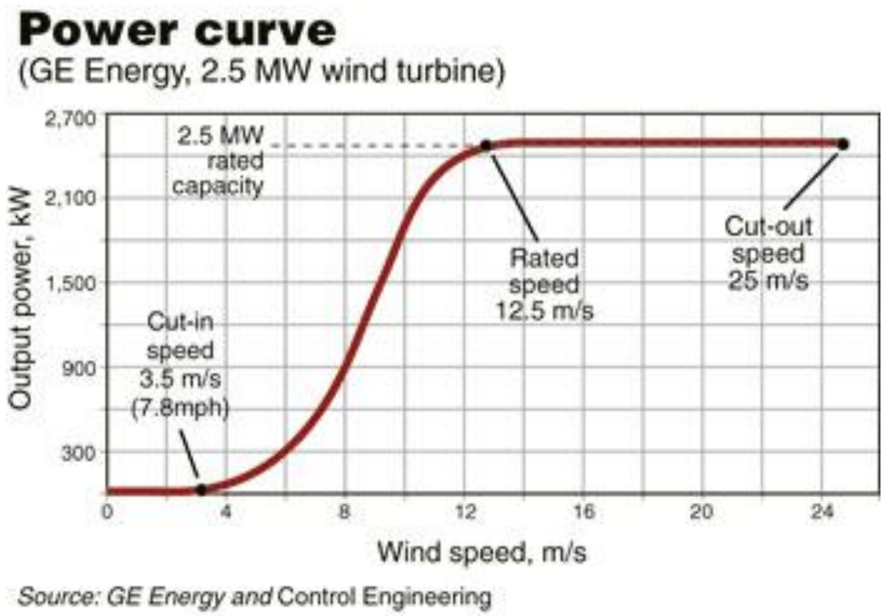


Figure 1.7: **GE Energy idealized power curve for a wind turbine. Typically, no energy is obtained until the wind speed is at least a few meters per second. This is known as the cut-in speed. At high wind speeds the energy obtained is maxed out due to limitations within the turbine. The turbine will have to shut down if the wind speeds are too high.**

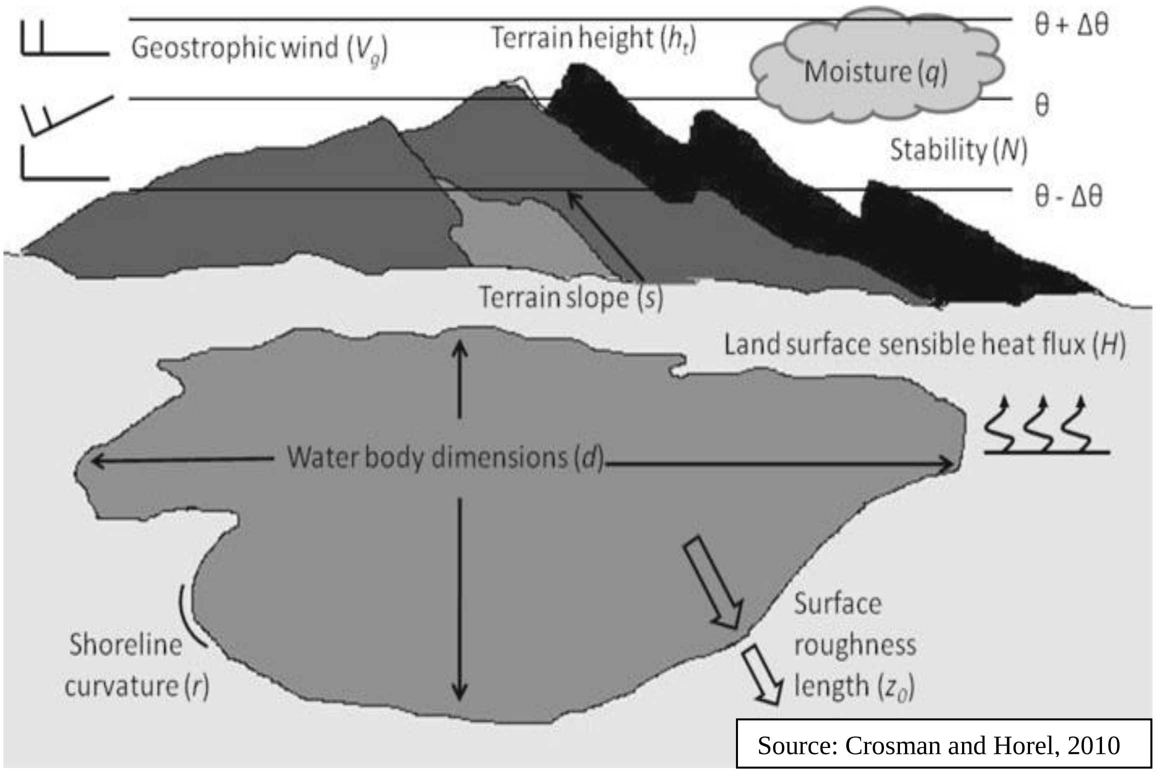


Figure 1.8: **Geophysical variables that control a sea breeze. There are many factors that control and influence a sea breeze circulation. Those that are particularly important to Delaware's Bay/Sea breeze are the following; H, Vg, d, r, and z_0 (Crosman and Horel, 2010).**

Chapter 2

DATA ACQUISITION

2.1 Observation Data

While Delaware is a small state it has a wide array of meteorological stations. These stations can be utilized to provide a detailed climatology for the southern half of Delaware, the Delaware Bay, and Delaware's coastline with the Atlantic Ocean. A sea breeze circulation often develops along Delaware's coastline in the summertime months. The meteorological stations are located on a variety of different land types including farmland and open water, as well as more urban areas. These surfaces can have a significant impact on the air temperature, wind speed, and relative humidity, all of which are investigated. A Google Earth generated image shows the geographic location of every station used in this study (Figure 1.1). Data is available for thirteen stations from the Delaware Environmental Observing System in the years 2005 through 2009. Five of these stations span the entire time frame while the rest are typically missing the first few years of the timeframe. All DEOS stations provide values at approximately five minute intervals for wind speed, wind direction, temperature, and relative humidity. Dew point values are calculated from temperature and relative humidity. Most DEOS stations have an anemometer height of three meters. For comparison between the stations and with modeling data, all stations will have their wind values interpolated to a height of ten meters. This height is chosen because it is a standard wind speed comparison height and other stations from other sources have anemometer heights between five and fifteen meters.

Table 2.1 compares the distance of each of the stations from the Atlantic Ocean and Delaware Bay. There are five stations that are within a few kilometers of either the Atlantic Ocean or the Delaware Bay. Two of the stations, DBBB and DBNG, are located in Bethany Beach. DBBB is located on the boardwalk which is within 100 meters of the shoreline. DBNG is located at the National Guard station in Bethany Beach. It is approximately one kilometer northwest of the boardwalk station. Located several kilometers north, DIRL is situated along the Indian River inlet. Further north DRHB is located on the boardwalk in Rehoboth Beach. Several kilometers to the north of Rehoboth beach is Lewes, Delaware which is located near both the Delaware Bay and Atlantic Ocean. DSJR is in Kitts Hummock, Delaware which is a few kilometers from the Delaware Bay but approximately 43 kilometers from the Atlantic Coastline.

The western edge of the study area is near southern Delaware's western border with Maryland. There are three stations located near the border and they are more than 40 kilometers from the Atlantic coastline. DHAR is located at the raceway station in Harrington, Delaware. It is approximately 23 kilometers from the Delaware Bay. DBRG is located in Bridgeville Delaware. It is about 22 kilometers to the south of DHAR. DLAU is located by the airport station in Laurel, DE. It is approximately 21 kilometers south of DBRG and marks the southwestern corner of the study area. It is expected that any of these three stations can capture the synoptic picture without significant influence from mesoscale coastal phenomenon like the sea breeze.

The remaining DEOS stations are located in south-central Delaware and are fairly evenly spaced. The furthest north of these stations is DELN which is located in Ellendale, DE. DWAR is located in Harbenson, DE and is only 16 kilometers from the Atlantic Ocean. DSTK is located in Stockley, DE and is only 8 kilometers from the DWAR station. Further west, the DJCR station is located at the Jones Crossing station. DSBY, located in Selbyville, DE, is the southernmost station located near the southern border of Delaware and Maryland.

Six stations are used from the National Data Buoy Center. LWSD1 is located in Lewes, Delaware right at the mouth of the Delaware Bay. BRND1 is mounted on a lighthouse which is located in the middle of the Delaware Bay. OCIM2 is located at the inlet in Ocean City, MD. CMAN4 is located right across the Delaware Bay in Cape May, NJ. SJSN4 is located at the entrance of the Delaware River to the Delaware Bay near Ship John Shoals, NJ. NDBC Buoy #44009 is located approximately 30 kilometers from the southern shore of Delaware in the Atlantic Ocean. It contains weather data every hour with minor gaps for the time period between 1984 and 2009. The remaining stations have data between 2005 and 2009 at 6 minute intervals. All NDBC stations included in this study have water temperature measurements in addition to air temperature, wind, and dew point values.

A station located in Lewes, Delaware and operated by WeatherBug will also be employed in this study. The station has standard meteorological data in one hour intervals from June 2001 through November 2008. DEOS stations also have pressure, solar radiation, and wind gust observations and some NDBC stations have water temperature values. These variables provide additional insight into the local weather climatology.

Data availability is always a concern when dealing with long time series. B44009 has fairly continuous coverage throughout the time series although there is a six month gap in data between November 1992 and April 1993. The overall coverage of wind data is approximately 90% over the 26 year period between 1984 and 2009. A separate analysis showed a similar availability of temperature data from this station.

BRND1 started collecting data in 2006 but there are large gaps during that year. From 2007 through 2009 there are fairly consistent readings at this station. Most monthly percentages of availability are between 60% and 80% with data taken every six minutes. LWSD1 has extremely consistent coverage from June 2006 through December 2009 with poorer coverage throughout 2005 and early 2006. SJSN4 started collecting data in 2006 and has consistent data except for a five month gap in summer of 2009. OCIM2 has no gaps throughout its timeframe of mid 2008 through 2009.The observation based wind climatology analysis is limited to stations with at least four years of data with more than 75% percent coverage. These stations include the following NDBC stations: BRND1, LWSD1, and SJSN4.

DEOS stations, as a collective group, have very high availability with relatively minor gaps in the time series. The following stations start coverage in the beginning of 2005; DJCR, DLAU, DWAR, DSJR, DBBB, and DBNG. The lowest average percentage of availability is DWAR with approximately 72% which includes two and a half months of missing data in the beginning of 2005. The other stations have over 85% coverage during this time frame. DBRG and DHAR have coverage starting in 2006. DHAR has some poor coverage months in 2006 but both stations have near complete coverage from 2007 through 2009. The remaining five stations (DSTK, DELN, DRHB, DIRL, and

DSBY) start coverage in 2008. Availability for all stations is high in 2008 and 2009 with an average of 91%.

One particular issue with this data is the effect of wind shadowing. This can occur if a building or other object is near the anemometer and disrupts the natural wind flow. Wind shadowing may completely block a range of wind directions. This may limit the frequency or lower the winds from the affected directions.

2.2 Modeling Data

2.2.1 Introduction

WRF is a next generation mesoscale atmospheric model that can be used in research or forecasting mode. WRF is an excellent model for this project because it has a proven record of simulating regional climate (Fung and Zong-Liang, 2008) and has been used in previous sea breeze studies (Bowers, 2004; Chen, 2004). These studies have suggested that WRF's ability to represent synoptic winds is equal to or exceeds other standard mesoscale models such as MM5 (Darby, 2007).

WRF was employed in this study to simulate the regional climate for the Delaware Bay for the summer months of June, July, and August from 2000 to 2009. Output from these runs is used to analyze the influence of the sea breeze and the summertime wind climatology. In addition, the entire year of 2009 was modeled for comparison with the observational wind climatology. Each run has a duration of one month with a one-day spin up from the end of the prior month.

2.2.2 Data Forcing

Figure 2.1 represents the three nests that are used for all modeling parts of the study. The smallest nest, with a two km resolution, can resolve small-scale features like a sea breeze front. It includes the southern half of Delaware, the Delaware Bay, and approximately twenty kilometers of the nearby ocean. The larger nests have resolutions of six and eighteen kilometers. They assure that a good simulation of the prevailing synoptic flow occurs. The simulations presented in this study use data from the North American Regional Reanalysis project (NCEP). Variables forced at the boundaries include air temperature, winds, pressure, geopotential height, and moisture. The forcing data have a spatial resolution of 40 kilometers and temporal resolution of three hours. These variables are given at 29 pressure levels. These boundary conditions allow WRF to focus on mesoscale events within grid boxes with a resolution of 2 km by 2 km.

2.2.3 Run Time Options / Schemes

The NOAH land surface model will be the primary one used in this study (Chen and Dudhia, 2001). It incorporates land use categories from the USGS but does not have any governance over water. Land surface models interact with the overriding atmospheric model to transport surface heat and reflect both shortwave and long wave radiation. The NOAH land surface model (LSM) uses four soil levels to provide an intricate representation of soil moisture flux. An advantage of this model is that is has the ability to modify surface emissivity properties by season. With the NOAH LSM, there is the possibility to attach an urban canopy model to better deal with manmade surfaces. An urban canopy model was not used in this study but could be advantageous in future studies of the region.

WRF has a preprocessing system (WPS) which interpolates geographic data onto the user-determined grid. WRF has complex microphysics which can resolve water based processes including clouds and precipitation. The Atmosphere Research Dynamical core is used since idealized scenarios are investigated with forcing at the boundaries to simulate the synoptic conditions. This core allows for hydrostatic mass and arbitrary vertical resolution. Sixth order spatial differencing equations for fluxes are used to conserve mass and entropy. There are many preprocessing and run time options. Second order diffusion is used with a constant vertical coefficient. This coincides with the PBL of choice (YSU PBL scheme) which calculates the vertical diffusion. The Kain-Fritzch cumulus parameterization is used in the larger two nests. It is suggested that no cumulus parameterization is needed for grid boxes smaller than 3 km by 3 km (Dudhia, 2008).

2.2.4 WRF Represented Coastline

The landscape used for the WRF runs does not precisely reflect the true coastline of the region (Figure 2.2). There are several instances where WRF locates a station to be over water when it is actually located over land at the coast. In the cases of DBNG, CMAN4, OCIM2, LWSD1, and UNIVDE, a neighboring grid point from WRF is used for comparison. DIRL is located along a coastal strip that borders the Atlantic Ocean to the east and the Rehoboth and Indian River bays to the west. WRF recognizes the presence of both bays but not the coastal strip. Therefore DIRL is four longitudinal grid boxes (8 km) away from the nearest WRF land point. This point will be used for comparison because it is of interest to compare the model to observations in coastal regions as opposed to over the ocean, even though the spatial location is not ideal. Future work may include correcting errors within WRF's coastline.

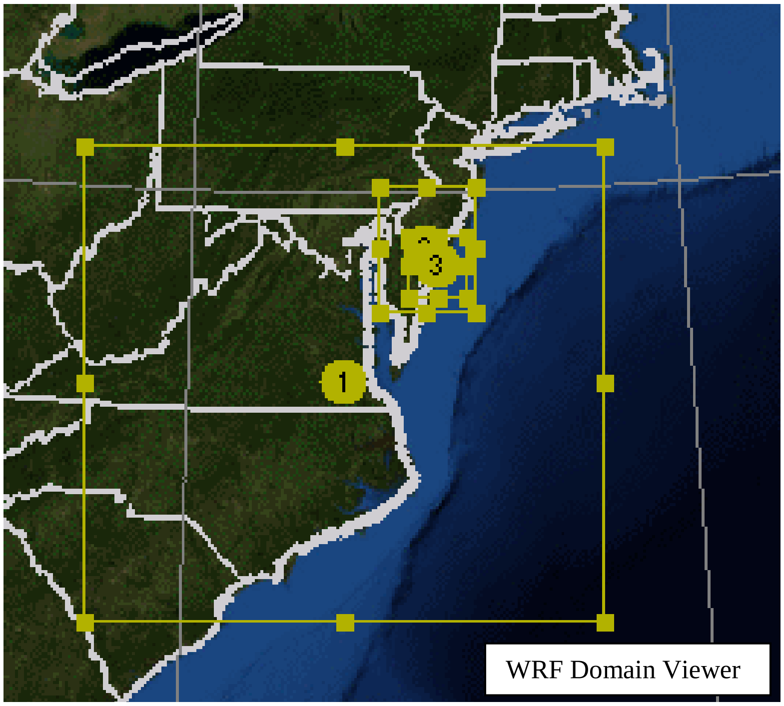


Figure 2.1: **Domains used in WRF. The larger nest has a spatial resolution of eighteen kilometers and receives boundary forcing from NARR data. The middle nest has a resolution of six kilometers and is used to transition into the smallest grid box that has a two kilometer resolution. The smallest grid box is used to investigate the region's winds in fine detail and can resolve mesoscale features such as a sea breeze circulation. (WRF Domain Viewer)**

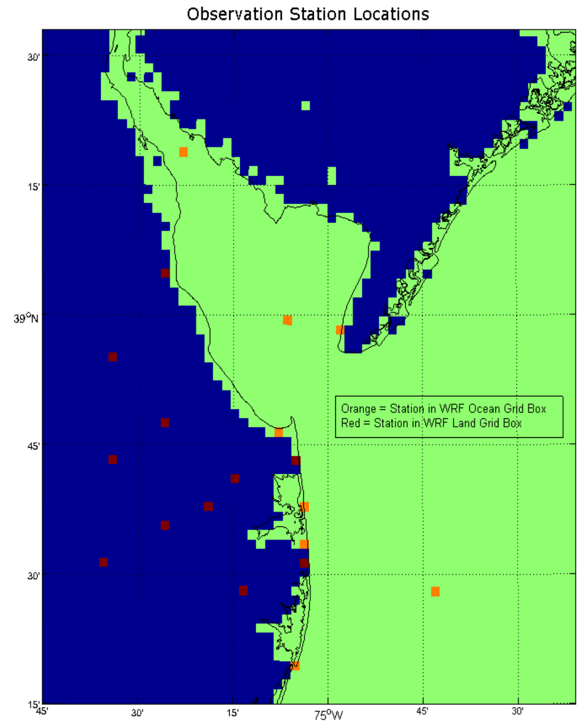


Figure 2.2: **WRF Grid cell representation of obs. stations. The WRF represented coastline underestimates the landward extend of Delaware's coastline. This is especially evident along barrier islands separated by tidal inlets. To account for this all stations that WRF incorrectly assigns as being over water are moved to the nearest land point for comparison. In future studies, the coastline should be altered to better approximate the true coastline.**

Table 2.1: Obs. station distance from water bodies. Negative values represent oceanic stations that are embedded in the bay or ocean and their distance to the nearest coastline.

Station	**Distance to Coast** (km)	**Distance to Ocean** (km)	**Distance to Bay** (km)
B44009	-30	-30	53
BRND1	-13	14	-13
LWSD1	<1	3	<1
CMAN4	<1	4	<1
UNIVDE	<1	6	<1
DRHB	<1	<1	8
DIRL	<1	<1	17
DBBB	<1	<1	28
OCIM2	<1	<1	53
SJSN4	<1	56	<1
DBNG	1	1	26
DSJR	3	43	3
DWAR	14	16	14
DSBY	15	15	36
DELN	17	31	17
DSTK	22	22	22
DHAR	23	45	23
DJCR	31	32	31
DBRG	33	44	33
DLAU	47	47	47

Chapter 3

SOUTHERN DELAWARE WIND CLIMATOLOGY

3.1 Introduction

Southern Delaware is a dynamically interesting area, even if lacking in altitudinal variability. Interactions between the Delaware Bay, Atlantic Ocean, and the Chesapeake Bay can clearly affect the climate of the Delmarva Peninsula. Through the use of wind roses, time series, and model output it is shown just how vibrant the winds of the region are. Particular attention is paid to coastal areas that are notoriously difficult for models to resolve.

To better analyze the region, the meteorological stations will be divided into several categories. The open water category will comprise of BRND1 over the Delaware Bay and Buoy #44009 over the Ocean. The coastal category will account for all stations within 2 kilometers of the bay or ocean. The remaining stations will fall into the inland category.

3.2 Data Validity

A wind rose captures a significant amount of information about the wind climate of a region. High quality anemometers have no obstructions and produce wind roses with smooth transitions between dominant wind directions. Figure 3.1 displays wind roses for many stations in the study using all available data from 2005 to 2009. A minimum velocity of one meter per second is designated to minimize low speed wind direction errors. The thirty-six sectors comprising each wind rose correspond to ten degree segments. Each sector is graded by color according to the frequency of the component wind speeds.

The image for NDBC Buoy #44009 is an ideal example of a complete and illustrative wind rose. Wind flows from every direction and there is a seamless transition between apparent dominant directions. The following additional stations have high quality wind roses; B44009, BRND1, DBNG, DBRG, DHAR, DLAU, OCIM, LWSD1, and SJSN4. Several other stations have minor issues. For example, DIRL has a severe surplus of readings from the north. This is most likely due to some malfunction with the anemometer. UNVDE has a very narrow gap in the northerly direction (355° to 360°). This is possibly due to wind shadowing involved in the placement of the anemometer. The placement of this station is such that it may not be affected by the location of docked ships to the North because of the anemometer height. There is no evidence of major deviations from this station and LWSD1 which is located within three kilometers of the station. LWSD1 may have minimal wind shadowing due to its location to the Lewes terminal. DSTK has readings from all directions but with lower wind speeds relative to comparable stations. The remaining stations have significant wind shadowing problems mainly caused from buildings or other obstructions. DRHB clearly has wind shadowing from the northwest and southwest. This creates a huge increase in wind from the west direction. This is also a problem for DBBB located along the boardwalk of Bethany Beach. These stations and others with significant shadowing give some information on the climatology of the wind and still retain significant value for the sea breeze portion of the study. CMAN4 has an anemometer that rarely recorded the wind direction and will not be used. DWAR has a peculiar shape to its climatological wind rose and is used with caution.

3.3 Buoy #44009

NDBC Buoy #44009 has the longest running time series with 26 years of data. While this station is 30 kilometers to the west of Delaware's coastline, it should provide some insight to the climatological representativeness of the years 2005 to 2009 which is the timeframe for most of the other stations. The mean maximum temperature approaches 25˚C during the day in the summer while the minimum approaches freezing in the early morning hours of late January (Figure 3.2). The lowest temperature recorded was -14.3˚C on January 19th 1994 at 11 A.M. A cold front passed through with strong winds of over 11 m/s from the northwest and an abnormally high pressure reading of 1038 mbs. This was the coldest day by several degrees. The highest recorded temperatures reach about 30˚C and are capped because of the evaporative effects of the surrounding ocean.

Every year between 2005 and 2009 had a positive mean temperature anomaly ranging between 0.16˚C (0.25 s.d.) and 0.94˚C (1.46 s.d.). Four out of the five years between 2005 to 2009 have a mean wind speed below average with the five values deviating -0.22 m/s (-.71 s.d.) to 0.31 m/s (0.99 s.d.) from the twenty-six year average. Comparing a wind rose from data from 1984 to 2009 against data from 2005-2009 illustrates minor differences (Figure 3.3). Both have clear dominant wind directions from the NW and SSW. The most obvious distinction is that the more recent data shows a slight clockwise shift in its southerly wind component. The wind speeds that comprise each segment of the wind rose are very similar. It is concluded that the years from 2005-2009 are representative of the long term climate for the region with the exception of a mean temperature warm bias.

3.4 Wind Roses

A classic wind rose is perhaps the best way to visually represent the dominant wind directions of a particular station. A method was designed to quantify these directions as well as examine the magnitude of each peak. The classic twelve compass directions are used to bin the wind data. If the wind was distributed in a uniform fashion each direction would contain data approximately 8.33% of the time. If a direction has over this amount then it is considered to be part of a dominant wind node. Sequences of neighboring directions that satisfy this condition are considered to be part of the same node. The magnitude of each node is defined by the sum of the departure of each of its components from that of a uniform distribution. A uniform distribution would have a magnitude of 8.33% per station (100% / 12 stations). If a node has component values of 12%, 13%, and 17% then the magnitude of the node would be: (12%+13%+17%) - (8.33% * 3) = 17.01%. The node is named according to the direction that contains the median value of the data. Since each node contains adjacent directions the mean and median should be similar but the median was chosen to avoid skewing the representation of the dominant wind direction. Eight stations have both the data availability needed for this project and a wind rose of high enough quality (no significant wind shadowing) to use in the five year comparison.

Using the method described above, the dominant wind directions are calculated by station for each month. Over the Atlantic Ocean (B44009), the winter months are defined by a moderate N and a weak SSW component. The SSW node shifts to the south in the spring months and increases in strength while the N component vanishes and is replaced by a weaker NNE component. The summer is marked by only a strong SSW component. The fall months are comprised of a weakened SSW component and a weak northerly component that shifts counterclockwise towards winter. In the Delaware Bay (BRND1), there is a persistent dominant wind component centered from the S which is roughly a 30 degree counterclockwise turn from the dominant wind observed over the Atlantic Ocean. The reason for this may be the geography of the Delaware Bay and its ability to filter incoming wind as it moves up the Bay. There is no such pronounced shift in dominant winds coming from any other direction. The three coastal stations (LWSD1, SJSN4, and DBNG) have unique dominant wind directions which again can probably be attributed to their respective unique locations. SJSN4 has a 30 degree counterclockwise shift from BRND1 in its southerly component and is therefore centered in the SSE direction. The northerly component is also shifted in the same way and is centered in the WNW direction. This feature is further exaggerated in LWSD1 where it has more of a westerly component especially in the winter months. There is no shift in the SSW component, although it has a weaker signal than corresponding stations. Both LWSD1 and DBNG show a weak but persistent wind direction from the ENE that fluctuates throughout the year. DBNG has a NNW and SSW component similar to but weaker than that of B44009. The three inland stations (DBRG, DHAR, and DLAU) show similar characteristics. DHAR has a persistent component from the S while DLAU shows one from the SSW. DBRG’s component oscillates between the two directions. There is significant distance between the three stations and the proximity of the Delaware Bay may be a cause for this difference. Figure 3.4 shows the sum of the strength of the dominant wind components for each month averaged for all the stations. Higher sums are representative of more well-defined wind regimes. There are minimum values of 12% and 13% at April and October respectively. There are maximum values of 28% and 26% in January and July respectively. This means that there are more pronounced dominant wind directions in the summer and winter than in the spring and fall.

The wind direction analysis gives insight into the strengths and seasonality associated with the local wind patterns. It is clear that the summer and winter months have the strongest signals across all stations while the spring and fall months transition between the two. There is a dominant northwesterly component that peaks in the winter and a dominant southerly component that peaks in the summer. In the spring and fall there is a weak north easterly component. For a more quantitative analysis, the components of each wind rose are analyzed.

There is considerable variance in the wind patterns on a seasonal scale. Figure 3.5 shows the seasonal progression for DBNG and a comparison to that simulated for the same location in WRF. One of the driving motivations of the study is to determine wind variability by location across the region. In the winter the wind flows from the WNW or NNW 34%, 30%, and 38% of the time for the land, coastal, and ocean stations respectively. Winds flow from the S and SSW 22%, 17%, and 20% of the time respectively. In the summer the wind flows from the S or SSW 28%, 24%, and 37% of the time for the land, coastal, and ocean stations. Winds flow from the WNW and NNW 17%, 13%, and 13% of the time. Dominant winds over the ocean are stronger than coastal and inland areas. Narrowing in on the E, ESE, and SSE sectors, there is an interesting distinction between the stations. Percentages from these directions are nearly identical for the land and ocean stations at 9%, 19%, 19%, 17% and 10%, 20%, 19%, 19% for winter, spring, summer, and fall. However, on average, the coastal stations receive 20% to 25% more wind from these directions throughout the year. This may be a signal of the local sea breeze circulation. The NNE and ENE categories have the highest frequency for all regions in the fall season.

The diurnal effect on the winds is of particular interest for the region especially in relation to inland, coastal, and ocean stations. Solar energy is absorbed and reflected at different rates over land and water bodies. Upwelling can further complicate this gradient. Convective winds and a sea breeze circulation can develop and persist during the day. For simplicity, the day is split between 0:00-11:59 GMT (Night) and 12:00-23:59 GMT (Day) which translates to 8 AM through 8 PM (EST) during the summertime. Table 3.1 shows the frequency of wind from each direction by season for the inland, coastal, and ocean categories. Table 3.2 shows the diurnal effect by subtracting the night percentages by the day percentages for each segment. Winter has the least diurnal variability, with an average of 1.4% net deviation for each wind direction between day and night. This is elevated in spring and fall with an approximate deviation of 2.4%. The peak occurs in the summer with a net deviation of 4.2% per wind direction. As a whole, there is less diurnal variability over the ocean (2.1%) than the coastal and land areas (with 2.8% variability). However, there is a notable distinction between how the coastal and land stations accumulate their variability. Along the coast, especially in the summer there is a considerable increase in winds from the E, ESE, and SSE during the daytime hours while inland there is a decrease in SSW, WSW, and W directions. For the coastal stations in the summer the wind blows from the SSE 19% of the time during the day but only 7%

of the time at night. This 12% net increase is probably due to the sea breeze circulation. The opposite wind changes are present for landward stations. Here, in the summer, there is up to a 16% net decrease in winds from the south during the day and a small increase, up to 7%, between the WSW and NNW directions. The magnitude of the differences is about half as strong in the spring and fall months and about a quarter as strong in the winter.

There are two proposed mechanisms that aid in explaining the differences in the wind rose patterns in the region. The first is wind shift due to friction. Wind flowing from the south will typically be faster over the ocean as opposed to flowing up the Delmarva Peninsula. When the Delaware Bay is reached the wind from the ocean is likely to shift its orientation counterclockwise due to decreased friction and flow up the Bay. The second mechanism is the sea breeze circulation which helps to explain the diurnal variability of the stations. Temperature differences between the land and the ocean are more prevalent in the summer where the variations appear to be the strongest. This has been investigated in great detail and will be explained in the latter half of this thesis.

3.5 WRF Wind Direction Comparison

Twelve monthly WRF runs provide hourly data for the entire year of 2009 for all stations in the study. Eight stations have complete station availability for 2009 and a high quality wind roses with little to no wind shadowing. An additional station is missing some data but still encompasses three complete seasons. There are three inland, four coastal, and two ocean stations. The breakdown of WRF wind direction by season is presented in Table 3.3. As previously seen, WRF does a good job at capturing the dominant wind directions of each season. The magnitude of the peaks tends to be slightly higher and narrower than those seen in the observational data. For example, the winter averages for the inland stations are 9%, 18%, and 16% from the W, WNW, and NNW directions. In WRF these averages are 18%, 28%, and 8% representing a net 11% increase in winds from these directions. To compensate, WRF shows winds blowing from the ENE and E only 2% combined during the same time frame compared to 7% in the observed data.

The diurnal effect is investigated in the WRF in the same manner as the observed data (Table 3.4). There is a 22% decrease in the net winds from the SSE and S directions during the summer day for the WRF land stations. This compares with a 14% net decrease in the observed data. During the same time-frame, there is a 19% net increase in winds from the WSW, W, and WNW. A similar net increase of 20% is seen in the observed data. At the same time-frame for the coastal stations, WRF shows an increase in winds from the ENE, E, ESE, and SSE totaling 14% (22% for the observed data). WRF shows a sharp decrease of 18% in the S and SSW direction which is a 30º counterclockwise shift from the observed data which notes a decrease of 25% in the SSW and WSW directions. A similar diurnal effect is noted in the ocean stations. These results show that WRF does an excellent job at simulating the diurnal effect that is clearly present in the observed data. Some of the errors presented above may be attributed to how WRF handles the transition between ocean and land points.

To look at the coherence between WRF grid cells, three cases are presented, each comprised of two neighboring cells (Figure 3.6). The cases are located over the ocean, coast, and inland areas respectively and are on the same latitudinal plane as Bethany

Beach. This allows for the assessment of the importance of whether a grid cell is over land or water.

The coastal case shows that the winds are stronger over the oceanic point averaging 6.8 m/s compared to 5.3 m/s for the entire year of 2009 (Table 3.5). The wind speed correlation between the neighboring points is 0.92 and is strongest in the winter months. The wind directions are highly correlated with r values between 0.96 and 1.00 throughout the year. The oceanic point has a mean wind direction that tends to be slightly counterclockwise of the land mean direction during the summer. The temperature correlation is significantly stronger in the winter months averaging 0.90 compared to the summer where it is 0.60. The monthly standard deviation in temperature is lower over the ocean point (2.9°C to 5.3°C). In both cases the standard deviation is lower during the summer, probably because of the decrease in wind speeds.

Two neighboring land points (ocean points) are compared to each other to estimate the local variance. Comparing these results to the land/sea neighboring points isolates the strength of the coastal specific differences from background differences both land and seaward. The oceanic points have a better correlation to each other than do the neighboring land points although both correlations are strong. The land/sea correlation drops significantly for wind speed and temperature in the summer and this is not seen in the land/land or sea/sea pairs, thus isolating the coastal effect. The wind correlations are high for all groups. In the summer the mean wind direction varies by 4.5 degrees (ocean counterclockwise of land) for the land/sea group while the land/land and ocean/ocean groups have 1.9 and 0.3 degree differences respectively. The winds are less (more) in the inland case (oceanic case) with a mean wind of 4.5 m/s (7.6 m/s). Clearly WRF shows critical differences between land and ocean points. In comparison, the wind speed over land is less while the wind directions deviate more than over two neighboring land or two neighboring ocean points. Therefore, at a resolution of two kilometers WRF is capable of showing clear effects of a coastline on the local winds. This also shows the importance of accurately representing the true coastline in WRF. If the land type is misclassified then this introduces significant temperature and wind magnitude errors in the model.

3.6 WRF/OBS Time Series Analysis

A series of error statistics are calculated for the nine stations selected for this study, keeping the same inland, coastal, and ocean categories (Table 3.6). Wind speed correlations are highest for all categories in the fall and winter with r values typically ranging from 0.55 to 0.75. This value falls to around 0.20 to 0.40 in the summer. This most likely has to do with the dominance of synoptic systems over the cooler months and the influence of local forcing in the summer. Synoptic systems typically affect the area on a time scale of days and WRF typically does an excellent job of approximating the speeds associated with these systems (Figure 3.7). Thunderstorms are very difficult for WRF to accurately resolve given the forcing employed in this study. Overall, WRF shows higher correlations over the ocean stations (0.54) as opposed to the land (0.47) and coastal stations (0.48). WRF overestimates the winds in all three categories. The mean positive biases are 1.41 m/s, 1.05 m/s, 0.48 m/s for the inland, coastal, and ocean stations respectively. The fall months have the least amount of mean wind speed error. The average root mean squared error is 2.94 m/s, 2.79 m/s, and 2.34 m/s for the ocean, coastal, and inland stations. Relative to the average wind speed, this shows that the modeled wind speed at the ocean stations more closely agrees with observations than at the other stations.

Temperature correlations are nearly identical for the ocean and inland stations (0.80 and 0.81) while the coastal stations are more weakly correlated (0.71). This difference in correlation peaks in June with a coastal temperature correlation of 0.46 for inland stations and 0.70 the ocean category. This is most likely due to the large gradient in temperature between the ocean and land surfaces during this time. The average temperature bias is largest over the ocean stations with a 2.54ºC overestimation. The overestimation decreases to 1.25ºC and 1.39ºC for the coastal and inland stations. This positive surface temperature bias may be due to how the NOAH LSM in WRF handles its soil moisture. The model appears to lose a significant portion of the soil moisture in the first 72 hours of simulation. WRF also appears unable to accurately simulate precipitation. Figure 3.8 shows how the instantaneous temperature is sometimes approximated almost perfectly in WRF while other times it largely overestimates the daytime temperatures. Such errors appear to be common when there is considerable precipitation in the region as based on radar and Unisys data. The larger bias over the ocean is most certainly due to the poor resolution climatological SST's used in the WRF runs.

3.7 Summary

The wind climatology of southern Delaware, the Delaware Bay and nearby ocean is very complex. Surface wind characteristics including a dominant northwest wind in the winter and southerly wind in the summer persist throughout the entire region. However, there are notable shifts in the wind direction as a function of distance up the Delaware Bay (away from the ocean) especially from the southerly direction. The diurnal effect causes an increase in easterly winds for the coastal stations during the daytime while the inland stations see a nearly opposite effect. The WRF model reasonably simulates the dominant wind directions and the diurnal effect. WRF overestimates the wind speeds in comparison with that observed at the stations on the order of 1 m/s to 3 m/s. WRF accurately simulates the surface temperature on dry winter days relative to observations. There is less accuracy in the coastal temperatures, especially in the summer. Further investigation could expand the effect of synoptic conditions on WRF's ability to represent the local conditions in Delaware.

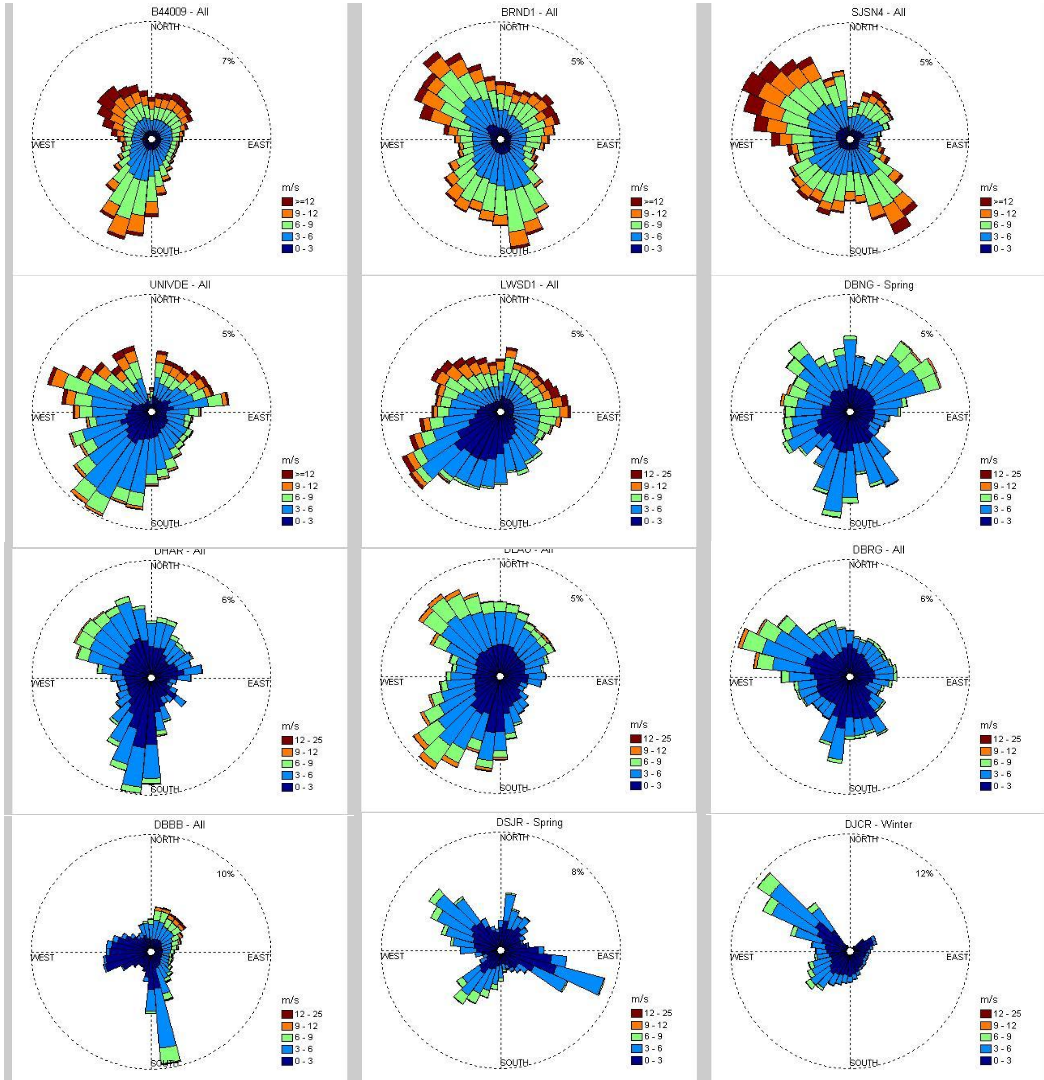


Figure 3.1: **Annual obs. station wind roses (2005-2009). The first row represents stations over the open water. The second row contains stations near the coastline. The third row shows stations that are over thirty kilometers inland. The last row shows stations with obvious wind shadowing issues.**

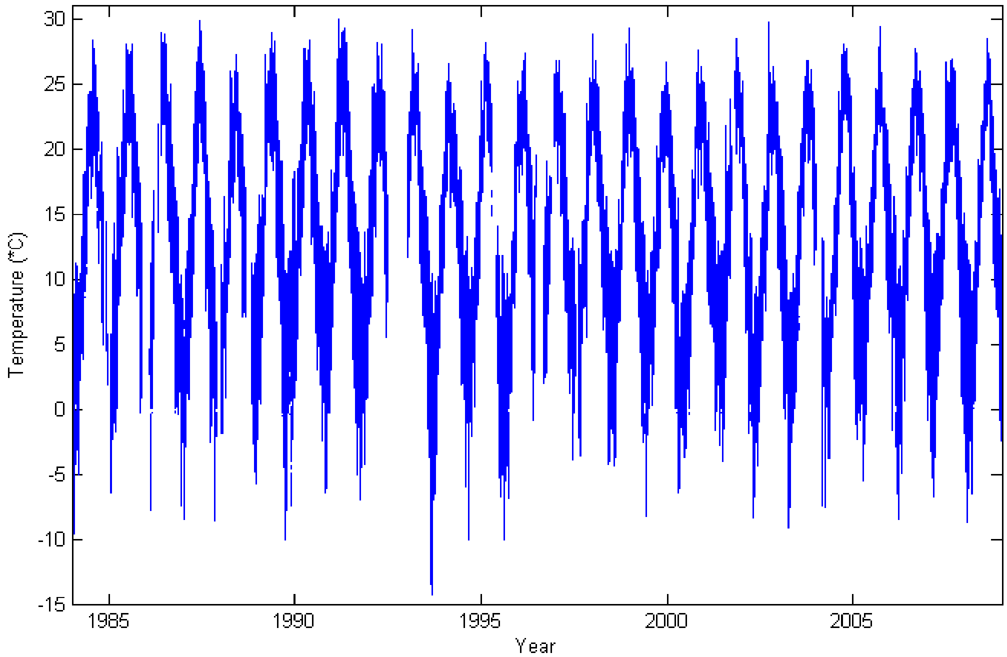


Figure 3.2: **Temperature time series for Buoy #44009 (1984-2009). There is more extreme variability in the wintertime surface temperature because strong west winds can occasionally bring abnormally cold air over the station. The temperatures are limited in the summer by the moderate sea surface temperatures and moist air.**

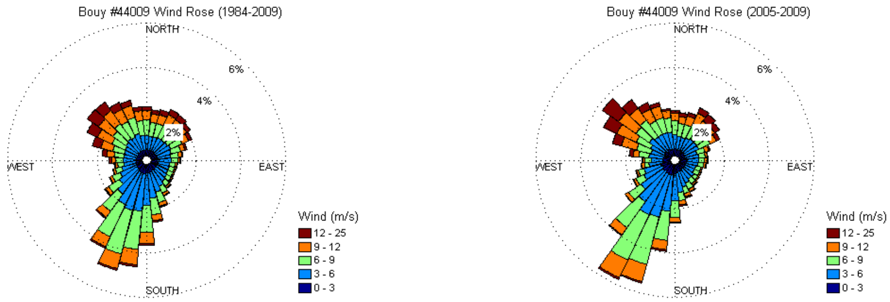


Figure 3.3: Buoy #44009 wind roses for 1984-2009 and 2005-2009. These two plots show minimal differences in the wind speed and wind direction over the last five years compared to the last twenty-six years.

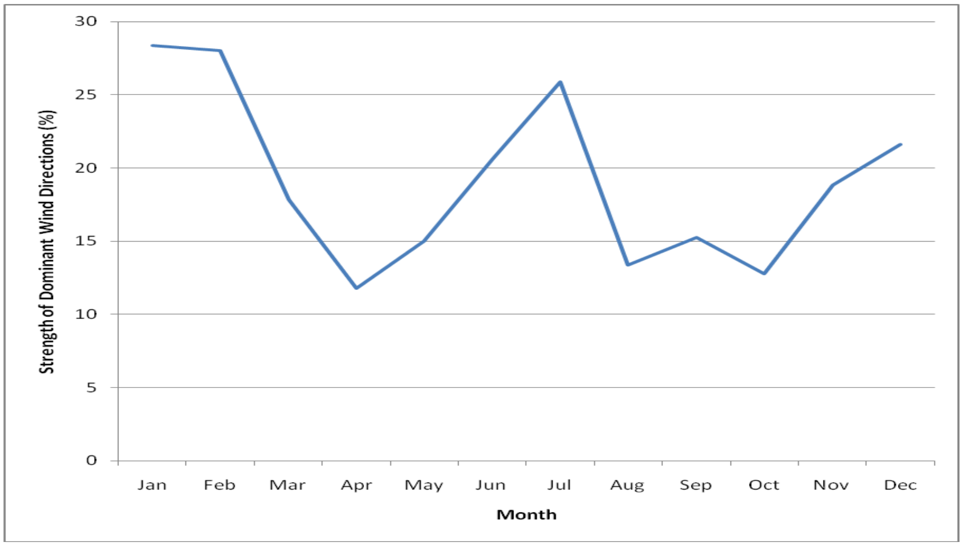


Figure 3.4: Regional strength of dominant wind directions (2005-2009). The summer and winter months have relatively more persistent dominant wind directions than the spring and fall months. The percentages displayed are a summation of the positive deviation from a uniform wind for each dominant direction for all stations.

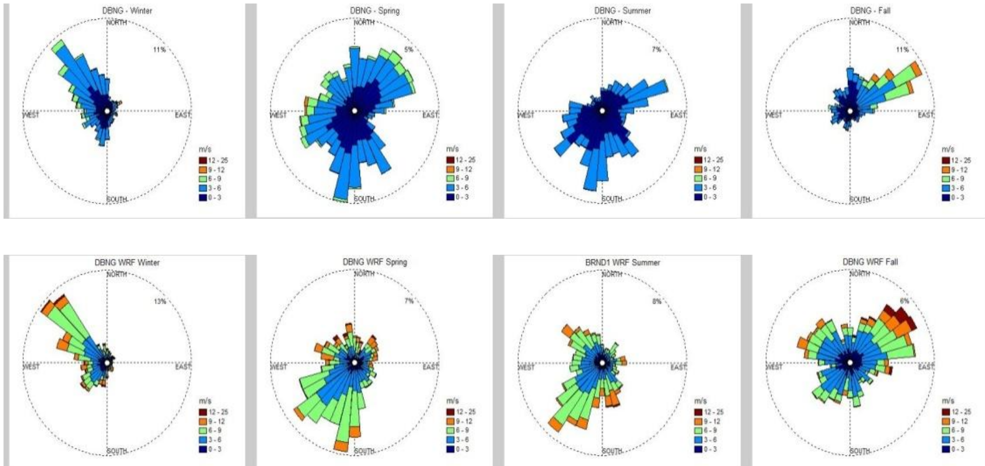


Figure 3.5: **Obs./WRF wind rose comparison by season: DBNG (2009). WRF does an excellent job at simulating wind direction as can be seen in the seasonal wind roses for DBNG. Strong winter winds are almost exclusively from the northwest while fall winds are the most varied.**

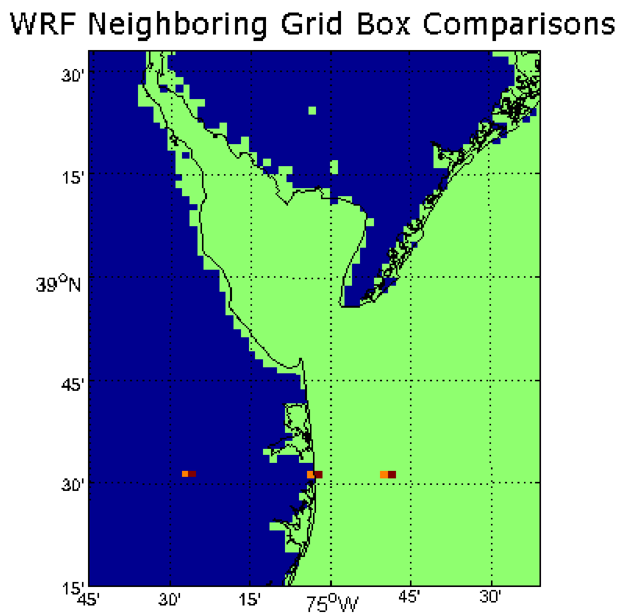


Figure 3.6: Location of selected grid cell pairs in WRF. Three sets of neighboring grid points in WRF are presented over the land, coast, and ocean. Comparisons of these points show the small scale variability presented and specifically isolates the effects of the differences in wind speed, wind direction, and temperature at the coastline.

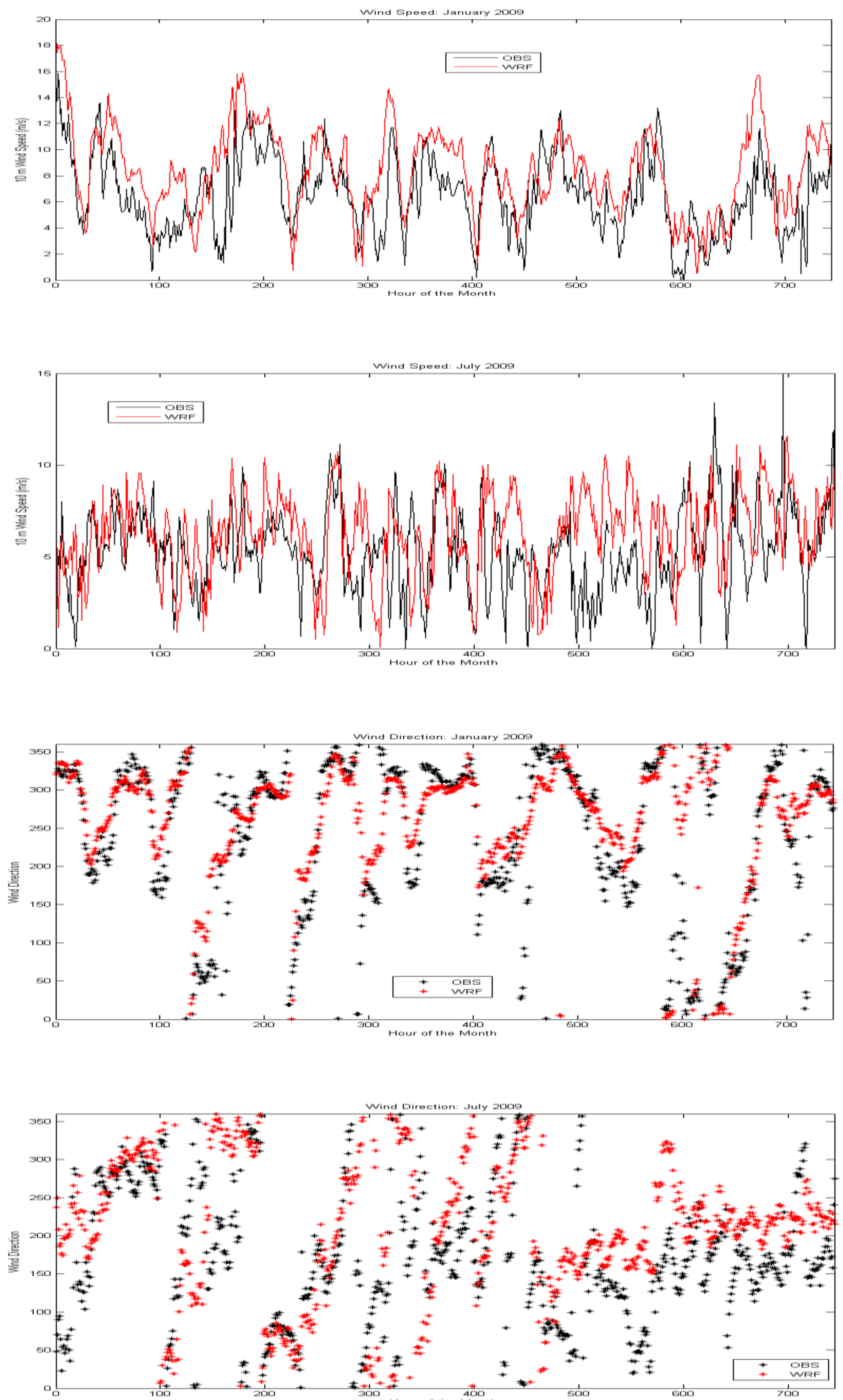


Figure 3.7: Obs./WRF wind comparison at BRND1 (Jan./Jul. 2009)

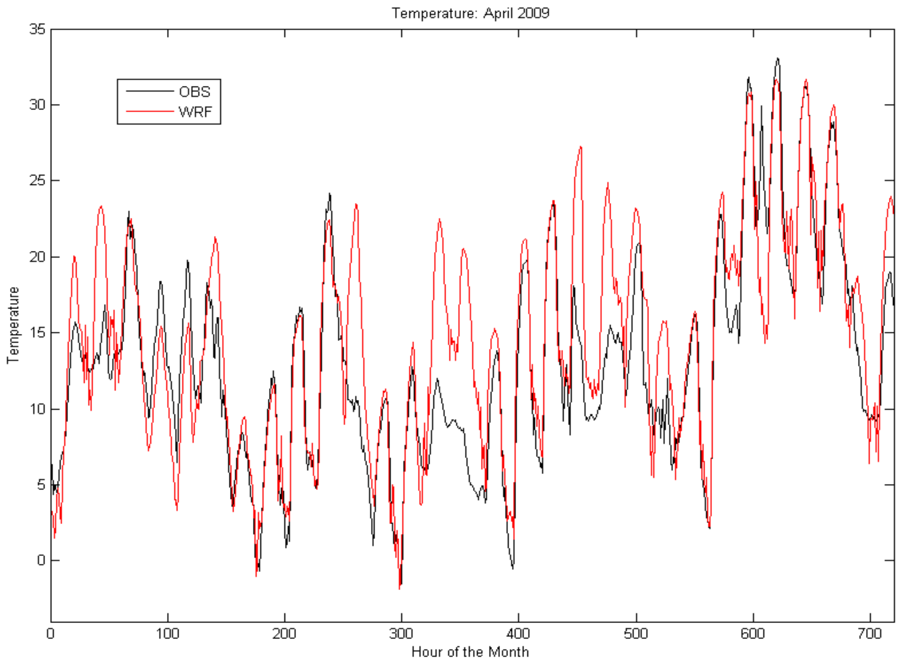


Figure 3.8: Obs./WRF temperature comparison at DLAU (Apr. 2009)

Table 3.1: Obs. station wind direction by land type (2005-2009)

	%	N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WN W	NNW
Land	Winter	8	4	4	3	2	4	11	11	9	9	18	16
	Spring	9	7	8	7	5	6	10	11	8	7	12	10
	Summer	8	6	4	6	5	8	15	13	10	9	9	8
	Fall	10	12	10	6	4	6	10	8	6	7	11	11
Coast	Winter	8	5	4	4	4	5	8	9	11	12	15	15
	Spring	7	6	8	7	6	10	9	9	9	8	11	8
	Summer	5	6	6	5	6	13	11	13	13	8	7	6
	Fall	7	9	11	7	6	9	8	8	8	8	10	10
Ocean	Winter	9	5	5	3	3	4	8	12	7	7	20	18
	Spring	8	9	7	7	5	9	12	14	7	5	11	11
	Summer	6	6	5	4	5	10	16	21	10	6	6	7
	Fall	8	11	13	8	5	7	9	11	6	5	10	10

Table 3.2: Obs. station wind direction diurnal difference (2005-2009)

	%	N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW
Land	Winter	-1	-1	0	1	0	-2	-6	0	4	3	2	0
	Spring	-1	-1	-1	0	1	-3	-7	-2	4	4	4	1
	Summer	-2	0	1	1	1	-6	-16	-2	7	7	5	4
	Fall	-4	-4	2	3	2	-2	-6	1	2	2	3	1
Coast	Winter	1	0	0	0	1	2	-1	-4	-3	-1	3	-1
	Spring	-1	-1	1	2	2	7	-1	-6	-5	-2	3	0
	Summer	0	1	2	3	5	12	1	-13	-12	-3	2	3
	Fall	1	-1	1	1	2	6	0	-6	-5	-3	3	2
Ocean	Winter	-2	0	1	1	1	2	-2	-2	0	0	1	2
	Spring	-2	1	-1	2	2	5	0	-4	-4	-2	1	3
	Summer	1	0	1	1	2	8	4	-9	-9	-3	0	3
	Fall	8	11	13	8	5	7	9	11	6	5	10	10

Table 3.3: WRF wind direction by land type (2009)

	%	N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW
Land	Winter	5	3	1	1	3	5	9	12	8	16	23	15
	Spring	5	4	5	4	5	8	16	19	10	10	7	9
	Summer	3	4	3	4	3	7	16	21	10	10	12	7
	Fall	6	13	13	7	6	6	8	9	5	9	10	9
Coast	Winter	3	3	1	1	3	3	9	13	11	18	28	8
	Spring	5	6	5	5	5	8	17	17	12	9	6	7
	Summer	4	5	5	4	4	8	18	22	11	7	9	6
	Fall	8	14	12	8	5	6	8	9	5	10	10	7
Ocean	Winter	4	3	1	1	3	4	10	11	10	17	24	13
	Spring	5	6	5	5	6	9	18	17	10	8	7	8
	Summer	3	5	5	4	5	9	20	20	9	7	10	7
	Fall	7	13	13	8	4	7	8	9	5	10	9	8

Table 3.4: WRF wind direction diurnal difference (2009)

	%	N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW
Land	Winter	-1	0	0	1	0	-2	3	-3	0	7	2	-6
	Spring	-2	-1	2	1	0	-5	-5	4	3	4	2	-3
	Summer	-3	1	0	1	-1	-4	-10	1	10	10	0	-5
	Fall	-1	-1	0	0	2	-3	1	-1	-1	7	0	-2
Coast	Winter	1	2	-1	0	0	-1	2	-4	0	4	-4	-1
	Spring	1	2	0	2	0	0	-2	-3	1	2	-2	-1
	Summer	1	3	5	4	1	4	-9	-9	7	3	-6	-2
	Fall	1	0	1	0	3	-1	-1	-2	-1	3	-4	0
Ocean	Winter	1	1	-1	1	-1	1	2	-3	-2	4	0	-4
	Spring	-1	1	0	1	3	2	-3	-2	1	0	3	-2
	Summer	-2	1	2	2	3	3	-4	-7	3	1	-2	1
	Fall	1	-2	-1	-1	3	0	0	-2	1	3	-3	2

Table 3.5: **WRF grid cell comparison by land type (2009)**

	Wind Speed			**Wind Dir.**			**Temp.**		
Land, Ocean	**R**	**L Mean (m/s)**	**O Mean (m/s)**	**R**	**L Mean (° from N)**	**O Mean (° from N)**	**R**	**L Mean (°C)**	**O Mean (°C)**
Jan	0.96	5.11	7.30	0.99	-78	-78	0.89	0.69	3.46
Feb	0.95	5.79	7.63	1.00	-86	-85	0.89	3.46	4.83
Mar	0.93	5.84	7.07	1.00	-75	-75	0.91	8.47	7.60
Apr	0.92	5.93	6.89	0.99	-131	-134	0.88	14.47	12.64
May	0.91	5.42	6.21	0.99	-154	-155	0.68	20.25	18.20
Jun	0.89	4.81	5.71	0.97	-150	-155	0.63	24.38	23.00
Jul	0.84	4.98	6.39	0.99	-135	-136	0.62	25.18	25.80
Aug	0.83	4.45	6.02	0.96	-132	-135	0.56	26.91	28.02
Sep	0.92	5.05	6.55	0.97	79	79	0.69	22.64	24.00
Oct	0.93	4.92	6.69	0.99	-96	-95	0.71	16.03	18.20
Nov	0.97	5.27	7.04	0.99	3	4	0.79	11.93	13.77
Dec	0.97	6.00	8.25	1.00	-67	-67	0.91	4.67	6.81
Average	0.92	5.30	6.81	0.99	-85	-86	0.76	14.92	15.53

	Wind Speed			**Wind Dir.**			**Temp.**		
Land, Land	**R**	**L1 Mean (m/s)**	**L2 Mean (m/s)**	**R**	**L1 Mean (° from N)**	**L2 Mean (° from N)**	**R**	**L1 Mean (°C)**	**L2 Mean (°C)**
Jan	0.99	4.48	4.53	1.00	-70	-71	0.99	-0.14	-0.07
Feb	0.99	5.14	5.19	0.99	-84	-84	0.99	3.02	3.03
Mar	0.99	4.89	4.90	1.00	-85	-85	0.99	8.46	8.41
Apr	0.98	5.12	5.21	1.00	-124	-124	0.99	14.50	14.56
May	0.98	4.65	4.72	0.99	-146	-146	0.97	20.40	20.40
Jun	0.97	4.13	4.17	0.97	-118	-120	0.96	24.68	24.70
Jul	0.96	4.22	4.30	0.99	-120	-121	0.95	24.75	24.83
Aug	0.95	3.87	3.90	0.98	-124	-124	0.95	26.79	26.69
Sep	0.97	4.14	4.18	0.98	76	76	0.97	22.13	22.09
Oct	0.98	4.32	4.37	1.00	-95	-95	0.98	15.36	15.38
Nov	0.99	4.24	4.25	0.98	8	6	0.97	11.28	11.08
Dec	0.99	5.01	5.09	0.99	-58	-59	0.99	3.80	3.88
Average	0.98	4.52	4.57	0.99	-78	-79	0.97	14.59	14.58

	Wind Speed			**Wind Dir.**			**Wind Dir.**		
Ocean, Ocean	**R**	**O1 Mean (m/s)**	**O2 Mean (m/s)**	**R**	**O1 Mean (° from N)**	**O2 Mean (° from N)**	**R**	**O1 Mean (°C)**	**O2 Mean (°C)**
Jan	1.00	8.52	8.55	1.00	-76	-76	1.00	4.41	4.46
Feb	1.00	8.66	8.69	1.00	-82	-82	1.00	5.16	5.17
Mar	1.00	7.81	7.83	1.00	-59	-58	1.00	7.79	7.80
Apr	1.00	7.51	7.52	0.99	-138	-137	1.00	12.64	12.63
May	1.00	7.07	7.09	0.98	-156	-156	1.00	18.23	18.22
Jun	0.99	6.51	6.54	0.99	-159	-159	1.00	22.98	22.97
Jul	0.99	6.92	6.96	0.99	-138	-139	0.99	25.83	25.83
Aug	0.99	6.49	6.51	0.98	-134	-134	0.99	28.14	28.14
Sep	0.99	6.78	6.76	0.99	81	81	1.00	24.14	24.14
Oct	1.00	7.30	7.31	0.99	-90	-91	1.00	18.45	18.47
Nov	1.00	7.61	7.61	0.99	6	6	1.00	14.15	14.16
Dec	1.00	9.31	9.33	1.00	-63	-62	1.00	7.52	7.56
Average	0.99	7.54	7.56	0.99	-84	-84	1.00	15.79	15.80

Table 3.6: Obs./WRF comparison statistics (2009)

	Wind Speed							Temperature						
	R	Obs. Mean	WRF Mean	Obs. s.d.	WRF s.d.	RMS	ME	R	Obs. Mean	WRF Mean	Obs. s.d.	WRF s.d.	RMS	ME
Ocean														
Jan	0.66	6.63	8.50	2.88	3.20	3.14	2.51	0.90	1.37	4.13	3.80	3.79	3.22	2.80
Feb	0.69	7.71	8.52	3.01	3.49	2.74	2.13	0.91	3.40	4.99	3.41	3.63	2.18	1.74
Mar	0.57	6.07	6.92	2.89	2.79	2.76	2.14	0.84	4.97	7.72	3.29	3.64	3.40	2.89
Apr	0.54	7.60	7.31	3.37	3.04	3.10	2.39	0.85	10.41	12.61	2.97	3.28	2.86	2.47
May	0.50	5.95	6.50	2.68	2.70	2.75	2.21	0.75	15.14	18.13	2.44	2.07	3.44	3.08
Jun	0.35	5.07	6.06	2.34	2.49	2.98	2.41	0.70	19.51	22.97	2.17	1.83	3.82	3.49
Jul	0.36	5.52	6.66	2.30	2.43	2.90	2.31	0.65	22.90	25.74	1.42	1.47	3.10	2.85
Aug	0.25	4.91	6.13	2.05	2.54	3.10	2.51	0.61	24.97	28.03	1.48	1.20	3.29	3.06
Sep	0.45	7.22	6.65	3.28	2.95	3.33	2.57	0.71	20.71	23.99	1.75	2.30	3.67	3.34
Oct	0.63	7.79	7.34	3.51	3.10	2.94	2.20	0.87	15.88	18.22	3.00	2.71	2.76	2.40
Nov	0.77	8.25	7.54	4.38	3.56	2.90	2.22	0.81	12.42	13.93	1.88	2.40	2.06	1.68
Dec	0.76	9.07	9.35	3.80	3.49	2.61	1.97	0.92	5.51	7.19	4.30	4.14	2.39	1.86
Mean	0.54	6.81	7.29	3.04	2.98	2.94	2.30	0.80	13.10	15.64	2.66	2.71	3.01	2.64
Coastal														
Jan	0.54	4.46	5.63	2.30	2.57	2.78	2.26	0.82	0.49	0.20	4.48	5.22	3.04	2.37
Feb	0.58	5.05	6.18	2.41	2.58	2.73	2.24	0.89	4.14	3.02	5.89	5.75	3.00	2.34
Mar	0.61	4.77	6.19	2.58	2.63	2.87	2.32	0.76	6.09	8.14	6.05	7.07	5.08	3.79
Apr	0.50	4.93	6.26	2.66	2.42	3.04	2.45	0.74	12.35	14.18	5.89	6.75	4.98	3.78
May	0.43	3.98	5.55	2.00	2.08	2.77	2.27	0.59	16.74	20.34	3.93	5.15	5.67	4.42
Jun	0.32	3.85	4.99	1.81	1.90	2.55	2.11	0.46	20.54	24.09	3.15	4.93	5.70	4.67
Jul	0.33	3.69	5.10	1.66	1.73	2.51	2.08	0.64	23.31	24.98	2.44	4.93	4.18	3.47
Aug	0.17	3.12	4.51	1.43	1.63	2.46	2.04	0.58	24.89	26.77	2.56	5.24	4.68	3.98
Sep	0.45	4.96	5.37	2.65	2.34	2.85	2.24	0.64	20.63	22.66	2.51	4.85	4.29	3.49
Oct	0.49	5.11	5.19	2.86	2.37	2.83	2.19	0.75	15.60	15.80	4.00	5.06	3.36	2.73
Nov	0.71	5.48	5.77	3.52	3.05	3.10	2.45	0.74	11.82	11.73	2.79	4.61	3.18	2.51
Dec	0.65	5.20	6.41	2.91	2.87	3.00	2.39	0.87	4.67	4.44	5.05	5.71	2.88	2.26
Mean	0.48	4.55	5.60	2.40	2.35	2.79	2.25	0.71	13.44	14.69	4.06	5.44	4.17	3.32
Inland														
Jan	0.48	3.62	5.08	1.84	2.19	2.55	1.96	0.80	-0.80	-0.38	4.90	5.44	3.37	2.52
Feb	0.63	4.45	5.62	2.15	2.26	2.30	1.85	0.92	3.72	2.82	6.86	6.00	2.82	2.20
Mar	0.59	3.85	5.38	1.86	2.05	2.40	1.94	0.83	6.20	8.29	7.51	7.53	4.83	3.64
Apr	0.50	3.93	5.46	2.01	1.91	2.52	2.06	0.85	13.00	14.45	6.85	7.16	4.16	2.97
May	0.43	3.30	5.12	1.63	1.75	2.59	2.14	0.74	17.90	20.42	5.19	5.65	4.69	3.41
Jun	0.32	2.95	4.20	1.27	1.68	2.16	1.74	0.70	21.59	24.71	4.08	5.37	4.94	4.02
Jul	0.28	2.98	4.46	1.29	1.46	2.24	1.85	0.82	23.66	24.75	4.04	5.43	3.34	2.72
Aug	0.18	2.51	4.00	1.09	1.44	2.22	1.85	0.74	24.80	26.70	3.86	5.89	4.41	3.70
Sep	0.42	3.18	4.56	1.46	1.73	2.23	1.84	0.75	19.26	22.05	4.09	5.66	4.69	3.82
Oct	0.52	3.65	4.99	1.77	1.96	2.30	1.86	0.83	14.00	15.28	5.46	5.71	3.54	2.65
Nov	0.70	3.96	4.93	2.21	2.18	2.05	1.63	0.79	10.57	10.94	4.22	4.94	3.07	2.39
Dec	0.60	4.03	5.52	2.16	2.27	2.50	1.95	0.90	3.20	3.68	5.64	6.03	2.69	2.05
Mean	0.47	3.53	4.94	1.73	1.91	2.34	1.89	0.81	13.09	14.48	5.23	5.90	3.88	3.01

Chapter 4

DELAWARE BAY/SEA BREEZE

4.1 Introduction

The sea breeze observational analysis focuses on the summers (June, July, and August) of 2005 to 2009 due observation station availability while the WRF analysis will cover the summers of 2000 to 2009. Continuous radar data are available from the Dover site (KDOV) is investigated in detail for the summer of 2008. The radar data comes in either dry-air or precipitation mode. In the dataset, there are days where the radar is clearly in precipitation mode, which is a hindrance to the visual detection of a sea breeze front. On the other hand there are clear-cut sea breeze cases in dry-air mode which allow for the detailed investigation of the frontal shape and propagation (Figure 1.3). On occasion, the sea breeze front can be detected in precipitation mode; however it is more difficult to detect because of the decreased sensitivity. Regardless of the radar mode, it is often difficult to detect the formation of a sea breeze along the coast. This complexity may be caused by the weaker nature of the sea breeze at that time or due to the different physical properties of the various coastal locations. A typical sea breeze will first be detected visually along the coast or very close to the coast. However, this usually occurs hours after a sea breeze is detected by coastal meteorological stations. Throughout the day the detection of the sea breeze often becomes easier to recognize, especially if it moves further inland. In some cases the sea breeze front is first detected approximately 20 kilometers inland.

Data from seventeen observation stations are used for the sea breeze analysis. While not possessing the high spatial coverage of radar, these stations provide meteorological data at high temporal resolution, approximately every five minutes throughout the day. The chosen land stations are well spaced throughout Delaware. The station at Brandywine Shoals is employed to examine how winds over the Bay respond in a sea breeze circulation. There is a certain degree of difficulty when it comes to detecting a sea breeze front using meteorological station data. Ideally, the passage of a sea breeze front will result in a quick shift in winds from seaward to landward. This shift in the dominating air mass should decrease the air temperature and possibly increase the dew point. There are also several unique occurrences that are observed in the area.

One such case involves a very slow shifting of winds from seaward to landward. It is difficult to distinguish if this occurs due to synoptic conditions, a sea breeze effect, or both. This occurrence is often accompanied by a slow drop in temperature and is biased towards the coastal stations. In general, this scenario would be classified as a sea breeze depending on how a reference station reacted during the same timeframe.

A second common case occurs when the wind shift is quick but the temperature change is minimal. This occurs in three different ways. First, this occurrence is common at coastal stations early in the morning, consistent with a developing sea breeze in which the temperature change is also impacted by the increase of solar radiation due to the sun's rising. The second case occurs later in the day or early evening at inland stations when it is typical to see the temperature drop over a given area by only 1˚C but the dew point increases between 2 ˚C and 3˚C. This appears to be the result of a sea breeze front that has to travel over land so far that the air heats up from contact with and proximity to the land surface. The third way that this quick wind shift and slight temperature drop occurs is also over inland stations in the latter part of the day. It involves a negligible increase in dew point and is usually associated with weak winds. Another possibility is that the weakening of a sea breeze front often propagates atmospheric ripples which may weakly effect stations further inland.

A different scenario involves a quick wind shift but a decrease in dew point, which again is primarily limited to the coastal stations. A typical dew point drop would be from 22˚C to 20˚C or 20˚C to 18˚C. This case is assumed to be a sea breeze that happened to occur on a very moist day. This is because the resulting dew point (18˚C-20˚C) is very similar to the conditions that occur on an obvious sea breeze day. However, sometimes the dew point can drop below 15 °C which is unusual for the summertime during a wind regime from the ocean. This is evidence of a back door cold front which has different properties than a sea breeze including size, life cycle, and vertical profile. Days of this dew sea breeze type are classified as sea breeze or non-sea breeze depending on the magnitude of the dew point increase.

As previously mentioned, a rare occurrence involved the passage of a backdoor cold front through the region. This front passed through the area in a similar fashion as a sea breeze front although at a quicker speed. In the radar data it is interesting to watch what are probably gravity waves drifting from the north to the south off the coast. It appears as though these waves get shifted eastward and then move across the Delaware region. Although these observations are made in precipitation mode it is still visually easy to recognize. The passage of this front causes a sharp drop in temperature and wind direction. Interestingly, the dew point also drops by a large amount from about 18˚C to 13˚C. This unusual dryness may possibly be caused by the origin of the air mass which may be from Canada as opposed to offshore. It is likely that the difference in temperature between the ocean and land helped propagate this front; however it is not considered a sea breeze circulation.

A final relatively rare scenario involves the interaction with a sea breeze front and a thunderstorm outflow. Since sea breezes often develop on hot summer days it is inevitable that a thunderstorm will sometimes develop near the front. If the thunderstorm develops landward of the front it typically has the effect of dissipating the sea breeze front. If the thunderstorm occurs seaward of the sea breeze front then it has the effect of giving the front a boost in speed and intensity as visualized on radar. There have been cases during the study that show a station experiencing a sea breeze front passage and then later in the day a thunderstorm develops right over or seaward of the station. From here, it is clearly shown on radar how the sea breeze front gets moved landward as a result of this storm. The convergence associated with a sea breeze front increases the likelihood of convection right along the front. Precipitation mode on radar makes this hard to see, but there are cases where this seems to occur. This is most likely to happen in the afternoon when the sea breeze has propagated several kilometers inland. In general, it is assumed that an outflow off the coast heading landward will interact with a sea breeze front in some fashion.

Radar and observation stations show that the sea breeze front interacts in complicated ways along Delaware's coastline. The following is a brief discussion of the qualitative aspects of the sea breeze front:

A sea breeze front does not always have to propagate landward. It can stall out and even retreat. This is most likely a result of fluctuating wind and temperature levels. This often occurs over coastal stations where there is a high frequency of sea breezes and the sea breeze front has little chance to develop momentum in the landward direction. An idealized example is a coastal station's temperature that goes from 33 °C to 28 °C to 33 °C to 26 °C all within a few hours. This fluctuation is not uniform laterally. In other words it can affect one station and not the other even if they are both right along the coast. The sea breeze fluctuation can at times be observed on radar, where it can be seen moving eastward across the Delaware Bay (Figure 4.1A).

There are a few stations that are particularly vulnerable to being impacted by both the Delaware Bay Breeze and Delaware Sea Breeze on a given day. The station at Rehoboth Beach is situated along the ocean but is still very close to the mouth of the Delaware Bay. It is often seen on a given day where there are two recognizable shifts in wind direction at this location. A typical shift would go from West to NE to SE. Usually the second shift is not accompanied by significant temperature or dew point changes. DSJR, which is further up the Bay, has the potential to experience the Bay breeze in the morning and the Sea breeze in the afternoon. This gives enough recovery time to see two changes in temperature and dew point each associated with the different fronts. This is a fairly rare occurrence because of the distance that the sea breeze must travel. This is also occasionally seen in Lewes where the bay breeze develops initially and the oceanic sea breeze develops later in the day. It is very difficult to see two separate sea breezes on the radar because of the fact that one will usually be far weaker than the other.

Often times the sea breeze develops over the coastal Bay and ocean of Delaware at the same time. The front often leaves the coast more quickly along the ocean than the Bay. When it does leave the Bay it moves westward slowly. Since the Bay is further west than the ocean throughout Delaware's coastline, the ocean sea breeze can catch up to the Bay breeze. The coastline of the Bay is angled to the northwest which can cause the sea breeze front to have a bulge near the south western part of the Bay. This is an area where the sea breeze front moves far slower than areas both above and below it (Figure 4.1B). This feature presents itself on several occasions but it is not a dominant feature. If the Delaware sea breeze front moves quicker or earlier it can catch up to the Bay breeze forming a straight line that bisects Delaware from North to South.

On several occasions the sea breeze forms along the entire oceanic coastline of Delaware and southern New Jersey. When this happens, the front can propagate northwestward across the Delaware Bay. It is suspected that this happens on hot days where there is a moderate breeze from the west or southwest. These conditions could heat up the air over the Bay and force its temperature to have a significant gradient relative to the temperature over the nearby Atlantic Ocean. This can happen regardless of whether there is a bay breeze present on that day. The Delaware Bay region can be affected by three distinct sea breezes (NJ Bay, DE Bay, DE/NJ coastal).

A few times each month over the course of the study the radar picks up some sort of front moving over the southern part of Delaware (Figure 4.1D). This appears to originate from the ocean but its path is irregular when compared to other sea breeze fronts. It is very straight, has a large southerly component, and is typically observed on radar late in the afternoon. It is possible that this is due to the Coriolis force combined with the geography of southern Maryland. It is also possible that it is some sort of gravity wave or even a thunderstorm outflow from a line of storm not seen on the radar.

It is common for the sea breeze to show itself in inland locations when it is stronger. However, in some cases, especially in September, a front presents itself well inland and with no momentum behind it. It is difficult to say what the cause of this feature is. It is possible that it is a weak sea breeze that finally gained strength towards the end of the day. Additionally, it is also possible that it is a lee-side trough or a dry line. Yet another possibility is that it is a response to or expression of the Chesapeake Bay Breeze.

There is considerable complexity in the interaction between synoptic features and the Delaware Bay and nearby Atlantic Ocean. It is apparent that a landward breeze can form over either, and possibly both the Bay and Ocean. They can interact in interesting ways which can be seen in the radar and meteorological station data. As expected, the sea breeze typically forms early in the day and slowly moves landward. The highest propagation speeds are usually observed in the early afternoon. There are days where the sea breeze is clearly observed in radar and station data. However, there are also days where there is a complicated interaction between the sea breeze circulation and other mesoscale and synoptic features. An analysis with a regional atmospheric model like WRF yields additional insight because of more complete meteorological data over land points as well as giving details about the lower and upper atmosphere.

4.2 Sea Breeze Detection Program

A novel sea breeze detection algorithm is developed to objectively detect the passing of a sea breeze front over a meteorological station using observations of wind speed, wind direction, temperature, and dew point. Changes in these physical characteristics are compared to the same features at a reference station that is far enough inland to generally be unaffected by sea breezes during the time frame studied. There are eleven DEOS stations and one NDBC station utilized by the program. Eleven are considered test stations and they are distributed from the coastal regions, including Rehoboth and Bethany Beach, to inland locations that are approximately 25 kilometers from the ocean. The timeframe for this analysis is between 2005 and 2009 for the summer months of June, July, and August between 8AM and 8PM EST. Each station provides all of the necessary data listed above in synchronized 5 minute intervals. NDBC stations have their readings compared to the nearest five minute value that coincides with DEOS data.

The sea breeze detection program looks for changes in meteorological conditions over the course of an hour and steps through at 5 minute intervals. For example, the first comparison is between 8AM and 7AM and the next comparison is between 8:05AM and 7:05AM. A thirty-minute average is used to smooth out high frequency variations in the data.

Three sea breeze categories are derived based on distinct changes in meteorological conditions. The Classic Sea Breeze category is defined by quick changes in wind direction and temperature. Quick dew point increases along with a shift to easterly winds defines the Dew Point Sea Breeze category. The Weak Sea Breeze category is defined by a gradient that can develop between a test station and a reference station. This can occur slowly and does not depend on conditions in the previous hour like the previous two categories. A Classic and Dew Sea Breeze can occur concurrently or separately and take precedence over the Weak Sea Breeze Category. Non sea-breeze days are separated into east dominant, west dominant, and variable winds. An east dominant wind is defined by winds that have an easterly component for more than 80% of the testing day.

It is very difficult to clearly define when a sea breeze front passes through a particular region. However, when compared with radar data as well as other stations a set of guidelines can provide useful feedback on when sea breeze front like changes occur. Table 4.1 shows all the conditions needed for each classification type.

The sea breeze detection program is designed to pick out the occurrence and timing of sea breeze fronts through eleven stations located throughout Delaware. There are cases where it detects fronts over just inland stations and not coastal stations. This could be a result of a developing sea breeze which was too weak to see over the coastal stations.

The following conditions are needed for a day to be classified as a 'Classic Sea Breeze Day' for a given station.

1. Current average wind from the test station has an eastward component. A sea breeze will almost always bring in a wind component from the ocean and Delaware's coastline is generally aligned vertically.

2. Current average wind speed from the test station is greater than 1 m/s. It is expected that the majority of sea breezes would bring with them wind speeds greater than 1 m/s. Also, at very low wind speeds the observation stations may misrepresent the wind direction.

3. The average test temperature is at least 1˚C less than the average reference temperature. A sea breeze is driven by a temperature gradient between air over a large body of water and air over land. If the temperature at the inland reference stations is relatively cool then it is unexpected that a sea breeze front will pass through the test station.

4. The temperature change for the test station over the last hour is at least 2˚C more negative than the corresponding temperature change for the reference test station. A sea breeze front passage typically results in a sharp temperature decrease. Of course this drop would not be present in the reference station. However, frequently sea breeze fronts effect coastal regions in the morning hours where the incoming solar radiation is not near its peak. It has been seen that these early sea breezes typically have the effect of slowly or stopping the increase of the temperature at the effected stations. Usually, in these cases there is not a significant drop in temperature. The temperature change condition is usually still satisfied because the reference stations are increasing their temperature quickly in comparison.

In addition, either of the next two conditions needs to be satisfied:

5. The average wind at the test station one hour prior has a component from the west. The most easily detected sea breezes show a quick shift in wind direction from the west (offshore) to the east (onshore).

6. The average wind at the test station one hour prior has an eastward component with an average wind speed less than 1 m/s. Sea breeze fronts can move through during calm conditions. They can even occur when there is a moderate east wind but it is rare and very difficult to distinguish from other effects.

Either of the next two conditions also needs to be satisfied:

7. The average wind at the reference station has a westward component.

8. The average wind at the reference station has an eastward component and an average wind speed of less than 1 m/s.

An interesting finding in the comparison of the observational data with the radar data is the occurrence of 'fronts' that bring with them changes in wind direction and dew points but not temperature. This can often occur at inland stations late in the day when the air from behind a sea breeze front has had time to warm up over land. This can also happen at coastal stations during the early morning with a developing sea breeze. These events need to be separated from a gradual increase in dew point that commonly occurs on a summer day. The following conditions are needed for a day to be classified as a 'Dew Sea Breeze Day' for a given station.

1. Current average wind from the test station has an eastward component.

2. Current average wind speed from the test station is greater than 1 m/s.

3. Current average dew point temperature is at least 2˚C greater than the average dew point temperature one hour prior. This seems to be a good measure for a significant increase in dew point over a relatively small timeframe.

In addition, either of the next two conditions needs to be satisfied:

4. The average wind at the test station one hour ago has a component from the west.

5. The average wind at the test station one hour ago has an eastward component with an average wind speed less than 1 m/s.

Also, either of the next two conditions needs to be satisfied:

6. The average wind at the reference station has a westward component.

7. The average wind at the reference station has an eastward component and an average wind speed of less than 1 m/s.

On occasion, especially along the coastal stations, there can be an eastward wind at the test station and a west wind at the reference station. This can occasionally develop without a dew or temperature drop that has already been classified, and may occur due to a very slowly developing sea breeze or when there is already a landward breeze in place. The follow conditions are needed for this ‘Weak Sea Breeze Regime’.

1. The average test temperature is at least 2 ˚C less than the average reference temperature.

Also, either of the next two conditions needs to be satisfied:

2. The average wind at the reference station has a component from the west.

3. The average wind at the test station has an eastward component with an average wind speed less than 1 m/s.

In addition, either of the next two conditions needs to be satisfied:

4. The average wind at the reference station one hour ago has a component from the west.

5. The average wind at the reference station one hour ago has an eastward component with an average wind speed less than 1 m/s.

The remaining days are divided into the following three categories: east dominant winds, west dominant winds, and variables winds. East and west dominant winds are classified by having 80% of the average wind readings for the day (8AM-8PM) having a component in their respective directions. Days that do not fall in any of the preceding categories are considered to have variable winds.

The complexity of the sea breeze formation and propagation along with its intrinsic interactions with other synoptic and mesoscale factors presents many potential sources of error in the detection algorithm. Synoptic events are a significant factor in determining the dominant wind direction over any region. Synoptic fronts approach Delaware from any direction and bring with them drastic changes in temperature and wind direction. One particularly interesting occurrence is the backdoor cold front (BDCF). This is a cold front that approaches the region from the north, northeast, or east direction. While this event is rare it can easily be mistaken for a sea breeze front. Depending on time of occurrence, it is possible that the sea breeze effect (differential heating between the land surface and water surface) contributes to the propagation speed of the backdoor front. It has been seen in one case that the BDCF can move twice as quickly as a sea breeze front. Also, in contrast to a sea breeze the BCDF can bring with it a large drop in the dew point temperature.

The Bermuda high is a synoptic scale occurrence that is semi-permanent over the Atlantic Ocean during the summer months. It often brings moderate southern or southeastern winds to the region. In contrast, it is also common for Delaware to experience winds from the southwest that are set up by low pressure systems that are frequently present in the Midwest during the summer months. This interplay between the two regimes can raise the potential for false detection of the sea breeze occurrences by the algorithm. Thunderstorm outflow is a mesoscale event that often interacts with sea breeze fronts. In general, summer thunderstorms occur on hot days in the summer where the differential surface heating often leads to sea breezes. This interplay can trigger the detection of false sea breezes, especially over the inland stations.

The weather stations that provide the data used in the algorithm have errors associated with them as well. For example, some stations may not be placed in ideal locations; nearby buildings or trees may block winds from certain directions. However, the detection program focuses on the coinciding changes in temperature and wind direction and breaks down wind direction into general components instead of specific directions. This minimizes errors associated with wind shadowing within some of the station's anemometers.

4.3 WRF Sea Breeze Detection Program

For the analysis of the WRF model data it is prudent to develop a routine that will detect the development and propagation of a sea breeze front in a manner similar to that used for the observations. Figure 4.2 shows the area that will be tested for the presence of a sea breeze. For each latitudinal row of cells, the testing area (shaded in yellow) encompasses the furthest land point on the eastern side and covers more than twenty kilometers inland for most areas. Towards the northern area of the Delaware Bay it is less practical to capture as large of a test area because of the area's proximity to the

Chesapeake Bay. Here, the analysis range is closer to ten kilometers. There is one case (represented by the light blue box) where a water point is included in the testing area. This is due to the shape of the representation of the coastline where the latitudinal transect from west to east intersects water points more than once before entering the ocean or bay. The detection algorithm developed with use of the meteorological observations uses only one test station. This suggests that local wind and temperature deviations that may affect the ability of the algorithm to recognize a sea breeze at another station. The detection scheme for the WRF analysis has the advantage of using a series of reference cells to capture the prevailing synoptic conditions for the region. The reference area is ten kilometers wide and extends the entire latitudinal height of the study (~116 kilometers). The edge of the reference area is eight kilometers to the west of the western edge of the testing area. This region is large enough to diminish the effect of local variability of temperature and wind direction.

It is clear that WRF can simulate a sea breeze circulation over Delaware's coastal region (Figure 4.3). As expected the circulation will first develop along the coast and then can propagate landward. A latter section of this paper shows that the return flow is simulated in WRF at a height of 1,000 to 3000 meters. From inspection, it is clear that the sea breeze front causes a wind shift over the effected region. However, the temperature drop is smaller than that in the observations, especially as the front moves landward. Observations of the temperature immediately along the coast can show a drop of up to 10 °C while stations only 1 kilometer further inland may only see a drop of 3 °C to 4 °C. The 2-kilometer resolution used in this study will not allow for simulation of this kind of variability in the current study. Poorly resolved SST's input to WRF may also lead to a decreased temperature gradient and reduced strength of the sea breeze front. Irregularities in the moisture distribution in WRF make it difficult to use dew points in conjunction with the recognition of a sea breeze. A poor soil moisture representation can introduce errors in the 2-meter mixing ratio. Studies have shown that mixing ratio is among the most difficult variables for WRF to approximate with correlation values often below 0.4 (Ozone Transport Commission). This has an effect on 2 m temperature but temperature correlation, mean error, and bias are reasonable between WRF and observed values. Therefore, a simple method using only temperature and east/west wind component is used to recognize the passage of the front. The following conditions need to be met for the test cell to be considered as experiencing a sea breeze circulation for a given time period.

1. The average wind magnitude of the reference region must have a westerly component.

2. The average wind magnitude of the test cell must have an easterly component.

3. The difference in the east/west wind magnitude between the reference region and test cell must be greater than 1 m/s.

4. The average temperature of the reference region must be at least 1 °C higher than the temperature of the reference cell.

5. Except along the coastline, the grid cell immediately to the right (seaward) must show signs of being in a sea breeze at the current hour or at a previous hour. The same time period as the observation sea breeze analysis is used (8AM – 8PM).

The fifth condition is put into place to help eliminate local scale variance from such things as horizontal convective rolls. From inspection, if condition five was not put into place there would not be a significant alteration of the sea breeze frequencies. This method is similar to the observation based weak sea breeze category with a weaker temperature condition.

4.4 Observed Sea Breeze Results

Table 4.2 displays the results from the detection scheme used on the observations for all available days spanning from 2005 to 2009. The number of valid test days range from 171 to 442 depending on test and reference station availability. The LWSD1 station is not equipped with dew point or relative humidity so the dew point sea breeze is not explored for this station.

Coastal regions have the highest sea breeze frequency. Summing the categories 1-4 result in a frequency of between 62% and 74%. These stations almost never experience a dew point sea breeze front alone (<1%) but they do experience it often in tandem with the classic sea breeze front (~11%). Sea breezes along the coast range in the weak sea breeze category occur from 25% to 41% of the time in the summer with the highest occurrence at Lewes, DE. This could be attributed to Lewes' unique location between the Delaware Bay and the Atlantic Ocean, and therefore likely to experience very complex, and possibly competing, wind conditions. The LWSD1 station immediately boarders the Delaware Bay to the north and is a few kilometers from the ocean. As the winds shift due to a sea breeze, the temperature may be unresponsive initially because of the modifying effect of the Delaware Bay. Other times a weak sea breeze occurs when winds are already weakly from the east before 8 AM along the coast while stations further inland have a westerly component. These landward winds often increase during the daytime but the 'sea breeze front' is not distinguishable in the radar. The remaining winds are split between east dominant (14%), west dominant (9%) and variable winds (7%). The non-sea breeze winds at LWSD1 shows a greater western component (15%) compared to the mean of the other coastal stations (6%). The sea breeze circulation in this location may be more sensitive to westerly winds, especially from the NNW where the fetch of the path of the winds through the Delaware Bay may increase wind speed. This is the only station in this part of the study with a higher anemometer height (10 m) which may influence wind speed and direction.

DBNG is less than two kilometers inland from DBBB which is right next to the Atlantic Ocean. However, there is a remarkable difference in the characteristics of the sea breeze at these two locations. The overall sea breeze frequency drops from 71% to 53% with nearly equivalent sample sizes. However, the percentage of weak sea breezes is nearly identical (~25%) between the two stations. This means that there are significantly less obvious sea breezes at DBNG. In addition, it is common that a clear sea breeze moves through DBBB but loses its observable frontal characteristics as is propagates eastward. Non sea breeze winds have a higher percentage of western component winds at DBNG than at DBBB (13% vs. 6%).

DSJR is located within a kilometer of the Delaware Bay but is over forty kilometers from the Atlantic Ocean. This station has a higher overall frequency (34%) of sea breeze occurrence (all categories) than stations that are 1 km from the Atlantic Ocean (~25%). Unlike other coastal stations DSJR occasionally experiences dew sea breezes (7%) without the corresponding classic sea breeze signals. Additionally, the station experiences classic sea breezes without dew sea breezes only 5% of the time which is less than other coastal stations that have a mean of ~ 27%. This station is somewhat anomalous, sharing characteristics from both inland and other coastal stations. If the Delaware Bay Breeze crosses the station then DSJR has early sea breeze occurrences. The Delaware Sea Breeze occasionally crosses the station later in the day with a similar frequency to inland stations.

DWAR is approximately fifteen kilometers from the ocean while the other inland stations are mostly over twenty kilometers from the ocean. The overall sea breeze frequency at DWAR is 28% while the other inland stations average 19%. The percentage of dew breezes that occur with classic sea breezes increases with distance from the coastline, reaching approximately 7% over the inland stations. The frequency of weak sea breezes drops from around 35% at coastal stations to around 5% for inland stations. The predominating result is that the temperature effects from the sea breeze lessens with distance from the coast while the dew point effects stay constant thus becoming more evident at inland stations.

The monthly sea breeze frequency at the stations studied is very similar for all summer months analyzed. Inland stations show the biggest differences among the months but there is no trend, and this difference is probably because of the small sea breeze sample size for these locations. There are two differences in the proportion of the non-sea breeze wind categories between inland and coastal stations. The frequency of the dominant west wind category is significantly less in August (mean of 15%) for the inland stations than it is in June and July (mean of 23%). This is compensated by an increase in the frequency of the dominant east wind category in August (mean of 21%).

The passage of a sea breeze front can occur anytime during the daytime hours. However, as previously discussed, the actual passage of the front can be difficult to detect. The Classic Sea Breeze category provides the most meaningful insight into the timing of the passage of the sea breeze front. Table 4.3 presents the mean arrival time of the classic sea breeze and the variation by month. The coastal stations have a mean frontal passage time of near noon. The mean passage time of the sea breeze at DBNG is approximately half an hour after passage at DBBB. DSJR has a mean passage time of roughly 2 PM. This is one to two hours before the mean time at the remaining inland stations. This is further evidence of the effect of the Delaware Bay Breeze on this location. Figure 4.4 displays the histograms of the sea breeze arrival time for several stations. DBBB has a significant skew to the right with the earliest arrival times between 10AM and 12PM. Arrival times past 4 PM occurred a handful of times. This may occur on days where there were cloudy conditions that faded away in the afternoon hours. Thunderstorm outflow may also play a role in these cases. DWAR shows a skew to the left with a peak later in the day around 4 PM. DSJR shows no peak which is probably attributed to the effect of the interaction between the Delaware Bay and Delaware Sea Breeze. Coastal stations as a group experienced the arrival times approximately 45 minutes earlier in July compared to June and August. With some variation, the inland stations experienced passage times about 30 minutes later in July. However, the sample size is not large enough to conclude if the frontal speed is slower in July.

The passage of a sea breeze front can bring with it a significant change in wind speed, wind direction, temperature, relative humidity, and dew point. The coastal effects are most significant along the coast. DBBB is a coastal station that recorded a large number of classic sea breezes between the hours of 9 AM and 2 PM. Grouping the sea breeze occurrences by hour provides insight into the average changes that the front brings about throughout the day. Figure 4.5 compares the temperature at this station on classic sea breeze days against days with constant west and constant east winds. The mean temperature for all listed categories is plotted from 6 AM to 6 PM. The east dominated wind category is associated with cooler temperatures during the entire timeframe with a narrow range between 20˚C and 22˚C. The west dominated wind category is associated with warm temperatures throughout the entire timeframe ranging from 21˚C in the morning and peaking above 30˚C around 3 PM. All the sea breeze subsets show significant drops in temperature immediately following the mean passage of the front. The earlier fronts show an average drop of 2˚C while the later subsets increase the drop to 5˚C. In all sea breeze cases listed, the temperature prior to the passage of the front is very similar to the west dominated wind category. In all sea breeze cases there is a recovery in average temperature in the hours after the front passage. This may be because of a front that retrogrades beyond the station or dies off. An alternate explanation may be that the air advecting from the ocean heats up due to solar radiation. The average temperature after the front tends to be between 23˚C to 26˚C. The peak difference between the west dominated wind category and the sea breeze categories is around 3 PM with an average difference near 6˚C.

DBNG has a high quality wind rose indicating that the wind data is reasonable and with at least five years of data available, this station can be used to accurately represent the general wind speeds of its location. Wind speeds in the hours preceding the passage of a classic sea breeze front are typically between 0.5 m/s and 2.5 m/s. Earlier sea breezes tend to happen in lighter winds than those that occur later in the day. There is a jump in wind speed after passage of the front resulting in peak winds averaging 2.5 m/s higher than before the front. During sea breeze days, wind speeds are often lower than average in the morning and near average in the afternoon.

The dew point often increases after the passage of a sea breeze front. This along with the typical temperature drop leads to a large increase in relative humidity that is shown for DBBB in Figure 4.6. Constant east wind days have an average relative humidity of 80% to 90%. West dominated wind days experience a relative humidity of near 80% in the morning that drops to 40% in the early afternoon. On average, the sea breeze front will raise the relative humidity at DBBB by 10% in the morning and 30% in the afternoon. Relative humidity in a sea breeze regime averages between 70% and 80% during the afternoon hours. Further inland stations follow the same trend with less overall relative humidity and tend to be more erratic, possibly due to their small sample size.

This study focuses on the summer months of June, July, and August but a sea breeze can occur in any month. Some of the largest temperature drops are associated with the spring months of March and April where the ocean temperature is cold but synoptic temperatures in Delaware can occasionally reach over 22˚C. In the five years of the study the largest temperature drop to occur at DBBB over a period of 15 minutes is 14.1˚C and was likely caused by a sea breeze front (Figure 4.7). This occurred on March 15th, 2007 at around 2 PM. The temperature fell from 25˚C to 11˚C. This temperature held steady for 2 hours before the entire region experienced a cold front. Interestingly, the temperature rose in response to the cold front as it pushed away the sea breeze regime. On November 1st, 2005, DBBB experienced a sea breeze that raised its relative humidity from 25% to 75%. The front passed through at around 1 PM and persisted for several hours. DBNG experienced this sea breeze as well and raised its relative humidity similarly. The sea breeze ended well before a cold front moved through which shifted the wind direction to the northwest. At DBBB, the strongest decrease in temperature and increase in dew point over 15 minutes also probably occurred from a sea breeze.

Synoptic conditions including temperature and wind magnitudes are the general drivers of the sea breeze circulation. However, mesoscale features including coastline shape, surface type, coastal upwelling, and horizontal atmospheric convective rolls may delay or prevent the movement of the sea breeze front along the coast. This variability is analyzed using the four coastal stations within a kilometer of the coastline (LWSD1, DRHB, DIRL, and DBBB). All days are split into the following three categories; Classic Sea Breeze, East/West Split, and non-sea breeze days. Table 4.4 shows how the relationship between two given coastal stations and the sea breeze. If a classic sea breeze affects two stations on the same day then then this would fit in the 'identical category'. If one station experienced a classic sea breeze while the other one experienced a weak sea breeze then this day would fit in the 'similar' category. The 'miss' category would occur if one station experienced either sea breeze while the other station did not. For any two of the given stations, between 53% and 83% of the days will have identical categories. LWSD1 has the lowest correlations possibly because the station is 3 kilometers from the Atlantic Ocean but only 1 kilometer from the Delaware Bay. The weakest correlation is between LWSD1 and DBBB which are the furthest apart. Clearly the correlation between sea breezes along the Delaware coast is strong; however mesoscale effects need to be investigated further to understand how they affect the onset of a sea breeze.

The Coriolis force acts to turn surface winds in a sea breeze circulation in a clockwise direction. To measure this effect the timeframe between approximately 0.5 to 5.5 hours after the initiation of every classic sea breeze was investigated at DBBB. Each sample has up to 61 data points in this interval. Since it is possible for a sea breeze circulation to vanish during this timeframe wind directions between 220˚ and 360˚ are ignored. The region between 180˚ and 220˚ is included because a sea breeze can shift to have a slight westward component during the event. Figure 4.8 displays the averages for every classic sea breeze day. There is indeed a strong correlation between time after passage and clockwise wind shift. Over the timeframe the average winds shift from approximately 125˚ to 155˚ over the course of 5 hours representing a 6˚ per hour clockwise shift. The r^2 value of 0.9748 adds significance to this conclusion. Similar analysis for DIRL, DRHB, and LWSD1 show similar results with starting values that are slightly to moderately counterclockwise of 125˚. If the 180˚ to 220˚ area is disregarded, the shift lessens to around 5˚ per hour with an r^2 value of 0.9616.

The sea breeze phenomenon is a persistent feature along Delaware's coastline. There is no clear cut definition of a sea breeze that encompasses the rich variety of sea breezes that occur is this area. Therefore several broad based categories are used to define this effect in southern Delaware. Classic sea breezes occur approximately 40% of the time along the coast. This value drops quickly with distance from shore. An east/west shift category accounts for weak sea breezes that lack sharp changes in temperature or wind direction. This type of sea breeze is common throughout the region and occurs about 30% of the time along the coast. Drastic changes in temperature, dew point, and relative humidity can be attributed to the sea breeze during all seasons. The Coriolis force is estimated to turn the sea breeze circulation by an average rate of 6˚ per hour along the coast.

4.5 WRF Sea Breeze Results

The WRF sea breeze detection program searched hundreds of grid cells for 919 days spanning the summers of ten years. Figure 4.9 shows the overall percentage sea breeze frequency of each of these stations during the entire timeframe. Frequencies are highest along Delaware's coastline with the Atlantic Ocean averaging over 40% of the time. Points along the coastline that stick out have even higher frequencies over 45%. The coastline along the Delaware Bay has a lower occurrence with an average frequency near 30%. According to these simulations, the sea breeze front typically propagates significantly further from the coastline along the ocean than along the Delaware Bay. The frequency of the sea breeze along the Delaware Bay reduces from 30% to 10% with a distance from the coastline of six kilometers. Approximately twelve kilometers of distance from the coast would be needed to see a similar reduction in frequency of sea breeze occurrence from the ocean. The outer edge of the study area has a frequency of about 5%.

The yearly variance in modeled sea breeze along the coastal regions is significant. The years 2002 and 2007 have anomalously higher frequencies (~12%) than the remaining years. The mean reference area temperatures are higher in the years 2002, 2006, and 2007 and the mean west wind component for these years is slightly below the ten-year mean. However, 2006 did not experience an increase in sea breeze events along the coast even though there was in increase in surface temperatures.

There is a minor amount of variation among the three months. June has the highest occurrence of sea breezes that travel over ten kilometers; compared with August, when the frequency is 5 to 10% higher. There is some additional propagation further north along the Delaware Bay coastline but it is significantly less than over southern Delaware. July has a slightly lower sea breeze frequency across the board than June. While August has fewer propagating sea breezes than June it does have higher sea breeze occurrence along the coast.

The timing of when each grid cell experiences these conditions is shown in Figure 4.11. It is important to note that this program looks for evidence of a sea breeze circulation as opposed to evidence that a sea breeze front has passed through a region. This is done because the temperature decrease experienced in the model is considerably less than that observed (section 4.6). The sea breeze in WRF occurs first along the coast at approximately noon (EST). The northern coastal regions seem to experience sea breeze effects approximately 30 minutes to an hour before the southern coastal regions. Also, the front appears to move inland considerably quicker along the northern most regions near the northwestern edge of the Delaware Bay. In WRF, often during a sea breeze circulation, strong SSE winds develop along the Bay which may aid in propagating the sea breeze. Along the Atlantic Ocean coast southern winds are more typical, which may hinder the initial propagation of the sea breeze. Along southern Delaware, the sea breeze conditions propagate the quickest between 3 PM and 6 PM covering 10 to 15 kilometers in propagation distance.

The temperature drop caused by the sea breeze circulation in WRF is significantly smaller than in the observed data. The reduced temperature gradient adds a large degree of difficulty in assigning which areas experience clear sea breeze fronts and their time of occurrence. Often winds are represented with an eastward component along the coast which gets stronger throughout the day. At the same time, areas in south-central Delaware experience winds with an increasing westward component. Due to computer time and storage concerns model output was saved every hour. This leads to some difficulty in pinpointing effects immediately following the passage of a sea breeze front. Therefore, just two cases are chosen to represent the sea breeze regime in WRF. A third case illustrates what happens when the region is controlled by synoptic wind conditions. The grid cell which contains DBBB is used as the coastal station and the entire reference area is used as described in section 4.2. Grid cells at BRND1 and B44009 are used to investigate how the Delaware Bay and Atlantic Ocean respond to the test cases.

Strong synoptic winds can eliminate the potential for a sea breeze to develop. On June 30th, 2009 the winds over the entire region are from the WSW including southern Delaware, the Delaware Bay, and the Atlantic Ocean (Figure 4.12). Winds were between 3 m/s and 5 m/s throughout the late morning and afternoon. The temperature between the coastal and inland areas remains near constant through the entire day. A synoptic east wind day is not listed as a case but results in similar conditions with the exception of the coastal station having a lower temperature than the reference region. This difference is persistent throughout the entire day.

In WRF, June 4th, 2009 simulates an evident sea breeze (Figure 4.13). The front appears to pass through the coastal station at 3 PM. The temperature drops approximately 3˚C which is one of the largest sea breeze related temperature drops in WRF. The wind shifts to the SSE and slowly rotates towards the south. The wind speed increases from 4 m/s to 7 m/s in the hours after the frontal passage. There are significant differences in the representative grid cell of the Delaware Bay and Atlantic Ocean. Winds near B44009 remain constant from the SSW. Winds near BRND1 are similar until 9 AM when they deviate by shifting in a clockwise direction. This shift persists past the afternoon where the wind flows from the east. This is strong evidence that this area is caught up in a sea breeze circulation.

On June 25th 2009, WRF represents winds over the entire region from the northwest in the morning (Figure 4.14). At around 1 PM winds from the coastal grid box shift clockwise to have an eastward component. However, there is no significant drop in temperature. Instead the difference in temperature between the coastal and inland region takes hours to develop eventually resulting in a 3˚C difference. Contrastingly to the previous case, the grid cell representing B44009 experiences a clockwise shift eventually leading to winds from the southeast.

It is clear that WRF can simulate a sea breeze circulation. A simple method was developed to capture the presence of an east wind over a coastal station and a mean west wind over a reference region located in south central Delaware. During the summer months, the frequency along the coast is between 0.4 and 0.5 while further inland it dips to around 0.1. Within this sample set there are few instances of large temperature drops associated with the front. Instead, the temperature gradient develops slowly with time.

4.6 WRF/OBS Sea Breeze Case Study

Analyzing the ability of WRF to accurately simulate the Delaware Bay/Sea breeze is a complicated task. Observation stations, although numerous in the region do not have the spatial resolution to account for the complete variability of the winds in the region, especially in the first few kilometers off the coastline. WRF is run with a 2 kilometer resolution which will not completely resolve certain portions of sea breeze systems that were found in the observation data to travel only one kilometer landward. The coastline in WRF further complicates such an analysis because it consistently underestimates the areal coverage of the land surface. Observed sea breezes that penetrate large distances are often difficult to recognize and lack large changes in temperature. A series of five cases is used to show how WRF simulates clear observed synoptic and sea breeze conditions.

4.6.1 Case 1: Strong West Synoptic Winds (7/3/2009)

Strong synoptic winds should be among the easiest for WRF to approximate (Figure 4.15). When forced with strong winds there is less chance for mesoscale circulation systems such as a sea breeze to develop. This day presents such a case with strong synoptic winds from the northwest over the entire region. A snapshot of all observed data superimposed on a WRF wind plot, show extremely good agreement between the two during the afternoon. A time series between DBBB, DBNG, and its corresponding WRF data point shows excellent agreement in wind direction throughout the day with errors often less than 30˚. The wind speed agrees well at DLAU with an average wind speed error of less than 1 m/s in the afternoon. The temperature curve in WRF agrees remarkably well at DBBB. WRF shows a slight overestimation in the temperature at DBNG which shares the same grid cell as DBBB in the model.

4.6.2 Case 2: Missed Synoptic Scenario (6/9/2009)

The boundary conditions used to force WRF have a resolution of 40 kilometers. On occasion, major synoptic features can be poorly represented in WRF. On this day a low pressure system is quickly moving off the Mid-Atlantic coast. The observed winds reflect this by shifting from the North to the southeast in a clockwise direction throughout the day (Figure 4.16). WRF misses this feature and shows winds from the southwest with no wind shift. WRF probably overestimated the speed of the movement of both pressure systems. This results in large errors in temperature along the coast of 5 ˚C probably caused from the opposing wind directions. Fortunately these errors are rare. A more common potential for synoptic based errors involve the timing of warm and cold fronts. WRF almost always simulates these features but the timing can be off by several hours.

4.6.3 Case 3: Accurate Sea Breeze Representation (7/17/09)

This day starts with light winds from DLAU (the reference station) of about 1 m/s to 2 m/s which is accurately depicted in WRF (Figure 4.17). In both cases, the winds in this location increase to around 4 m/s to 6 m/s in the afternoon. DBBB experiences a sea breeze front between 8 AM and 9 AM while DBNG sees the front approximately two hours later. The sea breeze regime winds for both locations start near 150˚ and slowly rotate clockwise during the afternoon. DBBB sees a resulting temperature drop of 5˚C while further inland DBNG sees only a 2˚C drop. The corresponding grid cell in WRF experiences sea breeze characteristics at the same time as DBNG (10 AM – 11 AM). There is no corresponding temperature drop although the temperature holds steady for a few hours. Interestingly, WRF's winds shift clockwise in response to the front and it takes several hours to shift to the southeast where the observation winds were oriented immediate after the passage of the front. A snapshot at 2 PM on this shows good general agreement between the observed and model data. The sea breeze is recognized accurately at all of the coastal stations including DSJR up the Delaware Bay. DWAR shows southeast winds at this timeframe while WRF shows west winds. However, the orientation of the front is within 4 kilometers of this station. Inland stations have winds that are somewhat variable but generally come from the southwest. WRF overestimates the wind speed but captures the general wind direction of these stations. BRND1 appears to be caught in the sea breeze circulation in both the observed and modeled time series. The shift from west to southeast winds occurs slowly in the observed data between 9AM and 1PM. WRF shows the same trend but with winds starting out from the northwest and shifting more quickly between 11 AM and 1 PM.

4.6.4 Case 4: WRF Coastal Ocean Sea Breeze (8/2/2009)

This is an interesting case where WRF appears to develop a sea breeze along Delaware's coast with the Atlantic Ocean but not the Delaware Bay (Figure 4.18). In WRF, most sea breeze fronts observed fill up at least a portion of the Delaware Bay with south east winds. The feature begins to take shape around 2 PM with winds having a very slight eastern component. The effected region is very narrow and penetrates the coast in a few areas. Some areas in the region still have a western wind component but deviate from the synoptic winds on both sides by at least 15˚ over a defined region. The synoptic winds are strong from the south southwest. The observed data shows the synoptic winds with a westerly component that die down during the early afternoon. Several coastal stations (DBBB, DBNG, DIRL, and DRHB) observe the passage of a sea breeze front but are just outside the range of the sea breeze circulation in the WRF representation. The feature is still detectible at 6 PM but appears to be moved eastward especially over the region near the mouth of the bay. Wind output for the 2 meter air temperature over the Bay is nearly 2˚ higher than over the neighboring area of the Atlantic Ocean. This is probably caused by the advection on warm air from southern Delaware. This temperature difference may prohibit the sea breeze along the Delaware Bay while allowing it to develop over along the ocean coastline.

4.6.5 Case 5: WRF missing an Observed Sea Breeze (7/12/2009)

The model does not correctly represent the sea breeze circulation on July 12^{th}, 2008 (Figure 4.19). It is clear that the model simulates local dynamics along Delaware's coastline but nothing that managed to move inland. WRF simulates the wind direction at the reference station about 50˚ clockwise of the observations but the model is very accurate in regards to a wind speed of approximately 4 m/s. Temperature at the coastal stations are well modeled (within a few degrees (˚C)) until the sea breeze passed through which cause overestimates in WRF of about 7 ˚C. Model represented winds at BRND1 are accurate in the morning and then the observed data shifts clockwise throughout the day leading to large errors in the afternoon. The coastal feature displayed in WRF is just to the northeast of BRND1 and would have significantly altered its wind direction possibly reducing the wind direction error.

4.6.6 Summary

WRF performs well in representing the atmospheric conditions in comparison to observation stations during strong synoptic wind conditions. Occasionally it can miss synoptic features which can introduce large errors in temperature and wind magnitude. There are a number of cases where WRF models the geography of the effected region in the observed sea breeze circulation quite well. However, in general the timing lags by a few hours. There are several possible causes for the reason why WRF can miss an observed sea breeze. Winds in the model tend to be at least 1 m/s stronger over most stations over land. While some of this can be attributed to station placement it is probable that WRF improperly handles surface friction. This could have the effect of preventing a developing sea breeze from progressing landward. Another cause may be the poor resolution mean SST's that were input to the model. This leads to a general overestimate of SST's along the southern coastline of Delaware and an underestimate over the Delaware Bay. An underestimate in advective properties of the front may prevent it from propagating large distances. Insufficiently small grid cell resolution and poor coastline representation surely introduce errors into this process as well.

4.7 Sea Breeze Forecasting

With an adequate bank of observationally detected sea breezes, the state of conditions prior to the passage of the front can be investigated to assess the ability to forecast the likelihood of the passage of a sea breeze front. DBBB is the primary station investigated because it has a high percentage of sea breeze occurrence in the summertime and five full years of data to work with. Most sea breezes move over this station between 10 AM and 12 PM. Therefore 8 AM is chosen as a reasonable timeframe where it is unlikely that a sea breeze has already occurred yet still hours after sunrise. All valid sample days are split into classic sea breezes and everything else. Classic Sea Breeze fronts are investigated because they have the largest changes in temperature which could impact tourism. The average temperature, dew point, and east wind direction are looked at for DBBB and the reference station DLAU. The average air temperature at BRND1 is also investigated to see if the temperature over the Delaware Bay can help predict the sea breeze. A generalized linear regression was performed using these variables separately and in various combinations. This model provides weights for each predictor which can be used to calculate the likelihood that a sea breeze will occur later in the day. Over this five year analysis, classic sea breezes occurred at DBBB about 45% of the time. Poor predictors would result in most mornings having a 45% chance of a sea breeze later in the day. Excellent predictors would result in more days having low or high likelihoods. A perfect scenario would have every sea breeze (non-sea breeze) day be preceded by a 100% (0%) likelihood prediction. A skill score can be generated by subtracting the mean predicted values on sea breeze days by those on non-sea breeze days. A perfect predictor would have a score of 100% while a meaningless predictor would have a score of near 0%. Table 4.5 displays the skill scores and relationship of each of the predictors separately as well as in relevant combinations. The predictors used are the temperature, dew point, and east component wind direction of the test station (DBBB) and the reference station (DLAU) and the air temperature over the Delaware Bay (BRND1). As expected the coastal and reference temperature had a positive influence on the likelihood of sea breeze development with respective skill scores of 13 and 5. This may be due to the effects of local variability. Temperature over the bay shows almost no relation with a skill score of 2. The coastal and reference east wind directions show the strongest relations with scores of 25 and 24. They show that wind direction from the west, independent of the speed, favors sea breeze development. Coastal dew point shows no significant relation but the reference dew point shows a positive relation with a score of 9. This could be because of the general correlation between dew point and temperature. Combining all coastal values (temperature, dewpoint, and wind direction) improves the score to 28 which is similar to all reference values (29). Combining these six values discussed leads to the highest skill score observed (52). The addition of the bay temperature lowers the score to 50 but this is probably because it limits the number of valid cases. In either case, the coastal temperature had a positive relation while the reference station had negative relations. The bay temperature also showed a negative relation. The coastal/bay temperature difference is a fundamental dynamic needed to trigger a sea breeze. The coastal/inland difference may be due to the location of the station on the boardwalk in Bethany Beach. On hot days this station generally heats up quicker in part due to the surface properties beneath it. The coastal/bay temperature difference is likely to be small on very windy or cloudy days which typically hinder the propagation of a sea breeze. As expected, an offshore wind has a positive relation in both the coastal and reference station. The dew point at the coastal station has a negative association while at the reference station there is a positive association. Figure 4.20 shows how well the seven variable model (score = 50) fits the observed data for all valid cases. There is a low frequency of cases where the model predicts the likelihood of sea breeze formation to be between 30% and 70%. Therefore at 8 AM the current conditions at DBBB and DLAU give significant insight into the probability of a sea breeze occurring later in the day at DBBB. Future analysis could increase the effectiveness of this model by adding more stations and including variables such as U wind speed, solar radiation, and synoptic wind trends.

4.8 Return Flow Analysis

The return flow of a sea breeze circulation is critical for mass balance and feeding the up and downdrafts that drive the surface front. WRF model output provides detailed wind speeds and directions at twenty-eight levels in the atmosphere from the surface to 100 millibars with a bottom heavy logarithmic distribution. Studies show that the top of the return flow can rise to approximately 1,000 to 3,000 meters which corresponds to the lower eleven of the twenty-eight standard vertical eta levels defined in WRF. The majority of runs utilized in this study have a temporal output rate of one hour which makes it difficult to see the genesis of the return flow or even distinguish it from a synoptic westerly wind. This is because the synoptic flow at an elevation of one to two kilometers is often strong. A developing return flow would be superimposed on top of this and be difficult to detect. However, a one day run with a one day spin-up was generated for June 30, 2002 with model output every two minutes. This day was selected because a sea breeze circulation was clearly visible from the corresponding monthly WRF run for June 2002. The Dover radar site is in precipitation mode for this day inhibiting radar detection of the sea breeze. The WeatherBug station in Lewes, DE, shows a shift in wind direction at approximately 11AM but there is no landward station to compare this observation to. Unfortunately, Buoy #44009 is also missing data for this day.

To investigate the vertical structure, plots were generated which show a latitudinal cross section of the study area that intersects the Delaware coastline several kilometers south of Rehoboth Beach. The bottom twelve vertical layers in WRF are shown which correspond to heights from the surface to approximately 3,500 meters. Snapshots show the vertical structure of the sea breeze throughout its life cycle (Figure 4.21). Longitudinal grid box #62 represents the coastline for the images. At 8:30 AM EST there is a moderate offshore breeze and a very weak onshore breeze above 500 meters. The first signs of a forming sea breeze circulation occur around 11:00 AM. Light offshore winds are present right along the coastline and arguably extend upwards to 100 meters. Very weak offshore winds predominate the remaining surface areas both inland and out to sea. This is a promising sign for inland propagation of a sea breeze front. The winds above 500 meters are unchanged at this point. At 12:30 PM the structure of the sea breeze circulation is evident. From an hour before, the onshore component of the sea breeze flow near the surface increased from 1 m/s to 3 m/s. At this point the return flow is indistinguishable from the weak synoptic offshore breeze. The height of the feature is about 150 meters and bows out at the surface by several kilometers. At 2:30 PM the circulation has significantly grown in size in all directions. It spans about forty kilometers, split evenly between the landward and seaward component. There is an abrupt edge of the circulation on the landward side and a weak cutoff on the seaward side. The strongest onshore winds remain near the coast at over 5 m/s. The highest part of the onshore flow penetrates to approximately 650 meters and this is at the edge of the advancing front. This is the first time that the return flow is clearly present. The return flow is significantly weaker in strength than the corresponding surface flow. It is reaching a peak offshore component of only 2 m/s. The background winds at this height have almost no onshore or offshore component. The return flow spans from 500 meters to 1200 meters and reaches its highest elevation at the leading edge of the front. Finally, at 4:30 PM the surface component of the circulation reaches a peak in size spanning over fifty kilometers. There was little additional increase in the magnitude of the shoreward component. The height remained relatively constant but the vertical differential between the landward edge and the rest of the onshore breeze is more level. The return flow expands in magnitude to a maximum of 2.5 m/s near the leading landward edge of the front. The overall height of the return flow increases to over 2000 meters but is unrecognizable over the ocean. After this point in time, it appears that the overall synoptic flow shifts to contain a slight onshore component thus blending in with the sea breeze and making it unrecognizable. The return flow of the Delaware Sea Breeze is clearly evident in this WRF simulation and its properties fit well with previous studies concerning strength and location. This gives much promise to a future study investigating this feature in more detail.

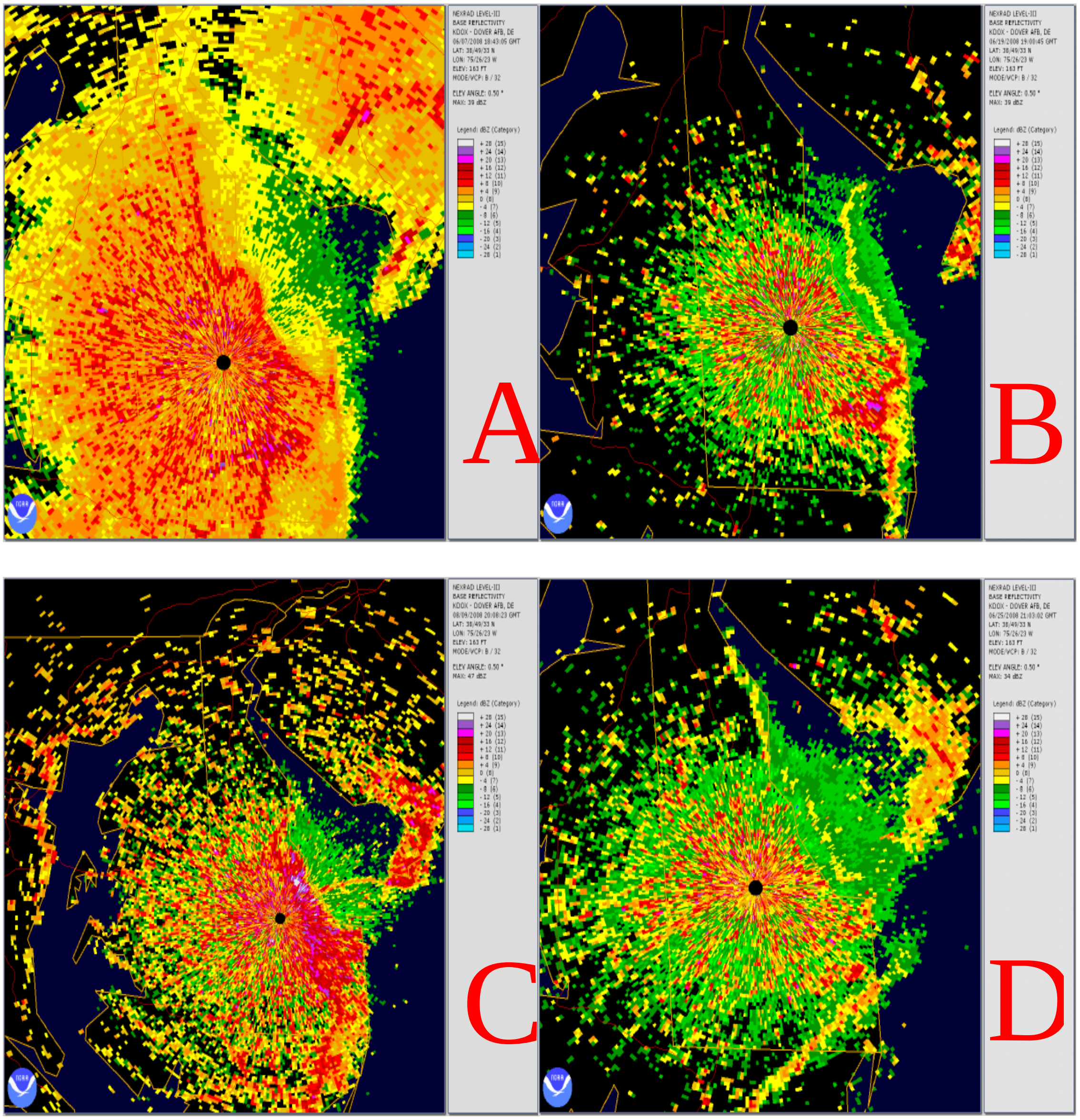


Figure 4.1: **Unique sea breeze features observed on NEXRAD radar (KDOV). The Delaware Bay/Sea Breeze can have unique shapes and can cross the Delaware Bay from a variety of directions.**

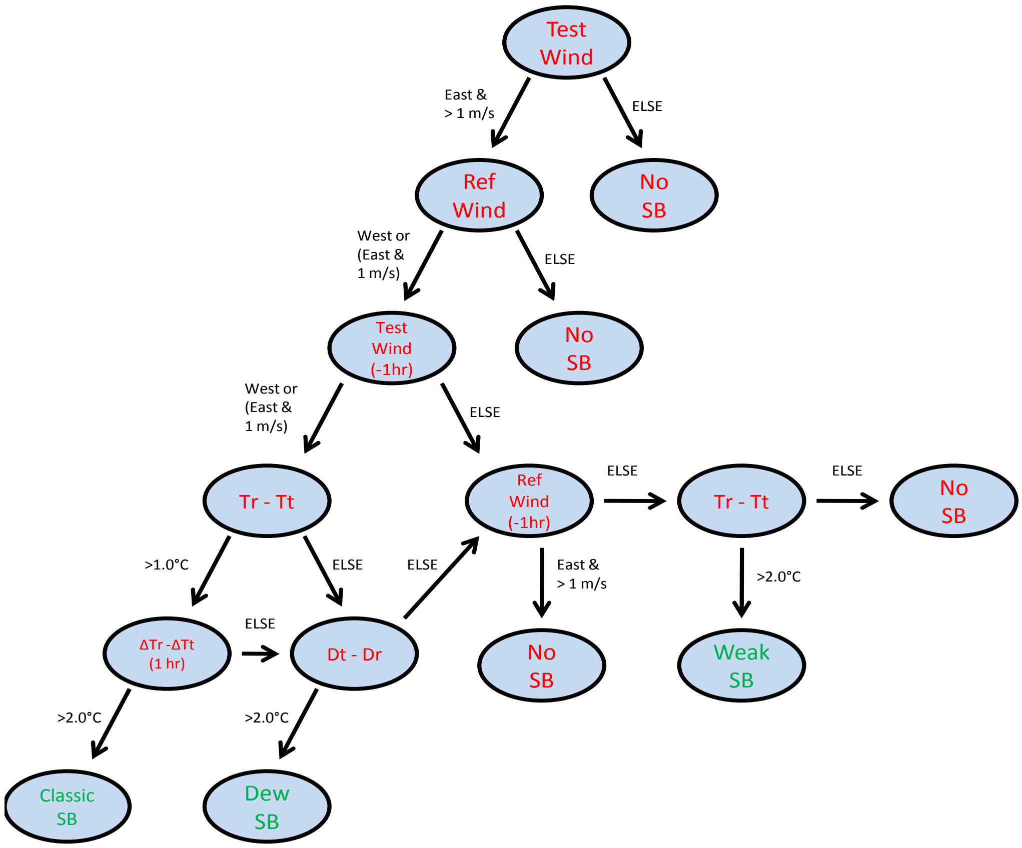


Figure 4.2: **Sea breeze classification scheme flowchart. This classification scheme is based on current and past wind, temperature, and dew point conditions at a test and reference station.**

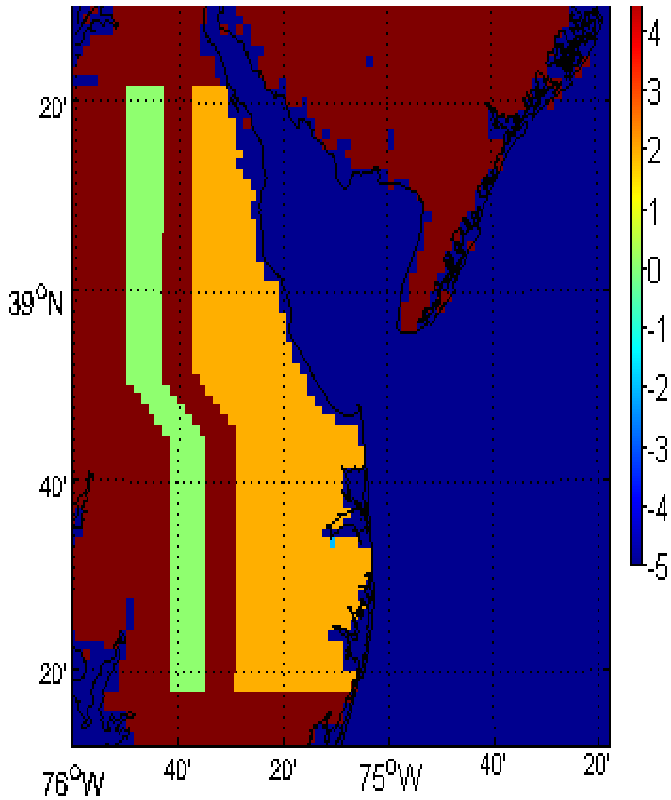


Figure 4.3: **WRF sea breeze test region. The yellow-orange area represents the every cell that will be tested for the presence of a sea breeze. The light blue station is a water point that will still be tested because it has several land points immediately to its eastward side. The green strip represents a series of reference stations that are reasonably far from the Delaware Bay, Atlantic Ocean, and Chesapeake Bay.**

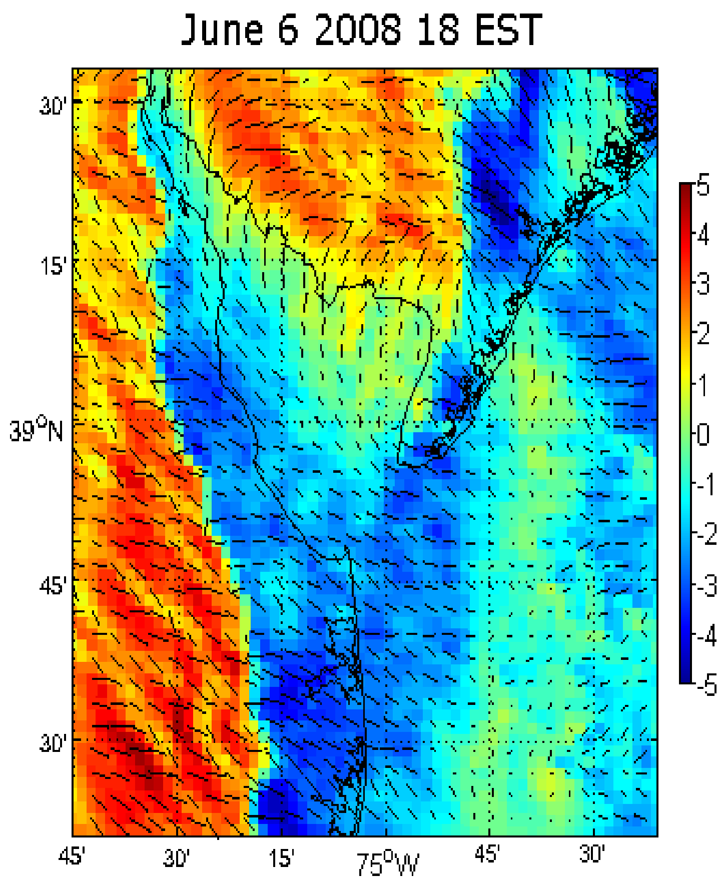


Figure 4.4: **Sea breeze representation in WRF: The U wind component (m/s) is presented with the blue color representing winds with a component from the east. The sea breeze front is located where the west and east winds meet.**

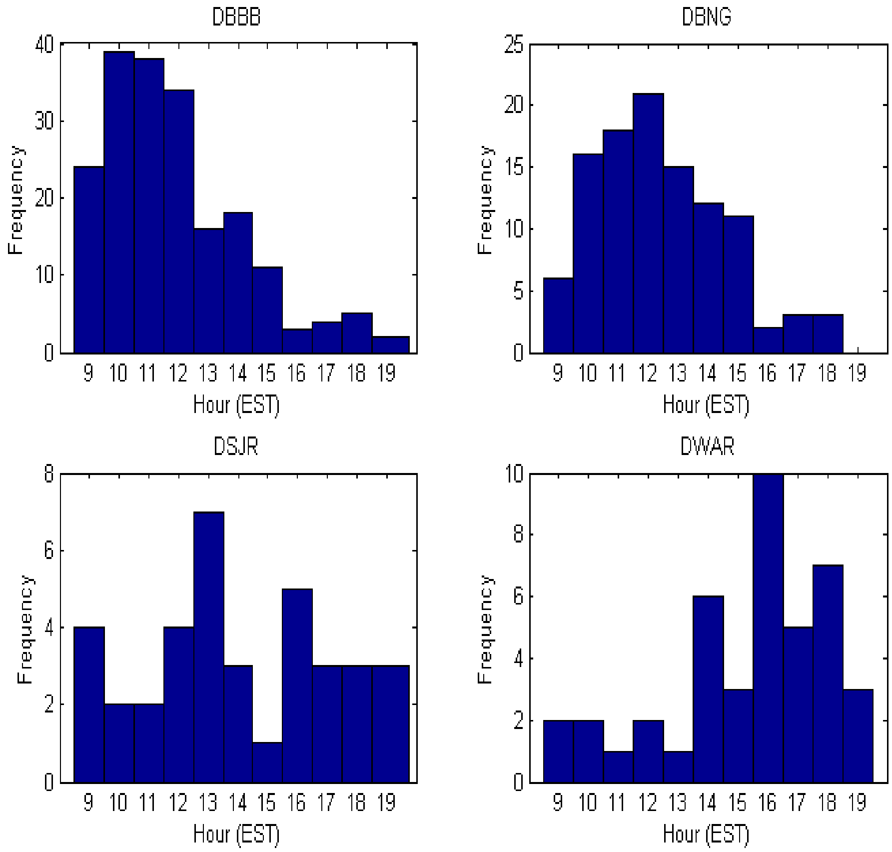


Figure 4.5: Arrival time of the classic sea breeze (obs. data). The mean arrival time of the sea breeze along the coast is between 11 AM and 12 PM. Areas further inland experience the front hours later. DSJR experiences both the Bay and Sea Breeze resulting in a more uniform arrival time distribution.

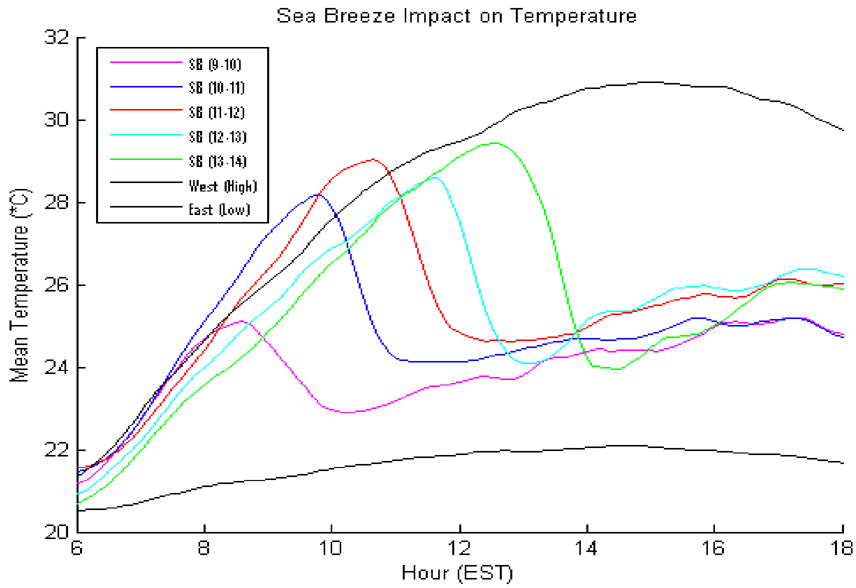


Figure 4.6: **Sea breeze impact on temperature (obs. data). The black lines represent days with constant east (cooler) and constant west (warmer) winds with no sea breezes. The colored lines represent sea breezes divided by hourly arrival time. Earlier sea breezes have smaller mean temperature drops associated with them.**

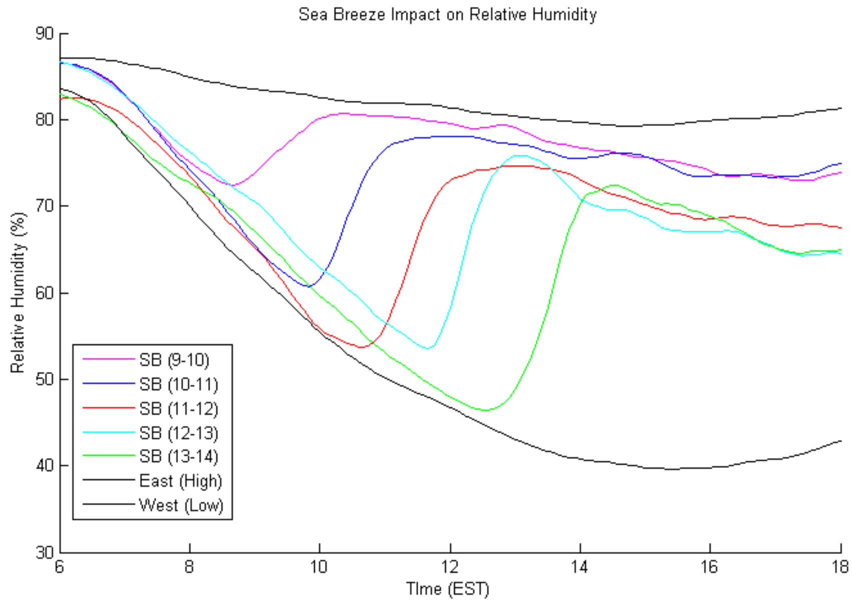


Figure 4.7: Sea breeze impact on relative humidity (obs. data). The black lines represent days with constant east (high rh) and constant west (low rh) winds with no sea breezes. The colored lines represent sea breezes divided by hourly arrival time. Earlier sea breezes have smaller increases in relative humidity associated with them.

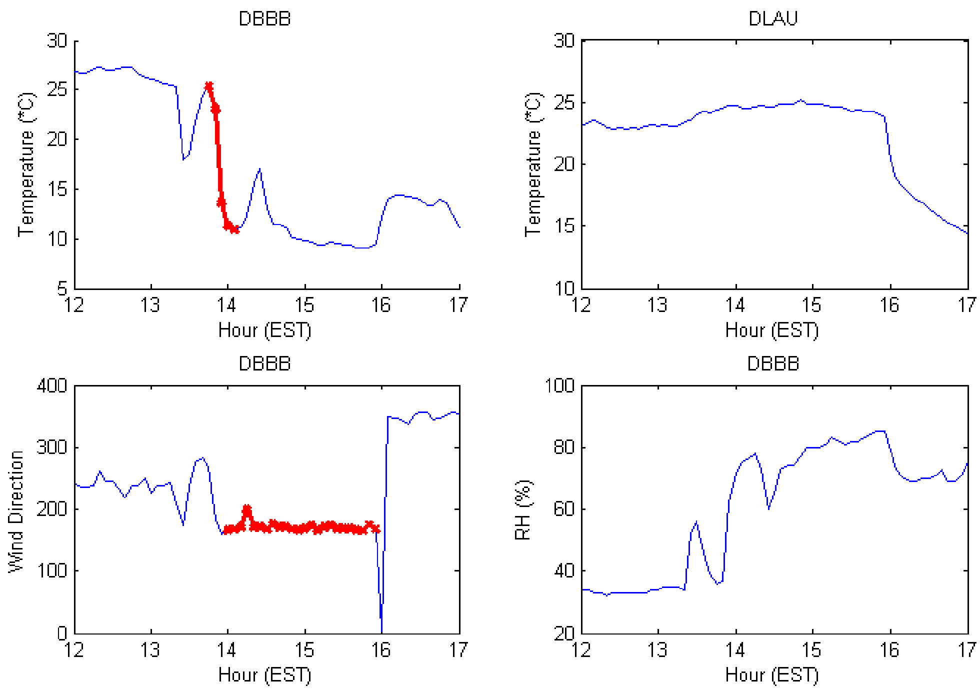


Figure 4.8: Extreme sea breeze at DBBB: 3/17/2007 (obs. data). The temperature drop associated with the sea breeze on this day is over 10˚C. A cold front passing through later in the day actually increases the temperature over the region affected by the sea breeze.

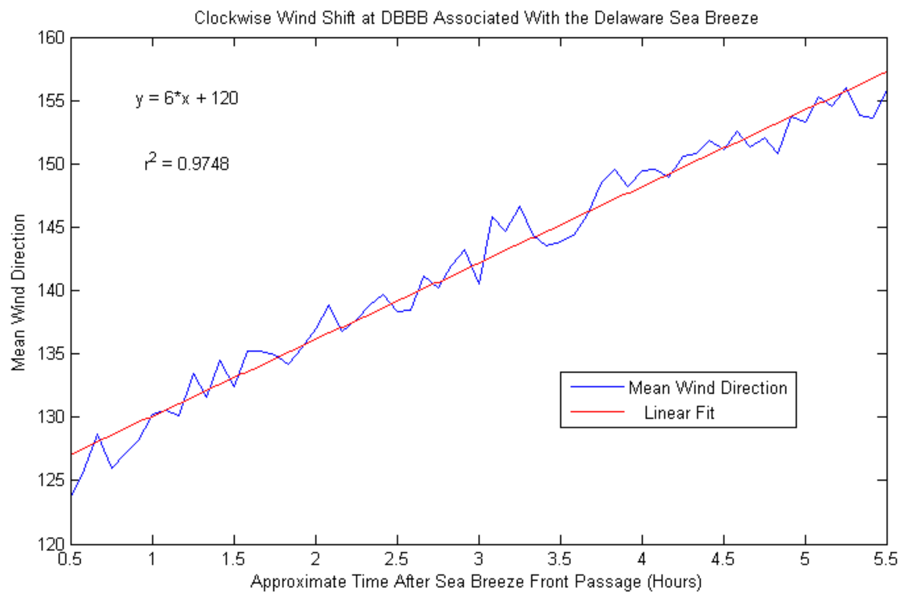


Figure 4.9: Sea breeze wind rotation at DBBB (obs. data). There is strong evidence of clockwise turning of the winds in a sea breeze regime. The average turning is approximately 6˚ per hour.

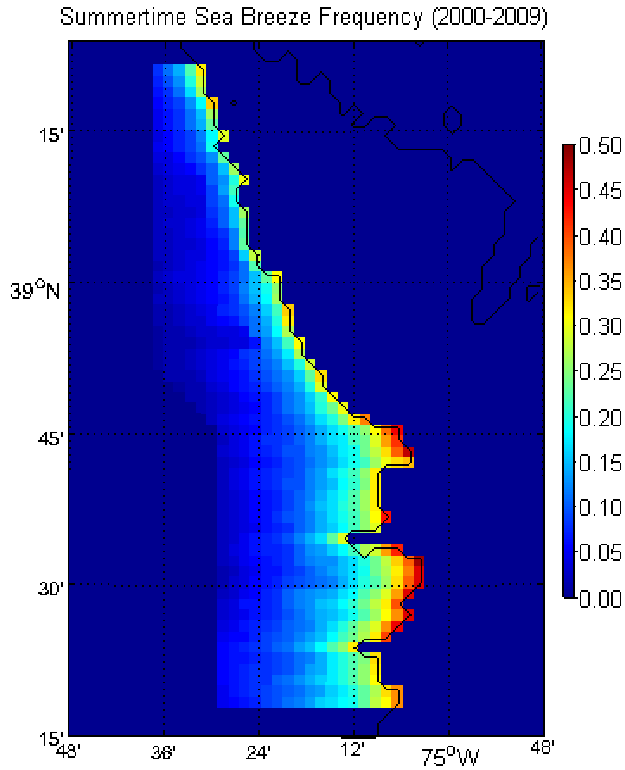


Figure 4.10: WRF represented sea breeze frequency (2000-2009). Through 10 summers of model output, the sea breeze frequency results are similar to the observed data. There is a higher frequency along the coast reaching nearly 50%.

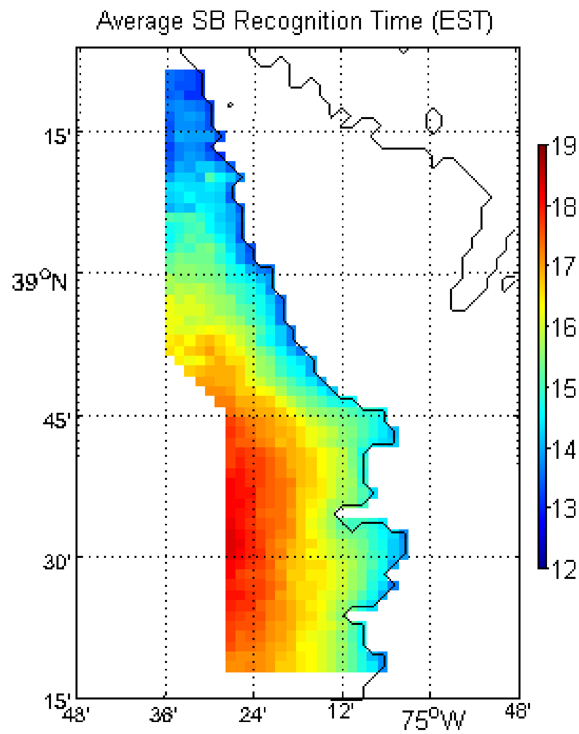


Figure 4.11: WRF sea breeze recognition time. The mean recognition time along the coast is around noon. Fronts cross through the innermost test area approximately six hours later.

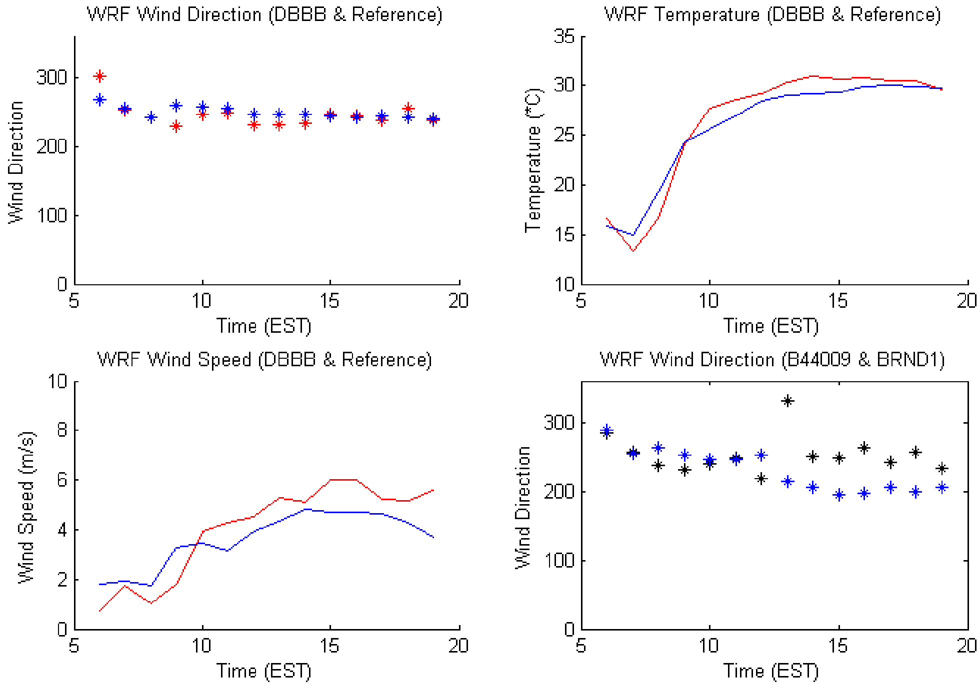


Figure 4.12 Synoptic west wind in WRF (6/30/2009)

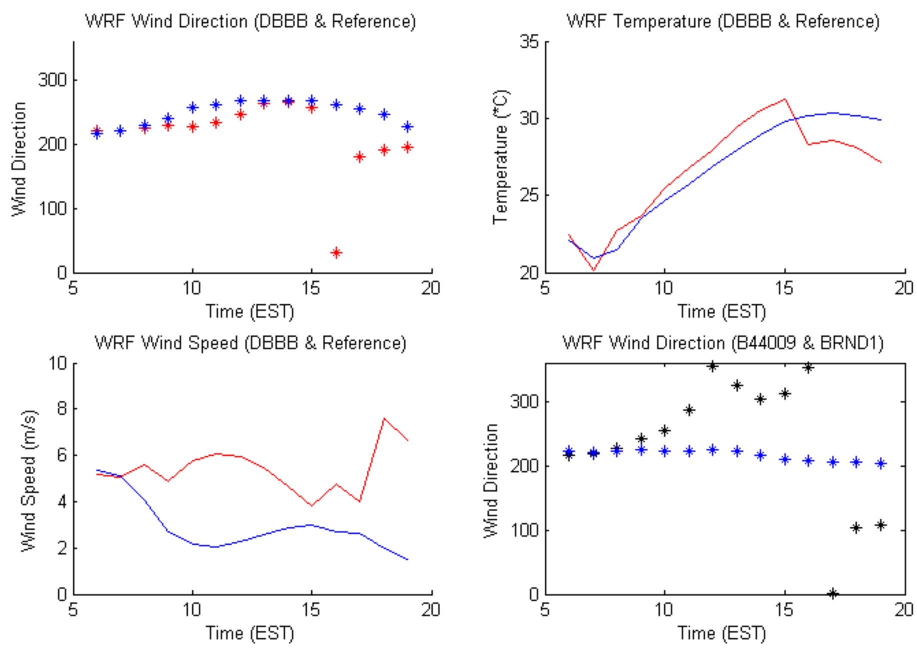


Figure 4.13: Classic sea breeze in WRF (6/4/2009)

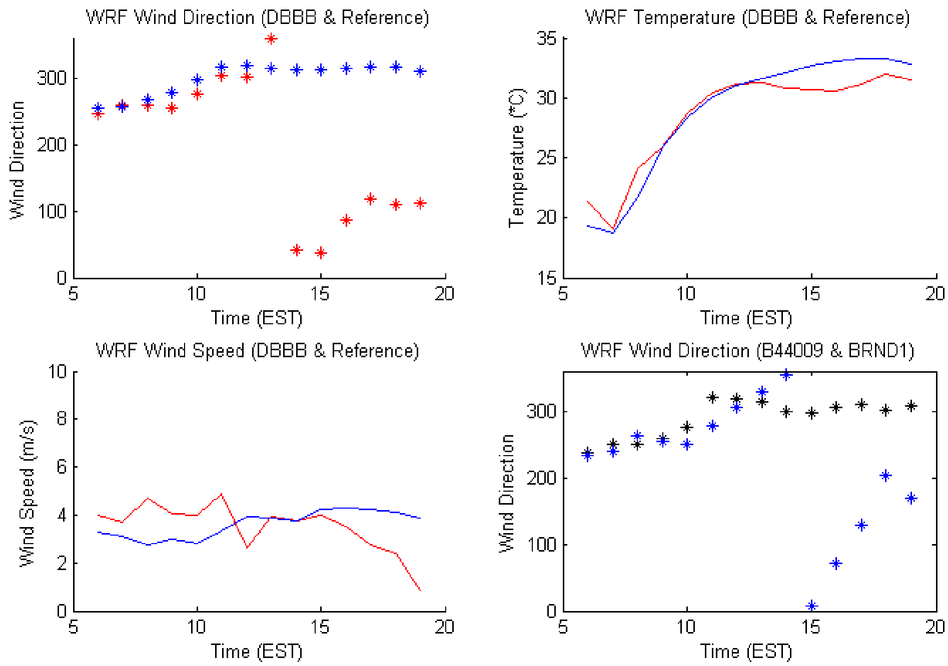


Figure 4.14: Weak sea breeze in WRF (6/25/2009)

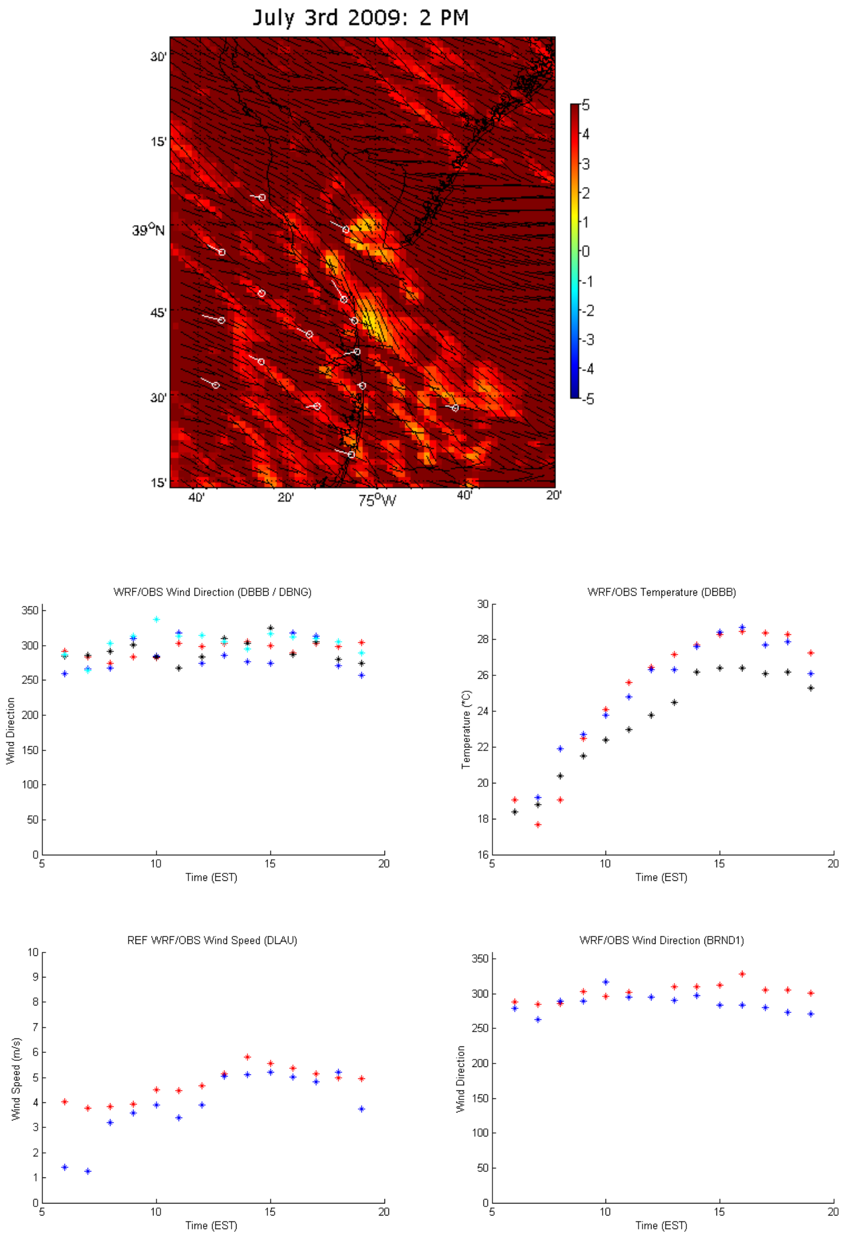


Figure 4.15: Case 1: Obs./WRF strong west synoptic winds (7/3/2009)

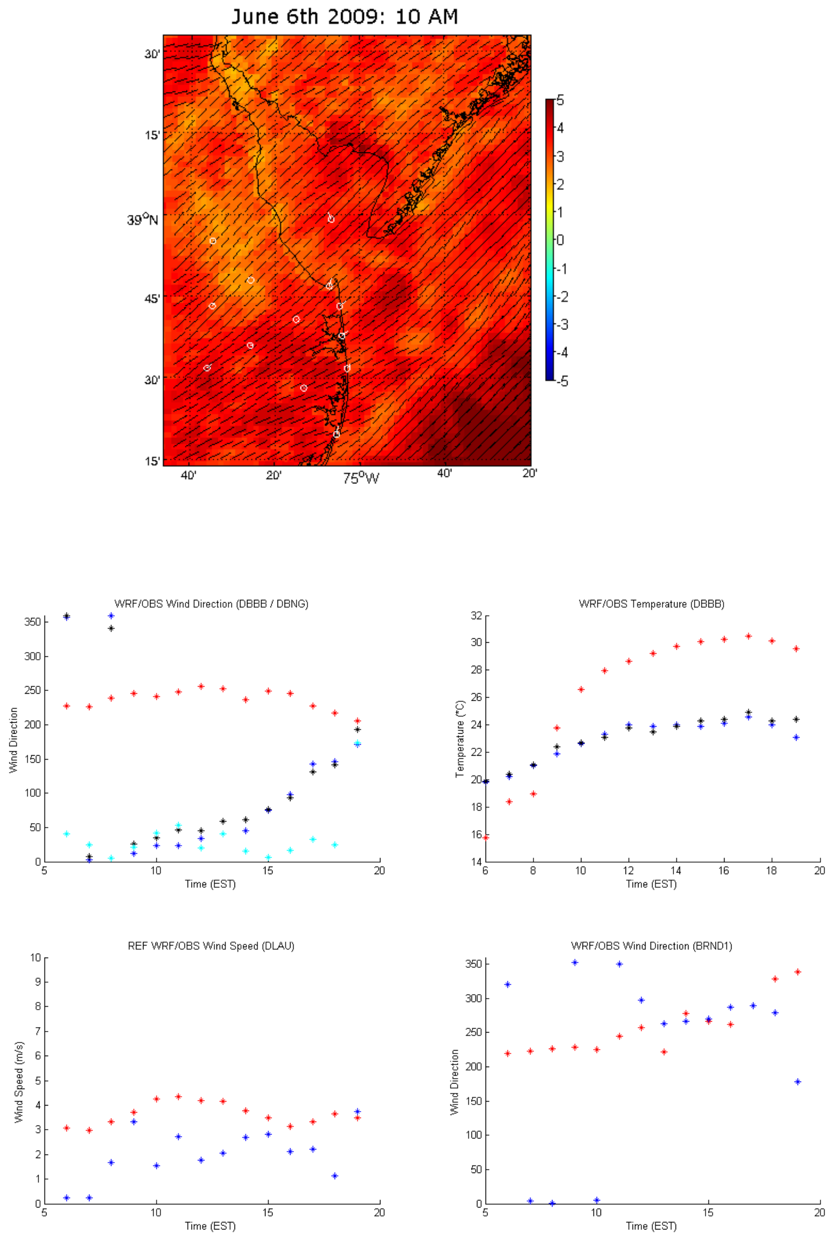


Figure 4.16: Case 2: WRF missing obs. synoptic conditions (6/9/2009)

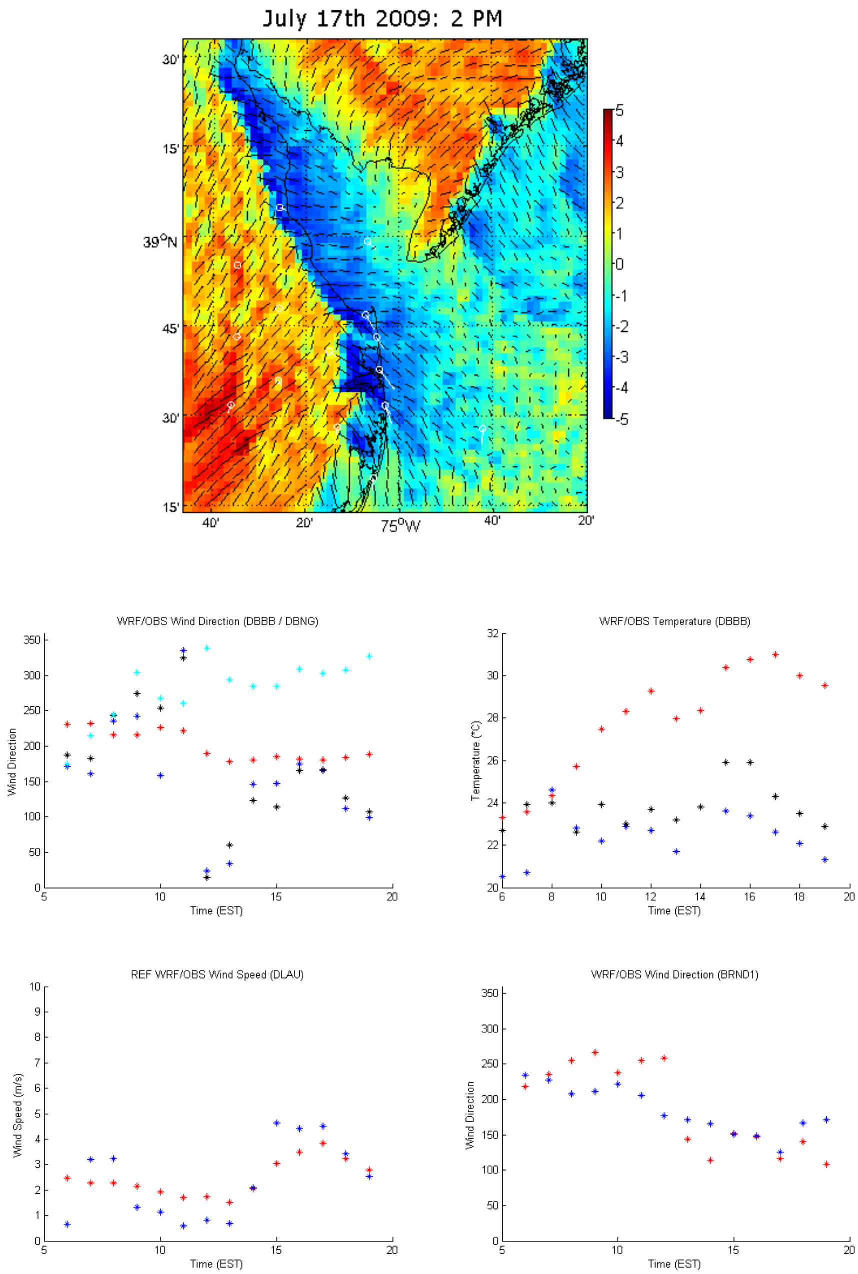


Figure 4.17: Case 3: Accurate sea breeze representation (7/17/09)

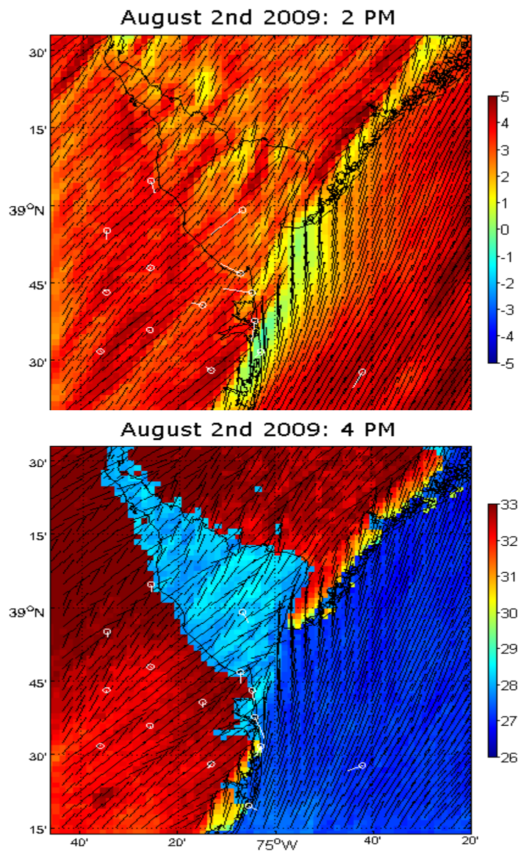


Figure 4.18: Case 4: WRF coastal ocean sea breeze (8/2/2009). The east wind component (m/s) and the 2-m air temperature (°C) show the location of the front along the coastline and mouth of the Delaware Bay.

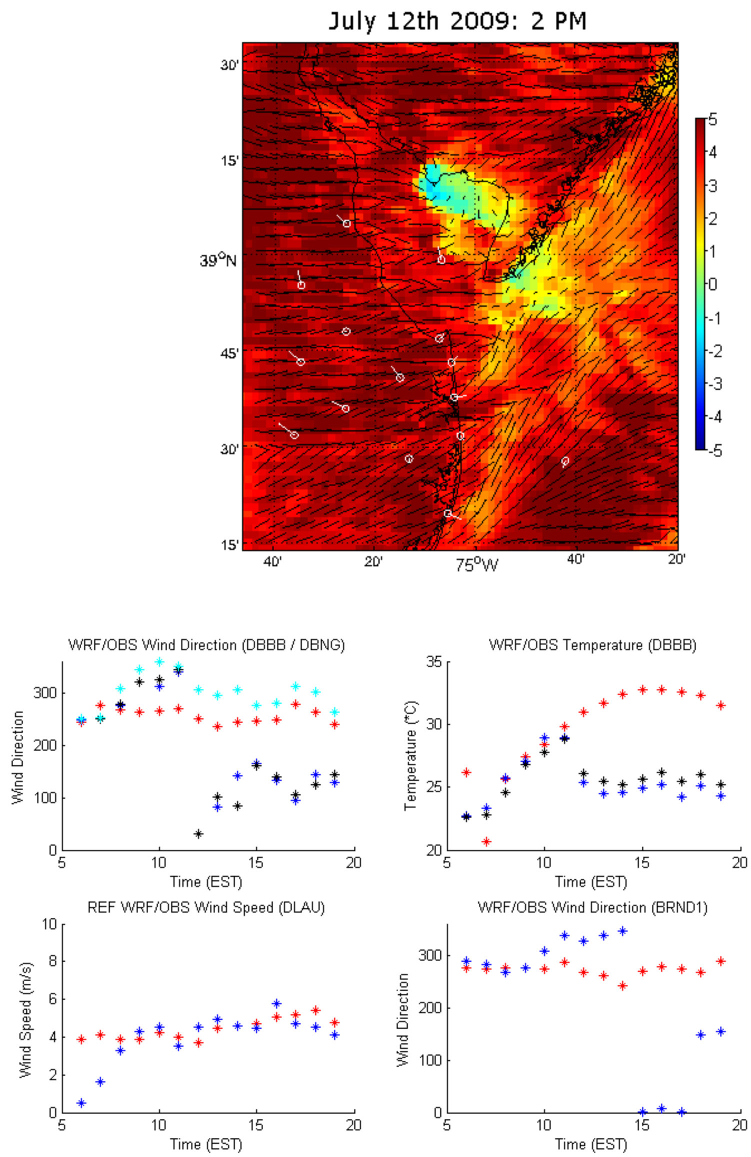


Figure 4.19: Case 5: WRF missing an obs. sea breeze (7/12/2009)

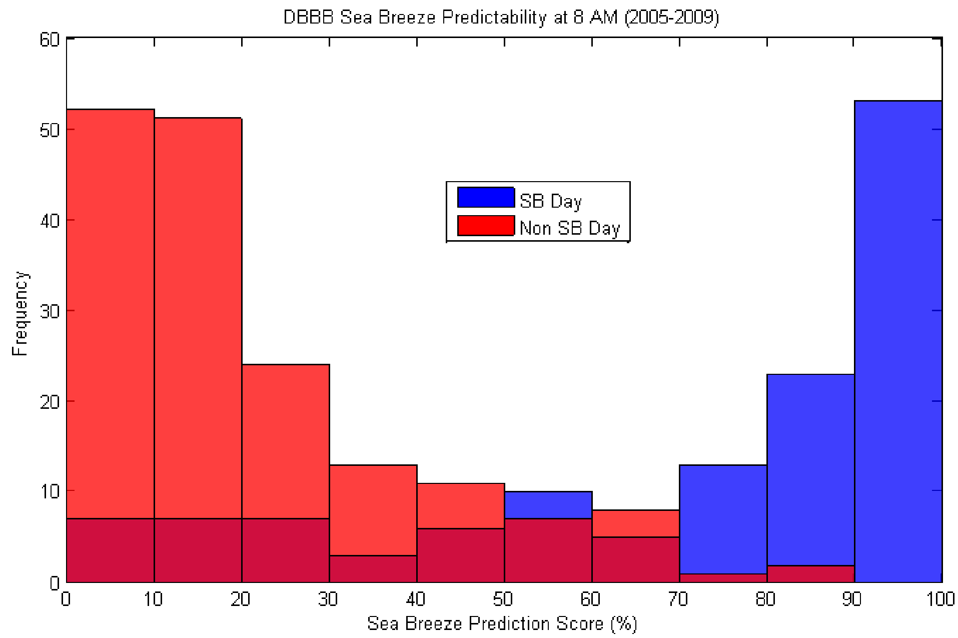


Figure 4.20: Sea breeze predictability based on conditions at 8 am (DBBB). The predictability scheme assigns a percentage likelihood of a sea breeze to every day of the study (2005-2009). The results are displayed and binned according to if a Classic Sea Breeze actually occurred on that day. The program is very accurate on days that it assigns a greater than 80% or less than 20% chance of a sea breeze.

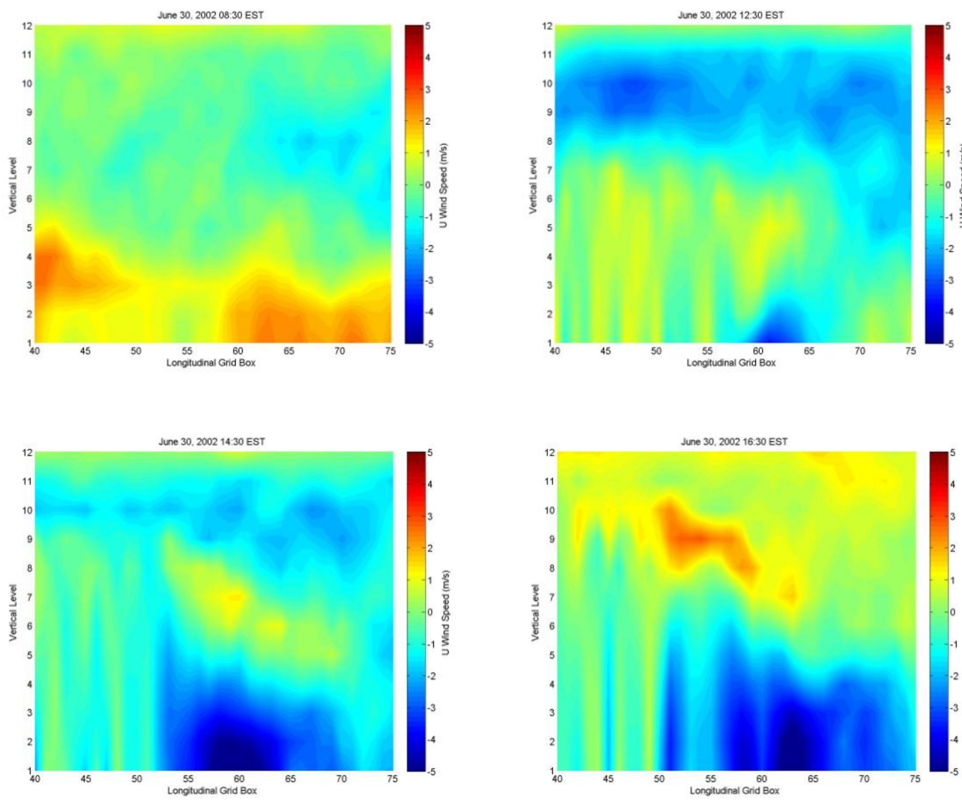


Figure 4.21: WRF simulated return flow of the sea breeze. The return flow originates well after the surface sea breeze front develops. It is approximately twice as thick and has half the wind velocity of the surface front.

Table 4.1: Sea breeze classification scheme

	Test Wind (Now)	Test Wind (1 HR ago)	Ref. Wind (Now)	Ref. Wind (1 HR ago)	Ref Temp – Test Temp	ΔRef Temp - ΔTest Temp	ΔTest Dew
Classic SB	East & > 1m/s	West or (East & < 1.0 m/s)	West or (East & < 1.0 m/s)	X	>1.0 ˚C	>2.0 ˚C	X
Dew SB	East & > 1m/s	West or (East & < 1.0 m/s)	West or (East & < 1.0 m/s)	X	X	X	>2.0 ˚C
Weak SB	East & > 1m/s	X	West or (East & < 1.0 m/s)	West or (East & < 1.0 m/s)	>2.0 ˚C	X	X

Table 4.2: Obs. station sea breeze frequency (2005-2009)

	Classic SB	Dew SB	Classic + Dew SB	Weak SB	West	East	Variable	Sample Size
LWSD1	21	*	*	41	15	13	11	357
DRHB	37	0	12	24	8	14	4	171
DIRL	31	0	7	36	6	14	6	171
DBBB	30	1	15	25	6	15	8	438
DBNG	17	4	7	25	13	17	17	442
DSJR	5	7	4	18	29	15	21	412
DWAR	6	5	4	13	26	21	24	404
DELN	5	4	1	2	32	14	42	184
DJCR	5	8	3	3	27	18	36	393
DSTK	7	10	4	1	26	16	35	184
DSBY	7	4	2	8	32	13	35	184
Coast	24	2	9	28	13	15	11	332
Inland	6	6	3	5	29	16	34	270
All	16	4	6	18	20	15	22	304

*Station missing dew point values.

Table 4.3: Arrival time of the classic sea breeze

(EST)	LWSD	DRHB	DIRL	DBBB	DBNG	DSJR	DWAR	DELN	DJCR	DSTK
Mean	12.45	12.1	12.16	11.89	12.51	14	15.36	15.47	16.33	15.97
June	12.59	12.91	12.62	11.79	12.63	14.89	15.29	14.88	16.85	15.75
July	12.39	11.53	10.89	11.59	12.06	13.74	15.65	16.69	15.76	15.75
August	12.26	12.11	12.72	12.27	12.8	13.4	15.26	14.5	16.39	16.43

Table 4.4: Obs. station sea breeze correlation along the coast. Match refers to two stations having the same kind of sea breeze (or no sea breeze) on a particular day. A partial match refers to two stations having different kinds of sea breezes on the same day. A miss refers to only one of the stations experiencing a sea breeze.

Match	LWSD1	DRHB	DIRL	DBBB
LWSD1	100	58	53	58
DRHB	*	100	73	83
DIRL	*	*	100	78
DBBB	*	*	*	100
Partial Match	LWSD1	DRHB	DIRL	DBBB
LWSD1	0	30	33	21
DRHB	*	0	23	13
DIRL	*	*	0	22
DBBB	*	*	*	0
Complete Miss	LWSD1	DRHB	DIRL	DBBB
LWSD1	0	12	13	21
DRHB	*	0	3	4
DIRL	*	*	0	1
DBBB	*	*	*	0

Table 4.5: Obs. sea breeze predictability based on conditions at 8 am (DBBB)

Predictor	Score	Relation 1	2	3	4	5	6	7
Tc	13	+						
Tr	5	+						
Tb	2	+						
Dc	2	+						
Dr	9	+						
Ec	25	-						
Er	24	-						
Tc-Tb	15	+						
Tc,Tb,Tr	16	+	-	-				
Ec,Er	29	-	-					
Tc,Dc,Ec	28	+	+	-				
Tr,Dr,Er	29	-	+	-				
Tc,Dc,Ec,Tr,Dr,Er	52	+	-	-	-	+	-	
Tc,Dc,Ec,Tr,Dr,Er,Tb	50	+	-	-	-	+	-	-

Code	Predictor
Tc	Coastal Temp
Tr	Ref Temp
Tb	Bay Air Temp
Dc	Coastal Dew
Dr	Ref Dew
Ec	Coastal East Wdir
Er	Ref East Wdir

Region	Station
Coastal	DBBB
Reference	DLAU
Bay	BRND1
Bay	BRND1

Chapter 5

SUMMARY

This study shows that the wind climatology over southern Delaware, the Delaware Bay, and nearby Atlantic Ocean is complicated. There is considerable spatial variability especially along the coastal areas during the daytime hours of the summer. This feature is adequately captured along the coastline in WRF. There is a slight counterclockwise tilt in the winds over the Bay as opposed to nearby the open ocean as seen by BRND1 and B44009. All variations mentioned are superimposed on the general wind scheme of southerly winds in the summer and northwesterly winds in the winter. Throughout the year 2009 WRF does a better job at representing the variations associated with late fall and winter time wind schemes that are synoptically driven. The summer, with a larger mesoscale component has larger errors that may also be associated with lighter and more variable winds. The sea breeze phenomenon is a common feature along Delaware's coastline during the summertime. Radar and observational data from this study show that there is both a bay and sea component which can interact in dynamic ways. The median starting time along the coast is between 10 AM and 11 AM but can range from the early morning to late afternoon. Although not formally addressed, sea breezes that occur in the late fall and early spring tend to have later starting times and can bring about the most drastic temperature changes (>10˚C). During the summer the sea breeze has a frequency of between 50% and 75% around coastal stations and 5% to 20% at inland stations. An initial analysis in WRF shows a slight underestimate in sea breeze frequency both in both regions. An overestimate in the general winds, inaccurate SST's, or poor temperature advection may be a cause of these errors. Increasing the resolution could help better diagnose the dynamics of the sea breeze in areas within five kilometers of the coast. It is hoped that the results found in this study can be used to further improve errors associated with the WRF and to increase the common understanding of the wind climatology and sea breeze effect in and around the coastline of southern Delaware.

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Data Cited:

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WeatherBug

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