

A RADAR ANALYSIS OF THE DELAWARE SEA/BAY BREEZE

by

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ABSTRACT

The Delaware sea-breeze circulation is a very influential factor on the climatology of Delaware. The sea-breeze has important implications on the transport of air-pollutants, thermal comfort, aviation, and coastal wind-power generation. This mesoscale density current has been traditionally investigated using a network of Automated Surface Observation Systems (ASOS). This thesis expands upon the traditional methods to introduce a new method to observe and characterize the spatial characteristics of the sea-breeze front using the WSR-88D weather radar. The sea-breeze is the result of the differential heating between the land and sea. This interface and associated scatterers between the two resultant air-masses make the sea-breeze front detectable using the WSR-88D radar platform. To supplement the radar data, high resolution Sea Surface Temperature (SST) composites are utilized to show the influence of the Delaware Bay and coastal ocean water temperatures on the behavior of the sea-breeze front. Behavioral characteristics examined were frontal inland penetration, speed, and shape.

Chapter 1

INTRODUCTION

1.1 Introduction

Until recently, the Delaware Sea/Bay Breeze (SBB) has been largely overlooked in academic research. However, this coastal breeze is a common occurrence along coastal Delaware, especially during the summer months. The Sea/Bay Breeze circulation is also important part of the local climate. Recent studies have detailed features of the Delaware SBB, established a climatology, and categorized the different types of sea and bay breeze circulations that occur over Delaware [Hughes, 2011], [Garvine and Kempton, 2008], [Bowers, 2004]. To date, the Delaware SBB studies have utilized observations from the National Data Buoy Center (NDBC), the Delaware Environmental Observing System (DEOS) and regional scale modeling with the Weather Research and Forecasting model (WRF). However, detailed observations of the geospatial evolution of the SBB front are not currently available using classic meteorological observational techniques. Many classic techniques utilize a complex network of strategically located meteorological ground stations to characterize the geospatial aspects of the local SBB circulation. This study combines classical and remote sensing techniques to characterize the geospatial characteristics of the Delaware SBB. This study inspects characteristics such as SBB frontal shape, propagation speed, and inland penetration by using the operational weather radar located at Dover Air Force Base. In addition, it inspects the correlation between synoptic type and SBB occurrence. The combination of the spatial analysis of the radar data and the synoptic typing paints a more cohesive picture of the evolution of the Delaware Sea/Bay Breeze.

1.2 Motivation

Atmospheric meso-scale density fronts, such as the SBB, owe their existence and evolution to synoptic scale variations in pressure and temperature. The atmospheric meso-scale is broken up into three subcategories by horizontal length scale: Meso-gamma (2-20 km), meso-beta (20-200 km), and meso-alpha (200-2000 km) [Markowski and Richardson, 2010]. The Delaware SBB circulation falls into the meso-beta subcategory with an along-front horizontal extent ranging from 10-200 km and with a time-scale ranging from minutes to several hours. As detailed below, these diurnal circulations have important impacts on the local transport of air pollutants, coastal wind power generation, and local tourism.

1.2.1 Air Pollutants

According to the Delaware Annual Air Quality report for 2011, there were 15 recorded days where the surface ozone concentrations “exceeded the new 8-hour standards statewide, with 11 days in New Castle County, three days in Kent County, and six days in Sussex County.” It is important to note that the stations nearest to a body of water have the least number of days that exceed the National Ambient Air Quality standards. One possible explanation for this is the evacuation of the polluted air by the local sea/bay circulation. A caveat to this phenomenon is mentioned in Simpson [1994] where he explains how after the passage of a sea breeze the new and more stable air mass may act as a “lid” to the local atmospheric boundary layer. This traps pollutants produced after the SBB front passage, which are then advected by the local ambient flow. Evidence suggests that the trapped pollutants can remain intact and move offshore before being re-advected onshore by the following day’s SBB. With an increase in the urbanization of coastal Delaware, detailed in appendix A, and the consequential increase of pollutants such as the photochemical production of O_3 further emphasizes the importance of better understanding the SBB dynamics and features.

1.2.2 Wind Power

With a growing population there comes a growing demand for power generation, more specifically renewable power generation. The National Renewable Energies Lab (NREL) ranks coastal Delaware in the “fair” regime in terms of wind power resource potential (figure 1.1).

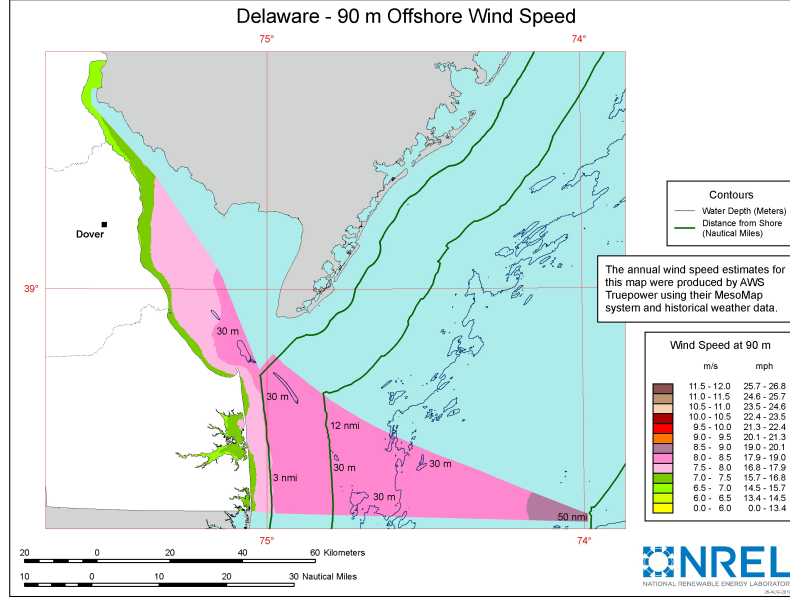


Figure 1.1: NREL wind power resource projection for Delaware.

The Delaware coast experiences a SBB 68% during the summer months [Hughes, 2011]. The SBB breezes typically occur on days with weak prevailing winds during the hours of peak electricity demand [Garvine and Kempton, 2008]. In addition, the vertical extent of the SBB often encompasses even the tallest terrestrial wind turbines with hub heights of 90 m. Understanding more about the driving mechanisms of these circulations may have important implications for the eventual adoption of coastal and near shore wind power generation. This study investigates second order driving mechanisms that can be a precursor for specific SBB frontal shapes, inland extents, and dynamics.

1.2.3 Study Area

Delaware is the second smallest state in the United States but shares one of the largest estuaries on the east coast, the Delaware Bay. The bay mouth is 18 km wide from Cape Henlopen, DE to Cape May, NJ and has an area of 2030 km². The state has about 180 km of coastline (includes the Delaware River, Bay, and Atlantic Ocean) and lacks any distinct topographic features. The northern portion of the state is the most densely populated with next most populated area located along the Atlantic coast (figure 1.2). What makes the coastal population very different from the population of northern Delaware is that it is largely seasonal. According to Vantage Strategy [2012], coastal Delaware is a popular

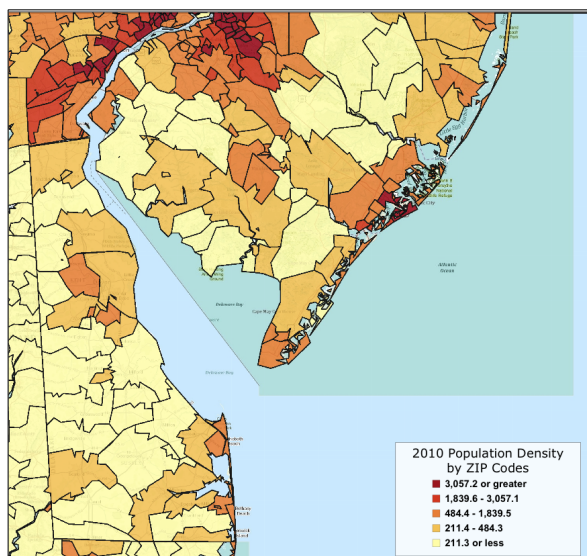


Figure 1.2: Population density by zip-code. The data was provided by the 2010 U.S Census

vacation spot for more than 1.4 million beach goers and sightseers each year, with most visits during the summer months. On any given summer day, hundred of thousand of people can be affected by a strong SBB.

1.3 Background

A sea breeze is a diurnal, thermally driven atmospheric circulation caused by differential heating between a land-surface and an adjacent body of water. Classic sea breeze theory predicts that on a warm, clear day with light offshore breeze or no wind, the land-surface will heat up more quickly than an adjacent body of water [Simpson, 1964]. This warming of the land surface increases surface atmospheric pressure, resulting in a localized upward transport of air. Meanwhile, the nearby surface-pressure over the water remains relatively constant, so the difference between terrestrial-surface atmospheric-pressure and maritime-surface atmospheric-pressure increases [Miller, 2003]. The development of this low-level horizontal temperature and pressure gradient sets the stage for water to land (high pressure to low pressure) transport of cooler maritime air, in an effort to regain thermodynamic equilibrium. The constant heating over the land during the day causes buoyancy driven, upward motion producing a localized area of low pressure. This initiates and landward transport of maritime air mass, formally known as a sea breeze. This air mass is then sent back to its origin in a similar, but inverted pressure gradient system aloft. There have been studies confirming the existence of a variety of sea breezes with distinct characteristics [Miller, 2003],[Bowers, 2004],[Hughes, 2011]. Each of these studies touches on how SBB fronts can be detected by radar platforms, a concept that was first introduced by Atlas [1960].

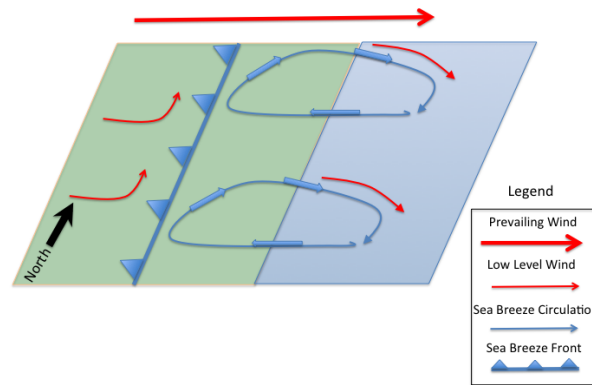
Atlas [1960] determined that a difference in refractive index between the terrestrial and maritime air mass boundaries was significant enough to produce a clear-air return thus making a SBB front detectable using a radar platform. From this first publication there have been numerous studies dealing with meso-scale meteorological phenomenon [Simpson, 1964], [Meyer, 1971], [Sauvageot and Omar, 1987], [Hadi et al., 2002], [Gilliam et al., 2004], [Bowers, 2004], [Keeler and Kristovich, 2012] and other studies that inspect the legitimacy of using air-born biota as clear-air tracers ([Campistron, 1975],[Achtemeier, 1991],[Wilson et al., 1994],[Buler and Diehl, 2009]). A similar methodology is applied to the radar data

collected by the NEXRAD platform at Dover Air force base (KDOX) for the current study.

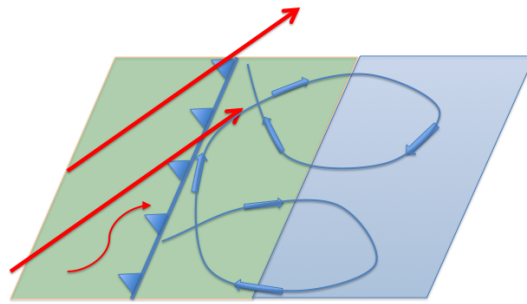
Similar to this study, Banta [1995] found that the complexity of the Monterey Bay coastline reveals an equally complex sea breeze circulation. Banta also quantified aspects of the sea breeze such as depth, maximum wind speed, and duration. Different from prior studies by Atlas [1960] and Meyer [1971], The author also found that the Monterey area often experiences sea breezes at two different depths and time scales. Banta [1995] utilized Doppler LIDAR and supporting synoptic conditions to find that the Monterey Bay area often experiences an initial sea breeze extending vertically from ground level to 300 m and a deeper sea breeze that extended to 1 km above ground level that occurred later in the day. This later, deeper sea breeze overtook the earlier shallow sea breeze.

Miller [2003] reviews recent advances in sea breeze research. He describes four general types of sea breeze circulations; pure, corkscrew, back-door, and synoptic. Figure 1.3 is a general schematic of the pure (figure 1.3a), corkscrew (figure 1.3b), and back-door (figure 1.3c) sea breeze types. Miller [2003] also reviews a number of different relationships for estimating sea breeze front characteristics such as frontal speed, head height, and inland penetration. These relationships will be further explored in chapter 3.

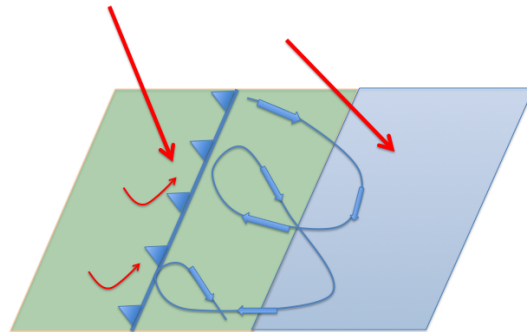
Gilliam et al. [2004] used a combination of Doppler radar, observations, and numerical model simulations to inspect the relationship between coastline shape, synoptic flow and sea breeze evolution. By inspecting 4 specific case studies each with slightly different synoptic flow directions, Gilliam et al. [2004] found that there is significant variability in the sea breeze front inland penetration and variability as a function of the large scale flow. Gilliam's results, illustrated in figure 1.1, shows that sea breeze front penetrates the least from the part of the coast that faces the direction of the large scale flow. Coastal Delaware and the Delaware Bay present a similarly complex coastline. The circulation of the Delaware



(a) Classic



(b) Corkscrew



(c) Backdoor

Figure 1.3: Sea breeze classification schematics as described in Miller [2003]

Table 1.1: This table is from Gilliam et al. [2004] describing 4 sea breeze case studies with characterizing inland extent over a complex coastline as a function of synoptic flow direction.

Case	Synoptic Flow	Inland Extent
1	North-Westerly	50 km East; 25 km South
2	Westerly	30 km East; 45 km South
3	South-South-Westerly	30 km East; 65 km South
4	South-Easterly	120 km

Bay adds even more complexity to the coastline due to changes in surface water temperature relative to the adjacent ocean water temperature. It is possible that the thermal fronts in the bay may act as a false coastline during the warmest months of the year. This topic will be revisited in section 4.3.

A more localized study focused on the effect of coastal upwelling on New Jersey’s sea breeze circulation. Bowers [2004] took a combined approach of modeling and observations of the New Jersey sea breeze circulation. Bowers found that, during the summer months, coastal upwelling plays a significant role in development and the behavior of the New Jersey sea breeze. Bowers [2004] utilized resources such as the Mount Holly WSR-88D radar (NEXRAD), AVHRR visible satellite imagery and sea surface temperatures, a numerical model, and surface observations. Using these resources he resolved the first order variables that affected the New Jersey sea breeze circulation. A similar study by Hughes and Veron [2010] presented trends and complexities of the Delaware sea and bay breeze circulations.

Hughes [2011] took a more climatological look of SBB trends in first order variables and developed more specific sea breeze classifications for coastal Delaware. In addition, he developed a sea breeze prediction and detection algorithm utilizing meteorological time series data provided by the DEOS (Delaware Environmental Observing System) mesonet. Comparing the results of the observational data with numerical model results, it was found

that Weather Research and Forecasting model (WRF) does resolve the Delaware SBB circulation at 2-km horizontal grid resolution. Hughes [2011] also notes that the model generally over estimates winds, and is very sensitive to the input of sea surface temperature, which is consistent with the conclusions of Bowers [2004] and Case et al. [2011]. The current study was motivated by of Hughes [2011].

Chapter 2

METHODOLOGY

This chapter discusses the data and methods used in this study for acquisition, processing, and analysis meteorological, radar, tidal, river discharge, and sea surface temperature observations. The region of interest of the study was the state of Delaware and the Delaware Bay during the summer months, defined as May through September, from 2007 to 2011. The methods are discussed in the order at which they were applied. To identify SBB events that are resolved by the radar requires multiple levels of filtering both meteorological observations and radar imagery. The first level of filtering utilized the DEOS meteorological data.

2.1 DEOS data

DEOS is regional mesoscale network that provides “meaningful data to help decision makers involved with emergency management, natural resource monitoring, scientific studies, and transportation for the state of Delaware.” Their primary operational goal is to provide state agencies and the public with real time information about environmental conditions including atmospheric state variables. Presently, the DEOS network is made up of nearly 50 meteorological observation stations, 30 of which are located within the region of interest for this study. Each station is equipped with an anemometer, temperature sensor, dew-point sensor, barometer, radiation sensor, and rain gauge, all of which are average and recorded every five-minutes. Since the establishment of the network, the DEOS engineers have been continuously adding more stations each year such that spatial coverage is more

dense in recent years than at the start of the study period. At five-minute temporal resolution, the meteorological stations provide a great platform to detect and evaluate SBB occurrences. The time-series data from select stations (2.1) were put through a sea breeze detection algorithm to detect days that SBBs occurred .

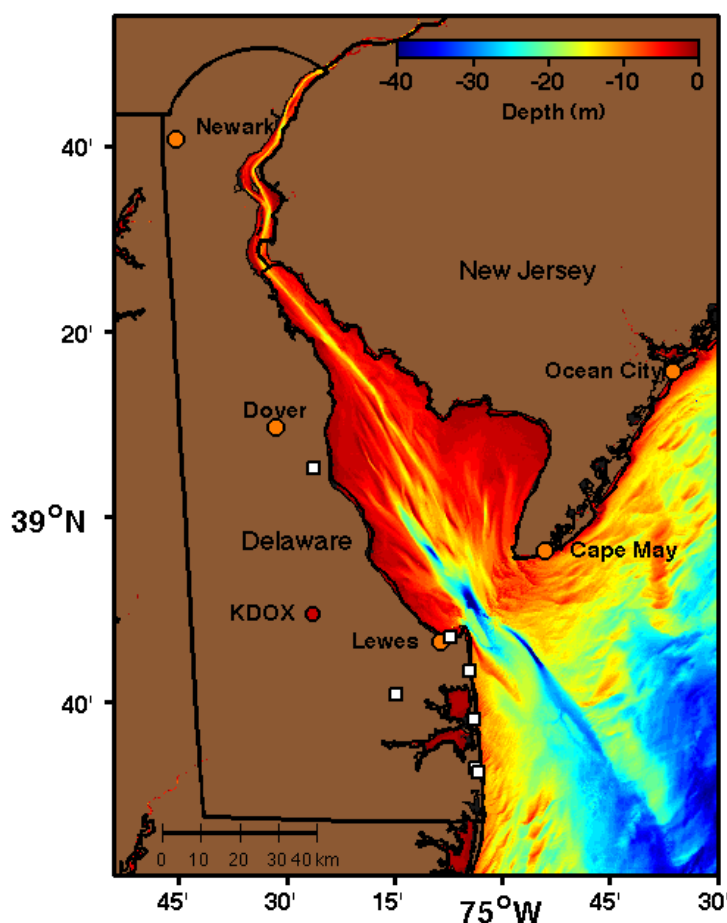


Figure 2.1: The white squares are the DEOS stations used for the sea breeze detection algorithm. The stations were best located for capturing the SBF. KDOX is the location of the radar platform. The bathymetry data was provided by NOAA NGDC (National Geophysical Data Set)

2.1.1 Sea Breeze Algorithm

The goal of the adapted SBB algorithm is to detect SBB events that were more likely to be detected by the radar. Though the radar can detect SBB events, it requires the front to be strong enough to produce detectable radar returns. This topic will be further discussed in section 2.2. Radar detected SBB frontal signatures are most often found from classical SBB occurrences. Given this observation, the sea breeze detection algorithm was built as follows: The first of the two criteria requires a 160-degree shift in wind direction over a 30-minute period of time. With the DEOS data having 5-minute resolution, a 30-minute period is well within the nyquist frequency of an abrupt shift in wind direction, indicative of a frontal passage. This wind shift was calculated using the arithmetic average over the 6 time steps (6 five-minute measurements). If the average change in wind direction was greater than or equal 160 degrees, then the second criterion is applied. The second criterion requires a change in temperature at the station of at least -1°C over the same 30-minute period. This decrease in ambient air temperature is indicative of the passing of an airmass boundary. The modified algorithm above is a modified version of that described by Hughes [2011].

For 2007-2011, the sea breeze detection algorithm utilized data from 5 DEOS stations. These stations were chosen by their location (figure 2.2 and table 2.1), and available data. The station's proximity to the coastline is very important for the detection of shallow penetrating SBB fronts. It should be noted that the Dewey Beach Boardwalk (DBBB) station is subject to wind shadowing due to its proximity to buildings just to the west of the station. For the purposes of detecting the onset of a sea breeze, this bias does not hinder the performance of the algorithm. The resultant list of dates that SBBs occurred was used to reduce the radar dataset to only include days that a SBB may be visible.

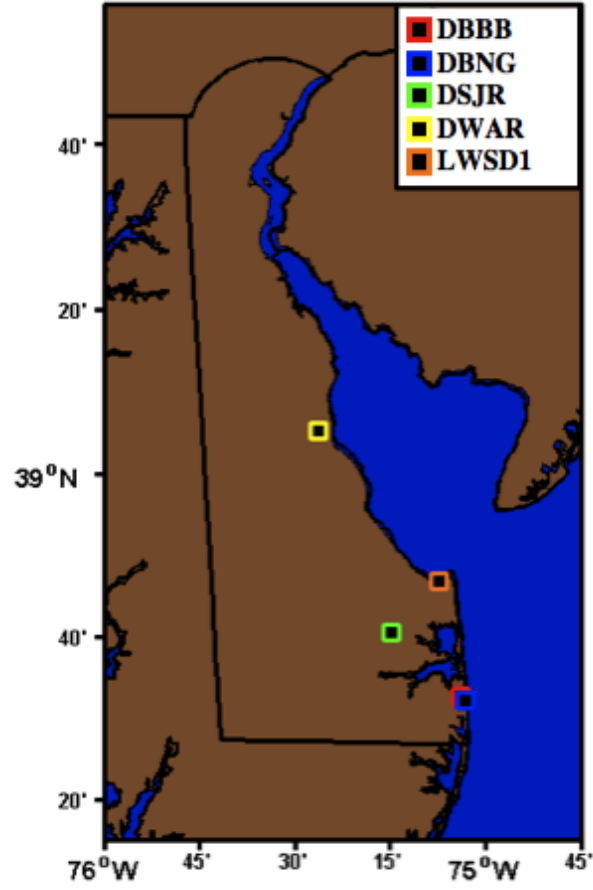


Figure 2.2: DEOS and NDBC stations utilized in the Sea breeze detection algorithm

Table 2.1: Table of station proximity to the Delaware Bay and Atlantic coastlines

Station	Distance to bay (km)	Distance to ocean (km)
BRND1	0	16
DBBB	27	<1
DBNG	26	1
DWAR	14	16
DIRL	17	<1
LWSD1	<1	3
DRHB	8	<1
DSJR	3	43
DELN	17	31
DLAU	47	47

2.2 Next-Generation Radar (NEXRAD)

2.2.1 NEXRAD Background and Data

The WSR-88D radar, also known as NEXRAD, is a meteorological surveillance radar primarily used to detect severe weather events in an effort to warn the general public of possible impending danger. Over 150 of these radars have been installed across the United States by different branches of the government, including the Departments of Defense, Commerce, and Transportation. NEXRAD uses wavelengths in the S-band (10.0-11.1 cm) with two primary operational modes. The first, and most often used, mode is known as the precipitation mode, intuitively named for its purpose of detecting hydrometeors. The second mode is called clear-air mode. Clear-air mode is a slower scanning mode with a full volume scan taking 10 minutes. This enhances both sensitivity to return signal and spatial resolution by allowing more power per unit volume to reach the antenna [Rinehart, 2007]. A SBB front can be detected in both operational modes, but are best detected in clear-air mode. Figure 2.3b shows a SBB front using clear-air mode. Figure 2.3a shows the same front at the very next time step after the radar’s operational mode was changed to precipitation mode. The reduction in resolution is apparent in that the front in panel B appears to be less intense than panel A.

NEXRAD data was retrieved from the National Climatic Data Center’s (NCDC) archive. The NCDC provides free, easy access via a data ordering query and FTP site. For this research, level II radar reflectivity (dBZ) data was collected from May-October from 2007 to 2011. Though SBBs can occur in every month of the year, the spring and summer months maximize the likelihood of the SBB front being visible in the NEXRAD reflectivity data. This is because enhanced aggregated insect scatterers and sharper gradients between terrestrial and maritime air-masses leads to an increase in frontal detection [Achtemeier, 1991],[Keeler and Kristovich, 2012]. The SBB front, when detected by radar, appears as a “thin line” of higher reflectivities relative to it’s surroundings as shown in figure 2.4. It

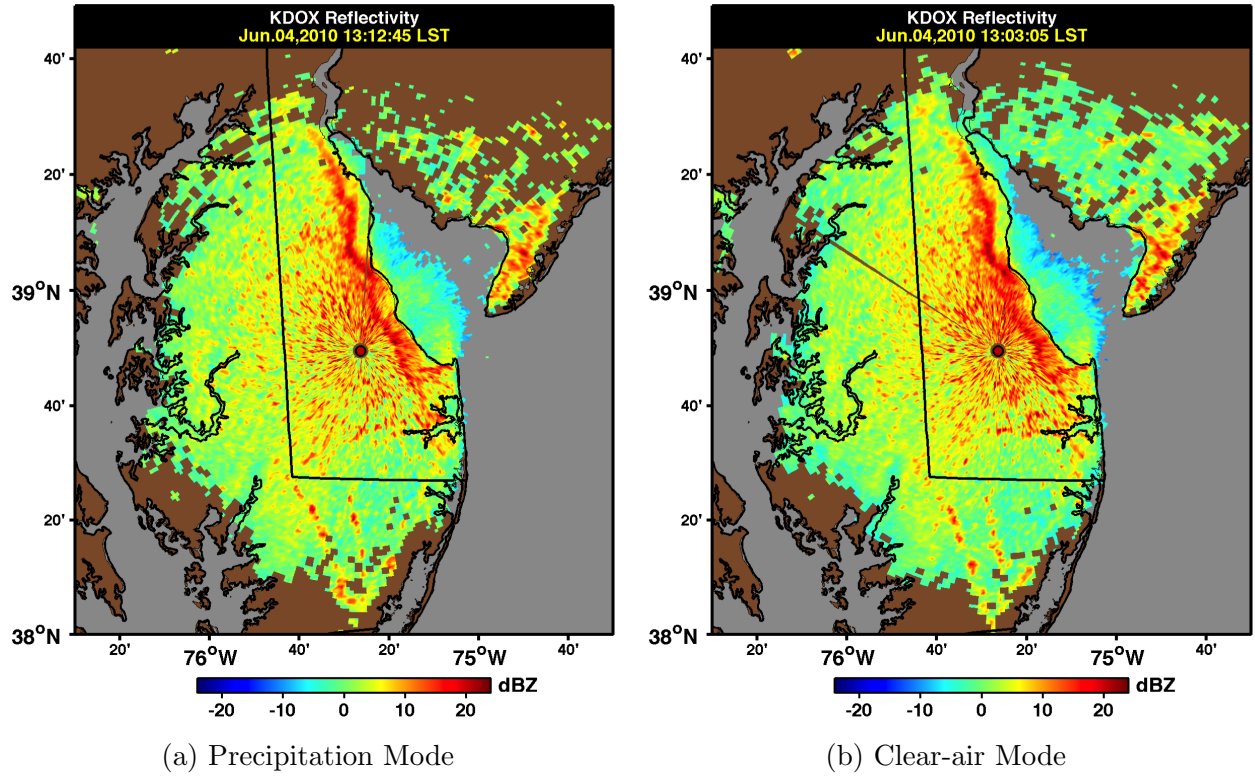


Figure 2.3: Radar mode changes from clear-air to precipitation mode. The SBB front becomes less defined as the resolution of the data decreases.

should be noted that for this study, the SBB fronts that are visible using radar data are the strongest, deepest penetrating, and most well developed fronts that Delaware experiences. This is because the strength and depth of these fronts make it possible to view them using NEXRAD. The less extreme cases are typically developed and exist below the lowest radar beam elevation. This analysis characterizes the strongest and most extreme cases. Because there is a clear distinction between the front and other scatters for these extreme cases, it allows for thresholding to help make the front more visible.

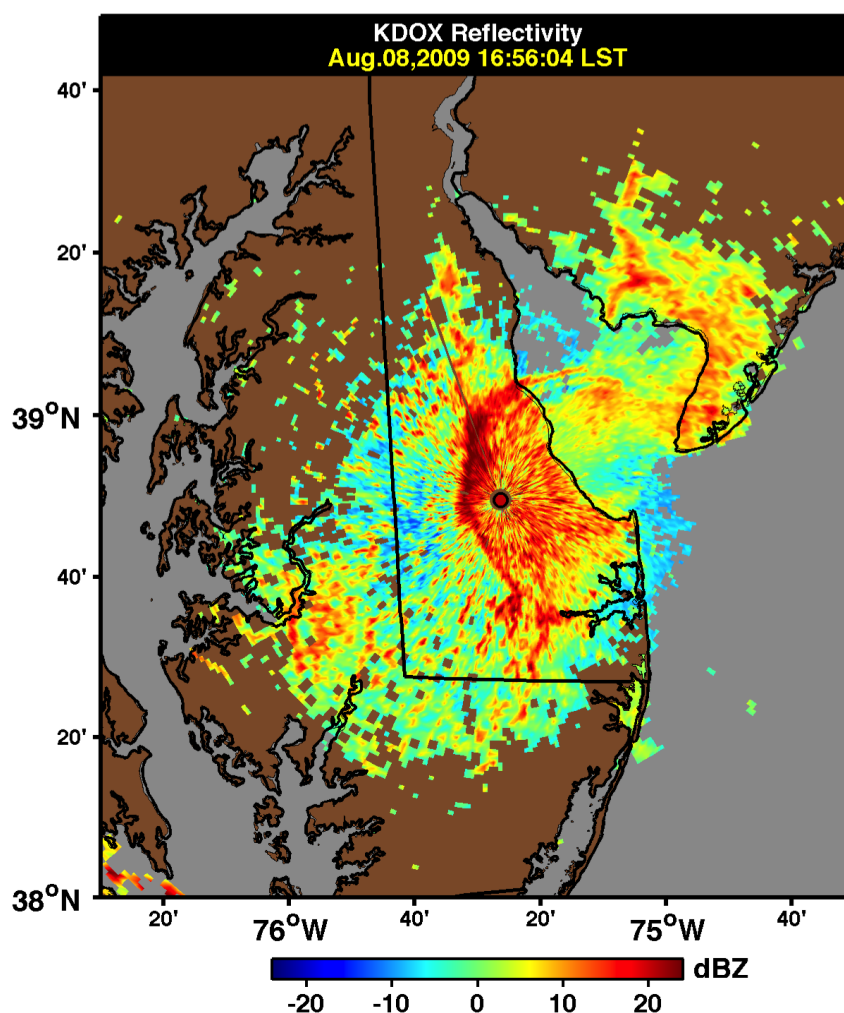


Figure 2.4: KDOX reflectivity showing the identifiable thin line generated by the SBB front.

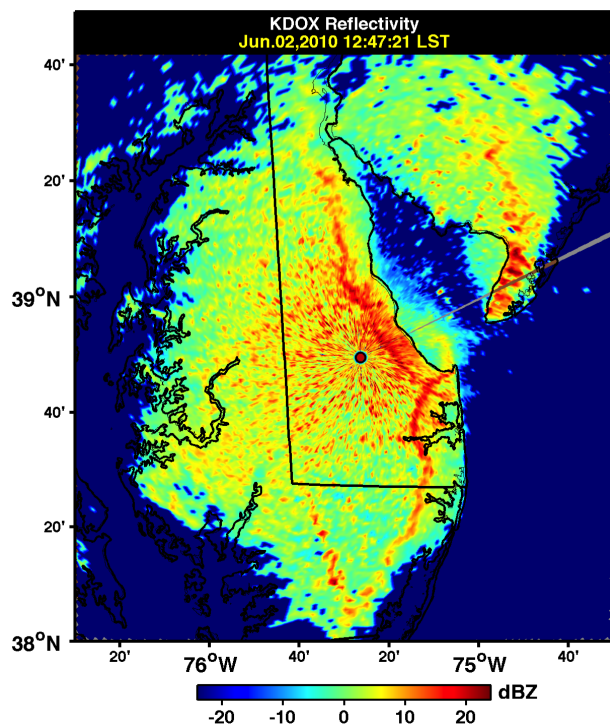
2.2.2 NEXRAD Thresholding

Sea breeze fronts, as shown in radar images, typically have reflectivity values above -8 dbZ. By simply requiring that the radar data have a reflectivities higher than 0 dbZ, in most cases, significantly mitigates returns not associated with the front. Due to the nature of the radar and the large amounts of low level scatters, thresholding is very important to the help remove ground clutter from the data to help better identify frontal position. Figure 2.5a shows a radar image without any thresholding applied. Figure 2.5b shows the same image after removing the reflectivities below the threshold from the image. In this case, removing the lower reflectivities leaves only reflectivities associated with the front. This method works for most cases where the radar is in clear-air mode and the front is strong enough to produce reflectivities greater than 8 dBZ over most of its extent. For the weaker, more shallow sea breezes this thresholding severely degrades the frontal signature making it more difficult to identify.

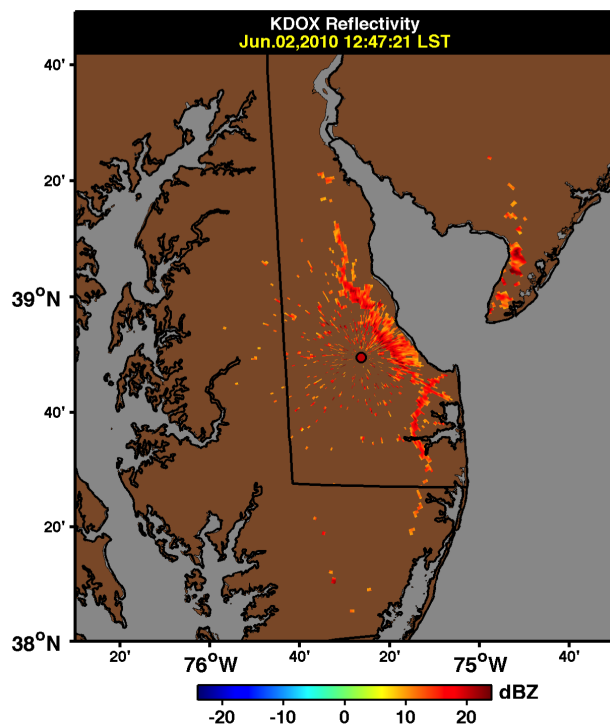
2.2.3 NEXRAD Spatial Filter

To reduce excess clutter not associated with the SBB front, a spatial filter was tested. The filter moves through the gridded data and assigns a value to each reflectivity. If the data point had a reflectivity value of between 6 and 30 dbZ, then it is assigned a value of 1, otherwise the assigned value is 0. The filter is structured in a box pattern as shown in figure 2.6. The filter then moves through the data frame changing all center data points that are not surrounded by 2 or more data points to 0. The resulting grid is then used to update the field of reflectivities. This filter was applied to each radar time step of the sea breeze day. This filter provided some mitigation of the excess clutter but also degraded reflectivities associated with the edges of the front. For this reason this filtering method was omitted.

A very similar technique was tested that utilized the same reflectivity threshold over an elongated y grid. This change in filter geometry was an attempt to improve the filtering



(a) No thresholding



(b) Reflectivity $\geq$ 8 dBZ

Figure 2.5: Radar data before and after 8 dBZ threshold

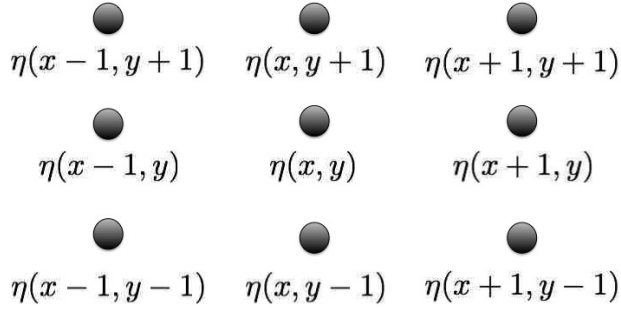


Figure 2.6: NEXRAD spatial filter grid configuration

of non-front related scatters from linear features with enhanced relectivities. This technique failed to significantly remove unwanted clutter from the data because the fronts are often not linear or are not oriented north-south like the filter.

It was found that no combination of the thresholding and filtering methods worked best for the entire data set. Using the human eye, more contrast is better for front identification so a threshold of -20 dBZ works unanimously. For the remainder of the thesis, all radar images have this threshold. A very important factor that affects the visibility of the SBB front using radar is the height of the SSB and the distance from radar antenna.

2.2.4 Importance of SBB Height

The proximity of the radar to the region of interest, coastal Delaware, is critical in order to properly observe boundary layer and mesoscale phenomena. It is imperative that the radar be within 60 km in order for the radar's lowest scan to be able capture SBB front. The coast must be in range of the lowest azimuthal elevation in which the radar scans because SBB fronts can have a vertical extent of only a few hundred meters. This distance requirement implies that the radar's field of view does not extend to the lowest parts of the

boundary layer, but can still capture the frontal characteristics. The Dover radar is located about 33 km from the coastal ocean and 16 km from the Delaware Bay (figure 2.8). As shown in figures 2.7a and 2.7b, both operational modes show the radar beams nonlinear increase in height as a function of distance from the platform. With the deepest sea breeze fronts only extending up to 2000 m, a front far from the radar may not intercept the radar beam, thus going undetected. The depth of the SBB front can be derived from the level of the radar scan and the radar range height, as shown in equation (2.1),

$$H = SR \sin(\phi) + \frac{SR^2}{2(IR)(R_e)} \quad (2.1)$$

where H is the height, SR is the distance from the radar, ϕ is the scan elevation angle, IR is the refractive index and is set equal to 1.21 for the WSR-88D (Rinehart [2007]), and R_e the average radius of the earth (6374 km). The head of the SBB front can often be detected on scan level 3 ($\phi = 2.4^\circ$). However, using this methodology it is very hard to extract a precise measure of the frontal height. The data provided by the NCDC is in the form of iso-surfaces along the trajectory of the radar beam. Given the fact that the trajectory and radar beam width changes as a function of distance from the radar antenna, it is very difficult to obtain a precise measure of the height of low level phenomena. In addition, it is also possible that the trajectory of the radar beam could be affected by the type of airmass it is passing through as the refractive properties change with a change in airmass. For this reason, SBB height calculations were omitted for this study.

2.2.5 Sea Breeze Front Digitization

When plotting the radar reflectivities, the SBB front will appear as a thin line of higher reflectivity values paralleling the coast [Atlas, 1960]. This “thin line” is visually discernible from ground clutter and is caused by the increased concentration of scatterers that

are aggregated by the convergence at the leading edge of the front. The ability to detect a SBB front in this way enables a high resolution synoptic analysis of characteristics such as inland extent and propagation speed. In order to obtain geospatial information about the evolution of the front in time, the front must be converted into a set of geo-located points. The manual method relies on 8 user defined points that include the 2 end points of the front and 6 points that best represent the front’s curvature along the “thin line” at each time step in figure 2.9. Between the established points, a spherical geodesic interpolation was used to generate a line segment to represent the remainder of the front. Utilizing this method 35 SBB fronts were digitized. These 35 were chosen because the SBB fronts were easily identifiable using the radar.

2.2.6 Automated Determination of Front Origin

Often when using NEXRAD reflectivities to inspect SBB front location, the front does not become visible until it is 1-10 km inland from the coast. Using a time-series of digitized line segments that represent the SBB front, it is possible to find the coast of origin. With the radar operating in clear-air mode during these events, the temporal resolution of the series is 10 minutes. Using the first 3 line segments in the time-series, the compass bearing of the 10 most central points were calculated using the following equation,

$$\theta = \arctan 2(\cos(\phi_1) \sin(\phi_2) - \sin(\phi_1) \cos(\phi_2) \cos(\theta_2 - \theta_1), \sin(\theta_2 - \theta_1) \cos(\phi_2)) \quad (2.2)$$

where ϕ is latitude and θ is longitude. The number of points used to make this calculation was dictated by the length of the shortest line segment. The two remaining line segments were cropped in such a way that only the most central points were used. These bearings are arithmetically averaged and compared to pre-determined bearings normal to each coastline. The pre-determined bearings were generated by taking the bearing of the normal vector of

each of the 3 coastlines. Using the average bearing of the first 3 segments ensures a more precise measure of the direction the SBB front is heading. The front’s coastline of origin is then determined by the minimum difference between the SBB front bearing and a coastlines normal bearings found in table 2.2.

Due to the complex nature of Delaware’s coastline, and the false coastline effect over the Delaware Bay, 3 different coastlines are defined. The first coastline is the southeastern Atlantic coast. This coastline has a north-south orientation. The second coast is the Delaware Bay coastline. This coast is a little more complex but has a general northwest orientation that extends from Lewes, DE to Delaware City, DE. The third coastline is a false coastline, shown in figure 2.10, that develops during the summer months when surface water temperature is very warm relative to the adjacent coastal ocean. This false coastline typically has a cross-bay orientation. Its location is depicted by the strongest horizontal temperature gradient in the bay. Due to the variability in location of this “false coastline”, the reference coastline for is made to be the location of the first digitized line segment of the front. With the ability to determine the coast of origin, it is possible to then calculate the inland extent of each front relative to the chosen coastline.

2.2.7 Inland Penetration Calculations

Inland penetration is defined by the distance at which the SBB front has moved inland from its coast of origin. Utilizing the above methodology to determine the SBB front’s coast of origin, the distance displaced over the lifetime of the front can be calculated using a

Table 2.2: Compass bearings lookup table

Coastline	Compass Bearing
Atlantic	270.02
Delaware Bay	213.26
False Coastline	332.99

simple spheric geodesic distance calculation between a digitized coastline and a digitized line segment that represents front position. The equation used to calculate spheric geodesic distance between two sets of geo-located points is shown in (Equation 2.3),

$$d = R_{avg} \cos^{-1}[\cos(\phi_c) \cos(\phi) \cos(\theta_c - \theta) + \sin(\phi_{base}) \sin(\phi)] \quad (2.3)$$

where R_{avg} is the average radius of the earth (6374 km), ϕ_c and θ_c are the coordinates of the coastal line segment defined in figure 2.12, and ϕ (latitude) and θ (longitude) are the geo-located points found along the digitized SBB front. Because the SBB front has been known to sometimes retrograde prior to extinction, a full time-series of distance traveled from the radar-determined initiation point is used. The maximum distance traveled over the time-series was determined to be the line segment that represents the maximum inland penetration. This entire line segment was then referenced to the appropriate coastline, as defined by the front origin algorithm (Section 2.2.6).

These coordinates are calculated at ground points, and the radar reflectivities are collected 10 m to 2000 m above the ground, therefore distance calculation must compensate for the height of the radar beam. By taking result equation 2.3 and the radar's scan elevation angle, Θ , in the following equation;

$$d_g = d \cos(\Theta) \quad (2.4)$$

corrects for the height of the radar beam relative to the ground. This corrected distance (d_g) is the true distance traveled over the land surface and corrects distance improves both the distance and speed calculations.

2.2.8 Speed Calculations

SBB front speed was derived directly from NEXRAD digitized SBB front time-series. Utilizing the 10 most centrally located points along each line segment and using the time stamp associated with each segment an average speed calculation can be made. The central portion of the front is used to represent the entire front because the center tends to be the most coherent and long lasting part of the front. In addition, the edges often introduce more error because of a decrease in the radar's resolution that is proportional to the distance from the radar. This leads to distortion of pixels and over exaggeration of scatters due to increased pixel size, as well as mis-representation of location. With that in mind, the calculated propagation speed is performed by simply taking the time derivative of distance traveled relative to the ground, i.e. $(\frac{d_g}{dt})$, where d_g is calculated using equations 2.3 and 2.4. The change in time (dt) is the elapsed time between each line segment used. The result is a time-series of along front average velocities.

This method does not come without limitation. Due to the nature of this method, some error in speed is introduced. This error is induced by the expansion and contraction of the front, causing the central portion of the line segment to change location very quickly and the resulting calculation of d_g to be very large, thus a very velocity. These errors are easily removed by imposing a filter that requires that the speed may never go above a threshold of 12 ms^{-1} . This threshold was determined by examining the distribution of velocity calculations over the entire data set. The speeds above 12 ms^{-1} were outliers in the distribution that were caused by a mis-placed digitized frontal position in the time-series.

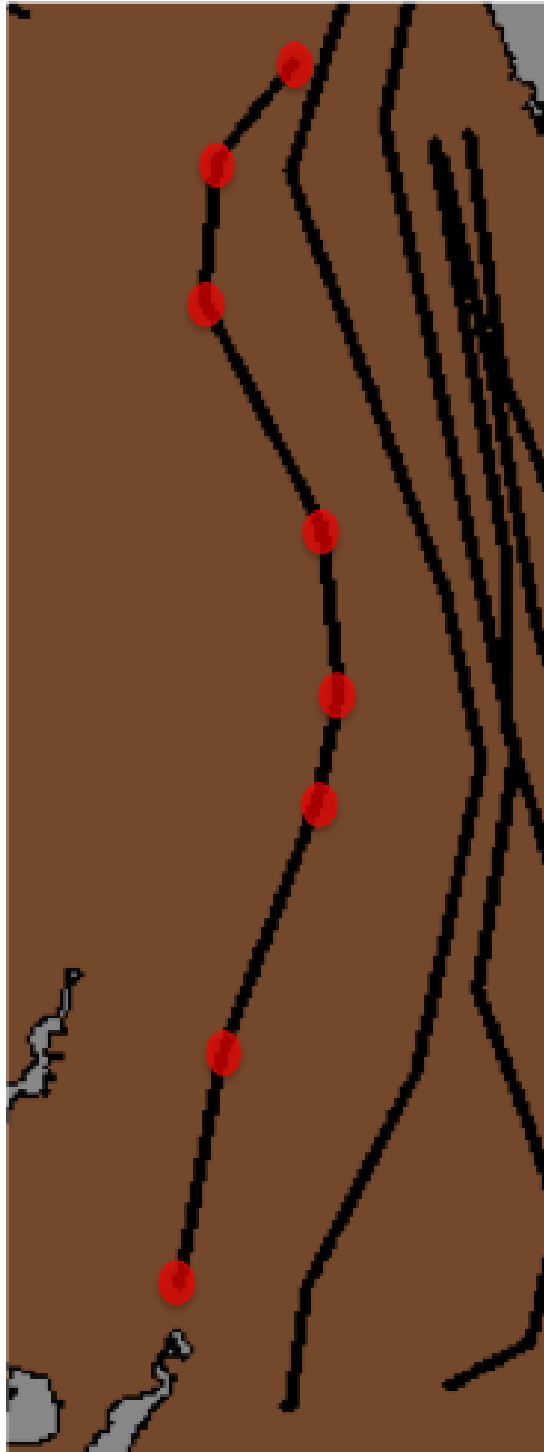


Figure 2.9: User defined points that represent inflection points along the radar “thin line.”

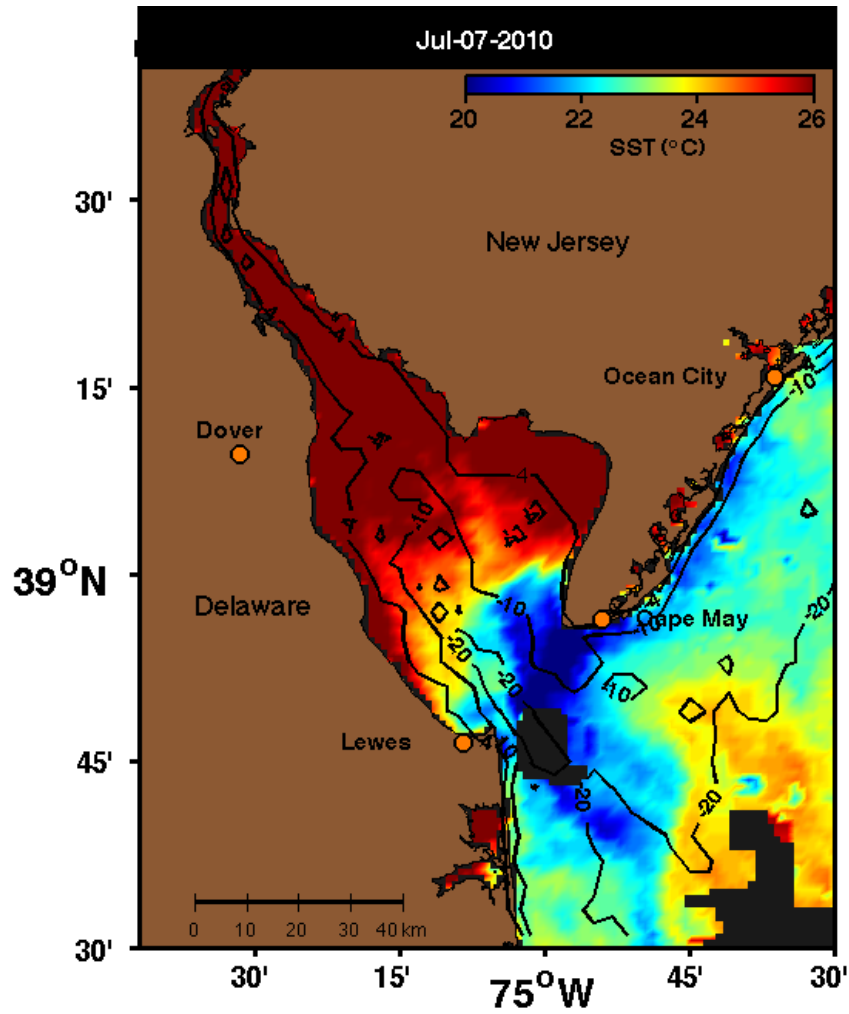


Figure 2.10: July 7, 2010 featured a strong axial gradient in the bay that could be a influential factor in the development of SBB fronts over the Delaware Bay. This feature has been named a “False Coastline” for this study.

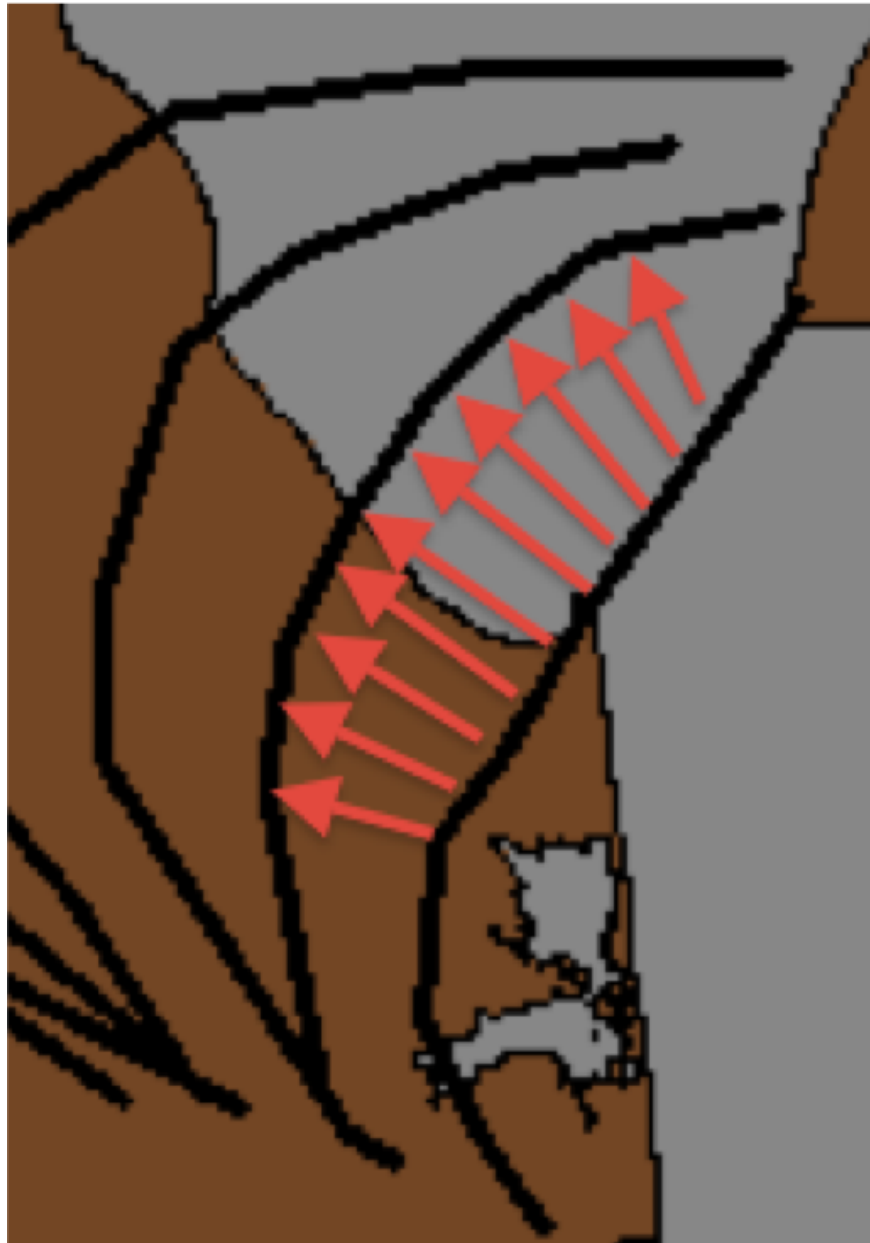


Figure 2.11: Bearing of the front is calculated by taking the vector average of the 10 central most coinciding points between the first 3 digitized line segments

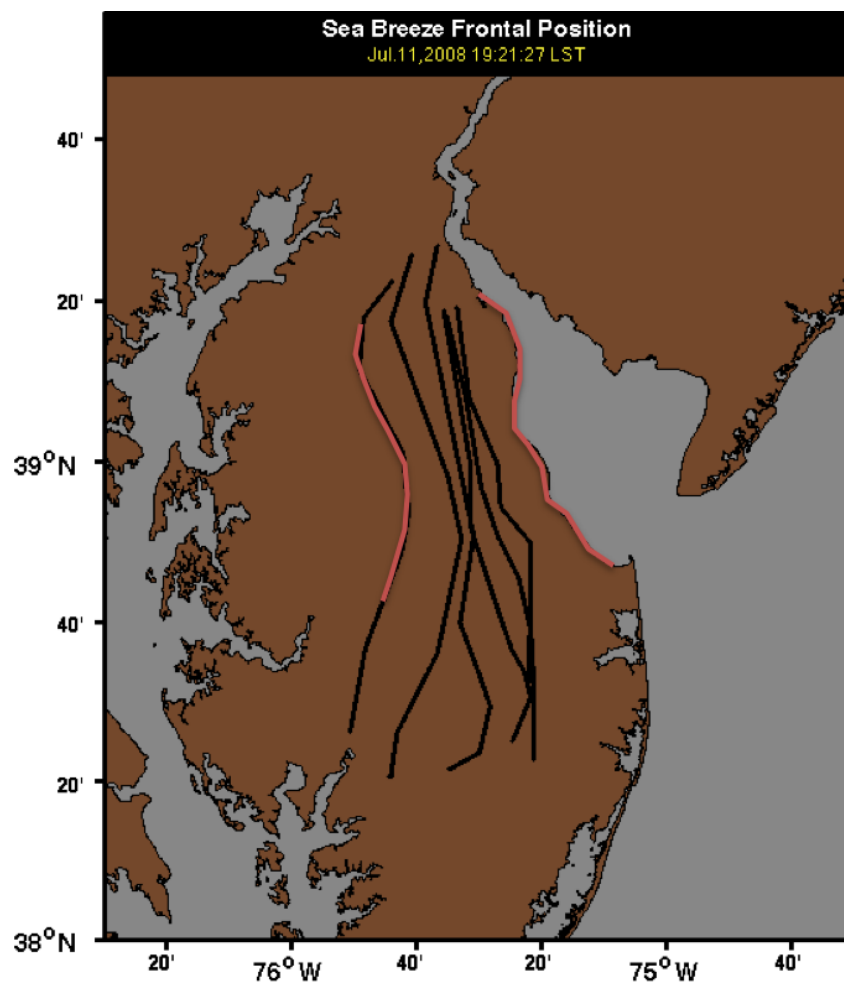


Figure 2.12: Example showing how the digitized line segment that is furthest from the coast of origin is chosen.

2.3 Sea Surface Temperature (SST) and River Discharge Observations

Mid-Atlantic Regional Associate Coastal Ocean Observing System (MARACOOS) is 1 of 11, regional associations in the US Integrated Ocean Observing System (IOOS) that provides satellite-based decision-making tools and data. The MARACOOS sea surface temperature data archive is a combination of products from the AVHRR-Pathfinder, MODIS-Aqua, and SeaWiFS platforms. The Ocean Exploration, Remote Sensing, and Biogeography Lab supplies MARACOOS with their cloud-filtered sea surface temperature product for public use. In Bowers [2004], he details the importance of coastal upwelling on the sea breeze circulation. It was found that there is a direct correlation between the strength of the upwelling and the strength of the sea breeze. Clancy et al. [1979] found using a simple coupled oceanic-atmospheric model that a stronger sea breeze also enhances coastal upwelling. He also determined that the influence the sea breeze had on the upwelling was much smaller than the influence of the upwelling on the sea breeze. This is due to the fact that the ocean responds on much longer timescales than that of the atmosphere. Given this relationship the SSTs used in this study should have little bias due to the presence of a sea breeze.

To quantify how the SST of the bay and adjacent coastal ocean affects the local SBB circulation, axial and lateral transects are extracted from the gridded SST field in the bay. Figure 2.13 shows where the SST measurements were extracted. In the figure, the red circles overlaid on the transect lines represent 10 km markers for each respective transect. Figure 2.14b shows the lateral transect of sea surface temperature with respect to distance from the Delaware Bay coast. Similarly, figure 2.14a is an axial transect of the SST with respect to the distance from the most south easterly point of the transect line in figure 2.13. Using the slope of these lines makes it possible to associate the distribution of water masses with the slope found from these transects. These lines represent is the average SST along each transect line for the length of the study.

Figure 2.15 shows the percentage of missing SST data for this study. The data that is considered missing is caused by cloudiness or abnormally very localized high or low temperatures.

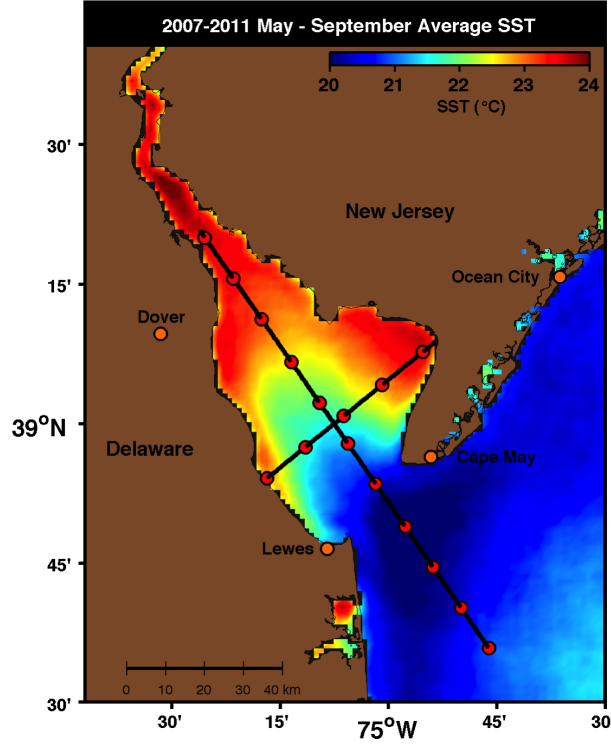
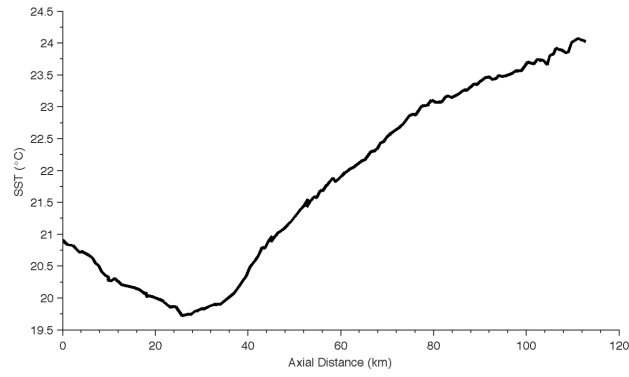
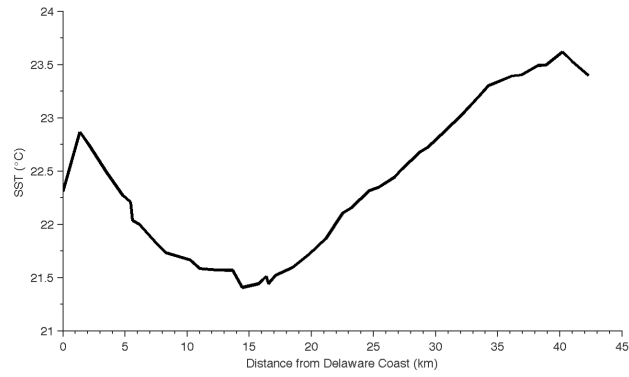


Figure 2.13: Axial and lateral transects used to evaluate the distributions temperature gradients in the Bay.

The Delaware Bay is a partially mixed estuary with a deep channel running up the center of the bay [Wong and Garvine, 1984]. The distribution of water masses in the bay is a function of the river inputs, tidal, and sub-tidal dynamics. The freshwater input from the Delaware River accounts for 60% of the freshwater discharge in to the estuary [Sharp et al., 1986] followed by the Schuylkill River contributing another 15%. No other single source contributes more than 1% of the total discharge into the bay [Garvine et al., 1992]. This river discharge varies seasonally with the largest discharge events residing in the spring [Figure 2.16]. This fresh water that is discharged into the bay has been found to hug both shores of the bay separated by colder, higher salinity water concentrated just to the right of the



(a) Axial Transect



(b) Horizontal Transect

Figure 2.14: Satellite derived vertical and horizontal transects. Distance measurements are taken with respect to the southeastern most transect points show in figure 2.13.

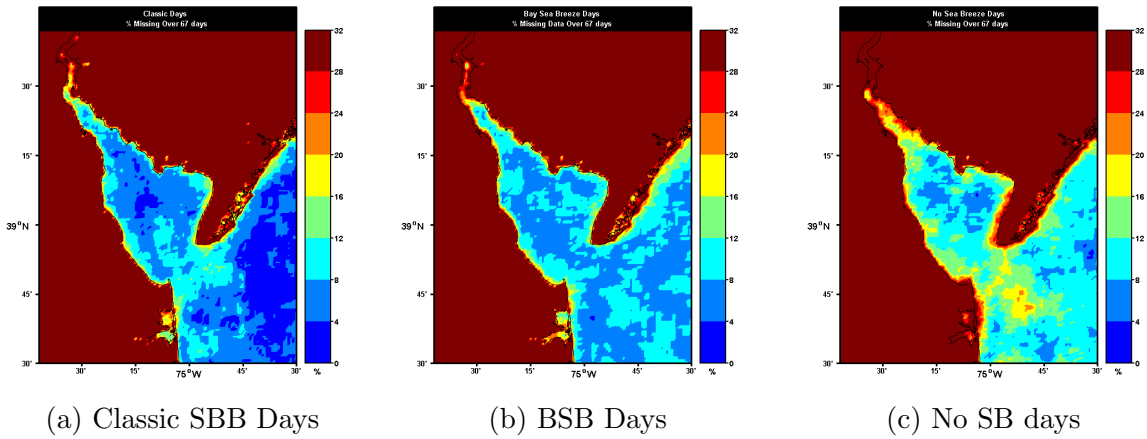


Figure 2.15: Percent Missing data points from sampled days

channel (Figure: 2.13). Wong and Münchow [1995] found that this cold, high salinity, is a good indicator of the intrusion of the adjacent shelf water during the spring and summer months. The location of this water varies up to 8 km as a function of the M_2 tide [Garvine et al., 1992]. Further examining this intrusion Wong [1995] performed an axial survey of salinity and found that it is strongly influenced by river discharge on seasonal timescales.



Figure 2.16: 100 year ensemble mean of river discharge from the USGS Trenton Station

To compliment the SST data, Delaware River discharge data was acquired from the United States Geologic Survey’s (USGS) Trenton station. The USGS provides a 100 year record of daily average river discharge ($\text{ft}^3 \text{s}^{-1}$), daily minimum, maximum, and mean water temperature. This data adds more insight on the timing of rain events relative to the observed sea breeze cases, as well as helps explain the distribution of water masses in the Delaware Bay as detailed by Garvine et al. [1992]. The contribution of river discharge is further discussed in section 3.4.1. Another contributing factor to the distribution of the water masses within the Delaware Bay is tidal mixing. The data used for this analysis was measured from the Lewes, Delaware ferry terminal collected by NOAA Tides and Currents data set. The datum chosen was the mean sea level which is the arithmetic mean of hourly heights observed over the National Tidal Datum Epoch. The tidal signal within the Delaware Bay is dominated by the M_2 tidal constituent. This tidal constituent has a frequency of 12 hours, resulting in 2 high tides and 2 low tides in a 24 hour period. Hourly height observations

were used for this portion of the study to avoid any aliasing.

Chapter 3

GENERAL ENVIRONMENTAL CHARACTERISTICS FAVORABLE FOR DELAWARE SBB: DEOS, SYNOPTIC TYPING, SSTs, RIVER DISCHARGE, TIDES

This chapter discusses the results of the modified sea breeze algorithm, as well as analyzes environmental variables that indicate conditions that favor the development of SBB fronts over Delaware. Atmospheric pre-conditioning is assessed using a large scale characterization of the regional atmospheric conditions, known as synoptic typing, and supporting surface meteorological observations from select DEOS stations. Estuary and oceanic pre-conditioning was evaluated using satellite SST compositing, river discharge, and water level observations.

3.1 Modified Sea Breeze Detection Results

The SBB algorithm successfully identified a total of 327 SBB fronts that were detectable using NEXRAD reflectivities. Table 3.1 summarizes the number of days detected by the algorithm as well as the annual distribution.

Table 3.1: SBB detection algorithm performance

Year	% SSB Fronts Detected	Number Detected
2007	55%	65
2008	64%	74
2009	44%	46
2010	64%	80
2011	57%	62
Avg	56%	327

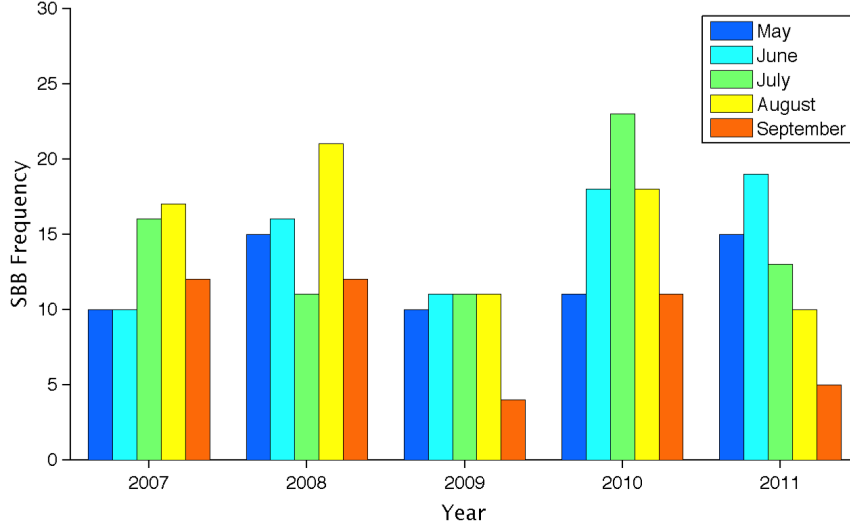


Figure 3.1: Histogram of sea breeze occurrences that were visible in the radar data.

As seen in figure 3.1, 2009 was a particularly uneventful year in terms of SBB development. Interestingly, the very next year was the most active year in the data set with nearly double the number of detected SBB fronts. Comparing the summer climatology from Georgetown, Delaware in figures 3.2 and 3.3, there is not much difference in the between the two years in terms of temperature. The variable that varies the most is precipitation. In 2009, Georgetown saw more than double the amount of rainfall. Rainfall can be detrimental to the development of the SBB circulation as it will break down the necessary temperature gradient between land and sea. In addition, heavy rainfall can trigger outflow boundaries that can mimic SBB fronts.

The largest source of error (false positives) for the algorithm were day where convective outflow boundaries passed over the stations. Outflow boundaries are very similar to SBB front when looking at the DEOS data only. This is a strong contributing factor to why the sea breeze detection algorithm did not perform as well in 2009 due to the fact that there were the largest number of false positives. 2009 saw 10 false positives caused by gust fronts while 2010 saw 6. Another source of error are cold fronts.

		Max	Average	Min	Sum
Temperature	Max Temperature	96 F	82 F	53 F	-
	Mean Temperature	88 F	74 F	52 F	-
	Min Temperature	80 F	65 F	41 F	-
Degree Days	Heating Degree Days (base 65)	13	1	0	104
	Cooling Degree Days (base 65)	23	9	0	1424
	Growing Degree Days (base 50)	36	23	2	3540
Dew Point	Dew Point	76 F	62 F	26 F	-
Precipitation	Precipitation	2.15 in	0.20 in	0.00 in	27.09 in
	Snowdepth	0.0 in	0.0 in	0.0 in	-
Wind	Wind	35 mph	6 mph	0 mph	-
	Gust Wind	61 mph	21 mph	16 mph	-

Table 3.2: Summer 2009 Georgetown, DE

		Max	Average	Min	Sum
Temperature	Max Temperature	102 F	85 F	58 F	-
	Mean Temperature	89 F	75 F	48 F	-
	Min Temperature	79 F	64 F	35 F	-
Degree Days	Heating Degree Days (base 65)	17	1	0	80
	Cooling Degree Days (base 65)	24	11	0	1625
	Growing Degree Days (base 50)	40	25	0	3781
Dew Point	Dew Point	79 F	63 F	19 F	-
Precipitation	Precipitation	2.79 in	0.09 in	0.00 in	12.93 in
	Snowdepth	0.0 in	0.0 in	0.0 in	-
Wind	Wind	32 mph	6 mph	0 mph	-
	Gust Wind	44 mph	20 mph	16 mph	-

Table 3.3: Summer 2010 Georgetown, DE

Cold fronts are characteristically very similar to SBB fronts in terms of changes in temperature, wind speed, and wind direction. For this reason, regular cold fronts and backdoor cold fronts accounted for a significant portion of the false positive SBB detection. Typically, Delaware experiences cold fronts that move west or northwest to East or Southeast. Prior to the front, the wind direction is typically southwesterly and westerly to northwesterly after the cold front passage. Precipitation and thunderstorms are often associated with spring and summertime cold fronts. Precipitation makes the fronts easily identifiable from SBB fronts using the radar. Another type of cold front, the backdoor cold front, is a bit trickier to differentiate from SBB fronts. Backdoor cold fronts are common during the springtime in the Mid-Atlantic region. These fronts propagate from the east-northeast towards the west. Similar to a SBB front, the backdoor cold front does not typically trigger widespread precipitation such that even on radar they can look very similar to a SBB front if they occur during the afternoon. Figure 3.2 shows an example of a backdoor cold front passing over Delaware in late spring. Figure 3.3 shows the a time series from June 9, 2007 of a backdoor cold front moving over the region. Figure 3.3a shows a stationary front over the continental shelf, which is a precursor to a backdoor cold front. The 00:00 UTC image shows the backdoor cold front after it moved on shore and was beginning to retrograde. This was a false positive derived by the sea breeze detection algorithm. At the DEOS stations these fronts are nearly impossible to differentiate from a SBB fronts when they pass over Delaware around the time of maximum heating.

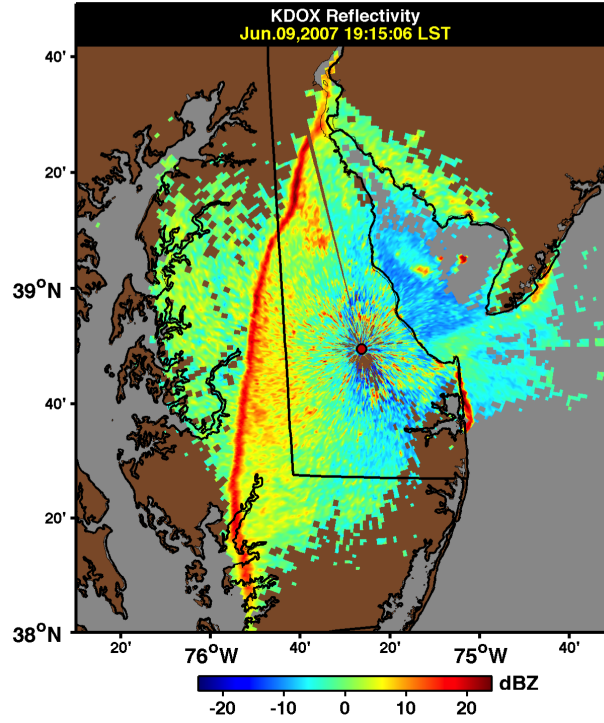
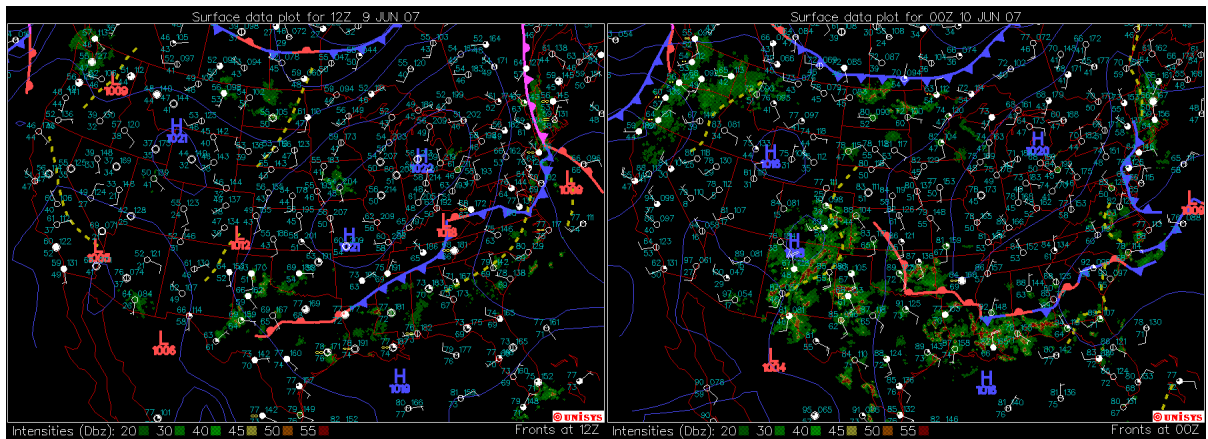


Figure 3.2: Backdoor cold front example



(a) June 9, 2007 - 00z

(b) June 10, 2007 - 00z

Figure 3.3: Surface analysis showing a the before and after picture of a backdoor cold front passage over the Delmarva Peninsula

3.2 Categorizing the Local SBB Based on Radar Signature

Three SBB front categories were established using by grouping similar radar derived SBB days together based on coast of origin and direction of motion. The first and broadest category was the Classic sea breeze day where a sea breeze front, that was visible on radar, moved inland from either the bay or the ocean. Of the 327 days studied, the Classic SBB occurred 259 times. The second, most rare, category was named a Bay Sea Breeze Day or BSB which occurred 66 times. The BSB days were days that the radar captured a sea breeze front moving up the bay. The final category was the No Sea breeze Day, intuitively named because these days exhibited no SBB that was detectable by radar.

3.2.1 The Classic Sea Breeze

The classic sea breeze is a sea breeze front that propagates from either the Delaware Bay or the Atlantic Ocean inland. Figure 3.4 shows a typical classic SBB front as it propagates inland. The SBB front parallels the Delaware Bay and Atlantic coastlines with an inflection point typically found just south west of Lewes, DE. This SBB front signature is not unique to Delaware even though the Delaware coastline has such complex geometry. It is also the most frequently observed of the SBB categories. The portion of the colored bars that are not gray in figure 3.5 represent the frequency of classic SBB occurrence over the temporal domain of the study. On the synoptic scale, the classic SBB days are, on average, very typical summer-time conditions with light southwesterly winds and warm temperatures.

3.2.2 Bay Sea Breeze

Intermittently, the Delaware Bay can experience a sea breeze that can be captured by radar as seen in figure 3.7. The Bay Sea Breeze or BSB is unique to the Delaware Bay and is nearly impossible to detect without radar observations. This is a sea breeze that originates over the Delaware bay and propagates up the bay. This phenomenon owes its existence to a

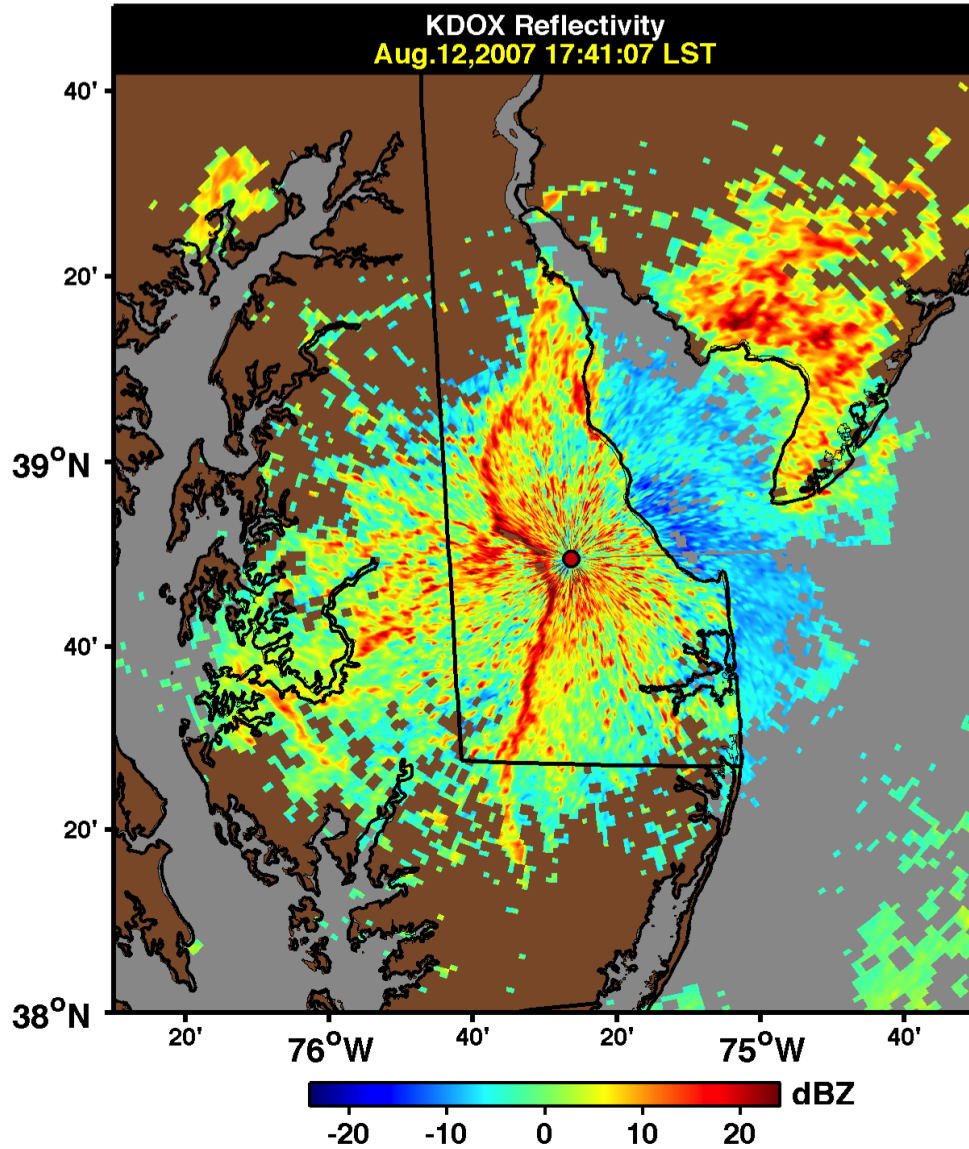


Figure 3.4: Classic SBB Front

thermal gradient at the surface sufficient to initiate and sustain a SBB circulation over the bay.

Figure 3.8 is a composite of the sea level pressure for all of the BSB days over the study period. The pressure gradients for these dates are very weak with the most influential features for the mid-atlantic being the relatively weak Bermuda high and more intense icelandic low

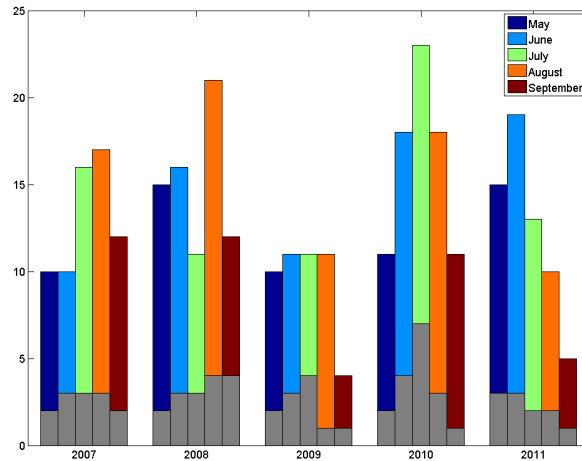


Figure 3.5: Histogram of sea breeze occurrences that were visible in the radar data.

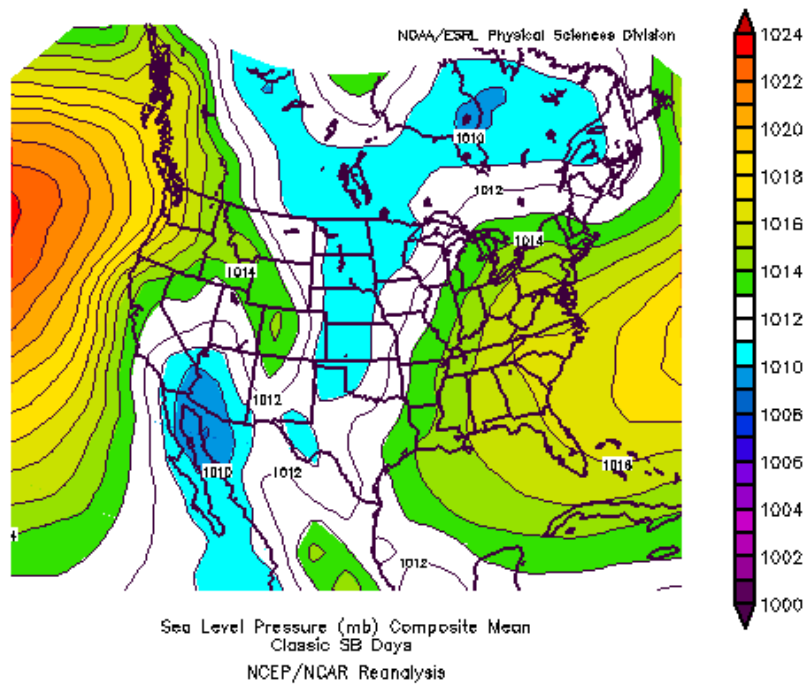


Figure 3.6: Composite of surface re-analysis for all classic days

as compared to the classic SBB days in figure 3.6. This relatively weak high pressure to the south and icelandic low pressure over the Davis strait just west of iceland. This more

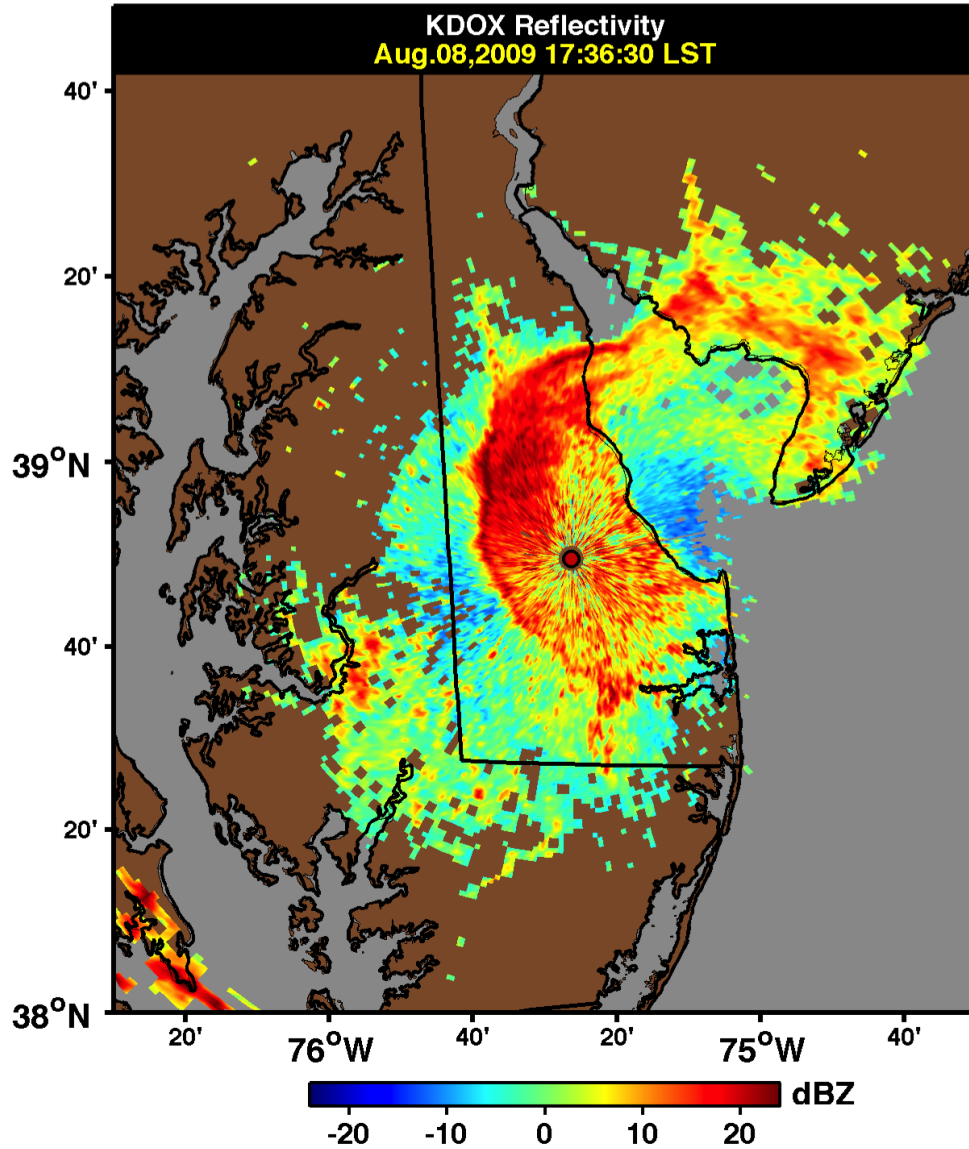


Figure 3.7: Example of a BSB event

intense low pressure causes a more northwesterly component to the synoptic wind. This wind direction during the summer months is indicative a recent cold front passage from the west. Such large scale systems and trends are characterized using a method known as synoptic typing.

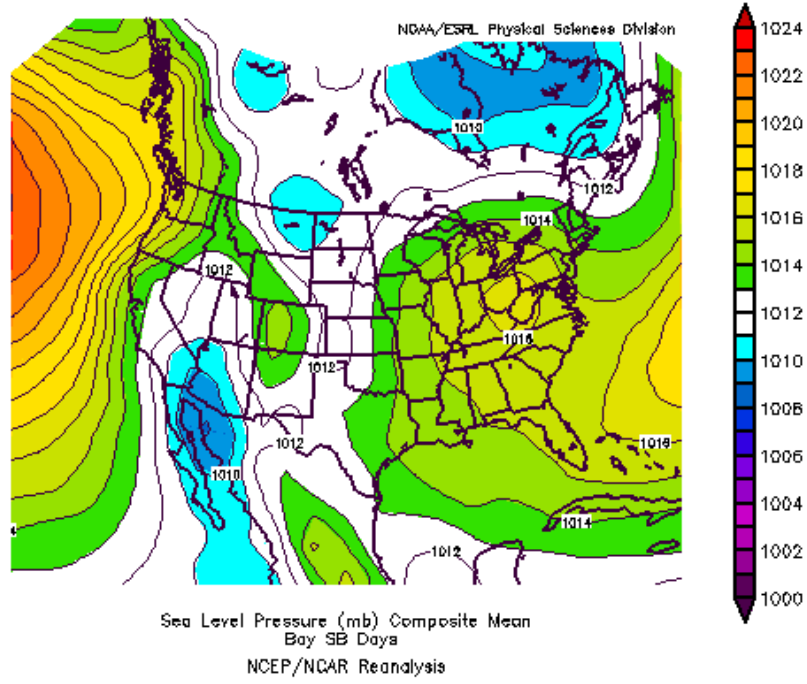


Figure 3.8: Composite of surface re-analysis for all BSB days

3.3 Synoptic typing

The next level of variability is on the a weekly timescale. The weekly variability found within each month is strongly influenced by the synoptic conditions. In order to quantify the influence, a method known as synoptic typing was employed. Synoptic typing is the classification of ambient weather conditions into categories based on season and similar large scale features. This is a useful tool for numerous climate impact applications. For this study, the synoptic typing methodology was developed by Sieger [2013]. It utilizes upper-air re-analysis data to characterize the regional synoptic conditions. For each season there is a different set of synoptic types and for this study the focus was on the summer months (June, July, and August). The synoptic types defined for the the summer months are described in table 3.4. The most common type for the study period was 3032, making up 35.5% of all days and is characteristic of pre-frontal southwesterly flow and warm air advection

Table 3.4: Synoptic type categories

Type	Description
3002	Weak upper trough
3004	Northwest flow (S.E Canada low pressure)
3007	High Pressure over head
3011	Zonal Flow Aloft
3031	Southwest flow
3032	Southerly flow, approaching front
3033	Cold Front Passage
3034	Northerly Flow, Midwest high pressure
3035	Southern trough aloft
3036	Great Lakes low pressure

(Figure 3.10a). The second most common is 3031, comprising of 20.3% study days and is very similar to 3032 but has a slightly stronger Bermuda high and lacks a front to the west of mid-atlantic (Figure 3.10b). The more intense Bermuda high causes the synoptic wind over the mid-atlantic to have more of west-southwest wind where 3032 has a slightly weaker westerly component. The proximity of the approaching front in 3032 tightens the isobars slightly over the mid-atlantic, increasing the speed of the prevailing wind on average. It is not uncommon for the summer synoptic types to have relatively weak gradients and more stagnant air-masses. The third dominant synoptic type 3033, accounting for 20% of the study period, is a cold front passage from the west. The synoptic situation has a trough and a weak cold front draped over the mid-atlantic (Figure 3.10c). The prevailing wind direction for this case is more than the previous cases. The proximity of the front depicts whether the wind direction is west-southwest, west, or west-northwest. For days that any kind of a SBB front was detected by radar, the dominant synoptic types are shown in figure 3.9. It is no surprise that the dominant synoptic type for all SBB days is also 3032 since Delaware experience some kind of a SBB circulation over 60% of the time [Hughes, 2011]. The same trend follows with 3031 and 3033 synoptic types making up the second and third dominant synoptic types. The wind rose in figure 3.11 is comprised of data from DEOS station DLAU, shows that southwest is the dominant prevailing wind direction for all SBB days. The prevailing wind speed and direction, which is a function of synoptic type, is very

influential on the existence and characteristics of the Delaware SBB circulation.

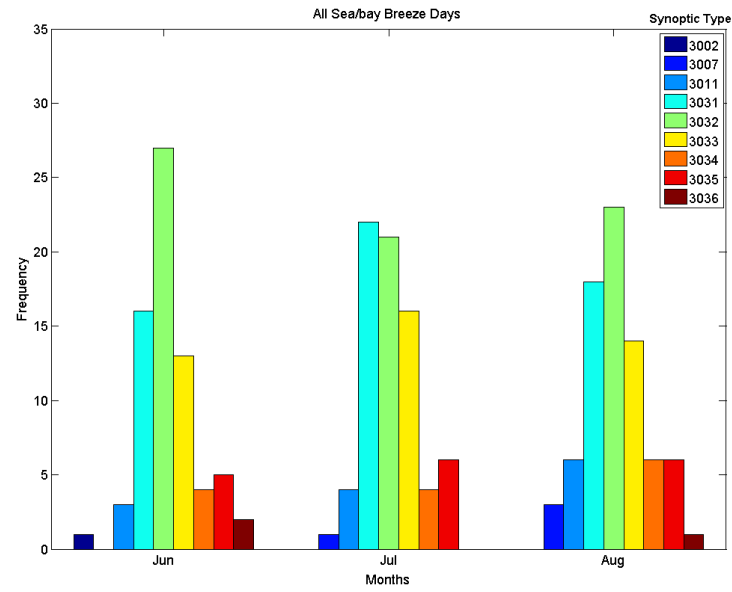
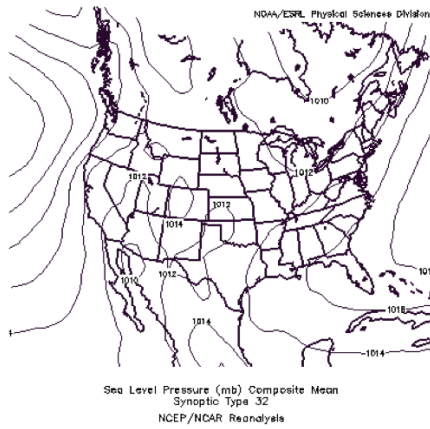
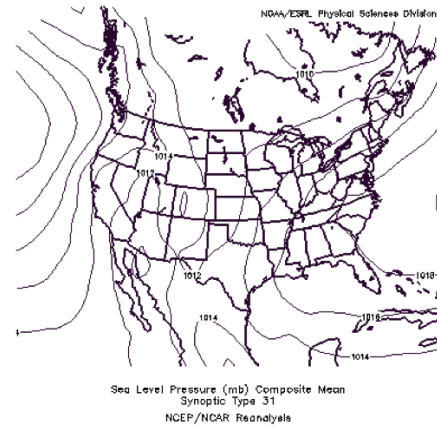


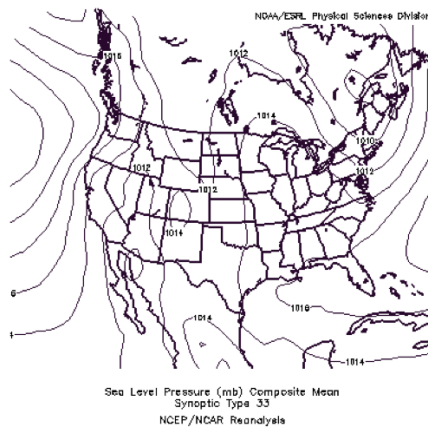
Figure 3.9: Frequency of synoptic types on days that a SBB front was observed using NEXRAD radar



(a) 3032 - Southerly flow, approaching front



(b) 3031 - Southwest Flow



(c) 3033 - Cold front passage

Figure 3.10: Re-analysis sea level pressure composites for the three dominant synoptic types for this study.

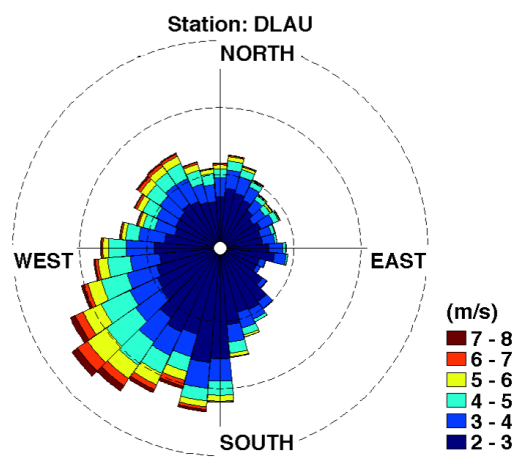


Figure 3.11: DLAU wind rose for all SBB days

3.4 SST Results

Utilizing the MARACOOS cloud-filtered SST data set described in chapter 2, 1 day averaged SST composites for the Delaware Bay and adjacent coastal ocean are used to inspect how the Delaware Bay affects the local SBB circulation. The local SST has a strong influence on the boundary layer air temperature, and Bowers [2004] has demonstrated the impact upwelling events have on sea breeze circulations. This section characterizes the distribution of water masses in the Delaware bay for Classic, BSB, and No SBB days to help explain some of the variability in the SBB circulation.

3.4.1 Comparing SSTs from Classic, BSB, and No SBB day's

The classic SBB days were sampled to match the temporal distribution in the BSB events. There are 67 classic SBB events distributed over each month and year based on the BSB distribution discussed in the Bay Sea Breeze section. Figure 3.12a shows colder water at the mouth of the bay with a cold tongue extending up the center of the bay just to the northeast of the channel. This cold tongue, is common and according to Wong and Münchow [1995] and is recognizable in the seasonally averaged SST in figure 3.13. Figure 3.17 shows 3 axial transects taken from the SST composite from figure 3.12. The transects begin 40 km southeast of Delaware Bay mouth and extends to Ship John Shoals Light House covering a distance of 118 km. These transects provide a means of quantifying the temperature gradient in the bay for each composite (figure 3.14) . From 0 - 35 km, there exists a decrease in water temperature in the transition from warm shelf water to colder waters as a result of coastal upwelling. This region is very susceptible to coastal upwelling due to the direction of the prevailing wind causing Ekman transport to advect surface waters offshore. Looking further up the transect, the largest positive gradient can be found just inside of the bay from 40km - 80km where the SST increases 3.5°C (slope: $0.0875^{\circ}\text{C}/\text{km}$). The region represents an important transition zone between bay intruding shelf waters and the brackish waters of the upper bay. From 80 - 188 km, the water temperature continues to increase to 26.1°C . Looking at the transect starting from the coldest point in the coastal upwelling to top of the

bay (30 - 118 km), there was an increase in SST of 5°C (slope: $0.057^{\circ}\text{C}/\text{km}$).

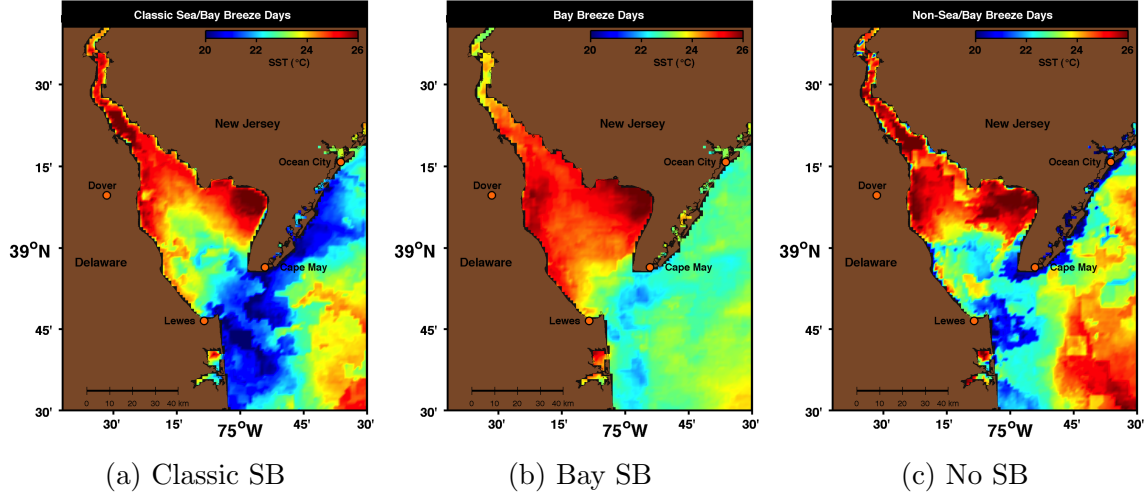


Figure 3.12: SST composites equally sample in months and years.

The BSB days exhibit a very different distribution from the classic cases with warmer shelf waters and a more linear SST front closer to the mouth of the bay and warmer water just outside of the bay. In theory, a very warm bay and relatively cold coastal ocean could assist in the generation of these environmental conditions. This “False Coastline” effect could influence the behavior, location of origin, and shape of the SBB front. Over the study period there have been 67 occurrences that were visible in the radar reflectivities. Due to the high heat capacity of the water, the SST has a strong influence on marine boundary layer air temperature. Figure 3.12b is the average SST where the BSB were captured by the radar. The SST gradient that runs normal to the direction of the deep channel supports the “False Coastline” concept. The BSB transect, figure 3.15, shows that the shelf waters are of very similar temperature to the classic transect with a smaller decrease in between 0 - 35 km. This is evidence that, on average, BSB days experience weaker coastal upwelling as compared to the classic SBB days. The transition zone (40 - 80 km) shows a sharp increase in temperature between 40 - 55 km (slope: $0.140^{\circ}\text{C}/\text{km}$) followed by a much slower increase from 55 - 80 km. The steep part of the gradient is the false coastline followed by

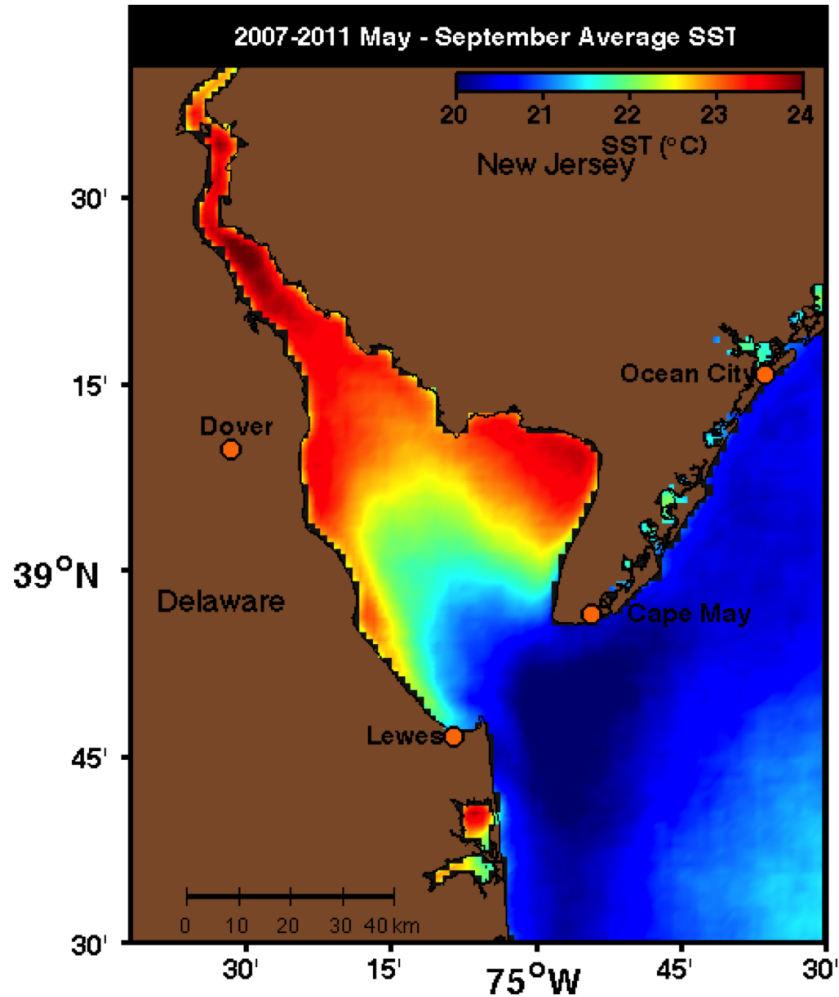


Figure 3.13: Study Period Mean SST

the warmer mix of bay and river water. The upper bay portion of the transect shows a peak in water temperature of 25.4°C followed by slight decrease in temperature. This decrease in temperature could be evidence that the BSB front occurred soon after precipitation events that resulted in a cooling of the river water.

The No SBB days exhibit the most intense cold tongue with a localized patch of cold water located just outside of the bay mouth at Cape Henlopen. It should be noted that the No SB days have the largest amount of missing data, as presented in chapter 2, so the SST

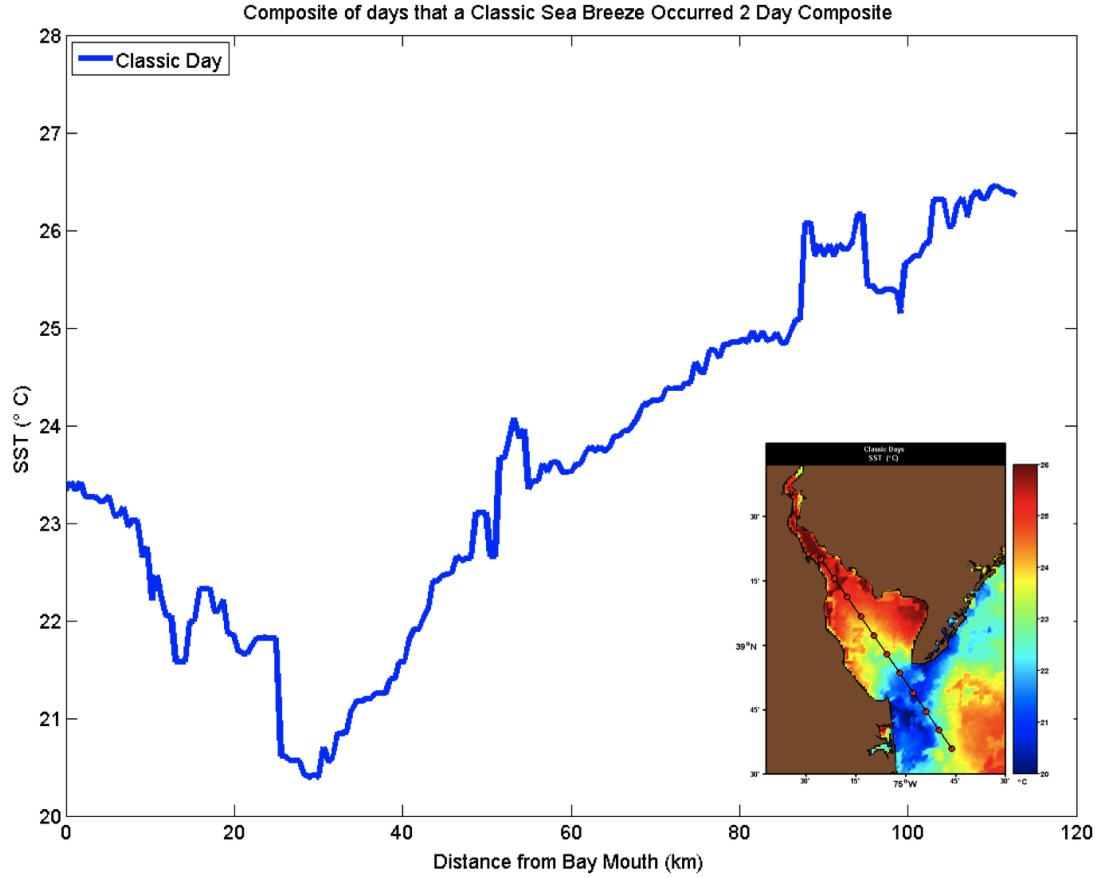


Figure 3.14: Axial transects of SST for classic SBB cases. The distance is the distance traveled from the first point in the coastal ocean.

composites might be slightly biased due to a reduction of good data points. Upon inspection of the axial transect in figure 3.16, on average, the shelf water is 1.5 - 2°C warmer than in the classic and BSB cases. Similar to the other two average SSTs, there is a negatively slope temperature gradient that bottoms out between 20 km and 30 km with a slope of 0.123 °C/km. The transition region through the upper part of the bay shows a fairly constant increase in temperature with a slope through the transition region of 0.065°C/km and the upper bay region of 0.053°C/km.

Comparing all of these transects, figure 3.17, can be used to quantify how different the transects are from one another. First inspecting the shelf region, it's apparent that

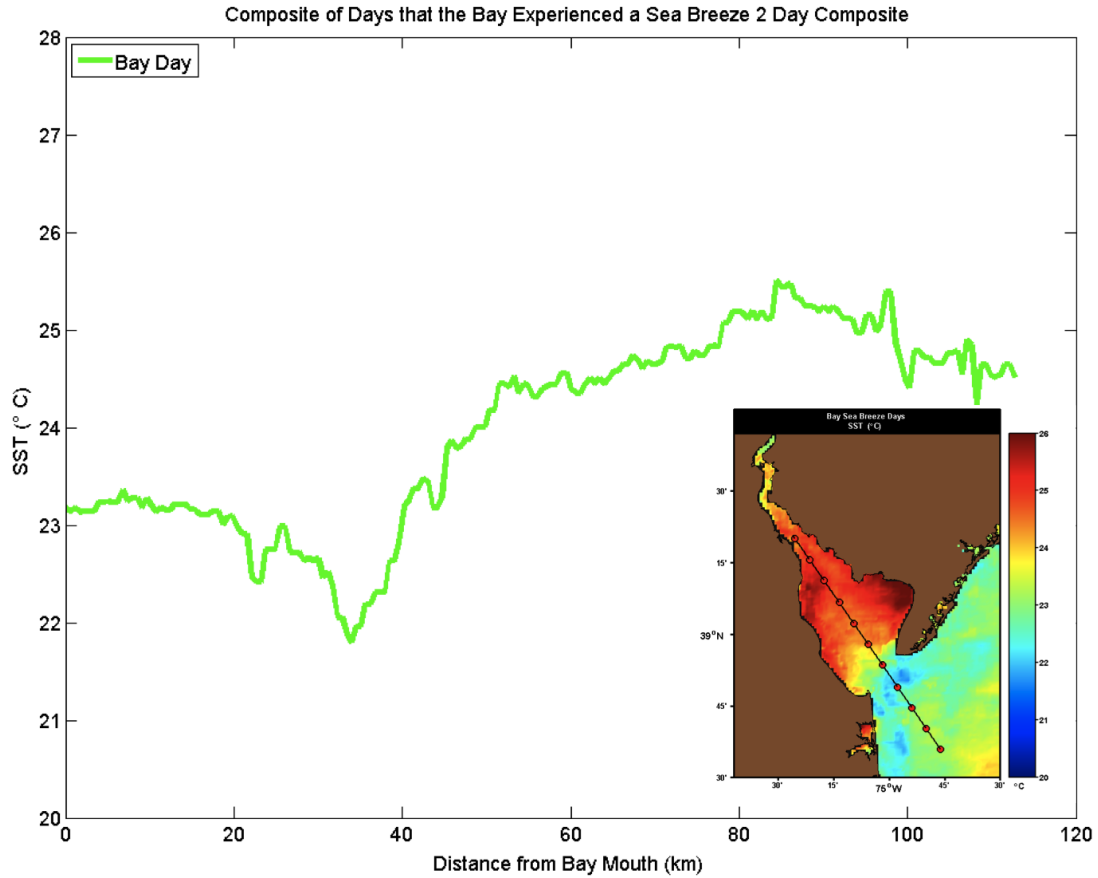


Figure 3.15: Axial transects of SST for BSB cases. The distance is the distance traveled from the first point in the coastal ocean.

the No-SBB days have the warmest shelf water and the weakest of the coastal upwelling just outside of the bay mouth. The Classic transect shows the intense upwelling center just outside the bay mouth. The BSB cases have the coolest shelf waters and has the smallest temperature drop in the coastal upwelling region. The BSB days have the shortest but the steepest gradient in the transition zone followed by the classic days. The classic and the No-SBB days have a continual increase in temperature with distance travelled up the bay while the BSB days do not.

Horizontal transects of the Delaware Bay's SST provides a means of assessing the horizontal distribution of water masses in the bay. When comparing the horizontal transects

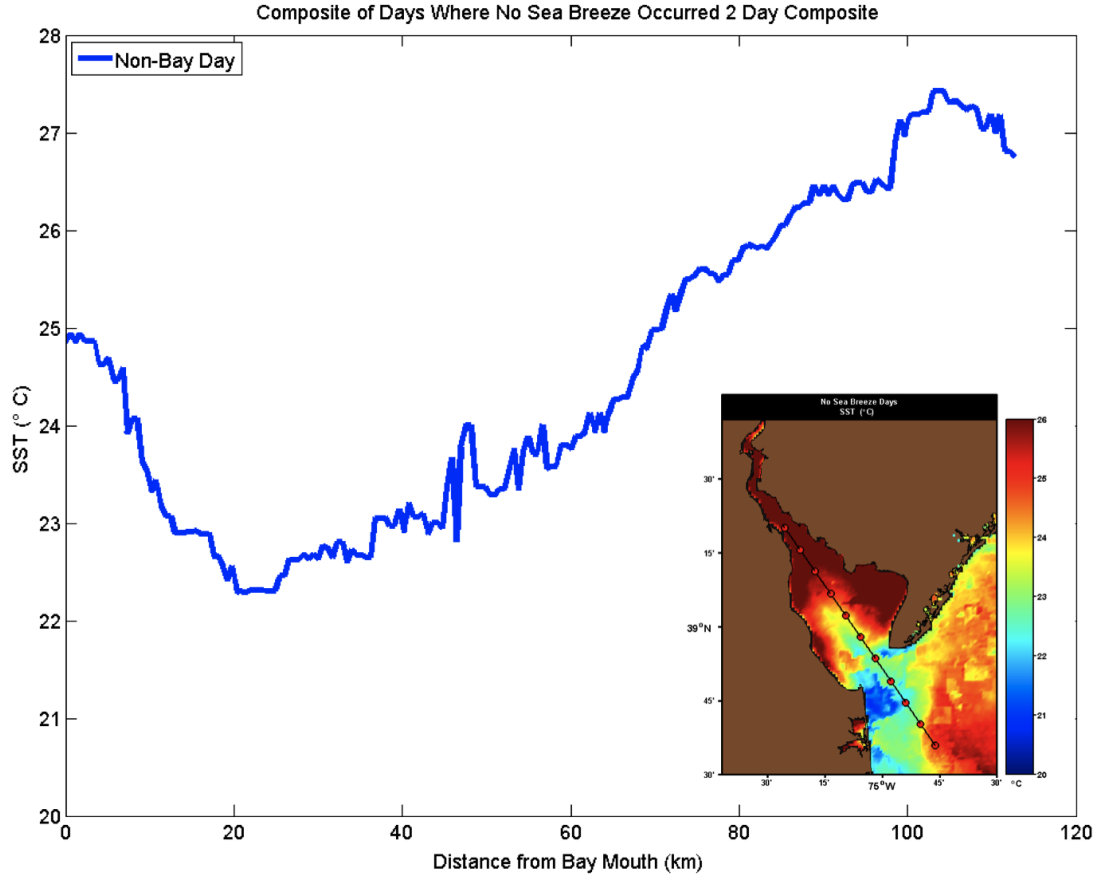


Figure 3.16: Axial transects of SST for No SBB cases. The distance is the distance traveled from the first point in the coastal ocean.

from the Classic, BSB, No-SBB days, and the study period average in figure 3.18 show how different the BSB days are from the Classic, Non-SBB, and the average. The BSB days show very little change in temperature moving from west to east while all the other cases have a noticeable decrease in temperature from 3 - 12 km then an increase from 12 - 43 km. This decrease in temperature is the cold tongue of shelf waters that intrude into the Delaware Bay. For the BSB cases, as also seen in figure 3.12b, the tongue of cold water is nearly nonexistent. This uniformity in SST over the Bay may be a function of the synoptic type and the resulting prevailing wind over the bay.

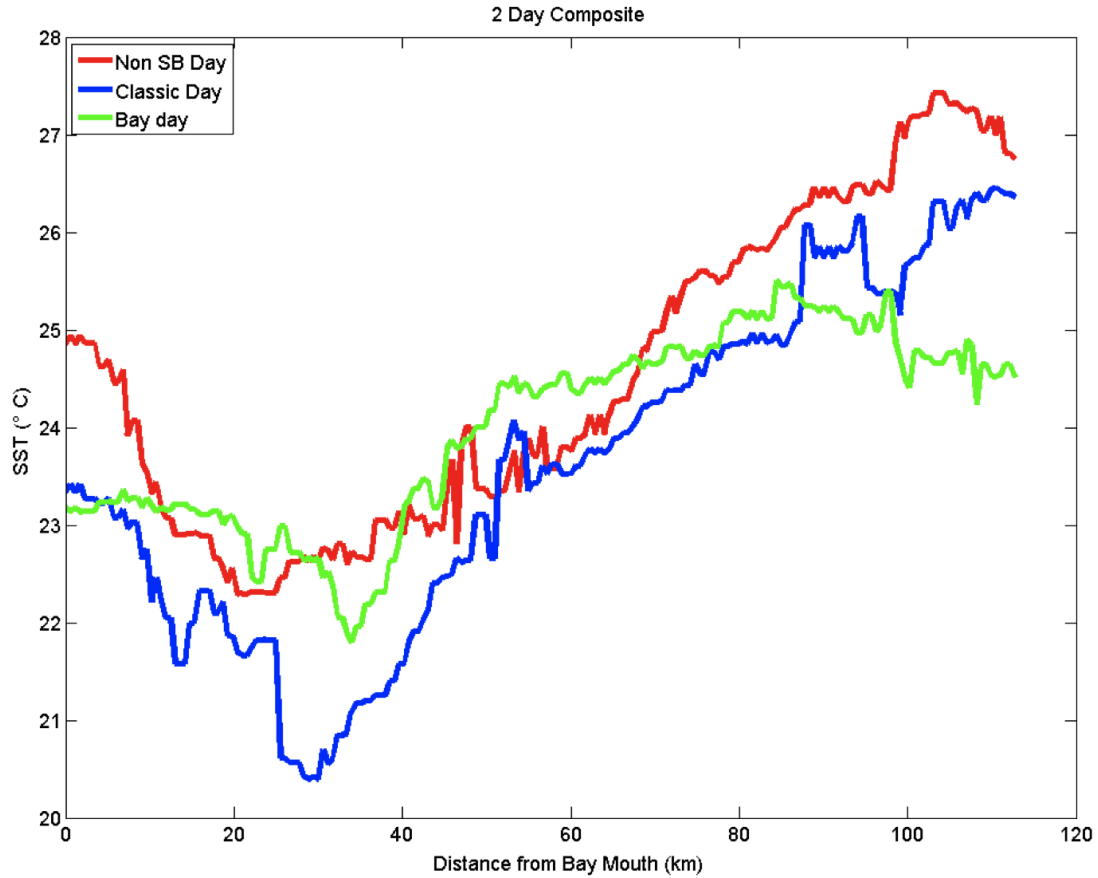


Figure 3.17: Axial transects of SST. The distance is the distance traveled from the first point in the coastal ocean.

3.4.2 Case Study I: July 7-8, 2007

The bay's SSTs have a distinct seasonal signal, but also have sensitivity to synoptic type. July 7th and 8th could be characterized as your typical summer days in Delaware with nearly identical local environmental conditions. The synoptic conditions on July 7th and 8th were very similar with the synoptic types being 3033 and 3032 respectively. On July 5th a cold front passed which trigger some light precipitation over the area. This left July 6th, 7th, and 8th with precipitation free conditions. A SBB developed early afternoon each day, but the SBB fronts that developed were starkly different when observed using radar. Figure 3.21a shows a SBB front almost normal to the Atlantic coastline. Looking at July 8 in figure

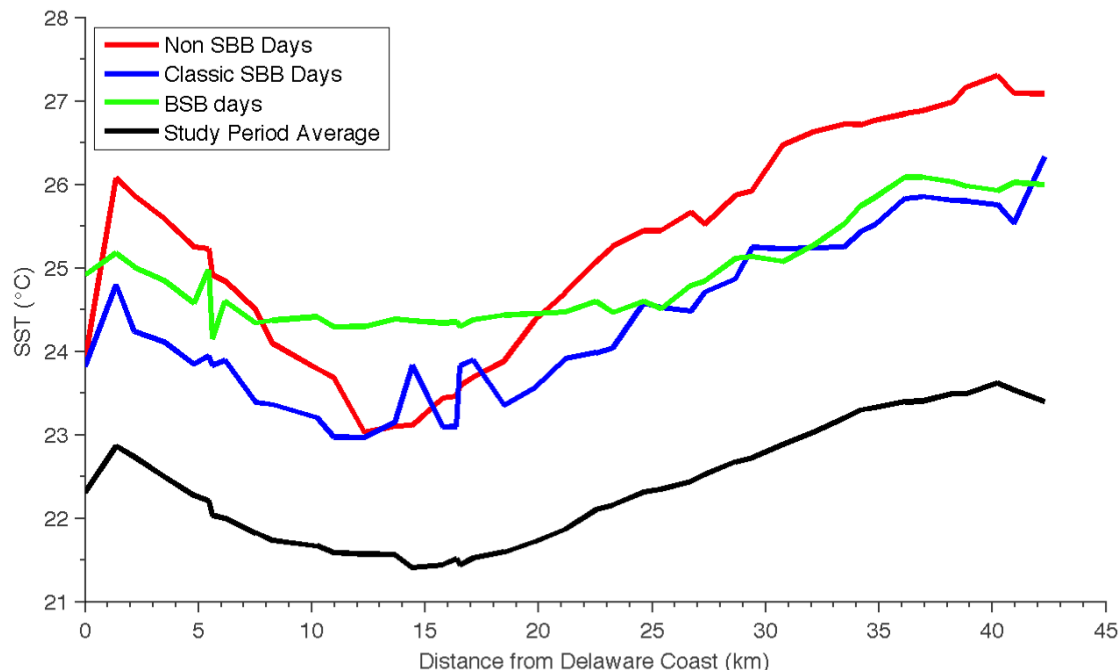


Figure 3.18: Horizontal transects of SST. The distance is the distance traveled from the first point at the Delaware Coast.

3.21b the SBB front is oriented normal to the Delaware Bay coastline. Figure 3.20 shows a time-series of the environmental variables show how little difference existed at DEOS station DLAU. In this situation, DLAU was the best station to describe the prevailing atmospheric conditions over land with no influence of the SBB circulation.

Interestingly, the SST of the bay was very different between the two days. Figure 3.21 show SST observations taken at 14:00 local time. During both days, the river discharge was near normal, figure 3.22, lending the bay to having a very shallow thermocline [Sharp et al., 1986]. With the water level being .1m different at the time of the satellite images between the two days, tidal mixing is not likely to play a significant role in the discrepancy between the two SST images. A possible explanation for this difference in surface temperature is wind stress. The time-series plots from BRND1 shown in 3.23 shows a significant drop in wind speed on July 8th, just before the satellite passed over the bay. This reduction in wind

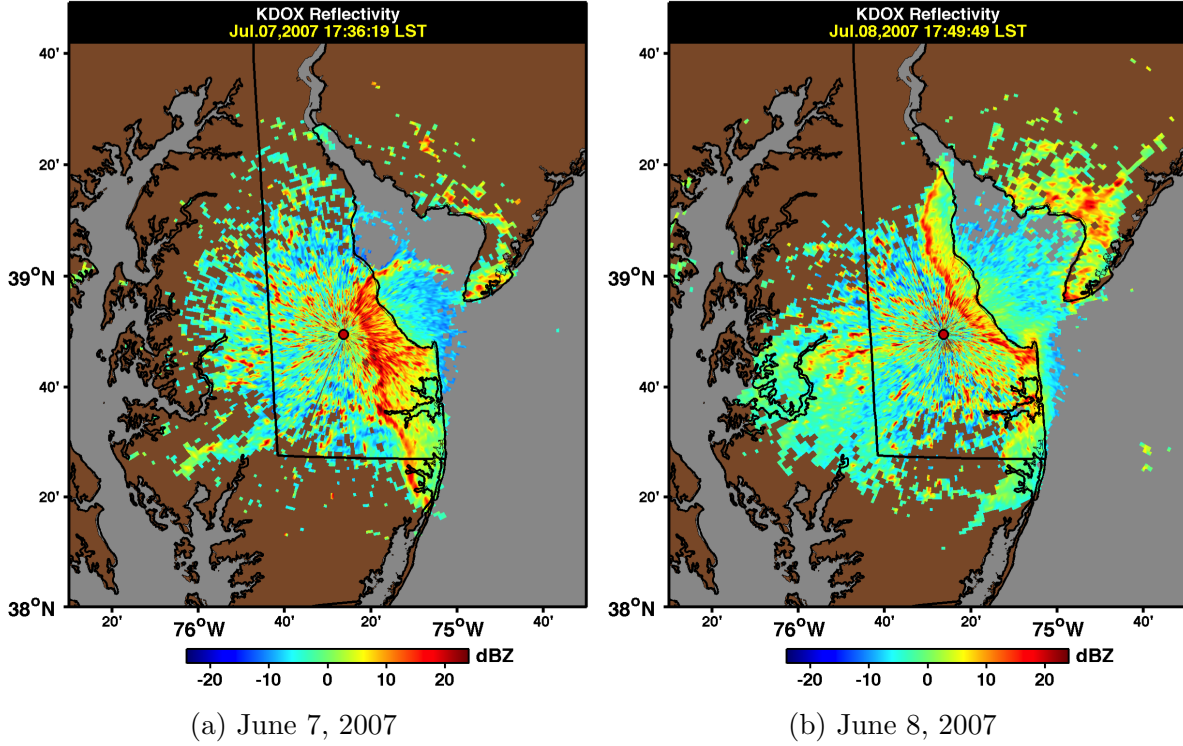


Figure 3.19: July 7 and 8, 2007 NEXRAD reflectivity

speed, and slightly lagged reduction in turbulent mixing at the surface, allows the surface skin of the water to heat up more quickly, resulting in a slightly higher SST observation. It is important to note that satellite SST measurements are only representative of the surface skin temperature. This surface skin temperature is strongly influenced by turbulent mixing induced by wind. This slight change in wind speed and direction is an indication of the slight shift in prevailing synoptic conditions. The prevailing synoptic situation can have a strong influence on bay surface temperatures through wind driven upwelling.

The connection this has to the SBB circulation is in the air temperature response. This air temperature response is important for generating the a sufficient differential temperature between the cold coastal ocean and warm terrestrial airmass to support a thermally

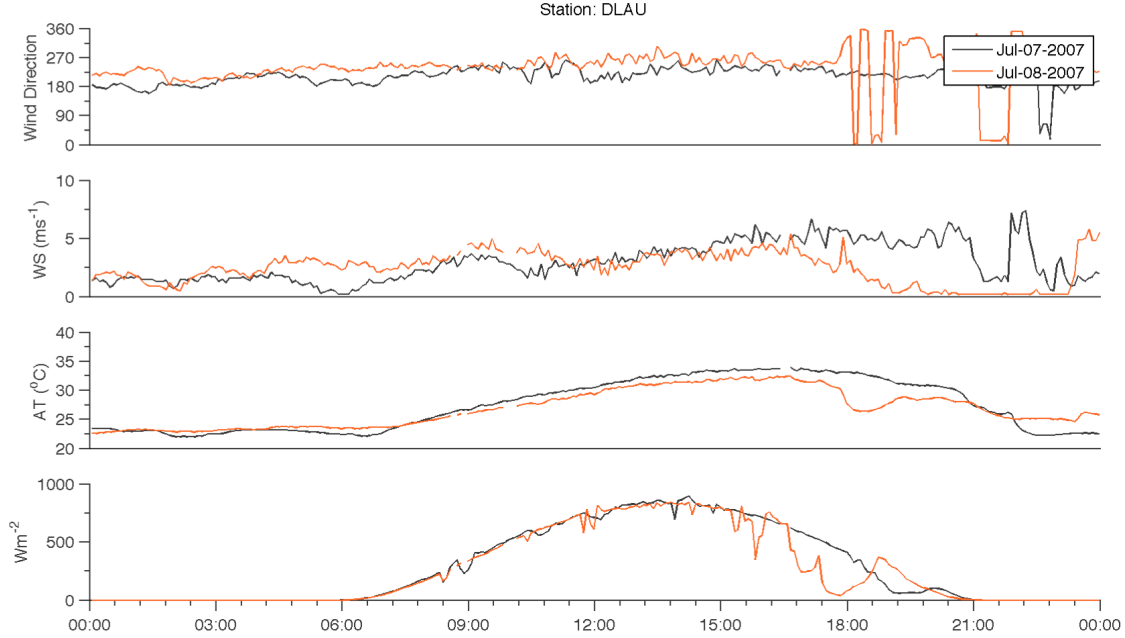


Figure 3.20: July 7 and 8, 2007 time-series

direct circulation. With that in mind, this case displays another sensitivity of the SBB circulation to the change in SST. Taking a second look at figure 3.21b, one would expect that this SST distribution would support a BSB due to the presences of what looks to be a false coastline. In addition, this warming of the bay water should inhibit the development of the SBB front along the bay coastline. Figure 3.19 shows the opposite of this intuition.

This leaves the only logical explanation to be the subtle difference in wind speed and wind direction prior to the development of each SBB. Referring back at figure 3.23, it can be gleaned that before 12:00 LST over the bay the wind direction on July 7 had a slightly stronger southerly component than July 8. In addition, the wind speed on July, 7 was slightly less than that on July 8. The combination of a slightly stronger wind that was nearly normal to the to the atlantic coast could have been the inhibiting factor for a SBB front originating from the atlantic coast. With all other influential environmental factors being equal, this shows how subtle differences in wind speed and direction can have a large

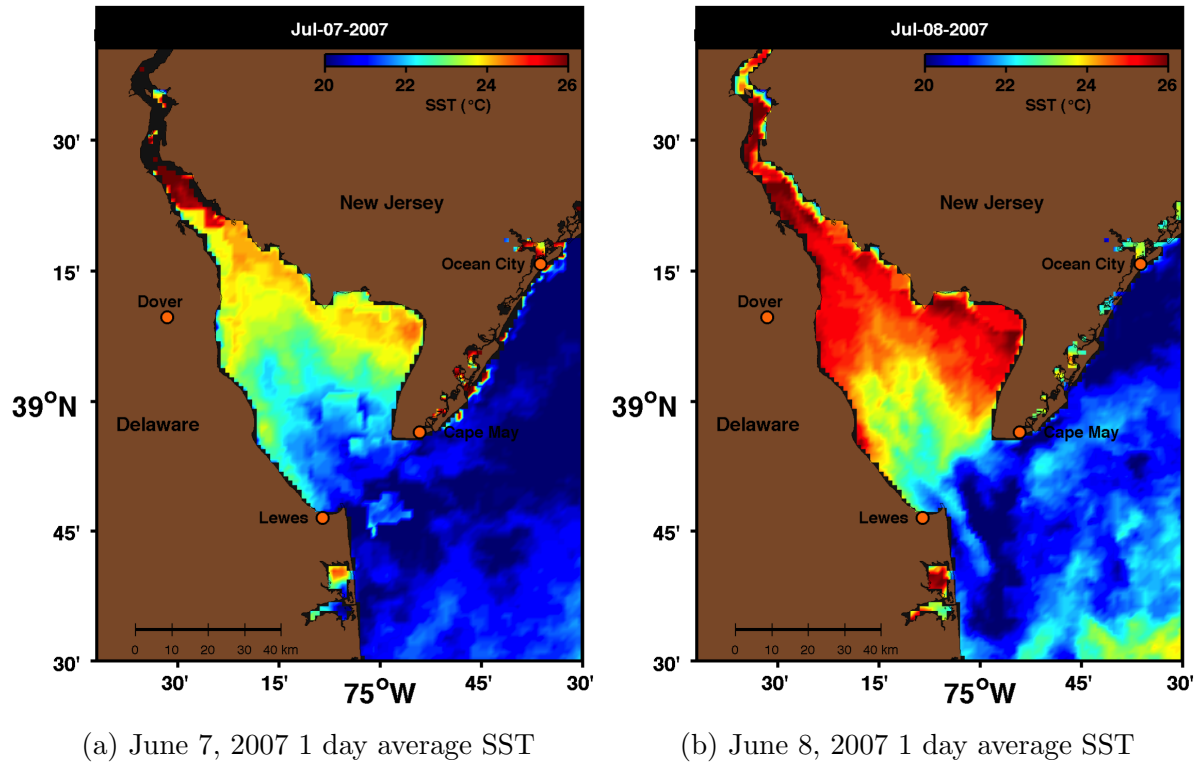


Figure 3.21: July 7 and 8, 2007 1 day average SST

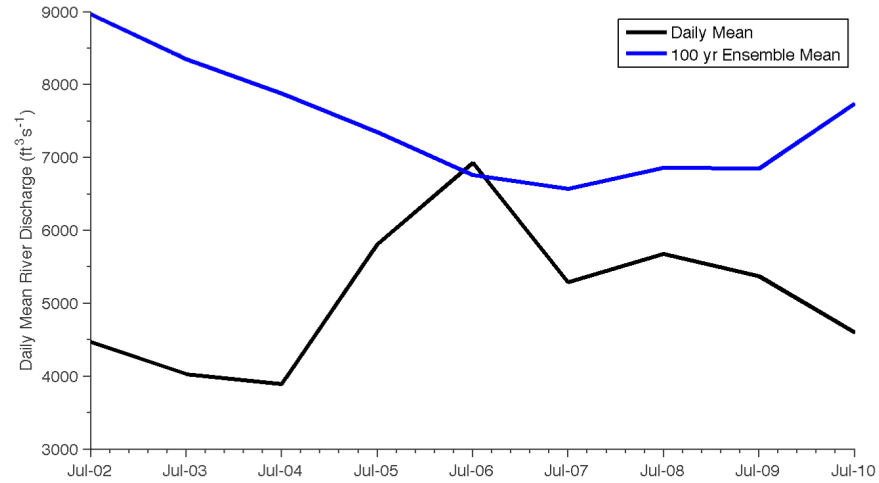


Figure 3.22: July 7 and 8, 2007 Delaware River discharge

affect on the development and location of a SBB front.

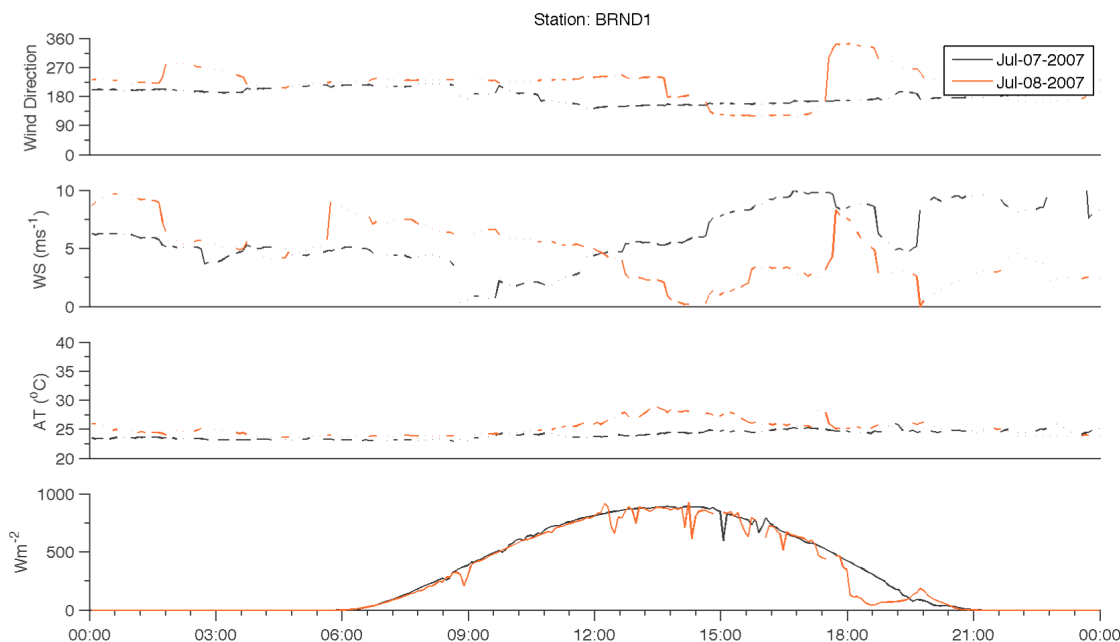
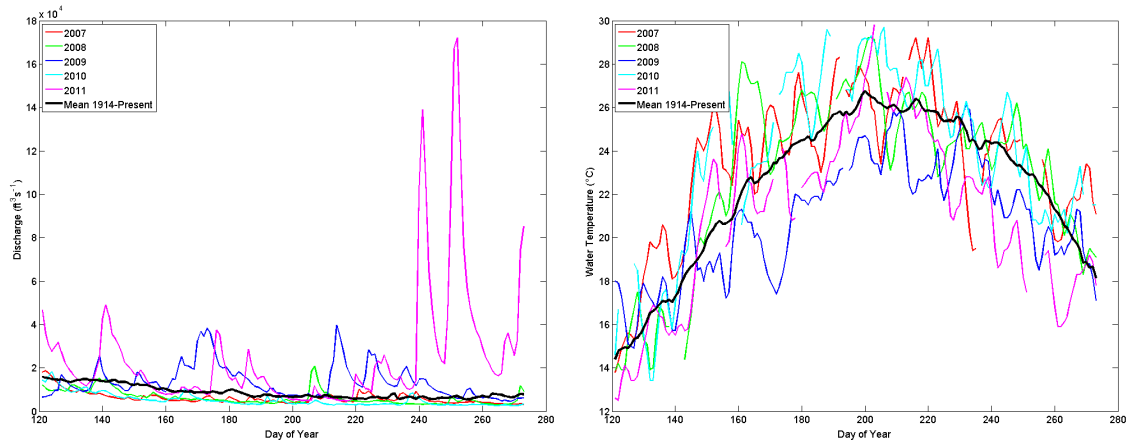


Figure 3.23: July 7 and 8, 2007 time-series

3.4.3 Additional Environmental Variables Effect the Delaware Bay SST

The Delaware River, being the largest contributor to the Delaware estuary, could be influential on the Delaware Bay surface temperatures. Theoretically, a large discharge of relatively fresh water could ride over top of the more dense water of the bay. This influx of surface water could assist in the explanation of the “false coastline”. Figure 3.24a shows the daily averaged river discharge for the study period. Anomalously-high discharge in 2009 and 2011 are well correlated with cooler than average river temperatures found in figure 3.24b. Interestingly, these years experienced the least amount of radar detectable BSB fronts.

Since the SST measurements are made at 14:00 each day, it is possible that the upwelling near the mouth of the bay could be enhanced by an incoming tide and suppressed with an outgoing tide. For BSB days, one would expect there would be an outgoing tide during early afternoon causing a suppression in tidal mixing and supporting the development of a false coastline. Interestingly, there was an outgoing tide at the time of BSB initiation



(a) Delaware River daily averaged river discharge for study period (b) Delaware River daily averaged river temperature for study period

Figure 3.24: USGS Camden station river discharge and temperature

nearly 46% of the time and outgoing tide the other 50% of the time. This sheds some light on how dynamic the Delaware estuary truly is. The possibility exists that there is a balance between river discharge and tidal phase that could help better explain the existence of the false coastline.

3.5 Summary

This chapter has presented results from the sea breeze detection algorithm. The sea breeze detection algorithm successfully identified 326 SBB circulations that were visible using the NEXRAD platform. The most common source of error were caused by backdoor cold fronts and gust fronts. With 326 identified SBB fronts, 2 distinct types of fronts were observed. The first and most common being the classic SBB front which is a front that propagates only over land away from the coastline. The second, more rare type, is the Bay Sea Breeze (BSB). The defining feature of this front is the existence of the frontal signature moving up the Delaware Bay. Synoptic typing was introduced and it was found that the classic SBB days with an approaching cold front from the west and a south westerly wind

(3032). The BSB days had a dominant synoptic type of 3035, which had a large scale light west north westerly wind. In addition to differing synoptic characteristics, differences between these SBB types can be found in the Delaware Bay SST. The Classic SBB days on average have a large cold tongue of water that extends axially up the center of the bay while the BSB days lack such a feature. Instead, the BSB days have a thermal front that runs parallel to the mouth of the bay. This front can cause a false coastline effect, mimicking the thermal characteristics of a coastline that can help support a sea breeze circulation. It was found that wind mixing could have a profound effect on the SST of the bay. Lastly, the discharge from the Delaware River and tidal mixing seemed to show little correlation with these events.

Chapter 4

RADAR DERIVED RESULTS

This chapter characterizes the defining features and variability of the SBB fronts derived from radar observations. It also correlates environmental variables with some of the characteristics of the SBB fronts. Utilizing the methods discussed in the Chapter 2 sections 2.25-2.28, a subset of all of the observed SBB fronts were digitized. This subset of events has an even distribution of Classic and SBB events.

4.1 General Characteristics

Delaware can experience a SBB in all months of the year, but the majority develop from May through September when incoming solar radiation is high, causing enhanced uneven heating of the land and ocean. During these summer months, the Delaware SBB exhibited some inter-annual variability over the study period, where 2010 had the largest number of radar detectable SBB fronts, with 80 identified. 2008 had the second most, with 74 identified events. 2009 had just over half the amount of the detectable SBB fronts, with 46. There also exists monthly variability shown by figure 3.5.

Table 4.1: SBB Averages

Event	Average
$t_{initial}$	13:20 LST
t_{final}	19:22 LST
Δt	06:06
Speed	2 ms ⁻¹
Penetration Distance	66 km

July and August, being the warmest months of the year on average, holds the largest frequency of radar identified SBB fronts. This trend is also consistent of the digitized samples

SBB fronts. Of the sampled SBB fronts, table 4.3 describes the average radar derived initiation time, dissipation time, elapsed time, along front speed, and inland penetration distance. It should be noted that these number are influenced highly by the vertical extent and proximity of the SBB front to the radar platform. This implies that digitized events data set has a bias towards stronger and more well defined SBB fronts based on the KDOX radar imagery. Keeping this in mind, this data set of positions can be used to find the mean initiation point and extinction point of all of the sampled fronts.

4.1.1 Front Positions

This visual representation, figure 4.1, of the average Delaware SBB front sheds some light on how the complexity shape of the coastline and the axial thermal gradient in the bay both play a role in the location of the typical strong SBB fronts over Delaware. The blue line segment represents the average initial SBB front position, and the red line segment represents the average front at the point of extinction. First inspecting the average SBB front position, it can be seen that the northern most portion of the front lies over the Delaware Bay where there exists, on average, a significant gradient in SST. It is possible that SBB fronts that extend over the bay do in fact correspond to the average position of the axial thermal gradient in the bay. This correspondence can be seen in individual cases found in figure 4.2. Figure 4.2a shows how the portion of the front that became visible over the bay when it was in close proximity of the gradient in SST. Figure 4.2b shows a slightly different case where a front develops over western Cape May, NJ and propagates around the edges of the cold tung. The third case, figure 4.2c, is a more extreme case where the SBB front developed over the bay within very close proximity to the strong axial SST gradient.

Another interesting aspect of 4.1 is that, on average, the SBB front is not detected until the front's vertical extent intercepts the lowest scanning angle (0.5°) of the radar. The SBB front begins as a very low level phenomenon. As the day progresses, and the land temperatures increase, there is also an increase in localized upward motion. This intensifying

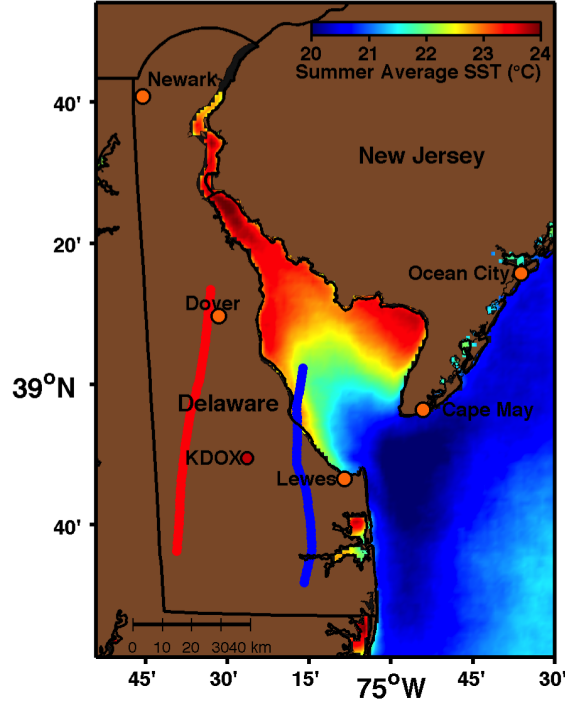


Figure 4.1: Radar derived average initial front position (blue) and final front position (red)

upward motion, as a function of time, not only strengthens the localized surface low pressure, but also enhances the upward motion at the SBB front nose. This helps strengthen the circulation as well as increase the vertical extent or the height of the SBB front head. This is the portion of the front that is first visible on radar and is often too shallow to be detected until it is a few km inland. This explains why the radar derived initiation time and location is different from that found in Hughes [2011].

4.1.2 Front Shape

The McPherson [1970] study shows that a convex coastline is sea breeze favorable. The Atlantic coastline of Delaware is slightly convex at Fenwick Island near the Maryland boarder. Otherwise, the Atlantic coastline is very linear with only 1 major inlet at Indian River. Other features on the Atlantic coast that could alter the shape of the SBB is the 3 inland bays. The largest of the bays is the Rehoboth Bay which is 8 km long (north/south)

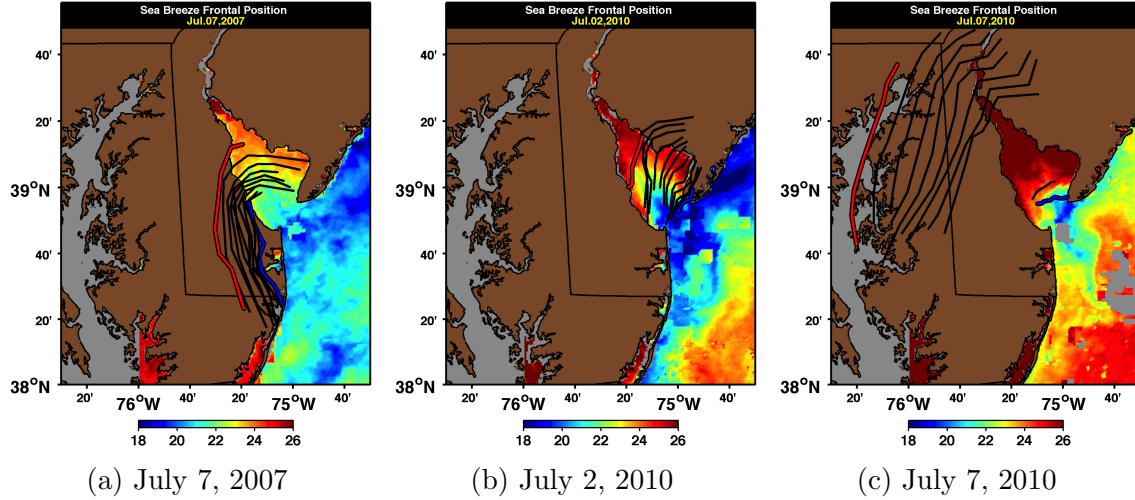


Figure 4.2: BSB front examples with respective SST measurement

and 5 km wide. The second largest bay is the Indian River Bay which is about 5 km long and 11.8 km wide. These two bays are likely to contribute the most variability in the shape of the SBB due to both their size and their proximity to the radar. The Little Assawoman Bay, just west of Fenwick Island, is a bit smaller with a length of 5.8 km and a width of 3 km. Though this bay is likely to cause some variability in the sea breeze shape, it is less likely to be recognized due to its distance from the radar. The SBB front that is likely to move inland from this area must be very mature to reach the vertical extent required to intercept the radar beam. The existence of these bodies of water could be an inhibiting factor in the local development of the SBB circulation in the area and a reduction of the inland penetration. It is possible that the bay, in this situation, could retard the inland propagation causing the front to become convex until it passes over both of the bays. As described in McPherson [1970], the modulation of the sea breeze convergence zone inland of the point of initiation affects the front shape, but typically dissipates when the front moves further inland.

The Delaware Bay coastline overall has a concave shape with a convex lobe between Bowers Beach and Slaughter Beach. According to McPherson [1970], this type of coastline

shape is less favorable for sea breeze development. Interestingly, the bay coastline experiences a SBB quite often and in concert with the Atlantic Coastline SBB, but rarely has comparable inland penetration. Typically, the Bay front takes on a concave shape with two large lobes that develop north and south of Bowers Beach, as seen in figure 4.3. The southern lobe typically moves inland more quickly than the northern lobe due to its influence on the sea breeze from the Atlantic coast. The bay front more often is detectable on radar before the sea breeze front so the interaction between the two fronts is easy to spot. After a few hours, the larger lobes disappear and smaller irregularities in the front become more apparent. These smaller irregularities are caused by geographic features such as large areas of development and pavement. The enhanced upward vertical motion caused by the urban heat island effect over these area are enough to cause an increase in scatters in the radar data. This can potentially cause a false detection of the frontal position.

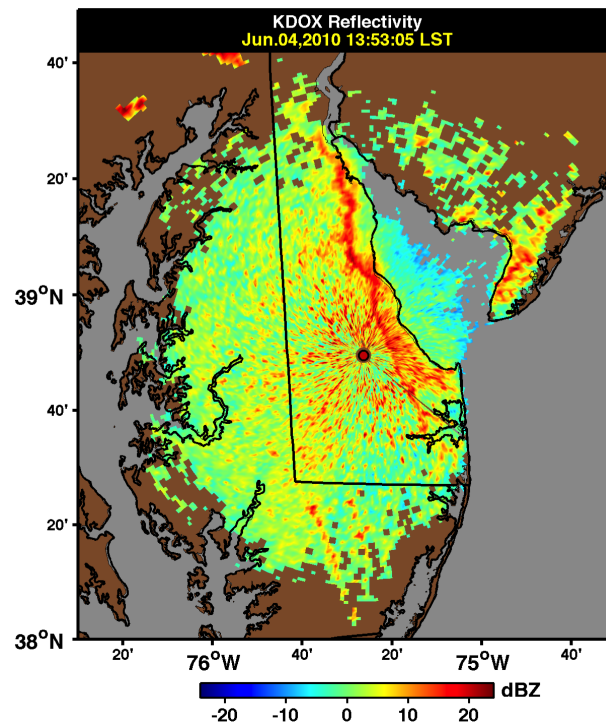


Figure 4.3: June 4, 2010 shows 2 lobes on either side of Bowers Beach, DE

Combining both the Bay and Atlantic coastlines, it is possible to see how the shape of the coast affects the interaction between the bay and sea breeze front. The Cape Henlopen/Lewes area is the center point of this interaction. As the fronts pass over this area and become unified, they often keep the convex shape of intersection point of the two coasts. As the front matures and moves inland the portion of the front that was once convex due to the coastline shape becomes progressively more concave as it propagates faster than the other parts of the front. This typically happens to fronts that penetrate past the KDOX radar. The cause of this could be the convergence zone of the two breezes, enhancing upward motion in this portion of the front. Figure 4.4 shows an example of the large scale shape of the front changing from convex (figure 4.4a) to slightly concave (figure 4.4b).

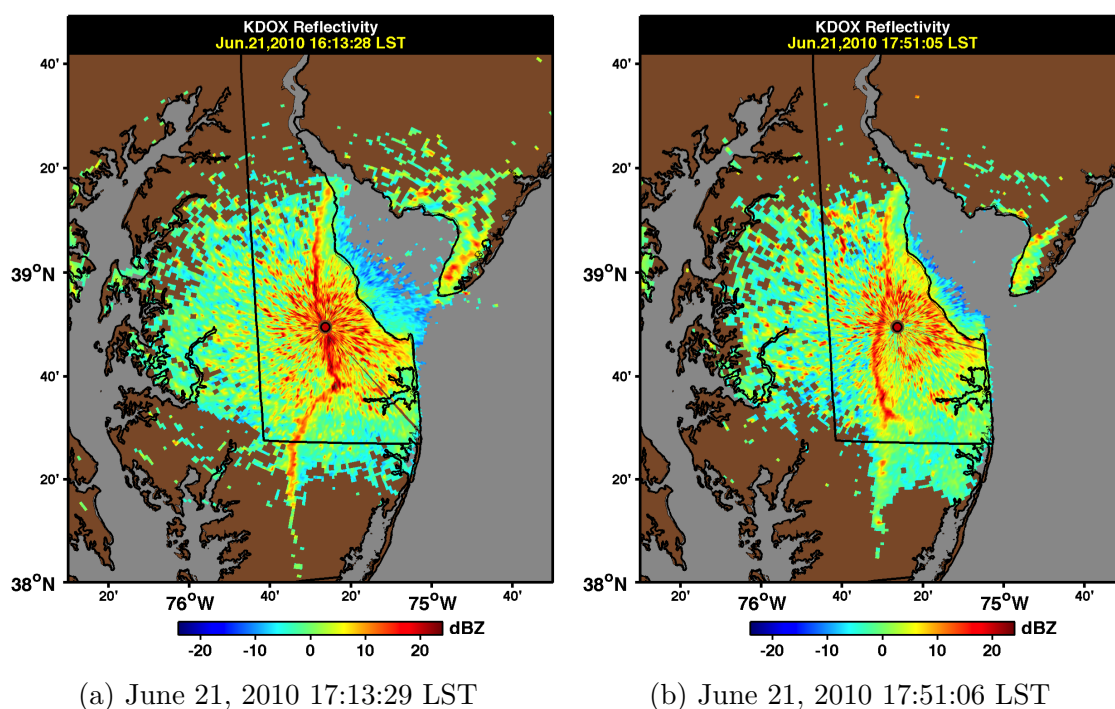


Figure 4.4: Example of how a SBB evolves from the shape of the coastline (convex) to a convex shape

4.2 Case Studies

4.2.1 Interaction with the Chesapeake Bay Front

The upper portion of the Chesapeake bay can generate its own bay breeze and occasionally the bay breeze front is visible by KDOX. On two occasions the Chesapeake Bay front was not only visible on radar, but collided with the Delaware SBB front. The first case where this occurred was August 31, 2008. On this day, the synoptic type was 3034, meaning there was northerly flow caused by a high pressure in the Midwestern portion of the country. In this case, the Chesapeake Bay breeze propagates across the northern portion of the eastern shore of Maryland into western Delaware from the west-northwest. Simultaneously, a SBB developed from the Atlantic coast and propagated from the southeast. It should be noted that the fronts did not become visible until after the hours of peak heating. The first signs of interaction between the two fronts occurred at 16:20 LST when the southern portions of the fronts collide. At 19:19 LST, an even larger portion of the fronts collided. At this point, the solar forcing was rapidly decreasing and the fronts were beginning to slow down. Figure 4.5c shows the final frame before the fronts diminished. The parts of each front that did collide became a unified area of scatters that did not propagate.

The second case of the Chesapeake Bay breeze front interacting with the Delaware SBB front was on May 21, 2010. On this day, the Chesapeake Bay front propagated from south-southwest while the Delaware front was propagating from almost due east. Similar to the previous case, the southern portion of the Delaware front interacted with the Chesapeake Bay front first, but the result of the interaction was very different. The strong southern component of the Chesapeake front altered the direction of the Delaware front upon their collision. After the collision, the unified front propagated in a more north-northwesterly direction. At the point of collision, the reflectivities increased greatly indicating strong upward motion and an increase in the vertical extent of the front. In each subsequent frame this occurred, figure 4.6b, until the fronts were completely unified. At this point, the new

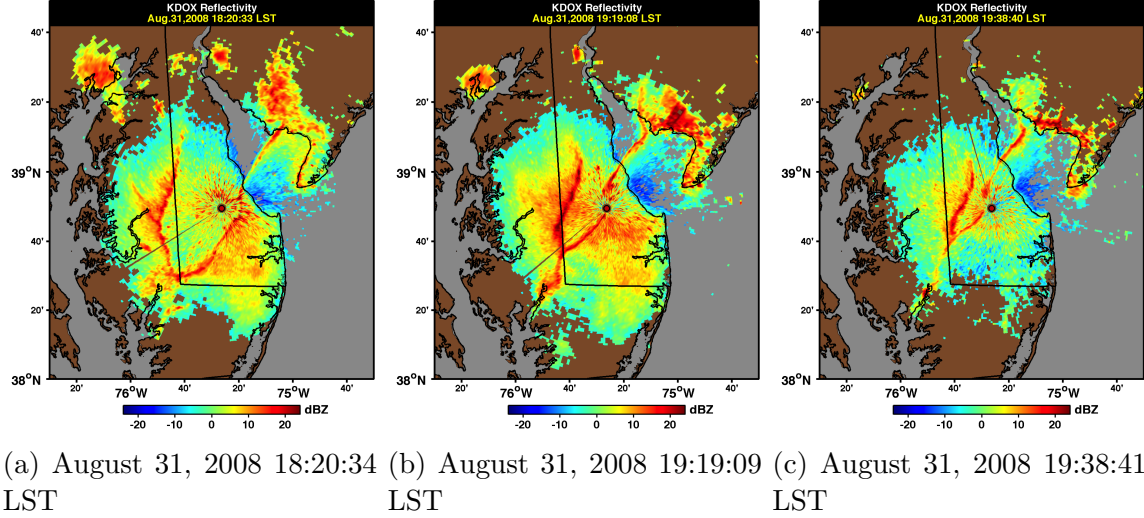


Figure 4.5: Collision of Chesapeake Bay Breeze front and Delaware SBB front

unified front was moving a north-northwesterly direction as it began to dissipate (figure 4.6c).

This phenomenon of the Chesapeake Bay breeze front being visible via KDOX and converging with the Delaware SBB occurs most frequently in spring when the Chesapeake Bay and Delaware Bay are cold enough to support deeply penetrating bay breeze fronts. In the case of June 26, 2010 the Chesapeake Bay breeze front was strong enough to collide with and over take the weak Delaware Bay breeze front at the Delaware Bay coastline. In all the cases, the synoptic wind was very light, enabling each front to develop without being over powered by the synoptic flow. In this data set, there are two cases where this occurred in August 2008. Both cases occurred when pressure gradients over the region were very weak, resulting in very weak synoptic flow. In this data set, the collision between these fronts occurred 4 times. It is likely that this happen more than 4 times because the Chesapeake Bay breeze front is far from the radar and could easily develop and propagate below the lowest scan angle of the radar.

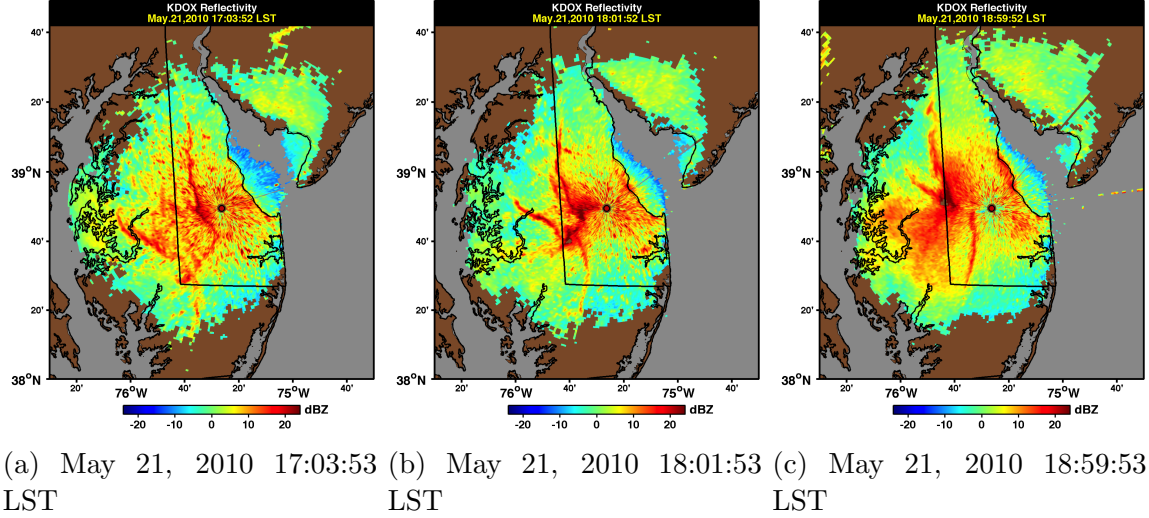


Figure 4.6: Collision of Chesapeake Bay Breeze front and Delaware SBB front

4.2.2 Case: Double Front

May 25, 2011 was a particularly interesting case where the SBB front did not appear amongst the ground clutter until it was near the western boarder of Delaware and Maryland shown in figure 4.7a. The front is concave and looks to have originated from the Delaware Bay coast. It is rare a front originating from the bay penetrated this far inland. As the front continues to propagate inland, it is proceeded by secondary front shown in figure 4.7b. The first front begins to slow as the second front over takes the first in figure 4.7c. This situation is was only visible 1 time over the course of this study. This shows how complex the Delaware SBB circulation can be.

4.2.3 SBB fronts that initiate convection

A strong SBB front occurring during days where the level of free convection (LFC) is within the vertical extent of the SBB front's vertical extent, can trigger very localized convection. July 16, 2007 is an extreme example of this where a SBB front moving west from the Delaware Bay generates numerous showers and thunderstorms over southern Delaware. In order to be considered SBB front-initiated convection the SBB front must be visible by KDOX prior to visible convection between the SBB front and the coastline. Figure 4.8 shows

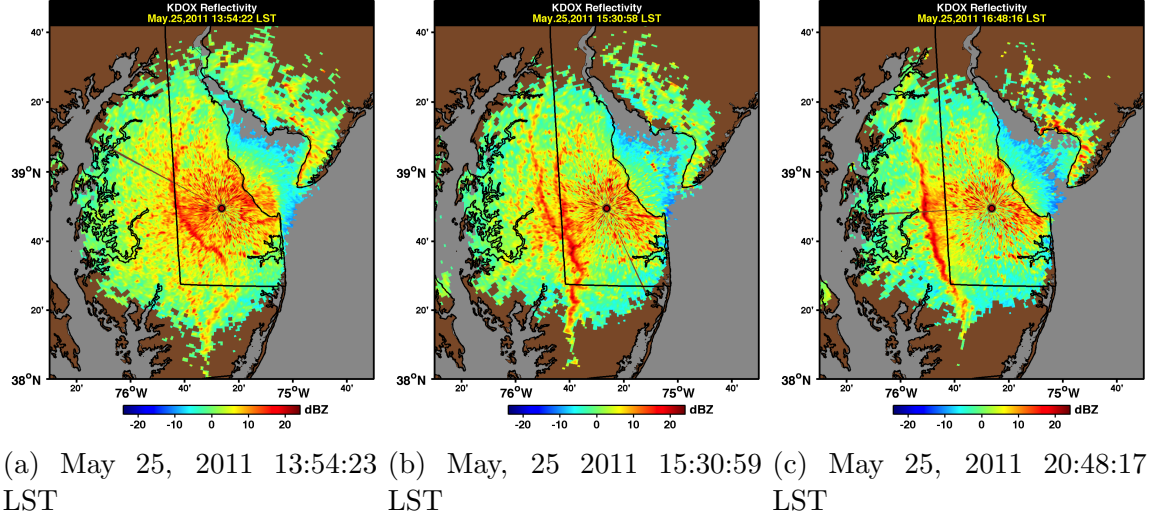


Figure 4.7: Double Front event

a time-series where the development of convection caused the a strong SBB front. The SBB front that initiated the convection is show in figure 4.8a. Figure 4.8b shows the development of the convection east of the front, between the front and the coast. In other words, the convection develops down-wind of the SBB front. In most cases, once the convection develops, it triggers a convective outflow boundary (COB), also known as a gust front, that can enhance the SBB front and push it further inland. Figure 4.8c shows how the shape of the SBB front was modulated by the influence of COBs pushing the center of the SBB front further west.

This type of situation was discernible on radar 38 times through the course of this study. The annual frequency is outlined in table 4.2. It is likely that many of the convection initiating fronts were more frequent than what was observed but were not visible. Typically, the KDOX radar is in precipitation mode on the days that convection is initiated and the data is very noisy. Also, if the LFC is lower than the hight of the radar beam at the location of the front and convection is triggered, than the front will likely go unseen by the radar. However, it is possible that a COB could be triggered, which would enhance the SBB front

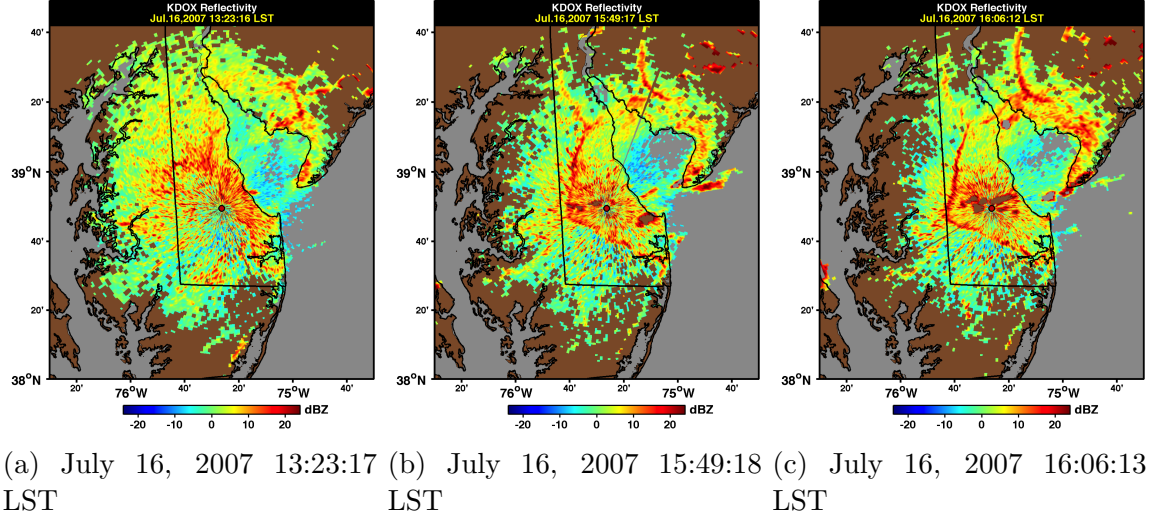


Figure 4.8: Convection initiation event

Table 4.2: Yearly distribution SBB fronts that initiated convection

Year	Frequency	Dominant Month (Frequency)
2007	5	July (3)
2008	6	June (3)
2009	6	June (2)
2010	6	July (3)/August (3)
2011	15	July (6)
Total	38	July (12)

to the point that is detectable by radar. Due to the large amount of uncertainty with these situations, they have been omitted when assessing the frequency at which SBB front initiated convection.

4.2.4 Characteristics of the Classic SBB and BSB front

The difference between Classic and BSB days is the existence of the SBB front thin line over the Delaware bay. Figure 4.9 and figure 4.10 shows a side by side comparison of a digitized classic SBB front and BSB front. The BSB front typically extends over land as

well as the bay (figure 4.9b) while the classic SBB front only resides over land (figure 4.10b). Another difference is how the BSB front seems to be unaffected by the existence and shape of the Delaware Bay coast. This is also evident when comparing the average positions of the classic and BSB front position in figure 4.11. Figure 4.11a shows the classic SBB front initiation point in blue. The average front takes on a slight S shape with the north half being concave and the southern half being convex. The concavity of the northern half is likely a function of the concave shape of the Delaware Bay coastline. The shape of the southern half could be both a function of the transition in the orientation of the coastline and the existence of the two large bays. These bays could modulate the shape of the front and retard the inland progression. The extinction point, denoted by the red line, shows a near vertical line from north to south. It is interesting to note that on average the northern portion of the front travels less than the southern portion of the front. This could be caused by Coriolis force or the fact that the differential temperature between the coastal ocean and the land is typically larger than that between the bay and the land. In figure 4.11b the northern half of the average initiation point lies over the Delaware Bay while the southern half lies over land. The portion of the front that lies over the bay completely ignores the bay coastline.

The classic SBB and BSB fronts are also noticeably different in aspects other than location and propagation direction. Table 4.3 shows the different characteristics that the two SBB types. The initiation time of the classic SBB is nearly 1 hour earlier than that of the BSB initiation. This could be explained by the fact that the BSB could require more solar forcing to initiate and mature to point that it's detectable by the radar. It is also possible that the BSB's vertical extent is below the radar beam for a longer period of time after initiation. Similarly, the average extinction times are just over 1.5 hours different and a difference in duration of 37 minutes with the BSB fronts lasting longer than the classic fronts. Interestingly, the BSB fronts also have a larger average penetration distance by nearly 20 km.

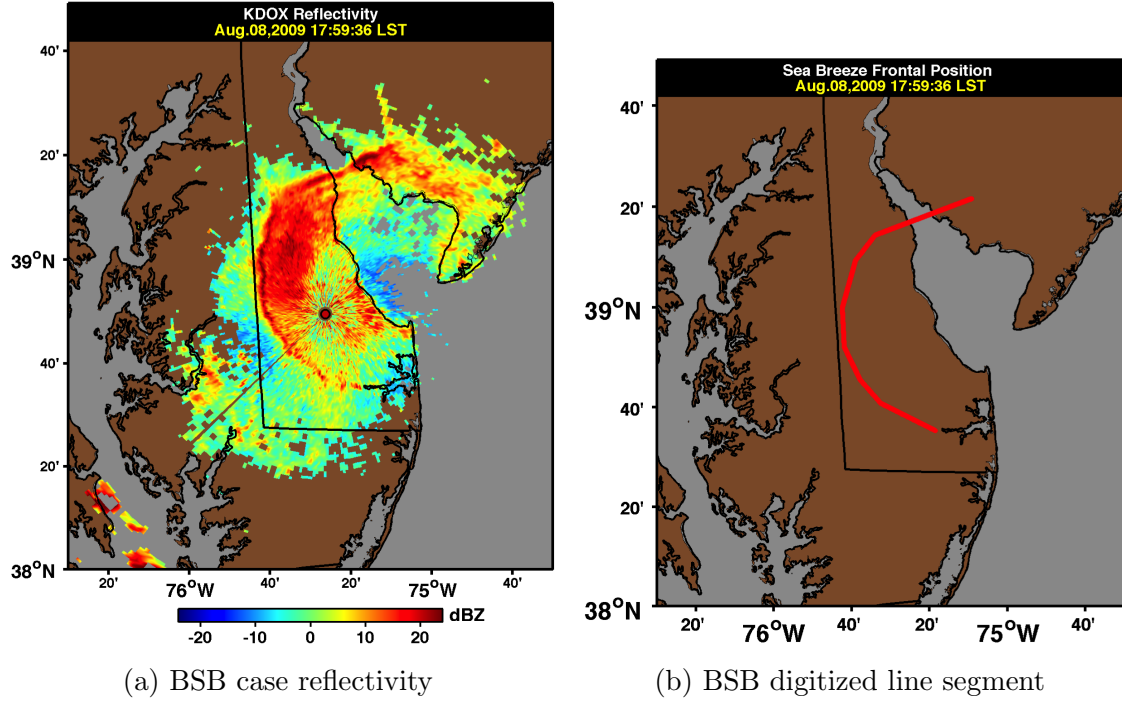


Figure 4.9: BSB reflectivity and interpolated digitized line segment

4.2.5 Correlating front characteristics with environmental variables

To further examine the relationship the SBB front has with it's surrounding environmental conditions, 4 observations stations were chosen to represent 4 different regimes that could influence the SBB front. These stations were comprised of 2 DEOS stations and 2 NDBC stations to represent an inland, coastal, Delaware Bay, and the coastal ocean regimes. The inland station was DLAU because it is near the center of the Delmarva Peninsula and for it's good data coverage for the entire study period. DBNG was chosen as the coastal

Table 4.3: Classic SB and BSB radar derived averages

Parameter	Classic Averages	BSB Averages	Delta
$t_{initial}$	12:50 LST	13:50 LST	00:50
t_{final}	18:40 LST	20:10 LST	01:30
Duration	05:50	06:30	00:40
Speed	2 ms^{-1}	3 ms^{-1}	1 ms^{-1}
Penetration Distance	61 km	71 km	10 km
Dominant Synoptic Type	3032	3035	NA

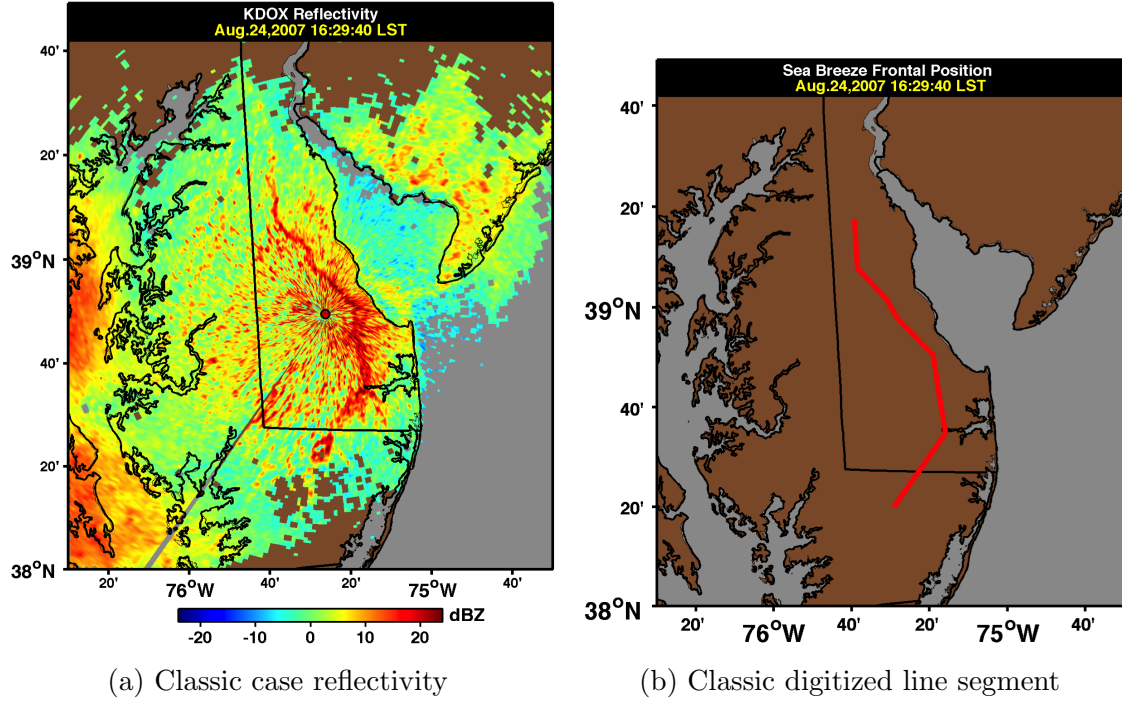
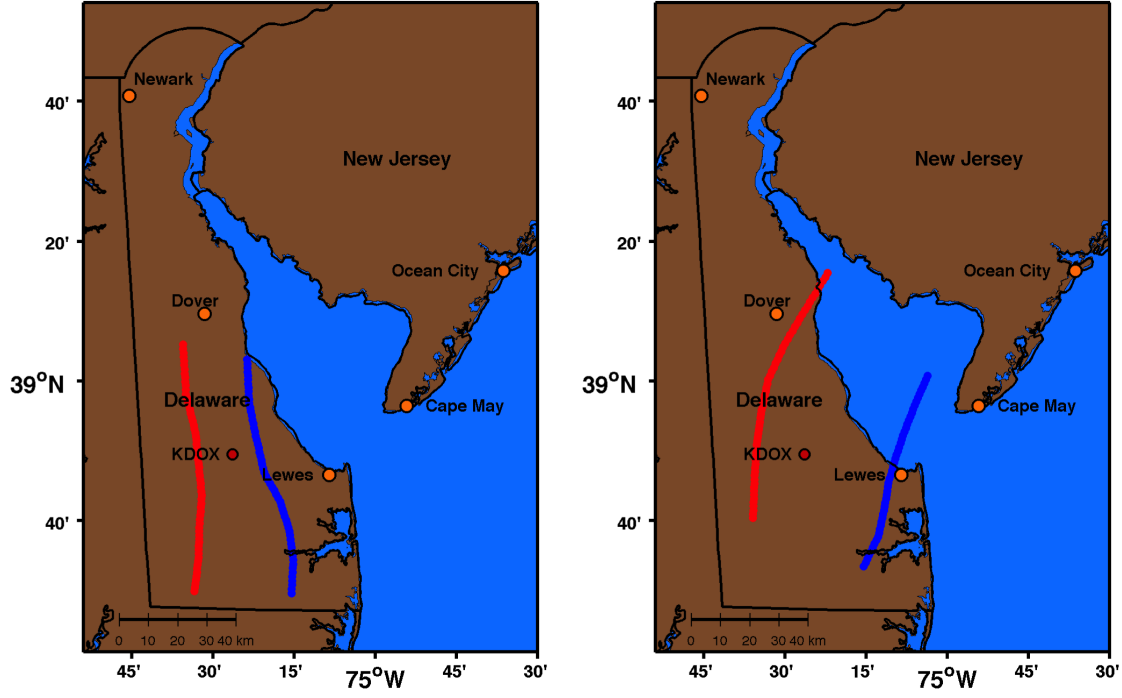


Figure 4.10: Classic reflectivity and interpolated digitized line segment

station due to it's proximity to the ocean. The Delaware Bay station, BRND1, is located just inside the mouth of the Bay at the Brandywine Shoals lighthouse. This is ideally located to represent the bay because it's nearly centralized location between Delaware and New Jersey coastlines. Also it's very close to the mouth of the bay near the area that the false coastline develops. The ocean station was chosen to be buoy 44009. This buoy managed by the NDBC resides 30 km off the southeastern coast of Delaware. Utilizing the meteorological data collected at each location, relationships between radar derived inland penetration, average front speed, and with other environmental variables can be inspected.

The first relationship examined the maximum inland penetration and along-front speed. Figure 4.12 shows some indication that the faster a front is moving the deeper front is likely to penetrate. With the markers colored by month it is possible to see that SBB front that occur in July follow this linear relationship the best and August having the largest



(a) An average of the digitized classic SB frontal positions (b) An average of the digitized BSB frontal positions

Figure 4.11: Classic SB vs BSB mean positions

amount of variability. It is no surprise that May and September see slower and more shallow penetrating SBB fronts due to the stronger prevailing synoptic wind. Interestingly, the relationship between inland penetration and front speed for the classic SBB days, figure 4.13, were not as well correlated as the BSB samples show in figure 4.14. When the SBB front is over land it experiences more surface friction which could slow the propagation speed of the front. In addition, the position can be mistaken due to the fact that a signal can be produced from the thermals generated by a very hot road. Those thermals can create very strong gradients in refractive index resulting in radar returns.

One reason for inspecting such relationships is to observe any possible atmospheric pre-conditioning that could affect the SBB front motion. Based on the classic sea breeze theory, it should be expected that prior of the development of the SBB, there may exist

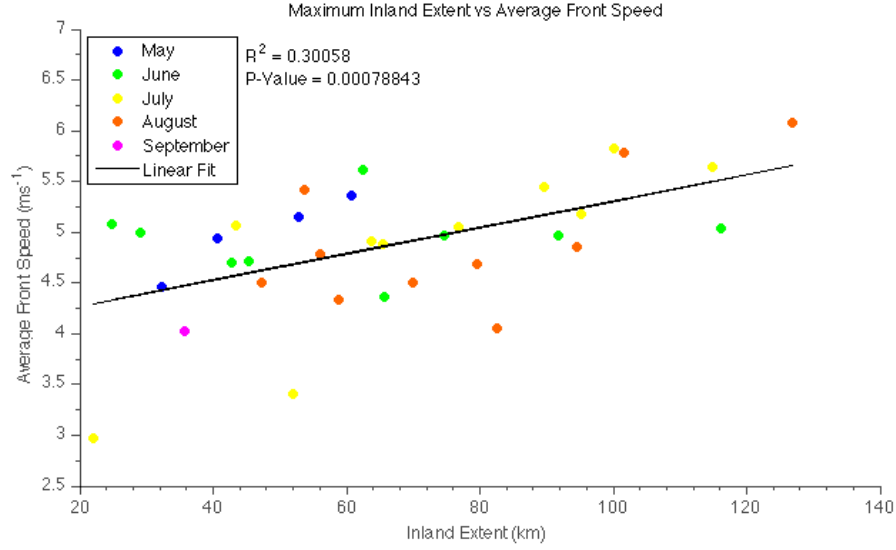


Figure 4.12: Relationship between along front speed and maximum inland penetration

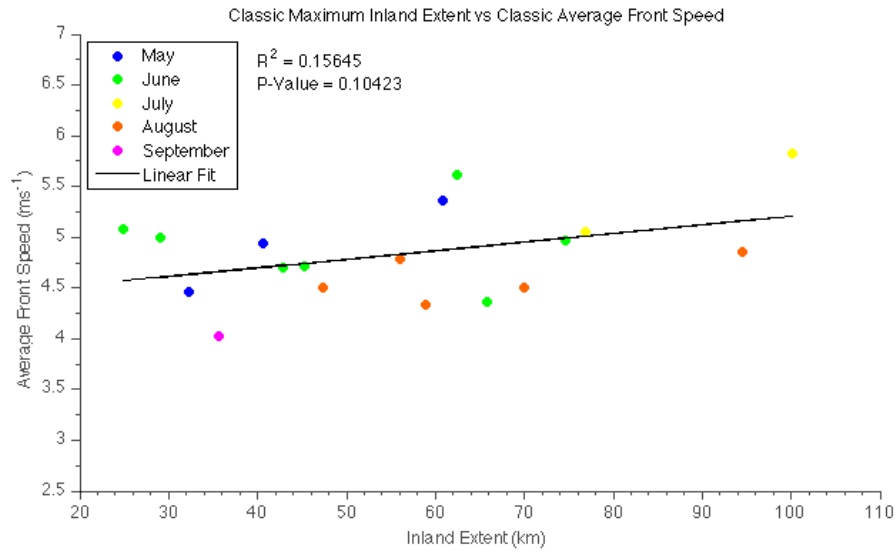


Figure 4.13: Significant correlation between front speed and inland penetration

a temperature gradient between the coastal and inland stations that may be influential in the characteristics of the SBB circulation. Figure 4.15 inspects the normalized differential minimum temperature between DLAU and DBNG. The temperatures at each station were normalized by their respective monthly mean 06:00-08:00 temperature. The temperatures

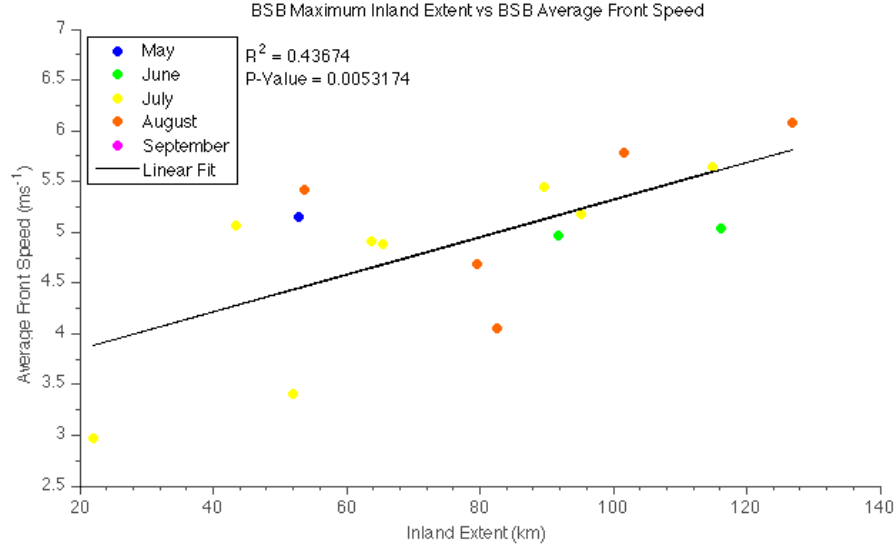


Figure 4.14: A hint of a relationship between front speed and inland penetration

are normalized in order to remove seasonal variability. This relationship shows that a SBB front moves faster on days when the difference of the overnight low temperature between the coast and inland is smaller. In other words, the more homogeneous the air-mass is over the land, the faster the SBB front moves. Another interesting feature is relatively large variability in June and August. It's possible that this variability could be a function of less stagnant synoptic patterns, similar to those found in May and September, affecting the cases in the beginning of June and the end of August.

Interestingly, there is not a strong relationship between inland (DLAU) stations high temperature anomaly and inland penetration. The high temperature anomaly was calculated using the high temperature at the DLAU station divided by the average high temperature for that particular day of the year. The purpose of this anomaly was to remove the seasonal signal embedded in the sample since the majority of the events occurred in the warmest summer months. Logically, the warmer the land mass, the stronger the SBB circulation should become. This is due to the enhanced upward motion and resulting more intense localized

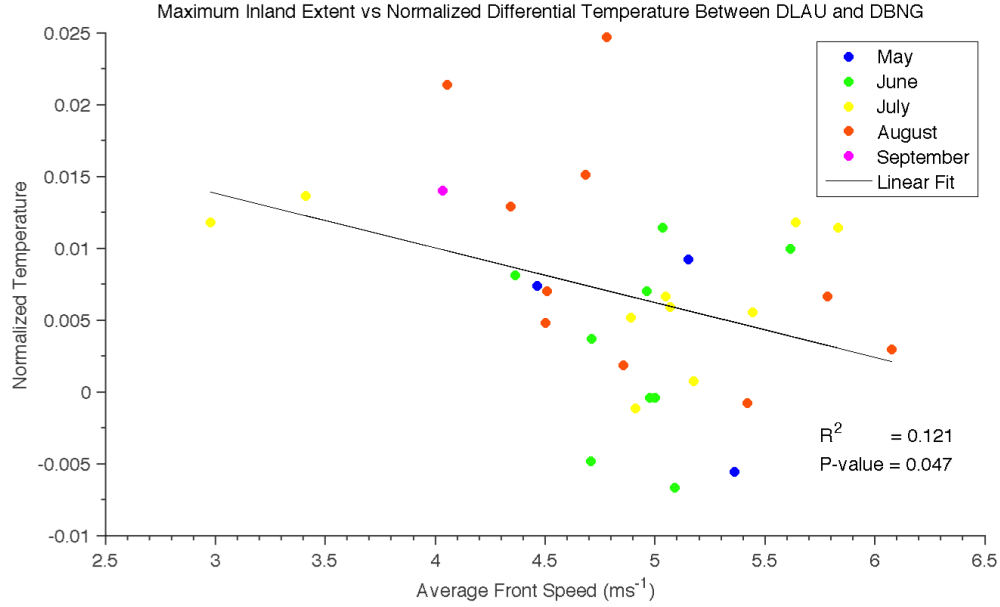


Figure 4.15: Relationship between maximum inland penetration and normalized differential low temperatures from DLAU and DBNG

low pressure. This enhanced upward motion should produce an environment that should be conducive to longer lasting SBB circulations, and deeper penetrating SBB fronts.

A similar comparison was made between the morning average temperature from buoy 44009 and DBNG. A relationship was not found it could be due to the fact that the SBB is more sensitive to upwelling closer to the coast. Upwelling can occur less than 10km from the coast, in which case the air temperature at buoy 44009 would not be affected as severely as the air closer to the coast.

4.3 Summary

This chapter characterizes the Delaware SBB fronts as observed by the KDOX NEXRAD platform. On average the SBB front becomes visible at 13:20 LST and has an average duration of a little over 6 hours. The average speed of all the fronts sampled was 2.5 ms^{-1} and on average penetrated 66 km inland. Of these cases the Classic SBB front were typically

visible an hour earlier than the BSB cases. The BSB cases were found to last longer by 37 minutes and penetrate nearly 20 km further inland than the classic cases. The classic SBB has some other interesting characteristics such as it's ability to initiate convection. This typically happens in July and August but it a pretty rare event that is only visible using radar. Another interesting characteristic is it's interaction with the Chesapeake Bay breeze front. This is an even more rare phenomenon. The most rare occurrence was the development of the SBB front behind and existing SBB front. This only happened once over the course of this study.

Lastly, relationships between environmental and radar derived variables show that there are many hidden complexities in the atmospheric pre-condition of the SBB circulation. The SBB front tends to penetrate further inland when the airmass over Delaware does not have a pre-existing temperature gradient between the coastal station and inland stations. Interestingly, there was little relationship found between the morning minimum temperature at buoy 44009 and the coastal station (DBNG). These two results may show that the time-scale for SBB pre-condition is shorter than 4 hours.

Chapter 5

SUMMARY AND CONCLUSIONS

This study provides a synoptic characterization of the Delaware SBB circulation using the KDOX WSR-88D radar platform and a conglomeration of other environmental observing systems for May through September from 2007 to 2011. The local meteorological observational network utilized for this study was DEOS and NDBC. A sea breeze detection algorithm was used to identify days that a sea breeze was identifiable in the DEOS time-series of wind speed, direction, and temperature. The NEXRAD data from the resultant dates from the algorithm were visualized for manual identification of SBB fronts over Delaware Bay. Utilizing this method 327 fronts were confirmed using the radar making the average success rate of the SBB detection algorithm 56%. July had the largest number identified SBB fronts. The largest source of error for the algorithm was the occurrence of COBs. The second source of error was the occurrence of backdoor cold fronts during the time of peak heating. Both COBs and backdoor cold fronts look very similar to SBB fronts when inspecting them using surface, temperature, dew point, wind speed, and wind direction data. There existed some inter-annual variability where the summer of 2010 had the most SBB fronts and the summer of 2009 has the least SBB fronts. The lack of SBB in 2009 can be explained by abnormal large amount of rainfall. Rainfall and cloud cover decreases the differential temperature between land and sea below what is needed to support a SBB circulation. Utilizing the 327, radar verified SBB fronts, two distinct types of SBB fronts were identified.

Delaware's most common SBB front was called a "Classic" SBB. This type of front exhibited a SBB front moving inland from either the Atlantic or Delaware Bay coast. This

type of SBB most commonly occurs when the dominant synoptic wind is from the southwest and there is an approaching cold front from the west. This synoptic pre-condition is one of the most influential factors on SBB development. This synoptic pre-condition also has an affect on the local SST of the Delaware Bay and the coastal ocean. Classic days typically have the coldest coast waters with an apparent cold tongue that extends axially up the bay. The existence of this cold tongue is important for the development of a SBB front from the bay coast. Another interesting characteristic of Classic SBB fronts are there ability to generate convection as they propagate inland. SBB initiation of convection is a rare event to identify using the NEXRAD platform. Only 12% of the SBB fronts observed in this study triggered convection. This may be slightly bias due to the fact that some SBB fronts don't have a high enough vertical extent to be detected or they are too far from the radar.

The second, more rare, SBB front observed was named a “Bay Sea Breeze (BSB)” front. This SBB front develops over the Delaware Bay and typically propagates up estuary. The synoptic situation most common for this type of SBB front is a trough over the southern states and a ridge over Delaware. Based on the isobar orientation, the synoptic wind direction for these case is from the northwest to north-northwest and is typically very light. The initiation point, as determined using radar, is normally well correlated with a steep, horizontally oriented, gradient in SST. This thermal front mimics a coastline and supports a near surface thermal gradient between the air above the colder shelf waters and warmer bay waters. It has not been confirmed that the false coastline must be present in order to have a BSB front This distribution of water masses in the Delaware Bay is not well correlated with Delaware River discharge into the bay or the dominant M_2 tidal constituent. These SBB fronts take on a concave shape as they travel up estuary. On average the BSB fronts initiate later than classic fronts, but are longer lasting and deeper penetrating.

Amongst the classic and BSB events there were a few cases that featured other interesting characteristics. The first set of events were the cases where the Chesapeake bay breeze front collides with the Delaware Bay SBB front. This is a very rare event that occurred twice over the course of the data set. The first occurred during a BSB and the second occurred during a classic SBB. Another interesting observation was that each front propagated in the exact opposite direction as the on coming front. Another rare, and interesting case is the double SBB front. The double front case shows how complex the SBB circulation can be.

For SBB front speed and inland penetration measurements, a sample of classic and BSB days were digitized and linearly interpolated to represent the each fronts location as a function of time. The along-front speed and inland penetration for each case were found to be related in that the faster the SBB moves, the further inland it is likely to penetrate. It was also found that there was a slight relationship between the along-front propagation speed and the normalized differential temperature between the inland station (DLAU) and coastal station (DBNG). This relationship shows that a pre-existing thermal gradient between the coastal station and inland station does not result in a faster moving front. This is a sensible result because the SBB circulation thrives off of strong thermal gradients and the resulting pressure differences.

5.1 Future Work

There is still much to be learned about the Delaware SBB circulation. The incorporation of NEXRAD into these studies makes it possible to inspect the SBB front on a much larger scale. To build on the above study, the New Jersey NEXRAD radar platform located at Fort Dix (KDIX) and mesonet can be included into this studies methodology to study the SBB fronts on a much larger scale. Little is known about how the Delaware BSB and the New Jersey sea breeze circulation interact.

Automated detection and digitization of the SBB front using radar reflectivities would greatly decrease the analysis time. It would also provide a higher resolution digitization of the SBB front which would increase the precision of the front speed and inland penetration measurements. In order to train such an algorithm a less complex coastline would be ideal. The New Jersey coastline would be ideal with the KDIX WSR-88D platform located close enough to the coast to detect SBB fronts. This automated detection could be implemented using commercial code called “correlCorresp,” which is a software package normally used for pixel tracking. To utilize this code, each time step of each event must to be converted into a raster and filtered to remove any non-front related scatter. Once sent through the code the results will be in a raster coordinate system and will have to be converted back to a geographic coordinate system to calculate distance traveled and speed. This increase in precision could also improve correlations between frontal characteristics and environmental variables such as temperature, wind speed and wind direction.

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