

**DETECTION AND ANALYSIS OF SEA BREEZE AND
SEA BREEZE ENHANCED RAINFALL:
A STUDY OF THE FLORIDA AND
DELMARVA PENINSULAS**

by

Daniel P. Moore

A thesis submitted to the Faculty of the University of Delaware in partial
fulfillment of the requirements for the degree of Master of Science in Geography

Summer 2019

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ACKNOWLEDGMENTS

Dana E. Veron, PhD for her constant support and encouragement.

My thesis committee for sharing their wealth of knowledge and expertise.

The Delaware Environmental Observing System, Florida Automated Weather Network, National Data Buoy Center, National Center for Environmental Prediction, University Corporation for Atmospheric Research, National Oceanic and Atmospheric Administration, and the Florida Department of Environmental Protection all for providing data to make this thesis possible.

The folks at Unidata, namely Sean Arms, PhD. and Ryan May, PhD., for maintaining (and upgrading) their servers to ensure I had consistent access to the radar data archive.

The Department of Energy Grant DESC0016605 and the University of Delaware Department of Geography for funding my education.

This thesis is dedicated to:

My friends and family, who have been with me every step of the way.

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ABSTRACT

The sea breeze circulation is a local phenomenon that can greatly impact the climate of coastal regions. Especially during the warm season, sea breezes influence near surface wind direction and magnitude, temperature, and alter, or even enhance, precipitation patterns. The location and timing of the sea breeze circulation affects wind and water resources, air pollution transport, and tourism. The leading edge of the circulation, or sea breeze front, is associated with enhanced uplift due to warm air buoyancy. Under certain environmental conditions, this uplift can lead to convective activity, greatly influencing summertime precipitation in coastal areas.

The purpose of this thesis, which consists of an introduction, two papers, a conclusion and an appendix, is to investigate the sea breeze circulation, specifically as it affects summertime precipitation in two coastal regions: Florida and Delaware. A state-of-the-art radar detection algorithm is introduced and employed in the first paper to study ten years (2009-2018) of summer (JJA) days in these two regions. We evaluate the characteristics of strong sea breeze fronts that are most likely to affect precipitation intensity and coverage. Analysis of the Dover, DE and Melbourne, FL study regions show that sea breezes associated with intense precipitation develop greater vertical extent closer to the coastline, and penetrate further inland compared to sea breeze days with no precipitation.

In the second paper, we take a regional approach to study the impact of the summertime sea breeze on precipitation patterns on the South Florida Peninsula. Station data are employed to characterize days based on sea breeze occurrence. Then,

precipitation frequency and amount on these days are analyzed and compared. Finally, we investigate environmental conditions, such as synoptic wind flow and coastal surface water temperatures, to better understand the environment within which the sea breeze develops and influences local weather, particularly precipitation. Results show that sea breeze significantly increases precipitation over Florida's agricultural lands where summertime precipitation is needed for crop growth, especially on days with sea breeze occurrence along both the east and west coasts of the peninsula. Synoptic flow direction and magnitude influence sea breeze occurrence, in addition to the location and probability of precipitation in the study region. Further analysis to understand the role of surface water temperatures on sea breeze occurrence, and thus precipitation, especially along the eastern coast where the Gulf Stream affects near land water temperatures is recommended.

Results presented in this thesis suggest that environmental conditions affect sea breeze characteristics and their ability to enhance or alter precipitation in coastal regions. The novel sea breeze detection algorithm presented here can be employed to study sea breeze circulations in any region where coastal radar data are available. Further, this study informs stakeholders interested in water resource management as to the physical mechanisms that influence summertime precipitation in these two study regions. Improved understanding of the summertime precipitation can lead to better economic decision making by farmers and water managers and enhanced preparation for a changing climate.

Chapter 1

INTRODUCTION

1.1 Research Questions

Local weather patterns are influenced mainly by synoptic conditions and surface heterogeneity. One example is the sea breeze circulation (SBC), which results from the differential heating of the land and sea surfaces. The Delaware-Maryland-Virginia (Delmarva) and Florida Peninsulas regularly experience SBC during the warm season, affecting local climate, air quality, energy supply and demand, and tourism in the region. Given certain environmental conditions, SBC influence convergence and convective activity, resulting in precipitation. The impact of SBC on precipitation has implications on the hydrologic cycle in coastal areas.

The research described in this thesis characterizes spatial variation of SBC and improves understanding of the subsequent role that SBC plays in precipitation events. Previous studies conducted on the sea breeze utilize automatic meteorological station detection (e.g. Frizzola and Fisher 1963; Hughes and Veron 2018; Cetola 1997; Crouch 2006), which can have low spatial resolution, or manual detection using radar and/or satellite data (e.g. Planchon et al. 2006; Gilchrist 2013; Vemado and Pereira Filho 2016). However, the literature lacks methods to automatically detect and analyze sea breeze fronts (SBF) using weather radar data, which could assist in detailed studies of SBF variation and dynamics, as well as improve current SBC climatologies. Similarly, the Florida sea breeze has been thoroughly analyzed for over 70 years mostly at a local scale (e.g. Byers and Rodebush 1948), however, a quantification of

its effect on precipitation and the resultant hydrology is lacking at the regional scale (Rickenbach et al. 2015).

This thesis addresses each of these gaps through the following research questions:

1. What are the characteristics of strong sea breeze fronts that lead to precipitation?
 - i. Do characteristics of the sea breeze circulations that lead to convection and precipitation differ between the two study regions (e.g. Florida and Delmarva)?
2. To what extent does the sea breeze circulation impact summertime precipitation in Florida?
 - i. What are the environmental conditions that contribute to SBC-related precipitation events?

Chapter 1 will highlight the background information on the SBC and its importance to coastal regions. Following this, the second chapter makes use of widely available radar reflectivity data to detect and track the SBF in two study regions (i.e. Melbourne, Florida and Dover, Delaware). A state-of-the-art automatic detection algorithm utilizes image-processing and spatial analysis techniques to study the movement of the SBF using these radar data. Chapter 3 analyzes the precipitation related to the Florida SBC using several observational datasets including meteorological stations, soundings, and statistically merged multi-sensor systems, in addition to surface water temperature from buoys. These data characterize sea breeze days that result in precipitation events in order to better understand the role that the Florida SBC plays in influencing summertime precipitation on the Peninsula. Finally, Chapter 4 summarizes the findings of the studies presented in this thesis and recommends future research to extend these results.

1.2 Background

The SBC is a mesoscale phenomenon in coastal regions that develops as a result of the differential heating of land and water (Simpson 1994). Water has a higher heat capacity than land, thus the solar energy input after sunrise heats the land and water at different rates, creating a low-level pressure gradient force as continental air heats and begins to rise, leaving a localized low-pressure over land, and a high-pressure over the water. The rising warm air is replaced by cool, marine air flowing in over the land surface. An upper-level return flow, which can precede, follow, or act in unison with the low-level onshore flow (Miller et al. 2003) completes the SBC (Figure 1.1).

The leading (most inland) edge of the SBC is referred to as the sea breeze front (SBF). This is the boundary where the marine air encounters the rising continental air prior to mixing and/or circulating back over the water in what is known as the return branch. Often, the SBF is identified observationally by a significant change in humidity and temperature as air properties change. Friction from the surface and/or the prevailing winds cause the rising air at the SBF interface to lag behind the advancing front and mix with the dry air aloft, forming the sea breeze head. Further turbulence throughout the return flow aloft creates Kelvin-Helmholtz billows (Figure 1.2).

The formation and development of SBC is largely based on the temperature difference between the land and water. As little as a 1°C gradient between the land and sea surface temperatures is enough for the formation of a SBC (Watts 1955). A larger land-sea temperature gradient is associated with greater SBF propagation velocity and, ultimately, propagation distance. For instance, Barry and Chorley (1992) found that the Australian sea breeze could penetrate as much as a 200km inland from the coast where land-sea temperature gradients were very large. Similarly, on the northern coast

of Brazil, the seasonal formation and propagation of the SBF were largely reliant on the temperature gradients (Planchon et al. 2006).

1.3 Importance of SBC and SBC-Related Precipitation

The presence of the SBC can significantly alter local weather, such as coastal winds and convective activity. Sea breeze-related precipitation can result in significant rainfall for coastal regions in a short amount of time, impacting the hydrology of urban and rural areas alike. A better understanding of environmental conditions conducive to these events will lead to improved forecasting of the timing and location of these storms, which will serve planning officials and stakeholders. Additionally, the SBC plays a vital role in pollutant transport, both improving air quality by the influx of pristine marine air, and depleting it by preventing mixing outside of the circulation itself (Papanastasiou and Melas 2009; Levy et al. 2009; Simpson 1994). In addition, understanding SBC can improve our assessment of offshore and coastal wind energy resources, decreasing our reliability on non-renewable energy. Finally, better forecasting of these diurnal events will assist in disaster response and recovery situations.

1.3.1 Hydrology of Coastal Regions

Low-level atmospheric convergence initiated by the SBC can influence the development of afternoon thunderstorms (Pielke 1974). On peninsulas, SBFs from opposing coastlines can converge and result in significant local precipitation during the summer months (Nicholls et al. 1991). However, the contribution of the SBC to the overall precipitation climatology of a given region is difficult to quantify (Rickenbach et al. 2015). In Florida it is clear that in the summertime there is a

significant contribution of non-mesoscale convection to the seasonal precipitation, some of which is SBC driven. Although the precipitation climatology of Delaware does not show significant seasonality, convective precipitation in this region can also result from the SBC (Gilchrist 2013).

From disease prediction to in-season water management decisions, agriculture is one of the industries most affected by weather and climate variation (Taylor 1967). For example, crop type and field patterns are chosen primarily on the climatology of the agricultural region (Knox et al. 2014). Rainfall is a major input for any crop, and thus the characterization of sea breeze-related precipitation during the growing season is of great interest to agricultural stakeholders where non-organized convective systems contribute significantly to warm season precipitation. A farmer relies on accurate daily weather forecasts to determine water resource management and to prepare for extreme events such as drought or flooding.

As urban areas and the presence of impervious surfaces increase, coastal towns will be more prone to flash floods with severe weather events. When coupled with the urban heat island (UHI), SBC can result in intense convective precipitation events (Freitas et al. 2007; Vemado and Pereira Filho 2016). A better understanding of the atmospheric conditions conducive to producing such events will lead to improved forecasting to prepare for changes in coastal climate, both rural and urban.

1.3.2 Air Pollution

Throughout the United States, many cities suffer from poor air quality and the state of Delaware is no different. For 19 consecutive years New Castle County, the northernmost county in Delaware, has received a failing grade during the American Lung Association's annual State of the Air report on ozone levels (American Lung

Association, 2018). Increased levels of ozone and other particulate matter can have serious negative effects on the community, specifically on those with respiratory illnesses.

The SBC plays an important role in the transportation of air pollutants such as ozone (Ding et al. 2004). The sea breeze is comprised of marine air that may be less polluted during the summer than the terrestrial air, and can circulate the pollutants to new locations, either further inland or back to sea. In North Carolina, the SBC has been identified as a large source of uncertainty for the dispersion and deposition of potentially harmful pollutants, although observations show a clear seasonality (Rhome et al. 2003). Rhome et al. (2003) showed that during the summer, SBC also plays a key role in the localized deposition of agricultural particulate matter. The stability of the SBC's return flow can also act to contain any pollutants within the boundary layer, preventing outflow and reducing surface air quality (Simpson 1994). In contrast, convective activity enhanced by the SBC has the ability to lift particles and detrain them high in the atmosphere, and/or supply a means for wet deposition through precipitation, which both improve surface air quality.

The population of the Delmarva Peninsula increases significantly due to tourism during the summer months when both airborne ozone concentrations and SBC frequency increase. As urbanization, and consequently, coastal population increases, improved understanding of SBC dynamics under certain environmental conditions are critical to human health in these regions.

1.3.3 Wind Power

As the global population increases, so does the need for reliable energy sources. Furthermore, a shift away from fossil fuel use and toward power generation

from renewable technologies is necessary to decrease the rate of GHG emissions and wean society's reliance on a diminishing fossil fuel supply. In 2017, 37 states in the US had established near-future renewable energy targets to decrease reliance on fossil fuels (Renewable Portfolio Standards, 2017). Wind power is a viable option for renewable energy generation in certain regions, especially in the mountains and in coastal areas. Offshore wind power projects are being pursued in several locations along the East Coast of the United States, including three within 30 miles of the Delaware coastline, which are set to be producing power as early as 2020 (Figure 1.3; US Wind 2019).

The SBC can greatly affect wind direction and wind speed along the coastline. Diurnal changes in offshore winds related to the SBC have the potential to increase or decrease energy potential depending on the predominant wind direction. Hughes and Veron (2015) developed a low-level wind climatology for coastal Delaware and then further explored the characteristics of the Delaware sea breeze (Hughes and Veron 2018). The dynamics of the SBC and its effect on coastal wind resources are important to optimizing wind energy production.

1.3.4 Disaster Response and Recovery

The Delaware River, at the north end of the Delaware Bay, is a high-volume oil port where at least 27 significant oil spills occurred since 1974 (Linton et al. 2010). Low-level winds in coastal regions can greatly affect response to and cleanup of these events, as they can influence surface transport of contaminants. As such, better forecasts of SBCs during these efforts will accelerate containment and mitigation. Similarly, search and rescue missions will benefit from real-time forecasts of low-level coastal winds during such missions.

1.4 Sea Breeze Detection

Many detection methods characterize and track SBC propagation, providing a rich literature and numerous options for detection methodologies using meteorological stations (e.g. Crouch 2006; Hughes and Veron 2018; Papanastasiou and Melas 2009), radar (e.g. Achtemeier 1991; Atlas 1960; Luchetti et al. 2017; Simpson 1967; Suresh 2007; Wilson et al. 1994) and satellite (e.g. R. Pielke 1974; Planchon et al. 2006; Vemado and Pereira Filho 2016). Most previous studies employ at least two meteorological stations, one coastal and one inland, and use the comparison between the two to indicate SBF passage.

1.4.1 Station Detection

Meteorological station data are used to identify surface properties and track how they change during SBF passage (Figure 1.4). First, onshore winds are expected, as suggested by the definition of the SBC (e.g. Watts 1955). Additionally, when a marine air mass replaces a terrestrial air one, environmental conditions change. For instance, generally when a sea breeze passes, a decrease in temperature coincides with an increase in humidity (Miller et al. 2003).

Although, most SBF station detection methods are dependent upon the orientation of the coastline and the temperature gradient by which the SBC forms, the same environmental variables signify its presence. Typically, the following conditions (from Papanastasiou and Melas 2009) must be met for sea breeze occurrence:

- The wind blows onshore for several hours consecutively during daylight hours.
- The wind blows offshore for the majority of hours from sunset to sunrise.
- The wind at 850 hPa pressure level blows offshore during daytime.

- The daily maximum air temperature over land is higher than the sea surface temperature.

Most detection methods include surface-level winds, as surface-level onshore winds define a SBC, and low-level atmospheric wind vector to ensure surface-level onshore flow is not caused by synoptic forcing, in addition to land-sea temperature gradients. The current study utilizes methods similar to Hughes (2011) and Hughes and Veron (2018) to detect and characterize the Florida sea breeze, which expand on the criteria above.

1.4.2 Radar Detection

Initially used for tracking aircrafts, radar systems were soon recognized as powerful tools for making meteorological observations (Atlas 1960). High-frequency radiation emitted from the radar antenna is reflected when the emitted signal encounters an object. The radar emits radiation while rotating in scans around a vertical axis at wavelengths around 10 cm. The beam then scatters in all directions with a portion of it reflected back to the antenna and detected by the receiver. Reflections from objects that are small in radius relative to the radiation wavelengths, i.e. raindrops (1 mm), provide a strong enough signal to the antenna to be detected (Bacon 1962). The returned radiation power is used to calculate the reflectivity of the detected object using the radar equation:

$$\bar{P}_r = \frac{P_t G^2 e^2 H_x \pi^3 K^2}{1024 (\ln 2) \lambda^2} \times \frac{Z}{R^2} \quad 1.1$$

where P_r is the average return power of the radiation received by the antenna, Z is the reflectivity of the target, from which we can derive number and size of the target, and R represents the radial distance to the target. P_t is the transmitted power, G is the

antenna gain, e is the beam width, H_x is the pulse width, K is a physical constant, and λ is the wavelength of the radiation, in meters.

For the purposes of this study, the most important variable derived from radar scans is the reflectivity (Z), which can be related to rain rate by the following equation:

$$Z = a R^b \quad 1.2$$

where Z is the reflectivity in dBZ and R is the rain rate in mm h⁻¹. Since the 1960's, this relationship has been employed to relate weather radar reflectivity to rain rate (e.g. Fujiwara 1965); however, exact values of empirical constants ' a ' and ' b ' have been disputed (Joss and Waldvogel 1969). WSR-88D radars such as the NEXRAD radars used in this study at Dover (KDOX) and Melbourne (KMLB), utilize the accepted values of $a=300$ and $b=1.4$ (Lakshmanan et al. 2007). In general, the reflectivity thresholds for stratiform and convective precipitation are $Z > 15$ dBZ and $Z > 40$ dBZ, respectively (Anagnostou 2004).

As remotely sensed data have become more available in the last half century, satellite and radar reflectivity data have been used, in addition to station data, to analyze and track SBF propagation in many coastal regions (Figure 1.5; e.g. Atlas 1960; Keeler and Kristovich 2012; Simpson 1967; Vemado and Pereira Filho 2016). Initially, weather radar reflectivity was used to detect SBCs and relate SBC case studies to synoptic patterns (Atlas 1960; Simpson 1967). Since then, many studies have investigated meteorological conditions using radar systems (Lhermitte and Gilet 1975; Sauvageot and Omar 1987; Wilson et al. 1994; Keeler and Kristovich 2012). Additionally, aerosols such as sea salt, insects, and other biota have been observed in

radar return signals and used as tracers (Campistron 1975; Achtemeier 1991; Wilson et al. 1994).

Achtemeier (1991) confirmed that the increase in radar return power due to passive tracers like insects is especially apparent in regions of updrafts where the entrainment is strongest. This phenomenon has been used to track the propagation of SBF in Brazil (Planchon et al. 2006; Vemado and Pereira Filho 2016), Southern Peninsular India (Suresh 2007), Florida (Lhermitte and Gilet 1975), Delaware (Gilchrist 2013), and Eastern North Carolina (Luchetti et al. 2017).

1.5 Precipitation Detection and Characterization

Typically, precipitation is characterized by the type of clouds that generate the precipitation, either stratiform or convective, and by the precipitation phase and intensity. Numerous studies have attempted, with varying success, to separate rainfall into these two categories using data from models (Li et al. 2014), satellites (Hong et al. 2004; Kummerow et al. 2001, 1996), weather radar (Anagnostou 2004; Biggerstaff and Listemaa 2000; Steiner et al. 1995; Lhermitte and Gilet 1975), and precipitation gauges (Nystuen 1999; Woodley et al. 1975).

The National Centers for Environmental Prediction (NCEP) produces a precipitation product that utilizes both gauge and radar data. The Stage IV, 4-km, gridded and gauge-corrected radar precipitation dataset covers the contiguous United States, in addition to Alaska and Puerto Rico. Regional, hourly multi-sensor precipitation estimates (MPEs) are archived and quality controlled by 12 River Forecast Centers (Lin and Mitchell 2005).

Each method of precipitation detection has its own unique benefits and drawbacks. The major limitation of the precipitation gauge as a tool, for instance, is in

its spatial nature. As a single point measurement, precipitation gauges often miss isolated precipitation events, such as those that occur during unorganized convective activity. Further, when multiple gauges are used together in a mesonet, such as the Delaware Environmental Observing System (DEOS), small storm cells can pass between the sensors (Figure 1.6). Additionally, precipitation gauges are normally located on land and in populated areas leaving a significant portion of the world unobserved by autonomous weather stations.

Active and passive sensors, such as radar and satellite remote sensors, have their own limitations as well. As most radar systems are land-based, the same issue of global coverage exists. Polar orbiting satellite sensors have the unique ability to sense the entire globe over any given day, although the temporal resolution is poor due to the characteristics of the polar orbit. Geo-stationary satellites, or those that do not orbit the earth, remain fixed over a given position with high spatial and temporal resolution. The major issue with satellite-derived precipitation products is that they use cloud-top radiance as a proxy for precipitation intensity because of the impenetrability of clouds to the transmitted wavelengths (Hou et al. 2014). This leads frequently to an underestimate of precipitation (e.g. Ringard et al. 2015).

1.5.1 Precipitation Gauge

Fixed, surface-based precipitation gauges have been shown to be effective in various rainfall conditions (Nystuen 1999), however, the tipping bucket rain gauge, which is used by DEOS, tends to underestimate intense rainfall (Nystuen 1999). This is relevant to the present study as we are seeking to quantify the precipitation attributed to the presence of a SBC, which is often intense. In-situ measurements can

be underestimated both due to the type of sensor and large distance between them. Thus, remote sensing products, such as radar, can be used to fill these gaps.

1.5.2 Radar

Although the in-cloud vertical velocities of particles define rainfall categorically as stratiform or convective (Houghton 1968), this information is not available from current in situ precipitation measurements. Consequently, Steiner et al. (1995) developed a simple computational algorithm to categorize rainfall into convective or stratiform based on the intensity and gradient of the reflectivity from radar measurements. Moreover, if a radar reflectivity of $> 40\text{dBZ}$ was found, it was automatically classified as convective, as such reflectivities are rarely found in stratiform rainfall. A reflectivity value can further be determined to be convective if the reflectivity is high enough to lie above the curve defined by:

$$\Delta Z = \begin{cases} 10, & Z_{bg} < 0 \\ 10 - Z_{bg}^2/180, & 0 \leq Z_{bg} < 42.43 \\ 0, & Z_{bg} \geq 42.43 \end{cases} \quad 1.3$$

where ΔZ is the difference between the reflectivity at a grid point and the background reflectivity, measured in decibels, and Z_{bg} is the background reflectivity in dBZ, averaged over a circle of radius 11km, as defined by the authors. If these criteria were met, then that data point in the radar scan, along with the area surrounding it, would be labeled as convective. The points with reflectivity values that did not satisfy these criteria were labeled as stratiform (Figure 1.7). This likely underestimates the amount of convective precipitation (Biggerstaff and Listemaa 2000).

1.5.3 Satellite & Multi-Sensor Products

Biggerstaff and Listemaa (2000) incorporated upper air observations to improve the radar classification algorithm introduced by Steiner et al. (1995) using bright band fraction, as well as reflectivity gradient and reflectivity lapse rate. The improved algorithm incorporates new volumetric data, modifying approximately 25% of the area in question and 14% of the total rainfall volume, though it varied significantly based on storm type. The greatest correction was seen within the first 100km of the radar location due to the height at which the radar data are gridded (Biggerstaff and Listemaa 2000).

Anagnostou (2004) further altered the original algorithm developed by Steiner et al. (1995) by introducing a detection method of bright band occurrence used by the Tropical Rainfall Measuring Mission (TRMM). Although this method implements satellites, it is statistically more accurate when compared to the methodologies of Steiner et al. (1995) and Biggerstaff and Listemaa (2000). Anagnostou's algorithm has a significantly improved success rate when detecting stratiform precipitation and the false alarm rate is also significantly lower, resulting in a higher overall success rate. However, the probability of detecting convective precipitation using Anagnostou's (2004) methodology is roughly 20% lower compared to the earlier two.

The National Oceanic and Atmospheric Administration (NOAA), in conjunction with the University of Oklahoma, has developed a fully automatic system called the National Mosaic and Multi-sensor Quantitative Precipitation Estimate (QPE) System (NMQ) to process raw data from individual radar stations in the United States into several products for the consumption of government agencies and research institutions (Zhang et al. 2011). An important part of creating NMQ data is the development of a gridded mosaic of radar reflectivity values for the continental United

States. Several forms of pre- and post-processing of the data by the NMQ system eliminates ground clutter, resulting in clear precipitation patterns (Figure 1.8). For the detection of the sea breeze, this clutter or ‘noise’ is beneficial as small signals within the reflectivity values highlight its presence.

Further, a separate product by the NMQ categorizes precipitation into stratiform or convective. In a method similar to Zhang et al. (2008), convective precipitation was detected based on radar reflectivity and/or the presence of cloud to ground lightning. This is important because convective rainfall can be the result of a strong SBC. The NMQ datasets are reliable for any region in the CONUS within 230 km of a radar system.

Through the use of these products, a seasonal and diurnal climatology of precipitation for the southeastern United States highlighted the Florida Peninsula as an area of interest (Rickenbach et al. 2015). Their study points to the seasonal presence of unorganized convective activity on the Florida peninsula during the summer months, when SBC would be most active. The NMQ will be discontinued and replaced by the Multi-Radar Multi-Sensor (MRMS) QPE (Zhang et al. 2016). The majority of the algorithms and products remain the same, however the MRMS integrates the NMQ QPE with Warning Decision Support System-Integrated Information (Lakshmanan et al. 2007). These data are not employed by the current study due to data availability across the entire study period 2008 – 2018.

1.6 Relating SBC to Precipitation

Certain meteorological conditions, such as weak synoptic forcing, high land-sea temperature gradients, and atmospheric instability, are conducive to convection initiated by the SBC, resulting in the formation of cumulus clouds and precipitation at

the SBF (e.g. Azorin-Molina et al. 2014; Burpee and Lahiffi 1984; Chen et al. 2016; Lhermitte and Gilet 1975; R. A. Pielke et al. 1991; Suresh 2007; Vemado and Pereira Filho 2016; among others). Synoptic-scale winds also play a key role in the formation and strength of the SBC. Additionally, sea breeze-initiated rainfall can occur in response to significant convective available potential energy (CAPE) in the atmosphere (Luchetti et al. 2017). Moreover, if the level of free convection is low enough in the atmosphere, the uplift at the leading edge of the SBF can be strong enough to initiate convective activity (Luchetti et al. 2017).

Luchetti et al. (2017) provided observational evidence that synoptic flow along the coastline in the northern hemisphere with the land to the left (similar to southerly synoptic winds along the Delaware coastline) is most conducive for sea breeze-initiated convection (Figure 1.9-top). Sea breezes developing under these conditions are called corkscrew sea breezes, in contrast to backdoor sea breezes, which develop under synoptic flow with the land to the right of flow (i.e. northerly flow in Delaware; Figure 1.9-bottom). Additionally, synoptic winds are, on average, much weaker on sea breeze precipitation days when compared to sea breeze events without precipitation (Luchetti et al. 2017).

Convective activity due to the SBC often occurs as isolated thunderstorm cells. Isolated convective systems can be separated from mesoscale convective systems by simple spatial criteria based on the size and reflectivity of contiguous features, as defined by Rickenbach et al. (2015). Areas that experience strong, regular sea breezes, such as Florida, receive a significant amount of annual rainfall from isolated precipitation events. Further, a strong convective cell initiated by a SBF will produce strong downdrafts coinciding with the precipitation. These downdrafts can act as a

lifting mechanism for further convective activity, depending on atmospheric instability. These events are readily seen by radar on the Florida peninsula during the summer months (Figure 1.10; Lhermitte and Gilet 1975).

1.7 Land Surface Heterogeneities and Sea Breeze Enhanced Precipitation

The earth's surface has heterogeneous land cover with unique properties such as roughness, porosity, reflectivity and absorptivity that affect surface heat, moisture and momentum fluxes (Pielke et al. 1999). Consequently, the presence and alteration of the land surface properties are important in predicting the dynamics of weather patterns such as the sea breeze. Soil moisture, land type, coastline curvature, as well as the presence of large water bodies are important surface characteristics to consider when studying the dynamics of the SBC.

1.7.1 Soil Moisture

There is some disagreement about the role that soil moisture plays in influencing mesoscale circulations. For example, Ookouchi et al. (1984) determined that soil moisture gradients alone can produce mesoscale circulations and, consequently, associated precipitation. However, Baker et al. (2000) more recently concluded this is not the case. Their study revealed that although elevated soil moisture could not cause precipitation, when combined with other factors, it could have an influence in strengthening or weakening other circulations. The heaviest precipitation in their study was found where initial soil conditions were the wettest. The high soil moisture enhanced atmospheric humidity through evaporation, ultimately increasing the CAPE over a given region (Baker et al. 2000).

Overall, soil moisture heterogeneities greatly affect the distribution of rainfall (Nicholls et al. 1991). Regardless of crop type, irrigation has become common practice among farmers to regulate soil moisture, combatting drought (Zhang and Lin 2016) and increasing soil salinity (Herrero et al. 2007). In coming decades, the amount of irrigated land across the United States is expected to increase at a steady rate. Consequently, the impact of changes in soil moisture on local and mesoscale circulation patterns should be assessed.

1.7.2 Urbanization

SBC can be positively or negatively affected by interaction with increased urbanization along coastlines (Crosman and Horel 2010). For example, an increase in urban and agricultural areas in South Florida has drastically altered its weather and, moreover, the hydrology of the region (Pielke et al. 1999). Using the Regional Atmospheric Modeling System (RAMS), Pielke et al. (1999) performed three experiments using past (1900, 1973) and present (1993) landscapes. They found an 11% decrease in precipitation in South Florida comparing 1993 and 1900 landscapes for July and August, which experience frequent sea breezes, due to overall surface warming. Similarly, a more recent study has shown that a decrease in natural vegetation leads to a decrease in precipitable water, which can be vital to the climatology of a region (Ryu et al. 2015).

The presence of urbanization along a coastline impacts the genesis and propagation of SBFs and resultant convective activity (Ryu et al. 2016; Vemado and Pereira Filho 2016). The heightened thermal gradient caused by the presence of urban areas can enhance the strength of a SBC event, causing increased convective motion (Crosman and Horel 2010). For instance, in a modeling study using the RAMS model

coupled with the Town Energy Budget urban parameterization, Freitas et al. (2007) found a five-fold increase in vertical motion due to the UHI over the Metropolitan Area of Sao Paulo when compared to the results of a control run without the presence of the urban area. Associated precipitation occurred over the metropolitan area as a result of this increase in vertical motion, whereas the control run lacking an urban area displaced the precipitation further inland, in line with Ryu et al. (2016).

In contrast, by means of increased surface friction, urbanization can also alter the location and intensity of sea breeze-initiated rainfall, having obvious impacts on the region. Such results have been found in New York City (Bornstein and Thompson 1981; Childs and Raman 2005), Houston (Chen et al. 2011), and Hong Kong (Wang et al. 2017).

1.7.3 Coastline Orientation and Curvature

The location of convergence from SBC may largely be affected by coastline irregularities unique to a given location (McPherson et al. 1970; Baker et al. 2000). By means of idealized model runs, McPherson et al. (1970) identified convergence on convex coastlines, and divergence along concave coastlines. In the convex situation, the sea breeze is centralized and converges on a more focused area, leading to a higher potential for convection and resultant precipitation. Coastline curvature also may influence the timing of precipitation (Baker et al. 2000). Convex coastlines experience an earlier peak in precipitation when compared to an idealized straight coastline.

Spatial variations of inland penetration by sea breezes along the northern coast of Brazil can largely be explained by small differences in the orientation of the coastline (Planchon et al. 2006). Subtle differences in temperature gradients and prevailing wind orientation can lead to enhancement or impediment of the SBF. Both

the Delmarva and Florida Peninsulas have complex coastlines, with areas of convex curvature, which may act to enhance convergence and uplift, leading to increased precipitation.

1.7.4 Large Bodies of Water

The presence of significant bodies of water such as bays and large lakes also affects the wind patterns as well as the location and intensity of precipitation events. As with the land-ocean gradient, large bodies of water provide differential heating that further alters atmospheric circulation patterns. Ryu et al. (2016) found that bay breezes from the Chesapeake Bay significantly enhance uplift of preexisting convective storms, altering the location of precipitation. They performed a modeling study using the Weather and Research Forecasting (WRF) Model coupled with the Princeton Urban Canopy Model to simulate a storm with heavy rainfall, and study the land-water interactions in the Baltimore-Washington metropolitan area from both the Chesapeake and Delaware Bays. The authors found that the bay breeze interactions were more influential on the location of precipitation than the presence of the urban area (Ryu et al. 2016).

Lake Okeechobee has a similar impact on the convective activity in Southern Florida influencing the location and timing of convective precipitation due to the presence of the lake breeze (Baker et al. 2000). When lake, bay and ocean breezes interact, a zone of convergence can result in enhanced uplift and increased convective activity (Abbs 1986). This is specifically important for regions that are constrained by water bodies on at least two sides, such as the Delmarva and Florida Peninsulas.

Further, in modeling the formation and propagation of a SBC, representation of the sea surface temperature is important. Fluxes and temperature gradients can play a

key role in local atmospheric phenomena. For instance, using the WRF model, Lombardo et al. (2018) determined that modeled offshore fluxes were sensitive to varying representations of the sea surface temperatures (SST). However, they found that the stability of the marine air may suppress vertical mixing and thus the depth of the SBC.

1.8 Introduction Summary

This thesis is composed primarily of two research chapters, written as papers, that investigate the influence of SBC on water resources in coastal regions. Strong SBCs that initiate as a result of land-water temperature gradients can enhance uplift at the SBF, increasing convective activity (Pielke et al. 1991a) and/or displacing precipitation (Ryu et al. 2016). We employ many data sources, including weather stations, radar systems, gridded precipitation products, buoy stations, and soundings across two study areas to study the effects of strong SBC on precipitation patterns. The first research chapter, Chapter 2, introduces a novel radar detection scheme that increases spatial resolution of SBF detection and tracking given certain environmental conditions. By using this new technique in the areas surrounding the Dover, Delaware (KDOX) and Melbourne, Florida (KMLB) NEXRAD stations, we seek to answer the following questions in Chapter 2:

1. What are the characteristics of strong sea breeze fronts that lead to precipitation?
 - i. Do characteristics of the sea breeze circulations that lead to convection and precipitation differ between the two study regions (e.g. Florida and Delmarva)?

In the second research chapter, Chapter 3, we investigate the role of the SBC on peninsular-scale precipitation patterns in South Florida. We also seek to understand

the role of environmental conditions, such as low-level synoptic-scale flow and surface water temperatures, as they affect the development of the SBC. Chapter 3 investigates the following questions:

2. To what extent does the sea breeze circulation impact summertime precipitation in Florida?
 - i. What are the environmental conditions that contribute to SBC-related precipitation events?

Results from these two papers will inform stakeholders interested in summertime water resources in Florida and Delmarva. We introduce a new method for the detection and tracking of SBFs with a greater spatial resolution than station detection, which can be used anywhere weather radar data are available. Finally, we are the first to characterize precipitation patterns in South Florida at a regional, climatological scale based on SBC occurrence, informing a larger study that is interested in understanding the mechanisms of water resources.

FIGURES

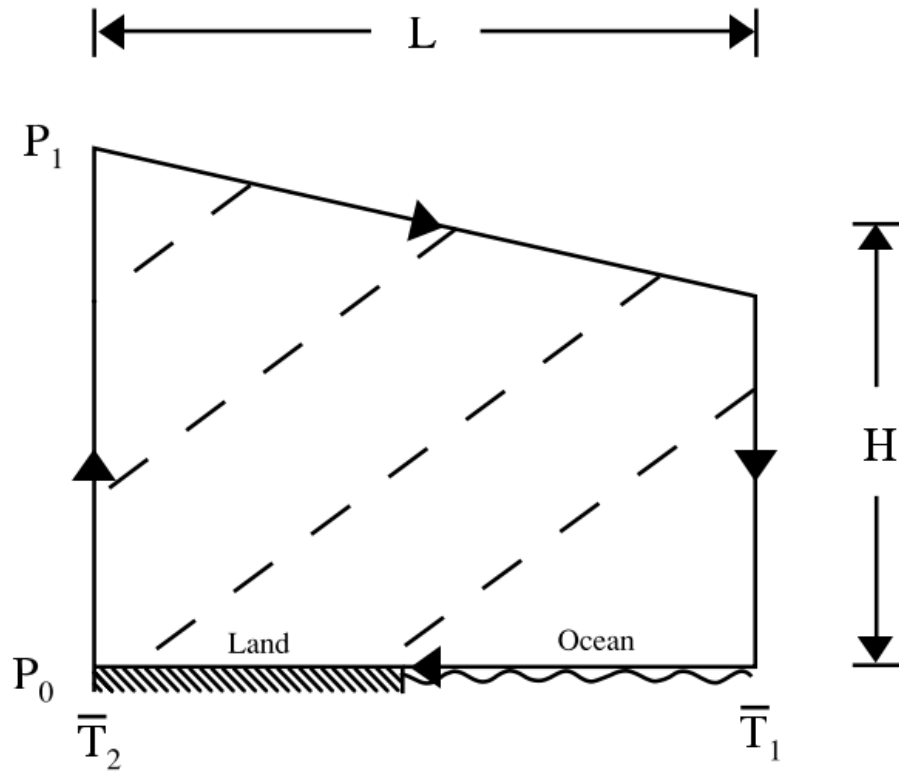


Figure 1.1 Drawing of the sea breeze circulation showing land to the left and ocean to the right. The average air temperature over land ($\bar{T}_2$) is higher than that over the ocean ($\bar{T}_1$), and thus the air over land rises more rapidly than that over the water and is replaced by the cooler marine air (Miller et al. 2003).

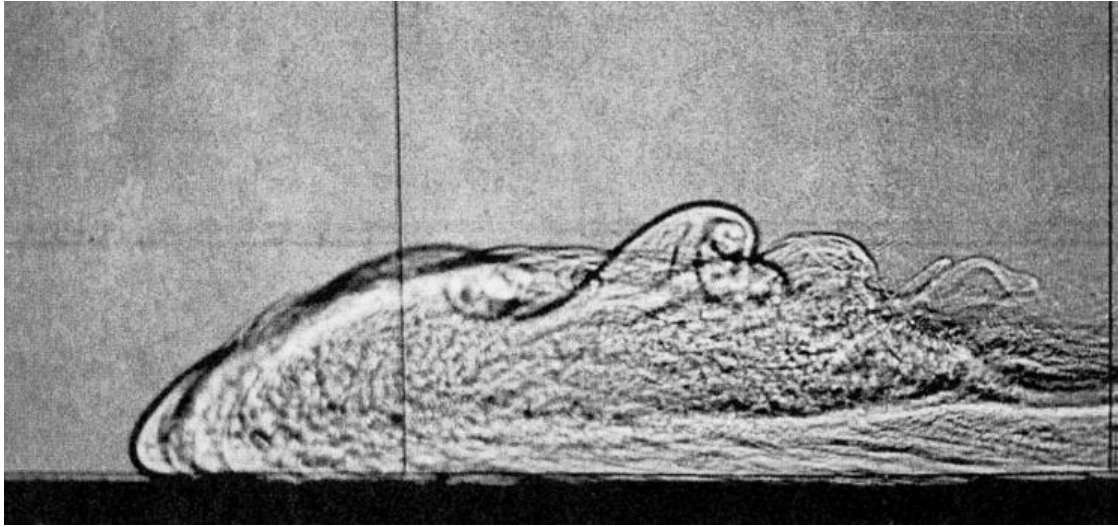


Figure 1.2 Photography of a laboratory gravity current depicting an influx of denser saline water (right) into pure water (left). This study emulates the larger scale sea breeze circulation. The sea breeze front can be visualized as the leading edge of the saline current and the wave-like features in the middle of the image portrays Kelvin-Helmholtz billows trailing behind (Simpson 1997).

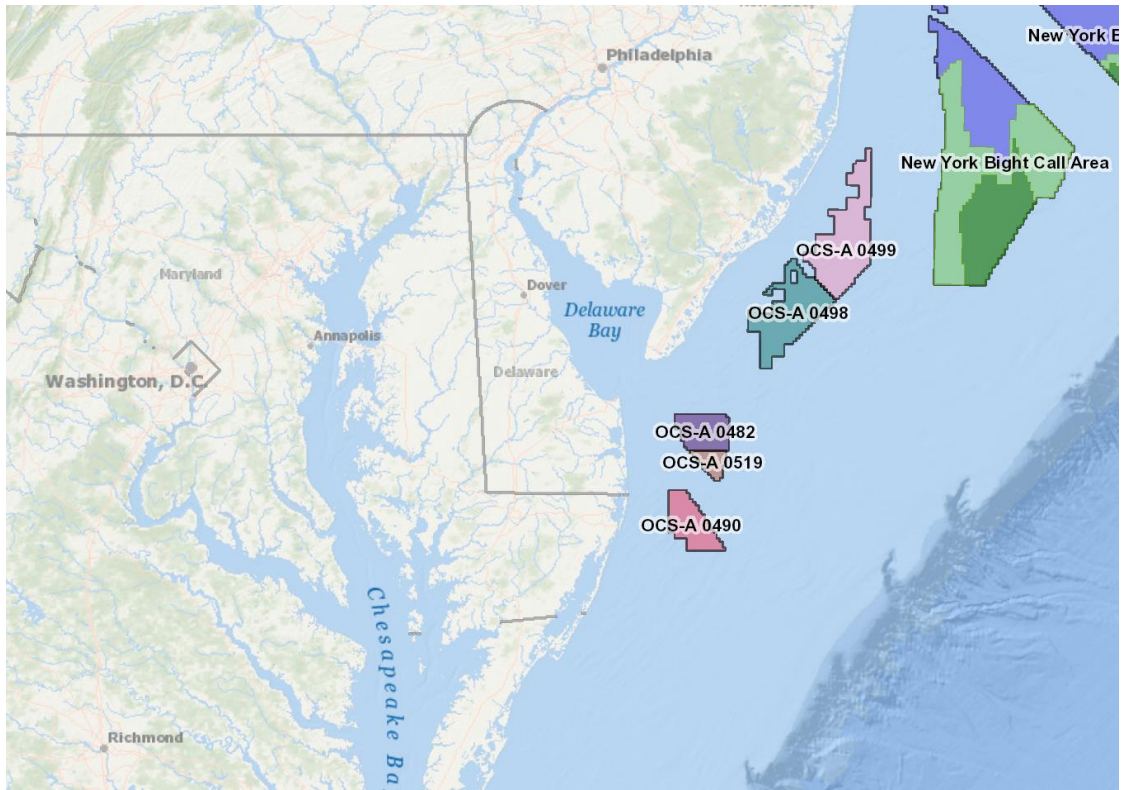


Figure 1.3 Offshore wind power lease map for the mid-Atlantic region of the eastern United States. Three proposed projects have been pursued, and OCS-A 0490 is set to begin producing power in 2020 (Lampman 2019).

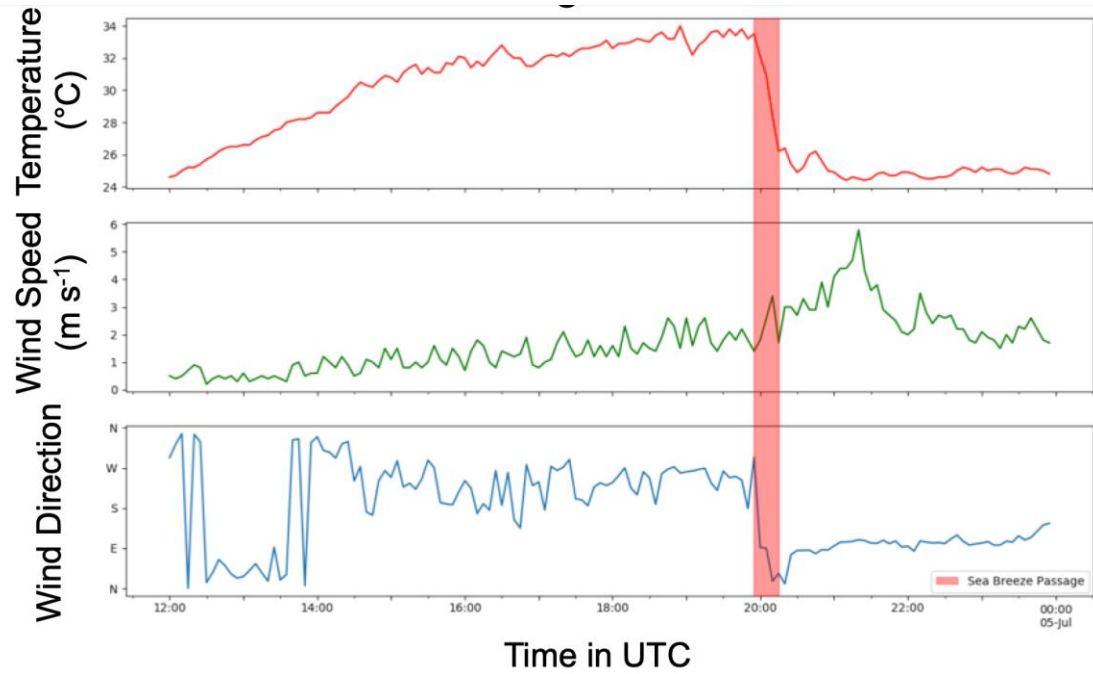


Figure 1.4 Case study from 4 July 2017 portraying the meteorological effects of a sea breeze frontal passage at a coastal station on the Atlantic Ocean. The temperature (top), wind speed (middle) and wind direction (bottom) before and after SBF passage are shown. The red shading indicates SBF frontal passage.

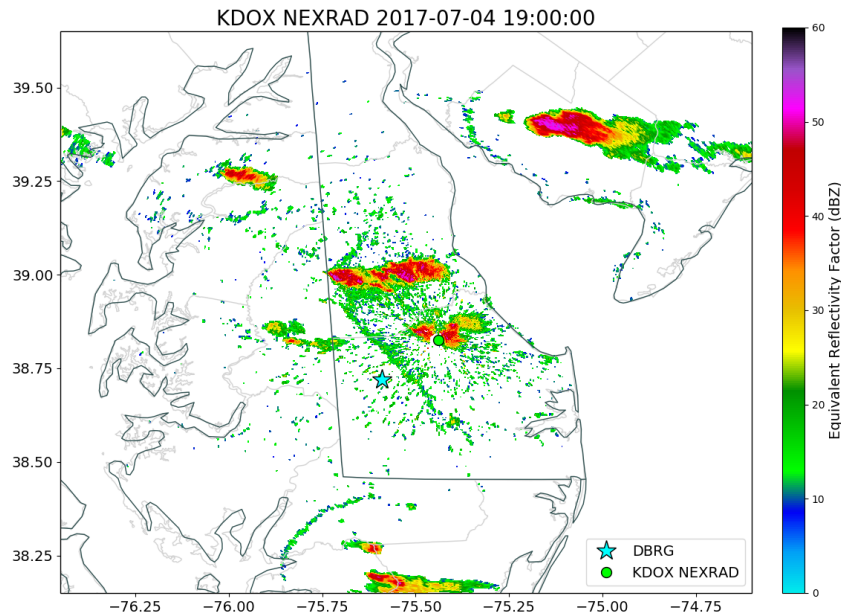


Figure 1.5 Development of a SBF in the region surrounding the KDOX (Dover, DE) NEXRAD station on 4 July 2017 at 1900 UTC. The front can be identified by the thin line of ~10-20 dBZ reflectivity oriented roughly parallel to the Delaware Bay coastline. Meteorological observations at a nearby station (DBRG; blue star) show a drop in temperature, increase in wind speed and change in wind direction around 2000 UTC (see Figure 1.4), roughly one hour after this radar image.

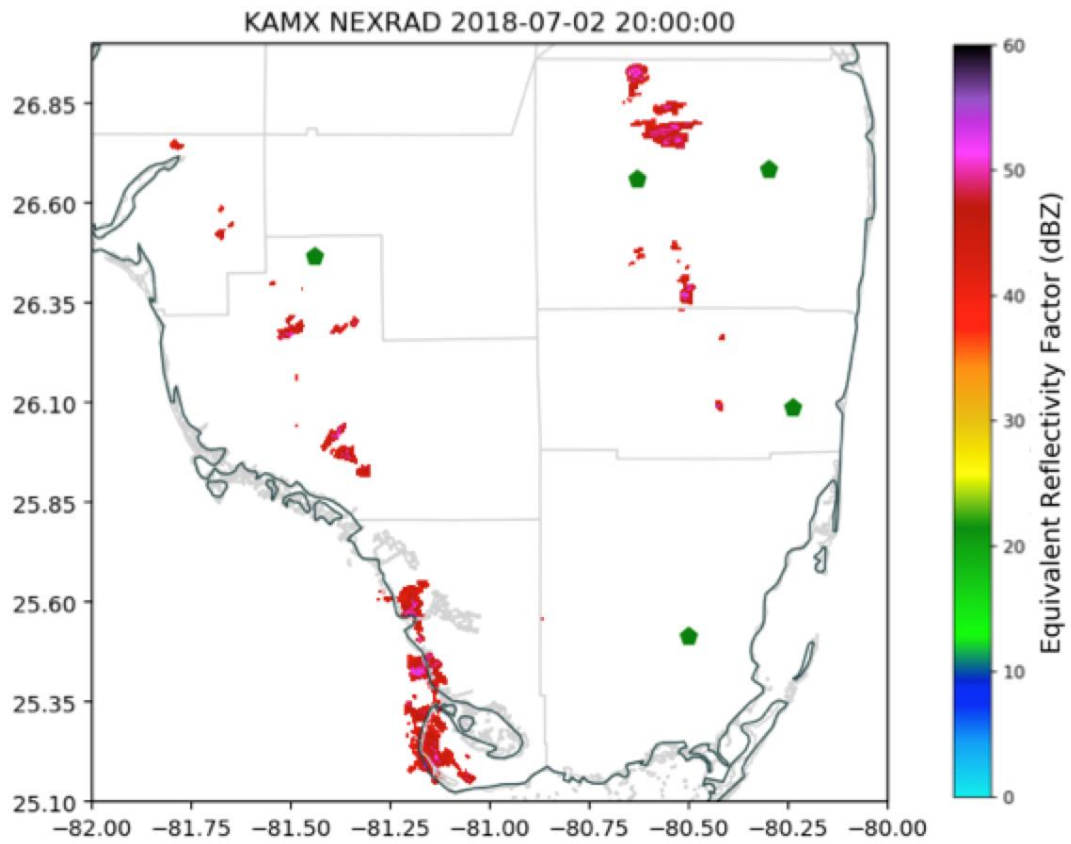


Figure 1.6 Map of Florida Automated Weather Network (FAWN) meteorological station locations near the Miami NEXRAD station. Convective precipitation cells (pink and purple) elude the sensors (green), but are detected using the radar reflectivity data.

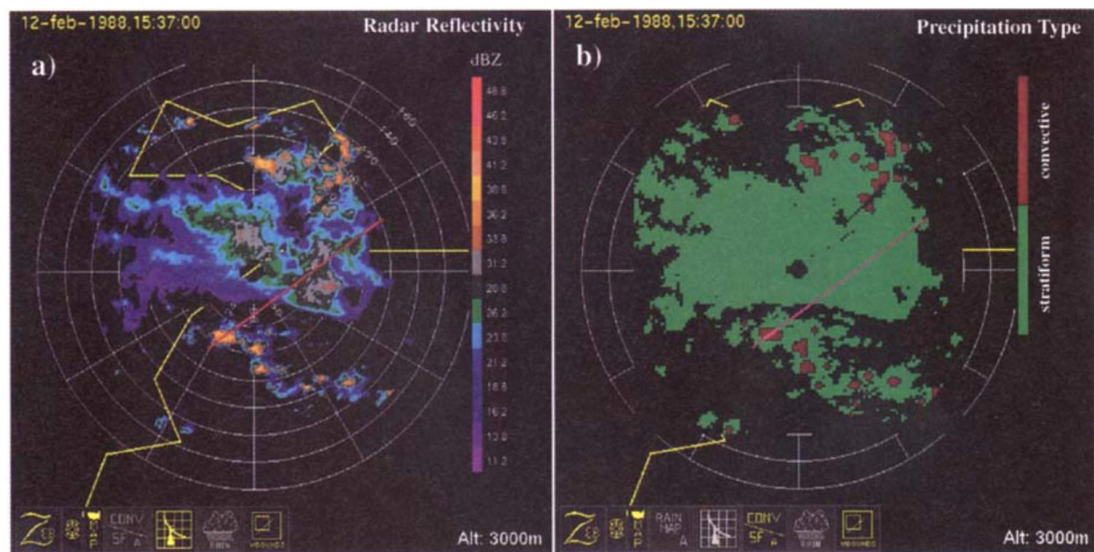


Figure 1.7 Raw radar reflectivity data (a) are shown on the left. The image on the right (b) portrays the same image passed through the algorithm defined by Steiner et al. (1995). Convective data points are in red while stratiform precipitation data points are in green (Steiner et al. 1995).

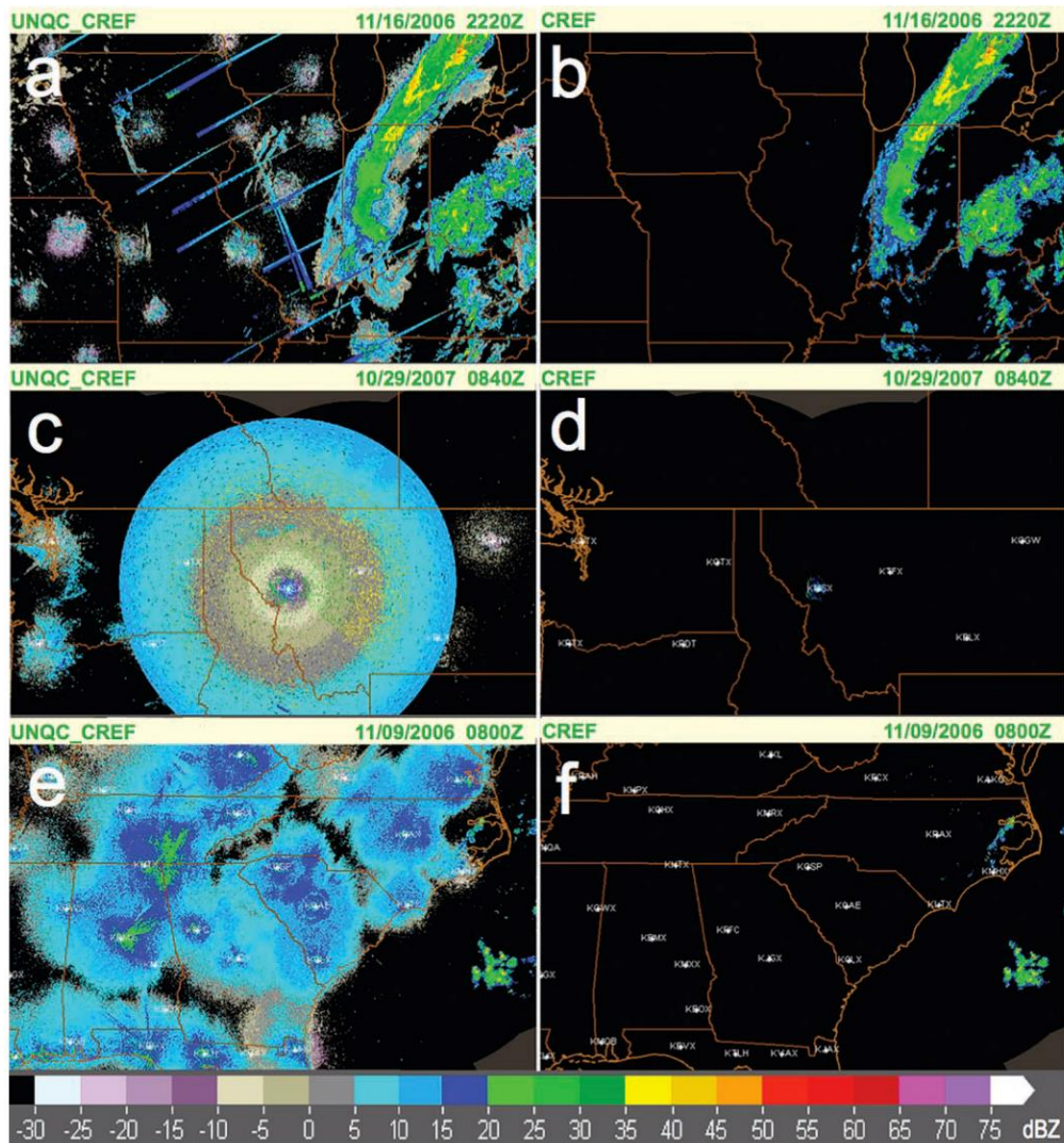


Figure 1.8 Composite raw (a, c, e) reflectivities from several weather radar systems and products after quality control that eliminates non-precipitation features (b, d, f). Reflectivity maps are valid for 2220 UTC 16 Nov 2006 (a, b), 0840 UTC 29 Oct 2007 (c, d), and 0800 UTC 9 Nov 2006 (e, f; Zhang et al. 2011).

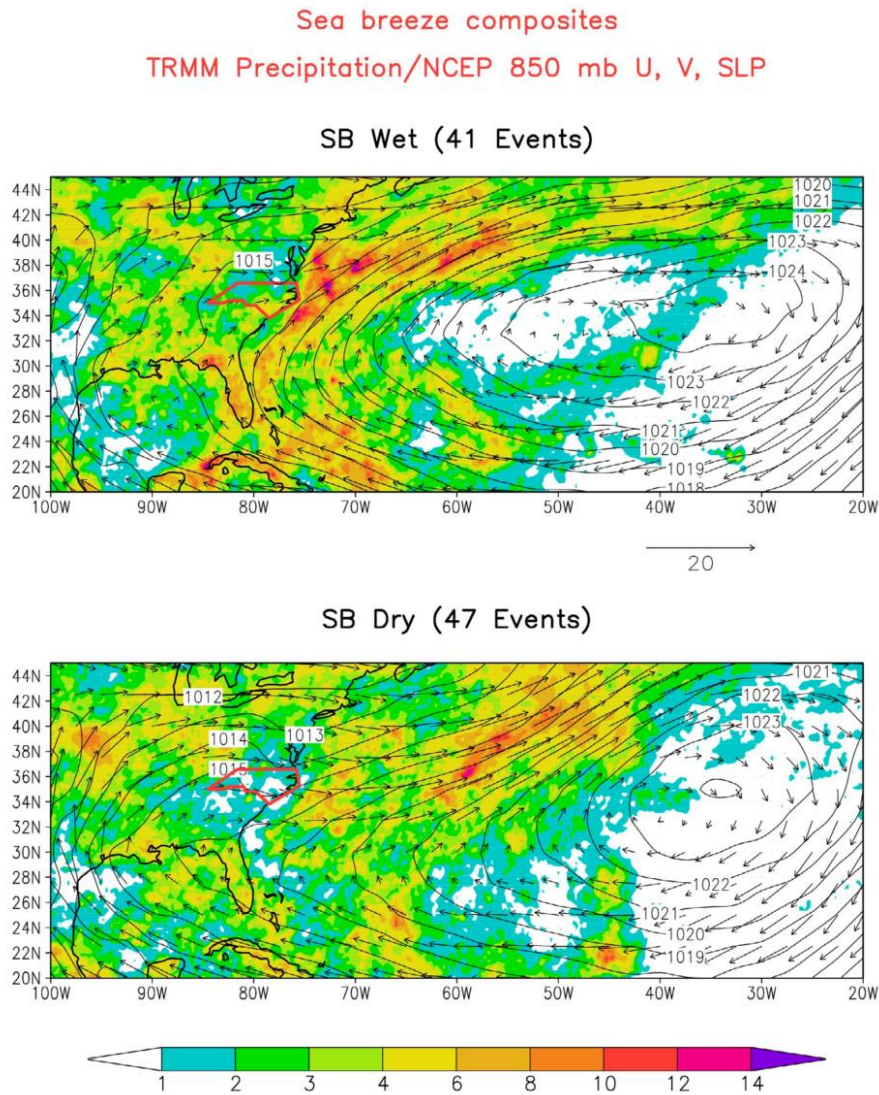


Figure 1.9 Average synoptic setup for sea breeze events resulting in precipitation (top) and dry sea breeze events (bottom) in coastal North Carolina. NCEP reanalysis sea level pressure (hPa; contours), 850 mb height wind speeds (m s^{-1} ; arrows) and Tropical Rainfall Measuring Mission (TRMM) precipitation (mm d^{-1} ; color) are shown. The synoptic settings are characterized as parallel (offshore) flow for SBC events with (without) precipitation (Luchetti et al. 2017).

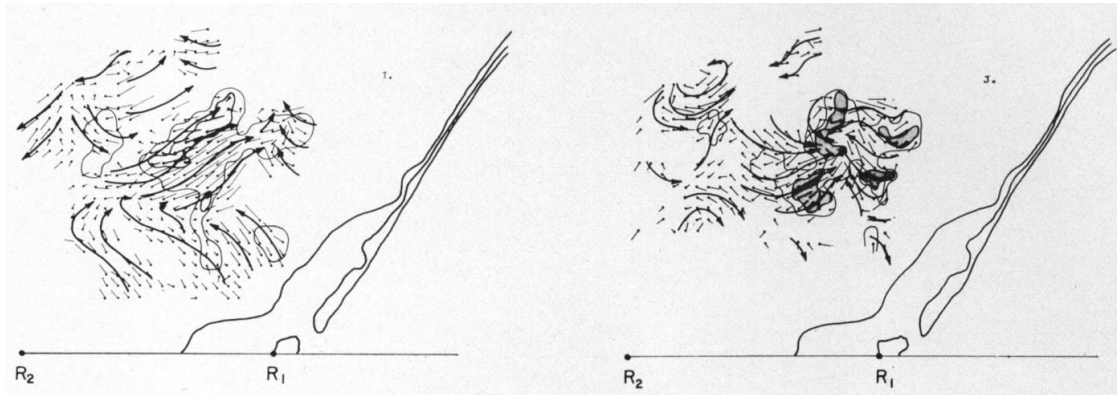


Figure 1.10 Sea breeze-initiated precipitation in South Florida as seen by two radar stations. These two images show a storm on 30 June 1973 at 1422 EDT at altitudes 1.5 km (left) and 3 km (right). The solid lines contours encompass areas with a rain rate of at least 5 mm h^{-1} . The arrows show wind velocity fields, displaying a clear sea breeze influence at low levels, and the return flow at 3 km is vaguely visible (Lhermitte and Gilet 1975).

Chapter 2

AUTOMATED DETECTION ALGORITHM FOR SEA BREEZE FRONTS USING GROUND-BASED RADAR

SBC influences local wind and temperature variability in coastal regions, enhancing convergence and influencing precipitation patterns under certain conditions. Particles and biota are often entrained at the SBC boundary between the terrestrial and marine air masses, referred to as the SBF, sometimes producing a detectable signal in radar reflectivity data. A state-of-the-art automated sea breeze detection algorithm employs radar reflectivity data for the summer months of 2009-2018 for the areas surrounding Melbourne, Florida and Dover, Delaware to detect and track the SBF as it propagates inland. The detection algorithm performs well in capturing the presence of strong SBCs in coastal regions, specifically those associated with precipitation. The findings suggest that SBFs associated with intense precipitation in Delaware are detected closer to the coastline and propagate further inland at a higher velocity compared to the average SBF, especially near the convex coastline where the bay and ocean meet.

This paper, authored by Daniel P. Moore and Dana E. Veron, will be submitted to the American Meteorological Society's Journal of Atmospheric and Oceanic Technology (JTECH). The findings herein will advance alternative detection methods of SBCs in coastal regions where radar data are accessible. Results from this study will lead to a better understanding of SBCs, especially as they interact with and cause precipitation, which will have potentially substantial impacts on the hydrologic system in coastal regions such as Delmarva and Florida.

2.1 Introduction

The SBC is a meteorological phenomenon that occurs in coastal regions when a surface pressure gradient develops from differential heating of the land and ocean surfaces that moves marine air over the land surface. Air close to the land surface heats in response to solar insolation and rises, creating a localized area of low pressure. The rising air is replaced by dense, cool air from over the sea surface; this low-level onshore flow is referred to as the sea breeze (Miller et al. 2003). The SBC is most frequent in coastal regions when the temperature gradient between the land and sea is greatest, generally in the summer (e.g. Hughes and Veron 2018; Pielke et al. 1991). During these times, the sea breeze impacts local wind variability (e.g. Hughes and Veron 2015), as well as precipitation (e.g. Pielke 1974) under certain conditions.

SBC presence can alter local weather, changing coastal winds and increasing convergence. Sea breeze-related precipitation can result in large amounts rainfall for coastal regions in a short amount of time (e.g. Luchetti et al. 2017; Nicholls et al. 1991; Pielke 1974), impacting the hydrology of urban and rural areas alike (Moore and Veron 2019). Improved understanding of environmental conditions conducive to SBC will lead to improved forecasting of the timing and location of these enhanced rainfall events. This may better serve stakeholders like water managers and farmers who rely on sea breeze-related precipitation (C. Maran 2019, personal communication).

The SBC also plays a vital role in pollutant transport, changing air quality by the influx of marine air (Simpson 1994; Levy et al. 2009). It can also create a cap, decreasing the depth of the mixing layer, and trapping pollutants close to the surface (Gaza 1998; Kitada 1987). SBC greatly affects wind direction and wind speed both onshore and offshore along the coastline (Seroka et al. 2018; Hughes and Veron

2015). Thus, understanding SBC can improve our understanding and utilization of wind energy resources, decreasing our reliability on non-renewable energy (Arritt 1989; Seroka et al. 2018; Mazon et al. 2015).

2.1.1 Sea Breeze Detection

Analysis of the SBC over the previous half-century have employed detection methods using meteorological stations (e.g. Crouch 2006; Cetola 1997; Hughes and Veron 2018; Papanastasiou and Melas 2009), ground-based radar (e.g. Achtemeier 1991; Atlas 1960; Luchetti et al. 2017; Simpson 1967; Suresh 2007; Wilson et al. 1994; Gilchrist 2013), satellites (e.g. Planchon et al. 2006; Vemado and Pereira Filho 2016), and other remotely sensed data, such as sonic detection and ranging (SODAR; Rakesh et al. 2017).

Meteorological station detection methods often include criteria for 1) surface-level winds, because surface-level onshore winds define a SBC, 2) prevailing synoptic winds to ensure surface-level onshore flow is not caused by synoptic forcing, and 3) land-sea temperature gradients (e.g. Hughes and Veron 2018). One drawback of these methods, however, is that a dense network of meteorological stations is often necessary to capture small-scale variations of the sea breeze. Thus, recent studies have exploited data availability from remotely sensed datasets.

Weather radar was used initially to detect SBC and relate its presence to synoptic patterns (Atlas 1960; Simpson 1967). Since then, aerosols such as sea salt, dust, insects, and other biota have been observed in radar echoes and used as tracers (Campistron 1975; Achtemeier 1991; Wilson et al. 1994). Achtemeier (1991) confirmed that the increase in echoes due to passive tracers like insects is especially apparent in regions of updrafts where the entrainment is strongest. This phenomenon

has been used to track the propagation of SBFs in Brazil (Planchon et al. 2006; Vemado and Pereira Filho 2016), Southern Peninsular India (Suresh 2007), Florida (Lhermitte and Gilet 1975), Delaware (Gilchrist 2013), and Eastern North Carolina (Luchetti et al. 2017). However, automating these detection methods present challenges due to the inherent variability of SBCs and to the large amounts of radar data that must be analyzed.

The first automatic detection of weather features using radar reflectivity data dates back over 40 years (Crane 1979). Crane (1979) utilized peak frequencies along transects to detect and track cells of thunderstorms surrounded by otherwise low reflectivities. Since then, this technology has improved with the primary focus remaining on thunderstorm cell detection, tracking and short-term prediction (e.g. Dixon and Wiener 1993; Johnson et al. 1998). A similar approach to detecting gradients of reflectivities is used in the present study, however difficulties exist due to the lower reflectivity gradients between the feature (SBF) and the background reflectivities.

The present study employs ground-based radar reflectivity data to develop and analyze an automated sea breeze detection algorithm. The algorithm will then be used to explore the characteristics of the Delaware and Florida SBCs with and without the presence of associated precipitation. Sea breeze and rainfall characteristics for the two regions of interest are compared to understand how differences in geography affect this phenomenon. In Section 2.2, we review the datasets and methodology used to create the algorithm. We then analyze the output of the code to develop statistics on the SBC and related precipitation in the two study regions in Section 2.3. In Section 2.4 we discuss the effectiveness of the algorithm relative to other studies, and provide

commentary on possible future work. Finally, we provide a conclusion and summary in Section 2.5.

2.2 Methods and Materials

The sea breeze and precipitation detection and analysis employ weather data and a suite of image processing techniques. The input data for the analyses are radar reflectivity values from individual scans throughout the warm period of 2009-2018. There are two focus regions in this study: Delmarva and Florida's central east coast. These two study regions are chosen for three primary reasons: 1) they are regions where SBC have been well-studied with station data and radar, 2) they are different dynamically, even though 3) they have similar geographic setups (e.g. bordered by the Atlantic Ocean).

Previous work has shown the viability of radar detection methods on the Delmarva Peninsula (Gilchrist 2013). Furthermore, the region surrounding Melbourne located on the central east coast of Florida was chosen because the station's close proximity to the coastline, in addition to the suspected presence of stronger, more vertically developed SBCs in Florida relative to the SBCs that develop in Delaware. The study focuses on June, July, and August (JJA) because of the tendency for stronger and more frequent SBC during these months in Delaware (Hughes and Veron 2018) and Florida (e.g. Moore and Veron 2019). The radar detection is verified using data from five coastal meteorological stations in Delaware (Figure 2.1), and one coastal station in Florida (Figure 2.2), based on a previous study (Moore and Veron 2019).

We employ data from two of National Oceanic and Atmospheric Administration's 160 Next-Generation Radar (NEXRAD) stations (NOAA 1991).

NEXRAD is a collection of high-resolution Doppler radars deployed to identify and track weather events utilizing a 1988 Doppler weather surveillance radar (WSR-88D) system. The radar systems have two operational modes with different scanning frequencies. The first, and most common, mode is precipitation mode, which is primarily used for storm system tracking. Thus, it operates at a faster scanning frequency than the second mode: clear air mode. The latter is used when there is little or no precipitation in the area surrounding the radar system.

Depending on operational mode, the radar can complete a scan of the surrounding area in 4.5-10 minutes. At a wavelength of 10 cm, these systems capture meteorological features such as raindrops, hail, snow, etc. However, they are also able to detect biota, such as birds and insects, as well as other non-weather features, such as dust (Achtemeier 1991) and, in some cases, use them as tracers for meteorological phenomena.

This study analyzes level 2 radar data from two NEXRAD stations: KDOX (Dover, DE) and KMLB (Melbourne, FL). The raw return signals captured by the radar antenna, level 1 data, are pre-processed by the National Weather Service resulting in digital radial base reflectivity, mean radial velocity and spectrum width products, along with polarization values. The resulting dataset is referred to as level 2 data. These data are then further processed to create level 3 products, which include a suite of output variables that assist weather analysis and forecasts. However, these products are often focused on major meteorological features, such as precipitation. Thus, they often eliminate unimportant features, such as ground clutter and reflectivities from biota and other non-weather signals, including the presence of a sea breeze. As a result, level 2 data are employed here to detect the SBF.

2.2.1 NEXRAD Data Access

NEXRAD level 2 data are accessed remotely utilizing the input/output functions of the Python Atmospheric Radiation Measurement (ARM) Radar Toolkit (Py-ART) (Helmus and Collis 2016). The level 2, rather than level 3, data are analyzed due to the relative weak signal of the sea breeze, which is often eliminated as noise from more heavily processed radar products. The data are archived and accessible through an Amazon Web Services (AWS) THREDDS Data Server stored at Unidata as a part of the National Oceanic and Atmospheric Association's (NOAA) Big Data Project (<https://www.noaa.gov/big-data-project>). Data are retrieved either one radar scan at a time or by time range. This technique allows for remote retrieval of scans for a given time window, with local analysis of the data.

Previous studies show the depth of the SBF close to the coastline ranges from <300 m to >1 km (Banta 1995), varying with time of day, solar insolation, and low-level atmospheric flow strength (e.g. Frizzola and Fisher 1963). Therefore, the distance between the radar and coastline is important, and potentially limiting, to detecting the SBF because the radar scan height increases with radial distance from the radar. Therefore, if the radar is too far from the coastline, it is possible that a shallow sea breeze does not become visible to the radar until it penetrates further inland. For instance, at a distance of 31 km from the coastline, the Delaware station (KDOX) station may not detect weak or developing SBFs that have limited vertical development (Gilchrist 2013).

2.2.2 Formatting Raw Data

The automated technique described in this chapter employs a series of steps (Figure 2.3) to analyze radar reflectivity data and detect SBFs by searching for

features along parallel latitudinal transect lines that are roughly perpendicular to the coastline. Therefore, it is necessary to re-project the data retrieved from the NOAA archive, which have a native polar coordinate system (Figure 2.4), into a geographic (latitude/longitude) coordinate system. The level 2 radar data are in a polar coordinate system that is dependent on the elevation scan angle (θ), an azimuth angle (Φ), and radial distance from the gate (r). By changing coordinate systems, reflectivity values are projected onto the x - y plane at the elevation of the radar to locate and track the SBF geographically. As such, the reflectivity returns close to the radar antenna are from lower heights than those captured farther away along the same elevation scan angle (θ).

First, the reflectivity data are projected onto an x - y Cartesian plane relative to the location of the radar, which are then converted into distance, in kilometers, east and north of the antenna location. Then these distances are transformed to a geographic coordinate system using the radar's geographic coordinates. The georeferenced reflectivity values are then masked to a study area bounded by a $1.5^\circ \times 2^\circ$ (latitude $\times$ longitude) box (see Figures 2.1, 2.2) that encompasses the coastal area where SBCs initiate and propagate in order to decrease the computing power required for the subsequent analysis.

Once the data are re-gridded, a reflectivity threshold eliminates ground clutter and other unwanted reflectivity values from the study area. Low reflectivities (<10 dBZ) are common in NEXRAD radar data, especially during clear air mode operation, as the lowest elevation radar beams refract and reflect off features on the Earth's surface like trees and buildings. This provides an empirical threshold that is useful in detecting the presence of a SBF relative to background reflectivities. A similar high

pass filter (8 dBZ) was successfully used in a study that manually detected and tracked SBF on the Delmarva Peninsula (Gilchrist 2013).

The masked data are associated with geographic coordinates in an array structure such that one column of data contains reflectivity values along one beam angle, with constant θ and Φ and a varying r . This means that the ground-projected footprint associated with each reflectivity value varies with distance from the antenna. The detection methodology described here employs a pixel-by-pixel east-west analysis transects across the study area to detect the SBF. To assist with this detection technique, the data are resampled to a 750 x 925 rectilinear grid using a conservative method (e.g. Ramshaw 1986) such that each row (column) of the grid corresponds to constant latitude (longitude). This resampling method preserves total reflectivity in the area, allowing for a more accurate analysis of precipitation area and intensity derived from these data. Furthermore, each grid point then represents a 0.22 x 0.17 km² area in Delaware, and 0.22 x 0.20 km² area in Florida. The difference in area between the two locations is due to the increased east-west distance between longitude lines closer to the equator.

This data re-mapping allows the detection algorithm to search along latitudinal lines (grid rows) to detect features in the study area in a computationally efficient and intuitive fashion. Due to the re-sampling, grid points represent equal areas so calculating spatial extent requires a simple summation of grid points regardless of their location relative to the individual radar. However, geographic areas must be calculated individually for Florida and Delaware because of changes in grid spacing between study regions.

2.2.3 Individual Radar Scan Analysis

After the conservative re-map, the resulting subset of data is analyzed to highlight meteorologically important features, such as the SBF and/or high-reflectivity clusters associated with precipitation (Figure 2.5). Several types of precipitation events may be detected by weather radar, but can be classified as either convective or stratiform. Convective precipitation events associated with localized cells of intense rainfall (>40 dBZ reflectivity) may occur with, or be influenced by, a SBC (Steiner et al. 1995; Biggerstaff and Listemaa 2000; Anagnostou 2004). Stratiform rainfall from an incoming front, however, occurs over larger regions with more uniform reflectivities (15-35 dBZ). The presence of stratiform precipitation rarely coincides with the SBC because stratiform clouds prevent the radiative heating of the surface that drives the SBC. Additionally, depending on precipitation particle size, shape and phase, it may cause false detections of the SBF. Thus, if any type of precipitation >25 dBZ covers more than 33% of the study area ($\sim 8,500$ km²), the scan is skipped and is not analyzed for a SBF. This may result in an underestimation of precipitation surrounding SBF detection if precipitation covers a great area coincidental with, or following detection.

Once the scan passes the $<33\%$ areal rainfall criteria, a function analyzes individual features and distinguishes precipitation from other meteorological phenomena, namely the SBF. The function characterizes clusters of pixels in the study area as (1) a precipitation feature, (2) a potential SBF, or (3) erroneous values by using empirically derived thresholds. A cluster is defined here as adjacent pixels that have passed the threshold and data trimming described above, and which share either a side or a point (Figure 2.6). Each cluster of pixels is identified and given an identification

number utilizing the ‘*ndimage*’ processing package from SciPy (Jones et al. 2001). Each feature is individually analyzed by size, shape and reflectivity values.

The *ndimage* SciPy package calculates the area (in pixels), major axis length (in pixels), and geographic location of the center of mass for each feature. Similarly, the mean and maximum reflectivity values for each feature are calculated to determine the likelihood of a given cluster to fall into one of the three categories listed above. The unique shape and size of the classic SBF is distinguishable from other features and thus empirically derived spatial analysis thresholds, discussed below, are applied to successfully identify SBF features.

2.2.4 Precipitation Detection

A precipitation feature is defined in this study as having an area of at least 100 pixels and a mean reflectivity of >22.5 dBZ. This area represents clouds of radius >1 km, typical of a small precipitating cumulus cloud, while the reflectivity threshold marks the lower limit of reflectivity associated with precipitation (Steiner et al. 1995). The areal coverage, geographic location, and mean and max reflectivities are retained for further analysis.

2.2.5 Radar Detection of the Sea Breeze Front

A relatively thin and long cluster of higher reflectivities relative to the background, oriented roughly parallel to the coastline is characteristic of the classic SBF as defined by Simpson (1967, see Figure 2.5). The shape of the sea breeze can be defined with the compactness ratio developed by (Gibbs 1961) which determines the relative shape of a feature. The compactness ratio, S_g , is defined as:

$$S_g = 1.2732 \frac{A}{L^2} \quad 2.1$$

where A is the area of the feature and L is the major axis length (Figure 2.7). As S_g approaches one the shape approaches a circle. In contrast, as this value approaches zero the shape approaches a line. Considering the linear shape of a SBF, an empirically derived threshold of 0.3 is used to eliminate unwanted features, while maintaining those that resemble a front. The approach of the compactness ratio is helpful because it does not bias against curved, thin features that may orient along a convex or concave coastline. In this step, each remaining feature is analyzed and these criteria eliminate unwanted features (e.g. precipitation and/or clutter) from the study area, leaving us with only potential SBF features (Figure 2.8).

The reflectivity data on the rectilinear grid are analyzed pixel-by-pixel from east to west along transect lines of constant latitude. For both study regions, a total of forty-one transect lines, spanning 1° of latitude, or ~ 111 km, centered on the radar location, are assessed and the values of surrounding reflectivities are analyzed (Figure 2.9). The height of the radar beam at 50 km from the radar location and a scan angle of 0.5° is about 0.4 km above radar level. Miller et al. (2003) found that the vertical extent of the SBF can range from less than half a kilometer to more than two kilometers. The location and extent of the transect lines are used because preliminary analysis found that, within this range, the radar reliably interacts with the SBF. However, beyond this 50 km range, the sea breeze may become incoherent or have too little vertical development to be visible in the radar reflectivity data. The sea breeze detection algorithm begins slightly offshore to allow for the SBF retrograding over the water, specifically under the influence of strong prevailing offshore winds (Hughes and Veron 2018; Hughes 2016).

The algorithm progresses through each transect line beginning at the easternmost pixel, or that which is located over the water body, mimicking the progression of a SBF after initiation. The algorithm analyzes the surrounding 100 pixels (10x10), hereafter called the nugget, in addition to the 50 pixels (10x5) to the west and east of the nugget to determine the presence of a SBF feature. Previous steps have eliminated the majority of ground clutter, precipitation and other erroneous features. Thus, this portion of the analysis focuses on detecting features in the remaining pixels. This methodology does not, however, allow for the detection of two fronts along the same transect line, which is known to occur (Figure 2.10 ; Hughes 2016). On days where two fronts form along the same coastline, the algorithm will bias toward the one closest to the coast, possibly resulting in biases on final detection location toward the coast. It will also influence calculation of SBF penetration distance and propagation speed under these conditions.

If 60% of these pixels in the nugget are present, having passed the thresholding and detection criteria, then the algorithm analyzes the gradient along the transect to determine if the nugget is located in a peak reflectivity area relative to its surroundings. The mean reflectivity of the 50 pixels (10x5) on both sides, west and east, of the nugget, beginning with the pixels adjacent to the east and west sides of the nugget, is compared to the mean reflectivity of the nugget. If a reflectivity gradient exists, such that the mean value of the nugget is greater than the mean value on either side (Figure 2.11), then it is designated a possible SBF coordinate. The algorithm then continues along the transect line looking for more suitable locations for the SBF. In other words, if a pixel that fits the above criteria and the proportion of remaining pixels in the nugget is higher than the one found previously along the same transect,

then the SBF location is overwritten with the coordinate associated with the highest number of remaining pixels in the nugget. These steps are repeated for all transect lines in the study region.

The preceding steps can lead to false detections of a SBF under various circumstances. Typically, a fully developed SBF usually spans 10-100km or more. However, with the current algorithm, if the reflectivity signal of the SBF is weak such that it is broken into very small patches of high reflectivity with large spacing between the patches, then the detection scheme will flag the identified SBF locations as outliers and remove them from the dataset. The algorithm accomplishes this by maintaining a record of 'runs' and 'skips' as it moves through the transect lines from North to South. A 'run' is defined as a series of transect neighboring lines where the SBF was located, and a 'skip' indicates that the SBF was not detected on at least one transect. If at least four transect lines detect a SBF ('run') without the presence of three or more consecutive transect lines that do not detect a SBF ('skips'), then the coordinates are kept. However, if a run of three or fewer consecutive lines with a SBF location are found, followed by three or more consecutive lines where SBF coordinates are not found, then the run of detected coordinates are eliminated as erroneous values. This effectively removes any SBF that is not well-developed vertically. As a result, this method may bias against bay breezes, as they are frequently shallower than sea breezes (Gilchrist 2013).

After all transect lines have been analyzed, the algorithm categorizes the scan as having detected a SBF or not. If 8 of the 41 (>19%) transect lines successfully detected a SBF, the coordinates of the front are recorded for future analysis, and the next scan is analyzed. Although the algorithm does not require these lines to be

consecutive, the minimum length for a detectable SBF in this algorithm is ~22 km. This minimum length was chosen to decrease false detections of small features. This is nearly a third of the length of Delaware's bay coastline (~60 km) and half the length of its ocean coastline (~38 km). The current methodology allows for a detected SBF to be broken into multiple parts if two runs of four or more lines are detected in separate locations within the study area, following the method above. This occurs where the SBF signal is weaker in certain portions of the front, relative to others, or the bay and ocean branch of the SBF develop separately. Hence, the algorithm may not detect the SBF on several lines amongst or between transects that did detect SBF coordinates.

Finally, in order to more easily analyze the movement of the SBF over time, we must maintain a consistent list of coordinates that represent a detected SBF. A method for linear interpolation of the SBF location onto the lines that have not detected a SBF is then used to appropriately place the SBF coordinate onto these transects (see Figure 2.9). If there are three or more lines between SBF points, however, the algorithm assigns these as two separate segments of the SBF and interpolation is not used. In the case where only one or two transect lines without a SBF coordinate separate two lines with a coordinate, interpolated SBF coordinates are placed at the intersection of these transect lines and the line defined by the successful SBF coordinates. Figure 2.12 shows each stage of SBF detection after pre-processing of raw data.

The purpose of the study is to determine whether or not an objective, automated SBF detection routine that employs radar data can be used to identify strong SBF that have concurrent or subsequent precipitation. If the SBF is detected for

at least three scans, or roughly 1.5 hours, then the day is characterized as a sea breeze day.

2.2.6 Station Detection of Sea Breeze Front

Results from the radar detection method in Delaware are tested against a station detection methodology using five observational stations located along the coast (see Figure 2.1), which report observations in five-minute increments. Four of these stations (DBBB, DBNG, DWAR, and DSJR) are a part of the Delaware Environmental Observation System (DEOS) mesonet, while station LWSD1 is controlled and operated by the National Buoy Data Center (NDBC). Two criteria are applied to these data to test for the passage of a SBF. The station detection algorithm iterates through each observation and compares the present values to the values 30 minutes (6 time-steps) prior.

The first criterion necessary for SBF detection is a wind direction shift from an offshore direction, relative to the nearest coastline, to an onshore direction over the 30-minute period. If this criterion is passed, the data are tested for a drop in temperature often associated with the influx of cooler, marine air. A drop in temperature of $>1^{\circ}\text{C}$ is required over this test period. If both criteria are met at any station in the study region, the day is characterized as a SBC-day. The results of this analysis are compared against the radar detection to determine differences in overall statistics, in addition to false detection rates. This algorithm is a modified version of similar detection methods used in the Delaware study region (e.g. Gilchrist 2013; Hughes 2011) focused on detecting strong SBFs that may be associated with subsequent precipitation.

Radar detection in the Melbourne, FL study region are compared to station analysis performed by Moore and Veron (2019) for one station near the KMLB NEXRAD station (see Figure 2.2). Similarly, detection statistics and rates will be compared between these two methods for this region.

2.3 Case Studies

To understand the complexity of the SBC in Delaware that contributes to the difficulty in radar detection, we will discuss two case studies: one with associated convergence and precipitation, and one without.

2.3.1 3 July 2012

Figure 2.13 shows the complex development and movement of a SBF in the Delmarva region that leads to local intense precipitation as the front matures. The front develops soon after local sunrise along the Delaware Bay coastline (Figure 2.13a), and remains within a few kilometers of the coast for over four hours (Figure 2.13b). As the ocean SBF develops and becomes visible, a localized region of intense precipitation forms near the intersection of the ocean and bay coasts in Delaware (Figure 2.13c). This precipitation event is likely a result of localized convergence of the two branches (bay and ocean) of the sea breeze front at a convex coastline, enhancing uplift and convection. As this convective cell moves toward the southeast, presumably due to the synoptic flow (Figure 2.13d), an outflow boundary enhances the velocity of the ocean branch of the SBF as it propagates inland to join the bay branch (Figure 2.13e). Finally, as the front propagates inland, a secondary front can be seen developing along the bay coastline (Figure 2.13f).

An important aspect of this particular event is the movement of the SBF after it forms and is visible by radar. In particular, the bay branch of the SBF forms and stalls close to the coastline for a significant amount of time before propagating inland. In addition, after it propagates roughly 10-15 km inland, it stalls and even slightly retrogrades toward the coast again (Figures 2.13c and d) before penetrating deeper inland.

2.3.2 30 July 2017

Another interesting SBC develops early on 30 July 2017 and lasts beyond local sundown, propagating nearly the full width of the Delmarva Peninsula (Figure 2.14). A primary SBF can be seen developing at the mouth of the Delaware Bay parallel to the New Jersey ocean coastline (Figure 2.14a). As the development of this front continues and lengthens to cover portions of the coastline in New Jersey and Delaware, a secondary front forms parallel to the first deeper into the bay (Figure 2.14b). The primary front begins to propagate inland and up the bay at a faster rate than the secondary front (Figures 2.14c, d). The two fronts combine and the southern branch of the SBF propagates the full width of Delaware, as a Chesapeake Bay breeze develops and propagates into the study region (Figure 2.14e). The two fronts converge late in the day and a localized region of high reflectivity values can be seen where there may be enhanced uplift (Figure 2.14f).

A manual analysis of sea breeze days visible on radar from 2007-2011 showed that 20% of detected sea breezes were events where a front progressed up the bay (Gilchrist 2013), such as presented in the current case study. During these events, it was shown that a strong enough temperature gradient exists between the Delaware

Bay and Atlantic Ocean to create a pressure gradient force similar to that which causes the classic sea breeze.

2.4 SBC Analysis

After processing available hourly scans within the study period, the algorithm determines the frequency of sea breeze detection in the two study regions. In addition, we characterize the detected sea breezes from each region, developing statistics for duration, penetration, and velocity.

2.4.1 Frequency

Overall, the algorithm detected a SBF with a frequency of 58% for all available JJA days from 2009-2018 in the Florida study region. In Delaware, the frequency was 26% over the same period. Both study areas revealed a similar pattern of monthly frequencies with June having the least detected sea breezes and August having the most. Specifically, Figure 2.15 shows that August has the highest frequency of detection with 64% (28%) of days analyzed in this study producing a detectable SBF in Florida (Delaware).

In a previous study, Gilchrist (2013) found that a SBF was visible on radar on 42% of days during May-September of 2007-2011. The difference between these results is likely due to two factors: 1) the methodology used in the current study analyzes one scan per hour, whereas the previous study analyzed every scan, or 2) the current method uses objective criteria to detect strong SBC events and will likely miss weak signals in the radar that are visible when analyzing manually.

Year-to-year variations in SBF detection differ between the two study areas. The range of detected SBFs per year in Delaware ranged from as few as 8, in 2011, to

as many as 41, in 2012 (Figure 2.16). This inter-annual variability is not as prominent in Florida, where the fewest number of SBF detections in a single year was 27 (2016) while the most was 56 (2010).

2.4.2 Onset Time and Duration

The Florida sea breeze onset time followed a normal distribution with a mean time of first detection at $18.0 (\pm 2.6)$ UTC. This distribution is maintained in June and July (Figure 2.17). However, a tri-modal distribution can be seen in August with the central, larger peak at 18 UTC and lower peaks at 14 UTC and 21 UTC. The average detected SBF in the Melbourne study region lasted for about $5.8 (\pm 3.0)$ hours, with an average time of final detection at $23.8 (\pm 2.4)$ UTC (Figure 2.18). It can be seen that the average sea breeze in August (6.3 ± 2.9 hours) lasts longer on average than June (5.6 ± 3.0 hours) or July (5.5 ± 2.9 hours), though this result is not significant at $p < 0.1$.

The SBC in Delaware shows a different pattern to Florida in that there is a heavily skewed distribution in SBF detection by time of first detection (Figure 2.19). There are no SBF detections before 15 UTC in any month, with the peak number of detections occurring at 15 UTC (June and August) and 16 UTC (July). The average Delmarva SBF first detection has been observed at 16 UTC using station data, but inland penetration of 1 km takes roughly two hours, on average (Hughes and Veron 2018). We find the mean first detection for Delaware was $17.8 (\pm 2.6)$ UTC, which may indicate a more slowly moving SBF. The average radar-detected SBF in Delaware lasted for about $4.6 (\pm 2.9)$ hours, with an average time of final detection at $22.4 (\pm 2.6)$ UTC (Figure 2.20). There is no significant difference among months for sea breeze duration in the Delmarva area.

2.4.3 Location

The location of the detected sea breezes is analyzed with respect to initial and final detection, after which the sea breeze becomes incoherent in the ground-based radar reflectivity data. The SBF primarily orients itself along the coastline, but alters orientation as it propagates inland. This can be seen in both study regions (Figures 2.20 & 2.21), where the average first detection is closer and more similar to the shape of the coastline. The average final detection resembles a more linear feature, losing much of the coastline shape.

The current algorithm is designed to identify strong SBFs with potential to alter local weather patterns. As such, the average initial detection of the SBF in both regions is well inland. In Florida, the average distance across the 41 transect lines to the coastline for initial detection is 22.6 km. The detected sea breeze propagates an average of 12.0 km further inland, resulting in a mean final detection 34.6 km inland, with an average penetration velocity of 1.03 m s^{-1} (Table 2.1; Figure 2.23).

This effect is evident, but less pronounced in Delaware (Figure 2.22), with average initial detection also well inland with respect to the coastline. However, it is evident that the two segments, or branches, of the sea breeze, namely the one aligned with the bay and that aligned with the ocean, develop and propagate very differently. Whereas the average inland distance for the onset of the northern 20 transects, generally aligned with the Delaware bay, is 10.1 km, the transects aligned with the ocean result an average distance of initial detection at 20.7 km inland. Further, the average initial detection for each transect clearly shows that the SBF is oriented parallel to the coastline, maintaining the coastline shape. The SBF develops such that the bay segment orients northwest to southeast, similar to the orientation of the bay coastline, while the ocean branch aligns north to south, also conforming to the nearest

coastline. The area of transition from bay to ocean coastline forms a convex coastline, which may enhance convergence and precipitation.

The average final SBF detected in Delaware still resembles the coastline shape, though less so. The ocean branch clearly penetrates inland more quickly, resulting in a relatively linear feature before the SBF is not detected by the algorithm. As a result, the final detection for the ocean (bay) branch is 25.2 (13.4) km, with a penetration velocity of 0.40 (0.20) m s⁻¹ (Figure 2.24).

The northern and southern extremes of the SBF in both study regions exhibit the least distance traveled from initial to final detection (see Figures 2.20, 2.22). This is most likely because the radar signal is too high to interact with the SBF at these extreme distances in the study region, especially when the SBC is not fully developed (i.e. beginning or end of its cycle). As a result, we also find that average durations at these extreme transects are lower (not shown).

2.4.4 SBC Associated with Precipitation

Analysis of the radar data shows that precipitation occurs concurrently or following detection of a sea breeze approximately 60% of the time in Delaware and 94% of the time in Florida. Following Steiner et al. (1995), the presence of intense precipitation is defined as a connected feature with a max reflectivity >50 dBZ and a mean reflectivity >30 dBZ. Intense activity in the study region at the time of SBF detection or the hours following occurs 49% (90%) of detections in Delaware (Florida).

On average, these intense precipitation features cover an area of 432 km² in Florida (Figure 2.25). The average feature size in Delaware during sea breeze events is 766 km², however the number of features detected surrounding Delaware SBFs is

much fewer. An average number of precipitation features is calculated by the summation of all features in scans following sea breeze detection including the initial SBF detection. An average of 3.9 features are found in the study region in Delaware following sea breeze detection compared with 6.2 in Florida. The coverage of intense precipitation in both study regions are well below the maximum area allowed (i.e. >33% of the study area, or ~8,500 km²).

The rainfall rates of each rainfall feature are normalized by the size of the feature and averaged by scan. This normalization prevents bias toward outlier low-coverage precipitation features. The mean reflectivity for each sea breeze day is defined as the mean reflectivity of intense precipitation features averaged across the scan of first SBF detection and all scans analyzed for that day after detection. The mean reflectivity of intense rainfall was 32.1 dBZ in Florida and 32.7 dBZ in Delaware, which result in rainfall intensities of 3.7 mm hr⁻¹ and 4.0 mm hr⁻¹, respectively (Figure 2.26). This difference is significant at $p < 0.001$.

The difference in precipitation characteristics between these two regions may be a result of differences in thermodynamics (Figures 2.27, 2.28). With a well-mixed moist boundary layer, Florida may experience less convective inhibition and CAPE than Delaware, which would result in more frequent, but less intense precipitation. The two soundings on 15 July 2017 at 0000 UTC coincide with sea breeze detection in both study regions associated with intense precipitation. The higher convective available potential energy (CAPE) in the Delaware region may lead to more intense rainfall once the convective inhibition is surpassed.

SBCs where intense rainfall was detected simultaneously with or closely following SBF detection, exhibited slightly different characteristics, specifically in

Delaware where associated rainfall is less frequent. The bay (ocean) branch of the SBF penetrates at an average speed of 0.40 m s^{-1} (0.44 m s^{-1}), more rapidly than the propagation speed averaged across all detected SBC days (see Table 2.1), specifically along the transects aligned with the convex coastline between the bay and ocean coastlines (see Figure 2.24). This relative increase in velocity along the bay branch is larger than along the ocean branch. The Florida sea breeze also penetrates deeper with a slight increase in average speed on days with intense precipitation in comparison to all days with detected SBFs (Table 2.1).

Furthermore, during days with intense precipitation, the bay branch of the DE SBF was initially detected closer to the coastline (Figure 2.29), although the ocean branch was not. The bay branch was first detected an average of 9.0 km inland of the bay coastline, while the ocean branch was first detected an average 22.9 km inland. This is most likely due to the close proximity of the bay coastline to the KDOX radar compared to the ocean coastline. As a result, greater vertical development of the SBF is needed along the ocean coast for the radar to obtain a reflected signal from the SBF. Additionally, the penetration distance of final detection increased to 14.7 km and 28.9 km inland for the bay and ocean branches, respectively.

2.5 Discussion

2.5.1 Sea Breeze Analysis

There are limitations as to how complete a picture weather radar can give of the SBC. For example, due to the sampling pattern of most weather radars and the limited sensitivity of the radar to weak updrafts (Achtemeier 1991), only the fronts

with strong updrafts are discernible from the ground clutter reflectivity. Additionally, the distance of the radar from the coastline places a limitation on the ability of the radar to detect the SBF. Depending on the scanning elevation angle of the radar, the altitude of the lowest scan along the coastline can be too high to capture the top of a weak SBC.

Utilizing a manual detection method, Gilchrist (2013) determined by individually analyzing radar reflectivity images that slightly under half of warm season days (May to September) during 2007-2011 had a visible sea breeze, with an overall detection rate of 48% of JJA days. This result is nearly twice what we found, however the purpose of our algorithm is to automatically identify and analyze sea breezes with the highest potential for influencing intense rainfall. In addition, Gilchrist (2013) manually analyzed every scan in the study period detecting SBFs, whereas we process scans every half-hour, which is only ~15% of daily scans.

Both Gilchrist (2013) and Hughes and Veron (2018) calculated sea breeze frequency using meteorological station data for the Delaware coastline. Their studies suggest that there is a classic sea breeze occurring along the Delaware coast 70–80% of the time during summer (JJA). In the current study, station detection in Delaware resulted in a frequency of 71% of JJA days (2010-2017) with an observable SBC at one or more stations in the study region (see Figure 2.1). During this same time, the radar algorithm detected approximately 25% of these events with a false detection rate of less than 26%. This false detection rate was calculated by the percent of dates identified by radar as observing an SBC that were not identified by station detection. However, on SBC days where the radar also detected intense precipitation, the false

detection rate minimized to 18%, reinforcing the algorithms relative success when strong SBFs are present in the region.

Using meteorological station data, a study of the Melbourne region found that approximately 60% of days had a detectable sea breeze in weather station data (Cetola 1997). This is much closer to the observed SBF frequency detected by the radar and reported in this study: 58%. This would suggest that the algorithm is capturing roughly 97% of sea breeze occurrence in this region. This result agrees with the frequency of sea breezes that penetrated at least 30 km inland (81% of all SBFs) identified by Cetola (1997).

Sub-hourly weather data are scarcely available in Florida and makes station validation difficult. However, a station located approximately 50 km inland of the KMLB radar (see Figure 2.2) detected a classic SBF on 26% of days during the same JJA 2009-2018 study period (Moore and Veron 2019). This difference between the SBF frequency detected with station data and our detection frequency of 58% is likely due to the SBF being disrupted by precipitation or thunderstorm activity after being detected by the radar but before penetrating inland far enough to reach the station. SBF detection may also be limited by the objective detection criteria employed by Moore and Veron (2019).

Gilchrist (2013) calculated the average time of initial detection to be 1720 UTC, which is in close alignment with our finding of 1748 UTC. Further, findings from an earlier study using coastal meteorological stations found SB onset at the most coastal stations to be around 1630 UTC (Hughes 2011). The difference between station and radar detection is likely due to time it takes the SBC to develop enough vertically to interact with the radar signal (Hughes and Veron 2018).

Gilchrist (2013) found the time of final detection to be 2322 UTC, slightly later than our result (2224 UTC). The difference between initial and final detections is likely due to relatively faint signals that preside before and after full development of the SBC. Further, the frequency distributions show a heavily skewed distribution of final detection times in both study regions (see Figures 2.18, 2.20).

Similarly, the average sea breeze duration in Delaware was previously determined to be longer (6.1 hours; Gilchrist 2013) than was found here (4.8 hours). Additionally, Gilchrist (2013) found that the average penetration distance is further inland (66 km) than our study, which determined that the penetration distance depends on the presence of precipitation. Both of these can be attributed to weak sea breeze signals in the radar while the sea breeze is first initiated, and as it matures and dissipates. Interestingly, however, the average position of the sea breeze front at initial detection is very similar to Gilchrist's (2013) findings (Figure 2.22).

The penetration distance and velocity found here are both less than what Gilchrist (2013) found previously. Further, the average velocities at the extreme north and south of the detectable SBF is negative (Figure 2.24), regardless of precipitation association, though it is more pronounced on intense precipitation days. This may be due to synoptic winds altering the position of weaker SBFs, resulting in stalling or retrograding (see 3 July 2012 case study and Figure 2.13). The occurrence of precipitation can also alter the position of the front when outflow boundaries act in unison with or opposition to the SBF.

The precipitation analysis reveals a difference between the two regions in both occurrence and characteristics. Florida experiences convective precipitation on most summertime days (Byers and Rodebush 1948), however the probability of

precipitation increases during sea breeze occurrence (Moore and Veron 2019). Thus, it is unsurprising that 95% of sea breeze detected days also detected intense rainfall in the region of Melbourne. Although precipitation seems to cover a larger area per cell in Delaware, the overall coverage is greater in Florida.

A previous study found that only 12% of radar detected sea breeze days in Delaware triggered convection (Gilchrist 2013), whereas the present detection algorithm found this frequency to be about 49%. It must be noted that the current analysis does not restrict the location of the intense rainfall relative to the detected SBF, thus it is difficult to determine whether the sea breeze caused the precipitation. However, sea breezes have been shown to enhance precipitation from afar under certain conditions through peninsula-scale convergence (e.g. Burpee 1979).

It is important to note that a sea breeze is most likely present far more frequent than can be detected in the radar data with the current detection algorithm for several reasons: 1) rainfall is initiated prior to detection, 2) the radar scan vertical height is too high to detect SBF, 3) there are not enough particles in the air for radar reflectivity, or 4) the level of free convection in the atmosphere is below the height of the SBF, causing convection and precipitation that disrupts the SBC.

2.5.2 Future Work

This study introduces an algorithm that, with minor modifications to the location and orientation of the transect lines, can be used to detect and analyze SBFs in any region with a maintained Doppler radar system within 100 km of a coastline. Further, the framework presented here can be applied to other remotely sensed data, such as satellite data, to detect meteorological features based on pixel gradients. For example, the line of clouds associated with the SBC, visible in infrared satellite data,

has been used to detect and analyze the SBC (Vemado and Pereira Filho 2016). The utilization of similar image-processing techniques can automate this process in a similar manner, allowing for analysis of larger amounts of data at lower human expense.

Finally, the method here can be markedly improved by employing machine-learning techniques with data from many different regions. Output from this algorithm can be used to train computer models to detect gradients in reflectivities and/or infrared values that are characteristic of SBF. This also may assist in detecting SBFs that have weaker reflectivities or situations with multiple SBFs or SBFs with complex shapes. The present study lays the groundwork for future research that employs higher-level computer science techniques to improve the success rate of this algorithm and create a more beneficial tool for the analysis of SBC globally.

2.6 Conclusion

We have presented an automated methodology for detecting and analyzing SBCs in coastal regions with radar stations. The detection algorithm developed here employs radar reflectivity data and spatial analysis techniques to detect and track the SBF near the Dover, DE (KDOX) and Melbourne, FL (KMLB) NEXRAD stations with minimal human input. Results show that the Florida region produces detectable SBFs on most days in the summer, though the frequency of detection is far less than previous observational studies in both regions. Limitations of the algorithm exist due to the often weak reflectivity returning from the SBF, particularly in the Delmarva study region. Therefore, this algorithm should be employed to study the strongest SBCs, which are often most likely to influence local precipitation. The presence of intense precipitation is shown to enhance the penetration distance and velocity in

Delaware compared to all days with detected SBFs. The Florida study region experiences intense precipitation on most days when there is an identifiable SBF. Finally, suggestions for future research involve applying this code to other parts of the world where similar data are available. Similarly, machine-learning techniques can improve the effectiveness of this method, increasing its sensitivity to weak SBC events and decreasing false detections.

TABLES

Table 2.1 Radar algorithm - derived location of initial and final detection as well as penetration velocity for the Dover, Delaware (DE) and Melbourne, Florida (FL) sea breeze fronts (SBF). The DE SBF is divided into two distinct branches (bay and ocean) characterized by the coastline of origin. Results for days with intense (>30 dBZ mean reflectivity) precipitation (precip) are given separately.

Sea Breeze Location	Subset	Average Initial Detection (km)	Average Final Detection (km)	Average Velocity (m s^{-1})
DE Bay Branch	All SBF Days	10.1	13.4	0.20
	Intense Precip Days	9.0	14.7	0.29
DE Ocean Branch	All SBF Days	20.7	25.2	0.40
	Intense Precip Days	22.9	28.9	0.44
FL SBF	All SBF Days	22.6	34.6	1.03
	Intense Precip Days	22.6	35.0	1.05

FIGURES

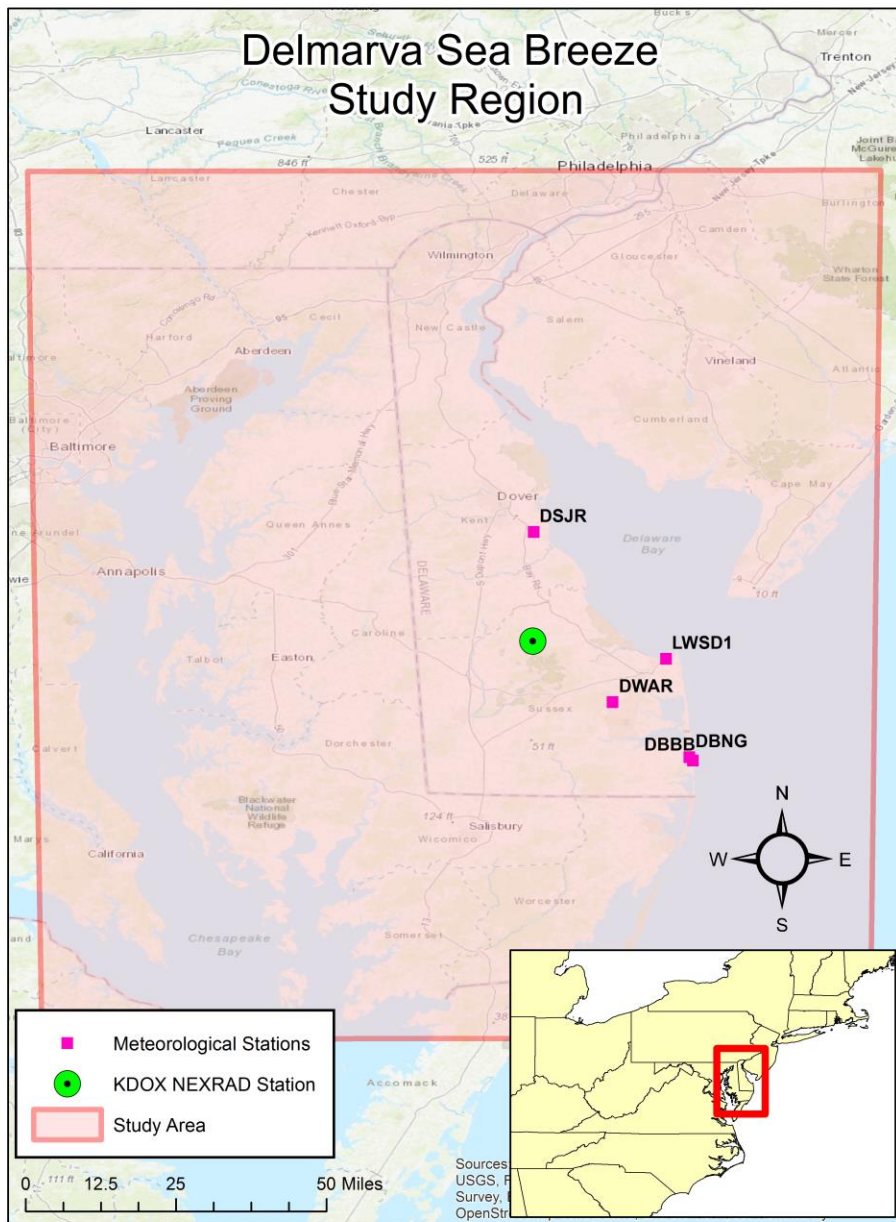


Figure 2.1 Delmarva study area for sea breeze front radar and station detection. Locations of five meteorological observation stations (pink) and KDOX NEXRAD station (green), as well as the $1.5^{\circ} \times 2^{\circ}$ data resampling bounds (red shading) are shown.

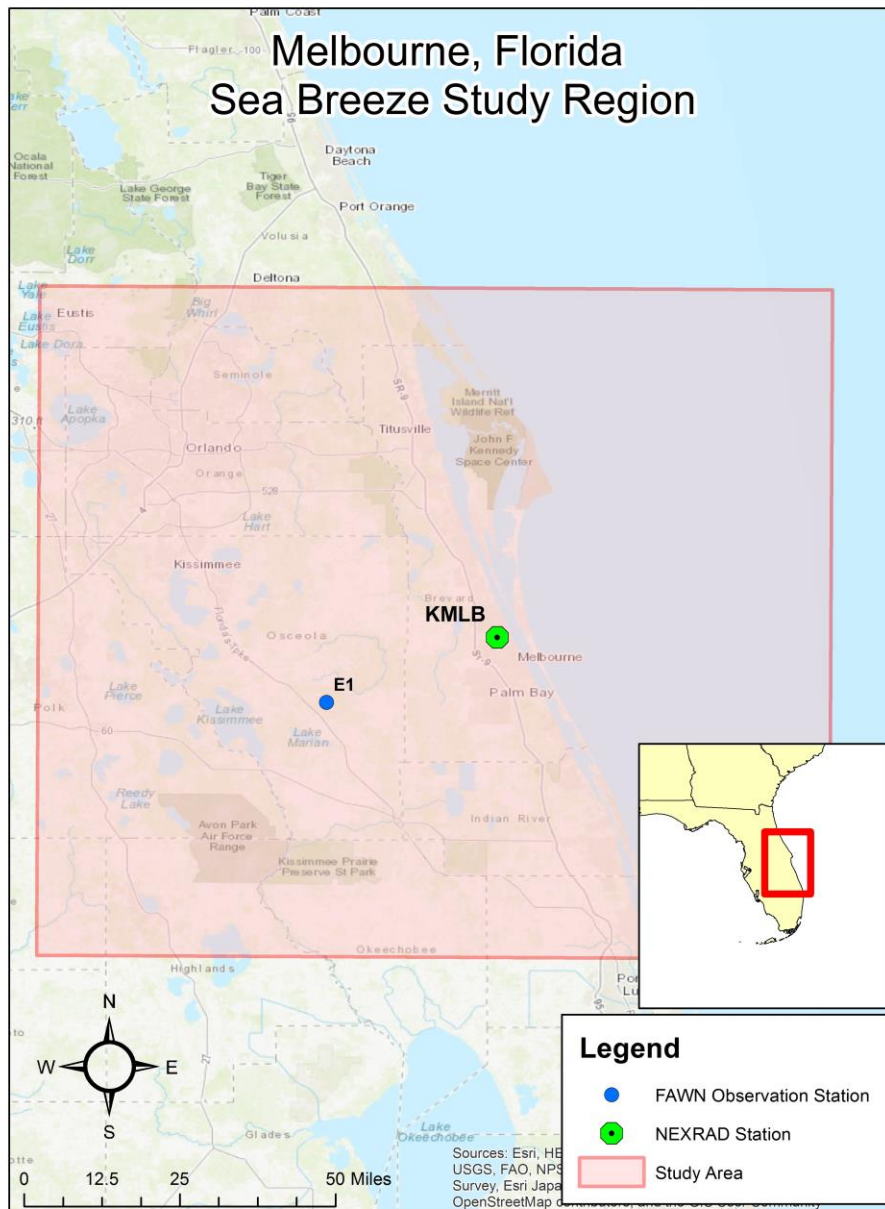


Figure 2.2 Melbourne, Florida study area for sea breeze front radar and station detection. Locations of one meteorological observation station used in Moore and Veron (2019; blue) and the KMLB NEXRAD station (green), as well as the $1.5^{\circ} \times 2^{\circ}$ data resampling bounds (red shading) are shown.

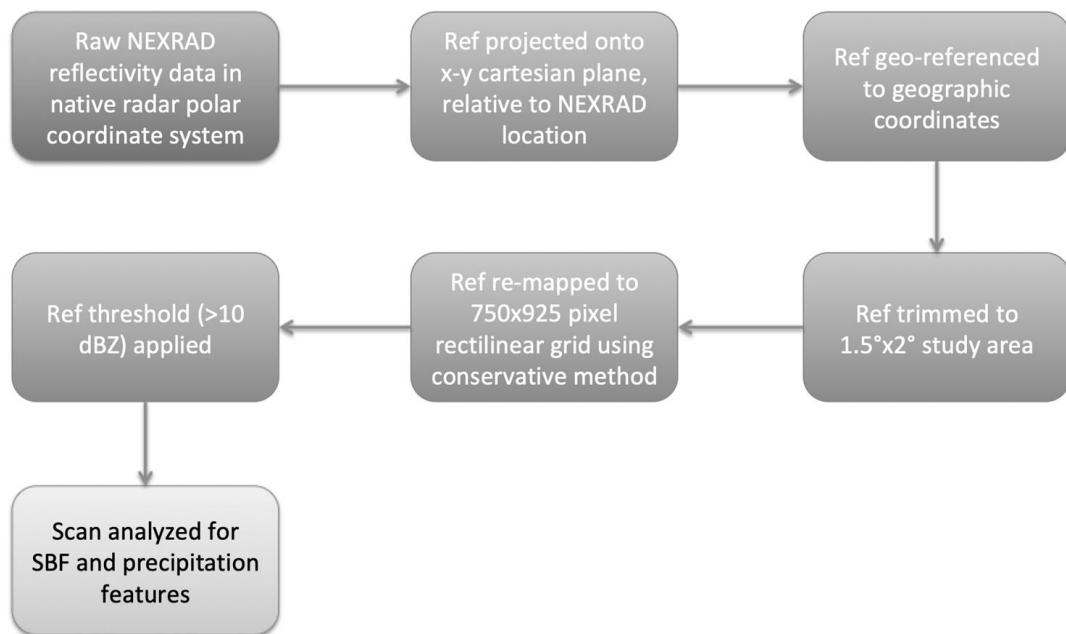


Figure 2.3 Data formatting flow chart beginning with raw NEXRAD reflectivity (Ref) data and concluding with a product that will be sent to the spatial analysis algorithm for sea breeze and precipitation detection.

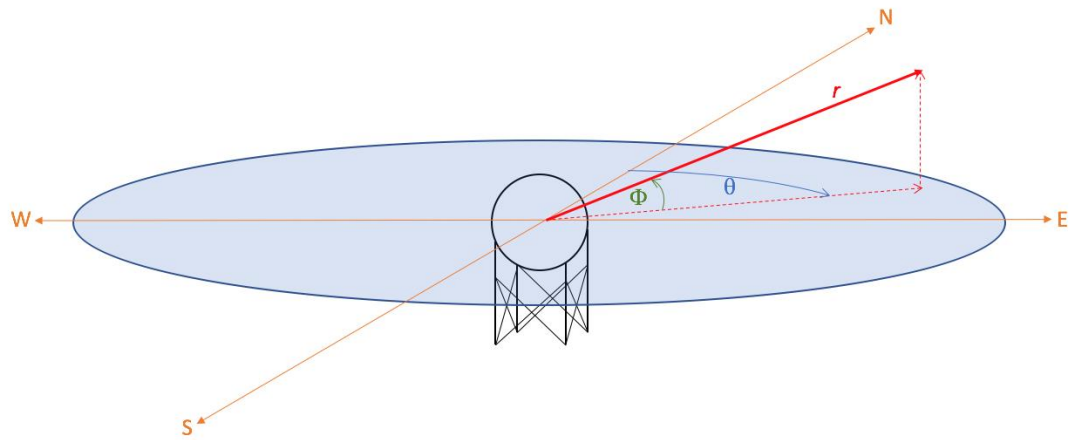


Figure 2.4 Diagram illustrating the radar coordinate system where θ is the elevation scan angle, Φ the azimuth angle, and r the radial distance from the gate. N, S, E, W refer to the geographic directions.

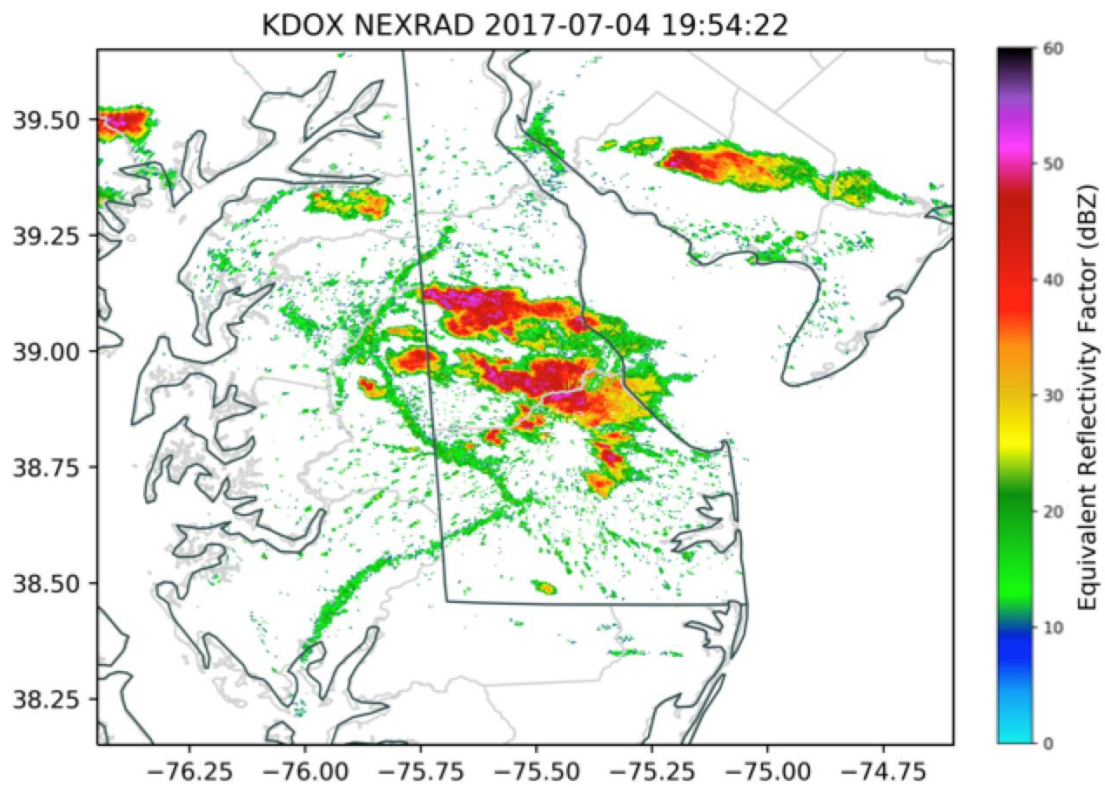


Figure 2.5 Dover, Delaware (KDOX) NEXRAD radar scan from 4 July 2017 at 19:54:22 UTC. The reflectivity data has been trimmed to the study area and a low threshold (>10 dBZ) has been applied. The SBF is identifiable as a near-continuous line of reflectivities from 10-20 dBZ that roughly mimics the shape of the coastline.

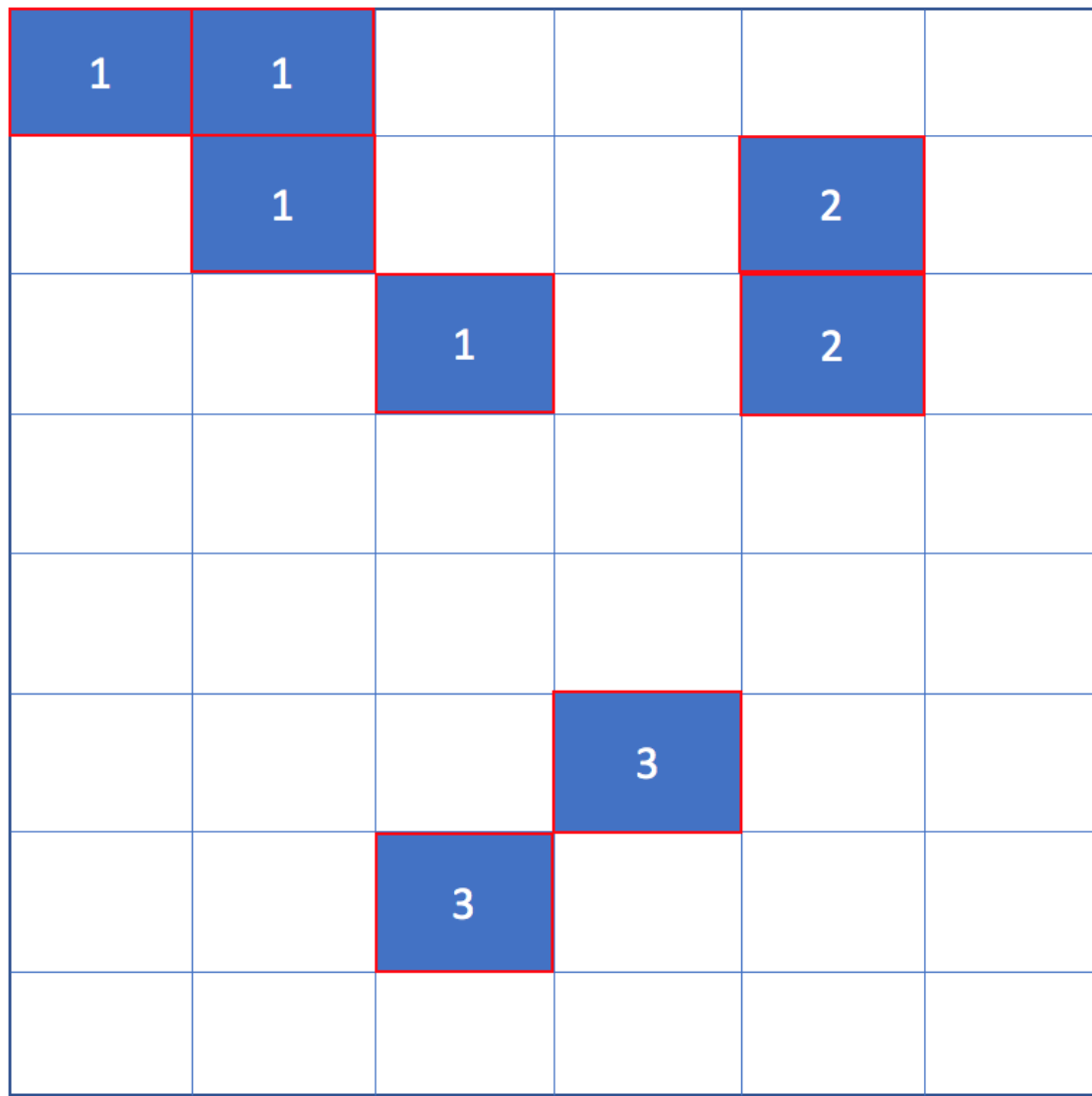


Figure 2.6 Example of three clusters utilizing SciPy *ndimage* connected areas function. The blue boxes represent pixels that have passed the previous steps in the algorithm and each number represents a cluster to be analyzed in the following steps of the algorithm.

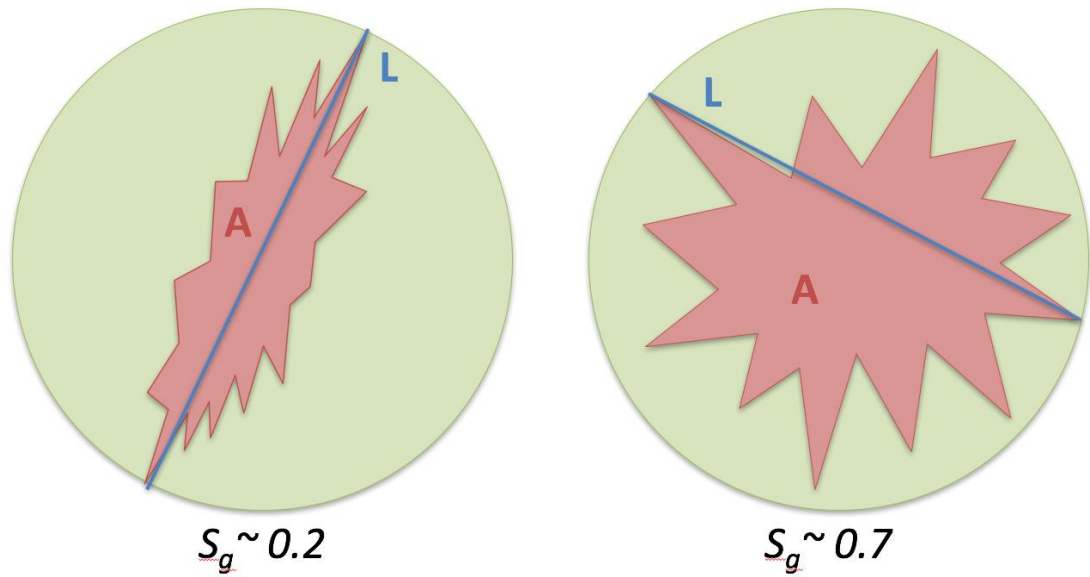


Figure 2.7 Illustration of the calculation of compactness ratio (S_g) for two, complex hypothetical shapes. A is the shape area and L is the length of the longest axis.

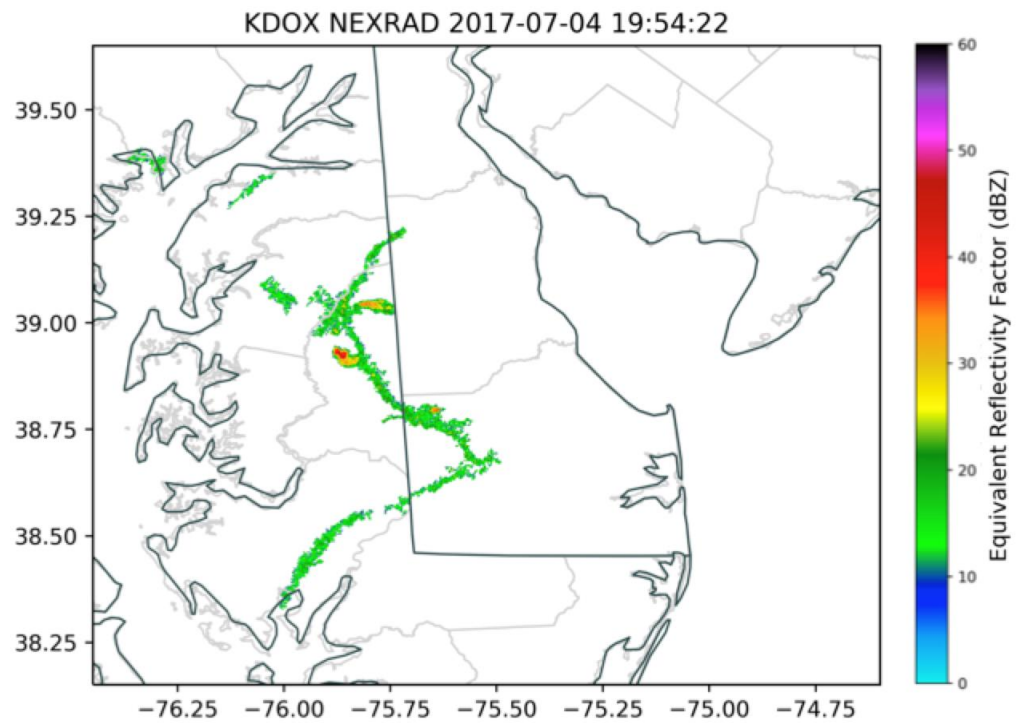


Figure 2.8 KDOX radar scan from 4 July 2017 19:54:22 UTC after feature identification and size, shape and reflectivity criteria are applied. The remaining features are primarily sea breeze front signals. Data shown are reflectivity data in dBZ remaining after thresholds and feature identification has been completed.

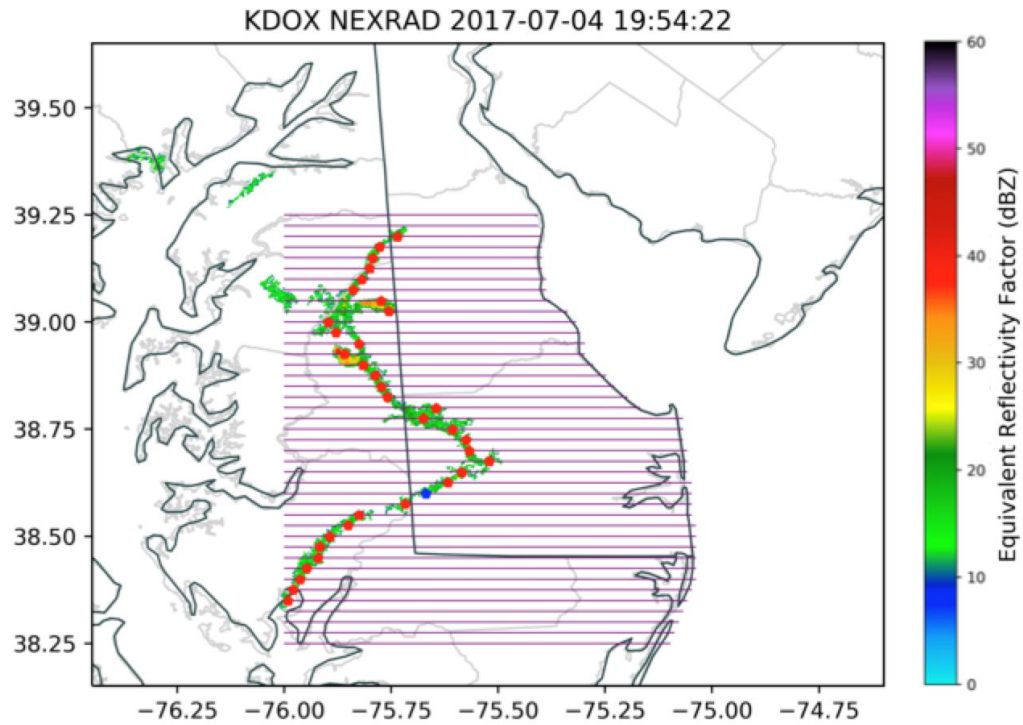


Figure 2.9 Extent of transect lines (purple) in the Dover, Delaware region. Reflectivity values show the product of a low (10 dBZ) threshold and processing utilizing connected features analysis. The coordinates of the SBF along each transect are shown (red points). Interpolated SBF points (blue) are placed on transect lines where SBF was not detected but present on adjacent transect lines. Data shown are reflectivity data in dBZ remaining after thresholds, feature identification, and sea breeze front detection has been completed.

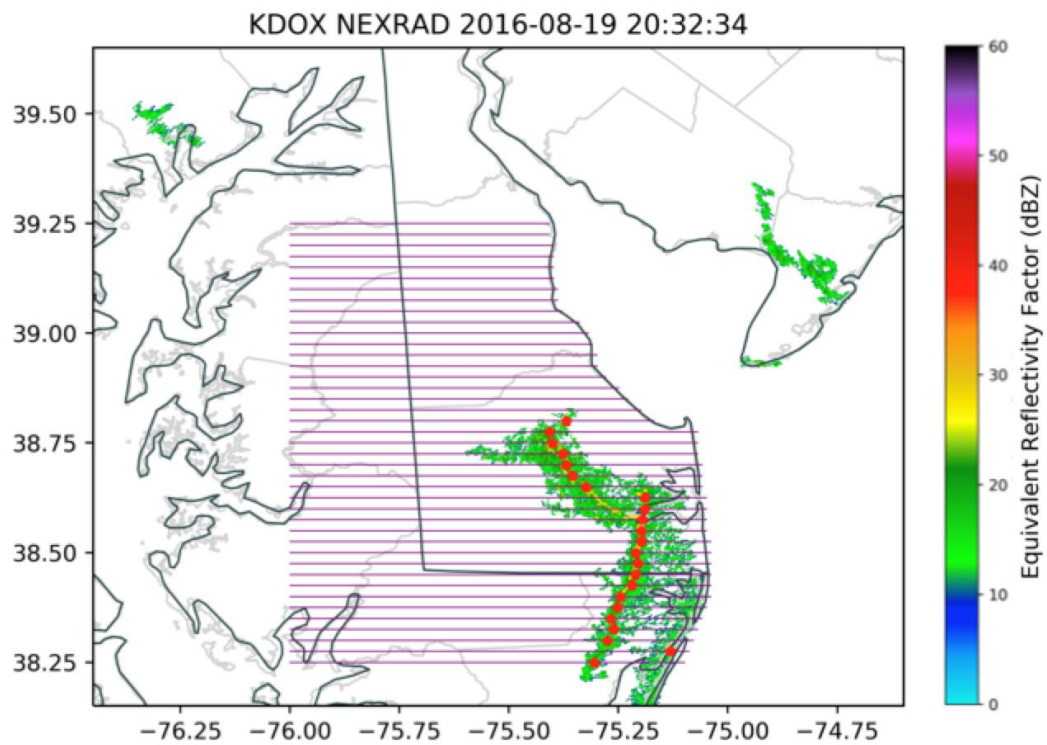


Figure 2.10 Processed radar imagery from KDOX NEXRAD station valid 19 August 2016 20:32:34 UTC shown in reflectivity (dBZ). The SBF is identified by the red points along the purple latitudinal transect lines. A double front forming along the inland bays causes one SBF coordinate to be detected closer to the coastline than the others, which have identified the primary front south of Delaware. Similarly, the two northernmost transects on the vertical branch of the SBC pass through both the ocean (vertical) and bay (diagonal) branches, but identify only the front closest to the coastline. Data shown are reflectivity data in dBZ remaining after thresholds, feature identification, and sea breeze front detection has been completed.

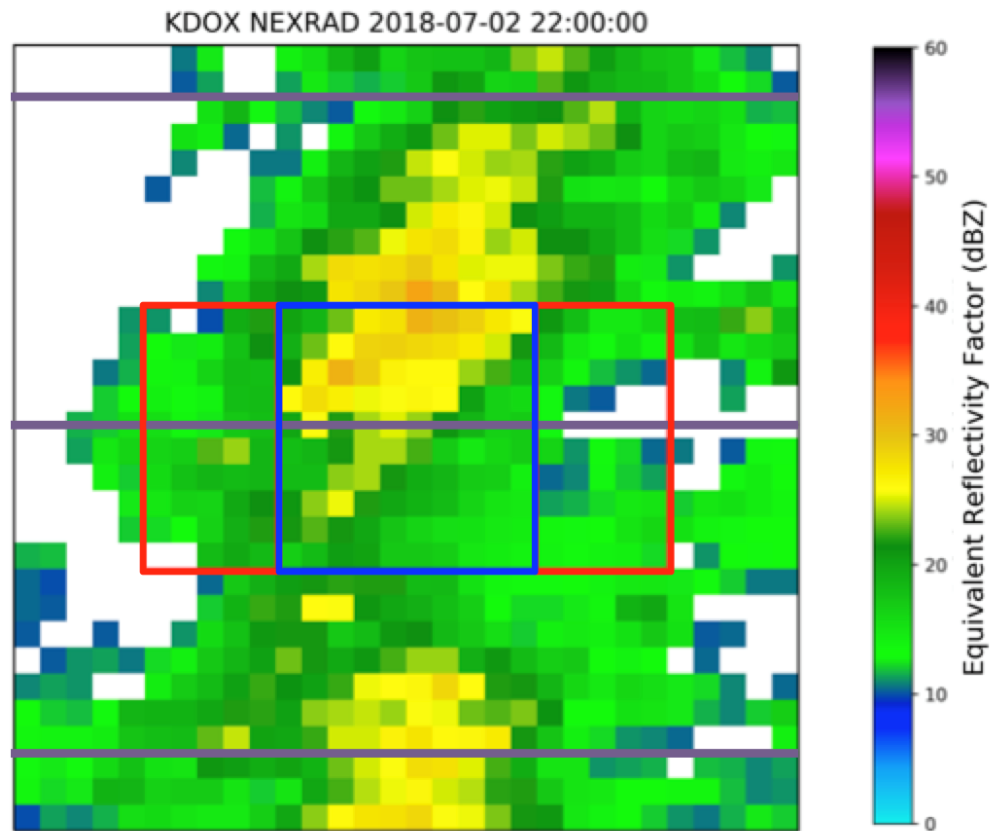


Figure 2.11 Testing a 10x10 nugget (blue square) and 5x10 gradient cells (red rectangles) for sea breeze front suitability along a transect (purple line) for the 22:00:00 UTC radar scan on 2 July 2018 in Delaware (KDOX). Data shown are reflectivity data in dBZ remaining after thresholds and feature identification has been completed.

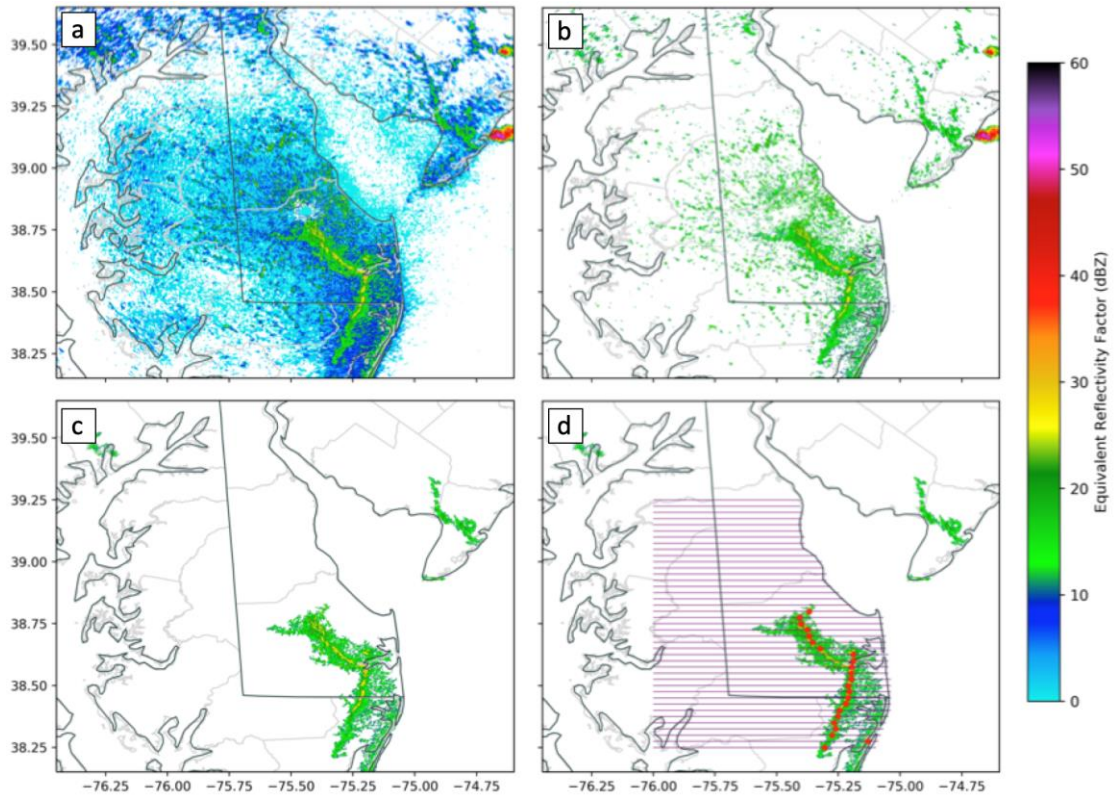


Figure 2.12 The three steps of SBF radar detection beginning with pre-processed reflectivity data (dBZ) that is projected onto a rectilinear grid (a). A >10 dBZ reflectivity threshold eliminates ground clutter and unwanted low reflectivity values (b), and remaining connected features are identified, characterized and eliminated by size, shape and mean reflectivity value criteria (c). Finally, remaining values are analyzed along transect lines (purple, d) to identify the sea breeze front (red, d).

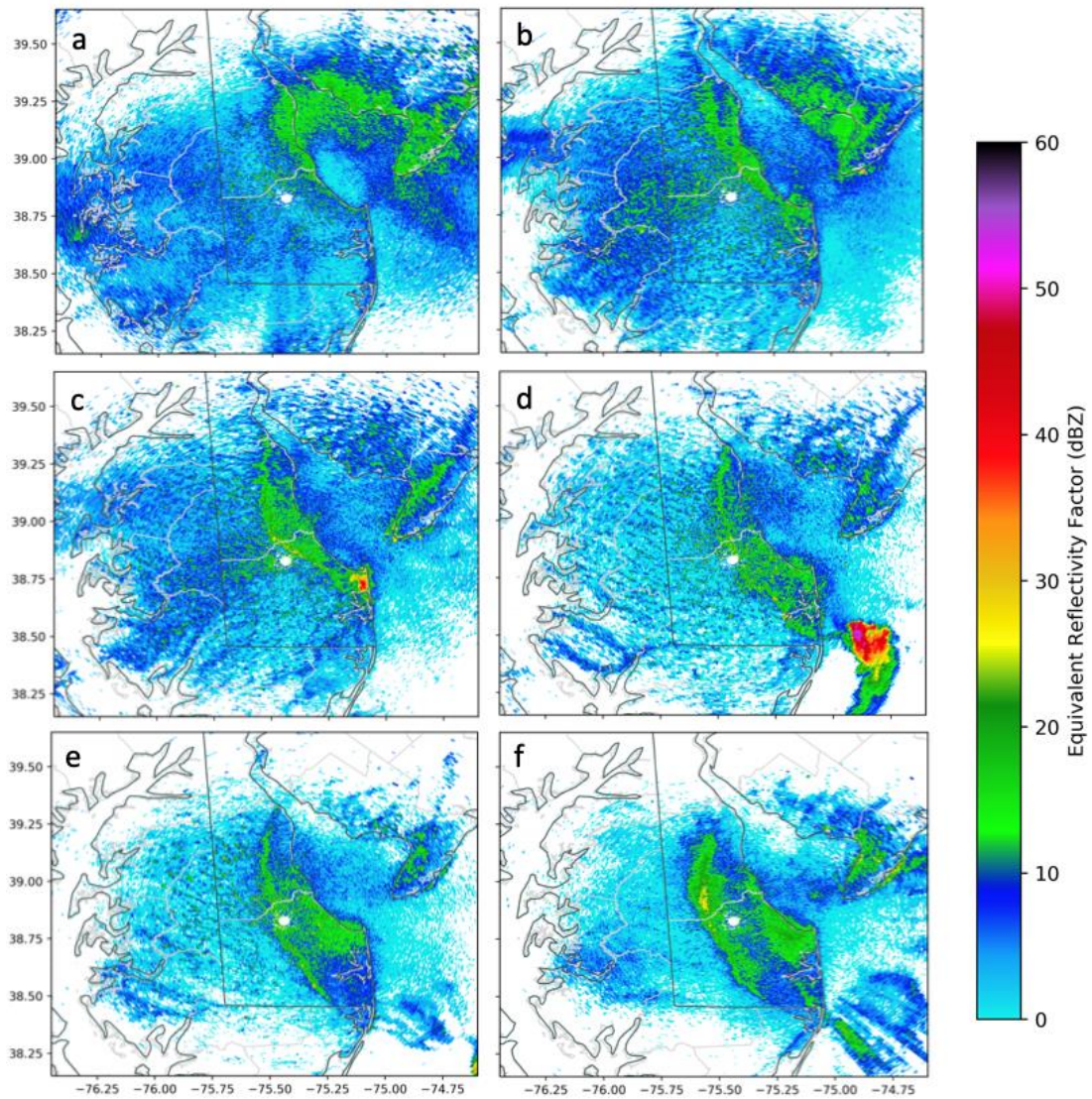


Figure 2.13 Delmarva SBC case study 3 July 2012 at 1303 UTC (a), 1602 UTC (b), 1717 UTC (c), 1921 UTC (d), 2122 UTC (e), and 2231 UTC (f). The SBF forms early (a and b) parallel to the bay (northeast) coastline of Delaware. The developed SBF can be seen as the thin line of 10-20 dBZ (green) reflectivities just onshore of the Delaware Bay in Figure 2.13b. A strong precipitation cell can be seen forming around the convex coastline where the Delaware Bay and Atlantic Ocean coasts meet (c). A second SBF forms along the coastline (e) as the initial SBF propagates inland and dissipates after 22 UTC (f).

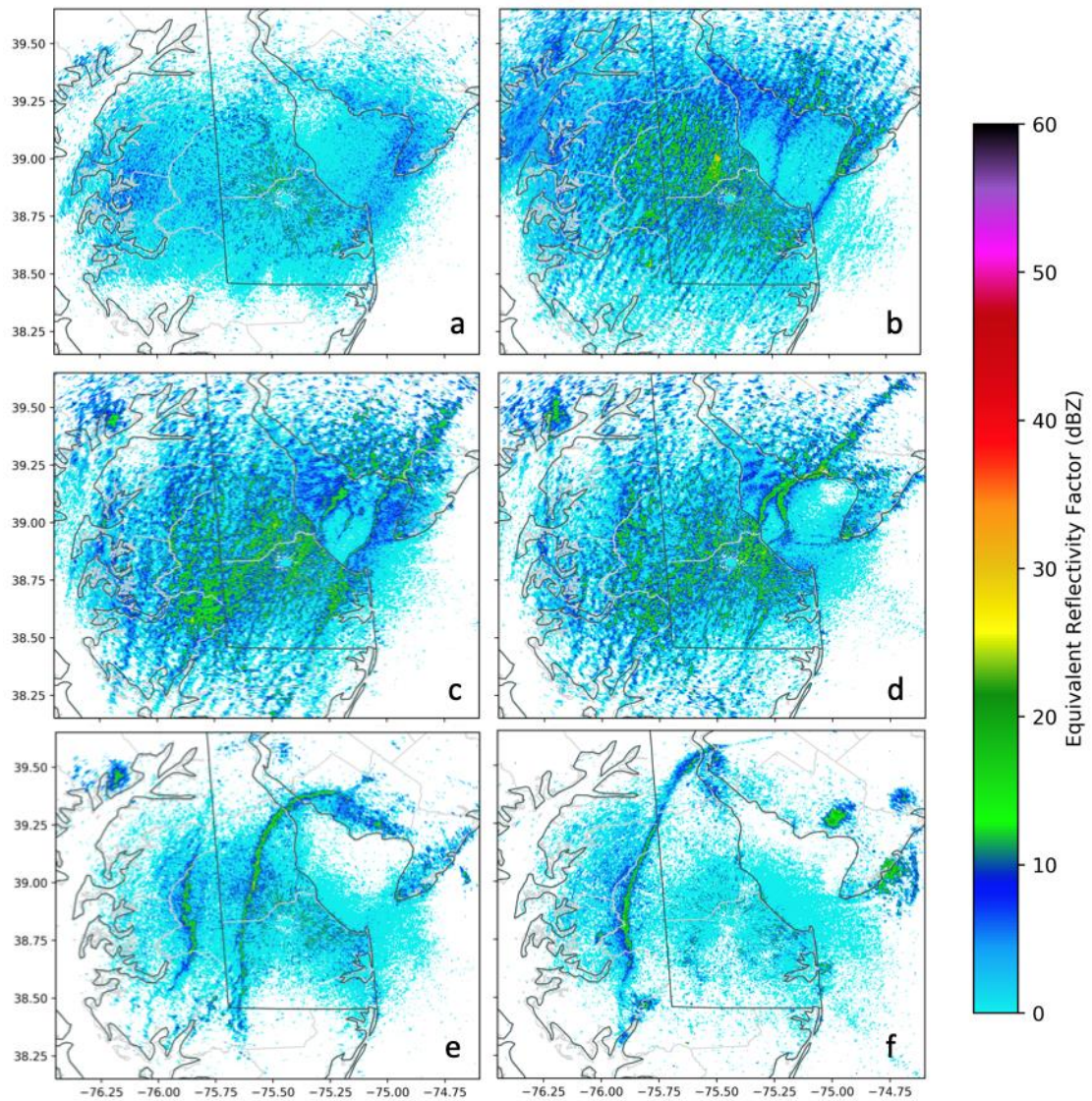


Figure 2.14 Delmarva SBC case study 30 July 2017 at 1300 UTC (a), 1637 UTC (b), 1912 UTC (c), 2011 UTC (d), 2227 UTC (e), and 0006 UTC the following day (f). The SBC is visible as a thin region of high reflectivities relative to the background values that develops roughly parallel to the New Jersey and Delaware Atlantic Ocean coastlines (c). A Chesapeake Bay breeze also enters the study region from the western side of the Peninsula and interacts with the primary SBF (e and f).

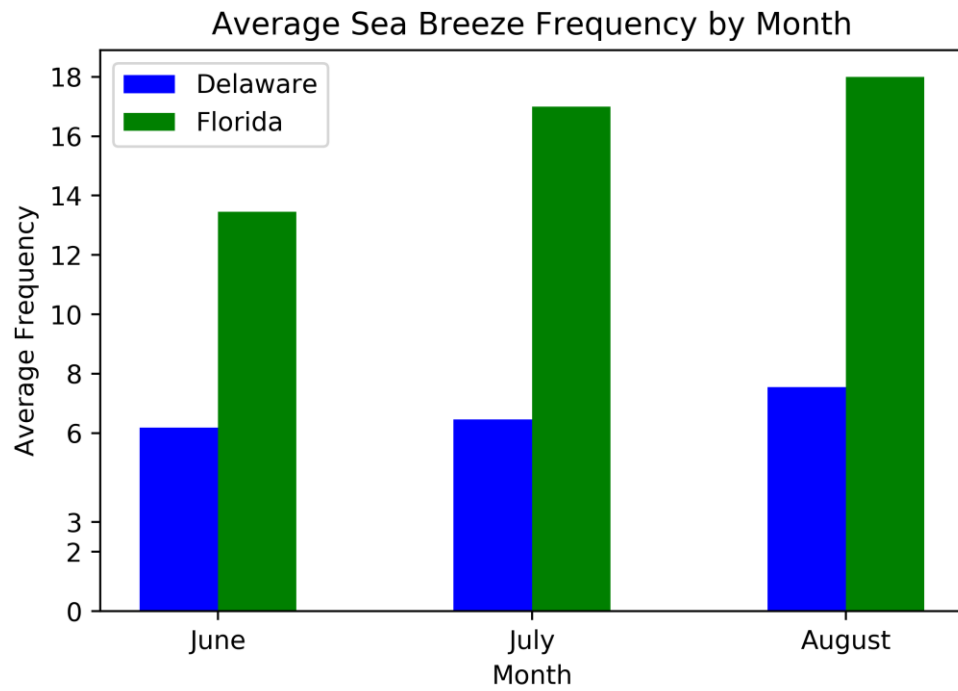


Figure 2.15 Summertime radar-detected sea breeze frequency by month for Delaware (blue) and Florida (green).

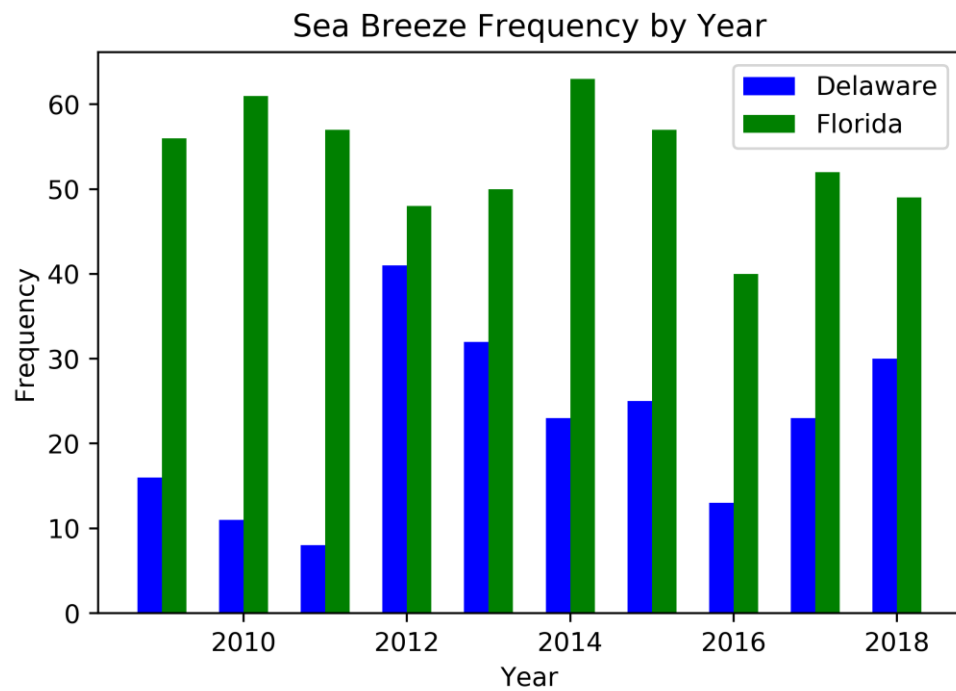


Figure 2.16 Summertime (JJA) sea breeze front detection by year from the Delaware (blue) and Florida (green) radar data using the automated detection algorithm.

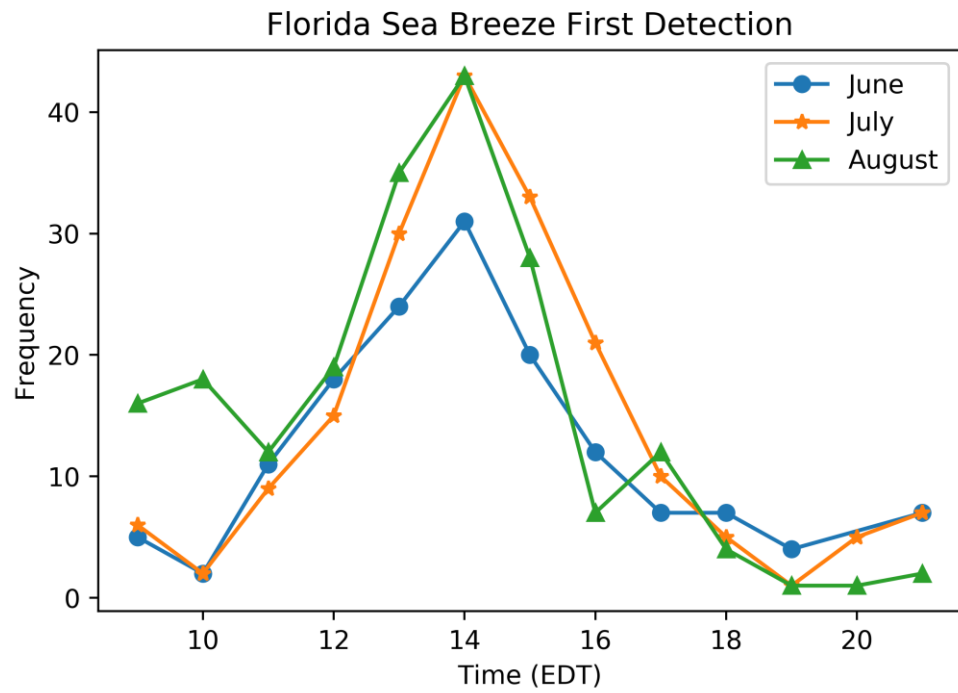


Figure 2.17 Frequency distribution of the time of first SBF detection by month for Florida.

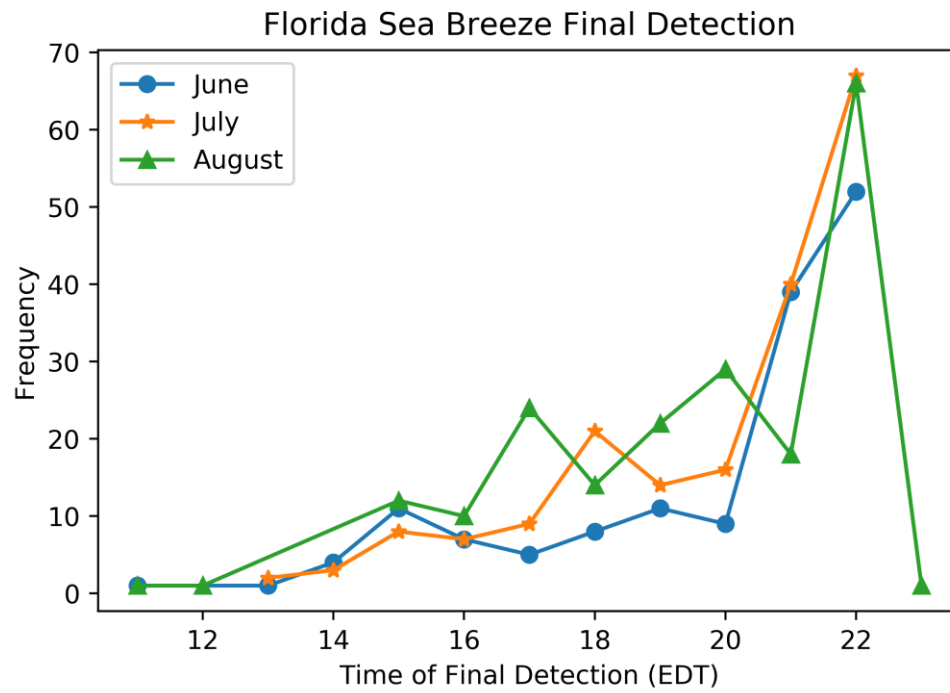


Figure 2.18 As Figure 2.17, for time of final detection.

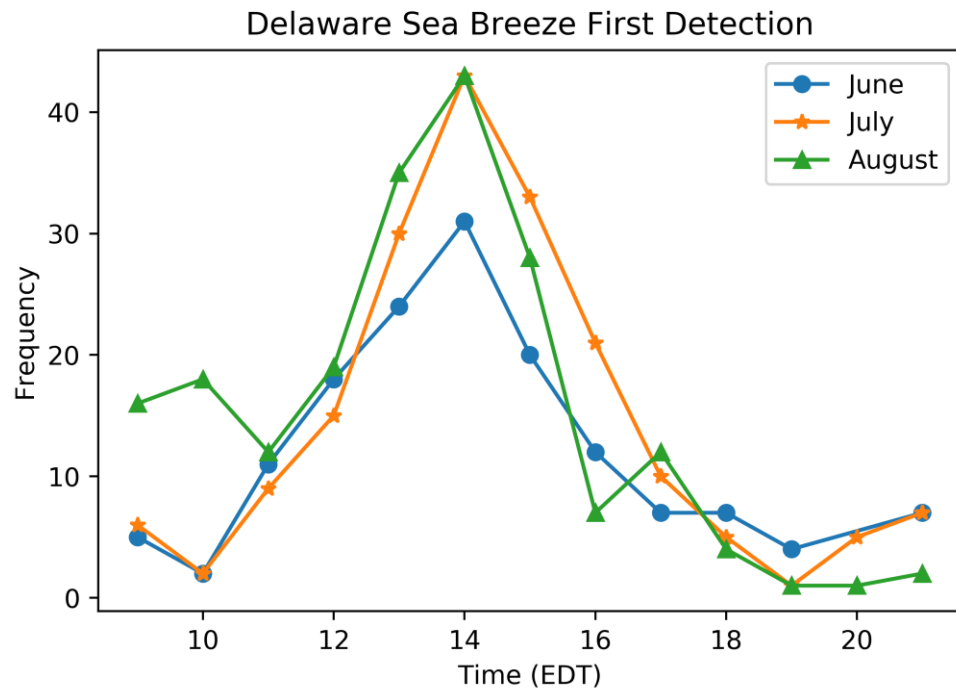


Figure 2.19 As Figure 2.17, for Delaware.

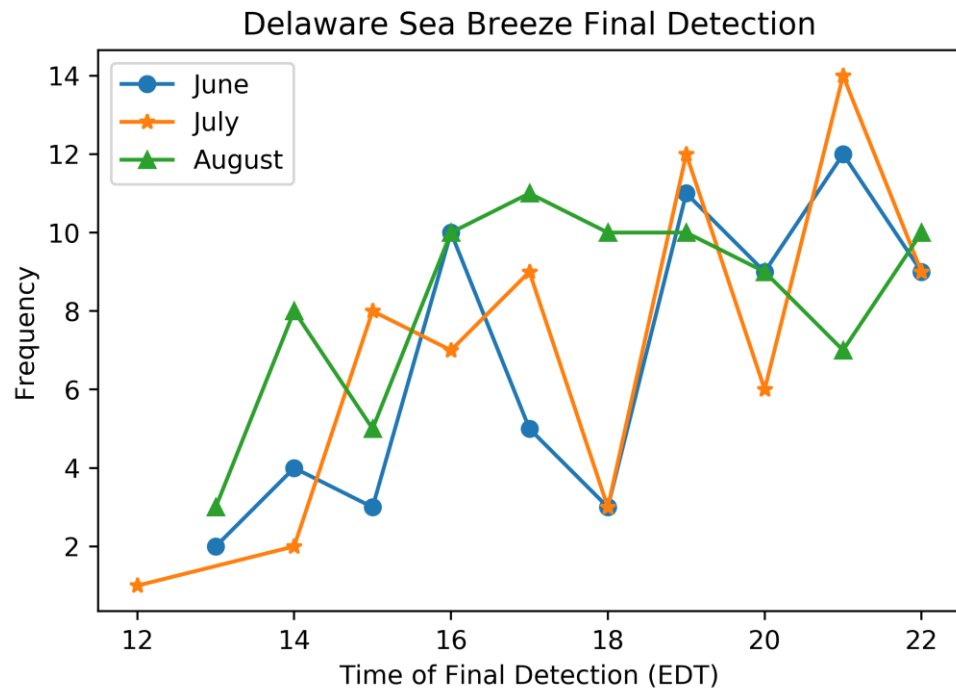


Figure 2.20 As in Figure 2.18, for Delaware.

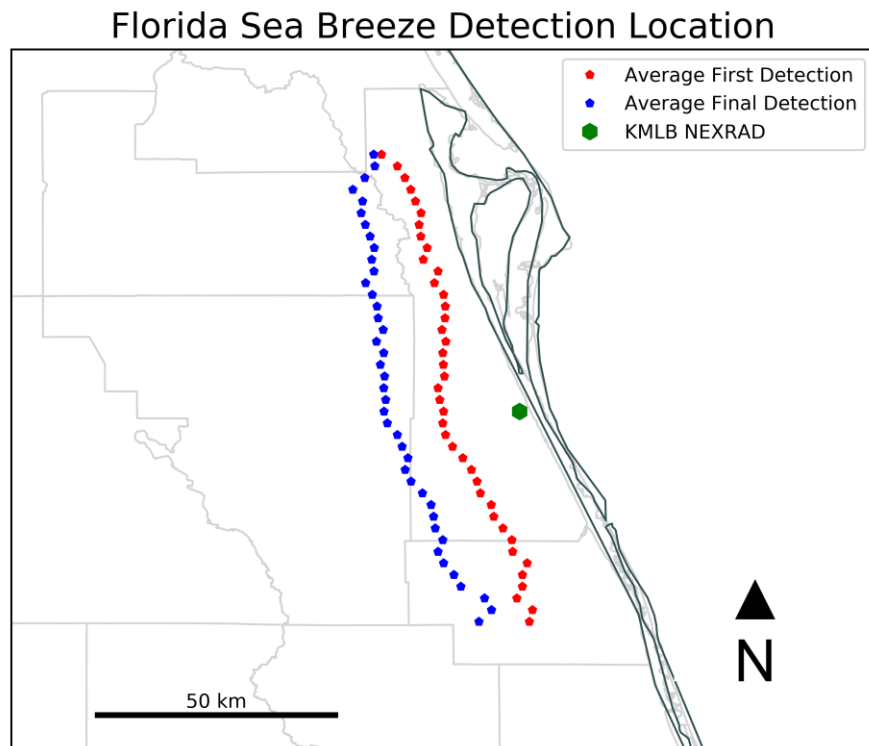


Figure 2.21 Average initial (red) and final (blue) coordinates of detected sea breeze fronts for the Melbourne, Florida (KMLB - green) study region.

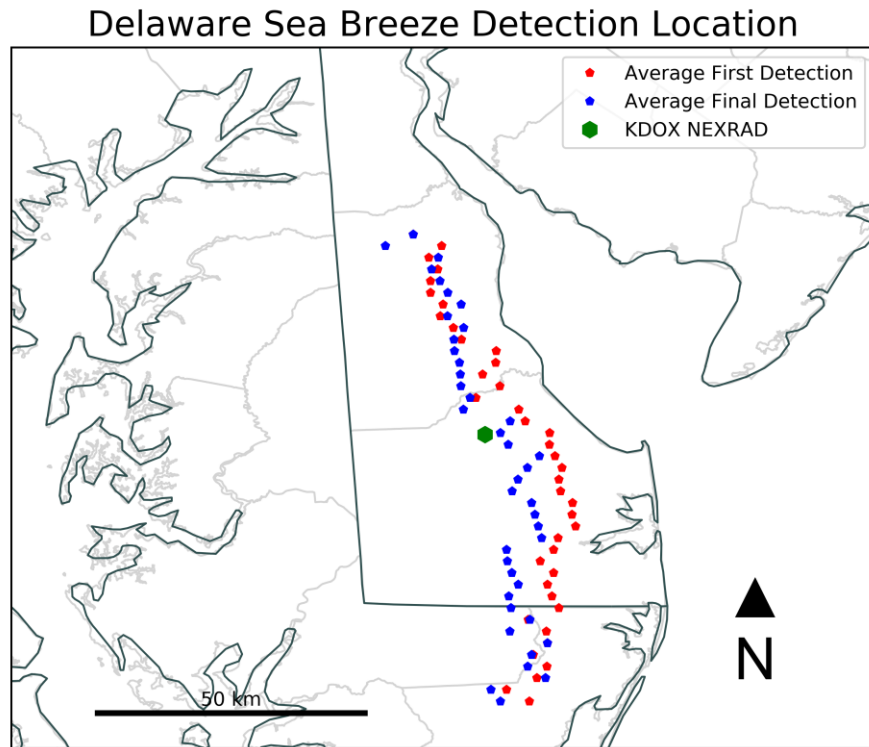


Figure 2.22 As in Figure 2.21, for the Dover, Delaware (KDOX - green) study region.

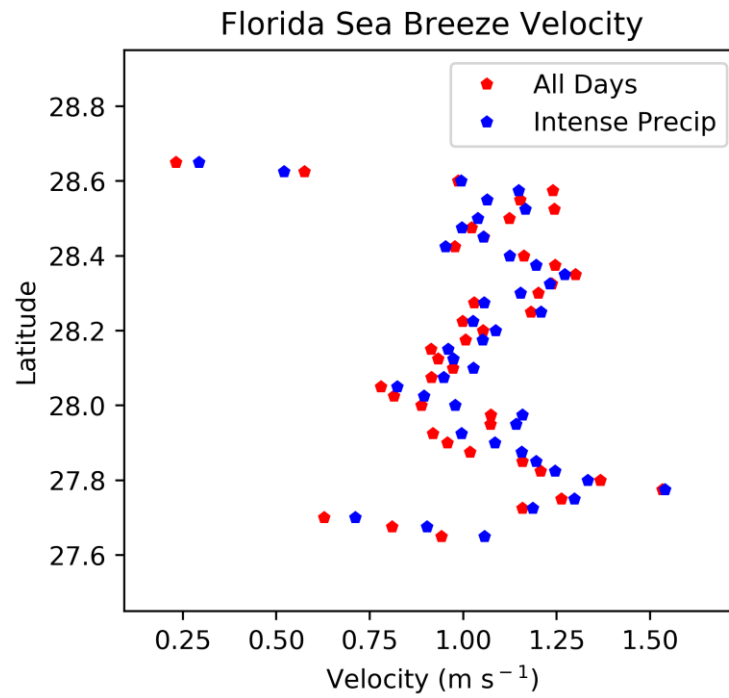


Figure 2.23 Melbourne, Florida SBF average velocity by transect line (latitude) for all days (red) and limited to days with intense (>30 dBZ) precipitation (blue).

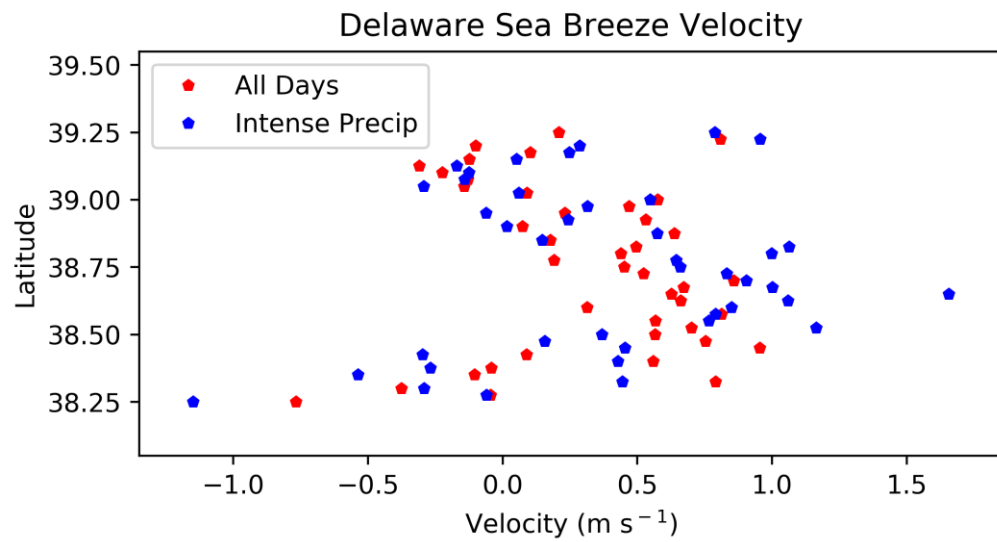


Figure 2.24 Delaware SBF average velocity by transect (latitude) on all days (red) and days where intense (>30 dBZ) precipitation was also detected (blue).

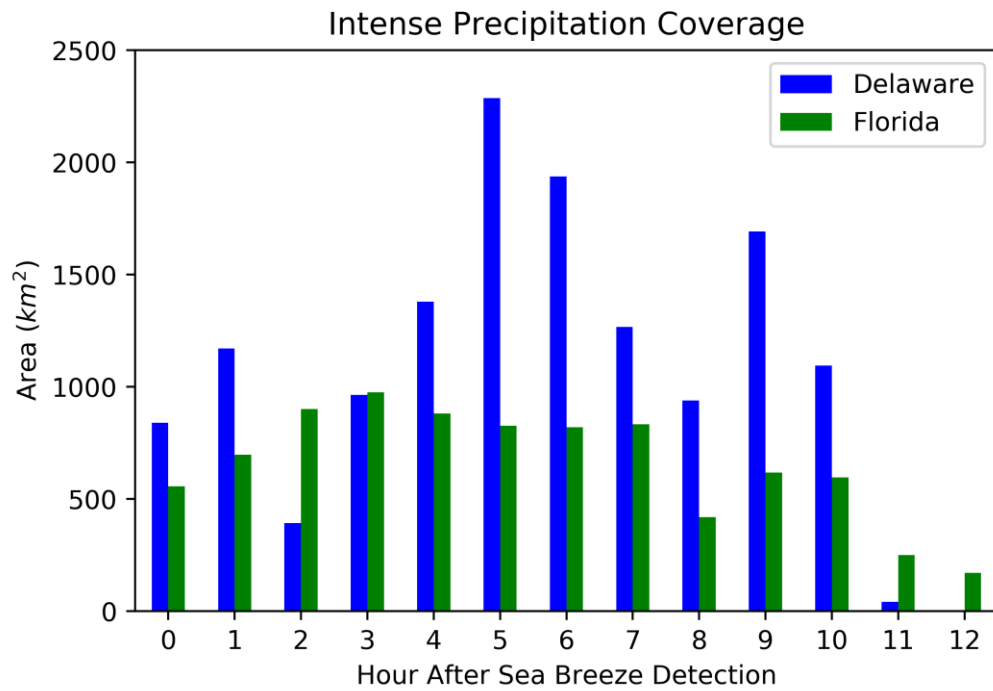


Figure 2.25 Areal coverage (km²) of intense (>30 dBZ) precipitation in Delaware (blue) and Florida (green) study regions by time after initial SBF detection.

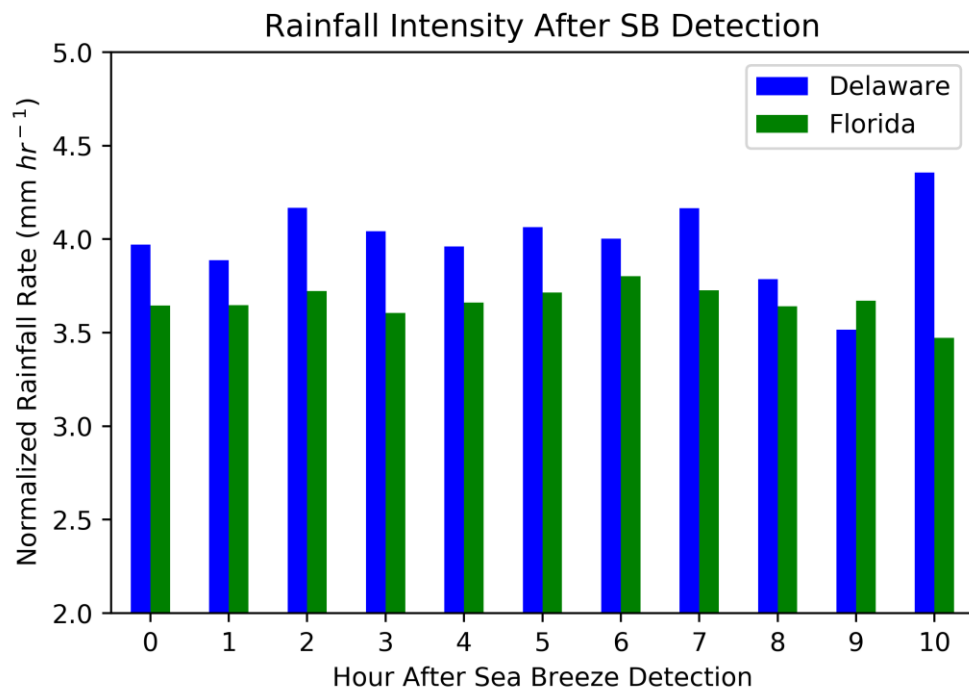


Figure 2.26 Normalized rainfall rate (mm hr^{-1}) of intense (>30 dBZ) precipitation in Delaware (blue) and Florida (green) study regions after initial SBF detection.

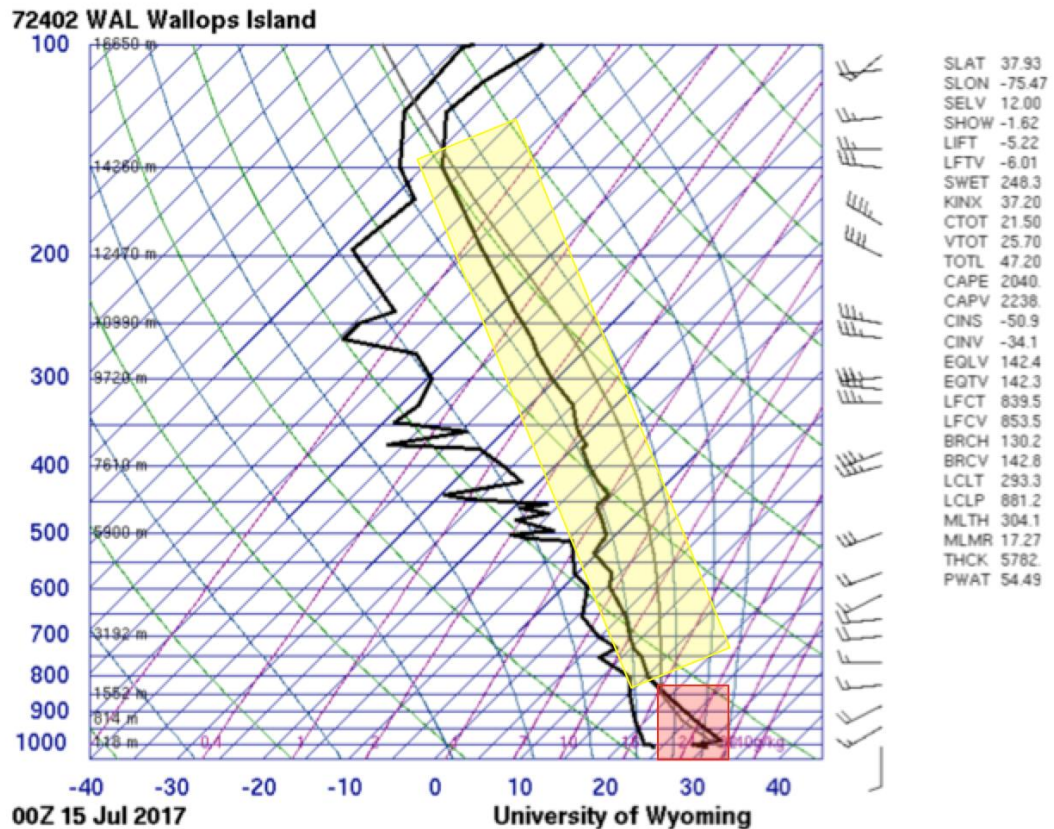
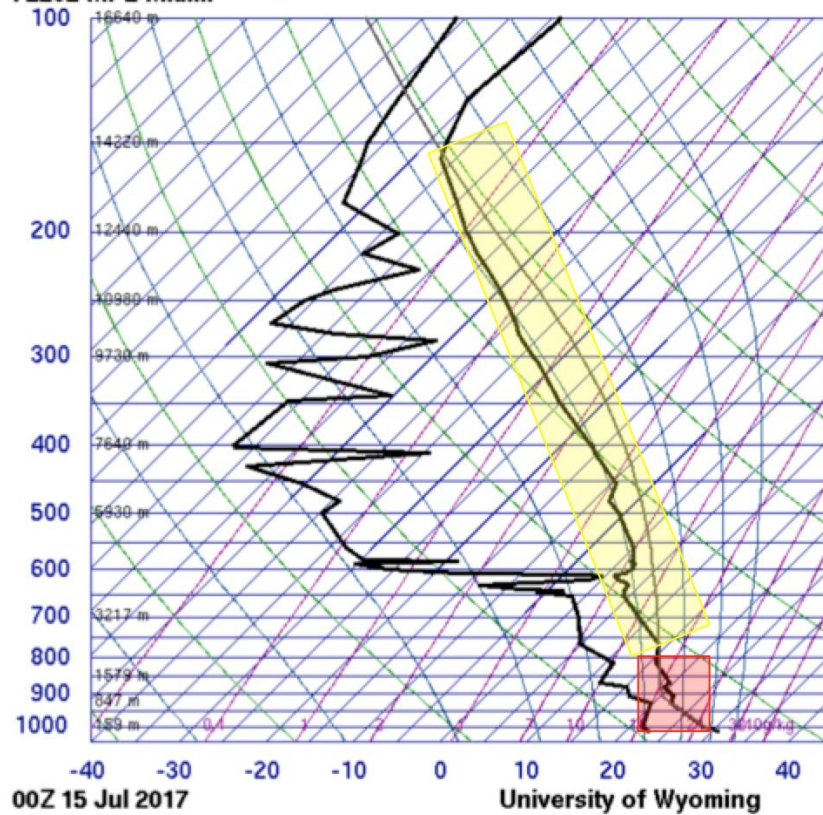


Figure 2.27 Atmospheric sounding valid 15 July 2017 0000UTC at Wallops Island, Virginia, located approximately 140 km south of the Dover, DE (KDOX) NEXRAD system. Convective inhibition (CINV), or cap, shaded in red, can be seen as the low-level area between the temperature profile (black, right) and the parcel lapse rate (gray). Significant convective available potential energy (CAPE), shaded in yellow, can be seen as the area between these two lines above the cap. Source: <http://weather.uwyo.edu/upperair/sounding.html>

72202 MFL Miami



SLAT 25.75
 SLON -80.38
 SELV 5.00
 SHOW 2.95
 LIFT -2.98
 LFTV -3.97
 SWET 173.7
 KINX 28.50
 CTOT 17.10
 VTOT 24.10
 TOTL 41.20
 CAPE 1592.
 CAPV 1835.
 CINS -21.0
 CINV -4.20
 EQLV 155.4
 EQTV 155.3
 LFCT 827.5
 LFCV 883.5
 BRCH 2617.
 BRCV 3016.
 LCLT 293.1
 LCLP 901.9
 MLTH 301.8
 MLMR 16.58
 THCK 5771.
 PWAT 42.92

Figure 2.28 As Figure 2.27 for Miami, FL, located approximately 300 km south of the Melbourne (KMLB) NEXRAD station. Source: <http://weather.uwyo.edu/upperair/sounding.html>

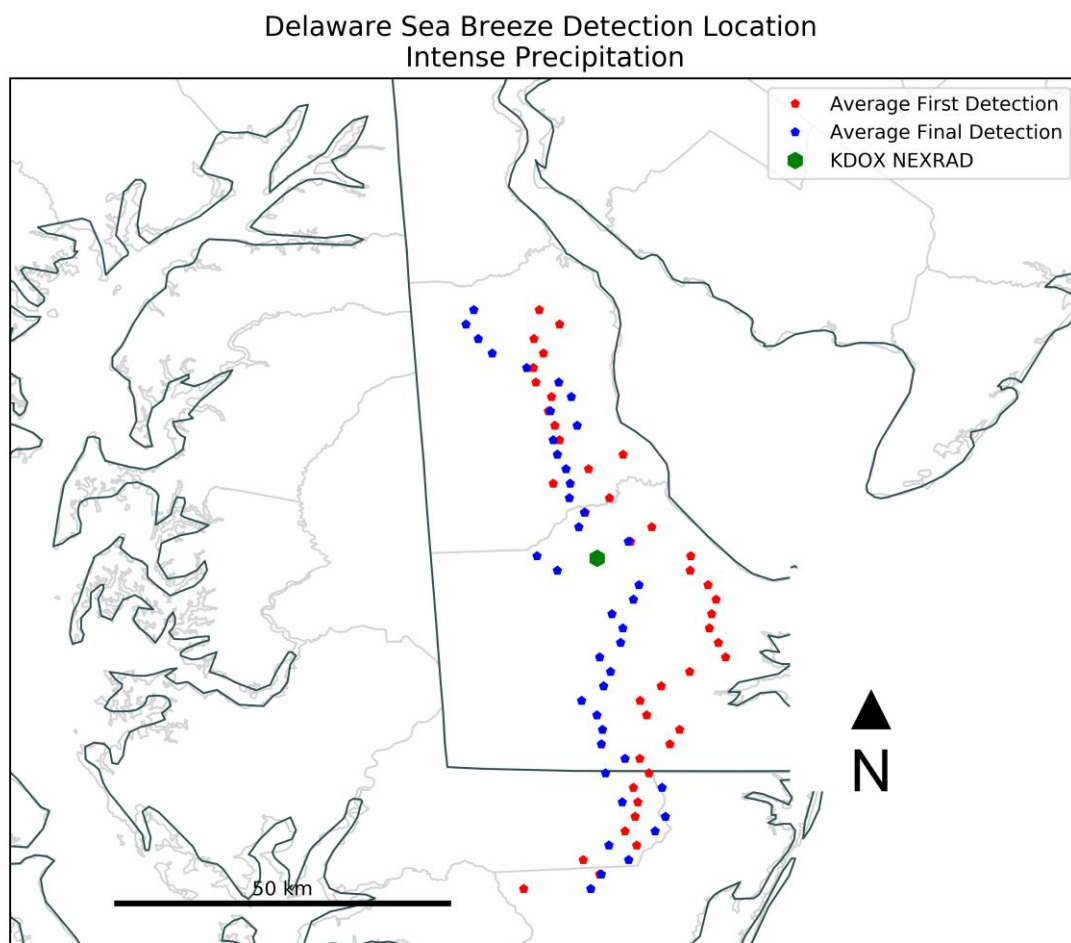


Figure 2.29 As in Figure 2.22 for only days where intense (>30 dBZ) rainfall is detected at the time of SBF detection or after (before 0300UTC the following day).

Chapter 3

A CHARACTERIZATION OF SEA BREEZE ENHANCED RAINFALL IN SOUTH FLORIDA

The summer sea breeze in Florida influences convergence and convection inland, frequently leading to precipitation. However, it is challenging to identify how much this local, low-level circulation contributes to total summer precipitation due to the high spatial variations typical of sea breezes, and the dominance of afternoon convection leading to thunderstorms in the Florida summertime climate. We investigate the Florida sea breeze from a regional perspective using 11 years (2008-2018) of meteorological station data, with a particular emphasis on comparing breezes that initiate on the west coast of Florida to those on the east coast. In addition, we use atmospheric soundings and in-situ surface water temperatures to contextualize the environmental conditions in which these sea breezes occur. The influence of the Florida sea breeze on precipitation is explored using gauge-corrected weather radar data for the same period. Days on which sea breezes are detected observationally are more likely to lead to precipitation than days without detected sea breezes. This is particularly true for days with light synoptic winds, and when sea breezes are detected on both coasts. Further, a case study analysis of summertime precipitation over agricultural areas in Florida reveals that the presence of the sea breeze circulation enhances the probability and accumulation of rainfall in these regions.

The authors of this article are Daniel P. Moore, Dana E. Veron, and Sara A. Rauscher. The chapter was submitted to American Meteorological Society's Journal of Applied Meteorology and Climatology (JAMC) in June 2019. Supplemental images that were not incorporated in the submitted article are referred to here and included as

a separate section after the primary figures. Results from this study increase the understanding of SBCs effects on regional summertime hydrology on the Florida Peninsula, where sea breezes frequently occur along opposing coastlines. Additional work done for this study (see Appendix), not presented in the submitted paper that encompasses this chapter, beckons for further investigation into the relationship between the Gulf Stream along the east coast of Florida and the occurrence of SBC in the Cape Canaveral region.

3.1 Introduction

The SBC is a thermally driven mesoscale phenomenon common in coastal regions that develops due to the differential heating of land and water (Simpson 1994). Water has a higher heat capacity than land. Thus, the solar energy input after sunrise creates a low-level atmospheric pressure gradient force as continental air heats and begins to rise. The warm, buoyant terrestrial air is replaced by cool, dense marine air flowing in over the land surface. An upper-level return flow, which can precede, follow, or act in unison with the low-level onshore flow (Miller et al. 2003) completes the SBC.

The leading edge of the SBC, or the boundary between the continental and marine air masses, is referred to as the sea breeze front (SBF). This area of vertical air motion is where the influx of marine air converges with the rising continental air prior to mixing and/or circulating back over the water. Often, the location of the SBF can be identified observationally by a significant increase in dew point temperature and a decrease in air temperature.

SBCs can occur with as little as a 1 °C gradient between the land and sea surface temperatures (Watts 1955). A larger land-sea temperature gradient is

associated with greater SBF propagation velocity and, ultimately, greater distance traversed by the front. For instance, Barry and Chorley (1992) found that the north Australian sea breeze penetrates as much as a 200 km inland from the Gulf of Carpentaria coast. Similarly, on the northern coast of Brazil, the seasonal formation and propagation of the SBF depends on the magnitude of the surface temperature gradients (Planchon et al. 2006).

Low-level atmospheric convergence initiated by the SBC can influence the development of afternoon thunderstorms (Pielke 1974). On peninsulas or isthmi, sea breezes from opposing coastlines can converge and result in substantial local precipitation (Nicholls et al. 1991). In addition, the low-level winds (i.e. below 700 hPa) may suppress or assist the SBC (Estoque 1962; Michaels 1985; Nicholls et al. 1991; Zhong and Takle 1993). For instance, offshore large-scale winds with speeds $<5 \text{ m s}^{-1}$ are most conducive to upward motion at the SBF, leading to enhanced convection (Blanchard and Lopez 1985).

In Florida it has been observed that isolated convective activity in the summertime contributes significantly to the seasonal precipitation (Miller and Mote 2017; Rickenbach et al. 2015); these isolated convective events are caused and/or enhanced by SBC convergence (e.g. Byers and Rodebush 1948; Kingsmill 1995; Pielke 1974; Pielke et al. 1991). Although the contribution of the SBC to Florida's overall precipitation climatology is difficult to quantify, prior results indicate it is significant (Rickenbach et al. 2015), and we aim to do this at a regional scale. More specifically, the complexity of the land surface in Florida lends itself to highly localized weather patterns based on vegetation, land use, coastline curvature, and soil moisture (Baker et al. 2000). The presence of Lake Okeechobee further complicates

observational studies that aim to characterize SBC related weather patterns in southern Florida. Lake breeze circulations interact with synoptic conditions and SBCs, creating unique, localized weather patterns (Baker et al. 2000).

Utilizing meteorological data extending for 11 warm seasons from 2008-2018, we analyze sea breeze characteristics and their influence on summertime precipitation over the entire south Florida peninsula. Previous work on Florida sea breezes has been limited to the analysis of individual events (e.g. Rao and Fuelberg 2000; Wakimoto and Atkins 1993), short time-series' (e.g. Kingsmill 1995; Ulanski and Garstang 1978), and specific regions, such as Cape Canaveral (Blanchard and Lopez 1985; Cetola 1997; Neumann 1969; Watson et al. 1991). In addition, we perform a statistical analysis of precipitation over agricultural lands to provide a quantitative analysis of the effects of sea breeze on precipitation amount in an area that depends on this rainfall for crop growth. In section 3.2, we introduce the data and methods used, and in section 3.3 we present the results. We then discuss the significance and relevance of our findings within the context of existing literature in section 3.4, and finally section 3.5 serves as a conclusion and summary of the study.

3.2 Methods and Materials

3.2.1 Observational Data

We analyze meteorological data from thirteen stations operated by the Florida Automated Weather Network (FAWN) for 2008 through 2018 (Figure 3.1; University of Florida 2019). Stations were chosen based on proximity to the coast, temporal resolution, and data availability for each year of the study. Although FAWN data are archived back to 1997, this 11-year period was identified as having the most abundant

data for coastal weather stations. Stations near the coast (“test” stations) are where the objective algorithm will detect the passage of a SBF, while stations further inland (“reference” stations) are for comparison of the concurrent meteorological conditions. A two-character identifier is assigned to each station, where the first character represents whether it is an east coast test station (E), a west coast test station (W), or a reference station (R) and the second character is a number assigned from north to south in ascending order, with the northern most test station on the east coast being E1. Due to the sparseness of stations in Florida with publically available sub-daily data, the majority of stations used in this study are at least 15 km inland from the coastline (Table 3.1). The FAWN stations sample precipitation, air temperature, relative humidity, wind direction and wind speed at a rate of 5 to 15 seconds. The data are then archived as fifteen-minute averages. Dew point temperature is calculated from air temperature and relative humidity.

We analyzed a total sample of 2354 days, spanning April to October of 2008 through 2018. Ten “test” stations were selected based on their proximity to the closest coastline (east/west), and further characterized by the directional orientation of that coastline. The three reference stations located near the center of the peninsula represent the dominant large-scale conditions likely unaffected by coastal wind variation at the time of a SBF passage at the coastal stations (Figure 3.1).

In order to characterize the large-scale conditions within which the SBCs develop, 1000-750 mb height atmospheric wind speeds and directions were obtained from the National Oceanic and Atmospheric Association’s Integrated Global Radiosonde Archive (Durre et al. 2016). These data were analyzed to separate warm season days by synoptic regimes following the technique initially developed by Gentry

and Moore (1954) and more recently expanded upon by others to study the Florida SBC and precipitation (e.g. Camp et al. 1998; Mroczka et al. 2010; Mroczka 2003). The 1200 UTC (800 Local Time – LT) Tampa sounding was selected for analysis on the central Gulf Coast of Florida as it has been used previously to highlight the influence of sea breeze on Florida precipitation (Mroczka 2003). Further, this sounding always launches within ninety minutes of sunrise in Florida, so it provides information about the conditions within which a sea breeze may develop.

Surface water temperature data were obtained from NOAA's National Data Buoy Center (NOAA/NDBC 2019) for six buoys on the western, eastern and southern coasts of Florida (see Figure 3.1) in order to relate sea breeze occurrence to periods of extreme warm and cool surface water temperatures. The surface water temperature data were available for the same time period (2008-2018) as the meteorological station data, reporting instantaneous measurements at least every 30 minutes (Table 3.2). Stations MLRF1 and FWYF1 are fixed platforms operated by the NDBC and they measure surface water temperature at varying depths due to the tidal cycle but are referenced to or near the Mean Lower Low Water.

There are frequent disruptions in surface water temperature acquisition from the stations used in this study (as seen in Table 3.2). As a result, in order to analyze the most days for anomalies, a primary station is used in conjunction with a secondary station for each coast (i.e. east, west, and south). In any instance where the data from the primary station for a given coastline are missing over 25% of data for a given day, data from the secondary station are used. Statistical analysis showed insignificant differences in surface water temperature measurements between the primary and secondary stations. The west coast (42013 and 42099) and the southeast (MLRF1 and

FWYF1) buoys produced $r^2 > 0.94$ for the 11-year period. The northeast buoys (41009 and 41113) were in less agreement, at $r^2 = 0.79$, though this correlation value is still sufficient to utilize the primary-secondary station technique (see Appendix).

Precipitation on sea breeze days in Florida is highly localized, and sparse gauge networks alone cannot capture this variability (Burpee and Lahiffi 1984). Thus, our precipitation analysis utilizes the National Centers for Environmental Prediction (NCEP) Stage IV 4-km gridded gauge-corrected radar precipitation dataset. The data cover the entire contiguous United States in addition to Alaska and Puerto Rico. Regional, hourly multi-sensor precipitation estimates (MPEs) are archived and quality controlled by 12 River Forecast Centers (Lin and Mitchell 2005). Data are available from 1 January 2002 onward at the National Center for Atmospheric Research's Earth Observing Laboratory (Lin 2011). Due to the lack of sea-based gauge data, as well as the limits of radar sensing capabilities, offshore MPEs are less accurate and, thus, are not included in this study (Figure 3.2). Further, an artifact exists in these data such that large time-series accumulations magnify a small bias in the rain gauge correction algorithm, which was rectified in 2016 but is present for a large portion of our study period (C. Schaffer 2019, personal communication) (Figure 3.3). Without correction, this effect produces a bias across the study area and prevents direct analysis of spatial variability of rainfall accumulation. Our methodology prevents this bias from influencing the results of this study by employing precipitation values as a proportion of the entire year by grid cell.

These NCEP radar data are obtained in GRIB format on an 1121x881 polar stereographic grid with approximate grid spacing of 4 km (4.7625 km at 60° N), then subset to a 210x280 grid region containing the state of Florida (Figure 3.2). For each

file, individual grid cells, located by center point latitude and longitude, contain the accumulated precipitation amount for the hour prior to the timestamp of the file.

Finally, a land-use mask identifying agricultural land is applied to quantitatively evaluate the potential impact of SBC-related summertime precipitation on agriculture. Farmers in Florida are particularly interested in understanding the mechanisms that drive precipitation during the growing season (C. Maran 2019, personal communication). Thus, Florida land cover and land use data were obtained from the Florida Department of Environmental Protection. These data are a compilation of land use data from five water management districts in Florida resulting from aerial imagery taken between 2012 and 2017. Classification codes are taken from the Florida Land Use, Cover, and Forms Classification System (FLUCCS-DOT 1999), which include nine overarching land use categories each with subcategories. Specifically, the agricultural lands are divided into subclasses; however, for the purpose of our study we will not discriminate between these.

3.2.2 Sea Breeze Characterization

Much of the sea breeze research over the previous 60 years has focused on forecasting the occurrence of sea or lake breezes (e.g. Biggs and Graves 1962; Hall 1954). Most studies utilize observations from two or more meteorological stations to detect the presence of a sea breeze (see Laird et al. 2001; Papanastasiou and Melas 2009 for an overview of these techniques). These detection schemes often require a wind direction shift from offshore to onshore along with a temperature gradient from a coastal station to an inland station to indicate the presence of a SBC (e.g. Arrillaga et al. 2016; Borne et al. 1998).

For this study, detection of the sea breeze at coastal stations is primarily characterized by a change in wind direction from an offshore to an onshore wind across a given time interval following Hughes and Veron (2018). Due to Florida's geography with a complex coastal shape and a landmass surrounded by water on three sides, wind direction shifts are defined at individual stations relative to the orthogonal of the nearest coastline. Previous methods eliminate days with onshore synoptic flow $>1 \text{ m s}^{-1}$ (e.g. Hughes and Veron 2018; Papanastasiou et al. 2010); however, it has been shown that the Florida sea breeze can still persist through such conditions (Cetola 1997) so we include them here, identifying five distinct sea breeze types while maintaining a particular interest in the classic sea breeze conditions (defined below and in Table 3.3) as they are most likely to affect precipitation.

Many factors influence the strength of the SBC, as well as the speed and orientation of the SBF. Prior studies have shown there is a large variation in sea breeze types, depending on coastline geography, prevailing large-scale winds, and strength of the land-surface temperature gradient. Therefore, in order to capture all variations of the Florida sea breeze, five types of sea breezes are identified using an objective detection algorithm: classic sea breeze, weak sea breeze, classic dew point sea breeze, classic wind speed sea breeze, and dew point wind speed sea breeze, as listed in Table 3.3. These five sea breeze types are categorized by spatial and temporal changes in temperature, dew point temperature, wind speed and direction over a one-hour period (Supplemental Figure S3.1). The one-hour evaluation period advances in 15-minute intervals during daylight hours. For each time step, a reference value is calculated as the mean value across the three reference stations R1-R3. A gradient refers to the difference between the test station value and the average value across the reference

stations. Compared with previous studies utilizing a similar detection method (Hughes and Veron 2018), this method allows for detection of classic sea breezes with an onshore reference wind as long as the test station wind is 45° closer to the onshore vector orthogonal to the nearest coastline.

The objective detection algorithm first checks for the presence of a classic sea breeze, which is the most likely of all sea breeze types in this study to generate precipitation. If a classic sea breeze is present, the day is categorized as a classic sea breeze day. If a classic sea breeze is not detected, the algorithm performs a second pass which categorizes days based on the first detected sea breeze type of the remaining sea breeze detections.

For the characterization of each detected SBF, wind direction, wind speed, dew point temperature, and temperature measurements at the test station are averaged for one hour prior to onset, and one hour after onset. The average reference values for each variable are calculated for the same time intervals. Pre- and post-SBC characteristics are then analyzed to better understand SBC occurrence in Florida.

3.2.3 Environmental Characterization

The lower atmospheric layer (1000-700mb) has an important influence on diurnal sea breeze activity (Gentry and Moore 1954; Nicholls et al. 1991; Wilson and Megenhardt 1997). To assess the large-scale regimes occurring during the warm season, an average wind vector was created by averaging wind speed and direction across the 1000, 925, 850, and 700mb height data from the Tampa radiosonde. A two-character code based on the direction (variable – V, north – N, east – E, south – S, west – W) and magnitude (light – L, moderate – M, high – H) of the mean wind speed vector indicates the assigned regime. Light winds are defined as <4 nautical miles per

hour (knots) (2.1 m s^{-1}), moderate winds are 4-10 knots ($2.1\text{-}4.1 \text{ m s}^{-1}$), while high winds are >10 knots ($>4.1 \text{ m s}^{-1}$) (National Weather Service 2016). The majority of study days ($\sim 86\%$) fall into regimes EH, SM, SH, WM, and WH (Table 3.4). Due to data availability, only 2311 out of 2354 days were classified into a regime with the remaining days lacking data for the 1200 UTC sounding.

Along with low-level atmospheric flow patterns, the land-sea temperature gradient is often the major driving force of the SBC, affecting the SBF penetration velocity and displacement (Barry and Chorley 1992). Consequently, inter-seasonal changes to surface water temperature can greatly impact the frequency and strength of the SBC by altering the diurnal surface temperature gradient. Surface water temperature anomaly lends insight into the impact that surface water temperature characteristics may have on the SBC-related precipitation on the southern Florida peninsula. We employ an anomaly analysis, as opposed to direct comparison of surface water temperature and sea breeze frequency, because of the similarities in their seasonal trends (D. Legates 2019, personal communication). For instance, peak surface water temperature values align with the highest frequencies in SB detection.

In order to detect anomalous surface water temperature values, each day was assigned a value, θ , from 0 to 2π according to the equation:

$$\theta = d \frac{2\pi}{365.25} \quad 3.1$$

where d represents the day of the year. A sinusoidal regression analysis was then performed to capture the seasonal surface water temperature cycle throughout the year. Daily predicted surface water temperatures for each coast are calculated using:

$$SWT(\theta) = \alpha \sin(\omega \theta + c) \quad 3.2$$

where SWT is the modeled (average) daily surface water temperature, α is the amplitude, ω is the frequency, and c is the phase shift of the sine curve. The modeled values are then subtracted from the daily observations to create surface water temperature anomalies. The time-series for each buoy shows an insignificant temperature trend over the 11-year period, thus a correction for an overall warming is unnecessary for the given study.

An extreme value is defined here as one standard deviation away from the mean value. Thus, if an observed daily surface water temperature is one standard deviation above (below) the predicted value for that day, it is categorized as a positive (negative) extreme. The sensitivity of the results to this definition of extremes was also explored by looking at two and three standard deviations from the mean.

A chi-squared one-sample test determines whether surface water temperature extremes influence sea breeze station detection. Extremes at buoy 41009 are examined with regards to station detection at E1 due to its location in the northeast of the study region. Stations E2, E3, and E4 are tested alongside buoy MLRF1, and water temperature extremes at buoy 42013 are used for all west (W^*) coast stations (see Figure 3.1).

3.2.4 Precipitation analysis

The importance of sea breeze to summertime precipitation in Florida has been long understood (e.g. Byers and Rodebush 1948; Estoque 1962; Neumann 1969; Pielke 1974). Recent studies emphasize that the SBC plays a role in coastal convective activity and precipitation (Birch et al. 2015; Chen et al. 2016; Liang et al. 2017; Vemado and Pereira Filho 2016).

For the purpose of this study, daytime accumulated rainfall (DAR) is defined as the accumulated precipitation for 1200-0300UTC (which corresponds to 0800-2300 EDT) and will be associated with the date during which the time-series begins. This time period is chosen because of its previously observed association with sea breeze duration and influence on daily precipitation (Burpee and Lahiffi 1984). A summation of DAR for the summer (JJA) days for each year gives the annual summertime accumulation (ASA); ASA averaged across our study period of 11 years (2008-2018) is defined as the mean annual summertime ASA (MASDAR). We analyze variations in MASDAR to investigate the influence of sea breeze presence on initiating and/or enhancing summertime precipitation. Accumulated DAR on subsets of days based on sea breeze detection was compared to the overall MASDAR to determine the influence of SBC on daytime rainfall totals in the summer.

Sea breeze enhanced precipitation is defined as precipitation that occurs on a day when a sea breeze is detected. Because of the complexity of the thermodynamics in the region, it is difficult to confirm through available observations that certain precipitation events are sea breeze-initiated. However, a size-based classification revealed that isolated precipitation events contribute up to half of all precipitation in southern Florida with the majority of these events occurring during the summer (Rickenbach et al. 2015). Further, the presence of sea breeze, specifically in conjunction with opposing synoptic flow, is shown to cause and/or enhance isolated precipitation events through convergence and convection (e.g. Byers and Rodebush 1948; Kingsmill 1995; Pielke 1974).

To investigate the role of the large-scale wind field on rainfall in Florida, we also analyzed the probability of precipitation (PoP) on subsets of days, based on sea

breeze detection and synoptic regime. PoP is calculated as the frequency each grid cell captures a “rainfall event” relative to the total number of cases. A “rainfall event” is defined per grid cell as a measured rainfall depth of greater than 0.5 mm for the defined 15-hour period. The purpose of this threshold is to avoid false detections of low rainfall totals due to measurement error at the meteorological station gauge used for radar correction. The accumulation bias discussed above (see Figure 3.3) is insignificant at the daily time scale, and thus can be ignored for the calculation of PoP (C. Schaffer 2019, personal communication).

3.2.5 Agricultural Land Case Study

In order to better understand the difference in precipitation characteristics on sea breeze and non-sea breeze days, we analyze PoP and MASDAR over agricultural land where the impact of SBC-influenced precipitation may be most important. Land use data from the Florida Department of Environmental Protection were used to mask the precipitation grids. A NCEP precipitation pixel is associated with agriculture if its center point is located inside an agricultural land use polygon. This method results in a slight overestimate of agricultural land (16%). For the present study, a primary focus will be placed on classic sea breezes, during which large-scale winds oppose the SBC, as they are most likely to influence local precipitation (e.g. Blanchard and Lopez 1985; Nicholls et al. 1991; Burpee and Lahiffi 1984).

Distributions of daily rainfall accumulations for the 15-hour daytime period of 12UTC-03UTC are created for each of the sea breeze categories (i.e. east coast, west coast, both coast, or no sea breeze) for the masked agriculture regions. A statistical analysis determines if there is a significant change in rainfall rate, and overall accumulation during days within these categories. The total rainfall accumulation

where rainfall is >0.5 mm for each grid cell is concatenated across all events that fit the following individual categories: classic east coast sea breeze, classic west coast sea breeze, classic sea breeze on both coasts, and no classic sea breeze. The median and inter-quartile range (IQR) values of these distributions are compared to determine if the average grid cell during these events amasses a statistically greater total amount of precipitation per event compared with days with no detectable classic sea breeze. An event is defined here as a single day 1200-0300UTC accumulation. For positively skewed distributions, like the precipitation amount per event, IQR is a better measurement than standard deviation because it is unaffected by outliers (Blalock 1972).

3.3 Results

3.3.1 Observed sea breeze characteristics

Analysis of the station data show that at least one type of sea breeze was detected by one or more stations in Florida on ~97% of days during the study period. Specifically, the classic sea breeze was detected by at least one station on ~65% of days, which is slightly higher than the frequency found for the Cape Canaveral sea breeze (Cetola 1997) of ~60% frequency for May-October. The frequency of classic sea breezes increases to approximately 84% during the peak summer months (JJA). The actual sea breeze frequency at the coast is likely higher as our detection algorithm is limited by station availability; most of the stations used in this study are >30 km from the coastline (see Table 1). Because of this, weaker sea breezes that do not penetrate far enough inland will go undetected. Further, this methodology may bias toward certain sea breeze types that penetrate further inland, like those associated with

onshore low-level flow (e.g. classic wind speed, and dew point temperature wind speed sea breezes).

The overall monthly frequency of Florida sea breezes detected in this analysis peaks in the summer months, specifically in July. However, this feature varies by sea breeze type (Figure 3.4). In particular, classic sea breezes follow the characteristic seasonality observed in other studies (e.g. Hughes and Veron 2018; Cetola 1997) with an increase in frequency during the hottest months when diurnal heating of the land surface is greatest. In contrast, sea breezes characterized by dew point temperature changes decrease in number during the summer months (see Figure 3.4). This is most likely due to the overall increase in humidity during the peak summer months in Florida (Gaffen and Ross 1999). A classic dew point temperature sea breeze propagating inland in June and July may pass through a station undetected because the increase in dew point temperature is below the threshold used in this study.

Temperatures drop after the passage of classic sea breezes along each coast as expected, with mean temperatures before and after sea breeze detection of $28.2 (\pm 3.4) ^\circ\text{C}$ and $25.1 (\pm 4.2) ^\circ\text{C}$ (Figure S3.2), respectively for the east coast, and $29.4 (\pm 2.2) ^\circ\text{C}$ and $26.4 (\pm 2.3) ^\circ\text{C}$ (Figure S3.3), respectively for the west coast. Similarly, the wind shifts from offshore to onshore in classic sea breezes on both coasts (Table 5; Figures S3.4 & S3.5). It is important to note here that results show no appreciable change to the wind speeds before (East – $2.93 \pm 0.87 \text{ m s}^{-1}$; West – $2.97 \pm 0.96 \text{ m s}^{-1}$) and after (East – $2.94 \pm 1.00 \text{ m s}^{-1}$; West – $2.87 \pm 0.97 \text{ m s}^{-1}$) SBF passage on either coast (Figures S3.6 & S3.7), contrary to other studies (e.g. Hughes and Veron 2018, 2015; Cetola 1997).

SBC occurrence in Florida varies spatially. The stations closest to the coastline detect SBF passage at a higher frequency than stations further inland (Table 6). However, this variation is very slight for classic sea breezes. Instead, the spatial variability of overall SBC occurrence is due to the high detection rate of weak and classic dew point sea breezes by the near-coastal stations in this study. In particular, classic dew point sea breezes are much less frequent inland of 32 km, with the exception of station E2, which may be influenced by its proximity to Lake Okeechobee. It is important to note that although strong lake breezes influence timing and location of precipitation, they have not been shown to greatly alter the precipitation intensity or overall precipitation amount (Baker et al. 2000).

There is a higher frequency of instances where multiple stations detected a classic sea breezes on the west coast (61%) compared to the east coast (43%). The difference in these frequencies may be attributed to the sparseness of meteorological stations on the east coast of Florida. Moreover, the sea breeze is a highly localized phenomenon, sensitive to small-scale (<1 km) variations in land-surface and coastal geography (Miller et al. 2003). The test stations used in this study are a mean distance 40 (± 28) km apart on the west coast, and 91 (± 40) km apart on the east coast so that sea breezes that pass between stations may be missing from the analysis.

Sea breeze arrival times differ significantly ($p < 0.001$) depending on the coastline with the east coast experiencing classic sea breezes roughly one hour earlier (14.3 ± 2.1 LT; Figure S3.8) than the west coast (15.2 ± 2.0 LT; Figure S3.9). This difference is not related to station distance to the nearest coastline. E3 and W5 are both located 15 km from the east and west coastlines, respectively. However, the average classic sea breeze passage at E3 (13.3 ± 1.9 LT) is one hour earlier than at W5

(14.4 ± 1.8 LT), significant at $p < 0.001$. This may be caused by greater land-water temperature gradients on the east coast.

In order to investigate the influence of surface water temperature variation on sea breeze frequency, we analyzed sea breeze occurrence for extreme daily surface water temperature values for the study period as described above. Our results show that anomalous daily variations in surface water temperature away from the seasonal average do not have a statistically significant influence on the frequency of sea breezes for the entire study period (see Appendix). Chi-squared one-sample tests of observed and expected frequencies of sea breeze detection given surface water temperature anomalies at one, two, and three standard deviations were performed. In each case, the null hypothesis could not be rejected at the $p < 0.1$ significance level. This result is likely due to the overwhelming effect of the solar insolation during the summer months creating buoyancy and onshore flow regardless of surface water temperature in this particular region.

3.3.2 Effect of large-scale wind on sea breeze

Previous studies show the importance of the prevailing synoptic winds on SBC development, strength and penetration (e.g. Estoque 1962; Michaels 1985; Watson et al. 1991). Specifically, the position of the Bermuda high pressure dominates the synoptic influence of weather on the Florida Peninsula (Blanchard and Lopez 1985). Analysis of the synoptic regime using sounding data shows that strong large-scale flow (e.g. regimes EH, SH, and WH) dominates the synoptic forcing outside of the peak summer months (Figure 3.5). In contrast, regimes characterized by decreased large-scale wind speeds out of the south and west (e.g. SM and WM) become more frequent in June, July, and August. During this same summer period, there is an

increase in sea breeze occurrence on the peninsula, underlining the importance of local dynamics under weak synoptic conditions.

In order to investigate whether synoptic regime has an influence on coastal SBC characteristics, we analyzed the frequency of classic sea breezes on the east and west coasts against the overall number of days in each synoptic regime (Table 7). These results emphasize the tendency for classic sea breeze events to occur when there is a light ($<2.1 \text{ m s}^{-1}$) or moderate ($2.1\text{--}4.1 \text{ m s}^{-1}$) opposing flow, which is in agreement with previous studies (Estoque 1962; Simpson et al. 1977; Wakimoto and Atkins 1993). For instance, 93.5% of days with a 1000-700mb mean wind vector <4 knots resulted in an observable classic sea breeze along the east coast, west coast, or both. Given an offshore wind vector, relative to each coast, between $2.1\text{--}4.1 \text{ m s}^{-1}$, a classic sea breeze on the east (west) coast was observed with a frequency of 78.6% (74.3%). Detection of classic sea breezes on both coasts simultaneously was significantly more frequent with moderate flow out of the west (41.1%) compared with moderate flow out of the east (18.2%).

For all flow directions (N, E, S, W), the frequency of sea breeze occurring on both coasts decreases, and sea breeze non-detection increases, with increasing low-level wind speeds. Interestingly however, sea breeze detection frequency along the west coast remains at around 75% regardless of the strength of the low-level flow when it is out of the south (regimes SM and SH). Moreover, isolated west coast sea breeze events, during which an east coast sea breeze is not detected, occur more than three times as often ($\sim 16\%$) as isolated east coast sea breeze events ($\sim 5\%$) with the presence of respective onshore flow.

Previous studies show that sea breezes propagate inland more quickly when the synoptic winds are in general alignment with the low-level sea breeze flow (e.g. Baker et al. 2000 and refs, therein). Analysis of the synoptic regime indicate that flow out of the south and west dominate in June and July (see Figure 3.5), and thus should create earlier and greater penetration of classic west coast sea breezes. Our results for classic wind speed and dew point wind speed sea breezes, which are characterized by reference winds in alignment with coastal sea breeze flow, show that these sea breezes tend to penetrate more quickly. We found that the mean detected arrival time for these sea breeze types is nearly two hours earlier on the west coast (13.4 ± 2.4 LT) than classic sea breezes (15.2 ± 2.0 LT; see Figure S3.8; $p < 0.001$), regardless of large-scale wind direction. Similarly, on the east coast, classic wind speed and dew point wind speed type sea breezes are detected earlier (13.0 ± 2.9 LT) than classic sea breezes (14.3 ± 2.1 LT; see Figure S3.9; $p < 0.001$). The prevailing winds acting in unison with the low-level SBC likely expedites the inland penetration of the SBF.

3.3.3 Rainfall characteristics

We analyzed the probability that rainfall will occur in the study area on days when classic sea breezes were detected on either coast by calculating the PoP at each grid cell. Classic sea breeze occurrence on either coast enhances the PoP by up to 50% relative to days that have no sea breeze detected (Figure 3.6). Days classified as having classic sea breezes along both coasts display an even more substantial increase in the average PoP, such that some areas along the west coast experience rainfall approximately 85% of the time (Figure 3.6c). Thus, when there are sea breezes on both coasts, it is highly likely to rain on the peninsula.

In order to investigate the propensity of sea breeze enhanced rainfall to occur under different synoptic regimes, we also analyzed the PoP by regime for instances of classic sea breeze on the east coast, west coast, and both coasts alongside days with no sea breeze detected (Figure 3.7). Overall, on days where the prevailing synoptic winds are onshore relative to the west coast (regimes WM and WH), the largest spatial coverage of high (>70%) PoP values occur throughout the peninsula. When sea breeze is observed along both coasts, regardless of regime, high PoP values have higher spatial coverage relative to isolated (just east or west coast) sea breeze days or non-sea breeze days. During all JJA days, however, the highest PoP values are primarily concentrated along the western coastline (Figure 3.8).

In a comparison of total rainfall accumulation on days with various sea breeze occurrences, a disproportionate amount of rainfall occurs on days that coincide with classic sea breeze detection (Figure 3.9). Although the frequency of days with east coast classic sea breeze detection is only about 22% of JJA days, there are regions, specifically in the northwest portion of the study region, that receive roughly 35% of MASDAR on these days. For west coast classic sea breeze days, which occur roughly 31% of JJA days, the result is even more pronounced, with localized regions along the west coast between Naples and Saint Petersburg experiencing up to 50% of MASDAR on these days. Along the eastern shore of Lake Okeechobee, the percent of MASDAR is ~ 35% (Figure 3.9b) for west coast SBC detection; this could be the result of lake breeze related convergence. Finally, days with classic sea breezes detected along both coastlines experience areas of ~50% of overall MASDAR, specifically around the Everglades and west of Melbourne, although this occurs on only 32% of JJA days.

Urban regions and agricultural lands are particularly interested in summertime precipitation patterns. As a result, we analyze SBC precipitation patterns masked to urban regions (Figure S3.10) with insignificant results. The findings over agricultural lands, however, were significant.

3.3.4 Agricultural Land Case Study

Through a statistical analysis of precipitation over agricultural land use areas, we investigate the overall importance of sea breeze occurrence to summertime rainfall totals in Florida (Figure 3.10). Over the 11-year period, 21.7% of MASDAR occurred on days when a classic sea breeze was detected on the east coast, compared with 14.9% on days when no sea breeze detected, where the frequency of these days were 22.0% and 15.8% days, respectively (Figure 3.11). However, where there is classic sea breeze detection along both coasts, which occurs with a frequency of 31.5% of days, it represents 35.6% of daytime agricultural precipitation.

The statistical analysis of rainfall intensity over agricultural lands per event (i.e. day) yields no significant difference between the event categories of classic east coast sea breeze, classic west coast sea breeze, classic sea breeze on both coasts, and no classic sea breeze, with median (IQR) values of 6.4 (12.1) mm day⁻¹, 6.3 (12.1) mm day⁻¹, 6.6 (13.0) mm day⁻¹, and 6.8 (13.6) mm day⁻¹, respectively.

However, when accumulating the precipitation beyond individual days, the results become significant. After finding no significant difference between percent MASDAR on June, July or August (not shown), a chi-squared one-sample test was performed using the percentage of monthly days that sea breeze occurred on both coasts as the expected result and the monthly percent MASDAR accumulated on those days as the observed result. This revealed that there is a significant ($p < 0.001$) increase

in precipitation over agricultural lands on days that observe sea breezes on both coast. Thus, we conclude that the presence of classic sea breezes along both coasts enhances precipitation accumulation over agricultural lands on the Southern Florida peninsula.

This result is likely understated due to the lack of meteorological stations along coastlines near most of the agricultural regions (see Figures 3.1 and 3.2). Furthermore, a large portion of the agricultural land is located near Lake Okeechobee, in Palm Beach County. It is very likely that complex interactions with lake breezes greatly influence local weather patterns both on days when sea breezes are and are not detected at the meteorological stations utilized in this study, an impact that may dominate rainfall characteristics in the region (Baker et al. 2000).

3.4 Discussion

The results of this study highlight the importance of the low-level atmospheric flow for aiding or suppressing sea breeze on the south Florida peninsula. In alignment with previous research (e.g. Blanchard and Lopez 1985; Estoque 1962; Michaels 1985; Nicholls et al. 1991), light to moderate winds ($<5.1 \text{ m s}^{-1}$) in the 1000-700 mb layer are favorable for sea breeze detection and, thus sea breeze enhanced rainfall events. High winds in this layer appear to suppress the low-level circulation. Further, the strength of the winds influences the spatial variability of precipitation on the peninsula (see Figure 3.8).

Interestingly, our study found no relationship between coastal surface water temperature anomalies and sea breeze detection. Due to the SBC reliance on land-sea temperature gradients, it was expected that lowered surface water temperatures relative to the land surface temperatures would be a primary precursor to sea breeze development. Specifically, as the high temperatures associated with the Gulf Stream

meander toward and away from the east coast, we expected sea breeze frequency to be affected. Our results show that the two buoys located on the northeast of the study region show the least agreement ($r^2 = 0.79$) with a generally lower surface water temperatures at buoy 41113 (see Appendix) located closer to the Florida coastline (see Figure 3.1). This is likely because of either upwelling near the coastline of Florida in this region, or the lateral movement of the Gulf Stream in this region. Further research utilizing higher resolution coastal station data is required to better understand this dynamic system, and thus improve predictability of sea breeze formation.

Our findings in this study are generally in agreement with a previous study that investigated Florida SBC characteristics at a local scale (i.e. one coastline) (Cetola 1997). However, differences in the SBF detection methodology present challenges for comparison with other studies. For instance, we employ a regional approach, with a longer time-series and a larger reference area (i.e. three reference stations) than previous studies. Our analysis demonstrates that classic sea breezes, which have been previously determined to enhance precipitation, occur on the east coast (i.e. summation of east coast and both coast classic sea breeze frequency) at a slightly lower frequency than a study performed closer to the coastline (Cetola 1997) is reasonable given that our study utilizes stations much farther inland. Our results reveal a lower frequency of classic sea breeze occurrence on the east coast (42%) during the warm period (May-October), compared to just over 61% found by Cetola (1997) using two years of data for the same months. However, Cetola (1997) also found that 50% of days observe SBF penetration 30 km or greater, which is within the range of frequency detected for the 11-year period studied here (not shown). Furthermore, we found the frequency of east coast sea breezes increase to over 53% during JJA days.

Other studies have relied upon the use of multiple stations to confirm detection and track the movement of the SBF in coastal areas (Cetola 1997; Hughes and Veron 2018). However, these techniques and analyses were not utilized in this study due to low station density. The average time of SBF passage during classic sea breeze days did increase with distance to the coastline on each respective coast. However, to examine the viability of the algorithm to detect the same sea breeze at multiple stations, we test one region where two stations are positioned such that the SBF is expected to pass through both successively. Station W3 is located directly inland of station W5, meaning that the onshore wind direction linearly connects the two stations (see Figure 3.1). In this region, it is theorized that every SBF that initiates and propagates inland to station W3 will first be detected by station W5. However, initial analysis shows that only 77% of the time inland station W3 detected a SBF, W5 also detected a sea breeze. This may be an effect of localized breezes from the Gasparilla Sound affecting only a portion of the coastline similar to the Delaware Bay Breeze (Hughes and Veron 2018; Gilchrist 2013). The coastline orientation is an important geographic component to understanding local sea breeze dynamics.

Coastline curvature impacts sea breeze related convergence and thus rainfall (e.g. Abbs 1986; Baker et al. 2000). Therefore, it is likely that in regions with convex coastlines localized sea breezes can converge and create isolated rainfall events, even during weak SBC. This can be seen in Figure 3.9b, which highlights a region of high MASDAR percentage on days with west coast classic SB inland of the convex coastline near Naples. High MASDAR, is located between the coastline and the line of test stations (see Figure 3.1), approximately 50-60 km inland. The region has a consistently high PoP (roughly 60%), regardless of SBC occurrence according to our

results (see Figures 3.5 & 3.7), which suggests that convergence and convection is enhanced because of the local coastline shape.

For this reason, meteorological stations inland of convex coastlines may also be prone to false sea breeze detection due to thunderstorm outflow boundaries during these events, which occur when cool downdrafts travel across great distances, especially along flat ground. When thunderstorms occur along the coastline, these traveling outflow boundaries may resemble a SBF to the detection technique. A shift in wind direction accompanied by cool moist air can appear to the test stations as a SBF passage. It is possible, for instance, that the region surrounding Naples experiences weak, localized sea breezes, which converge and create isolated thunderstorms before the SBF reaches the nearest test station, W6, located approximately 45 km from the coast. However, the outflow from these thunderstorms then reaches W6 and the station recognizes it as a SBF.

As expected, the PoP is higher and most widespread on days with sea breeze observed on both coasts relative to days with SBC on only one coast or neither coast experiencing an SBC (Figure 3.7). Single-coast sea breezes during regimes characterized by low-level atmospheric winds moving from west-to-east or east-to-west across the peninsula most clearly show this difference in spatial coverage. For instance, regime EM, characterized by a $2.1\text{--}4.1\text{ m s}^{-1}$ wind out of the east, produces a very isolated region of high PoP along the western coastline when only west coast sea breeze is observed. However, when both coasts observe sea breeze during this regime, the addition of the east coast sea breeze contributes to precipitation near the center of the peninsula creating a larger region of high PoP. A similar effect is observed when winds are out of the west (i.e. regimes WM and WH).

Finally, analysis of precipitation accumulation across agricultural lands shows a statistically significant increase during days with sea breeze detection along both coasts when accumulated over each month. Days with either isolated east coast or isolated west coast sea breezes did not produce an enhancement of daytime precipitation accumulation relative to non-sea breeze days. As a result, it is evident that the convergence resulting from opposing sea breezes significantly enhances precipitation across south Florida. Moreover, a large portion of agricultural lands is located in close proximity to Lake Okeechobee. The complex interactions among the ocean SBC and lake breezes are difficult to quantify with the current methodology. From prior work (e.g. Baker et al. 2000 and refs, therein), it is expected that local-scale interactions between the lake breeze and sea breeze drive convergence that may result in enhanced precipitation in this region. A similar study focused on this particular region is needed to analyze these complex interactions and their effects on precipitation accumulation.

3.5 Conclusion

The SBC is influential to local wind and temperature variation in Florida, often driving daytime warm season weather patterns on the peninsula. The prevailing low-level winds affect the influence of sea breezes on local weather, with stronger winds ($>4.1 \text{ m s}^{-1}$) often suppressing the circulation. Results presented in this study suggest that the sea breeze enhances localized precipitation across south Florida with the effects most pronounced on days where sea breezes are detected along both opposing coastlines. An analysis of agricultural lands indicates the importance of the convergence of these two opposing fronts to their hydrological needs. Days with only west coast sea breeze produce high rainfall amounts surrounding Lake Okeechobee.

Further research is needed to understand the impact of complex localized weather patterns in that region, where a significant amount of agricultural acreage is located. Better understanding of the local interactions between sea breeze and synoptic scale flow will result in enhanced predictability with regards to the localized hydrology in Florida.

TABLES

Table 3.1 Florida automated weather network (FAWN) meteorological stations used in this study.

Station Name	FAWN ID	Site Name	County	Lat (N)	Lon (W)	Elev (m)	Prox to Gulf (km)	Prox to Atlantic (km)	Missing Obs
E1	340	Kenansville	Osceola	27.96	81.05	21.0	173	56	643
E2	410	Belle Glade	Palm Beach	26.66	80.63	3.4	128	60	119
E3	420	Ft. Lauderdale	Broward	26.09	80.24	1.5	115	15	970
E4	440	Homestead	Dade	25.51	80.50	2.4	65	32	190
R1	390	Frost Proof	Polk	27.77	81.54	50.0	123	113	554
R2	470	Sebring	Highlands	27.42	81.40	35.7	125	111	485
R3	460	Palmdale	Glades	26.92	81.31	11.6	102	125	420
W1	360	Dover	Hillsborough	28.02	82.23	21.0	58	168	1159
W2	350	Balm	Hillsborough	27.76	82.22	39.3	51	179	87
W3	380	Ona	Hardee	27.40	81.94	22.9	71	164	1173
W4	490	Arcadia	Desoto	27.23	81.84	19.5	67	166	73
W5	480	North Port	Sarasota	27.14	82.34	4.9	15	217	5111
W6	450	Immokalee	Collier	26.46	81.44	10.7	45	137	543

Table 3.2 National Data Buoy Center (NDBC) buoy station information for 2008-2018. Sample size is compared to the total number of days in this study, 2354.

Station	Lat (°N)	Lon (°W)	Distance to Coastline (km)	SWT Depth (m)	Water Depth (m)	Measurement Frequency (min)	Sample Size (days)
41009	28.51	80.19	34	1	42	30	2097
41113	28.40	80.53	5	0.5	10	30	2261
MLRF1	25.01	80.38	11	Var	N/A	10	2237
FWYF1	25.59	80.10	20	Var	N/A	10	1909
42013	27.17	82.92	37	1	25	30	1253
42099	27.35	84.28	157	0.5	94	30	1698

Table 3.3 Sea breeze (SB) detection algorithm criteria for surface temperature (T), dew point temperature (T_D), wind direction (WD), and wind speed (WS) applied at each observational test station. Sea breeze types are classic, weak, classic T_D , classic WS , and T_D WS . All sea breeze detection types require an onshore wind direction (WD) of at least 1 m s^{-1} at the test station. SB types may be independent of certain criteria; N/A denotes this. A gradient (∇) refers to the difference between the test station and the average of the three reference stations. *Offshore reference wind direction can be onshore, as long as test wind direction is 45° more onshore.

SB Type	Test WD	Test WD (t-1hr)	Synoptic WD	1 hr Δ WD ($^\circ$)	∇ WD ($^\circ$)	1 hr Δ ∇ WD ($^\circ$)	1 hr Δ ∇ WS (m s^{-1})	∇ T ($^\circ\text{C}$)	1 hr Δ ∇ T ($^\circ\text{C}$)	∇ T_D ($^\circ\text{C}$)
Classic	On	Off	Off*	>45	>45	N/A	N/A	<-1.0	<-2.0	N/A
Weak	On	On	Off*	N/A	>45	N/A	N/A	<-2.0	N/A	N/A
Classic T_D	On	Off	Off*	>45	>45	N/A	N/A	N/A	N/A	>2.0
Classic WS	On	N/A	On	N/A	N/A	>10.0	>2.0	<-1.0	<-2.0	N/A
T_D WS	On	N/A	On	N/A	N/A	>10.0	>2.0	N/A	N/A	>2.0

Table 3.4 Synoptic regime classification based on daily 12 UTC soundings from Tampa, Florida with National Weather Service (NWS) original names.

Regime Name	NWS Name	Wind Direction (°)	Cardinal Wind Direction	Wind Speed (m s⁻¹)	Number of Days
VL	1	Variable	Variable	≤2.1	49
EM	2	<120	E/NE	2.1- 4.1	181
EH	3	<120	E/NE	>4.1	355
SM	4	120 - 190	S/SE	2.1- 4.1	367
SH	5	120 - 190	S/SE	>4.1	408
WM	6	190 - 290	W/SW	2.1- 4.1	371
WH	7	190 - 290	W/SW	>4.1	502
NM	8	≥290	N/NW	2.1- 4.1	21
NH	9	≥290	N/NW	>4.1	57

Table 3.5 Mean (mean absolute difference) values for meteorological observations averaged one hour prior to and after SBF passage at test stations. Wind direction values are the directional mean (circular variance) in degrees from north. The variables include temperature averaged over the hour before (T_b), and after (T_a) detection. Similar averages are calculated for dew point temperature ($T_{D\ a}$ and $T_{D\ b}$), wind direction (WD_b and WD_a), and wind speed (WS_b and WS_a)

Coast	SB Type	T_b (°C)	T_a (°C)	$T_{D\ b}$ (°C)	$T_{D\ a}$ (°C)	WD_b (°)	WD_a (°)	WS_b (m s ⁻¹)	WS_a (m s ⁻¹)
East	classic	28.2 (3.4)	25.1 (4.2)	23.2 (1.5)	23.1 (1.4)	173.0 (24.6)	126.4 (18.3)	2.9 (0.9)	3.0 (1.0)
	classic T_D	27.6 (3.1)	28.0 (2.6)	21.9 (3.0)	22.2 (2.9)	131.5 (33.8)	116.9 (22.3)	2.4 (1.1)	2.9 (1.0)
	classic WS	28.8 (2.0)	26.5 (2.1)	23.5 (1.4)	23.3 (1.2)	121.7 (17.8)	118.8 (18.3)	3.3 (1.1)	3.7 (1.1)
	T_D WS	27.6 (2.6)	27.9 (2.2)	22.0 (2.8)	22.2 (2.7)	94.1 (18.3)	98.7 (10.9)	2.9 (1.1)	3.9 (1.1)
	weak	28.2 (2.8)	28.5 (2.2)	23.1 (2.0)	23.2 (1.9)	131.7 (22.3)	130.7 (19.5)	2.5 (1.1)	2.8 (1.1)
West	classic	29.4 (2.2)	26.4 (2.3)	22.9 (1.7)	22.8 (1.6)	177.3 (21.2)	231.1 (22.3)	3.0 (1.0)	2.9 (1.0)
	classic T_D	29.2 (2.5)	28.9 (2.4)	20.8 (3.7)	21.3 (3.4)	202.6 (28.1)	247.6 (21.2)	2.3 (0.8)	2.7 (0.9)
	classic WS	27.6 (4.2)	24.7 (4.1)	23.9 (1.2)	23.2 (1.3)	232.7 (15.5)	244.7 (22.3)	3.2 (0.9)	3.3 (1.0)
	T_D WS	28.6 (3.0)	28.5 (2.7)	21.3 (3.5)	21.5 (3.3)	244.5 (16.0)	261.5 (13.8)	2.8 (1.0)	3.6 (1.1)
	weak	30.8 (1.9)	30.0 (2.1)	22.8 (1.8)	22.8 (1.7)	224.0 (29.8)	234.4 (26.4)	2.5 (0.9)	2.7 (0.9)

Table 3.6 Frequency of typical observed April-October sea breeze types with peak summer (JJA) in parentheses (2008-2018). Sea breeze types are classic, classic dew point temperature (T_D), weak, classic wind speed (WS), and dew point temperature wind speed (T_D WS). Meteorological station identification (ID) codes are divided into east (E*) and west (W*) coasts.

ID	Total (%)	Classic (%)	Classic T_D (%)	Weak (%)	Classic WS (%)	T_D WS (%)	Sample Size (days)
E3	70 (76)	15 (21)	17 (12)	25 (34)	3 (3)	10 (6)	2338
E4	68 (69)	12 (17)	22 (19)	18 (20)	4 (5)	12 (8)	2344
E2	54 (62)	13 (21)	14 (12)	8 (13)	7 (9)	12 (7)	2344
W5	52 (63)	17 (22)	16 (14)	10 (15)	3 (6)	6 (7)	2341
W6	44 (55)	18 (27)	9 (6)	6 (7)	5 (10)	6 (5)	2341
W1	41 (59)	14 (23)	7 (6)	12 (17)	5 (9)	3 (2)	2308
E1	39 (49)	18 (26)	6 (6)	6 (10)	4 (4)	5 (3)	2344
W2	39 (55)	12 (19)	6 (6)	10 (15)	7 (12)	4 (3)	2345
W4	38 (55)	16 (25)	5 (5)	6 (8)	8 (14)	3 (3)	2339
W3	37 (53)	15 (23)	5 (6)	5 (8)	8 (13)	3 (3)	2322

Table 3.7 Sea breeze occurrence in days based on synoptic regime. The regimes are characterized by the direction (East – E, South – S, West – W, North – N) and magnitude (Moderate – M – 2.1-4.1 m s⁻¹, High – H - >4.1 m s⁻¹) of the 1000-700hPa mean wind vector. Light (L – <2.1 m s⁻¹) wind vectors, regardless of direction (Variable – V), represent conditions with little synoptic influence.

		Percent of Total JJA Days (2009-2018)				
Regime	<i>Number of Days</i>	East Classic	West Classic	Classic Both	None	Total (%)
VL	31	0.2	1.0	1.7	0.2	3.1
EM	66	0.5	3.7	1.2	1.2	6.7
EH	91	0.3	3.5	1.5	3.8	9.2
SM	211	2.8	8.5	8.4	1.6	21.3
SH	142	0.9	6.5	4.3	2.6	14.3
WM	224	8.5	3.5	9.3	1.3	22.6
WH	207	8.4	3.4	4.3	4.7	20.9
NM	7	0.3	0.1	0.3	0.0	0.7
NH	13	0.3	0.3	0.3	0.4	1.3
All Regimes	992	22.2	30.5	31.4	15.9	100

FIGURES

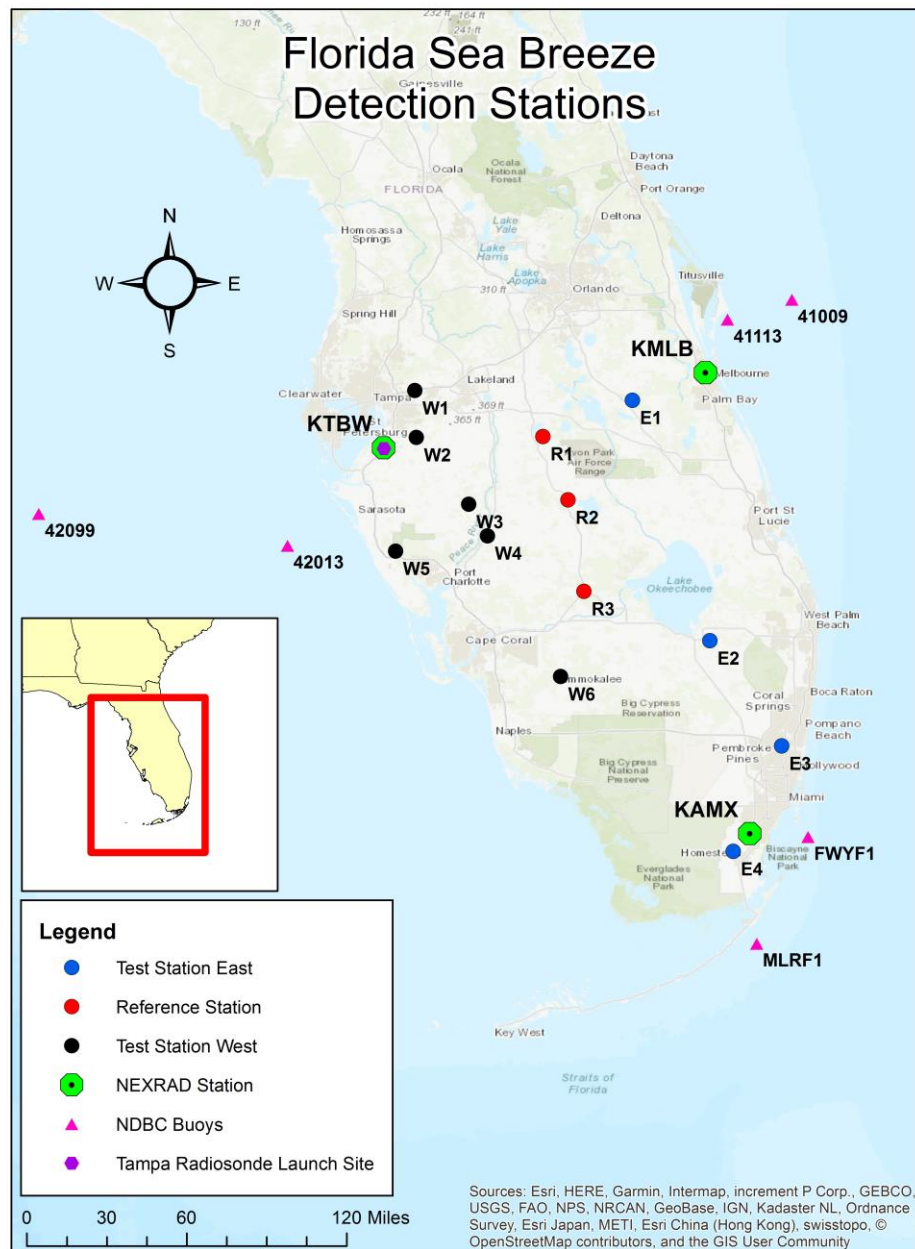


Figure 3.1 Map of South Florida study region with FAWN meteorological stations, NDBC buoys, radiosonde launching site and NEXRAD Radar locations indicated.

Florida NCEP Subset Study Area

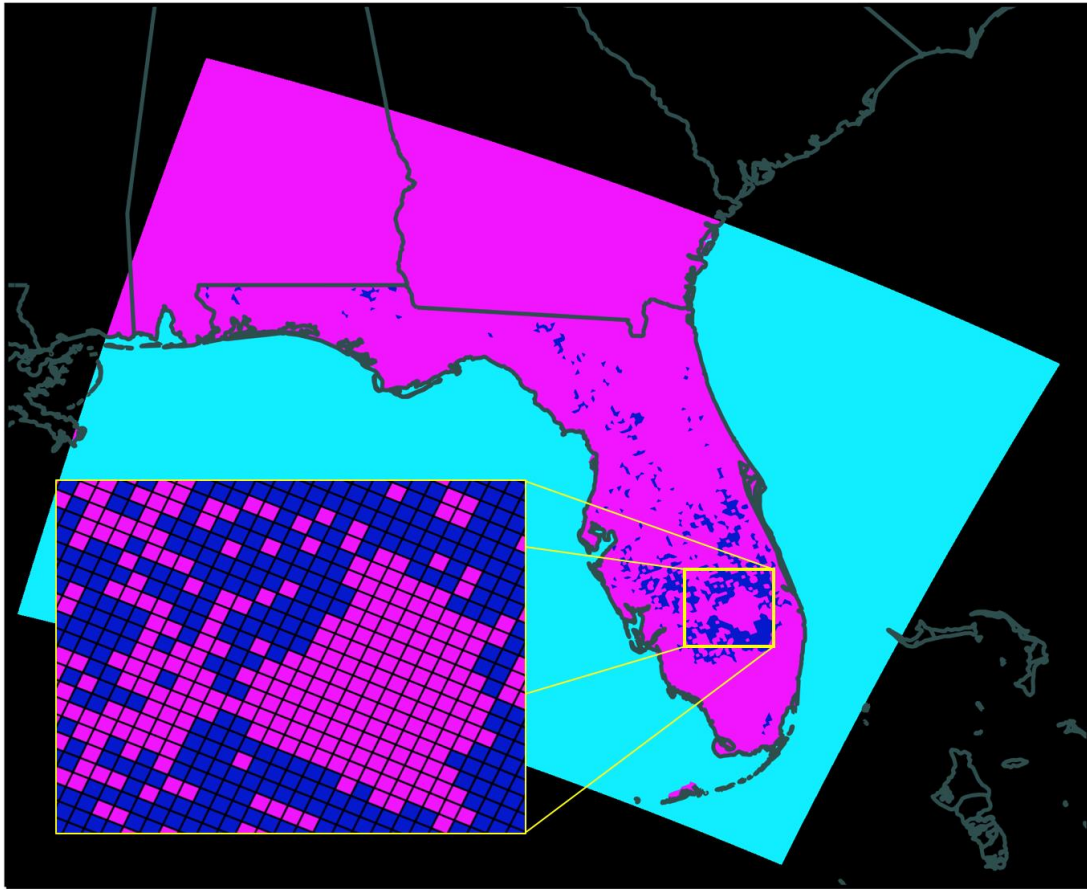


Figure 3.2 The 210x280 pixel subset of NCEP 4-kilometer MPE product used in this study. The light blue region represents the ocean grids, the pink represents land grids where quality control is applied, and the dark blue is a subset of the pink where an agricultural land-use mask is used. The inset shows the 4-km grid size relative to the study region.

Florida Average Summer Daytime Rainfall Accumulation

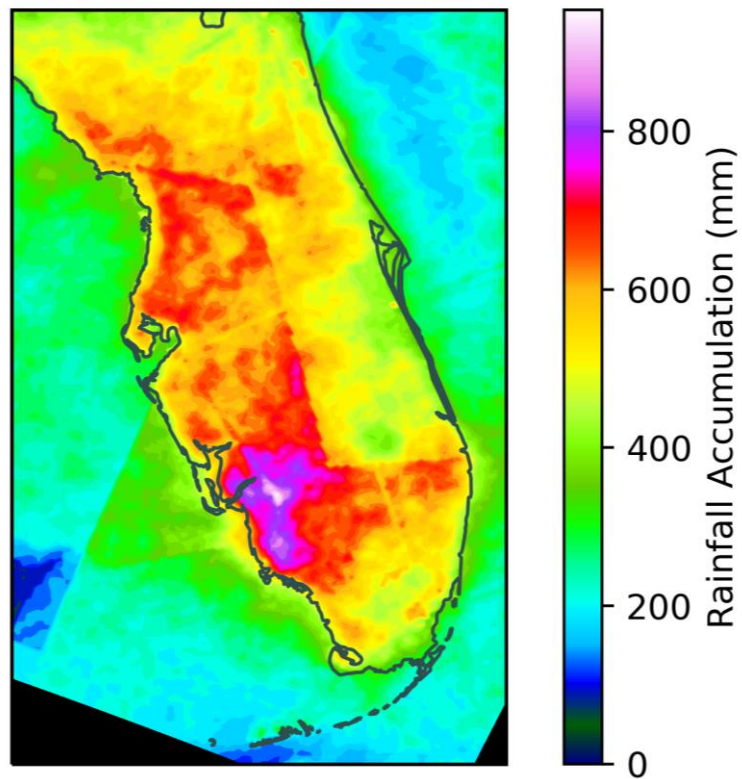


Figure 3.3 Mean annual summertime (JJA) daytime (1200-0300UTC) accumulated rainfall (MASDAR) averaged for 2008-2018.

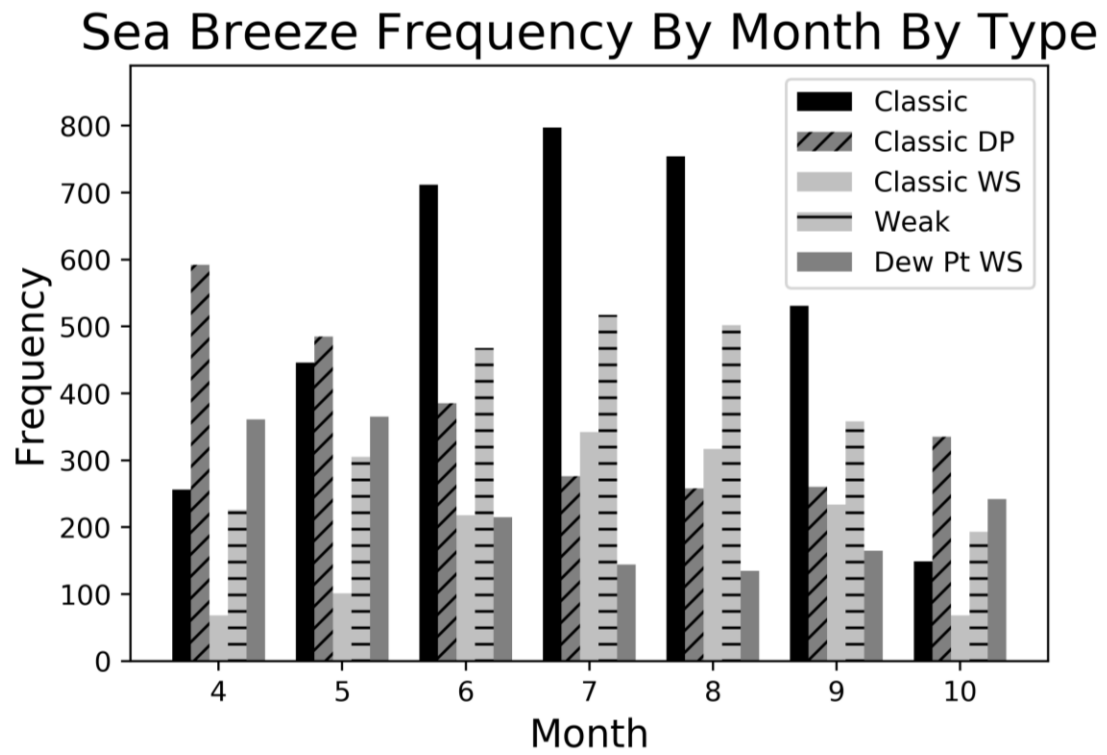


Figure 3.4 Frequency of SBC type detected on the Florida peninsula by month. East and west coast SBCs are combined.

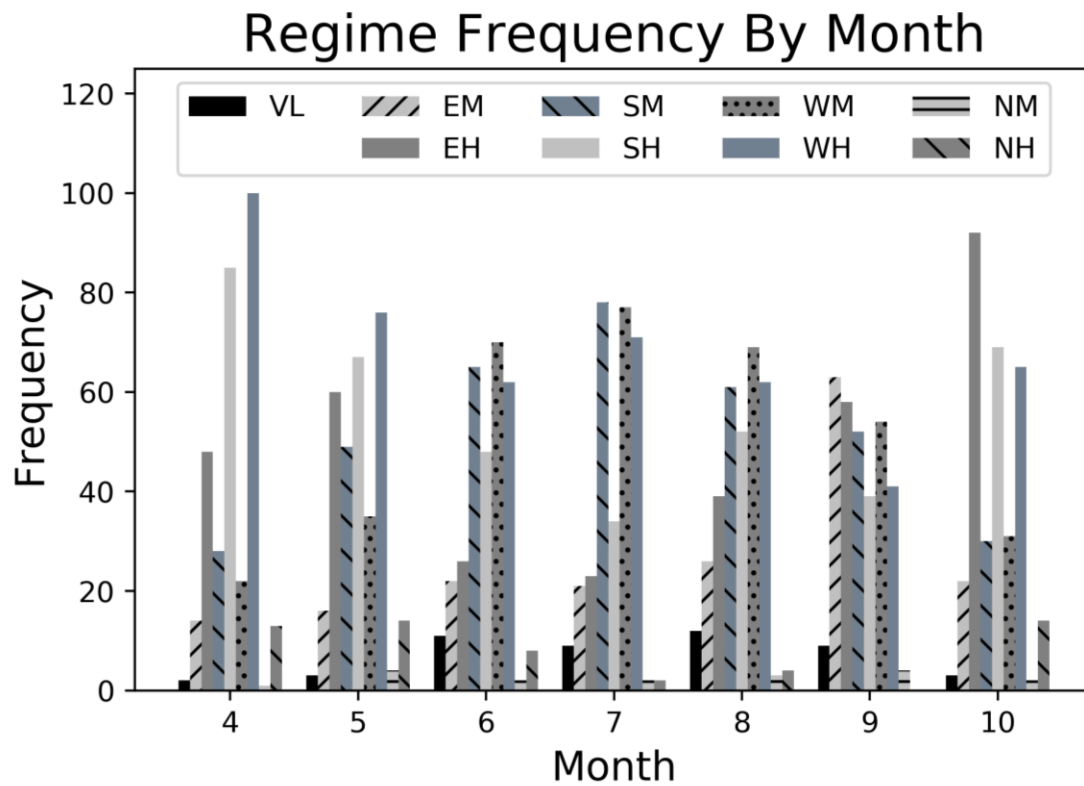


Figure 3.5 Synoptic regime type frequency by month for the study period (April-October) 2008-2018. Regimes are based on the 1000-700 hPa average wind vector magnitude and direction.

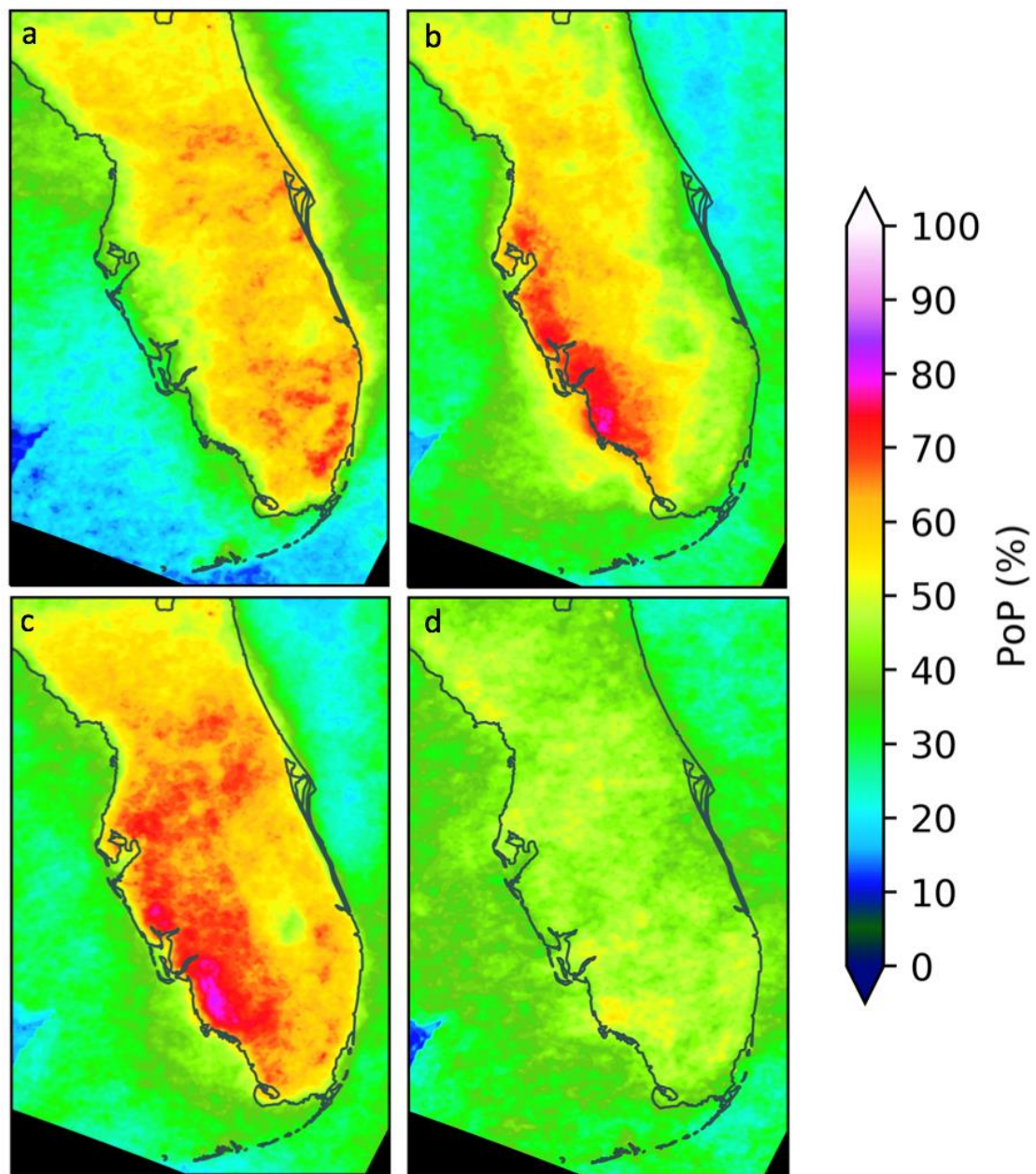


Figure 3.6 Summertime (JJA) daily probability of precipitation (PoP) for classic sea breeze occurrence on the east coast (a; 22% of days), west coast (b; 31% of days), both coasts (c; 31% of days) and when no classic sea breeze was detected on either coast (d; 16% of days).

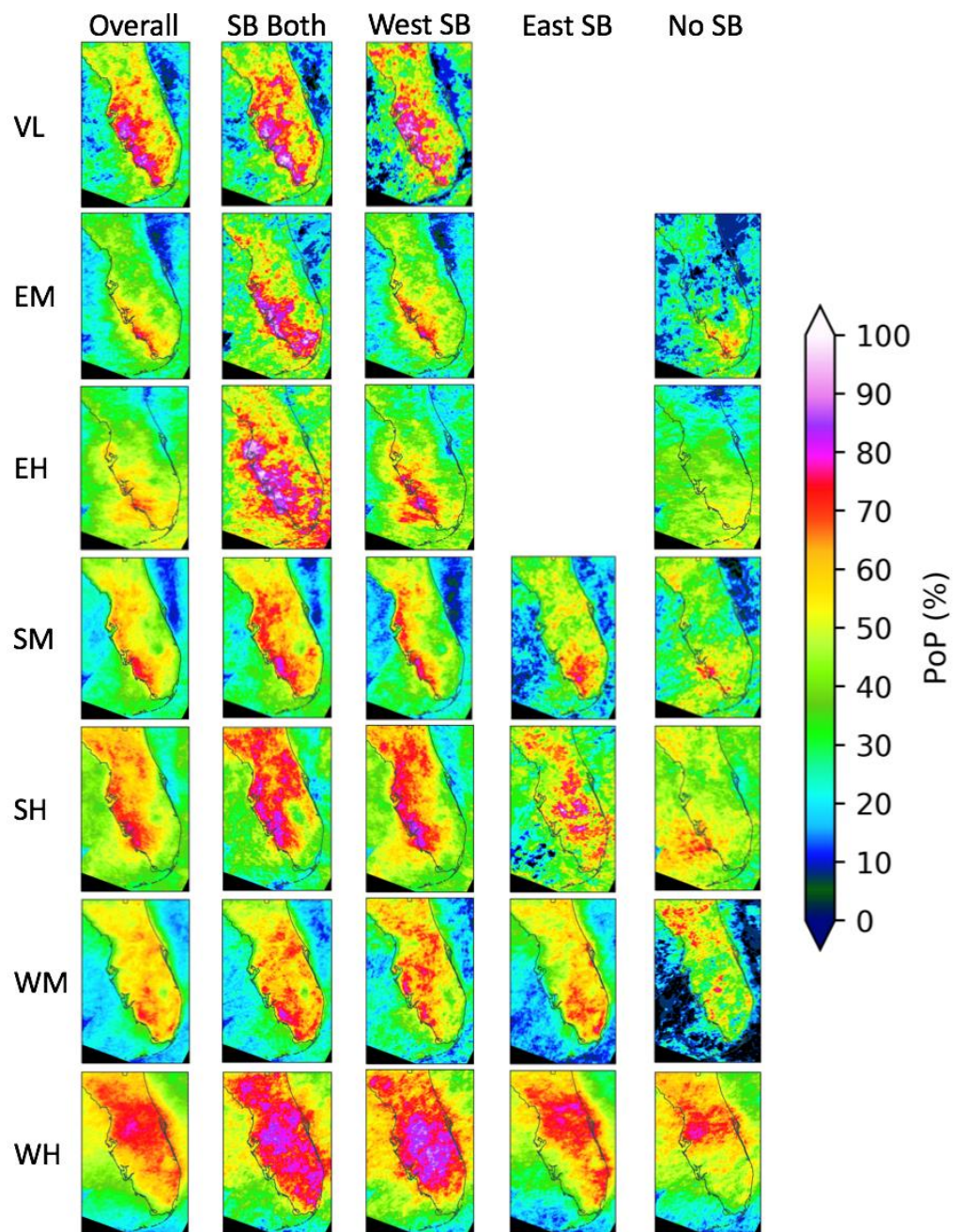


Figure 3.7 Probability of precipitation (%) for regimes VL, EM, EH, SM, SH, WM, and WH on all summer (JJA) days (col. 1), days with classic sea breeze occurrence on only the east coast (col. 2), only the west coast (col. 3), both coasts simultaneously (col. 4) and on days with no classic sea breeze detection (col. 5). Regimes NM and NH, along with the missing panels in VL, EM, and EH were left out of this figure due to a low sample size.

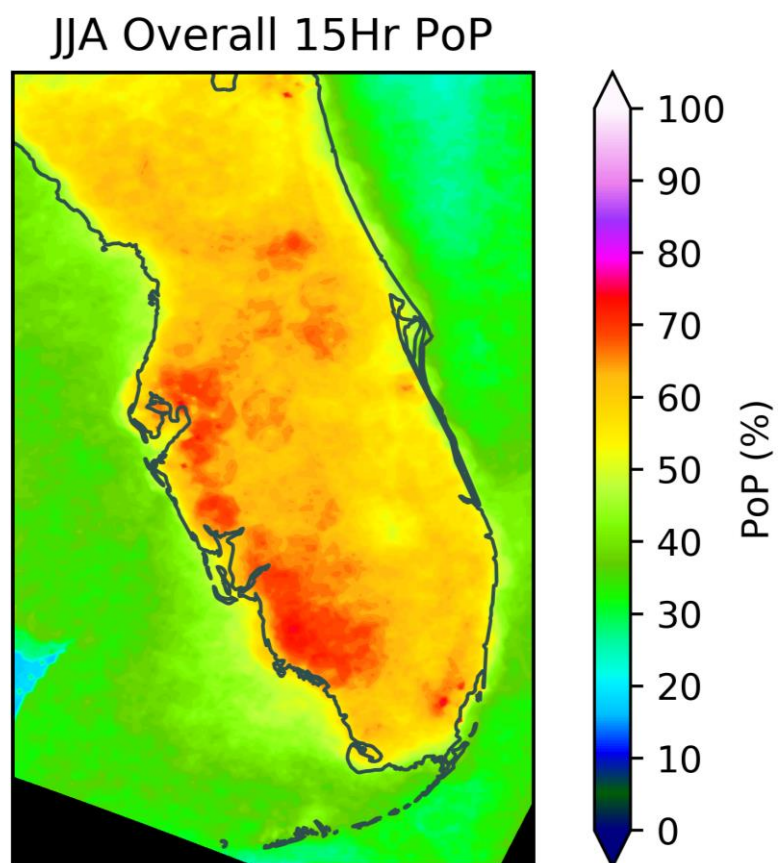


Figure 3.8 Summertime (JJA) average daily probability of precipitation (PoP) for 2008 – 2018.

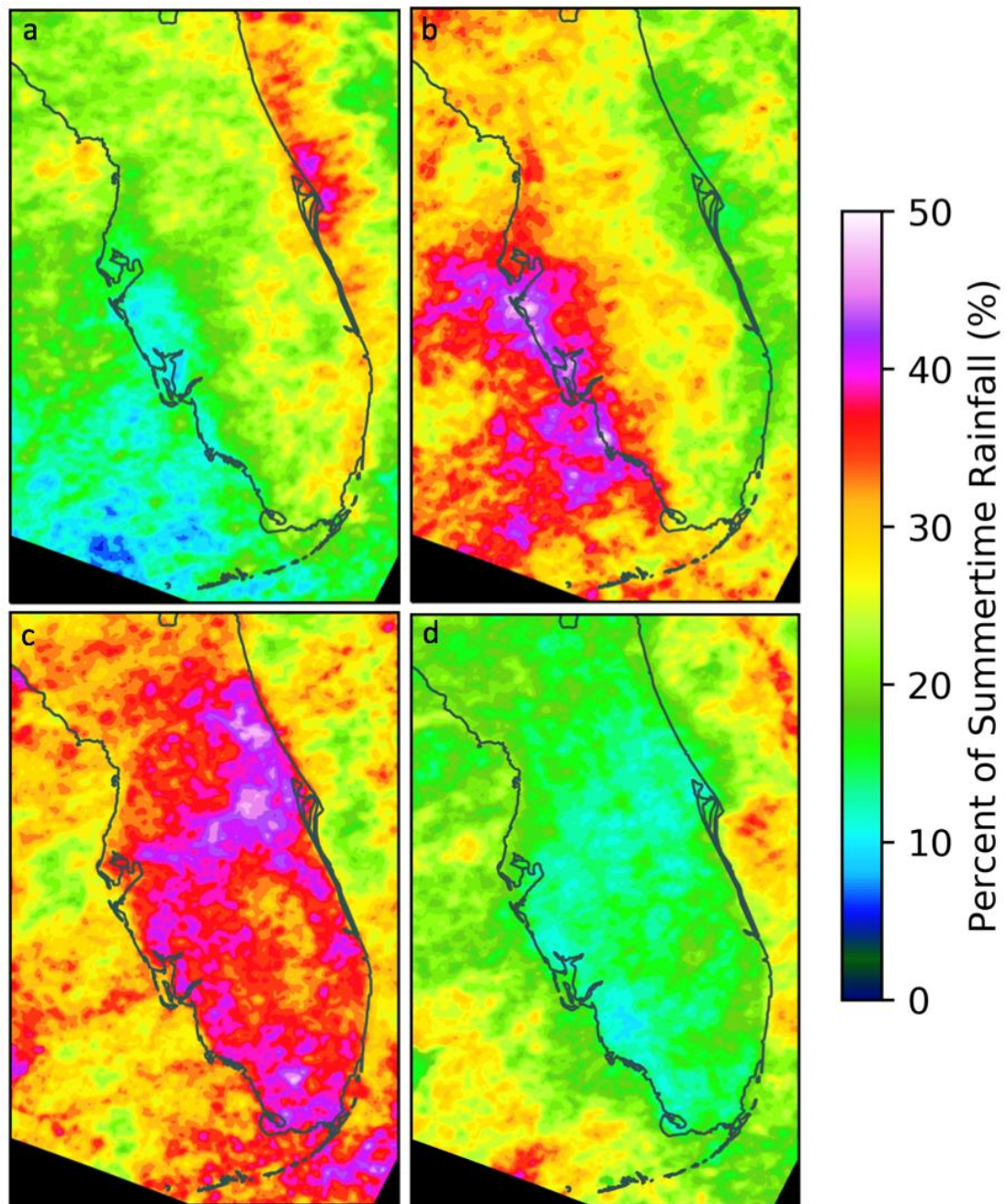


Figure 3.9 Percent of precipitation during summertime (JJA) days where a classic sea breeze is detected by at least one station on the east coast (a; 22% of days), west coast (b; 31% of days), both coasts simultaneously (c; 31% of days), and days where a classic sea breeze is not detected by any test station (d; 16% of days).

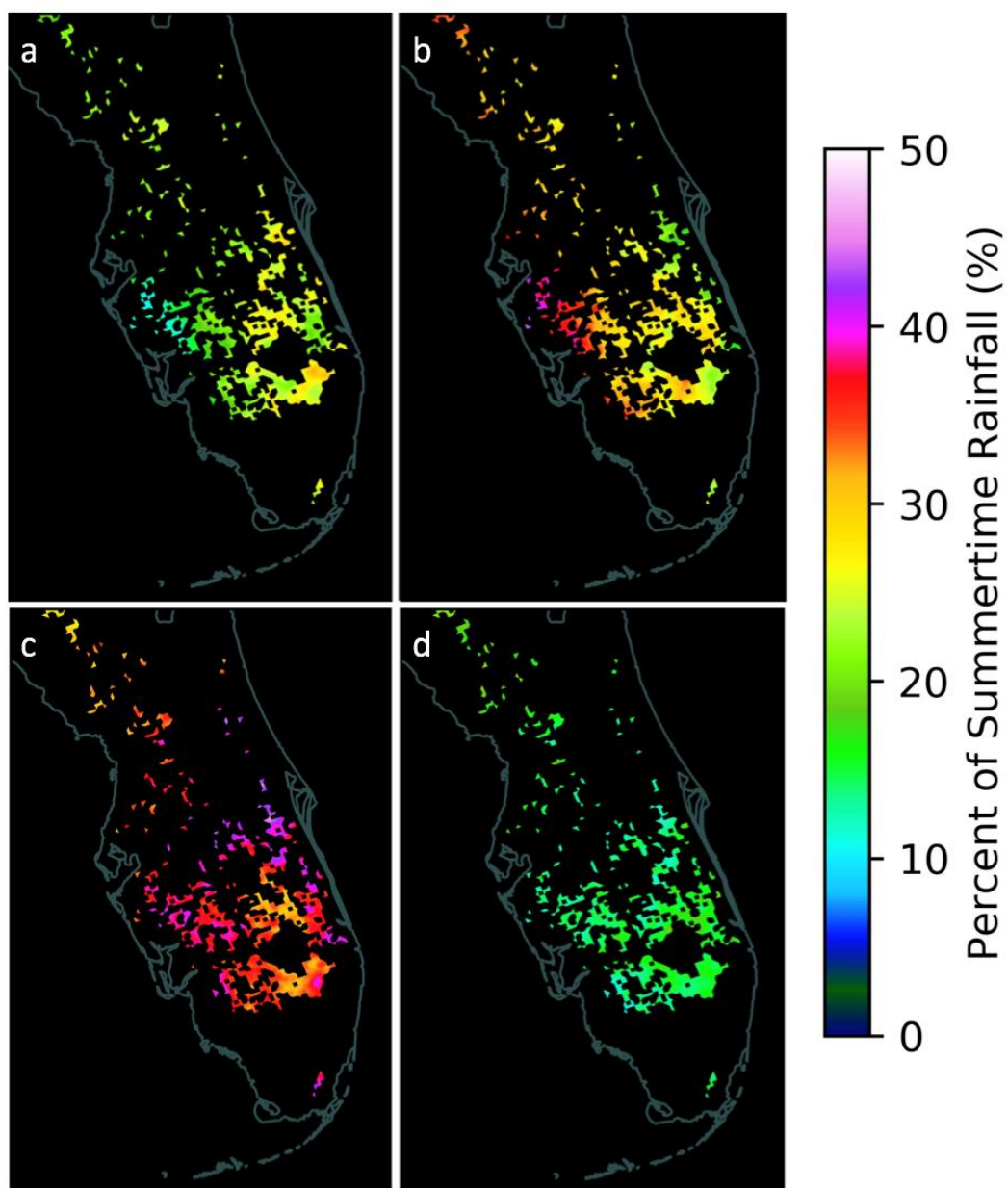


Figure 3.10 As in Figure 3.9, but masked to agricultural land use regions.

Percent MASDAR over Various Land Use Types for Sea Breeze Days

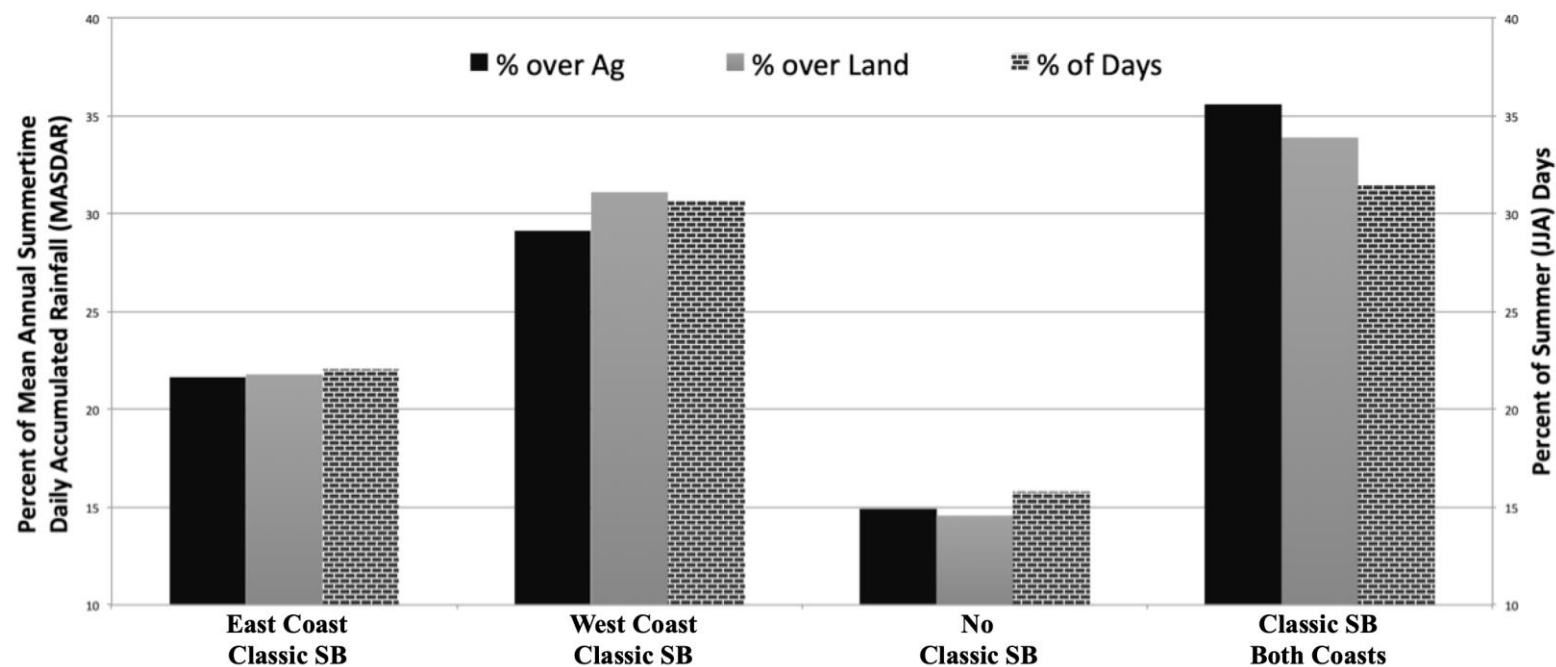


Figure 3.11 Percentage of summertime (JJA) days (pattern) when classic sea breezes were detected on each coast, both coasts, and when no classic sea breeze was detected in Florida, and the percentage of MASDAR occurring on these days over all land (gray), and just over agricultural lands (black), all for 2008 – 2018.

SUPPLEMENTAL FIGURES

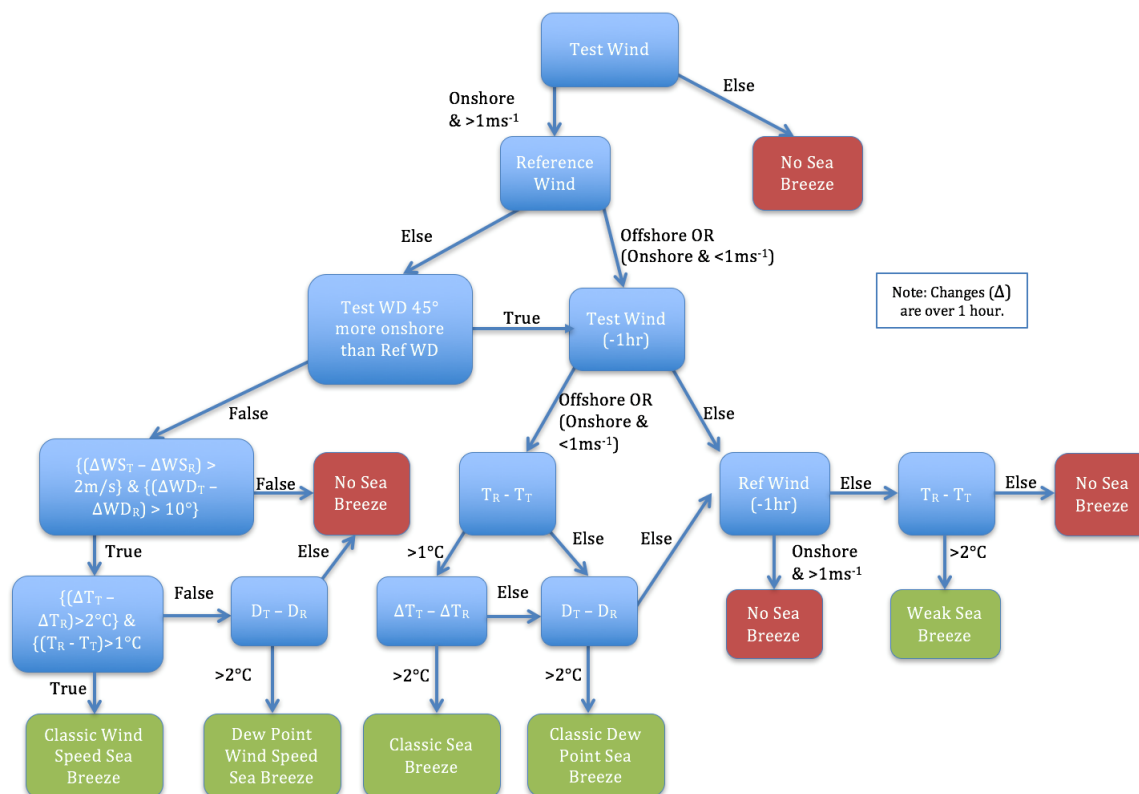


Figure S3.1 Florida sea breeze station detection flowchart utilizing meteorological observations from at least one test station and one reference station. The chart reveals the criteria (blue) to detect five unique types of sea breezes (green) or else a sea breeze is not detected (red). Data are analyzed to detect environmental changes at test meteorological stations over a 1-hour time period and compared to values from (a) reference station(s) for the same period.

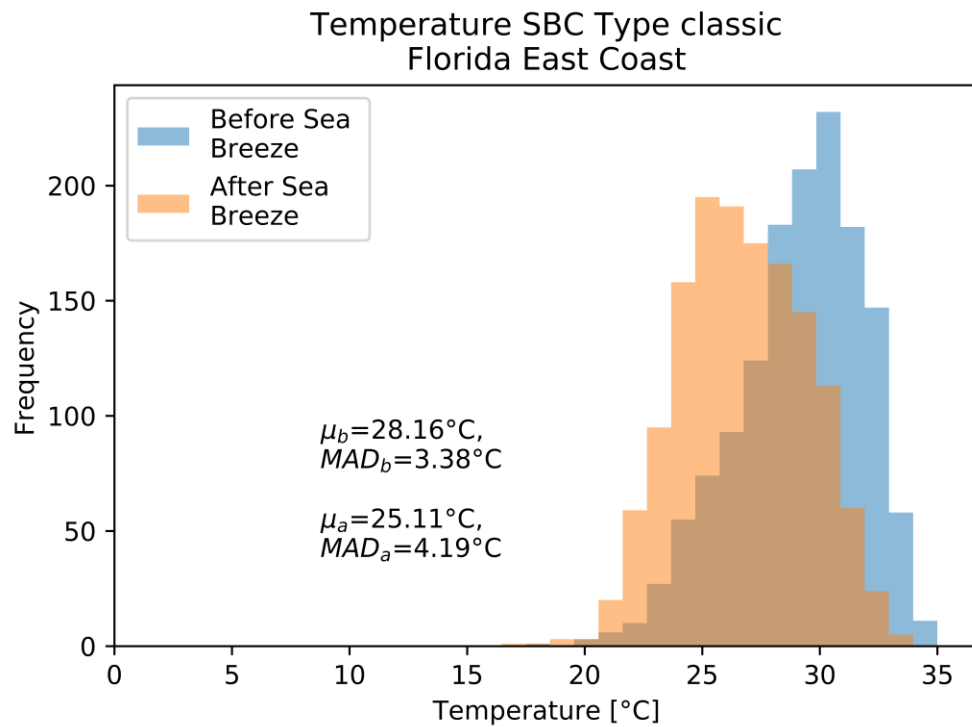


Figure S3.2 Distributions of temperature averaged over one hour prior to (blue) and after (orange) classic sea breeze passage at east coast Florida test stations for April – October from 2008 – 2018. The mean (μ) and mean absolute difference (MAD) are included.

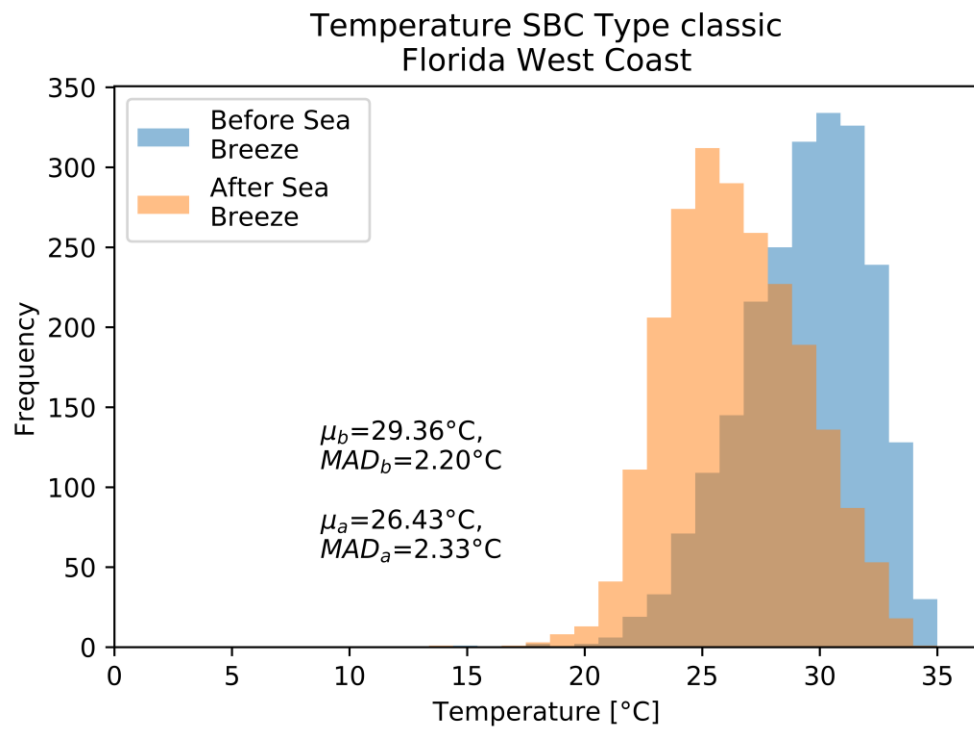


Figure S3.3 As Figure S3.2, for west coast Florida test stations.

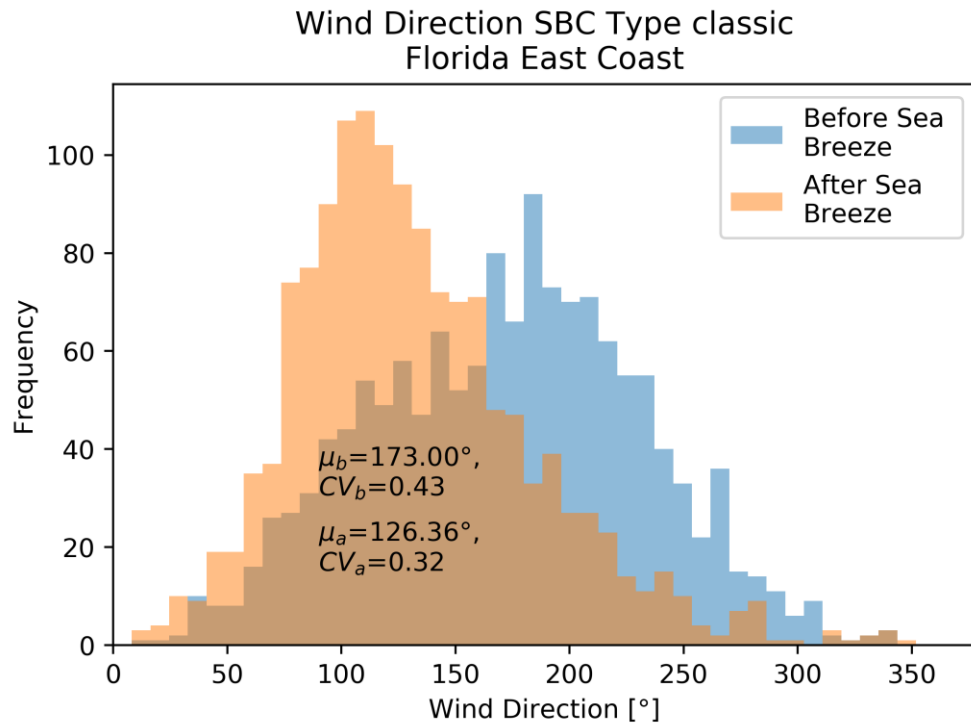


Figure S3.4 Distributions of wind direction as degrees from North averaged over one hour prior to (blue) and after (orange) classic sea breeze passage at east coast Florida test stations for April – October from 2008 – 2018. The mean (μ) and mean absolute difference (MAD) are included.

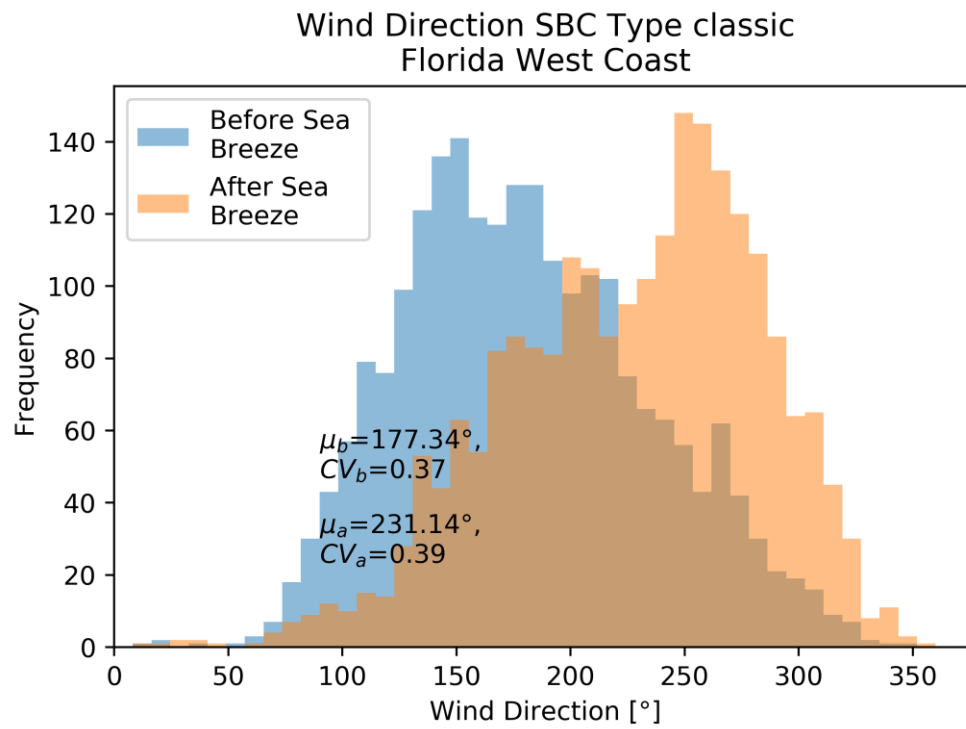


Figure S3.5 As Figure S3.4, for west coast Florida test stations.

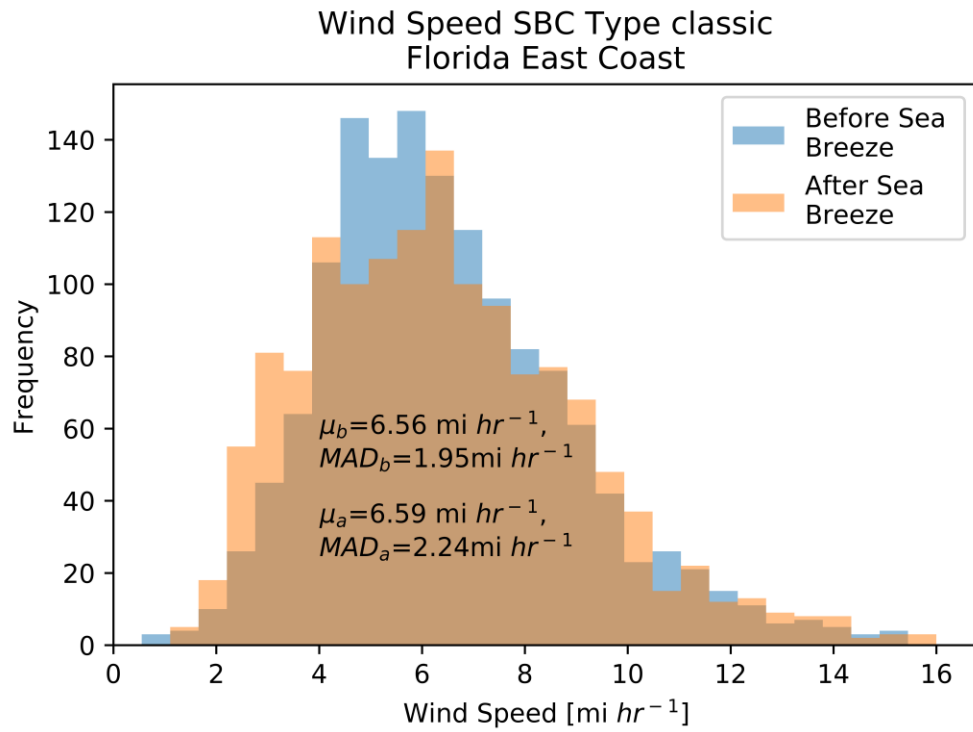


Figure S3.6 Distributions of wind speed averaged over one hour prior to (blue) and after (orange) classic sea breeze passage at east coast Florida test stations for April – October from 2008 – 2018. The mean (μ) and mean absolute difference (MAD) are included.

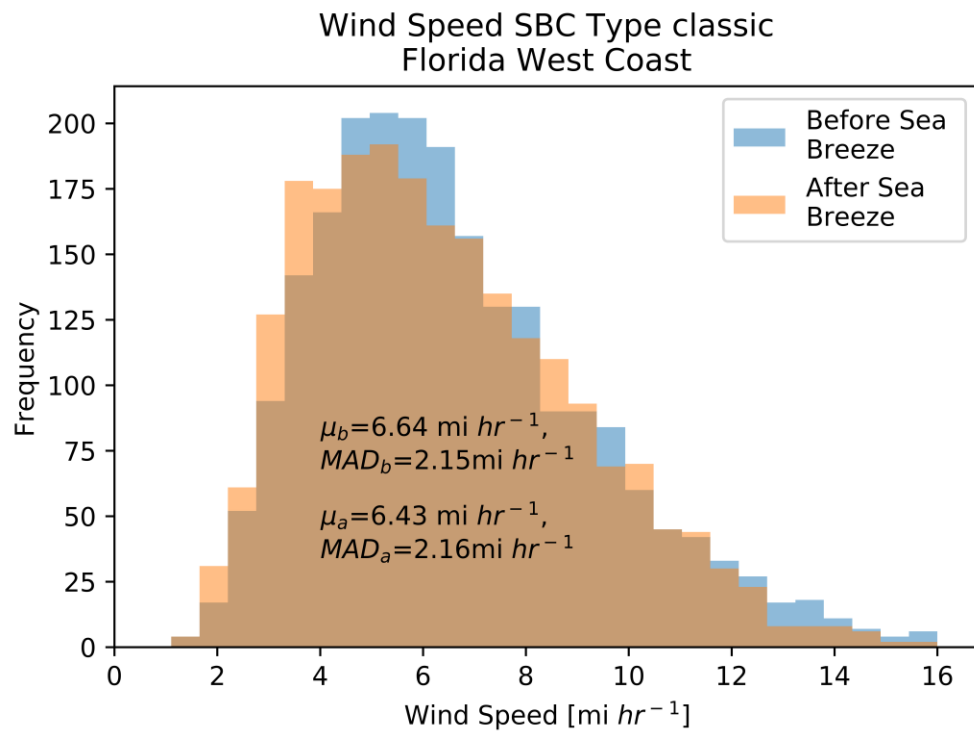


Figure S3.7 As Figure S3.6, for west coast Florida test stations.

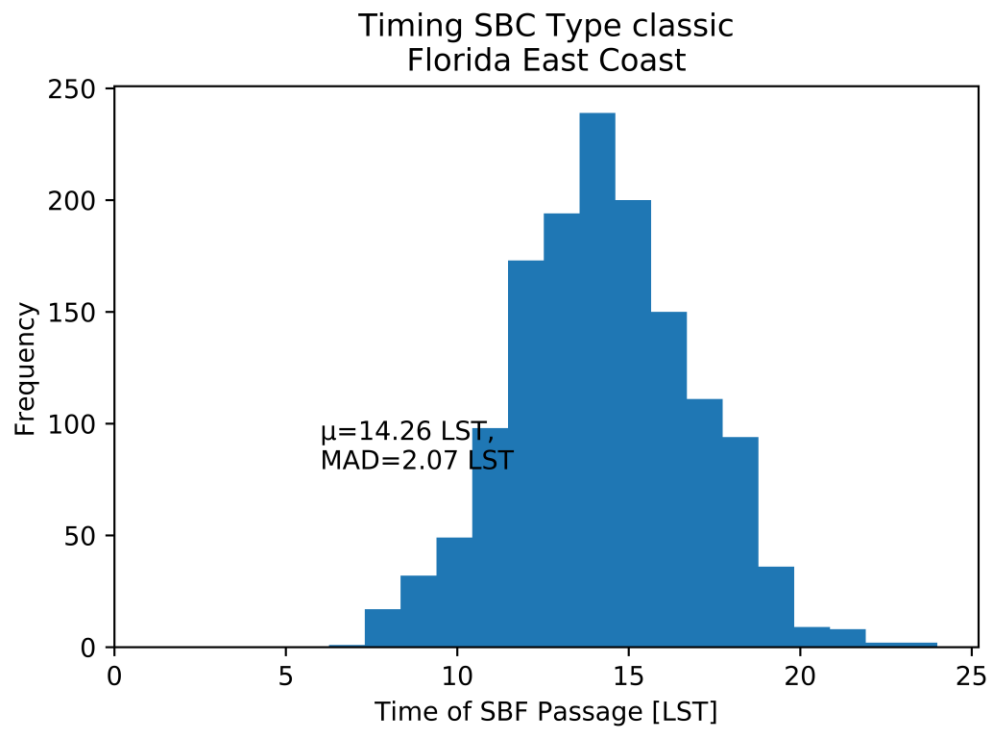


Figure S3.8 Distribution classic sea breeze passage time at east coast Florida test stations for April – October from 2008 – 2018. The mean (μ) and mean absolute difference (*MAD*) are included.

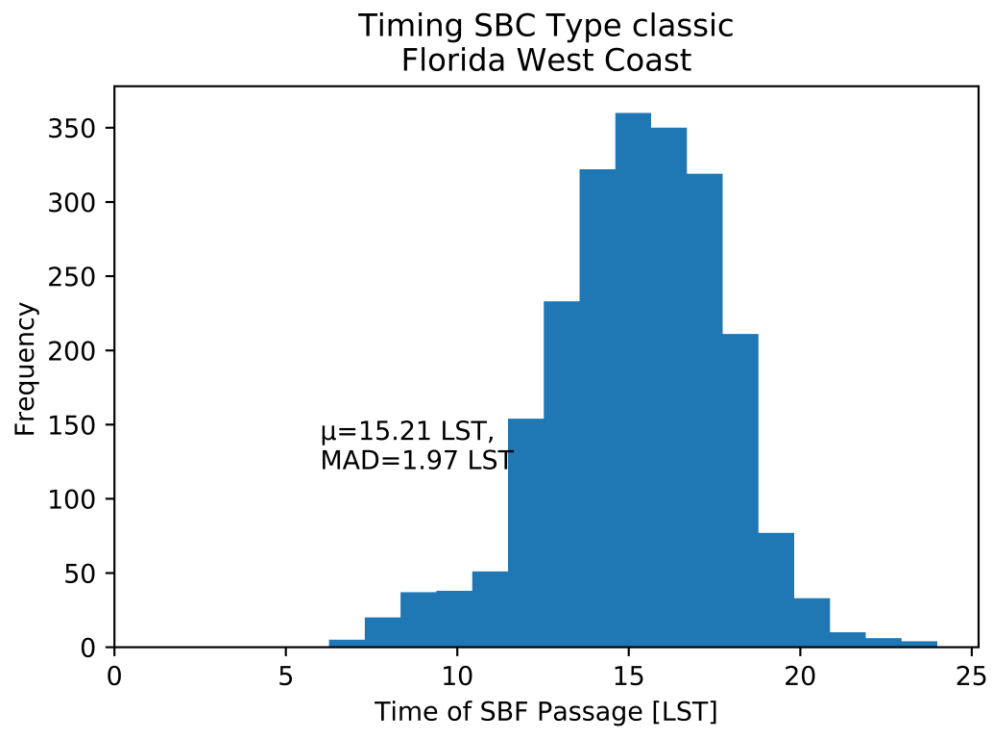


Figure S3.9 As Figure S3.8, for west coast Florida test stations.

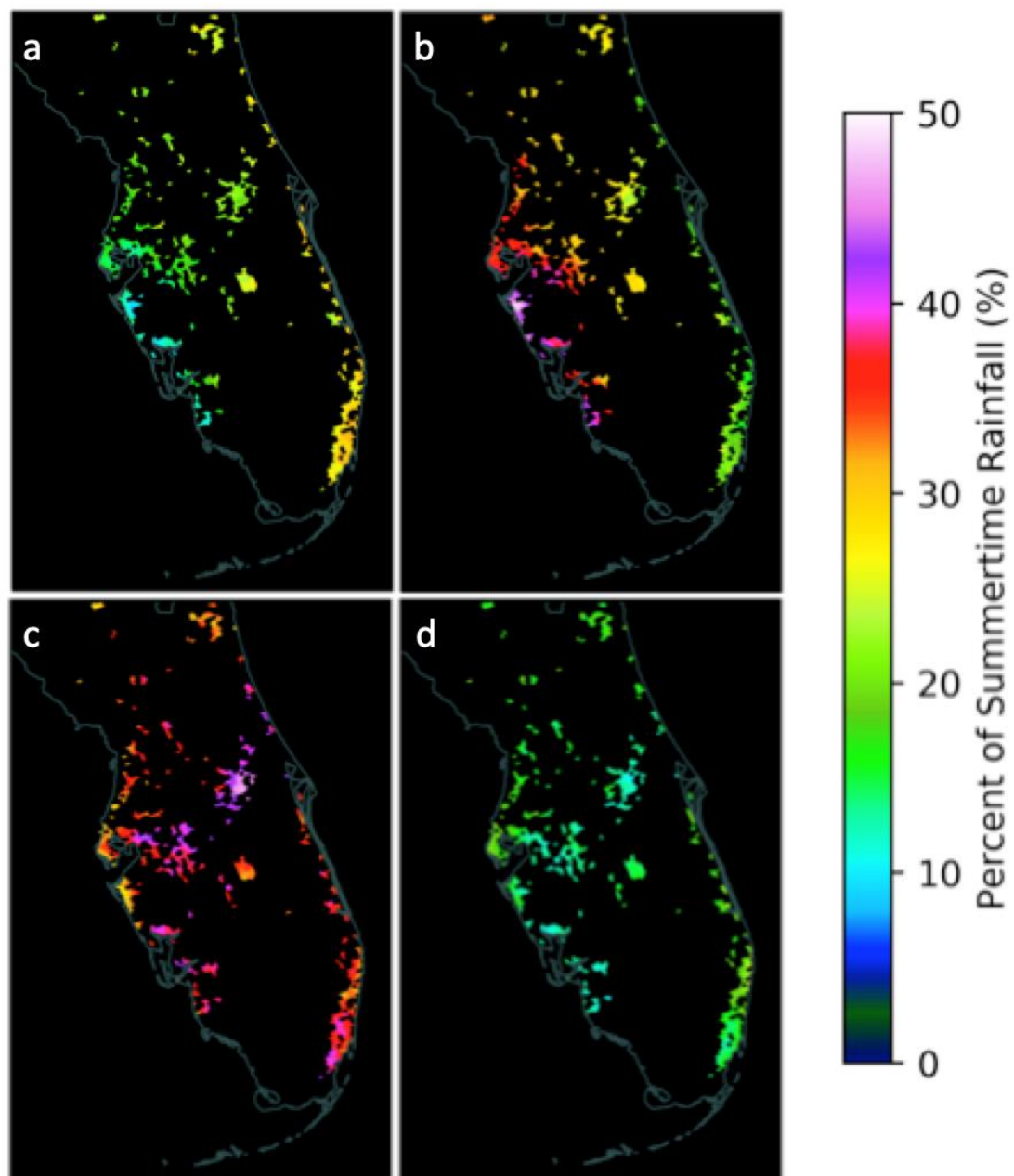


Figure S3.10 As Figure 3.10, masked to urban areas.

Chapter 4

CONCLUSION

4.1 Summary

This study produces new knowledge in two realms of sea breeze research. First, a state-of-the-art sea breeze detection algorithm is introduced, paving a new path for the automatic detection and analysis of sea breeze fronts globally where remotely sensed data are available. This technique utilizes radar reflectivity data and image analysis techniques to identify the sea breeze front and track its location over time. Furthermore, the methodology provided can be applied to various datasets with similar characteristics, such as infrared satellite data, so that the dependence on a coastal radar system is eliminated.

In the second chapter, the new detection algorithm was tested and then used for analysis of SBC-related precipitation in Delmarva and Florida. Results suggest that approximately 25% of classic sea breeze events detected by station data in Delaware are captured by the radar algorithm. However, analysis of rainfall coinciding with the algorithm detection shows that approximately 60% (94%) of detected sea breezes are followed by or occur simultaneously with radar detected precipitation in the study region surrounding Dover, DE (Melbourne, FL). This is significantly more precipitation occurrence than observed in previous studies of the Delmarva region (12% of radar detected SB; Gilchrist, 2013). Due to the sensitivity of the algorithm to strong SBF signals, in comparison to manual detection methods, the automatic algorithm under-performs in identifying total sea breeze occurrence, but captures a higher percentage of SBC associated with convection and precipitation.

The third chapter of this thesis highlights the importance of sea breeze convergence to summertime precipitation in peninsular regions utilizing meteorological stations and quality controlled precipitation data. Specifically, 35.6% of mean annual summertime (JJA) daytime (1200-0300 UTC) accumulated rainfall (MASDAR) in Florida occurs on days where a sea breeze is detected on both the east and west coasts during 2009-2018. Such days only represent 31.5% of total summertime days in this study. Thus, the major finding of this study provides a clear, significant relationship between the presence of the sea breeze on the Florida peninsula and summertime precipitation.

4.2 Future Research

The research presented here provides several further research possibilities. Specifically, the radar detection algorithm presented here can be improved upon and modified to answer many research questions. Most importantly, the image processing and spatial analysis methodology used can train an algorithm with machine learning techniques. Scans from days identified by the algorithm can train a computer model to capture similar gradient patterns in radar data. This approach will likely outperform any combination of objective thresholding and object identification, such as that used in this study. Moreover, with increased weather data sources and wider data availability, an algorithm like the one presented here will decrease human involvement in the early stages of research, increasing productivity on the backend.

This methodology can also be used to detect sea breeze and other meteorological phenomena utilizing many raster datasets, such as high-resolution satellite imagery. The major downfall with station detection, specifically in remote regions, is the lack of available weather networks capable of sea breeze monitoring.

This algorithm opens the door to analysis and now-casting of sea breezes and other meteorological features in these regions and with higher spatial resolution in regions with even the densest weather networks.

The sea breeze precipitation analysis in Florida also reveals unanswered research questions. The study presented in chapter three produces a regional overview of the significance of sea breeze-influenced precipitation in Florida. However, questions remain as to the influence of nearby ocean currents on the Florida sea breeze (see Appendix). Preliminary statistical analysis showed no dependence of the Florida sea breeze on anomalous coastal water temperatures as predicted. However, analysis of buoy correlation highlighted two buoy stations that may be influenced by the meandering Gulf Stream off the coast. Further analysis is needed to determine the effects of this lateral migration on coastal surface water temperatures and, resultant local weather patterns like the SBC.

REFERENCES

- Abbs, D. J., 1986: Sea-breeze Interactions along a Concave Coastline in Southern Australia: Observations and Numerical Modeling Study. *Mon. Weather Rev.*, **114**, 831–848, doi:10.1175/1520-0493(1986)114<0831:SBIAAC>2.0.CO;2. <http://cat.inist.fr/?aModele=afficheN&cpsidt=8014577>.
- Achtemeier, G. L., 1991: The Use of Insects as Tracers for “Clear-Air” Boundary-Layer Studies by Doppler Radar. *Journal Atmos. Ocean. Technol.*, **8**, 746–765.
- Anagnostou, E. N., 2004: A convective/stratiform precipitation classification algorithm for volume scanning weather radar observations. *Meteorol. Appl.*, **11**, 291–300, doi:10.1017/S1350482704001409. <http://doi.wiley.com/10.1017/S1350482704001409>.
- Arrillaga, J. A., C. Yagüe, M. Sastre, and C. Román-Cascón, 2016: A characterisation of sea-breeze events in the eastern Cantabrian coast (Spain) from observational data and WRF simulations. *Atmos. Res.*, **181**, 265–280, doi:10.1016/j.atmosres.2016.06.021. <http://dx.doi.org/10.1016/j.atmosres.2016.06.021>.
- Arritt, R. W., 1989: Numerical modelling of the offshore extent of sea breezes. *Q. J. R. Meteorol. Soc.*, **115**, 547–570, doi:10.1002/qj.49711548707.
- Atlas, D., 1960: Radar Detection of the Sea Breeze. *J. Meteorol.*, **17**, 244–258.
- Azorin-Molina, C., S. Tijm, E. E. Ebert, S. M. Vicente-Serrano, and M. J. Estrela, 2014: Sea breeze thunderstorms in the eastern Iberian Peninsula. Neighborhood verification of HIRLAM and HARMONIE precipitation forecasts. *Atmos. Res.*, **139**, 101–115, doi:10.1016/j.atmosres.2014.01.010.
- Bacon, P. J., 1962: Weather Radar. *Weather Sch. Suppl.*, **10**, 37–39.
- Baker, R. D., B. H. Lynn, A. Boone, W.-K. Tao, and J. Simpson, 2000: The Influence of Soil Moisture, Coastline Curvature, and Land-Breeze Circulations on Sea-Breeze-Initiated Precipitation. *J. Hydrometeorol.*, **2**, 193–211.
- Banta, R. M., 1995: Sea Breezes Shallow and Deep on the California Coast. *Mon. Weather Rev.*, **123**, 3614–3622, doi:10.1175/1520-0493(1995)123<3614:sbsado>2.0.co;2.

- Barry, R. G., and R. J. Chorley, 1992: *Atmosphere, Weather, and Climate. Sixth Edition*. Routledge Publishing,.
- Biggerstaff, M. I., and S. A. Listemaa, 2000: An improved scheme for convective/stratiform echo classification using radar reflectivity. *J. Appl. Meteorol.*, **39**, 2129–2150, doi:10.1175/1520-0450(2001)040<2129:AISFCS>2.0.CO;2.
- Biggs, G. W., and M. E. Graves, 1962: A Lake Breeze Index. *J. Appl. Meteorol.*, **1**, 474–480.
- Birch, C. E., M. J. Roberts, L. Garcia-Carreras, D. Ackerley, M. J. Reeder, A. P. Lock, and R. Schiemann, 2015: Sea-breeze dynamics and convection initiation: The influence of convective parameterization in weather and climate model biases. *J. Clim.*, **28**, 8093–8108, doi:10.1175/JCLI-D-14-00850.1.
- Blalock, H. M., 1972: *Social Statistics*. McGraw-Hill, New York,.
- Blanchard, D. O., and R. E. Lopez, 1985: Spatial Patterns of Convection in South Florida. *Mon. Weather Rev.*, **113**, 1282–1299.
- Borne, K., D. Chen, and M. Nunez, 1998: A method for finding sea breeze days under stable synoptic conditions and its application to the Swedish west coast. *Int. J. Climatol.*, **18**, 901–914, doi:10.1002/(SICI)1097-0088(19980630)18:8<901::AID-JOC295>3.0.CO;2-F.
- Bornstein, R. D., and W. T. Thompson, 1981: Effects of Frictionally Retarded Sea Breeze and Synoptic Frontal Passages on Sulfur Dioxide Concentrations in New York City. *J. Appl. Meteorol.*, **20**, 843–858.
<https://www.jstor.org/stable/26179625>.
- Burpee, R., and L. Lahiffi, 1984: Area-Average Rainfall Variations on Sea-Breeze Days in South Florida. *Mon. Weather Rev.*, **112**, 520–534.
- Burpee, R. W., 1979: Peninsula-Scale Convergence in the South Florida Sea Breeze. *Mon. Weather Rev.*, **107**, 852–860.
- Byers, H. R., and H. R. Rodebush, 1948: Causes of Thunderstorm over Florida. *J. Meteorol.*, **5**, 275–280.
- Camp, J. P., A. I. Watson, and H. E. Fuelberg, 1998: The Diurnal Distribution of Lightning over North Florida and Its Relation to the Prevailing Low-Level Flow. *Weather Forecast.*, **13**, 729–739, doi:10.1175/1520-0434(1998)013<0729:tddolo>2.0.co;2.

- Campistron, B., 1975: Characteristic Distributions of Angel Echoes in the Lower Atmosphere and their Meteorological Implications. *Boundary-Layer Meteorol.*, **9**, 411–426.
- Cetola, J. D., 1997: A Climatology of the Sea Breeze at Cape Canaveral, Florida. Florida State University, .
- Chen, F., S. Miao, M. Tewari, J. W. Bao, and H. Kusaka, 2011: A numerical study of interactions between surface forcing and sea breeze circulations and their effects on stagnation in the greater Houston area. *J. Geophys. Res. Atmos.*, **116**, 1–19, doi:10.1029/2010JD015533.
- Chen, X., F. Zhang, and K. Zhao, 2016: Diurnal Variations of the Land–Sea Breeze and Its Related Precipitation over South China. *J. Atmos. Sci.*, doi:10.1175/JAS-D-16-0106.1.
- Childs, P. P., and S. Raman, 2005: Observations and numerical simulations of urban heat island and sea breeze circulations over New York City. *Pure Appl. Geophys.*, **162**, 1955–1980, doi:10.1007/s00024-005-2700-0.
- Crane, R. K., 1979: Automatic cell detection and tracking. *IEEE Trans. Geosci. Electron.*, **17**, 250–262.
- Crosman, E. T., and J. D. Horel, 2010: Sea and Lake Breezes: A Review of Numerical Studies. *Boundary-Layer Meteorol.*, doi:10.1007/s10546-010-9517-9.
- Crouch, A. D., 2006: A climatology of the sea breeze front in the coastal Carolinas and Georgia. North Carolina State University, .
- Ding, A., T. Wang, M. Zhao, T. Wang, and Z. Li, 2004: Simulation of sea-land breezes and a discussion of their implications on the transport of air pollution during a multi-day ozone episode in the Pearl River Delta of China. *Atmos. Environ.*, **38**, 6737–6750, doi:10.1016/j.atmosenv.2004.09.017.
- Dixon, M., and G. Wiener, 1993: TITAN: Thunderstorm Identification, Tracking, Analysis, and Nowcasting - A Radar-based Methodology. *Jounral Atmos. Ocean. Technol.*, **10**, 785–797.
- Durre, I., Y. Xungang, R. S. Vose, S. Applequist, and J. Arnfield, 2016: Integrated Global Radiosonde Archive (IGRA), Version 2. doi:10.7289/V5X63K0Q.
- Estoque, M. A., 1962: The Sea Breeze as a Function of the Prevailing Synoptic Situation. *J. Atmos. Sci.*, **19**, 244–250.

- Freitas, E. D., C. M. Rozoff, W. R. Cotton, and P. L. Silva Dias, 2007: Interactions of an urban heat island and sea-breeze circulations during winter over the metropolitan area of São Paulo, Brazil. *Boundary-Layer Meteorol.*, **122**, 43–65, doi:10.1007/s10546-006-9091-3.
- Frizzola, J. A., and E. L. Fisher, 1963: A Series of Sea Breeze Observations in the New York City Area. *J. Appl. Meteorol.*, **2**, 722–739.
- Fujiwara, M., 1965: Raindrop-size distribution from individual storms. *J. Atmos. Sci.*, **22**, 585–591.
- Gaffen, D. J., and R. J. Ross, 1999: Climatology and trends of U.S. surface humidity and temperature. *J. Clim.*, **12**, 811–828.
- Gaza, R. S., 1998: Mesoscale Meteorology and High Ozone in the Northeast United States. *J. Appl. Meteorol.*, **37**, 961–977.
- Gentry, R. C., and P. L. Moore, 1954: Relation of Local and General Wind Interaction Near the Sea Coast To Time and Location of Air-Mass Showers. *J. Meteorol.*, **11**, 507–511, doi:10.1175/1520-0469(1954)011<0507:rolagw>2.0.co;2.
- Gibbs, J., 1961: A method for comparing the spatial shapes of urban units. *Urban Res. Methods*, 99–106.
- Gilchrist, J., 2013: A Radar Analysis of the Delaware Sea/Bay Breeze. University of Delaware, .
- Hall, C. D., 1954: Forecasting the Lake Breeze and Its Effects on Visibility at Chicago Midway Airport. *Bull. Am. Meteorol. Soc.*, **35**, 105–111, doi:10.1175/1520-0477-35.3.105.
- Helmus, J. J., and S. M. Collis, 2016: The Python ARM Radar Toolkit (Py-ART), a Library for Working with Weather Radar Data in the Python Programming Language. *J. Open Res. Softw.*, **4**, doi:10.5334/jors.119.
- Hong, Y., K.-L. Hsu, S. Sorooshian, and X. Gao, 2004: Precipitation Estimation from Remotely Sensed Imagery Using an Artificial Neural Network Cloud Classification System. *J. Appl. Meteorol.*, **43**, 1834–1853, doi:10.1175/JAM2173.1.
[http://hydro.ou.edu/files/publications/2004/Precipitation Estimation from Remotely Sensed Imagery Using an Artificial Neural Network Cloud Classification System.pdf](http://hydro.ou.edu/files/publications/2004/Precipitation%20Estimation%20from%20Remotely%20Sensed%20Imagery%20Using%20an%20Artificial%20Neural%20Network%20Cloud%20Classification%20System.pdf).
- Hughes, C. P., 2011: The Climatology of the Delaware Bay/Sea Breeze. University of

Delaware, .

- Hughes, C. P., 2016: The Impact of Land and Sea Surface Variations on the Delaware Sea Breeze at Local Scales. University of Delaware, .
- , and D. E. Veron, 2015: Characterization of low-level winds of southern and coastal Delaware. *J. Appl. Meteorol. Climatol.*, **54**, 77–93, doi:10.1175/JAMC-D-14-0011.1.
- , and ———, 2018: A Characterization of the Delaware Sea Breeze Using Observations and Modeling. *J. Appl. Meteorol. Climatol.*, doi:10.1175/JHM-D-15-0226.1.
- Johnson, J. T., P. L. MacKeen, A. Witt, E. D. W. Mitchell, G. J. Stumpf, M. D. Eilts, and K. W. Thomas, 1998: The Storm Cell Identification and Tracking Algorithm: An Enhanced WSR-88D Algorithm. *Weather Forecast.*, **13**, 263–276, doi:10.1175/1520-0434(1998)013<0263:TSCIAT>2.0.CO;2.
- Jones, E., T. Oliphant, and P. Peterson, 2001: SciPy: Open Source Scientific Tools for Python. <http://www.scipy.org/>.
- Joss, J., and A. Waldvogel, 1969: Raindrop Size Distribution and Sampling Size Errors. *J. Atmos. Sci.*, **26**, 566–569, doi:10.1175/1520-0469(1969)026<0566:RSDASS>2.0.CO;2.
<http://journals.ametsoc.org/doi/abs/10.1175/1520-0469%281969%29026%3C0566%3ARSDASS%3E2.0.CO%3B2>.
- Keeler, J. M., and D. A. R. Kristovich, 2012: Observations of urban heat Island influence on lake-breeze frontal movement. *J. Appl. Meteorol. Climatol.*, **51**, 702–710, doi:10.1175/JAMC-D-11-0166.1.
- Kingsmill, D. E., 1995: Convection Initiation Associated with a Sea-Breeze Front. *Mon. Weather Rev.*, **123**, 2913–2933.
- Kitada, T., 1987: Turbulence structure of sea breeze front and its implication in air pollution transport - Application of k-e turbulence model. *Boundary-Layer Meteorol.*, **41**, 217–239.
- Knox, P., C. Fuhrmann, and C. Konrad, 2014: Challenges and Opportunities for Southeast Agriculture in a Changing Climate: Perspectives from State Climatologists. *Southeast. Geogr.*, **54**, 118–136, doi:10.1353/sgo.2014.0017.
http://muse.jhu.edu/content/crossref/journals/southeastern_geographer/v054/54.2.knox.html.

- Kummerow, C., W. S. Olson, and L. Giglio, 1996: A simplified scheme for obtaining precipitation and vertical hydrometeor profiles from passive microwave sensors. *IEEE Trans. Geosci. Remote Sens.*, **34**, 1213–1232, doi:10.1109/36.536538.
- , and Coauthors, 2001: The Evolution of the Goddard Profiling Algorithm (GPROF) for Rainfall Estimation from Passive Microwave Sensors. *J. Appl. Meteorol.*, **40**, 1801–1820, doi:10.1175/1520-0450(2001)040<1801:TEOTGP>2.0.CO;2.
<http://journals.ametsoc.org/doi/abs/10.1175/1520-0450%282001%29040%3C1801%3ATEOTGP%3E2.0.CO%3B2>.
- Laird, N. F., D. A. R. Kristovich, X. Liang, R. W. Arritt, S. Journal, N. March, and L. E. T. Al, 2001: Lake Michigan Lake Breezes : Climatology , Local Forcing , and Synoptic Environment. *J. Appl. Meteorol.*, **40**, 409–424.
- Lakshmanan, V., T. Smith, G. Stumpf, and K. Hondl, 2007: The Warning Decision Support System–Integrated Information. *Weather Forecast.*, **22**, 596–612, doi:10.1175/WAF1009.1.
<http://journals.ametsoc.org/doi/abs/10.1175/WAF1009.1>.
- Lampman, G., 2019: Leasing Information Map.
<https://nyfisheriestwg.ene.com/Resources/LeaseMap>.
- Levy, I., Y. Mahrer, and U. Dayan, 2009: Coastal and synoptic recirculation affecting air pollutants dispersion: A numerical study. *Atmos. Environ.*, **43**, 1991–1999, doi:10.1016/j.atmosenv.2009.01.017.
<http://dx.doi.org/10.1016/j.atmosenv.2009.01.017>.
- Lhermitte, R. M., and M. Gilet, 1975: Dual-Doppler Radar Observation and Study of Sea Breeze Convective Storm Development. *J. Appl. Meteorol.*, **14**, 1346–1361.
- Li, X., G. Zhai, S. Gao, and X. Shen, 2014: A new convective-stratiform rainfall separation scheme. *Atmos. Sci. Lett.*, **15**, 245–251, doi:10.1002/asl2.493.
- Liang, Z., D. Wang, Y. Liu, and Q. Cai, 2017: A numerical study of the convection triggering and propagation associated with sea breeze circulation over Hainan Island. *J. Geophys. Res. Atmos.*, **122**, 8567–8592, doi:10.1002/2016JD025915.
- Lin, Y., 2011: GCIP/EOP Surface: Precipitation NCEP/EMC 4KM Gridded Data (GRIB) Stage IV Data. <https://doi.org/10.5065/D6PG1QDD>.
- , and K. E. Mitchell, 2005: The NCEP Stage II/IV hourly precipitation analyses: development and applications. *19th Conf. on Hydrology, American Meteorological Society*, San Diego, CA

<http://www.emc.ncep.noaa.gov/mmb/ylin/pcpanl/refs/stage2-4.19hydro.pdf>.

Linton, M., E. T. Doyle, F. Vignuli, J. Balzano, and J. Walsh, 2010: *Delaware River and Bay Oil Spill Advisory Committee Report*. 46-20 pp.

https://www.state.nj.us/drbc/library/documents/DRBOSAC_final-report122010.pdf.

Lombardo, K., E. Sinsky, J. Edson, M. M. Whitney, and Y. Jia, 2018: Sensitivity of Offshore Surface Fluxes and Sea Breezes to the Spatial Distribution of Sea-Surface Temperature. *Boundary-Layer Meteorol.*, **166**, 475–502, doi:10.1007/s10546-017-0313-7.

Luchetti, N. T., R. N. Ferreira, T. M. Rickenbach, M. R. Nissenbaum, and J. D. McAuliffe, 2017: Influence of the North Atlantic Subtropical High on wet and dry sea-breeze events in North Carolina, United States. *Investig. Geogr.*, **68**, 9–25, doi:10.14198/INGEO2017.68.01.

Mazon, J., J. I. Rojas, J. Jou, A. Valle, D. Olmeda, and C. Sanchez, 2015: An assessment of the sea breeze energy potential using small wind turbines in peri-urban coastal areas. *J. Wind Eng. Ind. Aerodyn.*, **139**, 1–7, doi:10.1016/j.jweia.2015.01.002. <http://dx.doi.org/10.1016/j.jweia.2015.01.002>.

Michaels, P. J., 1985: Anomalous mid-atmospheric heights and persistent thunderstorm patterns over florida. *J. Climatol.*, **5**, 529–542, doi:10.1002/joc.3370050506.

Miller, P. W., and T. L. Mote, 2017: A climatology of weakly forced and pulse thunderstorms in the southeast United States. *J. Appl. Meteorol. Climatol.*, **56**, 3017–3033, doi:10.1175/JAMC-D-17-0005.1.

Miller, S. T. K., B. D. Keim, R. W. Talbot, and H. Mao, 2003: Sea breeze: Structure, forecasting, and impacts. *Rev. Geophys.*, **41**, doi:10.1029/2003RG000124.

Moore, D. P., and D. E. Veron, 2019: A Characterization of Sea Breeze Enhanced Rainfall in South Florida. *J. Appl. Meteorol. Climatol.*, **In Review**.

Mrocza, B., 2003: The influence of the synoptic flow on warm season rainfall patterns over the Florida peninsula. Florida State University, .

———, P. Camp, K. Gould, and A. I. Watson, 2010: Improving the temporal and spatial resolution of the forecast of sea-breeze generated convection along the southeast U.S. coast. *26th Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, Session 4, Applications in Meteorology, Oceanography, Hydrology and Climatology Part I*.

- National Weather Service, 2016: Florida Sea Breeze Thunderstorm Regime Methodology. https://www.weather.gov/tbw/SB_Methodology (Accessed February 3, 2019).
- Neumann, C. J., 1969: Frequency and Duration of Thunderstorms in the Cape Kennedy Area. *Sp. Congr. Proc.*, **1**.
- Nicholls, M., R. A. Pielke, and W. Cotton, 1991: A two-dimensional numerical investigation of the interaction between sea breezes and deep convection over the Florida peninsula. *Mon. Weather Rev.*, **119**, 298–323, doi:10.1175/1520-0493(1991)119<0298:ATDNIO>2.0.CO;2.
<http://rams.atmos.colostate.edu/cotton/vita/58.pdf>.
- NOAA/NDBC, 2019: NDBC Buoy Surface Water Temperature Historical Data.
- NOAA, N. W. S. (NWS) R. O. C., 1991: NOAA Next Generation Radar (NEXRAD) Level 2 Base Data. doi:10.7289/V5W9574V.
- Nystuen, J. A., 1999: Relative performance of automatic rain gauges under different rainfall conditions. *J. Atmos. Ocean. Technol.*, **16**, 1025–1043, doi:10.1175/1520-0426(1999)016<1025:RPOARG>2.0.CO;2.
- Ookouchi, Y., M. Segal, R. C. Kessler, and R. Pielke, 1984: Evaluation of Soil Moisture Effects on the Generation and Modification of Mesoscale Circulations. *Mon. Weather Rev.*, **112**, 2281–2292.
- Papanastasiou, D. K., and D. Melas, 2009: Climatology and impact on air quality of sea breeze in an urban coastal environment. *Int. J. Climatol.*, **29**, 305–315, doi:10.1002/joc.1707.
- Papanastasiou, D. K., D. Melas, and I. Lissaridis, 2010: Study of wind field under sea breeze conditions; an application of WRF model. *Atmos. Res.*, **98**, 102–117, doi:10.1016/j.atmosres.2010.06.005.
<http://dx.doi.org/10.1016/j.atmosres.2010.06.005>.
- Pielke, R., 1974: A Three-Dimensional Numerical Model of the Sea Breezes Over South Florida. *Mon. Weather Rev.*, **102**, 115–139.
- Pielke, R. A., P. J. Michaels, W. A. Lyons, and R. W. Arritt, 1991a: The predictability of sea-breeze generated thunderstorms. *Atmosfera*, **4**, 66–78.
- Pielke, R. A., A. Song, P. J. Michaels, W. A. Lyons, and R. W. Arritt, 1991b: The predictability of sea-breeze generated thunderstorms. *Atmosfera*, **4**, 65–78.

- Pielke, R. A., R. L. Walko, L. T. Steyaert, P. L. Vidale, G. E. Liston, W. a Lyons, and T. N. Chase, 1999: The Influence of Anthropogenic Landscape Changes on Weather in South Florida. *Mon. Weather Rev.*, **127**, 1663–1673, doi:10.1175/1520-0493(1999)127<1663:TIOALC>2.0.CO;2, [http://dx.doi.org/10.1175/1520-0493\(1999\)127%3C1663:TIOALC%3E2.0.CO;2%5Cnhttp://journals.ametsoc.org/doi/pdf/10.1175/1520-0493%281999%29127%3C1663%3ATIOALC%3E2.0.CO%3B2](http://dx.doi.org/10.1175/1520-0493(1999)127%3C1663:TIOALC%3E2.0.CO;2%5Cnhttp://journals.ametsoc.org/doi/pdf/10.1175/1520-0493%281999%29127%3C1663%3ATIOALC%3E2.0.CO%3B2).
- Planchon, O., V. Dubreuil, and P. Gouery, 2006: A method of identifying and locating sea-breeze fronts in north-eastern Brazil by remote sensing. *Meteorol. Appl.*, **13**, 225–234, doi:10.1017/S1350482706002283.
- Rakesh, P. T., B. S. Sandeepan, R. Venkatesan, and R. Baskaran, 2017: Observation and numerical simulation of submesoscale motions within sea breeze over a tropical coastal site: A case study. *Atmos. Res.*, **198**, 205–215, doi:10.1016/j.atmosres.2017.08.006, <http://dx.doi.org/10.1016/j.atmosres.2017.08.006>.
- Ramshaw, J. D., 1986: Simplified second-order rezoning algorithm for generalized two-dimensional meshes. *J. Comput. Phys.*, **67**, 214–222, doi:10.1016/0021-9991(86)90122-1.
- Rao, P. A., and H. E. Fuelberg, 2000: An Investigation of Convection behind the Cape Canaveral Sea-Breeze Front. *Mon. Weather Rev.*, **128**, 3437–3458, doi:10.1175/1520-0493(2000)128<3437:aiocbt>2.0.co;2.
- Rheme, J. R., D. D. S. Niyogi, and S. Raman, 2003: Assessing Seasonal Transport and Deposition of Agricultural Emissions in Eastern North Carolina, U.S.A. **160**, 117–141.
- Rickenbach, T. M., R. Nieto-Ferreira, C. Zarzar, and B. Nelson, 2015: A seasonal and diurnal climatology of precipitation organization in the southeastern United States. *Q. J. R. Meteorol. Soc.*, **141**, 1938–1956, doi:10.1002/qj.2500, <http://doi.wiley.com/10.1002/qj.2500>.
- Ringard, J., M. Becker, F. Seyler, and L. Linguet, 2015: Temporal and spatial assessment of four satellite rainfall estimates over French Guiana and north Brazil. *Remote Sens.*, **7**, 16441–16459, doi:10.3390/rs71215831.
- Ryu, Y.-H., J. A. Smith, and E. Bou-Zeid, 2015: On the Climatology of Precipitable Water and Water Vapor Flux in the Mid-Atlantic Region of the United States. *J. Hydrometeorol.*, **16**, 70–87, doi:10.1175/JHM-D-14-0030.1, <http://journals.ametsoc.org/doi/10.1175/JHM-D-14-0030.1>.

- , ———, ———, and M. L. Baeck, 2016: The Influence of Land Surface Heterogeneities on Heavy Convective Rainfall in the Baltimore–Washington Metropolitan Area. *Mon. Weather Rev.*, **144**, 553–573, doi:10.1175/MWR-D-15-0192.1. <http://journals.ametsoc.org/doi/10.1175/MWR-D-15-0192.1>.
- Sauvageot, H., and J. Omar, 1987: Radar Reflectivity of Cumulus Clouds. *J. Atmos. Ocean. Technol.*, **4**, 264–272, doi:10.1175/1520-0426(1987)004<0264:RROCC>2.0.CO;2.
- Seroka, G., E. Fredj, J. Kohut, R. Dunk, T. Miles, and S. Glenn, 2018: Sea Breeze Sensitivity to Coastal Upwelling and Synoptic Flow Using Lagrangian Methods. *J. Geophys. Res. Atmos.*, **123**, 9443–9461, doi:10.1029/2018JD028940.
- Simpson, J. E., 1967: Aerial and Radar Observations of Some Sea-Breeze Fronts. *Weather*, **22**, 306–316, doi:10.1002/j.1477-8696.1967.tb02946.x.
- Simpson, J. E., 1994: *Sea Breeze and Local Winds*. Cambridge UP,.
- , D. A. Mansfield, and J. R. Milford, 1977: Inland penetration of sea-breeze fronts. *Q. J. R. Meteorol. Soc.*, **103**, 47–76, doi:10.1002/qj.49710343504.
- Steiner, M., R. A. Houze, and S. E. Yuter, 1995: Climatological Characterization of Three-Dimensional Storm Structure from Operational Radar and Rain Gauge Data. *J. Appl. Meteorol.*, **34**, 1978–2007, doi:10.1175/1520-0450(1995)034<1978:CCOTDS>2.0.CO;2. <http://journals.ametsoc.org/doi/abs/10.1175/1520-0450%281995%29034%3C1978%3ACCOTDS%3E2.0.CO%3B2>.
- Suresh, R., 2007: Observation of Sea Breeze Front and its Induced Convection over Chennai in Southern Peninsular India Using Doppler Weather Radar. **164**, 1511–1525, doi:10.1007/s00024-007-0234-3.
- Taylor, J., 1967: *Weather and Agriculture*. Pergamon Press, Oxford,.
- Ulanski, S. L., and M. Garstang, 1978: Some aspects of Florida convective rainfall. *Water Resour. Res.*, **14**, 1133–1139, doi:10.1029/WR014i006p01133.
- University of Florida, 2019: Florida Automated Weather Network.
- US Wind, 2019: US Wind Projects.
- Vemado, F., and A. J. Pereira Filho, 2016: Severe weather caused by heat island and sea breeze effects in the metropolitan area of são paulo, Brazil. *Adv. Meteorol.*, **2016**, doi:10.1155/2016/8364134.

- Wakimoto, R. M., and N. T. (UCLA) Atkins, 1993: Observations of the sea-breeze front during CaPE. Part I: Single-Doppler, Satellite, and Cloud Photogrammetry Analysis. *Mon. Weather Rev.*, **122**, 1092–1114.
- Wang, Y., S. Di Sabatino, A. Martilli, Y. Li, M. S. Wong, E. Gutiérrez, and P. W. Chan, 2017: Impact of land surface heterogeneity on urban heat island circulation and sea-land breeze circulation in Hong Kong. *J. Geophys. Res.*, **122**, 4332–4352, doi:10.1002/2017JD026702.
- Watson, A. I., R. L. Holle, R. E. López, R. Ortiz, and J. R. Nicholson, 1991: Surface Wind Convergence as a Short-Term Predictor of Cloud-to-Ground Lightning at Kennedy Space Center. *Weather Forecast.*, **6**, 49–64, doi:10.1175/1520-0434(1991)006<0049:SWCAAS>2.0.CO;2. [https://doi.org/10.1175/1520-0434\(1991\)006%3C0049:SWCAAS%3E2.0.CO%0Ahttp://0.0.0.2](https://doi.org/10.1175/1520-0434(1991)006%3C0049:SWCAAS%3E2.0.CO%0Ahttp://0.0.0.2).
- Watts, A., 1955: Sea breeze at Thorney Island. *Meteorol. Mag.*, **84**, 42–48.
- Wilson, J., and D. L. Megenhardt, 1997: Thunderstorm initiation, organization, and lifetime associated with Florida boundary layer convergence lines. *Mon. Weather Rev.*, **125**, 1507–1512.
- Wilson, J. W., T. M. Weckwerth, J. Vivekanandan, R. M. Wakimoto, and R. W. Russell, 1994: Boundary Layer Clear-Air Radar Echoes: Origin of Echoes and Accuracy of Derived Winds. *J. Atmos. Ocean. Technol.*, **11**, 1184–1206.
- Woodley, W. L., A. R. Olsen, A. Herndon, and V. Wiggert, 1975: Comparison of Gage and Radar Methods of Convective Rain Measurement. *J. Appl. Meteorol.*, **14**, 909–928, doi:10.1175/1520-0450(1975)014<0909:COGARM>2.0.CO;2. [http://journals.ametsoc.org/doi/abs/10.1175/1520-0450\(1975\)014%3C0909:COGARM%3E2.0.CO;2](http://journals.ametsoc.org/doi/abs/10.1175/1520-0450(1975)014%3C0909:COGARM%3E2.0.CO;2).
- Zhang, J., C. Langston, and K. Howard, 2008: Bright band identification based on vertical profiles of reflectivity from the WSR-88D. *J. Atmos. Ocean. Technol.*, **25**, 1859–1872.
- Zhang, J., and Coauthors, 2011: National mosaic and multi-sensor QPE (NMQ) system description, results, and future plans. *Bull. Am. Meteorol. Soc.*, **92**, 1321–1338, doi:10.1175/2011BAMS-D-11-00047.1.
- , and Coauthors, 2016: MULTI_RADAR MULTI_SENSOR QUANTITATIVE PRECIPITATION ESTIMATION : Initial Operating Capabilities. *Bull. Am. Meteorol. Soc.*, **97**, 621–637.
- Zhong, S., and E. S. Takle, 1993: The Effects of Large-Scale Winds on the Sea-Land-

Breeze Circulations in an Area of Complex Coastal. *J. Appl. Meteorol.*, **32**.

2018: *State of the Air Report*. Chicago, IL, 1-167 pp.

Appendix

ANALYSIS OF SURFACE WATER TEMPERATURES IN SOUTH FLORIDA

The temperature gradient between land and water is often the primary driver of the SBC. As a result, we analyzed within-season variation in surface water temperatures in three locations surrounding the Florida Peninsula (see Figure 3.1). The aim was to characterize extreme surface water temperatures in order to test whether significant deviations from the normal seasonal cycle had an influence on SBC formation and/or characteristics. In section 3.2.3 of this thesis, we found that, at a regional scale, surface water temperatures do not significantly influence SBC formation in South Florida for the time period 2008-2018. In other words, we found that even temperatures three standard deviations below the mean, which would hypothetically result in the greatest temperature gradient between land and water, did not result in a significant increase in SBC detection in any of the three regions.

As described in section 3.2.3 surface water temperatures were averaged by day of year at each buoy. Then a third-order least-squares regression captured the average seasonal variation along the central east coast (Figure A.1), the south-east coast (Figure A.2), and the west coast (Figure A.3). These were subtracted from the daily surface water temperature values at each station and the day was characterized by the deviation of the observation from the calculated 11-year mean for that day.

Due to data availability, two buoys were chosen in each region: a primary buoy and a secondary buoy, which is used on days when more than 25% of data from the primary buoy is unavailable. In order to perform this analysis with confidence, we

determined the correlation between the primary and secondary stations in each region. The r^2 for the primary and secondary stations on the west (Figure A.4) and southeast (Figure A.5) coasts were well correlated at $r^2 > 0.94$. Interestingly, along the central east coast of Florida, the temperature data from the two buoys was far less correlated ($r^2 = 0.79$; Figure A.6), compared to the other two coasts. Specifically, buoy 41113, located closer to shore than the primary central east coast buoy 41009, observes a consistently lower temperature.

There are three potential causes for the observed difference in this region (e.g. Figure A.7) compared to the other two. The first is instrumentation error, which is most likely ruled out due to the length of the study period (11 years), in addition to analysis of SST maps. Second, because of station 41113's proximity to the coastline, it may be located in a region that experiences coastal upwelling, which would bring cooler ocean waters from below toward the sea surface along the coast. Third, these two stations are located in a region where the position of the Gulf Stream potentially meanders. Finally, the coastal water temperatures are subject to rapid change over the time period of even a day (Figure A.8).

We investigate this further by comparing daily averaged surface water temperatures during the summer of 2017 for three buoys located 1 km (41113), 30 km (41009), and 180 km (41010) off the eastern coast of Florida (Figure A.9). The year 2017 was chosen due to data availability across these stations. Overall, water temperatures at buoy 41010 tends to be warmer than the other two buoys, with buoy 41113 showing significant abrupt drops in temperature (Figure A.10). During one abrupt drop at 41113 in June, station 41009 experiences a similar drop in temperature.

However, a decrease in temperature at station 41113 near the end of July and beginning of August is not experienced elsewhere.

To compare, we produced a similar analysis for three stations off the west coast of Florida during the summer of 2016. This year was chosen due to completeness of the daily datasets for each station for thorough comparison. The stations are located roughly 20 km (42098), 100 km (42022), and 150 km (42099) off the west coast of Florida (Figure A.11). In contrast to the east coast study, the water temperatures at each of these stations are largely consistent amongst each other in the summertime (Figure A.12). In other words, changes in temperature observed at one station are usually observed at the other two.

The preliminary results presented in this Appendix call for further investigation into the surface water temperature variability in the central east coast region of Florida, and specifically how it affects on-land SBC formation, and convergence and precipitation. This region consists of complex interactions between the Gulf Stream and coastal upwelling, which potentially drives on-land wind variability and specifically the SBC. Further, the station data used in Chapter 3 of this thesis was most likely insufficient to capture its effects on the east coast SBC due to station scarcity in that region. A higher resolution approach is needed to capture summertime wind variability very close to the coastline, in a method similar to Cetola (1997).

FIGURES

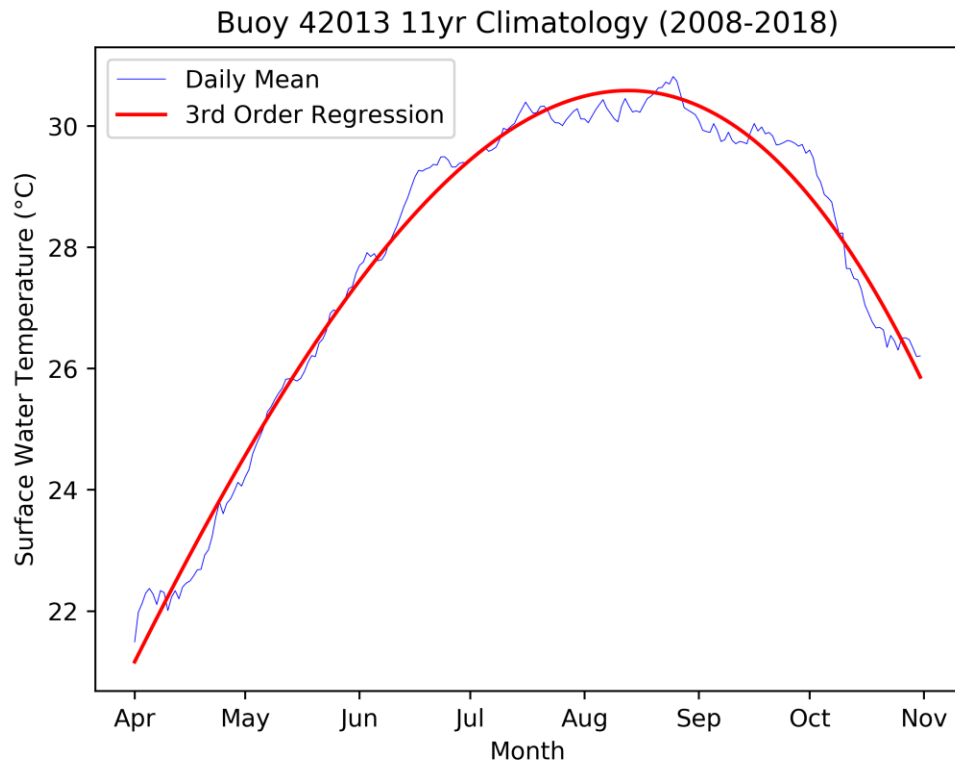


Figure A.1 11-year (2008-2018) daily average surface water temperatures (SWT) at buoy 41009. The third order regression used to de-trend seasonal variability is shown (red).

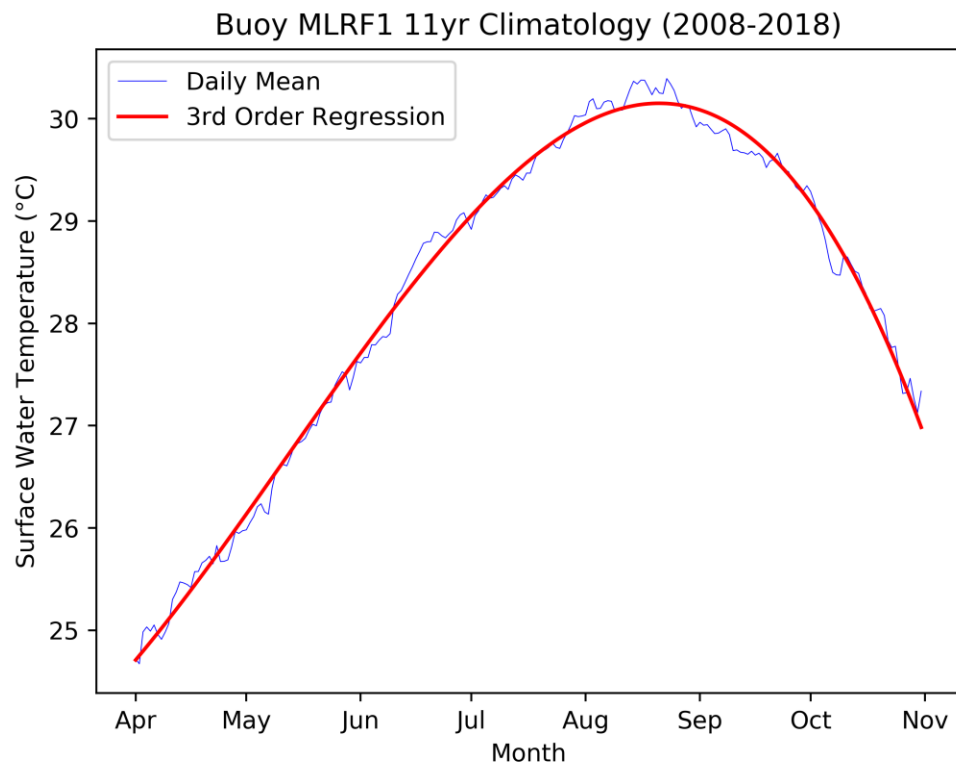


Figure A.2 As Figure A.1, for buoy MLRF1.

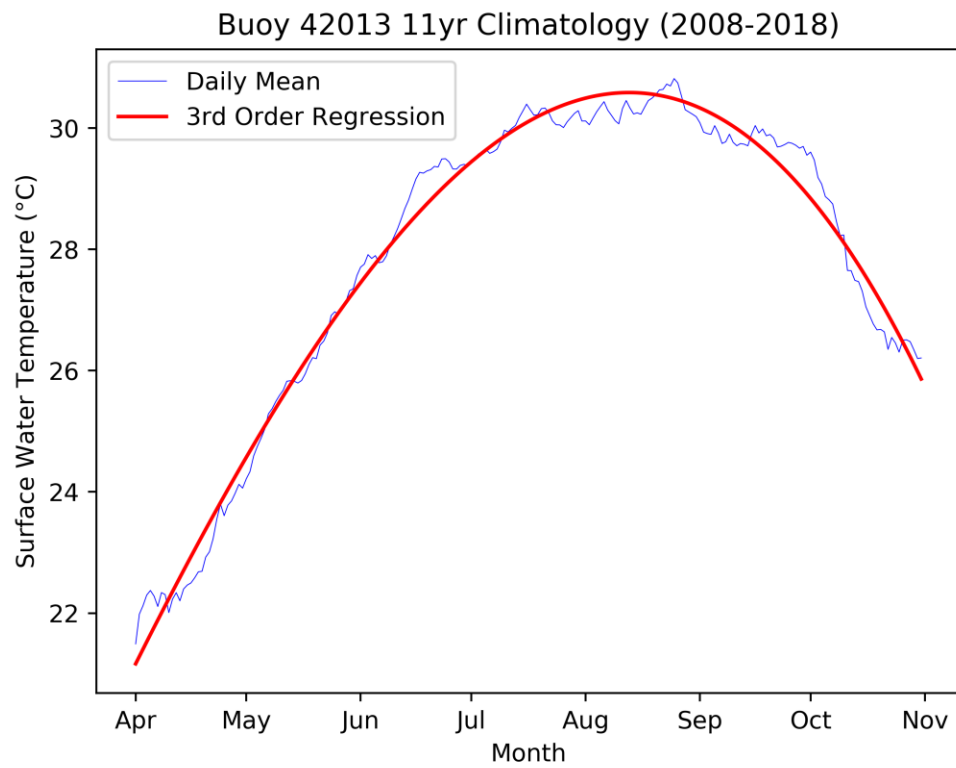


Figure A.3 As Figure A.1, for buoy 42013.

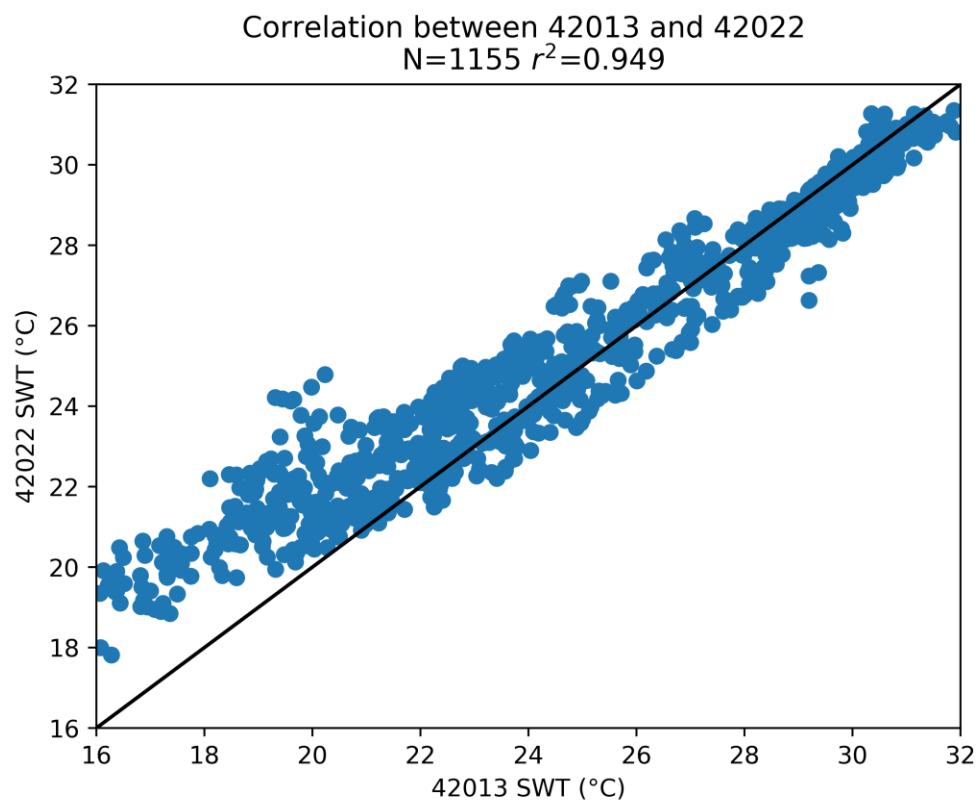


Figure A.4 Correlation analysis of daily surface water temperatures (SWT) between primary buoy 42013 and secondary buoy 42022 located on the west coast of Florida for April – October from 2008 – 2018. The number of data points analyzed (N) and correlation value (r^2) are presented in the title.

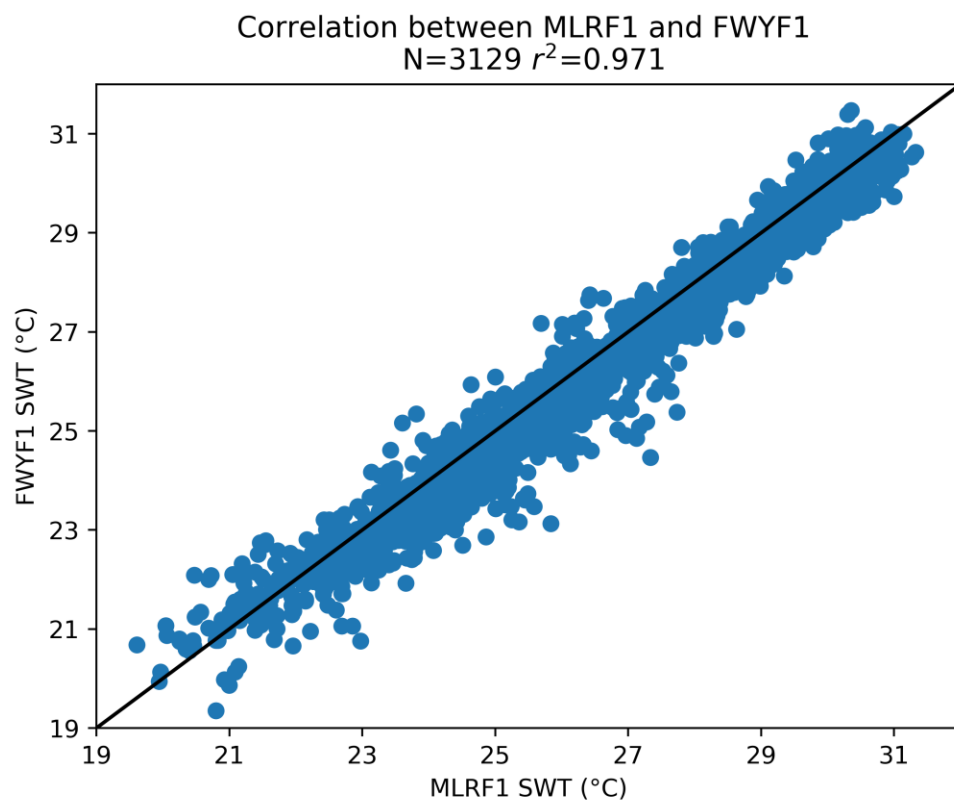


Figure A.5 As Figure A.4 for primary buoy MLRF1 and secondary buoy FWYF1 on the south-east coast of Florida.

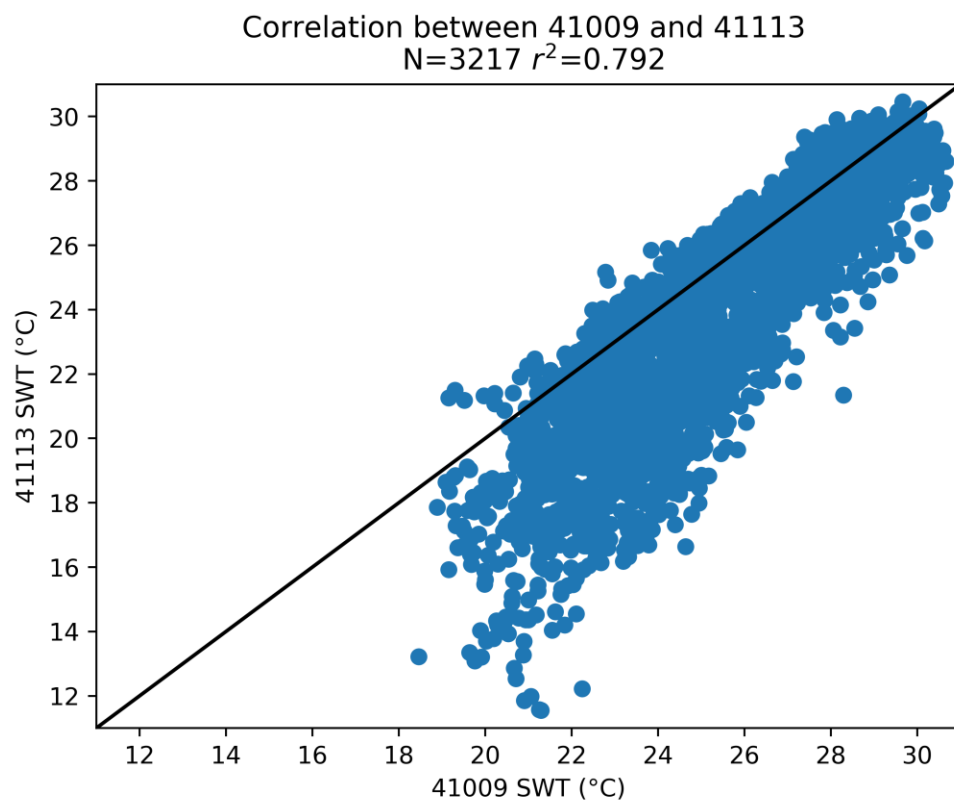


Figure A.6 As Figure A.4 for primary buoy 41009 and secondary buoy 41113 on the central east coast of Florida.

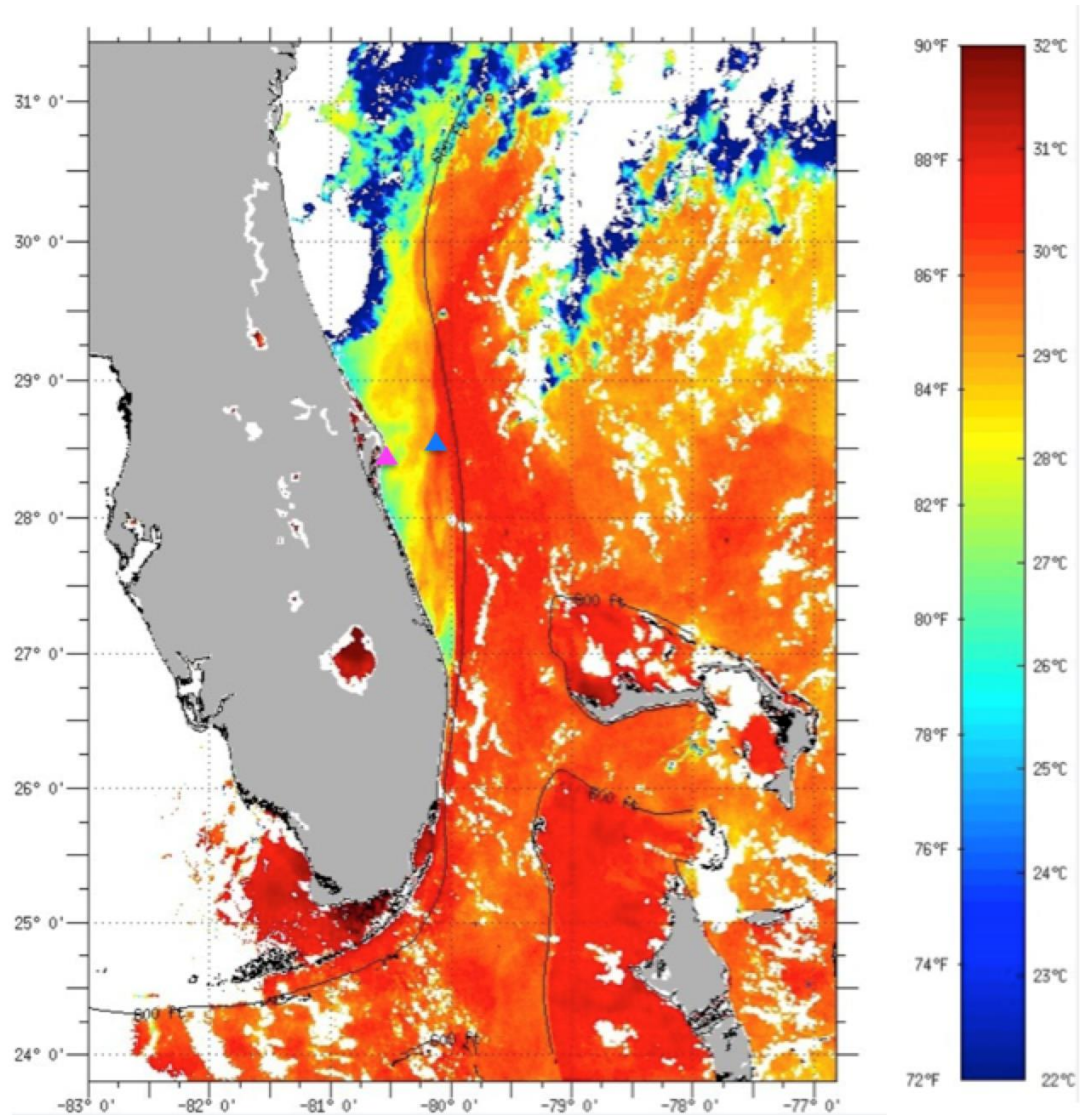


Figure A.7 Satellite derived sea surface temperatures surrounding Florida for 8 August 2017 valid 2018 UTC. The positions of buoys 41113 (pink triangle) and 41009 (blue triangle) are shown. The ocean depth contour (black) shows the location of 600 ft depth. (Source: Rutgers Coastal Ocean Observations Lab)

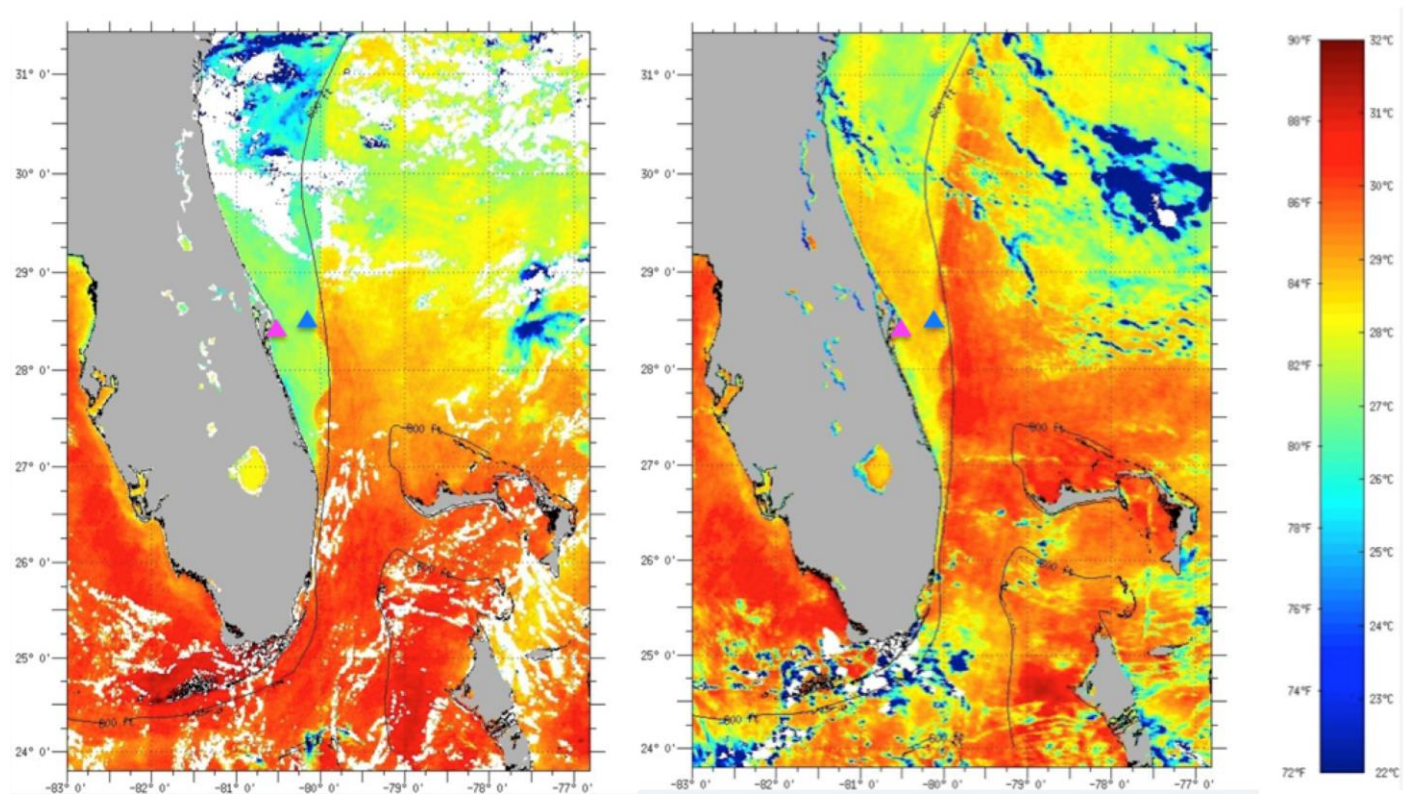


Figure A.8 Satellite derived sea surface temperatures surrounding Florida for 30 August 2017 valid 1257 UTC (left) and 31 August 2017 valid 0935 UTC (right). The positions of buoys 41113 (pink triangle) and 41009 (blue triangle) are shown. The ocean depth contour (black) shows the location of 600 ft depth. (Source: Rutgers Coastal Ocean Observations Lab)

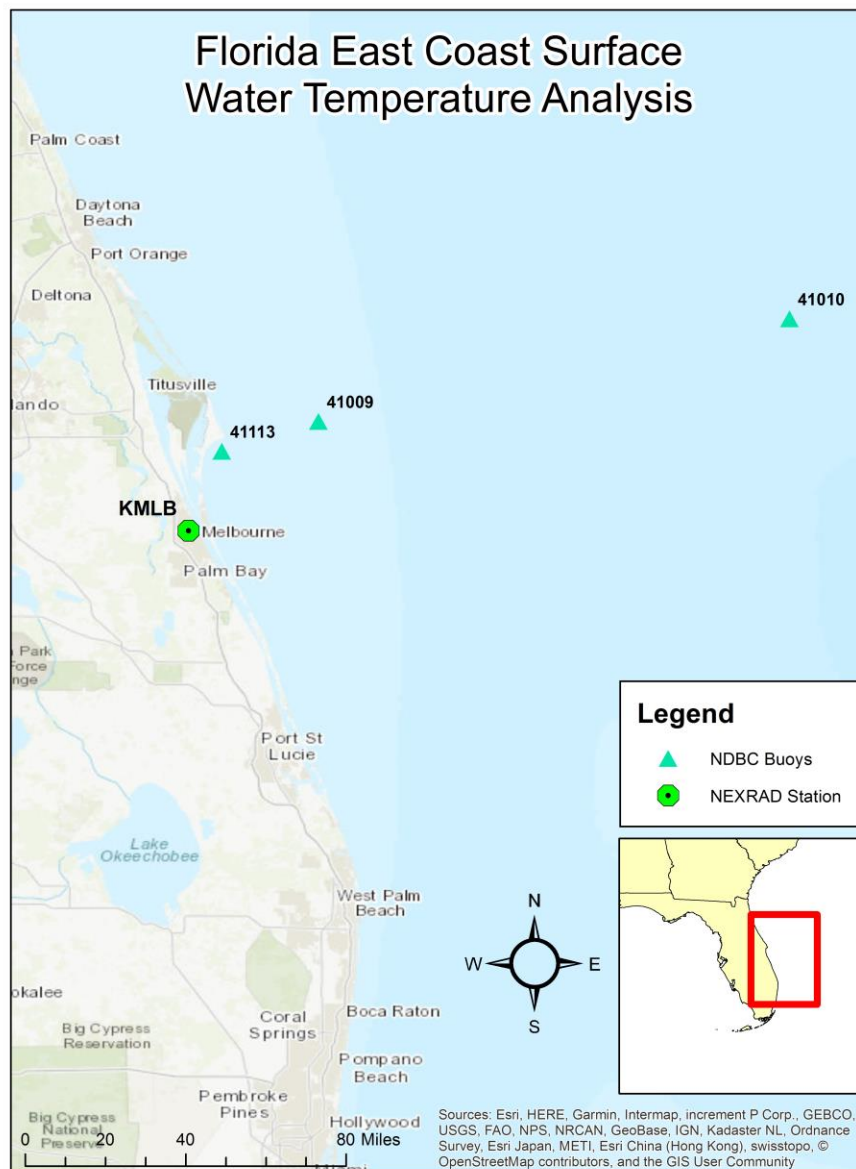


Figure A.9 Map of buoy locations used for 2017 analysis of east coast surface water temperatures in Florida. Positions of buoys 41113, 41009, and 41010, operated by National Data Buoy Center, are shown.

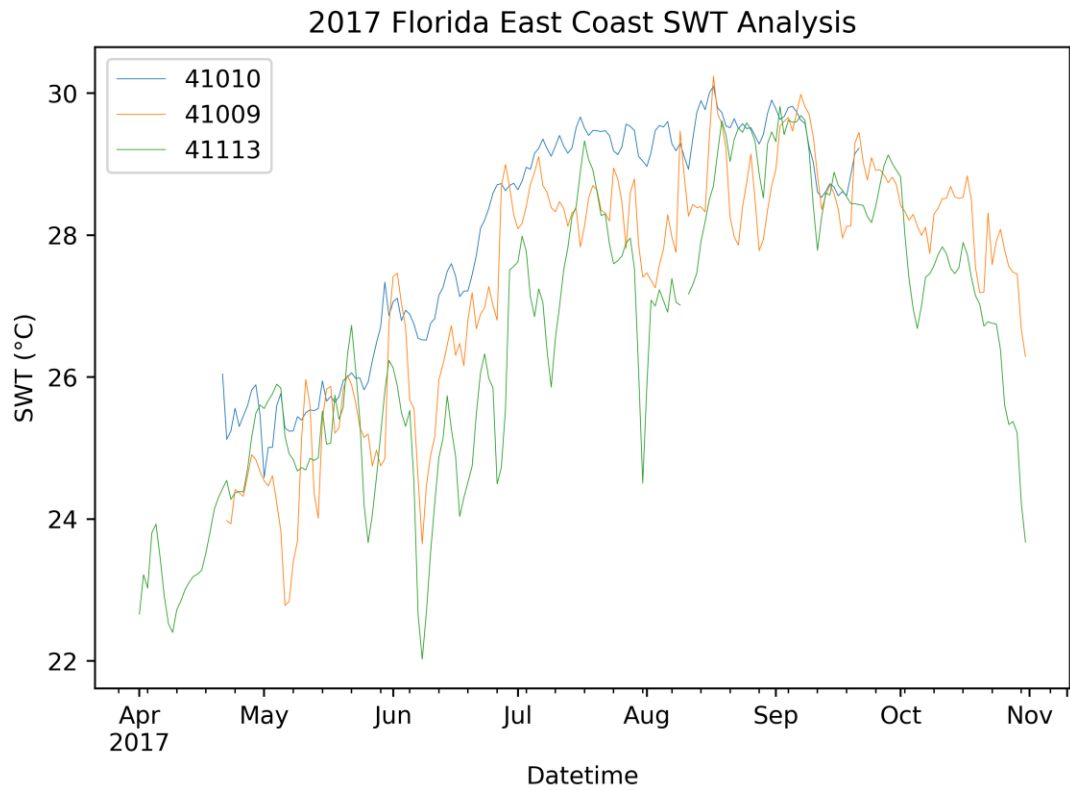


Figure A.10 Daily averaged surface water temperatures (SWT) for three buoys off the east coast of Florida during the warm season of 2017. Buoy 41113 is located approximately 1 km from the coast of Florida, buoy 41009 is approximately 30 km from the coast, and buoy 41010 is approximately 180 km offshore.

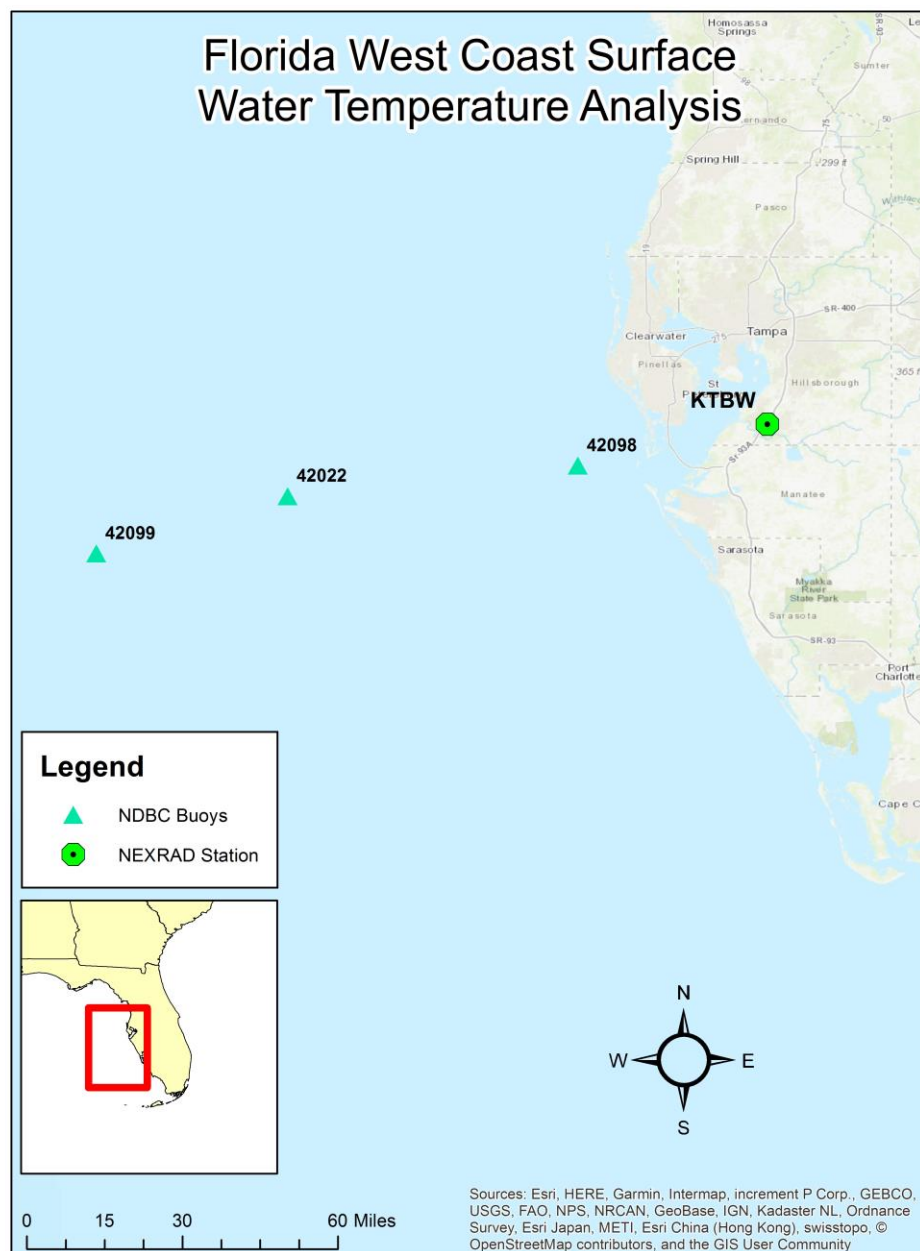


Figure A.11 Map of buoy locations used for 2016 analysis of west coast surface water temperatures in Florida. Positions of buoy 42098, 42022, and 42099, operated by National Data Buoy Center, are shown.

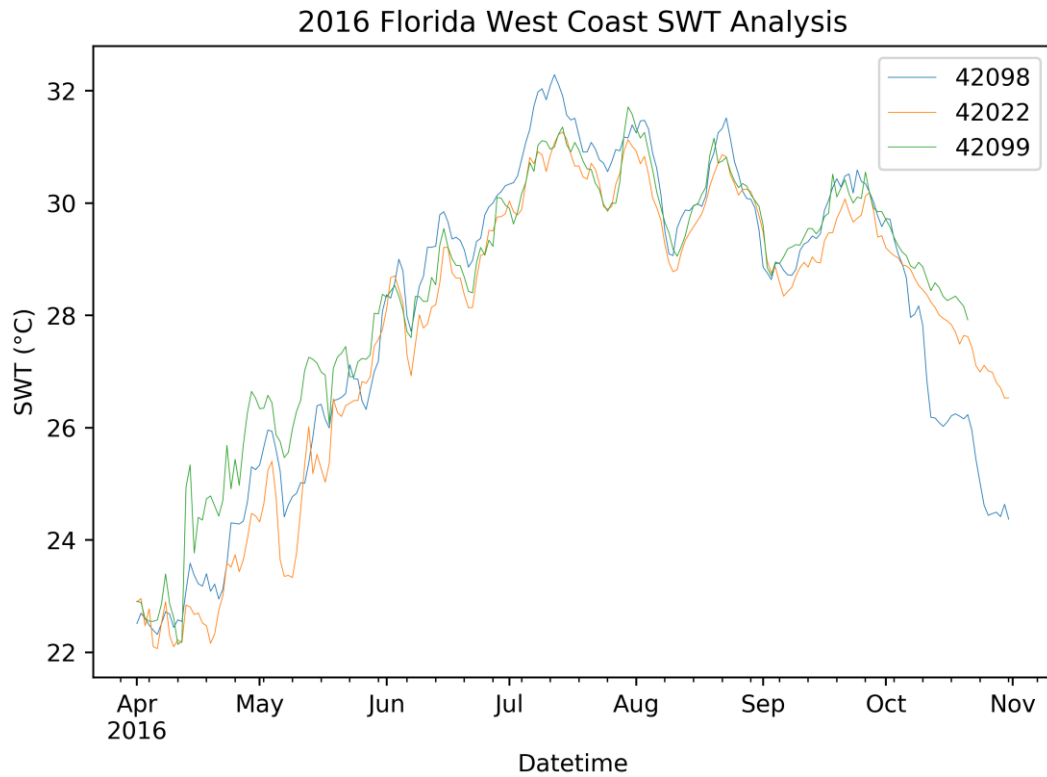


Figure A.12 Daily averaged surface water temperatures (SWT) for three buoys off the west coast of Florida during the warm season of 2016. Buoy 42098 is located approximately 20 km from the coast of Florida, buoy 42022 is approximately 100 km from the coast, and buoy 42099 is approximately 150 km offshore.