ABSTRACT

BOOTH, WILLIAM JAY. A Summertime Radar Climatology of Convection in the Coastal Region of South Carolina. (Under the direction of Matthew Parker.)

A radar climatology of the frequency of convection for the region around Charleston, South Carolina (CHS) was conducted to improve the understanding of the timing and location of summertime convective activity. Specifically, this study addresses the role of the sea breeze front (SBF) in organizing deep moist convection. To determine when a strong SBF passage occurred at CHS, a sea breeze detection index was created to isolate days when the SBF potentially had a large impact on the organization of convection. Consistent with previous studies, the strongest SBFs occurred with offshore 925 hPa flow. Onshore flow typically had weaker SBFs that were not the primary focus for convective development. Widespread convection occurred with southwesterly alongshore flow owing to the advection of high $\theta_e$ air from the Gulf of Mexico. The SBF was one among many possible lifting mechanisms for initiating storms in that flow regime.

The frequency of convection $\geq 40$ dBZ was examined for a range of environmental conditions including low level wind direction, shear, and instability. Prior work by Moncrieff and Liu (1999) suggested that a combination of offshore flow and onshore shear should be most favorable for convective triggering. However, storms did not occur most frequently in the optimal shear scenario envisioned by Moncrieff and Liu (1999), suggesting that the majority of convection in South Carolina was likely governed by other factors, including instability. The highest frequencies of strong convection occurred in 925 hPa southwesterly alongshore flow. The strength of the SBF passage at CHS was not typically the most important factor in determining the highest frequencies of convection. This study suggests that the flow direction, and its associated thermodynamic environment, is a better indicator of the areal coverage and frequencies of strong convection.
Dedication

My family always joked about how they helped me in school by not helping me when it came to solving problems in science and math, but they should know that they were the inspiration for my work. I dedicate this work to Mom, Dad, Grandma, Kristin, Corrie, Kerry, and Bobby for all they have done to make me a better person. I also dedicate this to Sharon Preski, the love of my life.
Biography

William Booth was born on July 18, 1984 in Fairfax, Virginia. He grew up in Matthews, North Carolina where he always watched the Weather Channel and reported what the weather would be to his neighbors while waiting for the bus in elementary school.

After graduating from Providence High School in 2002, William attended North Carolina State University to become an engineer and compete as a Division I athlete in the sport of swimming. When Hurricane Isabel approached North Carolina in 2003, William realized that he wanted to spend his life learning about the dynamics of storms. During his sophomore year, he switched his major to Meteorology. He graduated from North Carolina State University in May of 2006 with B.S. in Meteorology and a B.S. in History.

William enjoys swimming, watching New York Giants football, and observing convective storms.
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Chapter 1

Introduction

A sea breeze front is a mesoscale phenomenon caused by differential heating between a land mass and a body of water (Wexler, 1946). Diurnal heating creates warm, less stable air over the land compared to the relatively cool, more stable air over the ocean. The heating produces a low pressure perturbation over the land, inducing a circulation that drives the cooler, moister airmass from the ocean inland (Fig. 1.1). A return circulation develops aloft within the mixed layer (Reible et al., 1993) due to oppositely configured pressure perturbations. The leading edge of this air mass is accompanied by an increase in the onshore component of the surface wind, and is known as the sea breeze front (hereafter, SBF). After the SBF has passed, there is typically a drop in temperature and increase in dewpoint temperature associated with the cooler, moister marine airmass, and an increase in surface wind speed (Atkinson, 1981).

The SBF can be important for initiating deep moist convection along the coast. Byers and Rhodebush (1948) are credited with first attributing the near daily occurrence of thunderstorms in the summer over Florida to the SBF. The SBF provides a zone of enhanced lift for thunderstorms to develop. Pielke (1974) used a three-dimensional model with a horizontal grid spacing of 11 km to investigate the characteristics of the SBF over Florida. He found the sea breeze circulations to be the most important factor in determining the most favorable locations for deep moist convection over South Florida.

In the summer of 1991, the Convection and Precipitation/Electrification Experiment (CaPE) studied convection in the Cape Canaveral area in central Florida. CaPE involved multiple observational platforms (dual-doppler radars, an array of surface stations, soundings, and aircraft) in an intensive study of the SBF. Several authors (Wakimoto and Atkins, 1994; Kingsmill, 1995; Laird et al., 1995; Atkins et al., 1995; Atkins and Wakimoto, 1997; Wilson and Mengenhardt, 1997) highlighted observational and modeling results from CaPE. Results from these individual CaPE studies are discussed through the remainder of the chapter.
Although the SBF is prominent in coastal locations all over the southeastern U.S., most of the literature on the SBF and convective initiation focus on the Florida peninsula. The Florida peninsula is an ideal location to study convective initiation along the SBF owing to the Atlantic Ocean, Gulf of Mexico, and the abundance of afternoon convection. This paper addresses the frequency of convection in the vicinity of Charleston, South Carolina. Charleston may have been neglected in past research simply because storms are less frequent over S.C. than Florida, or alternatively because Florida’s two coasts provide more numerous examples for study. The last two decades have seen a dramatic increase in the population along the South Carolina coast. Summer coastal thunderstorms impact the economy and human safety through their rainfall, dangerous lightning, and occasionally hazardous winds and large hail. Because synoptic scale lift is less important for driving convection over South Carolina in June, July, and August, convective frequency diagrams for different stability, flow directions and shear environments should be useful for forecasters. Short term forecasting of thunderstorms is a challenge for forecasters due to the sensitivity of convective initiation to small scale processes. Forecasters must weigh the potential impacts that the early initiation of storms along the SBF or other boundaries could have several hours later into the day. The aim of this study is to improve the prediction of convective storms in the coastal region of South Carolina.

1.1 The effect of different wind directions on the SBF environment

Blanchard and Lopez (1985) identified 3 main types of precipitation patterns over the Florida peninsula and linked them to the flow patterns and thermodynamic environments associated with convective initiation. They concluded that convection over the peninsula is the result of complex relationships between synoptic and local scales. Peninsular scale processes such as the Florida SBF are most important for the initiation of storms (their type 1 cases) in synoptically weak flow (Cooper et al., 1982). Mid-tropospheric moisture was a good predictor of widespread convection over Florida (Burpee, 1979; Blanchard and Lopez, 1985; Nicholls et al., 1991) on days with little synoptic forcing for convection. Their type 2 cases involved a high pressure of continental origin to the northeast of Florida limiting moisture and instability, except for locations where the SBF was able to initiate storms. The type 3 cases had the most widespread convection due to the synoptic-scale influence of a 700 mb trough over north Florida and south-southwesterly flow at 1000 mb.

Arritt (1993) conducted 31 2-d simulations examining the features of the evolution of a SBF in onshore and offshore flow. The sea breeze front is weak in onshore flow, but is able to penetrate further inland with the aid of the prevailing wind. The strongest SBF (meaning SBF with the strongest lift) occurs in calm to moderate offshore synoptic flow (Arritt, 1993). Reible et al. (1993)
sum up their discussion of the SBF by saying that the SBF is a battle between convergence frontogenesis that increases the strength of the SBF and turbulent mixing that diminishes the strength of the gradients along the SBF. Reible et al. (1993) stated that an onshore flow inhibits convergence frontogenesis, while an offshore flow increases convergence frontogenesis.

Lyons (1972) found a lake breeze to be stronger in low-level flow parallel to the lake because of the increased temperature gradient between the air over the lake and the air over the land. Burpee and Lahiff (1984) observed increased rainfall over the Florida peninsula with stronger southerly low-level flow ($\geq 5$ m/s) parallel to the shore. The increased temperature gradient (owing to longer residence times of air parcels between the land and ocean in flow parallel to the coast) can lead to a stronger SBF.

Atkins and Wakimoto (1997) documented the appearance of radar reflectivity in onshore, offshore, and parallel flow directions. They found that a SBF in offshore flow appears as a distinct thin line of higher radar reflectivity. The SBF in onshore flow may be difficult to distinguish in radar reflectivity images due to the weaker and shallower SBF. The radar thin line did not occur until the late afternoon in parallel flow cases.

1.2 Detecting the SBF

Several studies have made attempts to create an objective method to detect the passage of a SBF. Miller and Keim (2003) used an objective method based on surface data at a single station in New Hampshire to determine if a SBF passed the station. A sea breeze occurred if the wind shifted to the southeast at anytime of the day and then shifted to another direction in the evening. Based on their synoptic analyses, SBFs occurred most often under northwesterly and northeasterly flow. A major drawback to their method was that days with onshore flow in the morning could not be included in their dataset. The prevalence of onshore flow over the Carolinas in the summer would make it difficult to adopt their method for detecting the SBF.

Frysinger et al. (2003) proposed using a statistical algorithm to predict the inland penetration of the SBF for the NWS Weather Forecasting Office at Charleston, SC. Their algorithm was based on a Sea Breeze Index (SBI) in Equation 1.1, where a positive $U$ is the cross-coast component of the wind and $\Delta T = T_{air} - T_{sea}$ (Walsh, 1974; Simpson, 1995).

$$SBI = \pm \frac{U^2}{\Delta T}$$ (1.1)

They used the SBI as a component of a decision-making algorithm to determine the behavior of a possible SBF (algorithm displayed in their Figure 4). However, their method and Equation 1.1 were not intended to handle a SBF under onshore flow, despite the fact that onshore flow can
occur frequently at Charleston, SC due to the Bermuda High. Outflow boundaries from convective initiation and cloud cover in the vicinity of the surface station can also interfere with their algorithm, by potentially changing the temperature and dewpoint at their surface stations. The present study did not use their algorithm because of the number of onshore flow days at CHS and the relatively high instability and low CIN on those days.

The present work builds off of the study by Crouch (2006). Crouch (2006) documented the timing and penetration distance of the SBF at five locations along the Carolinas and Georgia coasts (Wilmington, Brunswick, Myrtle Beach, Charleston, Savannah). He utilized a subjective method to classify days with SBF passages to determine the inland penetration distance of the SBF. His primary conclusion was that the peak time of SBF passages at the CHS airport was around 2000 UTC. Due to his strict threshold for the SBF days, several actual SBFs were likely not detected by his conservative method (more on this in chapter 4). Rather than adopt one of the preceding methods, we developed a new set of sea breeze detection techniques which are detailed in chapters 3 and 4.

1.3 Dynamic and thermodynamic mechanisms for convective initiation

Byers and Braham (1949) provided a basic understanding of the processes involved in an ordinary air mass thunderstorm. Storms consisted of an updraft of warm, moist air, followed by a subsequent downdraft of cooler, moister air that cuts off the inflow of unstable boundary layer air parcels. This downdraft reaches the ground, spreading out and propagating away from the storm as an outflow boundary.

Outflow boundaries from older thunderstorms can also collide, merge, and intersect to initiate new thunderstorms (Wilson and Schreiber, 1986; Koch and Ray, 1997). These storm scale collisions are often difficult to predict and must be watched closely by forecasters in a nowcasting setting. Koch and Ray (1997) used a variety of measurement platforms (surface stations, WSR-88D radar, and visible satellite images) to look at how different types of boundaries can influence convection over the Carolinas. Collisions between the SBF and other boundaries led to new convection on 88% of the collisions they studied. They determined that 72% of SBFs were autoconvective, meaning that the SBF was able to initiate storms on its own. A boundary colliding with the SBF does not automatically initiate convection. Kingsmill (1995) found that an east coast SBF in Florida colliding with a gust front from convection on the west coast did not produce convection. However, a convergence line initiated storms in the intermediate air mass between the two boundaries.

The cooler, moister airmass behind the SBF can be considered to be dynamically similar to a
density current (Reible et al., 1993; Simpson, 1995; Atkins and Wakimoto, 1997). A density current behaves differently with a headwind than a tailwind (Simpson and Britter, 1980; Xu et al., 1996; Liu and Moncrieff, 1996). A headwind promotes a deeper head in the density current owing to opposing flow at the leading edge. The deeper density current head can help lift boundary layer air parcels. A tailwind speeds the advance of the propagating density current and flattens the density current head. The tailwind regime is less favorable for the deep lifting of boundary layer air parcels. Rotunno et al. (1988) explained a dynamical mechanism for initiation and maintenance of storms by the interaction of a density current and vertical wind shear. Rotunno et al. (1988) suggested that an optimal balance between the cold pool generated horizontal vorticity and horizontal vorticity associated with the environmental shear was important for maintaining storms (Fig. 1.2d). The density gradient behind a SBF is not as strong as that of a traditional cold pool in the Great Plains, thus the relatively weak low-level vertical wind shear over the Southeast can still be sufficient to initiate storms if it is oriented in the optimal manner (according to the theory of Rotunno et al. (1988). Moncrieff and Liu (1999) linked the ideas of Rotunno et al. (1988) with the role of the low-level wind profile and the implications on convective initiation along the SBF. The most favorable condition to generate a density current with a deeper head and deeper lifting is one that has a surface headwind opposing the density current and a low-level shear circulation opposite the cold pool circulation (Fig. 1.3b, right hand SBF). This optimal shear-cold pool balance is consistent with the one described in Rotunno et al. (1988).

Not all SBFs will produce thunderstorms. Synoptic features such as a dry air mass (Burpee, 1979; Blanchard and Lopez, 1985) or an unfavorable wind shear profile (left side, Fig 1.3b) could suppress convection along the SBF (Rotunno et al., 1988; Kingsmill, 1995; Wilson and Megenhardt, 1997; Moncrieff and Liu, 1999). Even if there is suitable low-level wind shear, an onshore flow can make the SBF too diffuse to initiate convection. As well, a strong offshore flow could keep the SBF off the coast in the stable marine boundary layer (Arritt, 1993), limiting the SBF from providing enhanced vertical motion in the more unstable airmass over land.

### 1.4 Horizontal variability and convective initiation

Pielke (1974) asserted that 2-d simulations of the SBF may not be sufficient for a complete understanding of SBF owing to the alongshore variability of the SBF. Laird et al. (1995) used aircraft at Cape Canaveral and found that a SBF moving at different speeds in an irregular coastline can locally increase the vertical depth of the SBF circulation due to convergence. These locally enhanced areas of vertical motion can be important for forecasting the location of convective initiation along the SBF.
Weckwerth et al. (1996) examined the variability of moisture in horizontal convective rolls (HCRs). HCRs are caused by heat fluxes in the convective boundary layer associated with daytime heating. These updrafts can lead to deeper clouds with a lower LCL (Fig. 1.4) because of the additional moisture lifted by the roll circulation. HCRs are typically oriented in the same direction as the low-level shear vector. Wakimoto and Atkins (1994) looked at the along-frontal variability of the SBF owing to HCRs. They analyzed an offshore wind case and found the intersection points of the SBF and HCR updrafts were the preferred locations for cloud development. Atkins and Wakimoto (1997) showed how the orientation of HCRs over Florida can vary based on the synoptic orientation of the Bermuda High ridge axis (their Figure 2). The Bermuda High can also influence the low-level wind and transport of moisture over the Carolinas.

Dailey and Fovell (1999) ran simulations testing how the intersection of HCRs and the SBF initiate convection. Their base state environment utilized offshore shear, which happens to be prevalent over the Carolinas in June, July, and August. Neither the SBF or the HCRs alone were sufficient to trigger deep moist convection. Enhanced vertical motion occurred and convective initiation became favorable in locations where the SBF intersected the updrafts of the HCRs (Fig. 1.5). The SBF tilted the HCRs which caused increased along-frontal variability.

Fovell and Dailey (2001) conducted the same tests as Dailey and Fovell (1999) except with low-level shear in the along-shore direction. In this case, the HCRs were aligned parallel to the SBF. Their analysis documented a series of SBF-HCR mergers. HCR downdrafts suppressed cloud formation above the SBF by drawing dry air into the SBF cloud layer. The merger between the updraft at the SBF and the updraft in the HCR led to increased vertical motion. Higher order effects of the SBF-HCR interaction include dynamic and buoyancy pressure effects on the speed of the SBF as the circulations merge. Fovell (2005) further explained how convective initiation occurs ahead of the SBF in the same environment as Fovell and Dailey (2001). The SBF helped prime the environment with a moist plume near the top of the boundary layer. The interaction between this moist plume and atmospheric boundary layer rolls proved to be important for triggering deep convection. Although such processes could not be resolved in the present study, we presume that they are probably at work when we observe convective initiation along the SBF.

1.5 Structure of this paper

Chapter 2 provides the motivation for why Charleston, SC was chosen and an explanation for the data/methods utilized in this study. Chapter 3 explores the spatial and temporal frequency of convection at Charleston, SC under different wind directions, stability regimes, and vertical wind shear. Chapter 4 evaluates the strength of SBF passages at CHS by using an objective sea breeze
detection index and relates it to the frequencies of storms. Chapter 5 concludes the study with a summary and some ideas for future work.
Figure 1.1: Conceptual model of the SBF and associated pressure perturbations. Cooler, moister air resides in the airmass behind the SBF while warmer, relatively dryer air exists over land ahead of the SBF.
Figure 1.2: Schematic of the theory proposed by Rotunno et al. (1988) and its relevance to the initiation of storms. (a) shear dominates the circulation with the cold pool; (b) the cold pool dominates the circulation; and (c) the shear and cold pool are balanced, providing a deeper upright circulation that can initiate storms by its lifting. The colored field represents the cold pool with the darker shades of blue and purple representing the coldest temperatures. Images are from the COMET program, UCAR (1999).
Figure 1.3: Diagram of the behavior of a SBF on a peninsula in different low-level shear and surface flow directions. Panel (a) has the shear vector in the same direction as the surface wind. The height of the head of the density current is the same in both the left and the right SBF. The right hand SBF in panel (b) is most favorable due to the optimal low-level shear and opposing surface wind that both enhance the head of the density current to promote deeper lifting (Figure 10 from Moncrieff and Liu (1999)).
Figure 1.4: Example of horizontal convective rolls in the convective boundary layer. The maximum in mixing ratio is co-located with the updraft in the roll circulation, creating the deepest cloud with the lowest LCL (Figure 10 from Weckwerth et al. (1996)).
Figure 1.5: Schematic based on simulations of a SBF propagating inland and interacting with horizontal convective rolls. (a) cloud line along SBF. (b) Horizontal convective rolls develop and become oriented perpendicular to the SBF due to low-level offshore flow in the boundary layer. (c) Interaction of HCRs with SBF – enhanced vertical motion and tilting of HCRs (Figure 15 from Dailey and Fovell (1999)).
Chapter 2

Data and Methods

2.1 Motivation for choosing Charleston, SC

The primary motivation for choosing Charleston, SC for this analysis was its abundance of afternoon convection in the warm season and the availability of datasets to test the presence of a SBF along the SC coast. This study attempts to address the following key questions:

1. Which parameters (flow direction, instability, maximum predicted high temperature, etc.) might a morning forecaster focus on for predicting afternoon convection in the coastal region of SC?

2. What role does the strength of a SBF passage in different shear environments have in initiating convection along the SC coast?

3. What is the difference in the timing and distribution of convective initiation on sea breeze days vs. non-sea breeze days?

Gilliam et al. (2004) and Crouch (2006) investigated the timing of a SBF passage in locations of complicated coastline in the Carolinas. Charleston was selected for this study because of its relatively straight coastline and consistent coast angle (Fig. 2.1). Other locations such as Wilmington, Morehead City, and the Outer Banks could make detection of the SBF difficult due to oddly shaped coasts or differential heating among other bodies of water (e.g. sounds, inland rivers). The local/mesoscale variation of the coastal shape and geography can have an impact on the location of convection (Boybeyi and Raman, 1992; Laird et al., 1995; Baker et al., 2001). The convex shaped coast to the north of Charleston is important for additional convergence along the SBF. Since the coast curves and extends slightly outward towards the ocean, a SBF moving inland would intersect another segment of the SBF, increasing the vertical motion along the points where the SBF converged.
2.2 Datasets

2.2.1 Surface data

The primary surface data used for this study are from the ASOS site at Charleston International Airport (CHS), located approximately 27 km inland of the coast (Fig. 2.1). The study utilized hourly and special observations (i.e. observations between the hour, if they were recorded) of temperature, dewpoint temperature, wind speed and wind direction measurements from 1996 to 2006. The hourly data were used for an objective sea breeze detection index, which will be evaluated in Chapter 4.

2.2.2 SST data

To quantify the difference in temperature between the land and ocean, the temperature at CHS was compared to the sea surface temperature (SST). Two methods were used to evaluate the SST:

1. SST measurements from a mooring off the coast, in this case buoy 41004 located about 60 km from the coast (green dot, Fig. 2.2)

2. A gridded SST product of daily observations from satellite measurements, which were averaged to produce a mean SST.

Buoy 41004 is the closest buoy to CHS with data back to 1996. The buoy is about 60 km offshore and the SST could be affected by oscillations in the Gulf Stream. A gridded satellite-derived Optimum Interpolation daily SST dataset from the National Climate Data Center is used to find the mean SST near Charleston, SC. This dataset is interpolated to a 0.25 degree by 0.25 degree grid with one observation everyday. Our method finds the mean SST within a 100 km radius of the point at CHS (Fig. 2.2). The purpose of finding a mean SST is to gather a SST that is representative of the entire South Carolina coast. This grid includes the coordinates of buoy 41004. The calculated mean SST was within 0.5° Celsius of the diurnal SST range at buoy 41004 on 80% of the days. Chapter 4 will explain how the mean SST is incorporated within a sea breeze detection index.

2.2.3 Upper-air data

Upper air data were taken from the 1200 UTC sounding launched daily at CHS. Out of 920 days, 861 1200 UTC soundings were available. This study primarily utilized measurements from the mandatory levels of 925 mb, 850 mb, 700 mb, and 500 mb. The observations include temperature, wind speed/direction, and height. These observations were used to discriminate among environments with varying flow regimes, stability, and vertical wind shear.
The observations from the 1200 UTC sounding represent the upper-air environment in the morning (the sounding is launched at approximately 8 AM LDT). This sounding represents the pre-sea breeze environment a few hours before daytime heating is sufficient for the SBF to become active. For this work it is assumed that the 1200 UTC sounding measures the synoptic conditions that a SBF would form in on that particular day (if it does at all). Unfortunately, there were very few afternoon soundings (and, it would be hard to determine whether the sounding was launched in the pre-SBF or post-SBF environment anyhow).

The soundings were also used to assess the thermodynamic environment near CHS. Two measures of conditional instability were used for this study, Convective Available Potential Energy (CAPE) and the Lifted Index. CAPE is the summed amount of buoyant energy a parcel of air (in this case, the parcel is from the mixed layer in the lowest 500 m) has when lifted.

\[
CAPE = g \int_{LFC}^{EQL} \frac{T_{PAR} - T_{ENV}}{T_{ENV}} dz
\]

The Lifted Index (LI) is a measure of a parcel’s buoyancy at the 500 mb level where larger negative values imply that strong convection is increasingly likely. Because it isn’t possible to distinguish between very stable and weakly stable days when CAPE = 0 J/kg.

\[
LI = T_{500mb} - T_{parcel}
\]

Historically, environments with LI less than +2 have been considered to have the potential to be unstable. A LI value of less than -2 may be considered favorable for strong convection. Convective Inhibition (CIN) is measured to show the strength of the capping inversion that an air parcel must overcome to reach its level of free convection (LFC).

\[
CIN = -g \int_{mixedlayer}^{LFC} \frac{T_{PAR} - T_{ENV}}{T_{ENV}} dz
\]

Figure 2.3 shows a histogram of values of CAPE and LI for all of the soundings from this study. These soundings are taken in the morning before the sun has had a chance to substantially increase the CAPE. Because it isn’t possible to distinguish between very stable and weakly stable days when CAPE = 0 J/kg, LI was primarily used to distinguish how unstable the atmosphere was at CHS. It is a simple parameter for a meteorologist to compute and it can quickly show if the atmosphere has the potential to be unstable. Section 3 investigates the role of instability on convective frequency more closely.
2.2.4 Radar data

The radar climatology in this study utilizes the WSR-88D NOWRAD composites provided by the WSI Corporation. They use a proprietary algorithm that composites the NOWRAD data and maps them on to a 2km by 2km grid that is binned in 5 dBZ intervals. The data are also separated into 15-minute intervals so that there are 96 radar images for each day.

The period of interest for this study spans the years 1996-2000 and 2002-2006. The radar data for 2001 were incomplete, so they were removed from the analysis. The focus of this study is on the warm season from June-August (the choice of these months is discussed in chapter 3). Effectively, this is a 10-year radar climatology that spans 920 days.

Maddox et al. (2002) showed that the WSR-88D radar coverage is complete over South Carolina at a height of 3 km mean sea level (their Fig. 4a). Coverage at 2 km above ground level is complete at CHS but is not complete over the convex part of the SC coast (their Fig. 5a).

The frequency of convection is assessed by taking a binary "storm" variable \( i_{40} \) (Parker and Knievel, 2005; Parker and Ahijevych, 2007),

\[
i_{40}(x, y, t) = \begin{cases} 
1 & \text{when } dBZ(x, y, t) \geq 40 \\
0 & dhBZ(x, y, t) < 40
\end{cases}
\]  

(2.1)

and computing the probability (frequency) that a storm exists at a point \((x, y)\) for a time \(t\):

\[
Pr_{\text{storm}}(x, y, t) = \frac{1}{n} \sum_{t=1}^{n} i_{40}(x, y, t).
\]  

(2.2)

The advantage of this seemingly simple technique is that it allows for rapid objective analysis of very large datasets. The gridded dataset is amenable to statistical calculations such as the frequency of storms over a 10 year period.

A threshold of \(dBZ \geq 35\) was tested as well. Table 2.1 shows the overall frequency of pixels with \(dBZ \geq 5\). In other words, for all non-zero radar echoes (\(dBZ \geq 5\)), radar reflectivity with \(dBZ \geq 40\) occurs about 8.2% of the time. The threshold of \(dBZ \geq 40\) was chosen for this study because we are most interested in knowing the frequency of strong convection. Convection at a threshold of \(dBZ \geq 35\) occurs about twice as frequently than strong convection at a threshold of \(dBZ \geq 40\) (Table 2.1). Even so, the shape of the high frequency areas isn’t much different between the two thresholds. Range rings become apparent in composite frequencies because of differences in absolute radar calibration between the radars (see the Appendix in Parker and Knievel (2005) for a discussion of imperfections in the radar data).

Parker and Knievel (2005) used WSI radar dataset to investigate the frequency of convection
at several meteorologically significant locations across the country, using the method defined above. Their figure 6 shows prominent maxima in convection off the Carolinas’ Coast and over the Gulf Coast states. Parker and Ahijevych (2007) followed that same method to study the frequency of convection over the East-Central United States. The purpose of their study was to understand patterns of convective episodes that are independent of the diurnal cycle. They found several examples of mesoscale convective systems (MCS) crossing the Appalachians and continuing eastward to the Piedmont and coastal plain. In their plots that focus on the warm season, they also found a maximum in convection along the Carolinas’ coast in the afternoon. In short, this dataset and technique appear to be suitable for determining the spatial and temporal patterns of storms in the coastal region of SC.

2.3 Limitations of the methods used in this study

The upper air soundings were limited to the 1200 UTC soundings at CHS to represent the pre-SBF environment. It was possible that, as each day progressed, wind directions could change. We mitigated some of the possibilities of quickly evolving large-scale flow by limiting the climatology to the warm season of June, July, and August, when cold frontal passages occurred less frequently. The 1200 UTC soundings represented what a forecaster in the morning would look at to diagnose instability and wind shear to predict probable locations for storms later in the day.

CHS is located approximately 27 km inland. Therefore, not all SBFs penetrate all the way inland to the airport. Some SBFs that were strong enough to initiate storms may have lingered between the airport and the coast. Frysinger et al. (2003) noted the same limitation for their SBF prediction algorithm. To address this problem, we attempted to use a C-MAN observing station at Folly Beach with the SBDI method presented in Chapter 4. But, because the station is right on the beach, it likely already resides in the maritime airmass by late morning. SBF passages at that location were therefore much more ambiguous events in the Folly Beach data.
Table 2.1: Frequency (in %) of each dBZ category among all non-zero NOWRAD echoes during the study period.

<table>
<thead>
<tr>
<th>dBZ</th>
<th>frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>05-10</td>
<td>9.2</td>
</tr>
<tr>
<td>10-15</td>
<td>14.9</td>
</tr>
<tr>
<td>15-20</td>
<td>16.9</td>
</tr>
<tr>
<td>20-25</td>
<td>16.3</td>
</tr>
<tr>
<td>25-30</td>
<td>14.4</td>
</tr>
<tr>
<td>30-35</td>
<td>11.7</td>
</tr>
<tr>
<td>35-40</td>
<td>8.4</td>
</tr>
<tr>
<td>40-45</td>
<td>4.6</td>
</tr>
<tr>
<td>45-50</td>
<td>2.4</td>
</tr>
<tr>
<td>50-55</td>
<td>1.0</td>
</tr>
<tr>
<td>55+</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Figure 2.1: Map of the Carolinas’ coastline.
Figure 2.2: Map of the datapoints used in SST calculations. The yellow cells are within a 100 km radius CHS (red square), and were used in the mean SST computation (only the cells over the ocean are actually used in the SST computation). The green square represents the location of buoy 41004.
Figure 2.3: Histograms of instability indices for all soundings during the study period: (a) CAPE; (b) LI.
Figure 2.4: Comparison of the frequency of convection for when dBZ $\geq 35$ (top) to when dBZ $\geq 40$. The frequency of convection is computed for all days, 1500 UTC - 2100 UTC. The locations of WSR-88D radars most relevant to this study are marked with a white +.
Chapter 3

Temporal and spatial distribution of storms

3.1 Diurnal cycle and monthly patterns of convection in the warm season

The diurnal cycle dominates the timing of convection in the Carolinas during the warm season. To track patterns of convection separate from the diurnal cycle, Parker and Ahijevych (2007) used empirical orthogonal functions (EOFs) to remove the diurnal cycle of convection in the Mid-Atlantic region of the United States. A time series counting the number of grid boxes $\geq 40$ dBZ (strong convection) in a 60 km by 60 km box centered at CHS for all 920 days is remarkably similar (Fig. 3.1) to their first EOF, which they claimed was the diurnal cycle (see their Fig. 5a). Storms rapidly increase in coverage near CHS after 16 UTC for June, July, and August (Fig. 3.1). The peak time for storms occurs around 2000 UTC, which also happens to be the mean time when Crouch (2006) found most SBF passages to occur at CHS.

Storms follow a predictable diurnal pattern during the summer months of the warm season (June, July, and August), with July having the most pronounced peak in the late afternoon/evening (Fig. 3.2). The diurnal cycle during the summer is clearly distinct from the pattern in the non-summer months (April, May, and September), wherein synoptic forcing causes a more even daily distribution.

This chapter focuses on the frequency of storms ($dBZ \geq 40$) in the summer months for different measures of stability and flow direction from the 1200 UTC soundings at CHS. Judging from the similar values in the frequency of convection over the entire domain and perusal of radar data, storms in April are likely organized in linear squall lines associated with cold or warm frontal passages (Fig. 3.3a). May (Fig. 3.3b) is a month of transition toward the more convectively active summer regime (Fig. 3.3c,d,e) where convection becomes more favored over the coastal plain of the Carolinas. Storms are not nearly as frequent in September (fig. 3.3f) but the climatological
maximum for landfalling tropical cyclones in the southeast occurs in September, which partly helps to explain the more even distribution. The role of landfalling tropical cyclones on the patterns of coastal convection is not explored in this study, but their impacts are minimized by focusing on June-August. A subjective analysis of storm tracks from the National Hurricane Center found that a tropical cyclone was near the CHS area on 21 days for the months of June-August for the 10 year period of interest (Table 3.1). The tropical cyclones were important for the areal coverage of storms and radar reflectivity ≥ 40 dBZ on those 21 days (Fig. 3.4). However, compared to the frequency of storms in the total radar dataset (Fig. 3.5a), the patterns of the frequency of storms does not change by much if the tropical cyclone days are removed (Fig. 3.5b). The rest of this analysis includes the tropical cyclone days in the frequency plots.

June, July, and August all exhibit a similar pattern with late morning/early afternoon (1500 UTC - 1800 UTC, Fig. 3.6c,d,e) convective storms initially forming near convex coastline segments, which are known to enhance convergence. By the late afternoon (1800 UTC - 2100 UTC, Fig. 3.7), the highest frequencies of storms extend along the entire Carolina coast, and stretch about 50 to 60 km inland (Fig. 3.7c,d,e). These patterns are weak or non-existent in April, May, and September, suggesting that the influence of the SBF on storms is primarily a June-August phenomenon. July (Fig. 3.7e) has its highest frequency just northeast of Charleston. A secondary maximum of convection exists over the sandhills of the Carolinas in July. The sandhills are a favorable location for convection owing to the differential heating between different soil types (Koch and Ray, 1997; Raman et al., 2005). After 2100 UTC, the coastal and sandhills storms may begin to interact with one another, leading to even more widespread storminess.

Although a SBF passage can occur at CHS in April, May, and September, conditions are not usually as favorable for convective activity as in the summer months. April and May exhibit less CAPE and increased CIN compared to the summer months (Table 3.2). On average, the 925 hPa mixing ratio is also significantly lower in April and May. Due to the frequent lack of instability through late spring, thunderstorms simply are not a daily occurrence over the southeast. June, July, and August average over 800 J/kg of CAPE in the 1200 UTC sounding. Although the average maximum surface temperature is warmer in September than the spring months, the atmosphere becomes more stable, limiting the frequency of convection. Because the aim of this study involves the SBF and the frequency of convection, it became necessary to limit the analysis to the months when the SBF was most likely to initiate convection. The subsequent analyses only cover the summer months of June, July, and August for the ten-year dataset.
3.2 Stability characteristics and storm frequencies for 925 hPa flow directions at CHS

This study utilizes 925 hPa wind speed and direction to diagnose the basic low-level flow at 1200 UTC from CHS for June, July, and August (spanning all 10 years). The 925 hPa level ranges from 700 to 900 meters MSL, which puts it near the top of the developing boundary layer at 1200 UTC during the summer. The 850 hPa, 700 hPa, and 500 hPa winds were also tested, but did not appear to provide any advantage over the 925 hPa level, so they are not reported here. The first step in the analysis focused on eight principal 925 hPa flow directions and their impact upon the instability and frequency of convection at CHS (Fig. 3.8). Westerly 925 hPa flow occurred on the most number of days, while southeasterly 925 hPa flow occurred on the least number of days (Fig. 3.9).

Convection occurs significantly less often on the days with northeasterly 925 hPa flow (Fig. 3.10b). Those days are the most stable having an average of less than 350 J/kg of CAPE and a positive LI (Table 3.3). The northeasterly flow days are also the driest at 925 hPa (Table 3.3). An easterly wind component transports air with maritime temperature and moisture characteristics inland. Easterly flow is associated with increased CAPE and a more unstable LI, with roughly half as much CIN as northeasterly flow. There is a dramatic increase in the frequency of storms (compared to northeasterly) for easterly flow (Fig. 3.10c) with storm frequencies above 15% within 50 km of the coast at CHS.

The days with the most frequent convection in the afternoon occurred when the wind direction at 925 mb has a southerly component (Fig. 3.10d,e,f). The southerly component is associated with trajectories that transport high $\theta_e$ air from the Gulf of Mexico, Caribbean Sea, and Gulf Stream, northward to the CHS region. South and southwesterly flow were associated with the highest CAPE and most negative LI values of all, only modest CIN, and comparatively high mixing ratio at 925 hPa (Table 3.3).

A westerly wind component advects air of a continental origin toward CHS. Winds from the southwest, west, and northwest were associated with the highest average maximum temperatures at CHS. Surprisingly, the mixing ratio at 925 hPa in westerly flow was comparable to that under southwesterly flow (Table 3.3). However, storm frequencies were significantly higher in southwesterly flow (Fig. 3.10f) than in westerly flow (Fig. 3.10g), likely because westerly flow was associated with significantly larger CIN than southwesterly flow. Compared to westerly flow (Fig. 3.10g), storm frequencies were maximized solely along the coast for northwesterly flow (Fig. 3.10h). Northwest-erly flow, on average, was associated with the most CIN, limiting the coverage of storms over the Piedmont and coastal plain. Interestingly, this is in spite of the fact that the northwesterly flow days have the highest average maximum temperature at CHS. It is unclear what role downslope flow
from the Appalachian Mountains has in increasing the maximum average temperature at CHS under northwesterly flow. The predominantly offshore flow also likely prevents the SBF from penetrating inland to CHS before the time of maximum diurnal heating in the afternoon, thereby allowing CHS to realize a higher maximum temperature and preventing the triggering of storms farther inland. In short, the flow direction has a significant influence on the frequency of storms in the CHS region; this influence appears to be primarily linked to the prevailing stability (i.e. CAPE and CIN, Table 3.3). Later, possible differences in the presence and strength of SBF passage are also addressed.

3.3 Timing of convection

For the most part, under northwesterly, northerly, and northeasterly flow, storms do not become frequent until after the period of greatest daytime heating in the late afternoon (Figs. 3.11c,g,k). Large values of CIN in the morning require significant heating or a significant lifting mechanism to get boundary layer air parcels through the capping inversion. Northwesterly flow, which is roughly perpendicular to the coast, is associated with storms roughly 16% of the time within 30 km of the coast northeast of CHS (Fig. 3.11c). Storms generally become less frequent again in the evening (Fig. 3.11h,l) as the boundary layer cools, although they appear to persist for longer under northwesterly flow (Fig. 3.11d). It may be that offshore winds keep the SBF offshore longer under northwesterly flow, but that its a more effective trigger for storms once it eventually moves inland.

Storms that formed in the morning under southeasterly, southerly, and southwesterly flow (Fig. 3.12a,e,i) existed in a favorable environment because of high CAPE and a small cap (Table 3.3). Predictably, convection began earlier on the days with the lowest mean CIN. After daytime heating in the late morning/early afternoon, widespread storms were able to develop near the coast (Fig. 3.12b,f,j). Under southerly and southeasterly flow, when there is an onshore component, storms develop throughout the coastal plain (Fig. 3.12f,j). In contrast, under southwesterly flow, parcels move primarily parallel to the coastline and convection is only found right along the shoreline (Fig. 3.12b). These differences are likely due to the degree to which the maritime airmass can penetrate inland during the morning hours. By the late afternoon, convection is widespread over most of the piedmont and coastal plain of SC in all three southerly regimes flow (Fig. 3.12c,g,k).

The most frequent location for storms in westerly (Fig. 3.13g) was along the coast, a pattern similar to what would be expected for convective initiation along the SBF. Storm initiation was delayed until between 1800 - 2100 UTC in the late afternoon. The storms increased in coverage and frequency (Fig. 3.13h) after 2100 UTC. Patterns of convection are much different under easterly flow. The significantly smaller CIN under easterly flow likely helps to favor the relatively frequent storms offshore between 1200 and 1500 UTC (Fig. 3.13a). Storms progressively increase in frequency
onshore through the day, while decreasing in frequency over the ocean (Fig. 3.13b,c). By the evening, (Fig. 3.13d), storms decreased in frequency over most of South Carolina. Easterly wind days had the lowest mean temperature, which may have helped limit instability and the frequency of convection on some of the individual days.

3.4 SBF vs. non-SBF days

Overall, convection was most frequent within 60 km of the coast during the summer months (Fig. 3.14). Storms occurred almost 20% of the days to the northeast of Charleston where the convex coast extends into the Atlantic. Overall, a sufficiently large amount of CAPE and sufficiently small CIN existed on most days during the warmseason, supporting storms in the area around CHS (Table 3.4).

A simple test comparing the mean SST (determined via the method described in Chapter 2) with surface temperature observations at CHS served as a first approximation for determining whether a SBF passage was possible on each day at CHS. If the temperature at CHS exceeded the mean SST, then a SBF was possible. Out of 920 days, the temperature at CHS exceeded the mean SST on 873 days (vs. the remaining 47 days which likely did not have a SBF). The average difference in temperature between CHS and the ocean for the SBF and non-SBF days was 3.87°C and -1.84°C, respectively. Unfortunately, only 47 non-SBF days existed, so analysis was limited compared to the number of SBF days. There were not enough days to break the non-SBF days out into storm frequency diagrams to analyze the influence of different flow directions on convection.

Convection was more frequent over a broader area on the non-SBF days (Fig. 3.15e,f,g,h). In particular, the convection was more frequent over the water and was less confined to the coastline than on the SBF days. The non-SBF days possessed nearly 30 J/kg less CIN than the SBF days (Table 3.4). In the morning, non-SBF days had considerably more convection than SBF days, likely owing to decreased CIN (Fig. 3.15a,b vs. e,f). Convection became increasingly more frequent further inland as the day progressed and less frequent over the ocean later in the day. The early convection may have diminished daytime heating near the coast, limiting instability for the afternoon. Synoptic forcing may also play a greater role on non-SBF days, leading to differing timing and organization of convection (Blanchard and Lopez, 1985). The onshore flow regime dominates the non-SBF days, with nearly half of these days having a 925 hPa wind from about 70 degrees. Easterly and northeasterly 925 hPa winds are associated with higher stability than any other 925 hPa wind directions.

Late in the day, there is an absence of convection along the coast on non-SBF days, likely a result of convection earlier in the day limiting instability later in the day. It is possible that a morning land breeze provides additional lifting over the ocean on non-SBF days, although such a feature could
not be resolved in the data used for this study. The SBF days exhibit a maximum in convection just to the west of CHS.

The SBF days showed significantly less volatility than the non-SBF days because of the significantly larger sample size. Predictably, the morning was the time for the minimum frequency in convection (Fig. 3.15a). Storms did not become frequent along the coast until 1800 - 2100 UTC (Fig. 3.15c). This pattern is consistent with the expected pattern for convection initiated by the SBF along the coast. However, it is also likely that the population includes several days with SBFs that did not make it far onshore, thus limiting their influence on storms inland.

3.5 Timing of convection in 925 hPa flow relative to the coast

Throughout most of the sea breeze literature, the principal concern in sea breeze development and evolution is the onshore vs. offshore component of the wind. Owing to the interesting narrow coastal maximum under southwesterly flow (Fig. 3.12b), it was instructive to add categories for alongshore flow, where air parcels may reside in the land-sea temperature gradient for an extended period of time. For this reason, the rest of this paper will utilize the four flow direction categories relative to the coast at CHS shown in Figure 3.16. The alongshore flow categories were narrowed to represent 30° ranges that were parallel to the coast. The days tested with these four wind categories included only the possible SBF days (days when T > mean SST). The northeasterly alongshore cases (e.g. Table 3.5) are not plotted because they are both rare and have comparatively little instability and thus few storms. The reader can review Figs. 3.10b and 3.11i-l for more information.

Onshore flow at 925 hPa is associated with relatively early initiation and a steady inland progression of increasingly frequent convection until the late afternoon (Fig. 3.17a,b,c). The average CIN for 925 mb onshore flow days is nearly 50 J/kg less than that for offshore flow days (Table 3.5) on which storms are delayed (Fig. 3.17e,f). In the late afternoon, storms become increasingly frequent over the Piedmont and Coastal Plain under onshore flow. The storms near the coast are most likely to be ≥ 30 km from the ocean, probably due to the rapid inland penetration of the SBF. In the evening (Fig. 3.17d), the frequency decreases over the coastal plain of SC, at the same time the SBF circulation is likely to collapse. Although onshore flow from the southeast is favorable for storms, many onshore flow days also occur from the east-northeast, whose lower instability (Table 3.3) limits the frequency of storms in the onshore flow category.

Southwesterly alongshore flow days have the most moisture of all the days and are the most unstable (Table 3.5). The convective patterns in the morning of the southwesterly alongshore flow days (Fig. 3.17i) begin similarly to the onshore flow days (Fig. 3.17a), although storms are more widespread. In the early afternoon (Fig. 3.17j), there is a distinct maximum of convection northeast
of Charleston and near Cape Fear at Wilmington. These areas could likely see increased convergence from the SBF moving inland over a convex shaped coast (Laird et al., 1995; Gilliam et al., 2004). The maximum in convection is within 60 km of the coast, but storms become increasingly frequent further inland in the late afternoon (Fig. 3.17k). By the evening (Fig. 3.17l), storms are widespread increasingly over the piedmont and interior coastal plain, although slightly less frequent right at the coast (likely in the wake of the SBF).

Nearly half of the days in the dataset exhibit offshore flow at 925 hPa (Table 3.5). The initiation of convection along the coast (Fig. 3.17e,f) by the SBF is delayed by the opposing prevailing winds hindering the inland penetration of the SBF. The average value of CIN on these days is also -79 J/kg, which would require significant heating and/or a strong lifting mechanism to help break the cap. The frequency of convection does not increase until the late afternoon (Fig. 3.17g) when storms exist on over 15% of the days northeast of Charleston, but are largely confined to the coast. A weak secondary maximum is also visible over the interior coastal plain/sandhills region (Fig. 3.17g). By the evening (Fig. 3.17h), the SBF is likely waning, but the convection it initiates may interact with convection over the interior coastal plain. Koch and Ray (1997) found that 88% of collisions between the SBF and other boundaries in North Carolina initiated additional storms.

### 3.6 Yearly variability of strong convection at CHS

The following discussion highlights the overall trends and year to year summer season variability of the areal coverage of strong convection at CHS (Figs. 3.18, 3.19, 3.20, 3.21, 3.22, 3.23, 3.24, 3.25, 3.26, and 3.27). Overall, the diurnal cycle dominated the timing of convection around Charleston, but was not exclusive for all strong convection events. Possible explanations for those non-diurnal storms included long-lived mesoscale convective systems that originated from the west (e.g. Parker and Ahijevych, 2007), mesoscale convective systems that were initiated by the Piedmont Trough (e.g. Businger et al. (1991); Koch and Ray (1997)), and tropical cyclones. The tropical cyclone days were easily determined by cross-referencing the long-lived storm events at CHS with tropical cyclone tracks. This study does not explore the remaining non-diurnal events, but perusal of radar data for individual events could provide insight into the origin of these storms. Most of the larger storm events in the afternoon had offshore and southwesterly flow with most of the activity occurring between 1700 and 0000 UTC. The summer seasons of 2003, 2004, and 1998 (Figs. 3.24, 3.25, and 3.20, respectively) had distinctly different patterns of strong convection and will be used to highlight year to year variations.

Southwesterly flow led to frequent storms for the summer season 2003 (Fig. 3.24), with plenty of small convective events in the afternoon. On days with offshore flow, convective events typically
began after 1700 UTC (1300 LDT) with some of the larger events persisting into the next morning. Storm initiation was usually delayed until the afternoon on days with offshore flow and those storms may have been influenced by the SBF. Several larger convective events occurred over the late night and morning, but determining the origin of those storms would require a more extensive radar and surface analysis of those individual events. The month of August 2003 was relatively quiet after 0100 UTC (2100 LDT), but convection was just as frequent after 1700 UTC as it was in July.

The summer season of 2004 (Fig. 3.25) had less convection in the afternoon, possibly owing to less southwesterly alongshore flow days. The patterns of convection in August were heavily influenced by tropical cyclones (Table 3.1). In mid-August, Bonnie and Charley made landfall in Florida and their remnants curled north over Charleston. Hurricane Gaston made landfall near Charleston in the last week of August. If the storm pixel counts were large over the course of an entire day, it was likely that a tropical cyclone was influencing the CHS region.

The number of days that had storms at CHS were noticeably less for the summer season of 1998 (Fig. 3.20) compared to 2003 and 2004. The lack of southwesterly flow days in 1998 may have played a role in the smaller frequency of strong convection. Even so, the afternoon was still the time most likely to have strong convection.

3.7 Instability and the frequency of strong convection

3.7.1 High CIN vs. low CIN

To test the claim that storms should develop earlier in flow regimes typified by less CIN, the 1200 UTC soundings for the possible SBF days were separated into 2 categories, where,

1. high CIN days = CAPE > 0, CIN \leq -25.0

2. low CIN days = CAPE > 0 and CIN > -25.0.

For the most part, convection on the high CIN days (Fig. 3.28a,b,c,d) was delayed until the afternoon. The pattern of storms suggests that the SBF was usually the source of lift to help air parcels break through the cap and reach their LFCs. The high CIN days were dominated by westerly offshore flow (Table 3.6), with the increased CIN associated with an airmass originating over the continent. On low CIN days (Fig. 3.28e,f,g,h), storms first appeared in the morning and early afternoon. The initial pattern of convection for the low CIN days also is similar to what would be expected for convection initiated by the SBF. However, the signature of subsequent storms throughout the coastal plain implies that, although storms first appeared along the coast, the low CIN permits subsequent initiation regionally (due to increasing temperature, inland penetration of the SBF, and/or convective outflows).
3.7.2 Lifted Index

Unsurprisingly, the days with the most frequent convection in the coastal region of SC had the most negative Lifted Index (Fig. 3.29a). The frequency of storms in the coastal region decreased as values of LI increased (Fig. 3.29a-d). Although the LI values were measured from the 1200 UTC sounding, they still showed some skill in predicting strong convection in the late afternoon. A Pierce Skill Score test found that the days with the highest skill in forecasting storms during the late afternoon had a LI less than -1.0 (Fig. 3.30) with a probability of detection of 0.88 and a false alarm ratio of 0.33. It can be implied that a negative Lifted Index was usually a necessary condition for strong convection, but not always a sufficient condition on all days. Similar false alarm ratios were found for CAPE and CIN (Figs. 3.31 and 3.32 respectively) for the same skill score test. Although instability may be present, some other condition must be met for strong convection during the peak diurnal hours at CHS. The next section tests the role of vertical wind shear for organizing storms in the coastal region of SC.

3.8 Surface to 700 hPa shear and patterns of convection

So far, this study has explored how different flow directions influence the stability and frequency of convection near CHS. This section investigates how different shear directions influence the frequency of convection along the SBF. For simplicity, the only shear directions this study investigated were the coast-perpendicular directions (i.e. onshore and offshore).

Moncrieff and Liu (1999) stated that the role of vertical wind shear in sea-breeze dynamics has received little attention. Wilson and Megenhardt (1997) hypothesized that an onshore flow at 700 mb combined with and a low-level offshore wind could enhance the strength and duration of convection over Florida by allowing air parcels to continue to be lifted by the SBF. Their hypothesis is consistent with the windward shear profiles (Fig. 1.3) that Moncrieff and Liu (1999) claimed would enhance the height of a density current. This section explores the frequency of convection for varying vertical wind shear on the “possible SBF” days. Four combinations of 925 hPa wind and surface to 700 hPa wind shear were tested (Fig. 3.33) for all of the “possible SBF” days. Treating the SBF as a density current, in Fig. 3.33b and Fig. 3.33c (i.e. onshore shear) are most favorable for the lifting mechanism described in Rotunno et al. (1988).

As in the previous sections, the averaged wind directions were important in understanding the stability near CHS. For example, in the onshore wind/offshore shear category (Fig. 3.33a) mean 925 hPa southeasterly flow (Table 3.7) provided maritime air from the Atlantic that helped reduce CIN

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3 For these scatter plots, a storm day is defined as having at least 5 pixels in the 60 km by 60 km box around CHS for a 4 hour window (1800, 1900, 2000, and 2100 UTC) during the peak of the diurnal cycle (Fig. 3.1)
(Table 3.8), but relatively lower CAPE kept storm frequencies lower (Fig. 3.34a-d) than onshore flow/onshore shear (Fig. 3.34e-h). The first storms were initiated within 30 km of the coast just northeast of CHS between 1500 - 1800 UTC (Fig. 3.34b). Storms increased in frequency around CHS as the day progressed, but storms could not be considered to be widespread. Based on the theories of Moncrieff and Liu (1999) and Rotunno et al. (1988), lifting by the SBF was not ideal in this wind shear category, and that may be reflected by the lack of organization of convection by the SBF.

In contrast, onshore wind/onshore shear (Fig. 3.34e-h) was predominated by a larger southerly component of 925 hPa flow, and possessed lower CIN, larger CAPE, and widespread convection earlier in the day within 60 km of the coast. This shear profile represented a favorable setup for organizing convection based on the theory by Rotunno et al. (1988), but it did not represent the most optimal setup in Moncrieff and Liu (1999). The relatively high instability and low CIN favored storms all over the region. The absence of convection along the coast in the evening was a result of the onshore shear organizing storms further inland away from the coast as the day progressed. Overall, the frequencies for the onshore flow/onshore shear category were similar to those for the southerly flow category (Fig. 3.12e-h), with similar explanations.

The offshore wind/onshore shear category (Fig. 3.35a-d) had a modest amount of CIN owing to the westerly offshore flow, and a similar amount of CAPE to the offshore flow/offshore shear category. Storms became frequent along the coast just northeast of CHS between 1800 to 2100 UTC (Fig. 3.35c), but the larger frequencies shifted inland after 2100 UTC (Fig. 3.35d). This shear profile category is the hypothesized ideal setup for storms initiated by the SBF according to Wilson and Megenhardt (1997) and Moncrieff and Liu (1999). The idea is that the offshore 925 hPa flow opposes the SBF, deepening the head of the density current, while the vertical wind shear promotes enhanced lifting with the cold pool via the mechanism of Rotunno et al. (1988). This lifting mechanism may have been responsible for the high frequency of storms just northeast of CHS. The absence of convection along the coast in the evening was a result of the decreased influence by the SBF as a lifting mechanism. Overall, the SBF appeared to be important for storms along the coast in the late afternoon.

Finally, offshore 925 hPa wind/offshore shear category (Fig. 3.35e-h) had westerly flow from the surface to 700 hPa and the most CIN of these four categories (Table 3.8). This category was another example of the offshore flow delaying the inland penetration of the SBF (and storms) until the late afternoon (Fig. 3.35g). Although the shear does not balance the SBF circulation (Rotunno et al., 1988), the westerly flow over the depth of the surface to 700 hPa layer opposes the SBF, deepening the density current head (Moncrieff and Liu, 1999) and possibly aiding in convective initiation. This category also had the largest amount of surface to 700 hPa shear, and that may
have contributed to the organization of the storms. Dailey and Fovell (1999) ran simulations of the SBF interacting with HCRs oriented by offshore shear, which initiated convection. We can only speculate that, absent the ideal dynamic forcing provided by the density current and shear interaction, some other mesoscale forcing must take place to initiate storms, and the SBF-HCR interaction fits the mold. The continuation of the high frequency of storms into the evening (Fig. 3.35h) suggests that additional cell collisions, mergers, and intersections generated new convective storms (Wilson and Schreiber, 1986; Koch and Ray, 1997). In the CHS area, this effect seems to predominate over the mechanisms discussed by Wilson and Megenhardt (1997) and Moncrieff and Liu (1999). Overall, the frequencies for the offshore flow/offshore shear category were quite similar to those for offshore flow (Fig. 3.17a-d).

### 3.9 Summary

Based upon these convective frequency diagrams, it appears that the 925 hPa flow direction (and associated typical stability parameters) can be helpful for the prediction of storms along the SBF. Onshore flow days typically have weaker SBFs (Atkins, 1981; Reible et al. 1993); however, such environments appear to have less CIN. Offshore flow days have the potential to have stronger SBFs (Arritt, 1993; Moncrieff and Liu, 1999), but appear to normally have increased CIN. The southwest-erly alongshore flow is associated with the most instability at CHS. Because the strength of the SBF is potentially important, Chapter 4 evaluates the three previous statements with a simple diagnostic sea breeze detection index to help determine whether storm frequency may be significantly modified by SBF passages of different strengths at CHS.
Table 3.1: List of days with a tropical cyclone near CHS.

<table>
<thead>
<tr>
<th>year</th>
<th>storm</th>
<th>date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Arthur</td>
<td>June 18, 19</td>
</tr>
<tr>
<td>1996</td>
<td>Bertha</td>
<td>July 11, 12</td>
</tr>
<tr>
<td>1998</td>
<td>Danielle</td>
<td>August 26, 27</td>
</tr>
<tr>
<td>1999</td>
<td>Dennis</td>
<td>August 29, 30, 31</td>
</tr>
<tr>
<td>2002</td>
<td>Arthur</td>
<td>July 14</td>
</tr>
<tr>
<td>2003</td>
<td>tropical depression 7</td>
<td>July 26</td>
</tr>
<tr>
<td>2004</td>
<td>Alex</td>
<td>August 1, 2, 3</td>
</tr>
<tr>
<td>2004</td>
<td>Bonnie</td>
<td>August 12</td>
</tr>
<tr>
<td>2004</td>
<td>Charley</td>
<td>August 14</td>
</tr>
<tr>
<td>2004</td>
<td>Gaston</td>
<td>August 28, 29, 30</td>
</tr>
<tr>
<td>2006</td>
<td>Alberto</td>
<td>July 14</td>
</tr>
<tr>
<td>2006</td>
<td>Ernesto</td>
<td>August 31</td>
</tr>
</tbody>
</table>

Table 3.2: Mean values of stability parameters for each month.

<table>
<thead>
<tr>
<th>month</th>
<th>days with 12 UTC sounding</th>
<th>CAPE (J/kg)</th>
<th>CIN (J/Kg)</th>
<th>LI (K)</th>
<th>925 hPa mixing ratio (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>290</td>
<td>118</td>
<td>-89</td>
<td>5.92</td>
<td>7.03</td>
</tr>
<tr>
<td>May</td>
<td>292</td>
<td>358</td>
<td>-108</td>
<td>1.96</td>
<td>9.43</td>
</tr>
<tr>
<td>June</td>
<td>279</td>
<td>830</td>
<td>-61</td>
<td>-1.25</td>
<td>12.48</td>
</tr>
<tr>
<td>July</td>
<td>293</td>
<td>1462</td>
<td>-52</td>
<td>-3.37</td>
<td>14.59</td>
</tr>
<tr>
<td>August</td>
<td>289</td>
<td>1203</td>
<td>-39</td>
<td>-2.35</td>
<td>14.15</td>
</tr>
<tr>
<td>September</td>
<td>263</td>
<td>501</td>
<td>-54</td>
<td>0.75</td>
<td>12.42</td>
</tr>
</tbody>
</table>

Table 3.3: Mean values of stability parameters in different 925 hPa flow directions.

<table>
<thead>
<tr>
<th>925 hPa flow direction</th>
<th>days</th>
<th>CAPE (J/kg)</th>
<th>CIN (J/Kg)</th>
<th>LI (K)</th>
<th>925 hPa mixing ratio (g/kg)</th>
<th>Tmax (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>north</td>
<td>67</td>
<td>861</td>
<td>-66</td>
<td>-0.68</td>
<td>12.89</td>
<td>30.90</td>
</tr>
<tr>
<td>northeast</td>
<td>90</td>
<td>347</td>
<td>-63</td>
<td>1.43</td>
<td>11.39</td>
<td>29.70</td>
</tr>
<tr>
<td>east</td>
<td>76</td>
<td>830</td>
<td>-34</td>
<td>-0.47</td>
<td>13.10</td>
<td>29.24</td>
</tr>
<tr>
<td>southeast</td>
<td>45</td>
<td>1112</td>
<td>-25</td>
<td>-2.08</td>
<td>13.35</td>
<td>29.58</td>
</tr>
<tr>
<td>south</td>
<td>54</td>
<td>1529</td>
<td>-38</td>
<td>-3.91</td>
<td>14.28</td>
<td>30.45</td>
</tr>
<tr>
<td>southwest</td>
<td>189</td>
<td>1724</td>
<td>-38</td>
<td>-4.15</td>
<td>14.45</td>
<td>31.30</td>
</tr>
<tr>
<td>west</td>
<td>255</td>
<td>1179</td>
<td>-77</td>
<td>-2.97</td>
<td>14.36</td>
<td>32.43</td>
</tr>
<tr>
<td>northwest</td>
<td>85</td>
<td>1132</td>
<td>-94</td>
<td>-2.58</td>
<td>14.01</td>
<td>33.30</td>
</tr>
</tbody>
</table>
Table 3.4:  Mean values of stability parameters for all days, possible SBF days, and non-SBF days.

<table>
<thead>
<tr>
<th>Classification</th>
<th>days</th>
<th>CAPE (J/kg)</th>
<th>CIN (J/kg)</th>
<th>LI (K)</th>
<th>925 hPa mixing ratio (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>all days</td>
<td>861</td>
<td>1170</td>
<td>-61</td>
<td>-2.34</td>
<td>13.75</td>
</tr>
<tr>
<td>SBF possible</td>
<td>816</td>
<td>1197</td>
<td>-62</td>
<td>-2.50</td>
<td>13.76</td>
</tr>
<tr>
<td>SBF not possible</td>
<td>44</td>
<td>748</td>
<td>-29</td>
<td>0.39</td>
<td>13.53</td>
</tr>
</tbody>
</table>

Table 3.5:  Mean values of stability parameters in onshore, offshore, northeasterly alongshore, and southwesterly alongshore 925 hPa flow from the 12 UTC sounding at CHS.

<table>
<thead>
<tr>
<th>925 hPa flow direction</th>
<th>days</th>
<th>CAPE (J/kg)</th>
<th>CIN (J/kg)</th>
<th>LI (K)</th>
<th>925 hPa mixing ratio (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>onshore</td>
<td>181</td>
<td>1167</td>
<td>-22</td>
<td>-2.14</td>
<td>13.39</td>
</tr>
<tr>
<td>offshore</td>
<td>423</td>
<td>1154</td>
<td>-72</td>
<td>-2.65</td>
<td>14.05</td>
</tr>
<tr>
<td>northeast alongshore</td>
<td>66</td>
<td>422</td>
<td>-57</td>
<td>1.00</td>
<td>11.62</td>
</tr>
<tr>
<td>southwest alongshore</td>
<td>146</td>
<td>1708</td>
<td>-24</td>
<td>-4.13</td>
<td>14.36</td>
</tr>
</tbody>
</table>

Table 3.6:  Number of days that have high CIN \((CIN \leq -25.0)\) and low CIN \((CIN < -25.0)\) in the 12 UTC sounding at CHS for 925 hPa flow directions.

<table>
<thead>
<tr>
<th>925 hPa flow direction</th>
<th>high CIN</th>
<th>low CIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>northwest</td>
<td>63</td>
<td>15</td>
</tr>
<tr>
<td>north</td>
<td>35</td>
<td>14</td>
</tr>
<tr>
<td>northeast</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>east</td>
<td>15</td>
<td>39</td>
</tr>
<tr>
<td>southeast</td>
<td>9</td>
<td>32</td>
</tr>
<tr>
<td>south</td>
<td>13</td>
<td>38</td>
</tr>
<tr>
<td>southwest</td>
<td>56</td>
<td>124</td>
</tr>
<tr>
<td>west</td>
<td>181</td>
<td>62</td>
</tr>
<tr>
<td>total</td>
<td>408</td>
<td>342</td>
</tr>
</tbody>
</table>
Table 3.7: Mean values of different wind and shear layers in onshore shear, onshore 925 hPa flow/offshore shear, offshore shear, and offshore 925 hPa flow, onshore shear for the surface to 700 hPa level from the 12 UTC sounding at CHS.

<table>
<thead>
<tr>
<th>925 hPa/shear</th>
<th>925 magnitude, direction</th>
<th>700 hPa magnitude, direction</th>
<th>surface to 700 hPa shear magnitude, direction</th>
<th>onshore component of shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>onshore/onshore</td>
<td>6.29 @ 142°</td>
<td>6.52 @ 144°</td>
<td>7.61 @ 163°</td>
<td>6.70</td>
</tr>
<tr>
<td>onshore/offshore</td>
<td>4.42 @ 128°</td>
<td>7.13 @ 281°</td>
<td>8.15 @ 270°</td>
<td>-5.85</td>
</tr>
<tr>
<td>offshore/offshore</td>
<td>2.90 @ 276°</td>
<td>12.93 @ 275°</td>
<td>10.36 @ 281°</td>
<td>-8.67</td>
</tr>
<tr>
<td>offshore/onshore</td>
<td>7.34 @ 269°</td>
<td>5.17 @ 173°</td>
<td>5.87 @ 152°</td>
<td>5.60</td>
</tr>
</tbody>
</table>

Table 3.8: Mean values of stability parameters in onshore shear, onshore 925 hPa flow/offshore shear, offshore shear, and offshore 925 hPa flow/onshore shear for the surface to 700 hPa level from the 12 UTC sounding at CHS.

<table>
<thead>
<tr>
<th>925 hPa/shear</th>
<th>days</th>
<th>CAPE(J/kg)</th>
<th>CIN(J/kg)</th>
<th>LI(K)</th>
<th>925 hPa mixing ratio (g/kg)</th>
<th>700 hPa mixing ratio (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>onshore/onshore</td>
<td>132</td>
<td>1387</td>
<td>-19</td>
<td>-2.88</td>
<td>13.76</td>
<td>5.29</td>
</tr>
<tr>
<td>onshore/offshore</td>
<td>103</td>
<td>831</td>
<td>-34</td>
<td>-1.54</td>
<td>13.05</td>
<td>5.14</td>
</tr>
<tr>
<td>offshore/offshore</td>
<td>404</td>
<td>1169</td>
<td>-69</td>
<td>-2.59</td>
<td>13.94</td>
<td>5.87</td>
</tr>
<tr>
<td>offshore/onshore</td>
<td>62</td>
<td>1188</td>
<td>-47</td>
<td>-2.48</td>
<td>13.48</td>
<td>5.80</td>
</tr>
</tbody>
</table>
Figure 3.1: Diurnal time series of convection for entire warm season, calculated in a 60 km by 60 km box centered at CHS. The 60 by 60 km region includes a total of 900 pixels.
Figure 3.2: Diurnal cycle of convection at CHS based on the time series method of counting convection in a box centered on CHS.
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Figure 3.14: Frequency of convection for the entire warmseason, 15 UTC - 21 UTC, June, July, August, 1996-2000, 2002-2006. The number of days in each category are plotted in the lower right of each panel.
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Figure 3.20: Same as Fig. 3.18, except for the year 1998.
Figure 3.21: Same as Fig. 3.18, except for the year 1999.
Figure 3.22: Same as Fig. 3.18, except for the year 2000.
Figure 3.23: Same as Fig. 3.18, except for the year 2002.
Figure 3.24: Same as Fig. 3.18 except for the year 2003.
Figure 3.25: Same as Fig. 3.18, except for the year 2004.
Figure 3.26: Same as Fig. 3.18, except for the year 2005.
Figure 3.27: Same as Fig. 3.18, except for the year 2006.
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Figure 3.29: The frequency of convection for different ranges of Lifted Index, (a) LI < -2.0; (b) -2.0 ≤ LI < 0.0; (c) 0.0 ≤ LI < 2.0; and (d) LI ≥ 2.0.
Figure 3.30: Scatter plots of Lifted Index from the 1200 UTC sounding vs. the number of storm pixels in a 60 km by 60 km box around CHS during the 4 hour window of 1800 - 2200 UTC with (a) all days (861 days) and (b) storm days (439 days). The vertical black line indicates the value of Lifted Index with the highest skill based on the Pierce Skill Score. Some days had over 1000 storm pixels during the 4 hour window, but these scatter plots are zoomed in on the lowest 500 pixels for greater detail.
Figure 3.31: Scatter plots of CAPE from the 1200 UTC sounding vs. the number of storm pixels in a 60 km by 60 km box around CHS during the 4 hour window of 1800 - 2200 UTC with (a) all days (861 days) and (b) storm days (439 days). The vertical black line indicates the value of CAPE with the highest skill based on the Pierce Skill Score. Some days had over 1000 storm pixels during the 4 hour window, but these scatter plots are zoomed in on the lowest 500 pixels for greater detail.
Figure 3.32: Scatter plots of CIN from the 1200 UTC sounding vs. the number of storm pixels in a 60 km by 60 km box around CHS during the 4 hour window of 1800 - 2200 UTC with (a) all days (861 days) and (b) storm days (439 days). The vertical black line indicates the value of CIN with the highest skill based on the Pierce Skill Score. Some days had over 1000 storm pixels during the 4 hour window, but these scatter plots are zoomed in on the lowest 500 pixels for greater detail.
Figure 3.33: Schematic for the tests for surface to 700 hPa shear.
Figure 3.34: 3 hour progressions of the frequency of convection for onshore surface wind/offshore shear, (a) 12 - 15 UTC; (b) 15 - 18 UTC; (c) 18 - 21 UTC; (d) 21 - 00 UTC; and onshore surface/onshore shear (e) 12 - 15 UTC; (f) 15 - 18 UTC; (g) 18 - 21 UTC; and (h) 21 - 00 UTC.
Figure 3.35: 3 hour progressions of the frequency of convection for offshore surface/onshore shear, (a) 12 - 15 UTC; (b) 15 - 18 UTC; (c) 18 - 21 UTC; (d) 21 - 00 UTC; and offshore surface wind/offshore shear (e) 12 - 15 UTC; (f) 15 - 18 UTC; (g) 18 - 21 UTC; and (h) 21 - 00 UTC.
Chapter 4

Role of the strength of sea breeze frontal passages at CHS in storm frequencies

4.1 Method for evaluating the strength of the SBF

Crouch (2006) utilized a subjective method to detect the timing and penetration distance of SBF passages at five locations along the coast of the Carolinas and Georgia. He used 5 categories for classifying the SBF (Table 4.1) with categories 3, 4, and 5 indicating evidence for a SBF passage at CHS and categories 1 and 2 lacking evidence of a SBF passage at CHS. The subjective classification scheme involved looking at surface data and visible satellite images to designate whether there was likely to have been a SBF passage or not. The main criteria for a SBF passage in the surface data were temperature decreases, dewpoint increases, and existence of a wind shift. Considering that a SBF was at least possible on 816 of 861 days in the present study, his assessments appear to be quite conservative (Table 4.1).

Crouch admitted that his subjective analysis likely failed to detect several actual SBF passages at CHS, since nearby convection hindered judging the location of the SBF. Towering cumuli interfered with spotting the SBF and outflow boundaries also made it difficult to distinguish the SBF in the surface observations. After conducting our own subjective analysis of the data that Crouch (2006) used, we indeed found several SBF days that he had placed into categories 1 and 2 for the reasons stated. This motivated us to create an objective method for classifying the SBF at CHS.

This study involved developing an objective sea breeze detection index (hereafter, SBDI). The SBDI is a normalized index that is automatically computed for each day over the entire 10-year period. Unlike Crouch (2006), the SBDI includes SST in its determination of whether a sea breeze is present. In Chapter 3, possible SBF days were identified simply by taking the difference between the temperature at CHS and the mean SST. All of the possible SBF days from Chapter 3 were re-tested
using the objective SBDI method with the primary goal of identifying those days with *strong* sea breeze frontal passages at CHS. The overall aim was to understand how the SBF initiates storms on those days.

In order for the SBF to exist, the temperature over the land has to exceed the SST at some point in the day. Pressure perturbations associated with differential heating between the cooler maritime air mass and the warmer land are what drive the sea breeze front onshore. When the SBF passes a point, the wind direction shifts, with an increase in the onshore component of the wind. The index therefore incorporates the coast-perpendicular component of the surface wind or $V^*$ (in m/s). After the SBF passes that point, the cooler, moister, maritime air mass overtakes the station so that the temperature, $T$, decreases and the dewpoint temperature, $T_d$, increases. Therefore, the SBDI was constructed to identify significant increases in $V^*$ that were simultaneous with decreases in $T$ and/or increases in $T_d$.

The SBDI is defined as:

$$SBDI = \frac{\Delta V^*}{\sigma_{V^*}} + \frac{\Delta T_d}{\sigma_{T_d}} - \frac{\Delta T}{\sigma_T}$$

(4.1)

wherein,

$\Delta V^*$ = change in $V^*$ from previous surface observation,
$\Delta T_d$ = change in $T_d$ from previous surface observation,
$\Delta T$ = change in $T$ from previous surface observation,
$\sigma_{V^*}$ = Standard deviation of $\Delta V^*$,
$\sigma_{T_d}$ = Standard deviation of $\Delta T_d$, and
$\sigma_T$ = Standard deviation of $\Delta T$.

Each term is normalized by its standard deviation so that a shift in one variable does not dominate the index. The standard deviation was computed for all values of $\Delta V^*$, $\Delta T_d$, and $\Delta T$ between 1300 UTC and 2100 UTC (9 LDT to 17 LDT), representing the window of time a SBF passage may be expected at CHS. Normalizing the terms also allows the units to cancel so that the terms can be added together into one unitless index. Term A and Term B should be positive at the time of SBF passage and Term C should be negative. The only subjective part of this test is the selection of the threshold for a sea breeze day. For this study, a SBF passage at CHS was considered to be *strong* if values of SBDI were greater than 3. To exceed this threshold, shifts in $V^*$, $T_d$, and $T$ must contribute roughly one standard deviation each to the SBDI at the time of SBF passage at CHS (i.e. each term’s magnitude exceeds 1). $\Delta V^*$, $\Delta T_d$, and $\Delta T$ were all fairly decorrelated with one another (Table 4.2) such that if the appropriate shift in all the parameters takes place concurrently a strong SBF likely has occurred. It appears that the SBDI is more strongly governed by $\Delta V^*$ than by $\Delta T_d$ or $\Delta T$ (Table 4.2), which is fitting since the wind shift is the most reliable indicator of a
SBF passage

The SBDI is combined with other available information to identify a strong SBF passage as follows:

1. $T$ at CHS must exceed the mean SST at some time that day
2. $V^*$ must increase ($\Delta V^* > 0$) between observations
3. Either $T$ must decrease or $T_d$ must increase at the time of $\Delta V^* > 0$
4. The SBDI must also be $\geq 3$.

Three classifications of the SBDI were documented:

1. $SBDI \geq 3$: strong SBF passage at CHS;
2. $\frac{\Delta V^*}{\sigma_{V^*}} \geq 1$ but $SBDI < 3$: a significant windshift occurred at CHS increasing the onshore component of wind, but $\Delta T$ and $\Delta T_d$ were comparatively small; weak SBF passage at CHS;
3. $\frac{\Delta V^*}{\sigma_{V^*}} < 1$: no major windshift occurs; either SBF does not pass CHS or it was not significant.

The peak time of day for SBF passages at CHS is about an hour earlier in the day (1500 LDT) using the SBDI method (Fig. 4.1a) than that determined by Crouch (2006) (1600 LDT). The weak SBF passages peak (Fig. 4.1a) earlier in the day around noon LDT. The SBDI method includes any special observations that occur within the hour. It is unclear if Crouch (2006) included special observations (which would presumably be common at the times of major windshifts). Also, the SBDI analysis was for the months of June - August, while Crouch (2006) used the months of April - July. The SBDI is consistent with the conceptual model that a maximum in SBF passages should occur in the mid-afternoon around the time of maximum diurnal heating.

The SBF days (categories 3, 4, and 5) identified by Crouch showed a high frequency of convection just to the northeast of CHS in the late afternoon (Fig. 4.2a-d). A secondary area for storms appeared over the central Piedmont region of SC. The storms in the narrow band along the coast from CHS north to Wilmington are likely initiated by the SBF. Convective initiation appears to occur most frequently along the SBF and over the Piedmont or sandhills.

Crouch’s category 1 and 2 days (which likely erroneously included several actual SBF days), showed widespread convection between the coast and the Piedmont of SC in the late afternoon (Fig. 4.2e-h). Several undiagnosed SBF days made it into this category, artificially increasing the frequency of convection along the coast (Fig. 4.2f,g). Between 2100 and 0000 UTC, storms were suppressed within 20 - 30 km of the coast, likely because several SBF days existed in that category and a maritime airmass resided there. Storms were widespread and likely aided by collisions and mergers.
of outflow boundaries from other convection. Tracking collisions and mergers of individual storms is well beyond the scope of this study, but nevertheless important for the organization of storms over the Carolinas. Because the present SBDI dataset included many more cases than Crouch’s, and because of the clear importance of the prevailing wind direction to storm frequency (Ch. 3) we broke the SBDI results down into flow regimes for comparison to the Crouch classifications in Fig. 4.2.

4.2 925 hPa flow directions and the strength of the SBF

The previous chapter established patterns of convection in different flow directions from the 925 hPa level measured from the 12 UTC sounding. The following analysis combines the different flow directions with the three SBDI categories of the SBF strength. Because of the general lack of storminess in northeasterly flow (Ch. 3), only the other three flow regimes are discussed.

For 925 hPa onshore flow, storms first began in the early afternoon on the days with strong SBF passages at CHS (Fig. 4.3b) and continued to increase in frequency to around 15% to 20% of the days late in the afternoon (Fig. 4.3c). By the evening (Fig. 4.3d), storms were mostly absent from the immediate coast, likely because of more stable outflow boundaries from earlier convection and the more stable maritime airmass from the SBF that moved onshore.

The days with weak SBF passages at CHS (Fig. 4.3e-h) followed a similar pattern, except with increased frequency and coverage of storms further inland. The weak SBF days averaged 289 J/kg more CAPE than the strong SBF days (Table 4.3) and that was reflected by the increase in storm frequency in the late afternoon all along the South Carolina coast. Onshore flow days were more likely to have a weak SBF passage, likely because of the maritime airmass already being advected by the background flow inland. It could be said that the SBF passage in this wind direction typically occurs in a more ambiguous manner.

The no SBF onshore days at CHS had increased convective frequency within 70 km of the coast in the early afternoon (Fig. 4.3j). Storms decreased in frequency in the immediate vicinity of the coast in the late afternoon (Fig. 4.3k). Storms existed on well over 20% of the days the west in the Piedmont. These days did not show a distinct sea breeze convection pattern (i.e. storms strongly localized at the coast).

For days with strong SBF passages in southwesterly alongshore 925 hPa flow, storms were most frequent in the morning (Fig. 4.4a) about 100km off the coast over the Gulf Stream. Between 15 - 18 UTC, storms first appeared in the convex part of the coast northeast of Charleston (Fig. 4.4b). Storms became more widespread everywhere, except in the immediate vicinity of the coast, by the late afternoon (Fig. 4.4c) and evening (Fig. 4.4d).
The days with weak SBF passages at CHS (Figs. 4.4e-h) had convection after 15 UTC that extended 30 - 40 km further inland than the days with strong SBF passages (Fig. 4.4a-d). The frequency patterns appeared very similar for the afternoon and evening along the coast of SC for the days with weak and strong SBF passages. Storms began sooner (Fig. 4.4i) in the non-SBF penetration days than the other classifications. Only 27 days existed for non-SBF passage classification, so the pattern was more volatile. Overall, storms occur frequently in SC with 925 hPa southwesterly alongshore flow at 12 UTC regardless of the strength of the SBF passage at CHS. The widespread convection increases the probability that storm outflows could intersect or merge to initiate new storms. Predicting the locations of these cell interactions is well beyond the scope of this study. With average values of CAPE over 1600 J/kg and CIN greater than -30 J/kg (Table 4.4) for all of the classifications, it was easy to see why storms were widespread. The SBF was just another lifting mechanism in an environment already prone to widespread convection.

The offshore flow days consisted of over half of the available soundings. The patterns of convection were similar for all three types of SBF classifications in the morning and early afternoon (Fig. 4.5a,b), with convection at a minimum over land. Offshore flow opposes the inland penetration of the SBF, delaying the influence of the SBF in initiating storms. Convective patterns in the afternoon (Fig. 4.5c) had a similar pattern to the convective frequency diagram for Crouch’s definite SBF days (Fig. 4.2c). Storms line the coast north of Charleston, but then seem to abruptly stop to the south of CHS. Interestingly, storms occur on nearly 20% of the days (Fig. 4.5d) in a large area around CHS between 21 UTC and 00 UTC.

The days with weak SBF passages showed only a few 15% mid afternoon storm frequency pockets along the coast (Fig. 4.5g) while the days with strong SBF passages had storms all along the coast northeast of CHS (Fig. 4.5c). On the non-SBF penetrating days, storms had increased in frequency around Charleston between 1800 to 2100 UTC (Fig. 4.5k) compared to the other classifications. It is unclear from the averaged thermodynamic variables (Table 4.5) why there is a difference in convective frequency between the non-SBF penetrating days and the days with weak/strong SBF passages. The no-SBF penetration days had the least amount of CAPE and similar values of high CIN to the other categories. A SBF still likely existed on these days, but it did not pass CHS, possibly in part because of the opposing offshore flow. The opposing offshore flow creates a more stationary boundary that could possibly enhance lifting of air parcels from land at the SBF.

Overall, the days with strong SBF passages showed signs that the SBF was important for the organization of convection in all three flow directions, while the weak and no-SBF penetration days were more difficult to explain because storms were just generally more widespread (i.e. not localized to the coast). These diagrams primarily provide information about the frequency of storms in the different flow directions, but they do not provide a good dynamical explanation for why storms occur
where they do. It appears that the role of the large scale flow in determining regional instability is more important to the frequency of storms than is the strength of SBF passage at CHS.

4.3 Shear and the strength of the SBF

Section 3.8, examined where storms occurred in different shear environments. The analysis in that chapter presupposed that the relationship of the SBF to the vertical shear had a large impact on the organization of convection, but didn’t attempt to account for the strength of SBF passage at CHS. The following analysis evaluates the frequency of convection for days with strong SBF passages at CHS in the different shear environments. The days with strong SBF passages had significant SBFs that propagated more than 27 km inland (i.e. passed CHS). Overall, the stability parameters for the days with strong SBF passages in each wind shear category were similar to the parameters for all of the days in each category in Chapter 3 (Table 3.8 vs. Table 4.7).

The patterns of the frequency of convection for the days with strong SBF passages (Fig. 4.6a-h and 4.7a-h) are similar to their counterparts for “all SBF possible” days (Fig. 3.34a-h and 3.35a-h) discussed in chapter 3. This was especially true of both the onshore 925 hPa/onshore shear (Fig. 4.6e-h) and the offshore 925 hPa/offshore shear (Fig. 4.7e-h) categories. These results were somewhat surprising. For example, the shear pattern in (Fig. 4.6e-h) was optimal for initiating storms by the mechanism in Rotunno et al. (1988). It was expected that the stronger SBF passages would have greater influence on the patterns of convection for this wind shear regime, but the pattern is not much different from all the days (which included both weak SBF passages and some non-SBF passages, cf. Fig. 3.34e-h, Fig. 4.6e-h). The patterns of convection also did not change for the less optimal wind shear regime (Fig. 4.7e-h). This suggests that some other factor, such as instability was more important for organizing storms. Although it is apparent that the environmental wind shear has a role in organizing the location and frequency of storms (Section 3.8), the strength of the SBF passage at CHS (assessed via SBDI) did not have a clear impact. In other words, the frequency of convection for the wind shear regimes were not strongly sensitive to the strength of the SBF passage at CHS.

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1 This wind shear/SBF analysis focused on the days with strong SBF passages simply because those days objectively passed the test to be considered SBF days at CHS. There was some ambiguity over what caused the windshift to occur for the days with weak SBF passages, so they were not included. The no-SBF passages are left out because presumably they are days when the SBF remains close to the coast (if they exist at all) with uncertainty over their actual strength. The weak and no-SBF passage categories are also left out because there are not enough days in some of the surface to 700 hPa shear categories (Table 4.6).
Table 4.1: Sea breeze classification scheme from Crouch (2006).

<table>
<thead>
<tr>
<th>Class</th>
<th>Explanation</th>
<th>Charleston</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>no sea breeze</td>
<td>160</td>
</tr>
<tr>
<td>2</td>
<td>sea breeze unlikely</td>
<td>94</td>
</tr>
<tr>
<td>3</td>
<td>sea breeze possible</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>sea breeze likely</td>
<td>41</td>
</tr>
<tr>
<td>5</td>
<td>certain sea breeze</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 4.2: Correlations between parameters in SBDI calculation.

<table>
<thead>
<tr>
<th>SBDI classification</th>
<th>SBDI</th>
<th>$\Delta V^*$</th>
<th>$\Delta T$</th>
<th>$\Delta T_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBDI</td>
<td>1</td>
<td>0.815</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$\Delta V^*$</td>
<td>0.815</td>
<td>1</td>
<td>-0.002</td>
<td>1</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>-0.459</td>
<td>-0.002</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$\Delta T_d$</td>
<td>0.540</td>
<td>0.205</td>
<td>-0.056</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.3: Mean values of stability parameters for SBDI classifications in 925 hPa onshore flow from the 12 UTC sounding at CHS.

<table>
<thead>
<tr>
<th>SBDI class</th>
<th>days</th>
<th>CAPE (J/kg)</th>
<th>CIN (J/Kg)</th>
<th>LI (K)</th>
<th>925 hPa mixing ratio (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong sb</td>
<td>56</td>
<td>973</td>
<td>-20</td>
<td>-1.52</td>
<td>12.77</td>
</tr>
<tr>
<td>weak sb</td>
<td>79</td>
<td>1262</td>
<td>-26</td>
<td>-2.21</td>
<td>13.41</td>
</tr>
<tr>
<td>no sbf passage</td>
<td>46</td>
<td>1241</td>
<td>-20</td>
<td>-2.77</td>
<td>14.12</td>
</tr>
</tbody>
</table>

Table 4.4: Same as Fig. 4.3, except for 925 hPa southwesterly alongshore flow.

<table>
<thead>
<tr>
<th>SBDI class</th>
<th>days</th>
<th>CAPE (J/kg)</th>
<th>CIN (J/Kg)</th>
<th>LI (K)</th>
<th>925 hPa mixing ratio (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong sb</td>
<td>60</td>
<td>1721</td>
<td>-27</td>
<td>-4.21</td>
<td>14.39</td>
</tr>
<tr>
<td>weak sb</td>
<td>60</td>
<td>1723</td>
<td>-20</td>
<td>-4.14</td>
<td>14.09</td>
</tr>
<tr>
<td>no sbf passage</td>
<td>27</td>
<td>1608</td>
<td>-29</td>
<td>-3.78</td>
<td>14.91</td>
</tr>
</tbody>
</table>
Table 4.5: Same as Fig. 4.3, except for 925 hPa offshore flow.

<table>
<thead>
<tr>
<th>SBDI class</th>
<th>days</th>
<th>CAPE (J/kg)</th>
<th>CIN (J/Kg)</th>
<th>LI (K)</th>
<th>925 hPa mixing ratio (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong sb</td>
<td>202</td>
<td>1202</td>
<td>-65</td>
<td>-2.77</td>
<td>14.00</td>
</tr>
<tr>
<td>weak sb</td>
<td>135</td>
<td>1190</td>
<td>-79</td>
<td>-2.66</td>
<td>14.15</td>
</tr>
<tr>
<td>no sbf passage</td>
<td>86</td>
<td>912</td>
<td>-77</td>
<td>-2.24</td>
<td>14.02</td>
</tr>
</tbody>
</table>

Table 4.6: The number of days for the strong, weak, and no-SBF passage days in each surface to 700 hPa wind shear category.

<table>
<thead>
<tr>
<th>surface/shear</th>
<th>strong SBF</th>
<th>weak SBF</th>
<th>no-SBF passage</th>
</tr>
</thead>
<tbody>
<tr>
<td>onshore/onshore</td>
<td>38</td>
<td>64</td>
<td>30</td>
</tr>
<tr>
<td>onshore/offshore</td>
<td>41</td>
<td>40</td>
<td>23</td>
</tr>
<tr>
<td>offshore/offshore</td>
<td>191</td>
<td>126</td>
<td>87</td>
</tr>
<tr>
<td>offshore/onshore</td>
<td>28</td>
<td>27</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 4.7: Mean values of stability parameters in onshore surface flow/offshore shear, offshore shear, and offshore surface flow/onshore shear for the surface to 700 hPa level from the 12 UTC sounding at CHS.

<table>
<thead>
<tr>
<th>surface/shear</th>
<th>days</th>
<th>CAPE (J/kg)</th>
<th>CIN (J/kg)</th>
<th>LI (K)</th>
<th>surr. mixing ratio (g/kg)</th>
<th>700 hPa mixing ratio (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>onshore/onshore</td>
<td>38</td>
<td>1353</td>
<td>-23</td>
<td>-2.40</td>
<td>13.40</td>
<td>5.33</td>
</tr>
<tr>
<td>onshore/offshore</td>
<td>41</td>
<td>963</td>
<td>-24</td>
<td>-1.96</td>
<td>12.99</td>
<td>4.51</td>
</tr>
<tr>
<td>offshore/offshore</td>
<td>191</td>
<td>1059</td>
<td>-61</td>
<td>-2.77</td>
<td>13.89</td>
<td>5.74</td>
</tr>
<tr>
<td>offshore/onshore</td>
<td>28</td>
<td>1179</td>
<td>-49</td>
<td>-2.82</td>
<td>13.18</td>
<td>5.50</td>
</tr>
</tbody>
</table>
Figure 4.1: Diurnal cycle of SBF passage at CHS for SBDI method (a) strong SBF; (b) weak SBF.
Figure 4.2: 3 hour progressions of (a-d) SBF days in Crouch (2006); and (e-h) non-SBF days.
Figure 4.3: 3 hour progressions of the frequency of convection for strong, weak, and non-SBF passages at CHS in onshore 925 hPa flow.
Figure 4.4: Same as Figure 4.3 except for southwesterly alongshore 925 hPa flow.
Figure 4.5: Same as Figure 4.3 except for offshore 925 hPa flow.
Figure 4.6: 3 hour progressions of the frequency of convection for onshore surface wind/offshore shear, (a) 12 - 15 UTC; (b) 15 - 18 UTC; (c) 18 - 21 UTC; (d) 21 - 00 UTC; and onshore surface/onshore shear (e) 12 - 15 UTC; (f) 15 - 18 UTC; (g) 18 - 21 UTC; and (h) 21 - 00 UTC.
Figure 4.7: 3 hour progressions of the frequency of convection for offshore surface/onshore shear, (a) 12 - 15 UTC; (b) 15 - 18 UTC; (c) 18 - 21 UTC; (d) 21 - 00 UTC; and offshore surface wind/offshore shear (e) 12 - 15 UTC; (f) 15 - 18 UTC; (g) 18 - 21 UTC; and (h) 21 - 00 UTC.
Chapter 5

Conclusion

5.1 Summary

The influence of the SBF on convection at Charleston S.C. primarily occurred in the months of June, July, and August with a maximum of convection occurring within 50 km of the coast for those months. In July, a secondary maximum of convection existed over the sandhills of NC. On the most convectively active days, storms were widespread due to high CAPE, small CIN, and likely colliding outflow boundaries (Wilson and Schreiber, 1986; Koch and Ray, 1997) from the coastal and sandhills convection.

The 925 hPa flow directions from the 1200 UTC soundings were useful for classifying which days were most likely to be unstable around CHS. Convection was widespread over South Carolina on days with southwesterly 925 hPa flow owing to the advection of high $\theta_e$ air from the Gulf of Mexico. The offshore flow days averaged the largest amount of CIN, suggesting that convective initiation would be delayed until a sufficient lifting mechanism was present. We infer that the SBF was often the lifting mechanism to initiate storms in this flow pattern (judging by the highest frequencies of storms constrained to within 50 km of the coast between 1800 and 2100 UTC), but the inland penetration of the SBF was usually delayed until the late afternoon by the offshore flow. Storms increased in coverage progressively through the day under onshore flow, but the frequency of convection decreased along the immediate coastline late in the day as that area became increasingly stabilized in the wake of the SBF and earlier convection. The onshore flow days typically had relatively lower CIN which allowed for the earlier initiation of storms.

June, July, and August often had significant conditional instability. It was hypothesized that the key factor for convective development would be the intensity of the lifting mechanism. However, as measured in this study, the strength of the SBF passage at CHS did not appear to strongly influence the frequency of convection. In addition, the highest frequencies of storms did not occur in the
optimal shear regime (offshore flow, onshore shear) envisioned by Moncrieff and Liu (1999). The frequency of convection in this category closely resembled the 925 hPa southwesterly flow regime, where the frequency of convection was widespread over the southeast due to the relatively high instability. In short, a forecaster is better advised to focus on the thermodynamic environment than to worry about the possible strength of the SBF passage at CHS.

On days with high CIN, convection was limited to occurring along the coast between 1800 to 2100 UTC. Storms also were initiated first along the SBF on low CIN days, except earlier between 1500 - 1800 UTC. Later in the day, storms were widespread regionally owing to the low CIN, increasing diurnal temperatures, and outflow boundaries that fostered additional convective activity.

Instability played the largest role in the frequency patterns of deep moist convection at CHS. The low-level flow directions appeared to be important primarily because they influenced the amount of conditional instability, although it is also clear that offshore flow keeps the SBF forcing closer to the coast and delays convection.

In terms of practical operational applications, these results are perhaps unexpectedly simple. But, it is encouraging that the climatology of summertime storms near CHS is fairly well described by the morning sounding. Even so, for day to day forecasting, an awareness of the locations and motions of the SBF and other mesoscale boundaries will no doubt improve the anticipation of day to day variations in storm locations.

5.2 Ideas for future work

This study included the frequency of storms in different flow directions, but it did not attempt to fit those flow directions into the overall synoptic situation. Easterly flow at CHS owing to a low pressure system over Florida likely spelled a different frequency of convection for CHS than easterly flow from a high pressure to the north of CHS. A similar synoptic climatology of the SBF, utilizing Miller and Keim (2003)’s method of creating surface analyses for one year’s 1200 UTC observations, would be suitable (if it could handle detecting the SBF on convectively active days and days with onshore flow). Other studies, such as those by Gilliam et al. (2004) and Crouch (2006), observed the inland penetration distance of the SBF in different flow regimes over the Carolinas, but they did not put their findings into the context of the big picture synoptic flow. The most optimal measurement setup would take upper-air measurements in the pre-SBF passage environment around 1500 UTC (1100 LDT) and in the post-SBF passage environment around 2100 UTC (1700 LDT). To help account for the SBF passage, surface measurements should be gathered at a denser network of stations located about 10 kilometers inland.

Several authors (Blanchard and Lopez, 1985; Atkins and Wakimoto, 1997) talked about the role
of the Bermuda High in organizing the low-level wind field and transporting moisture over Florida. It would be interesting to know the climatology of the locations of the Bermuda High and its role in the transport of moisture and instability over the entire southeastern United States. Days with quiescent flow (under the influence of the Bermuda High Pressure) and high instability usually led to storms that were driven by boundary layer processes (Blanchard and Lopez, 1985; Atkins and Wakimoto, 1997) or peninsular scale processes over Florida (Cooper et al., 1982). Perhaps the Bermuda high is similarly predominant in the determination of coastal storminess over South Carolina.

Given that studies in Florida have emphasized the role of SBF dynamics, whereas our study emphasizes the role of instability, sensitivity studies with a numerical model could also be useful. The problem is that, in the Carolinas, the wind and shear profiles go hand-in-hand with the degree of instability. The goal of such a modeling study would be to isolate the impacts of SBF dynamics from the conditional instability in the environment by varying the wind and thermodynamic profiles independently. Ideally, the environmental profile would be one similar to that in the Carolinas during the summertime, with larger CIN than that over Florida.

As more people continue to relocate to the southeastern coast of the United States, the need for timely and reliable thunderstorm forecasts becomes increasingly necessary. Coastal thunderstorms are hazardous to the many people participating in outdoor activities. Although many coastal thunderstorms may not be considered severe, their sudden onset and frequent lightning are dangerous for people caught unprepared. This study is a first step toward the goal of assisting forecasters in their efforts predicting convective storms.
Bibliography


