ABSTRACT

SIMS, AARON P. Investigation of the Mesoscale Interaction between the Sea Breeze Circulation and the Sandhills Convection. (Under the direction of Professors Sethu Raman and Sukanta Basu).

In the Carolinas of the United States, there are two key land-surface features over which convective precipitation often forms during the summer months. These geomorphic features are the Sandhills and coastline. Along the coastline, sea-breeze circulations regularly form and are known to initiate convection. The Sandhills is a transitional zone of sandy soil surrounded by mixture of soils that include clay and loam. It extends through the central part of the Carolinas and into Georgia and is also the origin of convective storms. The two geographical features, the coastline and the Sandhills, are in regional proximity of each other and the resultant sea-breeze front and the Sandhills convection interact during summer. During this research, the investigation of the mechanism of interaction between these two features has led to the discovery of the Sandhills front, a shallow outflow density current that develops from deep convection over the Sandhills and propagates eastward toward the coast. The convergence of the Sandhills front and the sea-breeze front initiates and enhances convection between the Sandhills and the coastline.

Observations during the month of June for the period 2004 to 2015 are used to evaluate the interaction between these two phenomena. On average, these interactions occur on approximately 24% of all days in June and on 36% of all days in June when synoptic scale systems are absent. Thus, the interactions between the sea-breeze and the Sandhills circulations do contribute to the precipitation in this region. Background wind speeds and directions influence the location and the strength of convection associated with this
interaction. Onshore, offshore, and southwesterly flow classifications each present different strengths and locations of the interactions. Light winds (< 3 m s\(^{-1}\)) and moderate winds (> 3 m s\(^{-1}\) to 6 m s\(^{-1}\)) also influence the interactions differently. Observations indicate that moderate southwesterly flow has the highest total average and total maximum precipitation amounts over the region due to the advection of warm, moist air. Light offshore flow produces the highest totals of average precipitation due to opposing background winds that helps in the development of a robust sea-breeze circulation. Onshore flow produces the least amount of precipitation. The sea breeze circulation is weak in such cases, if it exists.

Vertical characteristics and the variations of different defining parameters during the interactions were evaluated using numerical simulations. To improve the representation of convection in the numerical model, modifications were made to the convective parameterization scheme and the interactions were simulated using this improved version. These modifications include the addition of subgrid scale clouds in the radiation scheme, adjustments to the convective timescale, modifications to the entrainment rates, and linking of the subcloud velocity scale to the turbulent kinetic energy from the boundary layer parameterization. Modifications improved the numerical simulations of the mesoscale convection and precipitation predictions.

Numerical simulations of the wind regime classifications reveal that the strength of the interaction, intensity of convection, and the location and depth of the convection and interaction are influenced by the background winds and moisture availability. Southwesterly flow regimes have the highest levels of atmospheric instability and produce
widespread regional precipitation. Light offshore winds produce the strongest interactions between the sea-breeze front and the Sandhills front. Onshore flow produces the least amount of convective precipitation.

In summary, mesoscale driven interaction events occur regularly during summer months in the coastal Carolinas. The principal driving mechanisms are surface-based differential heating over the Sandhills region caused by changes in soil heat capacity and the coastal sea breeze circulation. The location and intensity of these interactions are dictated by different wind regimes that regulate the strength of the interactions and moisture availability.
Investigation of the Mesoscale Interaction between the Sea Breeze Circulation and the Sandhills Convection

by
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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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DEDICATION

This manuscript is dedicated to my family, whose support has been endless.
BIOGRAPHY

Aaron Sims is a native North Carolinian. He was born in Durham. He attended Garner Senior High School and Wake Technical Community College where he received two Associate Degrees and transferred to NC State University in 1996. He received his bachelor’s degree in Meteorology with a Marine Science concentration, graduating as Summa Cum Laude in 1999. Aaron joined the State Climate Office of NC in 1998 as an undergraduate researcher and was recruited as a graduate student by Dr. Sethu Raman upon graduation. He graduated with his master’s degree in 2001 and worked in the private sector for several years before rejoining NCSU and the State Climate Office of NC as an employee. He has worked in the State Climate Office for over 12 years. He has been working on his PhD part-time and has recently taken on the role of Interim Director of the State Climate Office of NC. He is married to Amy Elizabeth and has three children, Jeremy, Ruben, and Hallie.
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1.1 Motivation

Summertime convective precipitation in the coastal Carolinas has a dominant influence on people and industries in the region. Local-scale variability of precipitation can be of great significance to individual communities, businesses, and emergency management agencies. Accurate mesoscale precipitation information can provide timely warnings and valuable information to local populations. The timing of precipitation has been studied for over a century and has economic impacts in sectors that are highly weather dependent, including transportation and agriculture (Kincer 1916). Additionally, the timing and amount of precipitation that may fall can have large impacts on surface characteristics affecting runoff, evaporation, and air temperature (Dai and Trenberth 2004).

Understanding the nature and frequency of mesoscale precipitation during summers in this coastal region has broad implications in many sectors. The coastal Carolinas have a vibrant tourism industry that encompasses state parks, golf courses, as well as major cities, all affected by the weather. Convective storms induce flash flooding and can produce storm water runoff with adverse effects on water quality. Precipitation monitoring and prediction of convection and precipitation are important for environmental, travel, and safety concerns.
There has been a lack of comprehensive understanding of mesoscale processes that influence precipitation variability in the coastal region of the Carolinas, USA during the summer. Previous research has identified the regular occurrence of sea breeze development as well as a low-level persistent trough (Koch and Ray, 1997) in the central Carolinas during summers. This region frequently develops strong localized convection. The differences in the soil characteristics of this region have been shown to play an important role in the development of this convergence zone (Boyles et al. 2007). Circulations that develop along the convergence zone can lead to increased precipitation in the region (Raman et al. 2005). These circulations produce strong convective storms causing additional precipitation development in this region (Sims and Raman 2016).

1.2 Geography

The multifaceted coastal region of North Carolina and South Carolina (the Carolinas), located in the mid-Atlantic region (USA), is bordered by the Appalachian Mountains to the west and the Atlantic Ocean to the east. The geomorphic features of the coastal Carolinas are shown in Figure 1.1. Along the coast is a series of small islands, inlets and sounds. The coastline is generally straight in the southern and middle portions of South Carolina. The northern portion has a cusp that extends into southern North Carolina. The coastal region in North Carolina has a mixture of barrier islands and sounds.
Figure 1.1 Topography of South Carolina and southern North Carolina. The Sandhills is identified by the black outlined polygon. The Sandhills is about 150 m above sea level.

Land-surface properties in this region are complex, exhibiting a variety of soil types and land use. In the central Carolinas there is a land-surface feature called the Carolina Sandhills, made up of sandy soils, extending along the central part of the Carolinas and into Georgia. It is a transitional zone between the Piedmont, a highland region east of the Appalachian Mountains, and the Coastal Plain, and is oriented parallel to the coastline, at about 180 km inland. The height of the terrain in the Sandhills is approximately 150 m above sea level. It has an average width of approximately 50 km. In between the Sandhills
and the coastline, the terrain slopes toward the sea. The location of the Carolinas, and the
dominant soil types of the Carolinas are shown in Figure 1.2, with data obtained from the
Digital General Soil Map of the USA (NRCS 2014).

Figure 1.2 Dominant soil categories in the Carolinas region. The Sandhills is located in
central South Carolina and extends into southern North Carolina and is outlined in black.

The Sandhills is a region with a marked change in soil-type. Along the eastern edge
of the Sandhills are mixtures of different soil types that tend to be sandier in nature,
particularly towards the coast. Directly along the western boundary of the Sandhills is a
distinct and sharp transition to clay-type soils. Summertime convective storms tend to form
here, and the climatology shows increase in precipitation along this boundary (Raman et al.
2005). This increase in convective precipitation has been shown to occur nearly 40% of the
days during the summer (Koch and Ray 1997). Additionally, this feature is evident during summers when surface heating is strong and synoptic forcing is weak. During other seasons, synoptic scale processes tend to dominate weather events.

### 1.3 Background

During summer, and in the absence of large-scale synoptic forcing, mesoscale processes are often caused by differential heating and can greatly influence the local weather in the coastal region of the Carolinas (Sims 2001; Raman et al. 2005). During early summer, the ocean is still relatively cool and strong heating over land creates a significant surface temperature gradient across the coastline. As a result, sea-breeze-induced precipitation occurs during 40% of the summertime from June through August and contributes to half of the average precipitation for this season (Boyles 2006). Sea breezes in this region can typically propagate 50 to 100 km inland and have been observed as far as 150 km from the coast (Koch and Ray 1997; Gilliam et al. 2004).

Similar to the differential heating across the coast, the Carolinas Sandhills also exhibits significant differences in heating due to the changes in the land-surface characteristics (Segal et al. 1988; Wootten et al. 2010). The Piedmont Trough, a low-level convergence boundary, often forms in this region during the summer and has been attributed to the differences in the heating of the different soils present (Koch and Ray 1997). Differential heating and moisture availability has been shown to influence the development of convection across land-surface boundaries using a 2-D model (Hong et al.
When comparing the relative contribution of land use and soil types to differential heating in this region, the differing soil types have been shown to be the dominant factor (Boyles et al. 2007). Using numerical models, the authors found the influence of the vegetation on the differential heating has less of an impact than the different soils by themselves. The vegetation over the clay soil to the west causes surface temperatures to decrease by evapotranspiration and can increase low-level convergence towards the Sandhills.

Multiple factors can influence the magnitude and the rate of heating of the soils; moisture content, thermal conductivity, and heat capacity all contribute to the relative heating of differing soil types. A prominent influence on the differential heating of the soils can be attributed to the soil moisture availability which is again dependent on the soil type (Mahfouf et al. 1987). The ground heat flux can be estimated using the diffusion equation for soil temperature (Chen and Dudhia 2001). The diffusion equation for soil temperature is given by

\[ \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left[ K_r(\Theta) \frac{\partial T}{\partial z} \right] \]  (1.1)

where the heat capacity, \( C \), and the thermal conductivity \( K_r \) are functions of soil moisture, \( \Theta \). The presence of water increases both the heat capacity and the conductivity of the soil. For sandy soils, thermal conductivity is higher and heat capacity lower than clay soils given the same volumetric water content. Therefore, it is useful to consider the ratio of thermal conductivity to heat capacity (thermal diffusivity, \( \alpha_h \)). A typical value of thermal diffusivity,
\( \alpha_h \) for sandy soil is 0.24 (dry) and 0.74 (wet) and for clay soils \( \alpha_h \) ranges from 0.18 (dry) to 0.51 (wet) (Arya 2001). Additionally, sandy soils are also more porous than clay soils and tend to drain more rapidly. Therefore, the Sandhills region heats more quickly and tends to be warmer than the surrounding area during the daytime. The differential heating of the surface can generate significant soil temperature differences noted with surface observations as well as satellite-derived surface temperatures (Doran et al. 1992).

1.4 Sandhills Circulation

Transverse mesoscale circulations have been shown to develop along boundaries of contrasting land-surface properties (Mahfouf et al. 1987; Taylor et al. 2012; Rihani et al. 2015) and has been shown in numerical simulations over the Sandhills (Sims 2001; Raman et al. 2005; Sims and Raman 2016). These authors note that significant heat flux gradients in the Sandhills region and the resulting airflow circulations can often resemble that of a sea-breeze circulation, though smaller in horizontal and vertical extents. It has been shown there is an increase in precipitation over the Sandhills relative to the immediate surrounding areas during the summer (Raman et al. 2005). The authors attributed this increase to the convective thunderstorms that develop along the convergence zone along the Sandhills.
1.5 Density Currents

Downdrafts from deep thunderstorms form cool dense outflows often taking on frontal characteristics similar to a density current. This dense air can quickly spread outward from the storm with a horizontal speed of about 10 m s$^{-1}$ (Simpson 1969). As a density current propagates, it forces the less dense ambient air to be lifted along its leading edge and is a preferred area for additional convection to develop (Goff 1976; Droegemeier and Wilhelmson 1985). Typical speed of the density current, $V$, has a relationship

$$V = k \sqrt{gd \left( \frac{\rho_2 - \rho_1}{\rho_1} \right) + bu_a} \tag{1.2}$$

where $b$ and $k$ are constants ($b$ is equal to 0.7 and $k$ ranges from 0.62 to 1.4), $g$ is gravity, $d$ is the depth of the density current, $\rho_1$ is the density of the ambient air, $\rho_2$ is the density of the cold outflow, and $u_a$ is the speed of the ambient flow (Charba 1974; Atkins and Wakimoto 1997). The depth of the cold pool can extend up to 2 km in depth (Wakimoto 1982); the horizontal speed of the density current and the associated updrafts are noted to be positively correlated to the depth (Trapp 2013). The role of topography has also been shown to play a role in the direction and speed of thunderstorm outflows (Fitzjarrald 1986).

1.6 Sea-breeze circulation and Sea-breeze front

Sea-breezes are also characterized as density currents (Atkins and Wakimoto 1997). Under favorable conditions, the cool, moist marine air propagates inland during the day as the sea-breeze front. Sea breeze development along the Carolina coast is a frequent
occurrence and can be quite strong during early summer when there is strong heating of
the land and the coastal waters are still relatively cool.

The Carolinas have curved coastlines with a series of inlets, sounds, and cusps along
their length. Where these concave structures intersect, sea breezes that develop can
converge and enhance precipitation (Gilliam et al. 2004). In addition to the curved
coastline, the warm Gulf Stream is in close proximity to the shoreline, and its meandering
can generate eddies advecting additional energy into the coastal system that can influence
sea-breeze development and produce mesoscale circulations offshore (Cione et al. 1993;
Jacobs et al. 2005).

The development of the sea breeze along the Carolinas is influenced by the coastline
shape and also the intensity and the direction of the large-scale winds (Gilliam et al 2004).
Research focusing on sea-breeze development, characteristics, and propagation in the
Carolinas has indicated the importance of the background wind flow and coastline shape
(Gilliam et al 2004; Crouch 2006). The speed and direction of the large-scale background
flow influences the formation, intensity, and propagation of the sea breeze front as it
evolves (Helmis et al. 1995). Koch and Ray (1997) found that during weak onshore flow,
the sea breeze front can propagate far inland due to unopposed flow at the surface. Gilliam
et al. (2004) also noted that offshore flow provided the strongest sea breeze; and when the
offshore flow was relatively weak in the afternoon, the sea breeze could rapidly progress far
inland. It has also been shown that the sea-breeze-induced precipitation occurs on
approximately 40% of days during the summer in the Carolinas (Boyles 2006).
1.7 Precipitation Climatology

Past studies investigating climatological precipitation patterns based on in situ observations as well as radar-derived estimates have shown increased amounts of rainfall in the coastal region (Boyles, 2006) and along the Sandhills region (Raman et al. 2005). Additionally, a climatology of average precipitation using Cooperative Observer stations from 1960 - 2015 was performed for the month of June as shown in Figure 1.3 (Sims and Raman 2016). In June, the highest precipitation, in excess of 150 mm, occurred approximately 50 km inland from the coast in South Carolina. Furthermore, higher precipitation amounts, ranging from 130 mm to 140 mm, is shown to occur over and along the Sandhills. This region of increased precipitation is located between the Sandhills convection and the sea-breeze front. These two phenomena are the likely candidates responsible for the increase in precipitation in this area. What has not been well known is how these two features interact and what role this interaction plays on precipitation patterns and amounts in the Coastal Carolinas.

Given favorable conditions, one would assume two circulations to form in this region, one over the Sandhills, and one close to the coast. One would also expect these two features to interact similarly to two sea breeze circulations that converge across an island or a peninsula as shown in Figure 1.4. Interaction of such circulations have been shown to produce enhanced convective precipitation along the intersection of these boundaries associated with sea-breeze formation along the east and the west coast of Florida (Blanchard and Lopez 1985; Xu et al. 1996), in the Italian Peninsula of Salento (Comin et al. 2005).
2015), and as shown by Crook (2001) for the Tiwi Islands, north of Australia, and by Pozo et al. (2006) for Cuba. These studies tracked the evolution of the sea breezes, their propagation inland, and highlighted the importance of the background flow as well as the impact of the surface energy budget on the development, persistence, and interaction of these circulations.

Figure 1.3 Precipitation climatology (mm) for South Carolina from 1960 – 2015 for the month of June.
The interaction between the sea-breeze front and the deep convection associated with the Sandhills, although similar in concept to converging sea-breezes, may have different mechanisms that influence the interaction. Previous research provides evidence of an increase in precipitation along the coast of the Carolinas resulting from the regular development of the sea-breeze along the coast (Boyles 2006; Crouch 2006). Additionally, increased precipitation has been observed from the low-level convergence and deep convection over the Sandhills (Raman et al. 2005). The regional proximity of the coastline
and the Sandhills provides an environment for the interactions between the mesoscale processes associated with these two phenomena. Characterization of the meteorological conditions conducive for the interactions will also be of interest.

1.8 Scientific Objectives

The purpose and the main scientific objective of this research is to investigate the mesoscale processes involved in the interaction between the sea-breeze circulation and the Sandhills convection in the coastal Carolinas during summer months. The hypothesis is that two circulations, one caused by the differences in soil heat capacity over the Sandhills region and the other, the coastal sea breeze, interact causing enhanced convection when their respective fronts merge (Figure 1.4). Additional scientific objectives that characterize the interaction are:

1. Identification of the criteria necessary for the interactions to occur, categorization of the processes that influence the interaction, and determination of the frequency of occurrence.
2. Examination of the mesoscale precipitation patterns that occur from the interaction.
3. Investigation of possible improvements in quantitative precipitation forecasts through a modified convection parameterization in a mesoscale numerical model.
CHAPTER 2

NUMERICAL SIMULATION OF THE PROCESSES ASSOCIATED WITH THE INTERACTION

2.1 Introduction

The sea-breeze consistently develops and produces precipitation during the summer in the coastal Carolinas regions (Boyles 2006; Crouch 2006). The Sandhills, oriented parallel to the coast and located 180 km inland, is also known to regularly influence the development of convective precipitation locally (Raman et al. 2005). Convection associated with these two phenomena tends to occur without external forcing, and their regional proximity provides the opportunity for these features to influence each other and interact. To better understand the mesoscale effects of the interaction between the sea-breeze circulation and the Sandhills circulation during summers, a numerical study is performed.

2.2 Description of Observational Data and Numerical Modeling

A combination of surface observations, analyses, remote sensing, and numerical modeling is used to identify the location of convective activity and the propagation of mesoscale features and their interactions. High frequency in situ observations are key to the identification of passing frontal features in the coastal region. Observations at

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Automated Surface Observing System (ASOS) stations along a line perpendicular to the coastline extending from Charleston, South Carolina toward Columbia, South Carolina are utilized to identify the progression of the sea breeze. Additionally, observations along the Sandhills in North Carolina were obtained from the North Carolina State Climate Office’s Environmental and Climate Observation Network (ECONet). The unique sub-surface temperature observations from this network emphasize the sharp temperature gradients that can develop over short distances as a result of differing soil types. All station locations are indicated in Figure 2.1.

Although these stations provide important information regarding the coastal interaction and propagation of the sea breeze, there is a lack of sufficient density in the observations to completely depict the spatial extent of complex mesoscale interactions. In locations where there are no in situ observations, surface analyses obtained from the real-time mesoscale analysis (RTMA) are used. These surrogate analyses fields from the RTMA help supplement the surface observations.

The RTMA is an hourly surface analysis product that incorporates downscaled model analyses with available observations from multiple sources. The RTMA is generated by downscaling the 13-km Rapid Update Cycle (RUC) model to 5 km to create a first guess field. Using real-time observations, a two-dimensional variational data assimilation system nudges the first guess fields to produce updated analyses (De Pondeca et al. 2011). The analyses can be used to supplement in situ observations and provide a gridded estimate of near-surface meteorological fields (Ancell et al. 2014; Novak et al. 2014).
Figure 2.1: Map of the study region showing the dominant soil type categories for the Carolinas. The Sandhills is outlined in the central Carolinas. Observational station locations discussed are also depicted. The location of the cross section used to present the modelling results is shown as a red line. This line is perpendicular to the coast and near several stations extending from the coast through the Sandhills. Hamlet, North Carolina located in the Sandhills has sandy soil and Lilesville, North Carolina, to the west has clay soil.
Additionally, remotely sensed observations are used to examine the horizontal spatial structure of the mesoscale processes. Radar reflectivity data help identify mesoscale convergence and convective development along the coast and the Sandhills. A time history of the reflectivity data indicates the propagation of spatially congruent frontal features on a high resolution scale. In addition to radar reflectivity, satellite observations afford the opportunity to identify land-surface temperature (LST) heterogeneities. Moderate Resolution Imaging Spectroradiometer (MODIS) 8-day composite average daytime LSTs are taken from multiple satellite passes to create a spatial composite of the surface heating.

To better understand the interaction between the sea-breeze front and the Sandhills-induced convergence, a numerical simulation is performed utilizing the WRFV3.3.1 model (Skamarock et al. 2008), which is initialized using the Global Forecast System (GFS) analysis at 0000 UTC (1900 Eastern Standard Time (EST)) on 24 June 2009. Due to the nature of the phenomena studied herein, and their development dependent on solar heating, we refer to EST as well. The simulation duration is for 36-h and ends at 1200 UTC (0700 EST) on 25 June 2009. A one-way nested domain configuration centered over the Carolinas is used consisting of an outer, intermediate, and innermost domain of, respectively, 12-km, 4-km, and 1-km grid lengths as shown in Figure 2.2. Additional model configuration information and model physics used are listed in Table 2.1. In this chapter, results are discussed relative to a portion of the innermost domain since many of the features examined are locally driven and require high resolution simulations in order to identify the boundary-layer processes and their interactions. Given the nature of the
processes, the innermost domain provides the most accurate lower boundary conditions where the soil inputs are on a 1-km grid. The location and formation of the Sandhills front is dictated by the sharp transition of the soil types.

Figure 2.2: Nested domain configuration consisting of an outer domain of 12-km grid length, an intermediate domain of 4-km grid length, and an innermost domain of 1-km grid length.
Table 2.1: WRF model set-up and physics packages used in the simulations. The model is initialized from the Global Forecast System (GFS). The physics packages used include: Kain-Fritsch cumulus parameterization (KF), Mellor-Yamada-Nakanishi-Niino (MYNN) boundary-layer scheme, Weather Research Forecast (WRF) Single Moment 6-class (WSM6) microphysics scheme, and the Rapid Radiative Transfer Model for General Circulation Models (RRTMG) radiation scheme.

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2.2.1 Convective Development and Sea-Breeze Progression

On 24 June 2009, the large-scale forcing is weak over the Carolinas. The prevalent mesoscale processes are largely responsible for the development of convective activity in the region. A sea breeze develops along the coast of the Carolinas resulting in convective precipitation along its frontal boundary. The line of reflectivity and convection seen in the radar imagery has been used to infer the location of the sea-breeze front. At approximately 1700 UTC (1200 EST), convection is noted along the South Carolina coast as shown in Figure 2.3a.

The convection forms a scattered line of cells extending from the North Carolina / South Carolina border and into the Georgia coastal region by 1900 UTC (1400 EST). At this time, scattered convection has formed in the Sandhills region in central South Carolina as
indicated in Figure 2.3b. Much of the discussion will focus on the South Carolina region where the interaction appears to be the strongest and the geography is simpler.

Figure 2.3: Level-III base radar reflectivity (in dBZ) on 24 June 2009. (a) Radar reflectivity indicates convection along the South Carolina coast associated with the sea breeze at 1702 UTC (1202 EST) on 24 June 2009. (b) Radar reflectivity at 1900 UTC (1400 EST) on 24 June 2009 indicates convection has formed in the Sandhills region in central South Carolina. (c) Radar reflectivity showing the sea-breeze front and the Sandhills front converging at 2045 UTC (1545 EST). The thin line of echoes denotes the frontal boundaries. (d) Development of enhanced convection indicated by the radar reflectivity in southeast South Carolina resulting from the interaction between the sea-breeze and the Sandhills convection at 2200 UTC (1700 EST) on 24 June 2009.
As the convective storms develop, the Sandhills convection and the associated Sandhills front propagate out toward the coast. Radar imagery indicates the sea-breeze penetrating well inland, approximately 100 km, during the afternoon. The interaction with the Sandhills front occurs around 2045 UTC (1545 EST). The location of these frontal features is identified using the thin line of reflectivity indicated by an arrow as shown in Figure 2.3c. Convergence of these two frontal features appear to enhance convection formation in the Coastal Plain as shown in Figure 2.3d. Intense convection develops at 2200 UTC (1700 EST) and persists for several hours.

By 0000 UTC (1900 EST) most of the convection in South Carolina has dissipated, but there is some additional convective development in the coastal region just east of the Sandhills in North Carolina. In North Carolina, the sea breeze does not trigger convection early on this day and the convection is less intense. The sea-breeze front in North Carolina propagates more slowly than in South Carolina and was visible in the radar reflectivity. Absence of precipitation along the sea-breeze front allows for easier identification of its location. About 0100 UTC on 25 June 2009 (2000 EST on 24 June 2009), the Doppler radar is no longer able to depict the location of the sea-breeze front in North Carolina as shown in Figure 2.4. However, it is interesting to note that the location of the last recognizable reflectivity signature of the sea-breeze front and its movement in North Carolina does coincide with late-evening precipitation development in this region. The convection continues for several hours and moves towards the ocean as nighttime progresses and is near offshore by 0600 UTC (0200 EST) as shown in Figure 2.5.
Figure 2.4: Base-level radar reflectivity (in dBZ) at 0100 UTC on 25 June 2009 (2000 EST on 24 June 2009), the black circle indicates the approximate location of the sea-breeze front in North Carolina.

Figure 2.5: Base-level radar reflectivity (in dBZ) at 0200 UTC on 25 June 2009.
Figure 2.6: (a) Simulated reflectivity (in dBZ) at 2200 UTC (1700 EST) on 24 June 2009. Intense simulated reflectivity in southern South Carolina between the Sandhills and the coast as a result of the interaction between the Sandhills and sea-breeze fronts. (b) The model produces widely-scattered reflectivity values over much of the coastal region at 1900 UTC (1400 EST) and shows a line of convection along the coast and the Sandhills.
Simulated maximum reflectivity from the model is examined and compared to the observed radar reflectivity for this event. Similar to the observations, the simulated sea-breeze convergence initiates convection along the coast between 1600 UTC (1100 EST) and 1700 UTC (1200 EST). The development of convection is also simulated in the Sandhills region starting at this time. The simulated reflectivity (in dBZ) of widely-scattered precipitation is evident from 1800 UTC (1300 EST) to 2200 UTC (1700 EST), with the maximum reflectivity of approximately 60 dBZ occurring at 2200 UTC (1700 EST) over the southern Coastal Plain in South Carolina as shown in Figure 2.6a. The timing, location, and intensity of the simulated maximum convection are consistent with the radar reflectivity that was shown in Figure 2.3c. Convective precipitation along the edge of the Sandhills and along the sea-breeze frontal boundary as seen in the radar reflectivity at 1900 UTC (1400 EST) (shown in Figure 2.3b) is also present in the maximum simulated radar reflectivity shown in Figure 2.6b. The model simulation clearly reproduces the lines of convection associated with the sea breeze and the Sandhills region.

Observed total daily precipitation (in mm) from precipitation gauges around the region are overlaid on the Stage IV precipitation estimates for 24 June 2009 as seen in Figure 2.7. Stage IV precipitation estimates are obtained from the National Center for Environmental Prediction and created by using a combination of radar-derived precipitation estimates that are bias-corrected using rain gauge data (Lin and Mitchell 2005). The gauges indicate widespread precipitation in the region, but are sparsely located and are not able to depict the precipitation patterns very well on this day. The Stage IV precipitation estimates
help verify the patterns of reflectivity as seen by the radar, but are relegated to indicate relative intensity, as exact amounts should be utilized with caution. Maximum estimated amounts of precipitation in South Carolina are on the order of 15 mm, while the highest estimated amounts exceed 25 mm and are located along the North Carolina / South Carolina border. Observations in the region indicate less precipitation totals than the estimated amounts, ranging from 3 mm to 10 mm in central South Carolina, but many of these stations are not located where the interaction and the most intense precipitation occurred.

Figure 2.7: Total daily precipitation (in mm) from gauge data overlaid on the gridded Stage IV precipitation estimates for 24 June 2009. Stage IV precipitation estimates indicate the precipitation patterns and the relative amounts.
2.2.2 Differential Heating of the Land Surface

Understanding the primary mesoscale driving forces for the development of the sea breeze and the convection in the Sandhills warrants an examination of the differential heating over the land surface. The magnitude of the strong differential heating induced by the surface temperature gradient over the Sandhills region is demonstrated using the composite 1-km MODIS LST shown in Figure 2.8. The sharpest temperature gradients appear to occur on the western edge of the Sandhills, consistent with soil-type differences shown in Figure 2.1. Surface temperatures over the Sandhills typically range between 35 and 45 °C. Surrounding area temperatures range anywhere between 30 and 35 °C.

Figure 2.8: Composite satellite land-surface temperatures (°C) based on data for eight days ending on 26 June 2009. Measurements taken at approximately 1600 UTC (1100 EST) averaged over eight days showing strong heating in the central part of the Carolinas in and around the Sandhills area. Surface temperature differences in this region can vary from 5 °C to 15 °C.
Figure 2.9: Simulated surface skin temperature (in °C) at the surface at 18Z (1PM EST) on 24 June 2009.

Additionally, in situ observations of air and soil temperature are obtained from two ECONet stations. These two stations, shown in Figure 2.1, are separated by a distance of approximately 22 km and are located near Lilesville, North Carolina (LILE) and Hamlet, North Carolina (HAML). The station LILE is located on clay soil, while HAML is on sandy soil. The maximum 0.1-m deep soil temperature difference of 3 °C occurred during the afternoon on
24 June 2009 2100 UTC (1600 EST) when the soil temperatures were 33 °C at LILE and 36 °C at HAML.

Strong heating at the surface is also evident in the simulated surface skin temperature. By 1800 UTC (1300 EST) the simulated land-surface temperature has reached 35 °C near the coast. Farther inland over the Coastal Plains and along the Sandhills region the surface skin temperature is even higher, reaching 46 °C in some locations as shown in Figure 2.9. The sea-surface temperature off the coast is cooler than the land surface and is approximately 27 °C while over land, the simulated surface temperature has reached 35 °C. Farther inland, the surface skin temperature is even higher, reaching 45 °C in some areas. These LST differences of almost 20 °C across approximately 100 km illustrate the heterogeneity of the heating and associated thermal gradients.

2.2.3 Near-Surface Temperature and Wind Variations

The strong differential heating of the surface is a primary driver of the near-surface air temperature gradients and for the development of the sea breeze. The development and the progression of the sea breeze as well as the development of convection inland over the Sandhills during the afternoon hours are presented. Examination of the near-surface air temperature at 2 m and wind field at 10 m during the afternoon hours clearly show the sea-breeze front and the Sandhills convergence and their interactions.

The development of the sea breeze is evaluated using in situ wind observations averaged over 15-min at several stations in the coastal region. Onshore winds along the
South Carolina coastline start to develop around 1600 UTC (1100 EST) as shown in Figure 2.10a. The sea-breeze circulation begins to strengthen with an onshore wind ranging between 2 to 4 m s\(^{-1}\) along the coast. Inland, winds are weaker and more variable in direction.

By 1900 UTC (1400 EST) observations indicate that there is strong onshore flow with a wind speed of about 10 m s\(^{-1}\) at the coastal stations extending from southern North Carolina down toward Georgia. The winds inland, in central South Carolina, are stronger at this time with an intensity between 5 and 7 m s\(^{-1}\). Inland, to the east of Orangeburg, South Carolina, convergent winds are associated with the convective activity in the area as shown in Figure 2.10b. These convergent winds correspond well with the mesoscale frontal features observed in the radar reflectivity as was shown in Figure 2.3b.

Closer examination of the timing of the sea-breeze progression and its potential interaction with the Sandhills convergence is essential to understand the enhanced convection occurring between the coast and the Sandhills. A time series of the wind speed and the direction at Charleston, South Carolina (KCHS) from 0000 UTC on 24 June 2009 (1900 EST on 23 June 2009) to 1200 UTC (0700 EST) on the 25 June 2009 is shown in Figure 2.11a. Winds are light and variable during nighttime with the direction largely offshore, possibly a land-breeze, from 0600 UTC (0100 EST) to 1200 UTC (0700 EST) on 24 June 2009. Early in the daytime, there are missing observations between the hours of 1400 UTC (0900 EST) and 1800 UTC (1300 EST). During this period the convection in this area begins at approximately 1700 UTC (1200 EST), as shown by radar reflectivity in Figure 2.3a.
Figure 2.10: Observed winds. The scale vector of 5 m s\(^{-1}\) is located in the box in the lower right. (a) Wind field (m s\(^{-1}\)) at 1600 UTC (1100 EST) on 24 June 2009. Winds are onshore along the coastline. Inland, winds are calmer and more variable. (b) Wind field at 1900 UTC (1400 EST) on 24 June 2009. Convergent winds near Orangeburg, SC are associated with the convective activity in this area.
Around 1800 UTC (1300 EST) the wind speed has started increasing to a maximum of 5 m s\(^{-1}\) with onshore wind direction indicating the arrival of the sea breeze at Charleston, South Carolina.

Inland at Orangeburg, North Carolina (KOGB) the winds during the night are light and variable with wind speeds around 1 m s\(^{-1}\) until 1200 UTC (0700 EST) on 24 June 2009 as shown in Figure 2.11b. Between 2000 UTC (1500 EST) and 2200 UTC (1700 EST) there is a significant change in the wind speed and direction seen both in the observations and in the numerical simulation; this phenomenon could be due to the outflow from a line of convective storms over the Sandhills region. This shallow outflow is similar to a frontal feature. There appears to be an interaction between the shallow Sandhills front advecting eastwards and the westward advancing sea-breeze front, with more intense convection occurring along the line of interaction. After the interaction of the two fronts, the sea-breeze front continues to move westward as indicated by the onshore flow observations at Orangeburg, South Carolina.

These processes and their changes over time can also be inferred from the observations and simulation of near-surface air temperature at 2 m. The passing Sandhills front can be identified by the changes in air mass characteristics as seen in the near-surface air temperature and dew points at 2 m at Orangeburg, South Carolina, as shown in Figure 2.11c. There is a sharp drop in air temperature from about 29 °C at 1900 UTC (1400 EST) to 24 °C at 2000 UTC (1500 EST). The model also simulates this passing frontal feature and captures the timing reasonably well.
Figure 2.11: (a) Time series of wind speed (in m s\(^{-1}\)) and direction from 0000 UTC (1900 EST) to 1200 UTC (0700 EST) in Charleston, South Carolina (KCHS). Winds speeds are indicated by the red line; the blue line indicates the direction. (b) Observed (solid) and simulated (dashed) winds at Orangeburg, South Carolina (KOGB). The wind speeds are indicated by the red lines and direction indicated by the blue lines. There is a rapid variation in the wind speed and direction, likely associated with the frontal passage (circled). (c) Observed (solid) and simulated (dashed) air temperatures (°C) and dew points (°C) at Orangeburg, South Carolina. There is a sharp drop in air temperature and dew point at 2000 UTC (1500 EST), circled.
Using the 2-m temperature from the RTMA, the location of the sea-breeze front at 2100 UTC (1600 EST) is shown in Figure 2.12a. The progression inland, and the location of the cold pools generated from rain-cooled downdrafts in the region are apparent. In south-central South Carolina, indicated by the letter A, there is a pronounced cold pool of air with a minimum value of 24 °C, while air temperatures are close to 32 °C to the west over the Sandhills, indicated by the letter B. The non-uniform propagation of the sea breeze inland is particularly noticeable in northern South Carolina and may be attributed to the curved, cusped coastline in the vicinity.

Farther inland, the near-surface air temperature at 2 m over the Sandhills in southern North Carolina and central South Carolina are higher by 2 to 6 °C than in the surrounding areas. Much of the coastal plain in South Carolina has seen a reduction of air temperatures, largely from the combination of the inland propagation of the sea breeze and also due to cooler downdrafts from the convection over the Sandhills. The cold pool is likely a result of the rain-cooled downdrafts from the convection generated over the Sandhills and of its interaction with the sea-breeze front.

The cold pool indicated by the letter A, increases in size over the next couple of hours as shown in Figure 2.12b at 2300 UTC (1800 EST). By this time, the sea breeze is well developed and has propagated inland all the way to the Sandhills as is evident in the air temperature gradient and in the wind pattern. The air temperature along the Sandhills is still 4 to 6 °C warmer than the air to the east. The in situ wind observations also indicate that there is a significant inland penetration of the sea breeze as far as Florence, South
Figure 2.12: (a) Gridded RTMA air temperature in (°C) and winds (m s\(^{-1}\)) at 2100 UTC (1600 EST) on 24 June 2009. A cold pool of air has formed just east of the Sandhills (location A) that can be attributed to rain-cooled downdrafts. In central South Carolina, the air temperatures are much warmer and the winds are from the northwest (location B). (b) The cold pool expansion and increase in size coupled with the divergent wind flow from the outflow boundary is evident in southern South Carolina. The sea breeze is well developed and has propagated far inland near the Sandhills.
Carolina and Lumberton, North Carolina, located about 100 km from the coastline with flow from the coast as shown in Figure 2.13.

![Map of Carolina and Lumberton](image)

Figure 2.13: Observed wind vectors at 2300 UTC on 24 June 2009. The approximate location of the sea breeze penetration inland is marked by the solid line.

The model confirms the initial development of the sea-breeze front along with the Sandhills-induced convection. This process driven by differential heating is apparent in the simulated near-surface temperature and winds at 1500 UTC (1000 EST) on 24 June 2009 as shown in Figure 2.14. In southern South Carolina, the winds are starting to push onshore and the development of the sea breeze there corresponds well with the cooler temperatures. For the same time, model simulations in NC show a temperature difference
of approximately 6 to 8 °C and winds along the coast at less than 3 m s\(^{-1}\); the sea breeze has not yet developed and the flow is still offshore. The temperature gradient simulated inland across the western edge of the Sandhills, is about 3 °C.

At 1800 UTC (1300 EST), the sea breeze has penetrated inland as is evident in the simulated near-surface 2-m air temperature in South Carolina as shown by a bold line in Figure 2.15a. The wind vectors indicate an organized onshore flow of about 3 to 4 m s\(^{-1}\) and
the associated cooler, near-surface air temperature at 2 m marks the edge of the sea-breeze front which extends roughly 30 to 40 km inland in the Charleston area. Inland, there is evidence of a pool of cool air likely as a result of convective activity in the area.

The simulated air temperature at 1900 UTC (1400 EST), shown in Figure 2.15b, indicates that the sea breeze is migrating inland from the coast in the area marked by the bold line, with the arrow indicating its westward propagation. Inland, downdrafts from strong convection generates shallow cold-pool outflow, “the Sandhills front”, marked by a bold line. The eastward propagation of the Sandhills front is indicated by another arrow. The Sandhills front advancing toward the coast is evident from the cooler temperatures and the northwesterly winds at approximately 5 m s⁻¹.

Sandwiched between the two fronts marked by the bold lines is a swath of warm air with temperatures between 35 and 37 °C, while the surrounding air temperatures are much cooler by approximately 8 to 10 °C. By 2000 UTC (1500 EST) the model simulates cool air advection from the northwest as noted by the wind vectors in this region. The sea breeze has strengthened with winds increasing to about 5 m s⁻¹ as it continues to penetrate inland about 90 to 100 km as shown in Figure 2.15c.

By 2100 UTC (1600 EST), the Sandhills front and the sea-breeze front have merged over central South Carolina as shown in Figure 2.15d. The model clearly simulates the merging of these two air masses as indicated by the strong opposing flow of the near surface winds at 10 m. Convergence of the two air masses enhances the convection in this region.
Figure 2.15: Near-surface air temperature (°C) at 2 m and wind field at 10 m simulated at 1800, 1900, 2000, and 2100 UTC. (1300, 1400, 1500, and 1600 EST) (a) The sea breeze has penetrated inland along the coastline of South Carolina. The cooler near-surface air marks the edge of the sea-breeze circulation. Inland, there is evidence of pockets of cool air formed as a result of convective activity. (b) The cooler air from the Sandhills in South Carolina is propagating toward the coast. The edge of the two air mass boundaries and their average directions are indicated with the arrows. (c) The Sandhills front is advancing towards the coast from the northwest. The sea breeze continues to move inland creating an area of convergence at the surface between these two features, as indicated by the dark lines. (d) The two air masses are merging as indicated by the strong opposing flow depicted by the near surface winds in the area encompassed by the oval.
2.2.4 Interaction of the Sea-Breeze front and the Sandhills front

To further understand the interaction between the sea-breeze circulation and the Sandhills induced convection, a vertical cross section across eastern South Carolina extending from the coast to the Sandhills region is considered. The location of the cross section is shown by a straight red line in Figure 2.1. Several ASOS stations in South Carolina are located close by.

Figure 2.16: Vertical cross section depicting the well-developed nocturnal boundary layer in the model. The shallow stable layer extends up to 500m vertically near Columbia tapers off to about 50m as it reaches the coast. At this time the winds are light and onshore extending inland approximately 40 km.
At 1100 UTC (0600 EST) on 24 June 2009, the simulated nocturnal boundary layer is well developed and a near-surface stable layer is evident as shown in Figure 2.16. The potential temperature near the surface has reached a minimum of 21 °C over land. This stable layer extends up to about 200-m height near Columbia, South Carolina. At this time the winds are onshore and light (≈3 m s\(^{-1}\)) extending inland approximately 40km reducing the boundary layer stability over the ocean and near shore.

By 1800 UTC (1300 EST) on 24 June 2009, a convective boundary layer has developed and there are strong vertical motions over land as the boundary layer becomes more mixed. Along the boundary between land and sea, there is a strong vertical updraft associated with the sea-breeze convection with a maximum vertical velocity of 3 m s\(^{-1}\) extending approximately to a height of approximately 2 km as shown in Figure 2.17a. The convective precipitation that forms in this area is associated with these strong vertical motions along the shoreline. The location of the sea-breeze front is evident in the potential temperature pattern at about 40 km inland from the shoreline. The sea-breeze circulation is not visible here due to the convective activity in the region, while the return flow can be easily distinguished by the wind vectors across the shore at approximately 1.5 km above ground. Along the western side of this cross section there is a strong upward motion along the Sandhills boundaries. On the east side of the Sandhills there is a strong upward motion and an associated strong downward component creating a pool of cooler air and a stable air mass. This cool pool near the strong downdraft is evident from the strong positive potential temperature gradient east of the Sandhills region.
At 1900 UTC (1400 EST), the sea-breeze circulation is better defined in the model and the edge of the front has moved inland about 20 km from the position during the previous hour as noted by the potential temperature gradient distribution in Figure 2.17b. There is still a strong upward motion along the leading edge of the front reaching to a height of roughly 1.8 km. Along the eastern edge of the Sandhills, the shallow cold air mass or the Sandhills front is now more evident and has begun propagating toward the coast.

This Sandhills front has characteristics somewhat similar to the sea-breeze front. They both show a minimum near-surface air temperature of 27 °C. The Sandhills front caused by the density current, discussed in Chapter 1 (Equation 1.2), is shallower in extent than the sea-breeze front and extends roughly 500 to 800 m in the vertical, whereas the height of the sea-breeze circulation is roughly 1000 to 1200 m above the surface. The horizontal winds associated with the Sandhills front have an intensity of approximately 10 m s\(^{-1}\) directed toward the coast. The inland propagation of the sea-breeze front is a bit slower with a speed of about 5 m s\(^{-1}\). As these two opposing fronts begin to move toward each other, the convergent winds between the two frontal features favor an increased upward motion in the interior coastal plain on the order of 1 m s\(^{-1}\) as shown in Figure 2.17b where no significant upward vertical motion existed earlier.

By 2100 UTC (1600 EST) the Sandhills front and the sea-breeze front are close to each other creating stronger ascent associated with their convergent air masses thus increasing the maximum vertical velocity to 2.3 m s\(^{-1}\) at 1 km above ground as noted in
Figure 2.17c. The simulated vertical updraft (in m s\(^{-1}\)) along the convergent boundary extends to a height of about 2 km, at a distance of about 50 km inland from the shoreline.

By 2200 UTC (1700 EST), these two frontal features fully merge, providing a significant updraft velocity of 3.7 m s\(^{-1}\) at an altitude of 4 km. At this time, the sea breeze is well developed and is progressing inland. Maximum horizontal wind is 9.3 m s\(^{-1}\) near the coast. The depth of the sea-breeze circulation extends to almost 2 km. The interaction with the Sandhills front enhances the sea-breeze front induced convection and is a significant contributor to the lifting and generation of strong convection in the region as shown in Figure 2.17d. Model data indicate a maximum vertical velocity of 20 m s\(^{-1}\) within the area of interaction to occur at an altitude of 6.4 km.

A schematic diagram depicted in Figure 2.18 illustrates the processes involved in the interaction and the enhanced convection based on the observational analysis and the numerical simulation presented. The Sandhills area has a convergent flow from both sides due to the strong differential heating. With this upward motion in the Sandhills region, convection forms over the Sandhills and produces rain-cooled downdrafts. These downdrafts result in an outflow boundary materializing into a shallow density current or Sandhills front, with a sharp potential temperature gradient near the surface. There is a sharp horizontal temperature gradient between the Sandhills front and the region of sea-breeze circulation. The depth of this contrast is about 1 km (Figure 2.17a and Figure 2.17b). This Sandhills front, propagating toward the coast, interacts with the approaching sea-
breeze front. When these two opposing air masses converge, additional strong convection develops.

Figure 2.17: (a) Well-developed convective boundary layer with strong upward vertical motions in the coastal region. A rain-cooled downdraft forms east of the Sandhills as indicated with the red arrow. (b) Along the eastern edge of the Sandhills, the Sandhills front is readily evident and is propagating toward the coast. The sea breeze is propagating inland. (c) The Sandhills front and the sea-breeze front converge, creating strong ascent as shown with red arrows. (d) The two frontal features fully merge resulting in significant updraft velocities. The collision with the Sandhills front enhances the sea-breeze front and is a significant contributor in the generation of strong convection in this region.
Two independent mesoscale processes over the coastal Carolinas contribute to enhanced convection in the region. One is the deep convection over the Sandhills (small red arrow) causing cool downdrafts (downward blue arrow). This air mass leads to the formation of a shallow density current, “the Sandhills front (SHF)” that propagates east toward the coast because of the topography. The other is the sea-breeze front (SBF) moving westward. The interaction between these two opposing mesoscale fronts results in enhanced convection over the intermediate zone as indicated by the bright red arrow. Diagram is not to scale.

2.3 Summary

During summer, synoptic-scale fronts in the Carolinas are few, and much of the precipitation that falls in the coastal region can be attributed to locally-driven convective processes. During June, the land-ocean temperature difference is at a maximum resulting in strong sea breeze development and there is increased precipitation in the coastal region of the Carolinas. In South Carolina, higher precipitation is observed between the Sandhills...
and the coast. These higher precipitation amounts may be directly linked to the interaction between the sea-breeze front and the Sandhills front. Regular development of these two phenomena and their interactions are likely key contributors to the climatological precipitation patterns seen in this region.

The sea-breeze circulation and the Sandhills front in the southeast USA are caused by the differential surface heating. Previous studies (Koch and Ray 1997; Raman et al. 2005; Boyles et al. 2007) have indicated that a convergence boundary forms along the Sandhills as a result of differential heating of differing soils, clay and sand, providing a mechanism for triggering convection. Development of the sea breeze in the summer and associated convection has also been studied (Boyles 2006). However, the interaction of these two features and the processes involved have not been previously explored.

The parallel orientation of the Sandhills in relation to the coastline provides a conducive environment for interaction between the two different mesoscale processes, one associated with the sea breeze and the other with the Sandhills region. Earlier, the interaction of these two features was deemed to be simplistic in nature. Two circulations, one over the Sandhills and the other, the sea breeze, were hypothesized to interact and increase convergence causing upward motion and ultimately convection as in an island or a peninsula. However, the interaction between these mesoscale processes appears to be much more complex.

Results presented indicate a different process. Convergence over the Sandhills initiates strong convection, which in turn generates an outflow towards the coast. This
outflow results in a shallow (~750 m) density current producing a front-like feature (Sandhills front) propagating eastward toward the coast. As the Sandhills front converges with the westward propagating sea-breeze front, strong upward motions occur. This interaction enhances convective precipitation between the Sandhills and the coast.
CHAPTER 3
NUMERICAL SIMULATIONS WITH IMPROVED CUMULUS PARAMETERIZATION

3.1 Introduction

Deep convection over the Sandhills and the resulting density current (Sandhills front) from the thunderstorm outflow interacts with the sea-breeze front during summer as discussed in Chapter 2. The interaction of these mesoscale processes results in additional convective precipitation. The skill of numerical models to accurately forecast locally-driven convective summertime precipitation is deficient when compared to other advancements in numerical weather prediction (Fritsch and Carbone 2004). At coarser grid spacing (> 4 km), cumulus parameterization schemes are necessary to help address the numerical model’s inability to resolve finer scale convective activity. While these parameterizations have improved over the past few decades, the ability to consistently simulate convective precipitation still remains elusive (Fritsch and Carbone 2004). Often, convective parameterizations over-predict areal coverage of surface precipitation as well as amounts (Liu et al. 2006; Clark et al. 2007). Additionally, models using convective parameterization schemes tend to over-forecast the frequency of precipitation events as well as under-predict the amounts in heavier events (Janowiak et al. 2007). In the southeast US, which includes the coastal Carolinas, models have a tendency to initiate convection earlier in the afternoon than is observed (Davis et al. 2003; Janowiak et al. 2007; Lee et al. 2007).
Model resolution is an important factor to consider when simulating mesoscale-driven precipitation events. Higher model resolutions have typically proven to be better at simulating precipitation maximums (Clark et al. 2009). In weak convection, it has been suggested that sub-kilometer resolution is required to adequately predict mesoscale events (Liu et al. 2006). Until recently, the prospect of running numerical simulations at resolutions fine enough to eliminate the need for a cumulus parameterization were computationally expensive.

While the capability to run models using only explicit convective processes does exist, computational resources are still limited and many research studies and operational modeling still need and use cumulus parameterizations. Also, many explicit schemes tend to produce excessive precipitation (Blossey et al., 2007). Until large uncertainties present in explicit cloud microphysics (Cintineo et al., 2014) are reduced, subgrid cumulus parameterizations are essential.

The Kain-Fritsch (KF) cumulus parameterization (CP) scheme is widely used in numerical models and generally performs well in the southeast U.S. (Wang and Seaman 1996; Liang et al. 2004). This parameterization is a mass flux scheme using convective available potential energy (CAPE) as the closure assumption. The KF CP scheme can be characterized by three distinct parts: the trigger mechanism for determining if convection will occur, the mass flux formulation highlighting the entrainment and detrainment plume model, and the CAPE closure assumption (Kain and Fritsch 1990; Kain and Fritsch 1993; Kain
2004). The modifications to the Kain-Fritsch scheme presented in this paper have been used earlier in air quality and regional climate simulations (Alapaty et al. 2012; Herwehe et al. 2014a; Bullock et al. 2015) and also to simulate synoptically driven events in the Midwest U.S. (Zheng et al. 2016). However, the application of these modifications to the cumulus parameterization for mesoscale, locally-driven convective events have not been previously evaluated.

3.2 Kain-Fritsch Modifications

Modifications to the Kain-Fritsch scheme include adjustments to the cloud fraction (Alapaty et al. 2012), changes to the convective turnover timescale and changes to the entrainment formulations (Zheng et al. 2016). Therefore, the Updated Kain-Fritsch (UKF) parameterization becomes more scale-aware and no longer assumes a default fixed grid. The effects of the contributions of each individual modification in the simulations are presented by Herwehe et al. (2014b). The CP modifications were evaluated for three-month summer seasonal simulations at 12-km grid spacing over the eastern two-thirds of the continental United States. Their results indicate that the individual and cumulative effects of the changes to the scheme improves the forecasts of precipitation, cloudiness, surface radiation, and air temperature. For clarity and completeness, these specific modifications to the CP scheme are described herein.
3.2.1 Subgrid-scale clouds

Modifications of the KF subgrid-scale cloudiness follow the methods of Xu and Krueger (1991) where the net cloud fraction is incorporated into the Global Rapid Radiative Transfer Model (RRTMG) shortwave and longwave radiation schemes (Iacono et al. 2008). Specifically, the KF scheme uses in-cloud updraft mass fluxes at each level to estimate convective cloud fraction, and then adjusts the resolved cloud fraction. The grid scale cloudiness formulation is determined by the amount of condensate available relative to complete saturation. The cloud fraction is largely driven by the moisture availability in the grid volume.

In the modified version, the subgrid-scale cloud fraction, $CLDFRAC$, is used to adjust the grid scale cloud fraction, $CLDFRAG$, using the formulation,

$$ACLDFRAG = (1 - CLDFRAC)CLDFRAG, \quad (3.1)$$

where the adjusted grid scale cloud fraction is $ACLDFRAG$. The total new cloud fraction is the sum of the adjusted grid scale clouds. The cloud fraction is calculated by the cumulus parameterization scheme. These modifications have been incorporated into the newest versions of the WRF model (V3.6 and newer) (Skamarock and Klemp, 2008).

3.2.2 Convective Timescale

Dating back to Fritsch et al. (1976) and Fritsch and Chappell (1980), the convective time step, $\tau$, has been proportional to the grid length, $DX$, where the convective
adjustment time scale is connected to the advective time scale of clouds. This relationship is given by,

\[ \tau_c = \frac{DX}{U_{cd}} \tag{3.2} \]

where \( DX \) is the grid length and \( U_{cd} \) is the mean wind speed over the cloud depth.

The convective time scale formulation was developed at grid lengths of 20 to 25 km. These grid lengths are related to the time it takes a cloud to be advected through a grid box by the mean wind. The convective time step is capped at 3600 s, and a floor of 1800 s is implemented as well. This relationship between grid lengths and the convective time step is still in practice today even as grid lengths have decreased well below 20 km. Regional models are regularly being run at 12 km and 4 km resolutions.

The convective timescale in the Kain-Fritsch CP scheme is predicated on the idea of stability restoration time, given a certain amount of convective available potential energy (CAPE) (Kain and Fritsch 1993). The amount of CAPE is, in general, independent of the grid spacing. Under the current formulation, as the grid spacing decreases, the convective timescale will always be the minimum prescribed value of 1800 s. In order to stabilize the atmosphere at finer grid lengths, the updrafts and consequent precipitation amounts will most assuredly be unrealistically too intense in many situations (Bullock et al. 2015). Additionally, as grid lengths decrease, the convection will become resolved by grid scale microphysics. The transition threshold from using the CP scheme and turning it off at
higher resolutions is subjective. The UKF (Updated KF scheme) accounts for the contribution of the subgrid-scale convection in a smoother and systematic physical manner by ramping down the CP scheme at higher resolutions.

The UKF convective turnover timescale, $\tau$ (s), is based on a relationship for the convective velocity, $w^*$ (m s$^{-1}$), derived by Grant and Lock (2004). In the cumulus layer, buoyancy is the dominant term in the TKE budget (Stull 1988). The buoyancy term (m$^2$ s$^{-2}$) can be estimated as $(m_b A)/z_{cl}$, where $m_b$ is the mass flux at the cloud base in kg m$^{-2}$ s$^{-1}$, $A$ is the potential energy of the incoming saturated air (m$^2$ s$^{-2}$), and $z_{cl}$ is the height of the cloud base in m. The authors note the dissipation of turbulence scales as $w^*/z_{cl}$ at high Reynolds number flows. When the buoyancy term and the dissipation term are in balance, the vertical velocity $w^*$, scales as

$$w^* = (m_b A)^{1/3} \quad (3.3)$$

in the cumulus layer (Grant and Brown 1999; Grant and Lock 2004). Additionally, the relationship for convective timescale in the ECMWF (European Center for Medium range Weather Forecasting) model is identified to be

$$\tau = \frac{H}{\bar{w}_u^H} \alpha, \quad (3.4)$$

where $\bar{w}_u^H$ is the vertical updraft velocity in m s$^{-1}$ over the cloud depth $H$ in m and $\alpha$ is a horizontal scaling factor in spectral space (Bechtold et al. 2008). The dynamic, scale-aware
convective timescale in updated KF CP scheme uses a combination of the convective velocity derived by Grant and Lock (2004), the convective timescale formulation used in the ECMWF, and a scaling parameter as a function of the grid resolution introduced by Alapaty et al. (2014) and Zheng et al. (2016). The scale-aware convective timescale is given by the relation

$$\tau = \frac{H}{(\delta m_A)^{1/3}} \beta, \quad (3.5)$$

where $H$ is the cloud depth in m, $\delta m$ is the cloud-base updraft mass flux in m $s^{-1}$, $A$ is the entrained CAPE in m$^2$ s$^{-2}$ and $\beta$ is the scaling parameter defined as

$$\beta = 1 + \ln(25 / DX). \quad (3.6)$$

The scaling parameter, $\beta$, plays an important role in determining the updraft mass flux magnitudes in the KF scheme. Essentially, the convective turnover timescale, $\tau$ is related to the number of updrafts needed to reduce the CAPE by the prescribed 90%. Small values of $\tau$ lead to intense updrafts and, hence, intense convection. As grid spacing decreases, atmospheric stability restoration needs to be performed by the grid scale cloud microphysics scheme, thus subgrid-scale convective tendencies have to become smaller. Ideally at cloud resolving scales, subgrid-scale tendencies should vanish completely. This kind of functionality of $\tau$ is achieved by utilizing the scaling parameter, $\beta$ which is analogous to the findings of a cloud resolving modeling study by Arakawa and Wu (2013). The authors showed using a simple case study, resolved cloud fraction varies in a bi-modal
fashion as grid spacing is reduced from that of a coarse general circulation model to a fine cloud resolving model.

Traditionally, the convective turnover timescale affects precipitation amounts inversely. Shorter timescales allow more precipitation to fall within the column before the cloud is advected out of the grid cell. With the new dynamic $\tau$ formulation, the convective turnover time scale and the grid length are inversely proportional, i.e., as the grid spacing decreases, $\tau$ increases. At higher resolutions, this allows the scheme to continue to activate, without prescribing a minimum $\tau$ of 1800 s. The UKF CP scheme does not stabilize the atmosphere as quickly and hence does not produce excessive precipitation. This formulation allows the moisture to be retained in the atmosphere, which in turn can increase the grid scale precipitation. To help facilitate grid scale saturation, the convective updraft mass flux is converted into updraft vertical velocity. This in turn enhances the grid scale vertical velocity (Zheng et al. 2016).

3.2.3 Entrainment

The Kain-Fritsch scheme entrainment of the updrafts is loosely dependent on the mean grid-resolved vertical velocity at the cloud base and the cloud radius. The cloud radius dependency in the entrainment formulation is somewhat arbitrary, predicated on creating a dependency of convection initiation on larger scale forcing (Kain 2004). The entrainment rate is given as
\[ \Delta M_c = m_b \frac{(\alpha \Delta p)}{R}, \quad (3.7) \]

where \( \Delta p \) is the pressure depth (Pa), \( \alpha \) (m Pa\(^{-1}\)) is a constant of proportionality, \( m_b \) is the updraft mass flux (m s\(^{-1}\)) at the cloud base, and \( R \) is the cloud radius in m. The cloud radius is defined to vary between 1000 m and 2000 m and is loosely dependent on the mean grid-resolved vertical velocity at the height of the lifting condensation level (LCL). The cloud radius relation incorporates some dependency of convection initiation on larger scale forcing. The constant of proportionality, \( \alpha = 0.03 \), is the critical value of entrainment as a function of the subcloud layer depth and is essentially the strength of convection triggering. (Tokioka 1988, Kang et al. 2009, Kim and Kang 2012, Lin et al. 2013). As grid spacing decreases, the assumption of a fixed cloud radius begins to cause grid box saturation. This also introduces a scaling problem in which the cumulus subgrid scale cloud can now be resolved on the grid scale, defeating the primary function of the CP scheme. To address this deficiency, the new dynamic entrainment formulation (Zheng et al. 2016) follows a similar concept as the dynamic \( \tau \) formulation.

Utilizing the scaling parameter \( \beta \), the mixing rate, \( \Delta M_c \), is defined by

\[ \Delta M_c = m_b \frac{\alpha \beta}{z_{LCL}} \Delta p, \quad (3.8) \]

where \( \beta \) is the scaling parameter (Equation 3.6), \( \Delta p \) is the pressure depth (Pa) of the model level, and \( z_{LCL} \) (m) is the height of the cloud base. The height of the cloud base
replaces the arbitrary cloud radius since the entrainment is a function of subcloud layer
deepth. As the product $\alpha \beta$ increases, the mixing rate will increase, thus limiting subgrid
convection, particularly in drier environments (Tokioka et al. 1988, Kang et al. 2009, Kim et

This new scale-aware configuration allows the mixing rate, $\Delta M_e$, to increase with
decreasing grid spacing, $DX$. This reduces the impact of the KF scheme by inhibiting its
ability to produce deep convection due to higher entrainment rates. Increased entrainment
associated with decreased grid spacing has been found by several large-eddy simulations
and cloud resolving modeling studies (e.g., Stevens and Bretherton 1999, Del Genio and Wu

### 3.3 Model Configuration

Two different cases of mesoscale-driven summertime convective events are
considered, one on 24 June 2009 (Case 1) and the other on 27 June 2010 (Case 2). The
model configuration for both the cases consists of a one-way nested domain configuration.
The outermost domain has a grid size of 12 km, with intermediate and inner domain grid
spacing of 4 km, and 1 km respectively. The innermost domain of the model covers the
Carolinas region as was shown in Figure 2.2. All simulations utilize the Weather Research
and Forecasting (WRF) model (Version 3.3.1), and each simulation is performed for 36
hours. The model is initialized at 0000 UTC giving ample spin up time before the
development of convection in the region during the afternoon hours.

Each case study has a simulation designated as CONTROL, where the KF CP scheme
is deployed on the 12-km domain, but is not utilized on the 4-km and 1-km domains. The
second simulation incorporates the UKF modifications to the KF CP scheme for all domains.
The ALLCU model simulation is included for the Case 1 to help provide a baseline
comparison of using the KF CP scheme on all model grid domains (12-km, 4-km, and 1-km).
Domains with grid lengths of 4 km or less typically do not employ a CP scheme. Physics
options, grid dimensions, initialization and boundary conditions used in all simulations are
shown in Table 3.1.

Table 3.1: Model Features

<table>
<thead>
<tr>
<th>Domain</th>
<th>12-km</th>
<th>4-km</th>
<th>1-km</th>
</tr>
</thead>
<tbody>
<tr>
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<td>none</td>
<td>none</td>
</tr>
<tr>
<td>CP Scheme (ALLCU)</td>
<td>KF</td>
<td>KF</td>
<td>KF</td>
</tr>
<tr>
<td>CP Scheme (UKF)</td>
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<td>UKF</td>
<td>UKF</td>
</tr>
<tr>
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<td>MYNN2.5</td>
<td>MYNN2.5</td>
</tr>
<tr>
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<td>Noah</td>
<td>Noah</td>
<td>Noah</td>
</tr>
<tr>
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<td>WSM6</td>
<td>WSM6</td>
<td>WSM6</td>
</tr>
<tr>
<td>Radiation</td>
<td>RRTMG</td>
<td>RRTMG</td>
<td>RRTMG</td>
</tr>
<tr>
<td>Initialization and Boundary Conditions</td>
<td>GFS Analysis</td>
<td>GFS Analysis</td>
<td>GFS Analysis</td>
</tr>
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<td>1069x809</td>
</tr>
<tr>
<td>Vert. Levels</td>
<td>51</td>
<td>51</td>
<td>51</td>
</tr>
</tbody>
</table>
3.4 Case 1 Simulation

Processes involved in the initiation of locally driven convective precipitation are evaluated using the numerical model on 24 June 2009. The effects of the modifications to the KF CP scheme influence the incoming radiation and the resultant 2-m temperature. The differences in the surface heating impact the initiation and development of convection in the model as well as the subsequent simulated precipitation. Evaluation of these effects and the differences in the simulations are described in the following sections.

3.4.1 Effects of Subgrid Scale Clouds on Radiation

A spatial comparison of the simulated downward shortwave radiation and observed clouds are shown in Figure 3.1. Comparison of the CONTROL and the UKF downward shortwave radiation confirms the presence of additional clouds generated by the UKF CP scheme, even in the 1-km domain. When compared to the CONTROL simulation, the UKF simulation has greater spatial coverage of clouds following peak heating of the day at 1700 UTC [12 PM Eastern Standard Time (EST)] on 24 June 2009 (Case 1) as shown in Figure 3.1a. The widespread attenuation of incoming solar radiation at the ground is much more noticeable in the UKF case (Figure 3.1b) which reflects the CP scheme’s modification of accounting for subgrid-scale cloud fraction. Central SC and eastern Georgia, where scattered precipitation is seen during the simulation, stands out as an area affected by the cloud fraction increase. These additional clouds appear to be more indicative of the nature of the cumulus production noted during the day as shown in a daily composite visible
satellite image in Figure 3.1c. Fairly uniform coverage of convective clouds over eastern NC and eastern SC was observed.

Figure 3.1: Simulated radiation and visible cloud imagery on June 24, 2009. North Carolina, South Carolina, and Georgia are label as NC, SC, and GA, respectively. (a) Simulated incoming shortwave radiation (Wm\(^{-2}\)) at the surface for the CONTOL simulation at 1700 UTC on 24 June 2009. (b) The UKF simulation of incoming shortwave radiation (Wm\(^{-2}\)) at 1700 UTC on 24 June 2009. Lower values indicate attenuation of radiation due to the effect of clouds predicted by the model. (c) Daily composite image from visible satellite on 24 June 2009.
The incoming downward solar radiation is used as a proxy for the average cloud cover over the region, where low values indicate the presence of clouds. To assess the impact of the daily cycle of clouds in the models, comparisons of grid average radiation amounts for all domain resolutions are performed. Given the location and the focus on mesoscale driven events, this comparison is limited to the area covered by the innermost 1-km nest. The differences in the downward shortwave radiation for each simulation is shown in Figure 3.2. The effects of the UKF modifications on the incoming radiation is apparent on all domains. The difference from the CONTROL simulation is most obvious for the 12-km domain averages where the scheme is more active than in the 4-km or 1-km domains. The maximum difference for the UKF simulation in the 12-km domain is a 60 W m$^{-2}$ reduction in downward shortwave radiation as shown in Figure 3.2a. The differences in the simulated incoming radiation begin at about 1400 UTC on 24 June 2009 and continue until near sunset at 0100 UTC on 25 June 2009, during the corresponding simulation hours, 14 to 25.

In the 4-km domain, differences in simulated radiation between the UKF and CONTROL simulations are still evident but are of less magnitude, with a maximum difference of about 12 W m$^{-2}$ that persists for several hours as shown in Figure 3.2b. The maximum differences peak at maximum daily heating (1700 UTC) and taper off towards sunset. The ALLCU simulation indicates higher radiation amounts at the surface than for the CONTROL, with a maximum difference of about 40 W m$^{-2}$. Even in the 1-km domain (Figure 3.2c), there is evidence of downward shortwave radiation differences between the
Figure 3.2: Differences in downward shortwave radiation (W m$^{-2}$) for each simulation from the CONTROL. (a) 12-km grid-averaged differences over the extent of the 1-km domain area. (b) 4-km grid-averaged differences over the extent of the 1-km domain area. (c) 1-km grid-averaged differences.
Simulations. These differences are most evident during peak heating. The incorporation of the subgrid scale cloud processes in the UKF simulation causes a maximum difference of 20 W m$^{-2}$ in the incoming radiation. The UKF simulation results in widespread reduction in downward shortwave radiation. Simulation of additional clouds is the reason for such reduction.

### 3.4.2 Impacts on 2-m Air Temperature

The changes in the incoming shortwave radiation in the UKF simulation have a notable effect on the near surface air temperature fields as well. The simulated near-surface air temperatures during the afternoon at 1900 UTC are shown in Figure 3.3a and Figure 3.3b for the CONTROL and UKF simulations, respectively. The spatial differences in air temperatures between the CONTROL and the UKF simulations for the 4-km domain are shown in Figure 3.3c. The radiation feedback in the UKF scheme tends to reduce the simulated air temperatures in the convective regions; but in locations away from convection, the UKF simulation appears to be warmer than the CONTROL simulation. Simulated differences in air temperatures for Case 1 are greater than 2 °C in some locations depending on where convection is predicted. There are similar differences between the 2-m air temperatures for the CONTROL and the UKF simulations in the 12-km domain as shown in Figure 3.4.

Hourly surface observations are used to generate a time series of area averaged root mean square error (RMSE) in South Carolina as shown in Figure 3.5. Each simulation hour in
Figure 3.3: Simulated 2-m temperature (°C) values for the 4-km domains at 1900 UTC for (a) the CONTROL simulation, (b) the UKF simulation, and (c) the difference between the two simulations (UKF – CONTROL).
Figure 3.4: Same as in Figure 3.3 but for the 12-km domain.
Figure 3.5: A time series of area averaged root mean squared error (RMSE) in °C of the 2-m air temperature using hourly observations in SC where most of the convection occurred. The black lines represent the CONTROL simulation with the solid line for the 12-km domain, the dot-dashed line for the 4-km, and the dotted line representing the 1-km domain. The gray lines indicate the UKF simulations following the same line style pattern for each domain.

The graph utilized an average of 45 stations. The model is compared to the observations using bilinear interpolation of the model grids to the observation locations. The effects of the modified CP scheme on the evolution of the 2-m air temperature are apparent throughout the simulation. In the pre-convective environment on 24 June 2009 (0600 UTC to 1600 UTC), it is apparent that the higher resolution domains have less overall error in the
simulated air temperatures. Forecast errors in the location and the intensity of convection during the afternoon hours (1600 UTC to 2200 UTC) translate into forecasted air temperature errors. The UKF simulation (gray lines) appears to have less temperature errors than the CONTROL simulation (black lines) in the 12-km and 1-km domains while the 4-km domain does not show improvement. In general, the UKF simulation outperforms the CONTROL simulation, particularly in the 12-km domain.

During the afternoon hours, the forecast air temperature errors are the highest. Errors in the simulated timing and location of the convective precipitation in the model can impact the air temperature error. Improved cumulus parameterization helps in the realistic evolution of near surface air temperature fields. Modified radiation, timing of convection initiation, and spatial distribution of clouds all contribute to near surface air temperature variations.

3.4.3 Development of Convection

Comparison of the observed composite radar reflectivity with the simulated reflectivity from the 1 km domain simulations at 1700 UTC (1200 EST) is shown in Figure 3.6. The sea breeze induced convection along the South Carolina coast is evident in the composite radar imagery at 1700 UTC on 24 June 2009 as shown in Figure 3.6a. There is a line of reflectivity along the coast and a few scattered cells inland as indicated by the composite radar. At 1700 UTC, the CONTROL simulation also produces a line of radar reflectivity along the coast as shown in Figure 3.6b. Widespread light convective activity is
evident across much of the eastern coastal region with a few isolated cells of more intense simulated reflectivity. The model does well in predicting the timing and location of the sea breeze induced convection in agreement with the observed radar observations (Figure 3.6a), but has more widespread and less intense convection than is observed across the region.

Figure 3.6: Composite Reflectivity (dBZ) at 1700 UTC (1200 EST) on 24 June 2009 over southeastern South Carolina. (a) Observed composite radar reflectivity. (b) Simulated reflectivity for the 1-km domain CONTROL simulation. (c) Simulated reflectivity for the 1-km domain UKF simulation.
The UKF results are consistent with the CONTROL simulation indicating the limited impact of the CP scheme in the 1-km domain as shown in Figure 3.6c. At the 1 km grid size, the microphysics scheme is producing much of the precipitation as is evident in the simulated reflectivity. It is important to remember that the simulated reflectivity from the model is based on the grid scale microphysics scheme alone and does not include the contribution of the CP scheme. While at 1-km grid spacing these differences are nearly negligible, the coarser domains of 12 km and 4 km underrepresent the hydrometeors via simulated reflectivity when compared to observed reflectivity.

The observed composite radar reflectivity at 2000 UTC is shown in Figure 3.7a. In the 4-km domain, both simulations capture the nature of the widespread distribution of convection as shown in Figure 3.7b and Figure 3.7c. While neither simulation predicts the exact location, intensity, and timing of convection, there is less simulated reflectivity and a reduced number of convective cells in the UKF simulation when compared to the CONTROL simulation. Simulated reflectivity at 12 km is not a good indicator of convective activity. The simulated reflectivity is based on the activity of the grid-scale microphysics and at this resolution, the cumulus scheme is producing most of the convection. Overall, both model configurations, the CONTROL and UKF, do over-predict the extent of the convective activity as compared with the radar observations. The timing and spatial distribution of the modeled convection match well with the observations. The CONTROL and UKF versions of the models indicate widespread convective activity across the Carolinas with a few stronger cells in central SC, and many small convective cells in the region.
Differences between the CONTROL and the UKF simulations in the evolution of mesoscale convection are demonstrated by evaluating the upward convective cloud mass flux (UMF) following methods similar to Robe and Emanuel (1996) and Wang et al. (2011). The UMF at each model level is determined by only including grid points in areas where the

Figure 3.7: Composite Reflectivity (dBZ) at 2000 UTC (1500 EST) on 24 June 2009 over southeastern South Carolina. (a) Observed composite radar reflectivity. (b) Simulated reflectivity for the 4-km domain CONTROL simulation. (c) Simulated reflectivity for the 4-km domain UKF simulation.
upward vertical motion exceeds 2 m s\(^{-1}\) and the total mixing ratio of cloud water \((q_c)\) and ice 
\((q_i)\) exceed 0.005 g kg\(^{-1}\). This relationship is given as

\[
UMF = \bar{\rho} \sigma_i \sum_{j} \frac{w_{i,j}}{A},
\]  

where \(\bar{\rho}\) is the average density of the moist air, \(w\) is the vertical velocity, the subscripts \(i\) and \(j\) represent the indices on the model grid in the horizontal direction, \(A_i\) is the area of a grid box and, and \(A\) is the total area of all the grid boxes. The region over which mesoscale convective precipitation is evaluated is indicated by the black box in Figure 3.8. This is the location where the interaction of the sea-breeze front and the Sandhills front during the afternoon hours enhanced convective precipitation (Sims and Raman 2016).

A time history of UMF, in the region of interaction on 24 June 2009, is shown in Figure 3.9. Throughout the afternoon, the UKF simulation is less convective as illustrated by lower values of UMF as compared to the CONTROL simulation. The increased convective turnover timescale from the modified KF CP scheme tends to dampen the development of strong convection in the early afternoon as the boundary layer becomes more mixed. During late afternoon, 2000 UTC to 2200 UTC (forecast hours 20 to 22), when the strongest convection occurs, the UKF simulation has larger values of UMF as compared to the CONTROL simulation.

The vertical profile of UMF at 2200 UTC on 24 June 2009 in the region of interaction, shown in Figure 3.10a, indicates the differences between the 1-km and 4-km simulations for the CONTROL and the UKF simulations. The values on the 12-km domain did not meet the
Figure 3.8: Dominant soil type categories for the Carolinas. The Carolina Sandhills area extends from Southern North Carolina through central South Carolina and is outlined in black. The red line shown corresponds to a cross section of the numerical simulation to be presented and is perpendicular to the coast extending from Charleston, South Carolina area to the Sandhills, approximately 260 km inland. The black box encompasses the region of interaction between the sea breeze front and the Sandhills front.

criteria of \( w > 2 \text{ m s}^{-1} \) and \( q_c + q_i > 0.005 \text{ g kg}^{-1} \) and hence are not included in the evaluation.

Each of the UKF simulated domains has a higher UMF than the respective CONTROL domains at the same resolution. The profiles indicate the convective mass flux to rapidly increase in the boundary layer and have the highest values in the lower to mid troposphere. The 1-km domain in the UKF simulation has a maximum UMF of 0.15 kg m\(^{-2}\) s\(^{-1}\) that extends to a height of 7500 m. The 1-km domain in the CONTROL simulation has a maximum value
Figure 3.9: Time history of convective mass flux (where \( w > 2 \text{ m s}^{-1} \) and \( q_c + q_i > 0.005 \)) in the region of interaction between the sea breeze front and the Sandhills front during the afternoon of 24 June 2009 for the 1-km domain. The region of interaction is shown by the black box in Figure 3.8. Forecast hours 14 to 24 correspond to times 1400 UTC June 24, 2009 to 0000 UTC June 25, 2009.

of 0.08 kg m\(^{-2}\) s\(^{-1}\) extending to a height of 4500 m. Overall, the vertical profiles of UMF indicate the UKF simulation to have stronger and deeper convection in the interaction area as compared to the CONTROL simulation.

The vertical profiles of average water vapor in the interaction area at 2200 UTC on 24 June 2009 illustrate increased moistening of the air column by the modified KF CP scheme as shown in Figure 3.10b. The vertical profile shows an increase in specific humidity
Figure 3.10: Vertical profiles of convective mass flux (kg m$^{-2}$ s$^{-1}$) and average water vapor (g kg$^{-1}$) in the interaction region for the CONTROL and UKF simulations for each of the domains at 2200 UTC on 24 June 2009. Solid (dashed) lines represent the CONTROL (UKF) simulations. (a) Convective mass flux (kg m$^{-2}$ s$^{-1}$). (b) Average water vapor (g kg$^{-1}$).
in the UKF simulation as compared to the CONTROL simulation. These differences are believed to result from the modifications to the entrainment and longer convective time step scale. The scaling parameter in the UKF simulation slows the ability of the CP scheme to overturn the atmosphere and remove the CAPE quickly. The entrainment rates are also higher at finer grid scales, diminishing the activity of the CP scheme. The combination of these modifications hinders the CP scheme and the model retains more moisture in the vertical column. This allows the grid scale microphysics scheme to produce more intense precipitation with strong updrafts resulting in less precipitation in other regions.

3.4.4 Interaction of the Sea-Breeze Front and the Sandhills Convection

The observed radar imagery indicates the development of a sea-breeze front and initiation of convection over the Sandhills region during the afternoon as shown in Figure 3.11. The development, progression, and interaction of these two frontal features is noted in the base-level radar reflectivity from the Charleston, SC radar. The location of the sea-breeze front is seen by a thin line of radar reflectivity at 2002 UTC as shown in Figure 3.11a. This line indicated by an arrow, shows the inland propagation of the sea-breeze front in southern SC. Additionally, convective storms are seen along the eastern border of the Sandhills. The outflow from the storms in the Sandhills can be seen at 2045 UTC by the thin line of radar reflectivity as shown in Figure 3.11b. The Sandhills front and the sea-breeze front are marked by the opposing arrows. At about 2130 UTC, the convergence and interaction of these two fronts are seen in Figure 3.11c. The inland convection over the
Figure 3.11: Time history of the base-level radar reflectivity (dBZ) from the Doppler radar in Charleston, SC on 24 June 2009. (a) The sea breeze front is indicated by the black arrow and the thin blue line of reflectivity at 2002 UTC (b) The development of the Sandhills front from the outflow of convection in the Sandhills at 2045 UTC (fronts indicated by opposing arrows). (c) Merging of the sea-breeze front and Sandhills front at 2132 UTC (circled area) (d) Intense convection in southern SC where the Sandhills front and sea the breeze front merge at 2200 UTC.

Sandhills generates cool outflow from the convective storms resulting in the Sandhills front that migrates towards the coast because of the gentle slope in topography (Figure 3.1). This
Figure 3.12: Cross section of CONTROL simulation at 2200 UTC on 24 June 2009. The location of the cross section is a red line illustrated in Figure 3.8. The black arrows represent the circulation vectors. Strong ascent is marked by the red arrows approximately 70 km from the coast. The red lines indicate the potential temperature (°C). The abscissa measures the distance (260 km) from west of the Sandhills towards the coast. (Top) Horizontal spacing between wind vectors are approximately 4 km and the scale vectors represent the length of the maximum vectors in the image. (Bottom) The inset, at 1-km vector spacing, is centered on the location of the interaction and illustrates the merging of the two fronts and the associated strong updraft depicted by the wind vectors.
front interacts with the inland propagating sea-breeze front (Sims and Raman 2016). The merging of these two frontal features initiates additional convective activity, at about 50 to 100 km inland in southern SC as shown in Figure 3.11d at 2200 UTC.

It will be of interest to investigate how the modified UKF CP scheme influences the development and the strength of the interaction between the sea breeze front and the Sandhills front. A model cross section, its location was indicated in Figure 3.8, oriented perpendicular to the coast and extending inland to the Sandhills (approximately 260 km) illustrates the strengths of the upward vertical motions and the interaction of these two frontal features. At 2200 UTC on 24 June 2009, the Sandhills front has merged with the sea breeze front providing enhanced convection in this region as noted in the observed radar imagery (Figure 3.11d). The merging location in the CONTROL simulation, similarly noted in the UKF simulation, is best marked by a strong updraft, opposing wind vectors, and the intersection of the potential temperature contours near the surface as shown in Figure 3.12. This merging and consequent interaction of the two fronts results in intense convection and enhanced precipitation.

3.4.5 Total Precipitation

To evaluate the simulated total precipitation for the 36-h period, these totals are compared to the Stage IV Multi-Sensor Precipitation Estimates (MPE) obtained from the National Centers for Environmental Prediction for the same time period. MPE data are generated from a combination of radar-estimated precipitation and data obtained from rain
gauges. These gauge-calibrated radar estimates also undergo a level of human quality control at the River Forecast Centers, and are mosaicked together onto a national 4.765-km grid (Lin and Mitchell 2005). The spatial density and six-hour time frequency make this dataset unique and valuable when evaluating convective precipitation patterns.

Quantitative precipitation comparisons of the model against MPE can offer insight into the model performance. However, it is important to emphasize the caveats associated with using the Stage IV radar-based precipitation estimates as “truth”. These estimates are known to have inherent biases, particularly in locally driven convective events. MPE tends to underestimate the heaviest precipitation and overestimate lower precipitation amounts (Wootten and Boyles 2014). Additionally, biases can range from 25% to 50% for any particular event (Habib et al. 2009). These inaccuracies in the Stage IV gridded data provide an additional source of uncertainty, particularly when comparing these data on a 1-km domain. While these known biases and errors associated with MPE data exist, these data are still very useful when comparing the relative amounts and spatial distributions to the precipitation simulated by numerical models.

The 36-hour total precipitation from MPE for the period of 0000 UTC on 24 June 2009 to 1200 UTC on 25 June 2009 are shown in Figure 3.13a. MPE precipitation is not considered over water where there are no gauge data available for use in improving the accuracy of the gridded estimates. The observed precipitation patterns indicate that the majority of the precipitation fell in the Coastal Plains of South Carolina with localized
maxima. Higher amounts of precipitation, up to 12.5 mm occurred over southern South Carolina near the coast.

Figure 3.13: Total accumulated precipitation (mm) centered over South Carolina, US for the time period 0000 UTC 24 June 2009 to 1200 UTC 25 June 2009. (a) Stage IV radar-derived precipitation estimates (MPE) re-gridded to the 12-km WRF domain. (b) Model-predicted precipitation amounts from the 12-km ALLCU simulation (c) Model-predicted precipitation amounts from the 12-km CONTROL simulation. (d) Model-predicted precipitation amounts from the 12-km UKF simulation.
In the 12 km domain, the ALLCU and CONTROL simulated precipitation fields shown in Figure 3.13b and Figure 3.13c are identical to each other since both these domains are configured using the same physics. The CONTROL simulation displaces the location of the maximum precipitation and over-predicts the spatial extent of the precipitation as compared to the radar-derived precipitation estimates. The simulated precipitation from the CONTROL case covers too much of SC with the highest amounts, 12.5 to 20.0 mm, occurring in central SC. This area was not the location of the maximum precipitation; MPE estimates indicate little to no precipitation in central SC. In contrast, the UKF simulation at 12-km resolution indicates much less precipitation during the simulation as compared to the CONTROL as shown in Figure 3.13d. The UKF simulation reduces the over-prediction of precipitation as compared to the CONTROL run.

Heaviest observed precipitation amounts occur just inland of the coast in South Carolina and along the North Carolina and South Carolina border. In the UKF simulation, the highest precipitation amounts are located nearer to the coast. The UKF-simulated precipitation maxima are more consistent with the observed precipitation from MPE data. The broad distribution of precipitation simulated by the CONTROL as well as the maximum values in central SC are not present in the UKF simulation. Qualitatively comparing the simulated total accumulated precipitation from the UKF to the accumulated MPE over the same time period, it is easy to identify the holistic improvement using the UKF CP scheme for the 12 km domain in Case 1.
The Stage IV precipitation shown in Figure 3.14a is gridded to the 4-km domain for comparison to the WRF simulations. Total simulated precipitation differences during the 36-h simulation are still apparent in the 4-km domain. The large differences noticed at 12-km resolution between the CONTROL and the UKF simulations are not as prominent in the 4-km domain, except for the ALLCU case shown in Figure 3.14b. The ALLCU simulation clearly overpredicts precipitation, as expected at this resolution when using the default KF CP scheme. Double counting of precipitation by the microphysics scheme and the cumulus parameterization scheme in the 4-km domain is clearly evident.

Qualitatively, the CONTROL and the UKF simulations are similar in terms of precipitation distributions as shown in Figure 3.14c and Figure 3.14d. Notable differences are a reduction in the widespread lighter precipitation and an increase in the number of stronger convective cells. The maximum precipitation amounts in the UKF tend to be higher than in the CONTROL, predominately along the coast in southern South Carolina where there is evidence of interaction between the sea breeze and the Sandhills fronts. The UKF simulation impedes the rapid over-development of convection as a result of the longer convective turnover timescale, as indicated in (Equation 3.5). These results are consistent with the effects of the UKF CP modifications seen in Figure 3.10 showing a stronger UMF and higher amounts of moisture in the column. The KF CP modifications reduces the spatial coverage of precipitation while retaining ample energy and moisture in the column
needed to allow additional strong convection to develop downstream (Raymond and Zeng 2000; Derbyshire et al. 2004).

Figure 3.14: Same as in Figure 3.13 but for the 4-km domain.
Examination of the 1-km simulated total precipitation indicates results consistent with the other domains. The Stage IV data is interpolated to 1-km grid spacing for comparison and is shown in Figure 3.15a. The ALLCU simulation, generates too much precipitation as expected (Figure 3.15b). The spatial coverage and the precipitation amounts are too large as compared to the radar derived precipitation estimates as well as to the other two simulations, the CONTROL (Figure 3.15c) and the UKF (Figure 3.15d). Qualitatively, the CONTROL simulation and the UKF simulation exhibit similar precipitation patterns and amounts. This is to be expected as the UKF CP scheme is highly attenuated at this resolution. The UKF CP scheme is still active but in a very limited capacity at this resolution.

The histogram of total precipitation amounts for each of the domains over the areal extent of the entire 1-km domain is shown in Figure 3.16. At 12 km, the CONTROL and the ALLCU simulations produce too much light precipitation in amounts between 3 mm and 6 mm as shown in Figure 3.16a. The UKF simulation is too dry at 12 km, it does not predict precipitation amounts greater than 9 mm. The CONTROL simulation predicts too much precipitation as compared to MPE. At 4 km, the UKF simulation matches the precipitation observations well for amounts less than 9 mm as shown in Figure 3.16b. There is a reduction in widespread light precipitation amounts in the UKF simulation.

For the 1-km domain (Figure 3.16c), the UKF simulation is similar to the CONTROL in the distribution of precipitation amounts. Both simulations still produce too much light
Figure 3.15: Same as in Figure 3.13 but for the 1-km domain.
Figure 3.16: Histogram of total precipitation for the three sensitivity studies and the Stage IV precipitation amounts over the areal extent of the 1-km domain. Frequency of occurrence for each precipitation bin is shown on the y-axis, and precipitation amounts for each bin (mm) is shown on the x-axis. (a) Precipitation distribution of amounts for the 12-km domains. (b) Precipitation distribution of amounts for the 4-km domains. (c) Precipitation distribution of amounts for the 1-km domains.
precipitation but are comparable to the observations for amounts greater than 6 mm. A positive contribution of the UKF CP scheme, even at 1-km grid spacing, appears to be the reduction of light to moderate spurious precipitation as compared to the CONTROL case. Comparing these results to the Stage IV MPE distribution of precipitation, it is apparent that there is too much spatial coverage of precipitation at 1 km in both the simulations.

3.5 Case 2 Simulations

In Case 2, simulation of the processes involved in the development of the mesoscale precipitation event of 27 June 2010 is performed. As in Case 1, two simulations, CONTROL and UKF, are presented to assess the effect of the KF CP modifications. The sea breeze develops along the coast and propagates inland where it merges with the outflow from the Sandhills convection (Sandhills front) in southern South Carolina. The two fronts are identified in the base-level radar reflectivity from the Charleston, SC radar at approximately 1930 UTC on 27 June 2010 as shown in Figure 3.17. The interaction of these two fronts produces strong convection.

To illustrate these effects, a time series of the upward convective mass flux (UMF) on 27 June 2010 is shown in Figure 3.18. The mass flux comparison is limited to the area of mesoscale interactions shown by the black box in Figure 3.8. The UMF in the CONTROL and the UKF 1-km domains indicates the differences in the evolution of the convection during the afternoon hours (1600 UTC to 2300 UTC). At approximately 1800 UTC on 27 June 2010,
Figure 3.17: Base-level radar reflectivity over South Carolina at 1936 UTC on 27 June 2010. The two opposing arrows indicate the sea-breeze front and the Sandhills front.

Figure 3.18: Same as in Figure 3.9 except during the afternoon of June 27, 2010. Forecast hours 16 to 23 correspond to times 1600 UTC June 27, 2010 to 2300 UTC June 27, 2010.
the UMF in the CONTROL simulation exceeds that of the UKF simulation, prematurely
developing deep convection. At 2100 UTC, convection in the CONTROL simulation has
subsided and the UKF simulation better captures the timing of the convective activity.
These results match well with the radar observations. Additional convection resulting from
the interaction at 2100 UTC is shown in Figure 3.19.

![Figure 3.19: Base-level radar reflectivity over South Carolina at 2101 UTC on 27 June 2010. The oval indicates the location of the interaction between the sea-breeze front and the Sandhills front.](image)

Vertical profiles of UMF and water vapor at 2100 UTC are shown in Figure 3.20. The
profiles of UMF over the area of interaction for the 4-km and 1-km domains are shown in
Figure 3.20a. The grid values on the 12-km domain did not meet the predefined UMF
criteria and are not included in the evaluation. Both domains in the UKF simulation have higher values of UMF as compared to the respective domains in the CONTROL simulation. This reveals that there is stronger convection in the UKF simulation in this area as compared to the CONTROL simulation at the time of interaction. In this case, the differences in the predicted timing of convection in the simulations cause the large differences in the Upward Mass Flux (UMF) for both the domains at 2100 UTC.

The vertical profile of average water vapor in the interaction region is shown in Figure 3.20b. The UKF CP scheme has larger values of water vapor than the CONTROL simulation indicating more moisture in the column, similar to Case 1. The vertical profile of water vapor indicates an increase of 1 to 3 g kg\(^{-1}\) on each domain in the UKF simulation as compared to the CONTROL simulation. These differences are also likely caused by the timing of the convective activity, with the UKF simulation being more consistent with the radar reflectivity observations. Improved timing of the strongest UMF for Case 2 is consistent with Case 1 presented earlier.

Total precipitation for the Stage IV precipitation estimates are shown in Figure 3.21a. The area of mesoscale interaction between the sea-breeze front and Sandhills front is indicated by the black oval. The Stage IV estimates indicate increased precipitation amounts related to the interaction and associated with the sea-breeze front in the northeast portion of South Carolina. Precipitation totals in the CONTROL simulation are illustrated in Figure 3.21b. This simulation does a reasonable job of predicting the spatial pattern of precipitation but misplaces the convection associated with the interaction to the
Figure 3.20: Vertical profile in the interaction area for the CONTROL and the UKF simulations for each of the domains at 2100 UTC on 27 June 2010. (a) Convective mass flux (kg m\(^{-2}\) s\(^{-1}\)). (b) Average water vapor (g kg\(^{-1}\)).
Figure 3.21 Total accumulated precipitation (mm) centered over South Carolina, US for the time period 0000 UTC 27 June 2010 to 1200 UTC 28 June 2010. (a) Stage IV radar-derived precipitation estimates (MPE) re-gridded to the 1-km WRF domain. Region of precipitation associated with the mesoscale interaction is indicated by the black oval. (b) Model-predicted precipitation amounts from the 1-km CONTROL simulation (b) Model-predicted precipitation from the 1-km UKF simulation.
southwest. For the UKF simulation, precipitation maximums occur in the interaction area indicating that the model better simulates the location of the interaction as shown in Figure 3.21c. Neither simulation captures the widespread high precipitation amounts associated with the sea-breeze front indicated by the Stage IV estimates in northeast South Carolina. The differences in the development of convection in the UKF and CONTROL simulations are evident in the resulting total precipitation distribution.

### 3.6 Quantitative Precipitation Comparisons for Case 1 and Case 2

A comparison of the total precipitation of each simulation to the Stage IV precipitation is performed at different thresholds. Frequency bias is used to quantify the ratio of the total number of events forecasted to the total number of observations of an event where,

\[
FBIAS = \frac{\eta_{11} + \eta_{10}}{\eta_{11} + \eta_{01}}. \tag{3.10}
\]

The subscripts of \( \eta \) represent a binary switch for an occurrence or non-occurrence of an event. The first and the second subscripts represent the model and the observations, respectively. A value of one for the model indicates precipitation was forecasted, while a value of zero indicates precipitation was not forecasted. Similarly, a value of one (zero) for the observations indicates precipitation occurred (did not occur). A perfect FBIAS has a value of one, which indicates the same number of forecasted and observed events.
occurred. Values higher than one indicate too many locations were forecasted to have precipitation (too wet), and values less than one indicate not enough locations were forecasted (too dry).

The Mean Error (ME) is used to evaluate the overall precipitation bias and is obtained using the relation,

$$ ME = \frac{1}{n} \sum_{i=1}^{n} f_i - o_i, \quad (3.11) $$

where $f_i$ represents the forecast values, $o_i$ represents the observed values, and $n$ is the total number of values. The mean error (ME) indicates the overall bias of all the forecast and observations pairs, where a perfect forecast has a ME that is equal to zero. Negative values indicate that the average model values are less than the observations, while positive values indicate higher values in the model.

The results for Case 1 are shown in Table 3.2. For the 12-km domain, the UKF simulation is less biased than the CONTROL simulation for smaller precipitation thresholds (< 2.54 mm) with the FBIAS close to one. For amounts exceeding 2.54 mm, the CONTROL simulation has a frequency bias of over 3.2, while the UKF simulation is too dry with a FBIAS value of 0.27. The frequency bias at amounts greater than 6.35 mm shows the CONTROL case to be unbiased with a value of 1.0. This indicates the overprediction of precipitation in the CONTROL simulation has been lessened as the overall bias (ME) is less in the UKF
simulation. The UKF simulation under predicts the average amount by 0.362 mm, and the CONTROL simulation over predicts the average amount with a ME of 0.928 mm.

Table 3.2: Frequency Bias (FBIAS) and Mean Error (ME) for Total Precipitation (mm) for Case 1 on 24 June 2009 over the South Carolina Region for each Simulation.

<table>
<thead>
<tr>
<th>Stat</th>
<th>Threshold</th>
<th>CONTROL 12km</th>
<th>UKF 12km</th>
<th>CONTROL 4km</th>
<th>UKF 4km</th>
<th>CONTROL 1km</th>
<th>UKF 1km</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBIAS</td>
<td>&gt;=0.254</td>
<td>1.571</td>
<td>1.311</td>
<td>1.369</td>
<td>1.421</td>
<td>1.386</td>
<td>1.497</td>
</tr>
<tr>
<td>FBIAS</td>
<td>&gt;=1.270</td>
<td>2.596</td>
<td>1.088</td>
<td>1.655</td>
<td>1.583</td>
<td>1.721</td>
<td>1.751</td>
</tr>
<tr>
<td>FBIAS</td>
<td>&gt;=2.540</td>
<td>3.216</td>
<td>0.270</td>
<td>1.811</td>
<td>1.647</td>
<td>1.921</td>
<td>1.921</td>
</tr>
<tr>
<td>FBIAS</td>
<td>&gt;=6.350</td>
<td>1.000</td>
<td>0.267</td>
<td>2.122</td>
<td>1.891</td>
<td>2.116</td>
<td>2.220</td>
</tr>
<tr>
<td>FBIAS</td>
<td>&gt;=12.700</td>
<td>0.000</td>
<td>0.250</td>
<td>4.485</td>
<td>4.121</td>
<td>4.246</td>
<td>4.886</td>
</tr>
<tr>
<td>ME</td>
<td></td>
<td>0.928</td>
<td>-0.362</td>
<td>1.332</td>
<td>1.279</td>
<td>1.301</td>
<td>1.450</td>
</tr>
</tbody>
</table>

For the 4-km domains, the UKF simulation has a reduced FBIAS as compared to the CONTROL simulation at all but one threshold category. The reduced frequency bias indicates a reduction in simulated precipitation, an improvement over the CONTROL simulation, at most thresholds. The average precipitation bias is also reduced in the UKF simulation with an amount of 1.28 mm compared to 1.33 mm for the CONTROL simulation. These improvements reflect the positive effect of the CP scheme modifications on the simulated mesoscale precipitation.

The 1-km domains for the CONTROL and UKF are more comparable in performance than the coarser domains. The FBIAS for thresholds between 1.27 mm and 2.54 have almost the same values. For the highest precipitation threshold exceeding 12.7 mm, the UKF simulation has a higher FBIAS indicating an over prediction of the precipitation. The
high frequency bias of precipitation in both simulations indicates the CP scheme is doing little to mitigate the over prediction of precipitation at this resolution. The average error of precipitation is 1.3 mm and 1.45 mm for the CONTROL and UKF simulations, respectively. The UKF simulation has a higher precipitation bias likely due to increased intensity of convection indicated by the higher frequency bias at the highest threshold of precipitation. These results support the qualitative analysis presented before, indicating more intense precipitation may result from the modifications in the CP scheme even at 1-km grid spacing.

Table 3.3. Frequency Bias (FBIAS) and Mean Error (ME) for Total Precipitation (mm) for Case 2 on 27 June 2010 over the South Carolina region for each Simulation.

<table>
<thead>
<tr>
<th>Stat</th>
<th>Threshold</th>
<th>CONTROL 12km</th>
<th>UKF 12km</th>
<th>CONTROL 4km</th>
<th>UKF 4km</th>
<th>CONTROL 1km</th>
<th>UKF 1km</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBIAS</td>
<td>&gt;=0.254</td>
<td>0.931</td>
<td>0.920</td>
<td>0.679</td>
<td>1.163</td>
<td>0.591</td>
<td>1.092</td>
</tr>
<tr>
<td>FBIAS</td>
<td>&gt;=1.270</td>
<td>0.943</td>
<td>0.905</td>
<td>0.623</td>
<td>1.113</td>
<td>0.512</td>
<td>0.978</td>
</tr>
<tr>
<td>FBIAS</td>
<td>&gt;=2.540</td>
<td>0.847</td>
<td>0.853</td>
<td>0.631</td>
<td>0.948</td>
<td>0.489</td>
<td>0.895</td>
</tr>
<tr>
<td>FBIAS</td>
<td>&gt;=6.350</td>
<td>0.760</td>
<td>0.333</td>
<td>0.709</td>
<td>0.887</td>
<td>0.433</td>
<td>0.758</td>
</tr>
<tr>
<td>FBIAS</td>
<td>&gt;=12.700</td>
<td>0.210</td>
<td>0.145</td>
<td>0.655</td>
<td>0.968</td>
<td>0.365</td>
<td>0.559</td>
</tr>
<tr>
<td>ME</td>
<td></td>
<td>-4.700</td>
<td>-4.999</td>
<td>-3.640</td>
<td>-0.927</td>
<td>-5.478</td>
<td>-3.511</td>
</tr>
</tbody>
</table>

Results for Case 2 are shown in Table 3.3. For the 12-km domain, the UKF and CONTROL simulations have similar frequency biases for precipitation thresholds less than 2.54 mm. A dry bias is seen in both simulations at amounts greater than the 6.35 mm threshold, where the UKF simulation has a frequency bias of 0.33 compared to 0.76 for the CONTROL simulation. Reduction in higher precipitation amounts for the UKF simulation in the 12-km domain are similar to that seen in Case 1. The magnitude for the ME for both the CONTROL and the UKF simulations are -4.7 mm and -4.99 mm, respectively. These large
Biases can be attributed to both simulations not predicting enough precipitation at higher thresholds.

For the 4-km domain, the UKF simulation is relatively unbiased at all precipitation threshold categories with the FBIAS ranging from 1.16 to 0.89. In contrast, the CONTROL simulation appears to have a dry bias at all thresholds, with the FBIAS ranging from 0.62 to 0.71. The improved predicted precipitation frequency in the UKF simulation can be attributed to the reduced efficiency of the CP scheme, allowing the grid-scale to retain moisture. This decrease in efficiency is achieved by reducing the CP schemes effects by the scaling parameter (Equation 3.6), thus predicting a more correct frequency of occurrence of precipitation as noted in the near unity values of FBIAS. The ME error analysis shows an average bias of -3.64 mm and -0.93 mm for the CONTROL and the UKF simulations, respectively.

The 1-km domains follow the trend in the biases as seen in the 4-km domains. The CONTROL simulation has FBIAS of 0.59 compared to the value of 1.1 for the UKF simulation for amounts greater than 0.254 mm. The UKF simulation is less biased than the CONTROL simulation at all precipitation thresholds. The CONTROL simulation has a ME of -5.5 mm and the UKF simulation has a ME of -3.5 mm indicating less average bias for the UKF simulation.

Generally, the UKF simulations modulate the prediction of precipitation, particularly in the 12-km and 4-km domains. The bias associated with the frequency of precipitation at
different thresholds is improved in the UKF simulations. Also, the UKF simulations tend to reduce the average total precipitation biases. Given the nature of mesoscale driven convective precipitation, reduced precipitation biases over an area may be the first step in improving weather forecasts.

3.7 Summary

In the Carolinas, there are two regional mesoscale circulations represented by the sea-breeze front and the Sandhills front. They regularly form and interact during summers. The mesoscale precipitation initiated by the interaction of these two features is difficult to forecast at high model resolutions. Better representation of the convective processes in the model is crucial in providing an improved mesoscale forecast during summers. Even at high resolutions, especially if the mesoscale forcing is weak, the precipitation generated by the grid-scale microphysics is not always adequate.

In this chapter, evaluations of modifications to the Kain-Fritsch (KF) cumulus parameterization (CP) in WRF were presented. The modifications include adjustments to the cloud fraction calculations that influence the development of subgrid scale cumulus clouds and the incoming solar radiation. Additionally, these modifications also incorporate a grid-spacing-aware scaling parameter. Grid size awareness is achieved through adjustments to the convective time step and through an entrainment formulation. These
adjustments modulate the strength of the simulated convection at higher model resolutions.

The KF CP modifications improve the model simulations of convection and precipitation in the 12-km, 4-km, and 1-km domains. Even at 1 km, where the updated Kain-Fritsch (UKF) effects are greatly attenuated, these modifications have a positive impact and reduce daytime precipitation biases. The effect of the modified KF CP scheme is stronger with the 12-km grid size as compared to the finer resolutions of the 4-km and 1-km domains. These results are expected since the scheme ramps down its impact as the grid spacing gets smaller. At finer resolutions, the UKF simulation tends to decrease the number of convective cells in regions adjacent to strong convection producing fewer, but stronger convective cells.

The CONTROL simulations for both the cases considered here initiate convection earlier in the afternoon than the UKF simulations in agreement with the observations. The UKF modifications help mitigate the early development of convection in the simulations by increasing the convective timescale and the entrainment rate. The longer convective turnover timescale increases available moisture for the grid-scale microphysics scheme. These changes in the CP scheme result in improved timing and strength of convection and helps the model forecast precipitation better.

While these results are promising, these two case studies represent a fraction of the mesoscale events that occur during a typical summer in the region. Also, the lack of
observations does not allow for direct comparison of the strengths of the convection in these simulations. However, the resultant improvements of the simulated convection are clearly apparent in the predicted precipitation in the UKF simulations.

The updated Kain-Fritsch (UKF) cumulus parameterization scheme has added value to the forecast of summertime mesoscale convective events in the Carolinas at high resolutions (<= 12km), addressing scientific objective four. The UKF modifications and the feedbacks to other model parameters, such as near surface air temperature and cloud cover, are consistent with the physical representation of the processes. The majority of the effects of the improved cumulus parameterization are manifested in the convective development and resultant precipitation. The ability of a numerical model to accurately predict precipitation is often considered the gold standard in model performance. In order for a model to predict precipitation accurately, all the physical processes must be well represented. The modified CP scheme slows the development of convection, produces fewer convective cells with strong updrafts, and mitigates the over-prediction of precipitation.
CHAPTER 4

OBSERVATIONAL ANALYSIS OF THE INTERACTION OF THE

SEA-BREEZE FRONT AND THE SANDHILLS FRONT

4.1 Introduction

Key processes involved and the associated mechanisms of the interaction between the Sandhills convection and the sea-breeze front were evaluated using observations and a numerical model in Chapter 2. To better identify the characteristics of the interactions and to investigate their frequency of occurrence, an observational analysis is performed for the month of June during the years of 2004 to 2015. Classification of these events are categorized by background wind speed and wind direction. This analysis aims to improve the understanding of the dependence of the frequency and the magnitude of the interactions on the ambient atmospheric conditions.

4.2 Observations

Multiple data types are used to identify and categorize the interaction events. Observations utilized include in situ measurements and remotely-sensed data. Products that are derived from multiple data sources are also used to provide best-estimates of observed conditions. These observational systems are described herein.

The raw base Level-II radar reflectivity data is the primary tool used to identify individual interaction events between the sea breeze front and the Sandhills front. The raw
radar reflectivity data includes unfiltered radar echoes that can capture the signature of the sea-breeze and the outflow boundaries at low levels in the vicinity of the radars. The mesoscale frontal features are normally indicated by thin lines of reflectivity and can be paired with other observations, such as visible satellite, to confirm these frontal boundaries. The level-II base-level radar reflectivity is obtained from the National Centers for Environmental Information (NCEI) for five radars in the Carolinas. These radars, identified as KCLX, KCAE, KLTX, KMHX, and KRAX are located in Charleston, SC, Columbia, SC, Wilmington, NC, Morehead City, NC, and Raleigh, NC, respectively. Radar station data are utilized individually for localized interaction events and are also combined together to create a composite base reflectivity over the region. The Warning Decision Support System – Integrated Information (Lakshmanan et al., 2007) is employed to combine the radars spatially, perform quality control, and to time-sync the radar data from multiple sites.

Background wind speed and direction influence the sea-breeze development and propagation (Gilliam et al. 2004) and are important meteorological characteristics to consider when evaluating the interactions. Additionally, the winds also advect moisture; the availability of moisture can influence the development of deep convective precipitation (Derbyshire et al 2004). Therefore, in situ wind observations from the Automated Surface Observing Systems (ASOS) and the Automated Weather Observing System (AWOS) are used to classify the background wind flow for each day of possible interaction. These stations
Figure 4.1 Topographic map of the Carolinas. The yellow oval identifies the Sandhills zone. The green oval identifies as the Intermediate zone. The purple oval identifies the Coastal zone. The red oval encompasses the region from which surface stations are used to determine the average background wind speed and wind direction.

provide real-time hourly 10-m wind observations in the Carolinas. Stations used to determine the background wind flow are indicated by the black dots contained within the red oval in Figure 4.1. This area is chosen to reduce the influence of the diurnal pattern near the coast associated with the land and sea breezes. Furthermore, the wind directions from these stations are vector averaged to obtain the wind directions over the area during the mid-morning hours (1300 UTC and 1400 UTC). Mid-morning hours represent the conditions before convection starts. Using two sequential hours in the morning provide a
sample size of 30 to 50 observations for determining the average flow over the region. The directions of these pre-convection background winds are then organized into three categories: onshore, offshore, and southwesterly flow. The details of the wind direction classifications and the number of occurrences are listed in Table 4.1.

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<thead>
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<th>Wind Category</th>
<th>Wind Directions</th>
<th>Number of Occurrences</th>
<th>Occurrences (%)</th>
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<td>Southwesterly</td>
<td>205 - 245 Degrees</td>
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<td>38</td>
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<tr>
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<td>15</td>
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<tr>
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<tr>
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<td>40</td>
<td>47</td>
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<tr>
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<td>26</td>
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<td>Offshore (&gt; 3 m s⁻¹)</td>
<td>245 - 45 Degrees</td>
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<td>21</td>
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Moisture availability is also evaluated in the region to investigate its relationship with the precipitation amounts and distributions. Two ground-based GPS-Integrated Precipitable Water (IPW) network sites are available in South Carolina and are located in Columbia (COLA), SC and Charleston (SCCC), SC, respectively. GPS signals from satellites to ground-based receivers are delayed by water vapor in the atmosphere (Bevis et al. 1992). A combination of water vapor radiometers and in situ observations can estimate the wet delay and in turn estimate the integrated precipitable water (Rocken et al. 1993). GPS-
Based water vapor data are available from June 2004 to June 2012 for Columbia, SC. Data from Charleston, SC are available in June for the period 2006 to 2014. Given that widespread vertical profiles of the atmosphere are not routinely available in this region, the IPW data from these locations are compared to the specific humidity measurements made in nearby ASOS stations to estimate moisture availability in the region.

The correlation between the IPW and the specific humidity \( (q) \) for the Columbia stations are shown in Figure 4.2a. The observations indicate a near-linear relationship between the integrated precipitable water and near-surface humidity with \( R^2 \) values of 0.49. The IPW values range from 1 cm to 6 cm and the values of \( q \) range from 7 g kg\(^{-1}\) to 20 g kg\(^{-1}\). The residuals confirm a meaningful linear relationship as shown in Figure 4.2b. Most of the values are clustered in the center with the largest differences in the observations occurring when there is less moisture.

Comparisons between IPW and \( q \) for Charleston, SC are shown in Figure 4.3a. Similar to the results seen for Columbia, SC, there is a near-linear relationship between the IPW and the \( q \) values with \( R^2 \) values of 0.37. The IPW values range from 1 cm to 6 cm and the values of \( q \) range from 6 g kg\(^{-1}\) to 22 g kg\(^{-1}\) indicating a similar range of values as was seen at Columbia, SC. Residual plots indicate a meaningful linear relationship as shown in Figure 4.3b. Values are clustered near zero and indicate more moisture near the coast with an average value of 1 g kg\(^{-1}\) more than in Columbia, SC. The IPW estimates have the same trend as the near-surface specific humidity observations. This improves confidence in using the available surface based observations for estimating moisture availability in the region.
Figure 4.2 (a) Integrated Precipitable Water (IPW) in cm compared with specific humidity ($q$) in g kg$^{-1}$ for during the month of June for the years from 2004 to 2012 for Columbia, SC. (b) Residual plot of predicted values (g kg$^{-1}$) compared to the difference between the observed and predicted values (g kg$^{-1}$).
Figure 4.3 Same as in Figure 4.2 except for Charleston, SC for years 2006 to 2014.

4.3 Representation of Interaction Events

Interaction between the sea-breeze front and the Sandhills front occurs on multiple days during June. Demonstration of the occurrence of multiple events is presented using base-level radar reflectivity and 4-km visible satellite imagery. The visible satellite imagery
allows a regional perspective of the convective clouds. The visible satellite imagery also indicates convective clouds that occur along the sea-breeze front and over the Sandhills region. The base-level radar reflectivity is able to spatially depict the location and the movement of the sea-breeze fronts and outflow from the convective storms. Five different interaction events are discussed in the following subsections.

### 4.3.1 Offshore Winds / 10 June 2004

Average wind speeds over the region are 2 m s\(^{-1}\) during the morning hours and indicate a light offshore flow from the west-northwest. Base-level radar reflectivity shows the development of a front parallel to the coast associated with the sea breeze at approximately 1800 UTC (1300 EST). Convective cells develop along the sea breeze front and over the south-eastern portion of the Sandhills near the South Carolina - Georgia border by 1931 UTC (1431 EST) as shown in Figure 4.4a. The black arrow indicates the location of the sea-breeze front, and the thin blue line radar reflectivity along the coast of South Carolina. At 2034 UTC the density current associated with the outflow boundary from the convective storms, “the Sandhills front”, is seen to have moved towards the coast due to topographical influence while the sea breeze continues to move inland. The locations are indicated by the black arrows as shown in Figure 4.4b. By 2146 UTC (1600 EST), there is an interaction between the Sandhills front and the sea breeze front at about 100 km inland as indicated by the black oval in Figure 4.4c. By 2231 UTC (1700 EST) additional strong
convection, on the order of 50 – 55 dBZ, develops along South Carolina and Georgia border. This location is indicated by the black oval in Figure 4.4d.

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Figure 4.4. Base-level radar reflectivity (dBZ) from the KCLX radar in Charleston, SC on 10 June 2004. The Sandhills is indicated by the black-outlined polygon. (a) The sea-breeze front is indicated by the black arrow and the thin blue line of reflectivity at 1931 UTC. (b) Development of convection south of the Sandhills, the edge of the outflow front and the sea-breeze front are indicated by black arrows at 2034 UTC. (c) Merging of the two fronts is indicated by the black oval at 2146 UTC. (d) Additional convection along the South Carolina and Georgia border at 2331 UTC as indicated by the black oval.
Figure 4.5. Base-level radar reflectivity (dBZ) from the KCLX radar in Charleston, SC on 7 June 2005. The Sandhills is indicated by the black-outlined shape in central South Carolina. (a) Convection is seen along the Sandhills at 1835 UTC. (b) The Sandhills front and the sea-breeze front are indicated by black arrows at 1949 UTC. (c) At 2133 UTC, the advancing sea-breeze is located in between the coast and Sandhills (southern black arrow). The Sandhills front is indicated by the other black arrow. (d) The merging of the two mesoscale fronts is indicated by the black oval at 2317 UTC.
4.3.2 Onshore Winds / 7 June 2005

On 7 June 2005, the average wind speed over the region is 2 m s\(^{-1}\) and the direction is onshore in the morning. Convection along the Sandhills begins to develop at approximately 1600 UTC (1100 EST). It quickly becomes widely scattered along the Sandhills boundary as is evident at 1835 UTC and is shown in Figure 4.5a. The sea breeze is close to the coast at this time and begins to propagate inland over the next few hours. By 1949 UTC the location of the sea-breeze front approximately 100 km inland, as indicated by the thin line of reflectivity, is marked by the black arrow in Figure 4.5b. Also at this time, the Sandhills front emerges from the convection in central South Carolina as a density current, its location also indicated by a black arrow, and begins to propagate towards the coast. At 2133 UTC, the two mesoscale frontal features are clearly evident in the radar reflectivity as shown by the black arrows in Figure 4.5c. In Figure 4.5d, these two frontal features can be seen merging at approximately 2317 UTC. Additional convection develops in the area of interaction with a maximum reflectivity value of approximately 50 dBZ. This line of convection continues to strengthen and persists until approximately 0200 UTC on 8 June 2005 (not shown).

4.3.3 Southwesterly Winds / 12 June 2009

Background wind flow is from the southwest with an average wind speed of 3 m s\(^{-1}\) over the region on 12 June 2009. Isolated convection develops over central South Carolina
at approximately 1800 UTC (1300 EST) (not shown). Scattered convection originates near the Sandhills or intensifies as shown in the radar imagery at 2122 UTC (1622 EST); the

Figure 4.6. Base-level radar reflectivity (dBZ) from the KCLX radar in Charleston, SC on 12 June 2009. The Sandhills is indicated by the black-outlined polygon. (a) The sea-breeze front is indicated by the thin blue line of reflectivity at 2122 UTC near the coast. (b) Development of convection along the eastern boundary of the Sandhills, the sandhills front and the sea-breeze front are indicated by black arrows at 2252 UTC. (c) Close proximity of the Sandhills front and the sea-breeze front are indicated by the black oval at 2339 UTC. (d) Additional convection has developed along the South Carolina coast over the region of the interaction at 0031 UTC on 13 June 2009 as the two fronts have merged.
convection seen in the coastal plain at this time originates over the Sandhills as shown in Figure 4.6a. The sea breeze front is also visible in the radar reflectivity near the coast at this time. At 2252 UTC, there is a possible interaction and strengthening of the convection along the coast in northern South Carolina where there is poor radar coverage and the fronts are not discernable. A Sandhills front can be seen developing in western South Carolina on the south side of the Sandhills at this time. The sea-breeze front location is indicated by the black arrow. At 2339 UTC, the radar reflectivity indicates the two approaching frontal features, circled in black, as shown in Figure 4.6c. These two mesoscale fronts extend across much of South Carolina. In Figure 4.6d, there is an indication that the north-eastern part of these frontal features merge at 0031 UTC on 13 June 2009 near the coast in central South Carolina, resulting in enhanced convection with maximum reflectivity values of approximately 60 to 65 dBZ. The interaction continues to develop along these fronts to the south as the convection from the Sandhills propagates towards the coast (not shown).

4.3.4 Southwesterly Winds / 26 June 2009

At 1200 UTC, the base-level radar reflectivity indicates precipitation along the coast in the lower part of South Carolina with a maximum value of about 35 dBZ (not shown). The convection propagates offshore over the course of the morning and is offshore by 1700 UTC. There are small cells of convective activity (< 35 dBZ) that develop near the Charleston, South Carolina radar during this time period. The average wind speed on this
day is $3 \text{ m s}^{-1}$ and from the southwest. At approximately 1800 UTC, a line of convection develops along the Sandhills that extends from North Carolina into Georgia. Convection

Figure 4.7. Base-level radar reflectivity (dBZ) from the KCLX radar in Charleston, SC on 26 June 2009. The Sandhills is indicated by the black-outlined polygon. (a) The sea-breeze front is indicated by the thin blue line of reflectivity and the black arrow at 1927 UTC. (b) Development of convection on the southern side of the Sandhills in Georgia, the edge of the outflow front and the sea-breeze front are indicated by black arrows at 2016 UTC. (c) At 2105 UTC, additional convection along the South Carolina and Georgia border. Convection in northeastern South Carolina is indicated by the black arrow. (d) Additional convection along the coast in South Carolina from the possible interaction between the Sandhills front and the sea-breeze front is indicated by the black oval.
that develops along the South Carolina and Georgia border over the Sandhills propagates toward the coast and is within about 100 km of the coast at 1927 UTC as shown in Figure 4.7a. The sea-breeze front in the Charleston area is evident in the radar reflectivity at approximately 30 km from the coast at this time and is indicated by the black arrow. The outflow from the Sandhills storms precedes the convective storms towards the coast; its location is also indicated by a black arrow. At 2016 UTC, the Sandhills front is approaching the sea-breeze front in southern South Carolina as shown in Figure 4.7b. The Sandhills front is obviously along the entire line of convection, but is not visible because of poor low-level coverage. The two fronts visibly merge at approximately 2030 UTC and the resultant enhanced convection (~ 60dBZ) is seen at about 2105 UTC as shown in Figure 4.7c. An approaching line of convective storms in north-eastern South Carolina is indicated by the black arrow. In Figure 4.7d. A similar interaction is likely in northern SC where the convection intensifies with reflectivity values of 65 dBZ along the coast as indicated by the black oval, but the radar is not able to depict the fronts. In southern South Carolina, the line of storms along the coast reduces in intensity to about 35 to 40 dBZ by 2150 UTC.

4.3.5 Offshore Winds / 28 June 2010

On 28 June 2010, the flow is from the west-southwest with an average speed of approximately 3 m s\(^{-1}\). The visible satellite imagery indicates the development of convective storms at 2045 UTC along the Sandhills in South Carolina (SC); its location is indicated by the black oval in Figure 4.8a. The line of cumulus clouds near the coast mark the edge of the
sea-breeze front as indicated by the black arrows over South Carolina. By 2115 UTC, the propagation of the sea-breeze inland is noticeable and is marked by the black arrows as shown in Figure 4.8b. Additionally, the line of convective storms that formed over the Sandhills has moved closer toward the coast as indicated by the black oval. In Figure 4.8c, there is indication that the sea-breeze front and the Sandhills front caused by the convection over the Sandhills are in close proximity at 2145 UTC. This area is marked by the black oval. Additional strong convection can be seen to develop where the Sandhills convection and sea-breeze front have merged at 2215 UTC in Figure 4.8d.

The base-level radar reflectivity on 28 June 2010 includes a composite of five radars in the region as shown in Figure 4.9. A line of convection develops along the Sandhills at 1925 UTC as shown in Figure 4.9a. The sea-breeze front is also noticeable at this time and is close to the coast as indicated by the thin blue line of reflectivity. By 2112 UTC, the sea-breeze front has propagated inland a distance of about 25 to 50 km and its location is indicated by the black arrow as shown in Figure 4.9b. There appears to be a break in the reflectivity delineating the sea-breeze along the coast in north-eastern South Carolina. This is likely a result of poor low-level radar coverage over this area. At the leading edge of the Sandhills convection, the Sandhills front location is marked by another black arrow. These two visible frontal features are in close proximity at 2221 UTC and are encompassed by a black oval as indicated in Figure 4.9c. To the northeast, the black arrow indicates an area of possible interaction. This area has poor radar coverage, but other observations suggest
Figure 4.8. Visible satellite imagery at 4km resolution over the Carolinas on 28 June 2010. North Carolina and South Carolina are labeled as NC and SC, respectively. (a) At 2045 UTC, the sea-breeze has developed along the South Carolina (SC) coast. Convection has developed along the Sandhills as indicated by the black oval. (b) At 2115 UTC the sea breeze is evident by the thin line of clouds and is indicated by the black arrows. The convection in the Sandhills has moved toward the coast, indicated by the black oval. (c) At 2145 UTC, the close proximity of the Sandhills convection and sea-breeze front are indicated by the black oval. (d) Additional convection is seen over the location where the two fronts have merged near the coast of SC, indicated by the black oval at 2215 UTC.
Figure 4.9. Composite base-level radar reflectivity (dBZ) from the five radars in region on 28 June 2010. The Sandhills is indicated by the black-outlined polygon. (a) At 1925 UTC, convection is seen along the Sandhills. The thin blue line of reflectivity indicates the sea-breeze front close to the coast. (b) At 2112 UTC, the sea breeze is evident by the thin blue line of reflectivity. The Sandhills front and the sea-breeze front are indicated by the black arrows. (c) At 2221 UTC, the close proximity of the Sandhills front and sea-breeze front are indicated by the black oval. (d) Additional strong convection is seen along the location where the two fronts have merged near the coast of South Carolina at 2318 UTC.
there are frontal features in this location as well. Additional convection develops in this area where the two fronts merge at 2318 UTC as shown in Figure 4.9d. The interaction of the two fronts near the coast has produced enhanced convection with a maximum reflectivity of about 60 to 65 dBZ. The portions of the Sandhills front and sea-breeze front along the South Carolina and Georgia border merge later, with enhanced convection developing by 2350 UTC (not shown). These interactions produce reflectivity values above 50dBZ. Most of the convection has diminished in strength by 0200 UTC and has propagated to the north and east.

4.4 Dependence of the Interaction on the Background Flow

These preceding cases illustrate the effect of different wind speeds and wind directions on the interaction of the sea-breeze front and the Sandhills front. Different wind regimes influence the convergence and propagation of the fronts differently. Additionally, the availability and the transport of moisture are affected by the wind speed and wind direction. These factors directly relate to the strength of convection in the region and the resultant precipitation.

Precipitation amounts and distributions are evaluated over three regions in the Coastal Carolinas. These regions are classified as the Sandhills zone, the Intermediate zone, and the Coastal zone and were shown in Figure 4.1. The Sandhills zone is identified by the yellow oval and encompasses the Sandhills in North and South Carolina. The coastal zone is contained within the purple oval. The study area for the Intermediate zone is defined by
an area that extends from the Sandhills to the coast in the Carolinas and is indicated by the
green oval. Stations used to obtain average values of wind speed, direction and specific
humidity, for each area are indicated by the black dots contained within each zone.
Precipitation and wind patterns are evaluated over the three regions for days where there is
a possible interaction between the two mesoscale fronts, the sea-breeze front and Sandhills
front.

4.4.1 Selection Criteria for the Interaction Days

Days where an interaction could occur in the month of June for the period from
2004 to 2015 are selected using the following criteria. Days influenced by synoptic-scale
systems are eliminated from the analysis. These days are determined by using the National
Oceanic and Atmospheric Administration (NOAA) Weather Prediction Center’s (WPS)
surface analyses. Additionally, the development of convection must develop regionally
from mesoscale forcing. The specific criteria for elimination of these days influenced by
synoptic systems are:

1. Synoptic scale features are not present within 200 km of the coastal region of
   the Carolinas.

2. The precipitation must be regional and not part of a large scale system.

3. There is no advection of large scale frontal features into the study area.

Days meeting these criteria are deemed “mesoscale days” and retained for further analysis
as shown in Table 4.2. Each mesoscale day is indicated by a binary indicator of zero or one.
Table 4.2. Number of occurrences of Mesoscale Days during the month of June (2004 - 2015). Values of one represent days counted as mesoscale days and values of zero represent days not counted as mesoscale days. Days considered as interaction days are a subset of mesoscale days and are highlighted in yellow.

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</tbody>
</table>
A value of one indicates that the day meets the above criteria, and a value of zero indicates a day that did not meet the criteria.

Precipitation patterns for the remaining mesoscale days, not influenced by synoptic systems, are examined. Gridded Stage-IV precipitation estimates are used to evaluate the precipitation patterns for selecting possible days for the interaction of the sea-breeze front and the Sandhills front. Since the interaction between these two frontal features is diurnally driven, hourly estimates are used to identify the location and timing of the precipitation. Using these estimates, additional criteria are set to identify the days where there is a possible interaction. These days are based on precipitation patterns that may result from the convergence of these two fronts.

On days when precipitation is observed in the study area, additional classification of events is necessary to isolate events where the interaction between the sea-breeze front and the Sandhills front are likely to have occurred. If the following conditions are met, these days are catalogued as possible interaction days for which convergence between the two frontal features and the convection are expected to occur:

1. Precipitation is observed over the Sandhills zone.
2. Precipitation is observed over the Intermediate zone.
3. Precipitation occurs in the Sandhills area prior to the Intermediate zone.

The timing of the precipitation is important since the Sandhills front develops as a density current from the deep convection over the Sandhills. Precipitation over the Sandhills is used as an indicator for the deep convection.
The days meeting these three criteria are defined as having strong potential for interaction. Days not meeting these criteria are not considered for further analysis.

Possible interaction days based on the precipitation patterns for the month of June for the period, 2004 through 2015 are highlighted in yellow in Table 4.2. These days are the ones with possible interaction between the sea-breeze front and the Sandhills front in central South Carolina. The highlighted days in the table are selected for additional analysis investigating the interaction between the sea breeze front and the Sandhills front.

Estimations of precipitation totals for each zone is obtained using the 6-hour accumulations from the Stage-IV dataset. The 6-hour precipitation estimates are used instead of the hourly estimates since there is human quality control incorporated into this data to improve the accuracy (Lin and Mitchell 2005).

### 4.4.2 Wind speed and Direction Criteria

These interaction days are cataloged based on wind speed and direction. To obtain the background wind flow patterns, winds from ASOS stations at 1300 UTC and 1400 UTC are averaged together over the area indicated by the red oval in Figure 4.1. These average winds are used to determine the background wind flow. Wind flows are organized into three categories: onshore, offshore, and southwesterly. Orientation of the South Carolina coastline is 45 to 225 degrees. The classification of southwesterly winds is included since the predominant direction in the region during June is southwesterly as shown by the wind rose in Figure 4.10. The frequency of occurrence of winds ranging from the southerly to the
westerly direction occurs approximately 50% of days during June. The southwesterly direction also tends to have stronger winds than other directions with more wind speeds in the moderate range of 3 to 6 m s$^{-1}$.

**Calendar days of: Jun. 1 to Jun. 30**  
**For years: 2004 to 2015 (daytime)**

Figure 4.10 Wind rose indicating the frequency of the wind direction and wind speed for the month of June during daytime hours (1200 UTC to 0000 UTC).

The direction classifications are indicated in Table 4.1. Southwesterly winds are classified as having the directions ranging from 205 degrees to 245 degrees. The winds in
this sector bring in warm moist air from Gulf of Mexico. Winds classified as offshore range from 245 degrees to 45 degrees. These winds bring in dryer continental air into the region. Onshore winds are grouped by the sector with wind directions ranging from 45 degrees to 205 degrees. These winds bring in cool moist marine air from the Atlantic Ocean.

Classification of winds into onshore and offshore categories are useful for understanding the role of moisture and the characterization of the sea breeze as has been done over Florida by Atkins and Wakimoto (1997) and by Gilliam et al. (2004) in North Carolina.

Winds in the region are classified by the wind speed in addition to the direction. The 10-m wind speeds observed at ASOS stations, shown in Figure 4.1, are averaged during the mid-morning hours (1300 UTC and 1400 UTC) before the Sandhills convection and the sea breeze circulation typically occurs. The average wind speeds are classified as either light or moderate. Light winds used in this analysis are assumed to have an average speed of less than 3 m s\(^{-1}\) and moderate winds with a range of speeds from 3 m s\(^{-1}\) to 6 m s\(^{-1}\), similar to classifications used by Simpson et al. (1977). This analysis did not indicate any days where the average wind speeds exceeded the moderate winds category.

### 4.5 Classifications of Winds and Precipitation Amounts

To study the interactions between the sea-breeze front and the Sandhills front, the days in the month of June are evaluated from 2004 to 2015, a total of 360 days. Surface analyses, obtained from the Weather Prediction Center (WPS), are used to eliminate days that may have been influenced by synoptic-scale systems. On average, during the month of
June, approximately one third of the days are influenced by synoptic systems and are eliminated from consideration as possible interaction days. The remaining 236 days for this period of twelve years, days influenced by mesoscale process, are retained for further analysis. Out of the remaining 236 mesoscale days, there are 85 days that meet all aforementioned criteria to be considered as a possible interaction day between the Sandhills circulation and the sea-breeze front. These 85 days correspond to approximately 36% of all mesoscale days. They also relate to an average of approximately seven days during June per year that have a tendency for an interaction between the two fronts.

Interaction days are organized into the three different regimes based on the average wind direction. The percentage and number of occurrence for each wind flow regime is shown in Table 4.1. Out of 85 interaction days, 38% of the days have southwesterly flow. Offshore flow is observed on 47% of the days, and 15% of days consist of onshore flow. Wind speed is an important parameter to be considered, light winds are \(<3 \, \text{m s}^{-1}\) and moderate winds are \(\geq3 \, \text{m s}^{-1}\) and \(<6 \, \text{m s}^{-1}\). For interaction days, the number of light flow days and moderate flow days are almost the same. There are 44 days classified as light wind days and 41 days as moderate wind days. While the number of days with light flow and moderate flow are comparable, there are more days with offshore flow than southwesterly and onshore flows.

Precipitation totals for each region for each wind direction category is indicated in Table 4.3. These precipitation totals indicate the normalized total maximum precipitation and the total average precipitation for each region. The normalized total maximum
precipitation amounts give an indication about the intensity of the precipitation that occurs in each zone in the region. The differences in the wind speed and wind direction frequencies and how they relate to the precipitation totals, both maximums and averages, are discussed in the next subsections.

Table 4.3. Sum of precipitation totals in mm for each region and wind direction for years 2004 to 2015.

<table>
<thead>
<tr>
<th>Average Precipitation</th>
<th>Southwesterly</th>
<th>Onshore</th>
<th>Offshore</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal Zone</td>
<td>186</td>
<td>64</td>
<td>186</td>
<td>436</td>
</tr>
<tr>
<td>Intermediate Zone</td>
<td>273</td>
<td>103</td>
<td>269</td>
<td>645</td>
</tr>
<tr>
<td>Sandhills Zone</td>
<td>259</td>
<td>98</td>
<td>221</td>
<td>578</td>
</tr>
<tr>
<td>Total Avg Precipitation</td>
<td>718</td>
<td>265</td>
<td>676</td>
<td>1659</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normalized Maximum Precipitation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal Zone</td>
<td>50</td>
</tr>
<tr>
<td>Intermediate Zone</td>
<td>57</td>
</tr>
<tr>
<td>Sandhills</td>
<td>60</td>
</tr>
<tr>
<td>Number of occurrences</td>
<td>32</td>
</tr>
<tr>
<td>Percent wind direction</td>
<td>38</td>
</tr>
</tbody>
</table>

4.5.1 Southwesterly Flow

Days with near-surface southwesterly flow occur approximately on 38% of the interaction days. This wind direction produces the highest totals of average precipitation (718 mm) in all three zones as shown in Table 4.3. The Intermediate zone has the highest total average precipitation of 273 mm. The Sandhills zone has a total average amount of 259 mm and the coastal zone has the least amount of total average precipitation (186 mm).
Thus more precipitation occurs inland during southwesterly flow than along the coast. The coastal region receives approximately 27% less precipitation when compared to the Sandhills.

For the normalized total maximum precipitation, the Sandhills region has the highest amounts of 60 mm. This indicates that high rates of precipitation for any given interaction day are likely to occur along the Sandhills. Specifically, when precipitation occurs in the Sandhills, it is likely to result from intense convection. The Intermediate zone has a normalized total maximum precipitation value of 57 mm. The Coastal zone has the least normalized total maximum precipitation amounts of 50 mm.

Although the southwesterly sector has a wind direction range of only 40 degrees, from 205 to 245 degrees, this background wind direction produces substantial precipitation in this region. This high precipitation amount is obviously due to moisture advection from the warm Gulf of Mexico. The average 10-m specific humidity for each zone in the coastal Carolinas region during the morning hour of 1400 UTC (1000 EST) is shown in Table 4.4. For southwesterly flow (SW), the average specific humidity is 16.2 g kg\(^{-1}\), 16.0 g kg\(^{-1}\), and 15.9 g kg\(^{-1}\) for the Coastal zone, Intermediate zone, and Sandhills zone, respectively. The highest specific humidity values occur when the wind speeds are light, < 3 m s\(^{-1}\). Light winds account for an increase in specific humidity ranging from 0.5 g kg\(^{-1}\) to 1.0 g kg\(^{-1}\) over those for the moderate winds. These differences could be the result of increased vertical mixing of moisture at higher wind speeds. The Coastal zone has the highest values of specific humidity, which decreases with increasing distance from the coast.
The precipitation amounts for different wind speed categories (light and moderate winds) are shown in Table 4.5. Total average precipitation amounts (502 mm) are associated with moderate wind speeds. A total average precipitation of 216 mm is observed for light winds. For moderate wind speeds, the total average precipitation for the Sandhills and Intermediate zone are similar with amounts of 189 mm and 183 mm respectively. The Coastal zone has the least total average precipitation amounts regardless of wind speed.

Table 4.4. Average Specific Humidity (g kg\(^{-1}\)) for each zone in the coastal Carolinas for interaction days, all mesoscale days, and other mesoscale days (not including interaction days) for years 2004 to 2012. The average specific humidity is listed for each wind direction category and wind speed. (Southwesterly flow is represented by SW).

<table>
<thead>
<tr>
<th></th>
<th>Coastal Zone</th>
<th>Intermediate Zone</th>
<th>Sandhills Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interaction Days</td>
<td>16.1</td>
<td>15.8</td>
<td>15.6</td>
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<tr>
<td>All Mesoscale Days</td>
<td>15.4</td>
<td>15.0</td>
<td>14.8</td>
</tr>
<tr>
<td>Other Mesoscale days</td>
<td>15.0</td>
<td>14.5</td>
<td>14.2</td>
</tr>
<tr>
<td>SW</td>
<td>16.2</td>
<td>16.0</td>
<td>15.9</td>
</tr>
<tr>
<td>SW &lt; 3 m s(^{-1})</td>
<td>16.9</td>
<td>16.4</td>
<td>16.3</td>
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<td>15.9</td>
<td>15.9</td>
<td>15.7</td>
</tr>
<tr>
<td>Onshore</td>
<td>15.8</td>
<td>15.3</td>
<td>15.3</td>
</tr>
<tr>
<td>Offshore</td>
<td>16.3</td>
<td>15.8</td>
<td>15.5</td>
</tr>
<tr>
<td>Offshore &lt; 3 m s(^{-1})</td>
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<td>Offshore &gt;3 m s(^{-1})</td>
<td>16.2</td>
<td>15.6</td>
<td>15.7</td>
</tr>
</tbody>
</table>

An examination of the normalized total maximum precipitation values in Table 4.5 indicates that lower values of precipitation occur during moderate wind speeds as compared to amounts during light winds. These differences may be related to lighter winds.
allowing the local mesoscale processes to enhance the development of convection and precipitation.

Table 4.5. Precipitation totals in mm for each wind direction and wind speeds categories for years 2004 to 2015. (Southwesterly flow is represented by SW)

<table>
<thead>
<tr>
<th>Average Precipitation</th>
<th>SW &lt; 3 m s⁻¹</th>
<th>SW &gt;3 m s⁻¹</th>
<th>Onshore &lt; 3 m s⁻¹</th>
<th>Offshore &lt; 3 m s⁻¹</th>
<th>Offshore &gt; 3 m s⁻¹</th>
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</thead>
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<tr>
<td>Coastal Zone</td>
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<td>130</td>
<td>64</td>
<td>119</td>
<td>66</td>
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<tr>
<td>Intermediate Zone</td>
<td>91</td>
<td>183</td>
<td>103</td>
<td>168</td>
<td>102</td>
</tr>
<tr>
<td>Sandhills Zone</td>
<td>69</td>
<td>189</td>
<td>98</td>
<td>130</td>
<td>91</td>
</tr>
<tr>
<td>Total Avg Precipitation</td>
<td>216</td>
<td>502</td>
<td>265</td>
<td>417</td>
<td>259</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normalized Maximum Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal Zone</td>
</tr>
<tr>
<td>Intermediate zone</td>
</tr>
<tr>
<td>Sandhills</td>
</tr>
<tr>
<td>Number of occurrences</td>
</tr>
<tr>
<td>Percent wind direction</td>
</tr>
</tbody>
</table>

4.5.2 Offshore Flow

Offshore flow is defined as the sector that has wind directions that range from 245 degrees to 45 degrees as defined in Table 4.1. Offshore flow occurs on approximately 47% of all interaction days as shown in Table 4.1. The total average precipitation (676 mm) for the month of June from 2004 – 2015 for all zones is shown in Table 4.3. The ratio of the amounts of total average precipitation between zones are similar to the ratios for the
southwesterly flow. The highest average precipitation occurs in the Intermediate zone (269 mm), followed by the Sandhills zone (221 mm) and then the Coastal zone (186 mm). The Sandhills has decreased total average precipitation when compared to the amounts from the southwesterly flow. Offshore flow tends to oppose the incoming sea breeze and may shift the maximum total average precipitation towards the coast. Additionally, there is less moisture available during offshore flow events, hence possibly less precipitation as compared to southwesterly flow. This decrease in moisture can be seen in the average specific humidity as shown in Table 4.4. The average specific humidity is greatest in the Coastal zone and decreases farther inland away from the coast. In the Sandhills zone, the average specific humidity is 15.5 g kg\(^{-1}\) for offshore flow. This value is a decrease of 0.4 g kg\(^{-1}\) when compared to the southwesterly flow. For light wind speeds, in the Coastal zone and Intermediate zone, the average specific humidity is higher than that for moderate winds speeds. The Sandhills zone has a lower average specific humidity for the light wind speed category as compared to the moderate winds.

The offshore background flow yields normalized total maximum precipitation amounts of 51 mm, 46 mm, and 46 mm in Sandhills zone, Intermediate zone, and Coastal zone, respectively as shown in Table 4.3. These amounts may be attributed to the opposing background flow of the inland penetrating sea breeze helping to increase the convergence along the front (Atkins and Wakimoto 1997). Normalized maximum precipitation totals for the coastal zone are comparable to the totals in this zone associated with southwesterly flow. The opposing flow increases the chances for a robust sea breeze and stronger
convection along the sea breeze front and relatively higher maximum values of precipitation. This indicates that while there may be less moisture and precipitation, strong convection that produces high amounts of precipitation still occur during offshore flow.

The number of occurrences of light wind speeds (< 3 m s\(^{-1}\)) and moderate wind speeds (> 3 m s\(^{-1}\)) are similar, 22 and 18, respectively, as shown in Table 4.1. Contrary to the southwesterly flow, light wind speeds are associated with the larger sums of both total average and total maximum precipitation for all zones as shown in Table 4.3. The Coastal zone has more total maximum precipitation for light wind speeds than for moderate wind speeds. The Coastal zone also has more total average precipitation when the winds are light. Even though opposing flow can strengthen the sea breeze, winds that are too strong can inhibit the sea breeze from propagating further inland (Gilliam et al. 2004). Similarly, the Intermediate zone has more total average precipitation during light winds than during moderate winds. During light winds, the sea breeze advances further inland and the interactions take place closer to the Sandhills where the Sandhills front is robust. Differences in totals of maximum and average precipitation amounts for light and moderate wind speeds are not as large in the Sandhills zone. The Sandhills zone has more total average precipitation during light winds (130 mm) than moderate winds (91 mm).

### 4.5.3 Onshore Flow

Onshore flow contains the wind directions in the sector that range from 45 degrees to 205 degrees as defined in Table 4.1. Onshore flow occurred on 15% of the number of the
interaction days, the least number of times as compared to the other wind direction
categories as indicated in Table 4.1. All of these days occurred during light wind flow (< 3 m
s\(^{-1}\)). This reduction in interaction days for onshore flow can be related to the inhibited
development and reduced strength of the sea breeze circulation due to a decrease in low-
level convergence. (Atkins and Wakimoto 1997; Gilliam et al. 2004).

The total average precipitation for onshore flow is 265 mm as shown in Table 4.3.
Similar to the other wind directions, the largest total average precipitation for onshore flow
occurs in the Intermediate zone (103 mm). The highest normalized total of maximum
precipitation occurs in the Sandhills zone (64 mm). For the Intermediate zone and the
Coastal zone, the values of normalized total maximum precipitation amounts are 54 mm
and 41 mm, respectively.

Examination of the average specific humidity for onshore flow indicates the Coastal
zone, Intermediate zone, and Sandhills zone have values of 15.8 g kg\(^{-1}\), 15.3 g kg\(^{-1}\), and 15.3
g kg\(^{-1}\), respectively as shown in Table 4.4. The onshore wind direction category has the
lowest values of specific humidity, as compared to the other wind direction categories. One
possible influence of reduced moisture may be due to the low percentage (< 5%) of
perpendicular onshore flow as indicated by the wind rose in Figure 4.10. Onshore flow
directions are assumed to range from 45 to 205 degrees for this research.

All of total average precipitation given in Table 4.5 occurred during the light wind
speeds for onshore flow. During moderate winds, the sea-breeze front did not form.
Without a sea-breeze front, no interaction could occur. Stronger onshore winds have little
to no opposing background winds reducing the possibility for the formation of a sea breeze circulation.

4.6 Precipitation Distributions

Precipitation amounts relative to the frequency of occurrences of interaction events are not represented in the preceding summary tables for total maximum and total average precipitation amounts. While yielding important information, these values do not reveal the magnitudes and variations of individual events. For example, onshore flow regimes for interaction days occur less frequently than southwesterly flow. When accounting for frequency of occurrence, a smaller sample size of a few extreme events can skew the magnitudes of precipitation, providing misleading results. Therefore, the distribution of precipitation for each type of wind flow (southwesterly, offshore, and onshore) are analyzed and compared.

The maximum precipitation in each zone represents the intensity of the precipitation and thus is related to the intensity of convection. Evaluation of the total maximum precipitation gives insight to where the most intense convection is occurring over the region. These results also allow the comparison of precipitation amounts during different background winds in the region.

For southwesterly flow, the Sandhills zone receives higher maximum precipitation on half of the possible interaction days as shown in Figure 4.11a. The Sandhills zone has the most number of days with the highest maximum precipitation (16 days). The Intermediate
zone has nine days with the highest precipitation totals. The coastal region has the least number of maximum precipitation values (7 days). The Sandhills zone contains the day that has the highest maximum precipitation value and consistently exceeds the other zones in the magnitudes of maximum precipitation as shown in Figure 4.11b. The Intermediate zone has four days where the maximum precipitation exceeds 100 mm and has maximum precipitation amounts that consistently ranks in the middle of the distributions. The Coastal
Figure 4.11b Same as in Figure 4.11a except ordered by greatest amount to least amount.
zone has three days where the maximum precipitation exceeds 100 mm and typically ranks third in amounts.

![Average precipitation in mm for the interaction days with southwesterly flow.](image)

Figure 4.11c Average precipitation in mm for the interaction days with southwesterly flow.

Average precipitation is used to determine the amount of precipitation that occurred in each zone. The total average precipitation gives a good indication of which zone tends to receive the most precipitation. Average precipitation for southwesterly flow for each zone is shown in Figure 4.11c. There are 14 days when the Sandhills zone has the highest average precipitation. The Intermediate zone has the highest average precipitation on 11 days, and there are 7 days in the Coastal zone that has the highest average.
Figure 4.11d Same as in Figure 4.11c except ordered by greatest amount to least amount.
precipitation. The largest value of average precipitation occurs in the Intermediate zone. Rank-ordered average precipitation totals are shown in Figure 4.11d. The distribution of average precipitation for the Intermediate zone and Sandhills zone are similar. The Coastal zone has the least average precipitation totals.

A comparison of the distribution of maximum precipitation amounts to average precipitation amounts reveal some distinct trends. The Coastal zone has the least amount of events with intense precipitation and overall has least average precipitation amounts. The Sandhills has the highest maximums, indicating that the most intense convection occurs in this zone for southwesterly flow. The Intermediate zone has the highest average amounts of precipitation, with contributions from the interactions between the sea-breeze front and the Sandhills front.

Interaction days associated with offshore flow occurs most often, 40 times, as shown in Figure 4.12a. There are 14 days where the Sandhills receives the maximum precipitation, 13 days where it occurs in the Intermediate zone, and 13 days for the Coastal zone. All three zones receive similar number of occurrences of the highest maximum precipitation amounts. The Intermediate zone and the Sandhills zone have the highest maximum precipitation amounts of 170 mm and 140 mm, respectively. The distribution of maximum precipitation, sorted from the most to the least, is shown in Figure 4.12b. The Sandhills zone and Coastal zone have similar precipitation trends in maximum precipitation above 50 mm at which point the Coastal zone has the least number of days with the
maximum amounts. The Intermediate zone has the least number of maximum precipitation events on the higher end of the spectrum of the precipitation distribution.

Figure 4.12a Maximum precipitation in mm for the interaction days with offshore flow.
Figure 4.12b Same as in Figure 4.12a except ordered by greatest amount to least amount.
Average precipitation amounts in mm for each zone for offshore flow is shown in Figure 4.12c. The Intermediate zone has the most occurrences of the highest average precipitation amounts, 23 days. The Sandhills zone has about half the number of days as the Intermediate zone, where only 11 days have the highest average precipitation. The coastal region has the least number of days (6) with the higher average precipitation amounts. The Intermediate zone has the single highest day total of average precipitation of
Figure 4.12d Same as in Figure 4.12c except ordered by greatest amount to least amount.
approximately 36 mm. Precipitation distributions ordered from greatest to least are shown in Figure 4.12d. The Intermediate zone typically has the highest values of average precipitation. The Sandhills zone average precipitation is less than the interaction region and coastal region at higher amounts, but distributions are similar to the Intermediate zone for amounts less than 5 mm.

When comparing the precipitation amounts and distributions of offshore flow to southwesterly flow there are apparent differences. There are higher maximum precipitation amounts in the Coastal zone for offshore flow than for southwesterly flow. Opposing offshore flow helps create the strongest sea-breeze fronts due to stronger convergence and hence stronger convection and higher maximum precipitation amounts. Maximum precipitation amounts are less in the Sandhills and Intermediate zone during offshore flow than for southwesterly flow. This difference is likely related to the transport of moisture from the Gulf of Mexico for southwesterly flow. A similar trend is seen in the average precipitation amounts in the Sandhills, where offshore flow is associated with less average precipitation in the Sandhills. The trend in the average precipitation in the Intermediate zone is similar for both offshore and southwesterly flow.

Onshore flow with light wind speeds has the least number of interaction days, approximately one third of the interaction days for offshore flow as shown in Figure 4.13a. There are two days when the maximum precipitation occurred in the Coastal zone. The number of days of maximum precipitation for the Sandhills zone and the Intermediate zone are eight days and three days, respectively. The highest maximum precipitation amount
occurs in the Sandhills zone. The sorted precipitation distributions are indicated in Figure 4.13b. A comparison of the three areas indicates that the Sandhills zone consistently has more maximum precipitation occurring there. The Coastal zone has the least values of maximum precipitation amounts.

![Figure 4.13a Maximum precipitation in mm for the interaction days with onshore flow.](image)
Figure 4.13b Same as in Figure 4.13a except ordered by greatest amount to least amount.
Average precipitation amounts in mm for onshore flow for each zone is indicated in Figure 4.13c. There are seven days when the average precipitation values are the largest in the Intermediate zone. The Sandhills zone contains five days when the average precipitation is the greatest. There is only one day when the Coastal zone has the greatest average precipitation. Rank ordered precipitation distributions are shown in Figure 4.13d. These distributions indicate that the Sandhills zone has the highest average precipitation.

Figure 4.13c Average precipitation in mm for the interaction days with onshore flow.
Figure 4.13d Same as in Figure 4.13c except ordered by greatest amount to least amount.
The Coastal zone has the least amount of average precipitation. A comparison of the maximum precipitation amounts to the average precipitation amounts indicate that the trends are similar. Both the Sandhills zone and the Intermediate zone have similar trends for both maximum and average precipitation. The Coastal zone has the least maximum and average precipitation amounts.

Comparison of the amounts of precipitation for each interaction day for each wind flow category is consistent with the total maximum and total average precipitation variations shown in Tables 4.2 and 4.5. The precipitation trends for the three different wind flow regimes indicate that there are consistently more days with maximum precipitation amounts in the Sandhills zone and Interaction zone for southwesterly flow. Offshore flow produces more events with maximum precipitation in the Coastal zone as compared to other wind direction categories. The slope of the rank-ordered precipitation amounts for onshore flow indicate that this wind regime produces the least amount of maximum and average precipitation.

4.7 Summary

Remote sensing observations are critical in identifying the interaction between the sea-breeze front and the Sandhills front. The visible satellite imagery and the base-level radar reflectivity are used to detect the frontal features and subsequent convective activity. Additionally, gridded precipitation estimates are used to quantify the maximum and average precipitation that occurs in the region. The three distinct regions selected for the
evaluation of precipitation amounts are the Sandhills zone, the Intermediate zone in central South Carolina, and the Coastal zone. Background wind speeds and directions influence the location of the interaction as well as the amounts of resultant precipitation.

Offshore flow occurs the most, 47% of the time, however, southwesterly flow has highest total average precipitation amounts given a lower percentage (38%) of occurrence. Generally, southwesterly flow also has the highest total maximum precipitation amounts per event. Moderate wind speeds exceeding 3 m s\(^{-1}\) account for the highest totals of average precipitation for southwesterly flow. In contrast, light wind speeds (< 3 m s\(^{-1}\)) produce the highest totals of average precipitation for offshore flow. Additionally, there are no occurrences of interactions for moderate onshore flow due to the lack of discernible sea breeze.

Additionally, the analysis of the precipitation estimates indicate that the Intermediate zone has the highest total average precipitation when compared to the other zones for all directions and speeds. However, an analysis of the total maximum precipitation indicates that largest precipitation amounts tend to occur in the Sandhills zone. The higher maximum precipitation amounts directly relate to the intensity of the convection. Therefore, the Sandhills zone appears to have the strongest convection.

An analysis of the frequency of occurrence of the interactions between the Sandhills front and the sea-breeze front indicates that these events occur often. These interactions occur, on average, approximately 24% of all days in June. When accounting for and eliminating synoptically driven precipitation events from consideration, the relative
frequency of these interactions increases. Considering only the days when synoptic scale events are absent, and possibly when mesoscale processes are dominant, the interactions occur on approximately 36% of these days.

This frequency of occurrence of these events would suggest that days in which interactions between the sea-breeze and the Sandhills convection occur contribute to a significant amount of precipitation that the coastal Carolinas region receives during June. The investigation and characterization of these events have identified the important criteria for the interactions, and determined the frequency of occurrence. A spatial depiction of the precipitation totals for the interaction days illustrates the contribution of these events to the total mesoscale precipitation and is shown in Figure 4.14. The Parameter-elevation Regressions on Independent Slopes Model (PRISM) is used to evaluate the spatial distribution of precipitation during the years 2004 to 2015. PRISM precipitation estimates are generated by combining multiple point data sources and Stage IV precipitation estimates with a digital elevation model on a 4-km grid (Daly 1994). The total precipitation for all days in June from 2004 to 2015 (a total of 360 days) are shown in Figure 4.14a. The heaviest precipitation amounts (2000 mm) are along the coast in South Carolina and along the Sandhills. The total precipitation for the 236 mesoscale days is shown in Figure 4.14b. Regional amounts are approximately 1000 mm and are more evenly distributed across the region than for all 360 days. The heaviest amounts are still seen along the coast and Sandhills, with comparable totals in the Intermediate zone. Precipitation totals associated with the interaction days (85) are shown in Figure 4.14c. The Intermediate zone, indicated
Figure 4.14 Precipitation climatology (mm) for South Carolina from 2004 to 2015 for the month of June using PRISM data. (a) Total precipitation from all 360 days. (b) Total precipitation from all 236 mesoscale days. (c) Total precipitation from the interaction days (85). The black oval indicates the Intermediate zone. (d) Percent of total precipitation that occurred on interaction days as compared to the mesoscale days. The black oval indicates the Intermediate zone.
by the black oval, indicates precipitation maxima of approximately 750 mm occurring in southern and northeastern South Carolina. The maximum at the coast in between these two locations may be related to the changing coastline shape. The percent of total precipitation that occurred on interaction days as compared to the mesoscale days is shown in Figure 4.14d. The black oval indicates the Intermediate zone. Approximately 40% to 70% of the precipitation from mesoscale driven processes occurs during the interaction days. The spatial patterns and precipitation totals indicate that the interaction between the sea-breeze front and Sandhills front makes an important contribution to the precipitation totals in the region during the month of June.

4.8 Investigation of other Summer Months

The preceding evaluation indicates the regular occurrence of mesoscale precipitation from interactions between the sea-breeze front and the Sandhills front in the coastal Carolinas region during the month of June. One would expect such events to occur during other summer months. Future work will expand the analysis into other summer months to evaluate the frequency of occurrence and intensity of interactions. Since the strength of the sea-breeze is largely driven by the land ocean temperature gradient, one might expect the frequency and intensity of interactions to be reduced in later summer months as the ocean warms. However, a warmer Sandhills region could cause more deep convection causing a stronger Sandhills front. Preliminary investigation presented here
reveals similar interaction events to occur during the months of July and August. Two
interaction days in July and one day in August are presented.

4.8.1 Southwesterly Winds / 29 July 2006

On 29 July 2006, the average background winds were light (~ 2 m s⁻¹) and from the
southwesterly direction. An interaction between the Sandhills front and the sea-breeze
front is detected using the base-level radar reflectivity from the Charleston, South Carolina
radar as shown in Figure 4.15. Convection forms along the Sandhills near the South
Carolina and Georgia border at 2029 UTC (1529 EST) as shown in Figure 4.15a. The location
of the sea-breeze front is indicated by a black arrow and is depicted by a thin line of
reflectivity in southern South Carolina. At 2128 UTC (1628 EST), the radar reflectivity is able
to depict the Sandhills front, its location marked by the black arrow, as shown in Figure
4.15b. The sea-breeze has propagated inland from its previous position in Figure 4.15a and
is marked by another black arrow. The location of the approaching frontal features at 2216
UTC are indicated by black arrows in Figure 4.15c. At this time, there are many convective
cells that have developed in the Intermediate zone. Outflow from these cells may have
strengthened the interaction. By 2315 UTC (1815 EST), the two frontal features have
converged and there is a strong line of convection near the coast as indicated in Figure
4.15d. This strong convection is noted by the high reflectivity values that are approximately
55 to 60 dBZ.
Figure 4.15. Base-level radar reflectivity (dBZ) from the KCLX radar in Charleston, SC on 29 July 2006. The Sandhills is indicated by the black-outlined polygon. (a) Convection is seen on the southeastern side of the Sandhills in Georgia at 2029 UTC. (b) The edges of the Sandhills front and the sea-breeze front are indicated by black arrows at 2128 UTC. (c) At 2216 UTC, the converging fronts are indicated by the black arrows along the South Carolina and Georgia border. (d) Additional convection along the coast in South Carolina from the interaction between the Sandhills front and the sea-breeze front is indicated by the black oval at 2315 UTC.
4.8.2 Offshore Winds / 17 July 2013

On 17 July 2013, the background wind direction was offshore. The average wind speed over the region was light at 2 m s\(^{-1}\). A time history of the composite base-level radar reflectivity from five regional radars are shown in Figure 4.16. At approximately 1800 UTC (1300 EST), convection has developed in the Sandhills and along the northern coast of South Carolina as shown in Figure 4.16a. A thin line of radar reflectivity along the southern coast of South Carolina is evident indicating a sea breeze front. Nearly three hours later, the convective activity in the region has become widespread as shown in Figure 4.16b. Strong convective storms have formed along the Sandhills and the location of the Sandhills front is indicated by a black arrow in central South Carolina approximately 100 km from the coast. The location of the sea breeze is also indicated by a black arrow at approximately 50 km inland from the coast. The two frontal features are just 50 km apart over central South Carolina. There is a larger distance of 100 km between the two fronts near the South Carolina (SC) and Georgia (GA) border. By 2200 UTC, the fronts have converged and there is additional strong convection (~50 dBZ) as indicated by the black oval in Figure 4.16c. Near the border between SC and GA the fronts are still visible (locations indicated by the black arrows), and are now approximately 50 km apart. By 2300 UTC, the southern portion of the two fronts also have merged and more convection from the interaction is noted by the black oval as shown in Figure 4.16d. Maximum reflectivity values are approximately 50 to 55 dBZ.
Figure 4.16. Composite base-level radar reflectivity (dBZ) from the five radars in the region on 17 July 2013. The Sandhills is indicated by the black-outlined polygon. (a) At 1758 UTC, the thin blue line of reflectivity indicates the sea-breeze front along the South Carolina coast. Convection is just beginning over the Sandhills. (b) At 2042 UTC, the sea breeze front and the Sandhills front are indicated by the black arrows. (c) At 2157 UTC, convergence of the two front has resulted in additional convection between the coast and Sandhills. The southern portion of the Sandhills front and sea breeze front are indicated by the black arrows. (d) Additional strong convection is seen along the converging boundaries in southern South Carolina at 2258 UTC.
4.8.3 Southwesterly Winds / 11 August 2009

On 11 August 2009 the winds are light and from the southwest. The average wind speed over the region was approximately 2 m s\(^{-1}\). There is evidence of an interaction between the Sandhills convection and the sea-breeze front as shown in the time history of the base-level radar reflectivity in Figure 4.17. Convection develops along the Sandhills boundary at 1744 UTC (1244 EST) as indicated in Figure 4.17a. The sea-breeze front is not evident at this time. Approximately two hours later, at 1951 UTC (1451 EST), the Sandhills convection has propagated eastward and is approximately 100 km from the coast as shown in Figure 4.17b. At the leading edge of the convection is an outflow density current, the Sandhills front, indicated by a black arrow. The sea-breeze front is recognizable at this time by a thin line of light blue reflectivity and its location is indicated by another black arrow. At 2027 UTC (1527 EST), the Sandhills front and the sea-breeze front, are adjacent to each other as shown by the black oval in Figure 4.17c. By 2124 UTC, these two mesoscale frontal features have merged as shown in Figure 4.17d. The line of radar reflectivity along this convergence location indicates additional convection, ranging from 35 dBZ to 50 dBZ. Outflow from the convection caused by the merging of the two fronts is also apparent near the coast at this time.

In this case, the line of reflectivity indicating the sea-breeze appears to be fainter, suggesting it to be weaker than previous cases in June. Additionally, the resultant convection from the interaction appears to be less intense, where maximum reflectivity values are approximately 50 dBZ. The weaker sea-breeze front does not advance much
Figure 4.17. Base-level radar reflectivity (dBZ) from the KCLX radar in Charleston, SC on 11 August 2009. The Sandhills is indicated by the black-outlined polygon. (a) Convection is seen on the southeastern side of the Sandhills in South Carolina at 1744 UTC. (b) The edges of the Sandhills front and the sea-breeze front are indicated by black arrows at 1951 UTC. (c) At 2027 UTC, the converging fronts are indicated by the black oval. (d) Additional convection along the coast in South Carolina from the interaction between the Sandhills front and the sea-breeze front is evident at 2124 UTC.
inland, but the Sandhills convection and Sandhills front still appears to be strong. The interaction may occur closer to the coast in later summer months. Further investigation may explain whether these differences are resulting from a reduction in the strength of the sea-breeze front or just specific to this case. In general, there is ample evidence of interactions between the Sandhills front and the sea-breeze front during all summer months.
CHAPTER 5
INVESTIGATION OF THE INTERACTION FOR DIFFERENT WIND REGIMES
USING NUMERICAL SIMULATIONS

5.1 Introduction

The Sandhills convection and the sea-breeze circulation were shown to interact through the convergence of two mesoscale fronts, the Sandhills front and the sea-breeze front in the previous chapters. These events occur frequently during summer months, and the mechanisms of interaction differ depending on the background wind regimes as discussed in Chapter 4. However, evaluation of the vertical structure of these interactions and the depth of the convection cannot be deduced from the near-surface observations. Also, vertical observations are scarce over this region. Investigation of the mesoscale processes that represent each of the background wind speed and direction regimes presented in Chapter 4 are assessed using numerical simulations. The Weather Research and Forecasting (WRF) model, Version 3.7.1, is used to examine the four-dimensional aspects of these interactions.

5.2 Modifications to the MSKF Cumulus Parameterization Scheme

Evaluation of the results in Chapter 3 indicated that the WRF model performs better for the two simulated mesoscale interaction events utilizing the Updated Kain-Fritsch (UKF) convective parameterization (CP) scheme. The UKF modifications discussed in Chapter 3
have been incorporated into the available version of the WRF model (Versions 3.6 and newer). The Kain-Fritsch CP scheme with these modifications is known as the Multi-Scale Kain-Fritsch (MSKF) CP scheme (Zheng et al. 2016). The MSKF scheme also includes an adjustment to the estimation of the subcloud velocity scale. In the UKF CP scheme, the subcloud velocity scale is estimated using the kinematic updraft mass flux and the available buoyant energy at the cloud base. In the MSKF cumulus parameterization, which is currently only linked to the Yonsei University (YSU) boundary-layer scheme (Hong et al. 2006; Hong 2010) in the WRF model, the subcloud-layer velocity scale is estimated by using the convective velocity scale below the cloud base and Monin-Obukhov similarity theory in the surface layer. In the convective boundary layer, the convective subcloud velocity scale, $e^*$, can be expressed as

$$e^* = \sqrt{e^2} = \frac{1}{2} \sqrt{\sigma_u^2 + \sigma_v^2 + \sigma_w^2}, \quad (5.1)$$

where $e^2$ is the turbulent kinetic energy (TKE), and $\sigma_i^2$ is the velocity variance where the subscript $i$ represents the u, v, and w directions. In the MSKF scheme, the subcloud velocity scale is first linked to the YSU scheme by the convective velocity scale below the cloud base by the relationship

$$v_{sc} = \left[ \frac{g z_{LCL}}{\theta_v} \left( \frac{w \theta_v}{\theta_v} \right) \right]^{1/3}, \quad (5.2)$$
where \( v_{sc} \) is the subcloud convective velocity scale, \( z_{LCL} \) is the height of the cloud base, and \( (g / \bar{\theta}_v)(\bar{w} \theta_v) \) is the buoyancy flux. The subcloud convective velocity scale, during unstable conditions where \( \left( \frac{z}{L} \right) < 0 \), is then estimated using a solution to the TKE equation by the relationship

\[
e^* = \sqrt{3.8u_*^2 + 0.22v_{sc}^2 + 1.9u_*^2 \left( \frac{-z}{L} \right)^2},
\]

(5.3)

where \( u_* \) is the friction velocity, \( z \) is the height above ground, and \( L \) is the Monin-Obukhov length (Mailhot and Benoit, 1982; Alapaty and Alapaty, 2001).

However, the simulations in Chapter 3 that use the UKF CP scheme also use the Mellor-Yamada-Nakanishi-Niino (MYNN) planetary boundary layer (PBL) scheme (Nakanishi and Niino 2004), which appears to do well in simulating observed daytime winds in coastal environments (Hariprasad 2014; Srinivas 2016). Also, during warm, moist conditions the MYNN scheme has been shown to be relatively unbiased in the prediction of temperature, moisture, and PBL depth (Coniglio 2013). Therefore, additional modifications to the MSKF scheme are performed to link the MSKF CP scheme to the MYNN PBL parameterization scheme. These modifications to the MSKF scheme incorporate the turbulent kinetic energy (TKE) from the MYNN boundary-layer scheme to directly determine the subcloud-layer convective velocity scale.
Utilizing a boundary layer scheme that predicts TKE has advantages over the estimation of the subcloud velocity scale utilizing similarity theory. The current MSKF subcloud velocity scale is highly dependent on friction velocity in the surface layer. Small changes in $u_*$ can lead to large subcloud velocity scale differences. Using typical values of PBL depth and the Monin-Obukhov scaling parameter during daytime convective conditions yields subcloud velocity scale values that range from 0.2 m s$^{-1}$ to 1.0 m s$^{-1}$. These values are highly sensitive to the surface wind stress.

In the MYNN PBL scheme, TKE is explicitly predicted and can be incorporated directly into the MSKF scheme. The average subcloud layer velocity scale, $e^*$, is implemented into the MSKF cumulus parameterization by using the TKE in the relationship

$$ e^* = \frac{1}{z_{LCL}} \int_{sfc}^{z_{LCL}} QKE \, dz \quad (5.4) $$

where $z_{LCL}$ is the height of the cloud base above the surface ($sfc$), and $QKE$ is twice the TKE. In the convective boundary layer, buoyant mixing is the dominant transport term, whereas the subcloud-layer velocity scale is proportional to the cloud-base updraft mass flux in the convective timescale (Equation 3.5). Typical values of TKE in the convective boundary layer yield consistent subcloud velocity scale values of approximately 0.5 m s$^{-1}$ to 0.65 m s$^{-1}$ and are not linked to surface wind stress making it more appropriate to use.
5.3 Case Studies

Five categories of background wind speeds and directions that were found to have interactions between the Sandhills front and the sea-breeze front are simulated using the WRF model. These categories are: offshore and southwesterly flow with light ($< 3 \text{ m s}^{-1}$) and moderate winds ($\geq 3 \text{ m s}^{-1}$ and $< 6 \text{ m s}^{-1}$), and onshore flow with light winds. The background wind direction classifications for onshore, offshore, and southwesterly flows were defined in Table 4.2. Three cases, moderate southwesterly winds, moderate offshore winds, and light offshore winds are simulated with the modified MSKF linked to the MYNN scheme and presented in the following sections, addressing scientific objective four. The simulations of the light onshore winds on 24 June 2009 was presented in Chapter 2 and Chapter 3. Additionally, a simulation of the light southwesterly wind case was presented in Chapter 3 as Case 2. A summary of these two cases are included in this chapter.

5.3.1 Light Southwesterly Flow

On 27 June 2010, observations indicated an interaction to have occurred between the Sandhills front and the sea-breeze front. The average near-surface background winds indicate the light winds are from the southwest on this day. The background winds are determined by averaging the wind speeds and directions at 1300 UTC (0800EST) and 1400 UTC (0900 EST) in the area outlined in red in Figure 4.1.

On this day, convection develops over the Sandhills at about 1800 UTC (1300 EST) as shown in Figure 5.1a. In southern South Carolina, the sea-breeze front is evident by the thin
blue line in the radar reflectivity data. Its location near the coast is indicated by the black arrow. The Sandhills convection moves towards the coast and outflow from the Sandhills front is visible along the leading edge of the convection at 2000 UTC (1500 EST) as shown in Figure 5.1b. The location of the Sandhills front is indicated by the black arrow. Also at this

Figure 5.1 Composite base-level reflectivity for five radars in the Carolinas on 27 June 2010. (a) Convection is observed in and near the Sandhills at 1800 UTC (1300 EST). The sea-breeze front is indicated by a thin line of reflectivity and the black arrow. (b) At 2000 UTC (1500 EST), the sea-breeze front has moved inland and is marked by a black arrow. Convection in the Sandhills has moved toward the coast, the location is marked with another black arrow. (c) The two fronts are converging at 2020 UTC (1520 EST) as indicated by the black oval. (d) Additional strong convection has developed at 2045 UTC (1545 EST) in the location of the merged mesoscale fronts.
time, the sea-breeze has moved inland from the coast from its previous position at 1800 UTC (1300 EST) and is marked by another black arrow. The two fronts merge at about 2020 UTC (1520 EST) approximately 50 km from the coast as shown in Figure 5.1c. The convergence area of these two mesoscale frontal features are indicated by the black oval. Additional convection develops where the interaction occurs with reflectivity values of approximately 60 dBZ at 2045 UTC (1545 EST) as shown in Figure 5.1d.

The interaction between the sea-breeze front and the Sandhills convection is also evident in the visible satellite imagery for the same day. At 1845 UTC (1345 EST), convection in the Sandhills is occurring in southern South Carolina (SC) as indicated by the black oval in Figure 5.2a. The development of clouds along the sea-breeze front is also evident at this time. The location of the sea-breeze front near the coast is indicated by the black arrow. By 1945 UTC (1445 EST), the sea-breeze front is clearly depicted by a line of clouds; its location is indicated by the black arrow as shown in Figure 5.2b. The convection in the Sandhills has moved closer to the coast from its previous location at 1845 UTC (1345 EST). The leading edge of the Sandhills front is indicated by another black arrow. The convergence of the two mesoscale frontal features at 2045 UTC (1545 EST) is shown in Figure 5.2c. The location of the interaction is indicated by the black oval. At 2115 UTC (1615 EST), additional convective clouds are evident due to the interaction as shown in Figure 5.2d. The location of the interaction is marked by the black oval.

The interaction between the sea-breeze front and the Sandhills front is simulated for this event using the WRF model described in Section 5.2. The model is initialized at
Figure 5.2 Visible 4km satellite imagery over North Carolina (NC) and South Carolina (SC) on 27 June 2010. (a) Convection is seen in the Sandhills area at 1845 UTC (1345 EST) in South Carolina as indicated by the black oval. The location of the sea-breeze front is marked by the black arrow. (b) At 1945 UTC (1445 EST), the leading edge of the Sandhills front is seen adjacent to the Sandhills convection and is marked by a black arrow. The sea-breeze front, identified by the thin line of clouds near the coast is also indicated by another black arrow. (c) The convergence of the two fronts is seen in the satellite imagery at 2045 UTC (1545 EST). (d) Additional convection is seen where the two fronts have merged and is noted by the black oval at 2115 UTC (1615 EST).
0000 UTC on 27 June 2010 (1900 EST on 26 June 2010). Model physics and configuration for each case study presented in this chapter are indicated in Table 5.1. A time history of

Table 5.1 WRF Version 3.7.1 Configuration

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the strength of the convection in each of the three zones, the Sandhills Zone, the Intermediate Zone, and the Coastal Zone, is determined using the simulated convective mass flux as shown in Figure 5.3. The convective mass flux is determined by following the methods of Robe and Emanuel (1996) and Wang et al. (2011) and are described in Chapter 3 in Section 3.4.3. The model predicts convection to develop at the edge of the Sandhills zone in the Intermediate Zone and also in the Coastal Zone associated with the sea-breeze front at 1800 UTC (1300 EST). The simulation predicts the strongest convection in the Intermediate Zone (IZ) with a maximum value 0.027 kg m\(^{-2}\) s\(^{-1}\) at 2000 UTC. Additionally, convection continues until 2200 UTC (1700 EST) in the Coastal Zone (CZ) as the storms
Figure 5.3 Upward convective mass flux (kg m\(^{-2}\) s\(^{-1}\)) on 27 June 2010 for each hour in each of the three zones: The Sandhills zone (SHZ) in grey, the Coastal Zone (CZ) in orange, and the Intermediate Zone (IZ) in blue. The strength of the convection is noted by the vertical bars for each zone. Forecast hours represent the number of hours since 0000 UTC on 27 June 2010).

...propagate into and through the Coastal Zone. The model did not predict convection to occur in the Sandhills zone, but rather on the eastern side of the Sandhills Zone in the Intermediate Zone at 1800 UTC (1300 EST). The simulated reflectivity for the 1-km domain indicates the location of the convection at 1800 UTC (1300 EST) as shown in Figure 5.4.

However, the simulated surface convergence does indicate convergence along the eastern edge of the Sandhills and the development of the sea-breeze front by the blue shaded areas at 1600 UTC (1100 EST) as shown in Figure 5.5a. By 1700 UTC (1200 EST), the
lines of convergence have strengthened, particularly along the coast as can be seen in Figure 5.5b. The increased magnitude of the convergence indicates strengthening of the sea-breeze front. The model simulates convection occurring in the Intermediate Zone between these two lines of convergence.

Figure 5.4 Simulated reflectivity for the 1-km domain indicates that the model simulates convection in the Intermediate zone at 1800 UTC (1300 EST) on 27 June 2010.
Figure 5.5 Simulated low-level convergence on 27 June 2010. Blue shaded regions represent convergence. Red shaded regions indicate divergence. (a) The line of convergence along the shore and divergence offshore is indicative of the sea-breeze. Additional convergence is seen over the eastern side of the Sandhills region. (b) The convergence along the coast has intensified with maximum values of approximately $10 \times 10^{-5}$ s$^{-1}$. 
5.3.2 Light Onshore Flow

On 24 June 2009, the interaction between the Sandhills front and the sea-breeze front occurred in southern South Carolina. This case study representing this background wind speed and direction category has been discussed extensively in Chapter 2 and Chapter 3. A comparison of the simulated upward convective mass flux (UMF) in each of the zones is shown in Figure 5.6. Convection begins in all three zones at 1600 UTC (1100 EST). The Sandhills convection is maximum at 1700 UTC (1200 EST) with a maximum value of 0.005 kg m\(^{-2}\) s\(^{-1}\). The upward convective mass flux is the strongest at 2200 UTC (1700 EST) in the Intermediate Zone where the interaction occurs. The maximum UMF is in the Intermediate Zone and has a value of 0.021 kg m\(^{-2}\) s\(^{-1}\).

![Figure 5.6 Same as Figure 5.3 except for 24 June 2009. Forecast hours represent the number of hours since 0000 UTC on 24 June 2009.](image-url)
5.3.3 Light Offshore Flow

On 2 June 2010, the highest average precipitation occurred in the Intermediate Zone. The average background winds indicate the flow to be offshore, from the west. Widespread convection develops along the coast in North Carolina (NC) and along the western edge of the Sandhills in northern South Carolina (SC) at 1843 UTC (1343 EST) as indicated by the radar reflectivity in Figure 5.7a. In southern SC, where no convection has developed, the sea-breeze front is evident at this time as is indicated by the black arrow. This sea-breeze front in southern SC propagates inland and is approximately 50 km from the coast at 2127 UTC (1627 EST) as shown in Figure 5.7b. Convection forms along the sea-breeze front at 2200 UTC (1700 EST) (not shown). The outflow from these storms, may strengthen the sea-breeze front by enhancing the temperature gradient from the cool downdrafts. At approximately 2325 UTC (1825 EST), strong storms are seen in the Sandhills region in central SC, with maximum radar reflectivity values ranging from 50 to 55 dBZ as shown in Figure 5.7c. Outflow from the Sandhills convection forms the Sandhills front and is indicated by the black arrow. The location of the sea-breeze front is also indicated by another black arrow approximately 100 km from the coast. At 0138 UTC on 3 June 2010 (2038 EST 2 June 2010), the sea-breeze front and the Sandhills front merge as shown in Figure 5.7d. The location of the convergence of these two features is indicated by the black oval. Additional convection also develops on the eastern edge of the Sandhills in central SC at approximately 0150 UTC 3 June 2010 (2050 EST 2 June 2010) and is indicated by the black arrow. This additional convection to the west in the Sandhills generates a second Sandhills
Figure 5.7 Composite base-level reflectivity in dBZ for five radars in the Carolinas on 2 June 2010. (a) The location of the sea-breeze front in South Carolina is marked by the black arrow at 1843 UTC (1343 EST) (b) By 2127 UTC (1627 EST), the sea-breeze front in southern South Carolina has moved inland as noted by the thin blue line of reflectivity. Convection has begun in the the Sandhills in central South Carolina. (c) The convection in the Sandhills has continued to develop and is more widespread at 2325 UTC (1825 EST). The sea-breeze front has moved inland and is marked by the black arrow. (d) By 0138 UTC 3 June 2010 (2038 EST 2 June 2010), The sea-breeze front has moved inland for a distance over 100 km and is merging with the Sandhills front. (e) The sea-breeze front has moved inland to approximately 120 km from the coast and has merged with the Sandhills front at 0150 UTC 3 June 2010 (2050 EST 2 June 2010). (d) Widespread convection is seen in the radar reflectivity data at 0330 UTC 3 June 2010 (2230 EST 2 June 2010).
front that then quickly merges with the interaction, indicated by the black oval as shown in Figure 5.7e. More convection occurs in this location with reflectivity values exceeding 50 dBZ values. This interaction forms a line of reflectivity in central South Carolina at about 0330 UTC 3 June 2010 (2230 EST 2 June 2010) as shown in Figure 5.7f. The convection then begins to weaken with most of the convection having reduced values of about 40 dBZ by 0410 UTC 3 June 2010 (1110 EST 2 June 2010) (not shown).

Figure 5.8 Simulated low-level convergence on 2 June 2010. Blue values represent convergence in \(10^{-5} \text{ s}^{-1}\). Red values indicate divergence. The line of convergence along shore and divergence offshore is indicative of the sea-breeze. Additional convergence is seen over the Sandhills region and on its eastern edge.
The simulation of this event is initialized at 0000 UTC on 2 June 2010. The near surface winds and convergence at 1800 UTC (1300 EST) are shown in Figure 5.8. A strong sea breeze is simulated by the model at this time. The line of convergence, illustrated by the blue colors, is seen near the coast with values exceeding $15 \times 10^{-5} \text{ s}^{-1}$. This line is adjacent to strong red values (divergence) just offshore indicating a sea-breeze in the model at this time. Similarly, to the convergence associated with the sea breeze, there are areas of convergence in the Sandhills that are adjacent to areas of divergence on the westward side of the Sandhills.

The strength of the convection across the region is evaluated using the upward convective mass flux in the three zones as shown Figure 5.9. There is widespread convection predicted by the model across the region in each zone, Coastal (CZ), Intermediate (IZ), and Sandhills (SZ). Convection over the entire region begins at 1500 UTC and strengthens during the afternoon until 2300 UTC. The maximum UMF in the Sandhills Zone is 0.015 kg m$^{-2}$ s$^{-1}$ at 2100 UTC. The coastal region also has convective activity along the sea-breeze front; the intensity is roughly two-thirds of the values seen in the Sandhills with a maximum value of 0.009 kg m$^{-2}$ s$^{-1}$ at 1800 UTC. The most intense convection is simulated in the Intermediate Zone at 2200 UTC with a maximum upward mass flux of 0.055 kg m$^{-2}$ s$^{-1}$.

The location of the strongest simulated reflectivity in the Intermediate zone shown in Figure 5.10 agrees well with the observations shown Figure 5.7. The model-simulated reflectivity at 2200 UTC, indicates values on the order of 60 to 65 dBZ in this region where
Figure 5.9 Same as Figure 5.3 except for 2 June 2010. Forecast hours represent the number of hours since 0000 UTC on 2 June 2010.

Figure 5.10 Simulated radar reflectivity in dBZ for the 1-km domain at 2200 UTC on 2 June 2010. Widespread simulated convection occurring in the Intermediate zone. The area of interaction is indicated by the red square.
the interaction occurred. The red box indicates the area of interaction coinciding where the strongest convection occurs in the model. A vertical profile of UMF at 2200 UTC is shown in Figure 5.11. The maximum UMF over the interaction area defined by the red box, is 0.24 kg m\(^{-2}\) s\(^{-1}\) at a height of 4500 m. The extent of the UMF reaches a height of about 14000 m. The maximum simulated vertical velocity is 30 m s\(^{-1}\) at a height of 8500 m.

Figure 5.11 A profile of upward convective mass flux at 2200 UTC on 2 June 2010 over the interaction area indicated by the red box in Figure 5.10.
5.3.4 Moderate Southwesterly Flow

On 23 June 2011, there is a moderate southwesterly flow over the Carolinas region that transports moisture into the region from the Gulf of Mexico. This background wind direction category has the highest total average precipitation in the coastal Carolinas as was shown in Table 4.5. Composite base-level radar reflectivity data indicates widespread development of convection in the entire region. At 1930 UTC, the sea-breeze front has formed along the coast and its location delineated by the reflectivity data is indicated by the black arrows in Figure 5.12a. The location of the sea-breeze front is evident by the thin blue line of radar reflectivity. Additionally, convection can be seen over the Sandhills region at this time. By 2000 UTC (1500 EST), the convection area has expanded near the eastern edge of the northern Sandhills. There are small areas of convective storms in the southern part of South Carolina. This location is indicated by the black oval in Figure 5.12b. By 2130 UTC (1630 EST), the line of convection from the Sandhills has moved toward the coast and is marked by the black oval in Figure 5.12c. The thin blue line of reflectivity is located in the center of the oval and marks the location of the sea-breeze front at the time of interaction. By 2200 UTC (1700 EST), the Sandhills front and the sea-breeze front have merged and additional strong convection exceeding 60 dbZ is observed near the coast as shown in Figure 5.12d. The location of the interaction occurs along most of the South Carolinas coast as indicated by the black arrows.

The interaction between the sea-breeze front and the Sandhill convection is simulated using the WRF model. The model is initialized at 0000 UTC on 23 June 2011. The
Figure 5.12 Composite base-level radar reflectivity in dBZ on 23 June 2011. (a) At 1930 UTC, there is convection along the Sandhills, the sea-breeze is located near the coast and are indicated by the black arrows. (b) By 2000 UTC, additional convection has begun to develop in central South Carolina near the Sandhills as indicated by the black oval. (c) These storms have propagated toward the coast and are converging with the sea-breeze front at 2130 UTC as indicated by the black oval. (d) Enhanced convection resulting from the interaction is observed near the coast of South Carolina at 2200 UTC as indicated by the black arrows.
strength of the convection over the region is indicated by the upward convective mass flux (UMF) for the three zones, Sandhills, Intermediate, and Coastal in the Carolinas as indicated in Figure 5.13. In the simulation, the convection begins in the Sandhills region as shown by the UMF at 2000 UTC. The strength of the convection in the Sandhills zone peaks at 2100 UTC with a value of 0.027 kg m\(^{-2}\) s\(^{-1}\). The convection in the Sandhills move towards the coast over the next two hours and can be seen in the interaction zone at hours 2100 UTC and 2200 UTC. The convection is the strongest when the Sandhills front interacts with the sea-breeze front in the Coastal zone. The upward mass flux in this region is nearly double that over the Sandhills with a value of 0.051 kg m\(^{-2}\) s\(^{-1}\) at 2300 UTC.

Figure 5.13 Same as Figure 5.3 except for 23 June 2011. Forecast hours represent the number of hours since 0000 UTC on 23 June 2011.
Figure 5.14 Simulated low-level convergence on 23 June 2011. Blue values represent convergence. Red values indicate divergence. (a) The line of convergence along shore and divergence offshore is indicative of the sea-breeze at 1600 UTC. (b) At 2000 UTC, a line of convergence is seen east of the Sandhills in Georgia and South Carolina marked by the black arrow. The line of convergence associated with the sea-breeze front is also marked with another black arrow. (c) The merging of the two fronts is indicated by the black oval at 2100 UTC. (d) The two fronts continue to merge in South Carolina at 2200 UTC. The strong outflow from the Sandhills convection is indicated by the black arrow. On the coastal side of the merging fronts, the winds are from the southwest, but still onshore.
The near-surface simulated convergence shown in Figure 5.14 shows the structure of the simulated sea-breeze and the Sandhills convection through the convergence-divergence pairs. The convergence represented by the blue colors along the shoreline indicates the location of the sea-breeze at 1600 UTC as shown in Figure 5.14a. This location of the sea-breeze is indicated by the black oval in South Carolina. The area of convergence, indicated by the blue shading is adjacent to the divergence (red shading) offshore. This pattern illustrates the sea-breeze circulation near the coast. By 2000 UTC, the near-surface convergence indicated by the blue shading inland illustrates the Sandhills front and near the coast the sea-breeze front as simulated by the model are shown in Figure 5.14b. The location of these two fronts are indicated by the two opposing black arrows. At 2100 UTC, the model simulates the converging of the two mesoscale fronts near southern South Carolina and is indicated by the black oval in Figure 5.14c. The simulated convergence and the winds indicate that the fronts converge near the South Carolina and Georgia border first and continue to merge northward at 2200 UTC as shown in Figure 5.14d. The flow behind the Sandhills front is offshore as indicated by the black arrow. The winds on the coastal side of the interaction area is from the southwest as indicated by another black arrow, but still onshore.
A vertical cross section of the simulation near the southern portion of South Carolina is considered to analyze the structure of the two fronts and their interaction. The location of the cross section is indicated in Figure 5.15. The sea breeze circulation for moderate southwesterly flow has a vertical extent of approximately 1000 m at 1900 UTC as shown in Figure 5.16a. The wind flow is onshore and the sea-breeze front is approximately 30 km inland from the shore as indicated by the blue arrows. By 2000 UTC, the location of the sea breeze is approximately 40 km from the coast as shown in Figure 5.16b thus advancing 10 km in one hour. The simulated boundary layer height is approximately 1500 m at 2000 UTC.
Figure 5.16 A cross section indicating the circulation vectors and potential temperature in °K on 23 June 2011. (a) The sea-breeze circulation is by the blue colors near the coastline and is approximately 20 km inland at 1900 UTC. (b) By 2000 UTC, the sea-breeze has advanced to approximately 30 km inland. Downward cool air from the convection over the Sandhills is simulated. (c) At 2100 UTC, the opposing flows of the density current and the sea-breeze is readily evident as shown by the circulation vectors. (d) The two simulated mesoscale air masses merge at 2200 UTC. Additional convection develops along the convergence area.

Development and intensification of convection near the Sandhills creates a cool outflow density current led by the Sandhills front. The development of this density current is
indicated by dark blue color shading. The Sandhills density current has stronger winds and cooler temperatures as compared to the sea-breeze circulation as indicated by the relative magnitude of the opposing arrows in Figure 5.16c. The depth of the Sandhills front is approximately 750 m; the sea breeze depth is approximately 1000 m at this time and its front is located approximately 50 km from the coast at 2100 UTC. These two mesoscale frontal features converge and additional upward vertical motion occurs upon interaction at 2200 UTC as shown in Figure 5.16d.

Figure 5.17 Simulated radar reflectivity in dBZ for the 1-km domain at 2300 UTC on 23 June 2011 representing simulated convection resulting from the interaction in the Coastal Zone. The region of interaction is indicated by the red square.
In the Coastal Zone, the simulated reflectivity indicates a line of convection resulting from the interaction as shown in Figure 5.17. The maximum value of simulated reflectivity is 60 to 65 dBZ at 2300 UTC in the interaction area depicted by the red box. A profile of the UMF at 2300 UTC over the interaction area is shown in Figure 5.18. The strongest UMF over this area occurs at a height of approximately 3200 m with a value of 0.12 kg m\(^{-2}\) s\(^{-1}\). The height of the UMF extends to a height of approximately 14000 m. The maximum simulated vertical velocity is 33 m s\(^{-1}\) at a height of 8000 m.

Figure 5.18 A profile of upward convective mass flux (kg m\(^{-2}\) s\(^{-1}\)) at 2300 UTC on 23 June 2011 over the interaction region indicated by the red box in Figure 5.17.
5.3.5 Moderate Offshore Flow

Four different simulations of moderate offshore flow were performed. The model was unable to accurately simulate the interaction events for these cases. In general, one or more of three outcomes occurred in each simulation of moderate offshore flow. The model (a) did not predict precipitation over the Sandhills, (b) did not simulate a sea-breeze along the coast, or (c) the timing and location of the interaction did not agree with the observations. For the observed interaction case on 28 June 2010, presented in Chapter 4, the model had a dry bias and did not predict strong convection in the Sandhills to occur. In another case, 1 June 2008, strong winds kept the simulated sea breeze at the coast. Simulated convection that occurred in the Sandhills region did not propagate all the way to the coast where the interaction occurred. Since the model was unable to simulate these events correctly, analysis of the simulations of moderate offshore flow is inconclusive.

5.4 Discussion of the Case Studies

Each of the salient wind speed and wind direction regimes deduced in Chapter 4 were investigated in the preceding sections with observations and simulations. These different regimes have differing influences in the interaction between the sea-breeze front and the Sandhills front. The strength of the interaction, the intensity of the convection, and the location and depth of the convection and interaction are all influenced by the background winds and moisture availability. A summary of these simulated parameters characterizing the vertical structure at the time of interaction is presented in Table 5.2.
Southwesterly flow has the most available moisture with maximum simulated specific humidity values of about 17 g kg\(^{-1}\) for both light and moderate flow in the interaction area. The average values of moisture are also the highest with amounts of 4.8 g kg\(^{-1}\) and 4.5 g kg\(^{-1}\) for both light and moderate flow respectively. Southwesterly flow also has the highest value of instability as is indicated by the simulated surface-based convective available potential energy (CAPE) maximum values of over 4000 J kg\(^{-1}\).

Moderate southwesterly flow regimes develop the most regional convection as has been observed in the radar reflectivity analysis in Chapter 4. The location of interactions for moderate flow tends to occur closer to the coast for all directions. Strong convection in the Sandhills and the associated Sandhills front propagates towards to the coast given the
robust winds for moderate wind regimes. Additionally, stronger winds under moderate regimes also keep the sea-breeze closer to the coast. The Sandhills convection for the southwesterly regime often forms an organized line of convection that arrives at the coast unevenly. Enhanced convection occurs at the initial interaction location and intensifies downstream as the two fronts converge.

Simulated light southwesterly flow has the deepest layer (16000 m) of convective mass flux as shown in Table 5.2. Although the characteristics for light (wind speeds < 3 m s\(^{-1}\)) southwesterly flow are similar to moderate (wind speeds between 3 m s\(^{-1}\) and 6 m s\(^{-1}\)) southwesterly flow, the interaction occurs farther inland during light background winds. These results are consistent with the observational analysis in Chapter 4.

Light offshore flow, opposing the sea-breeze, produces strong interactions between the sea breeze front and the Sandhills front as indicated in the observations and the simulations. The cool outflow from the Sandhills deep convection, the Sandhills front, and also the sea breeze front is easily identified in the radar reflectivity data for this flow regime. The maximum simulated specific humidity in the interaction locations at the time of interaction is 16.5 g kg\(^{-1}\) as shown in Table 5.2. The instability, represented by the surface based CAPE in Table 5.2, is not as high as in the southwesterly flow but a maximum value of 2899 J kg\(^{-1}\) is simulated in the interaction area. However, light offshore flow produces the strongest convection associated with the interaction as indicated by the maximum simulated mass flux, 0.24 kg m\(^{-2}\) s\(^{-1}\), at the time of interaction. Strong
convergence resulting from the opposing flows of the Sandhills front and the sea-breeze is the likely cause of the strongest upward convective mass flux.

Simulations of the moderate offshore background winds did not perform well and the model was unable to accurately simulate the observed interaction for this flow regime. Interactions during moderate offshore flow tend to have less precipitation as indicated by the observations in Chapter 4. The likely reasons for the poor simulations is that the model cannot trigger enough convection in the Sandhills due to lower instability and less moisture availability for this wind regime. With stronger offshore winds, the model also may not properly simulate the sea-breeze. Observations indicate the sea-breeze forms later in the day due to the strong opposing flow. The Sandhills front that develops from Sandhills convection has to travel approximately 180 km towards the coast before being able to interact with the sea-breeze front. This mesoscale frontal feature weakens and may even dissipate before an interaction occurs.

Onshore flow produces the least amount of precipitation as is shown in the summary tables in Chapter 4. The simulation of onshore flow events has the lowest values of specific humidity at the time and location of interaction as indicated in Table 5.2. This could be due to the wide swath of onshore flow direction assumed in this study that includes northeasterly flows. The simulated depth of convection (13500 m) at the location of the interaction is less as compared to other background wind flow regimes, (Table 5.2). Additionally, the instability is also less with simulated values of CAPE less than 2000 J kg\(^{-1}\) for onshore flow. For light onshore flow, the weak sea-breeze can propagate far inland,
about 100 km, as discussed in Chapter 2. The weak sea-breeze front is related to the lack of opposing flow.

Different background wind speeds and directions influence the development of convection differently in the coastal Carolinas region. Southwesterly winds bring in moisture from the Gulf of Mexico and under this flow regime highest levels of atmospheric instability exists. Moderate background winds tend to have interactions that occur near the coast. Light winds allow the sea-breeze to propagate far inland, and can approach the Sandhills. Light offshore flow produces the strongest interactions between the sea-breeze front and the Sandhills front due to the opposing flows. The sea-breeze circulation is the strongest in such cases. Moderate offshore winds keep the sea-breeze near the coast and can interact with the Sandhills front if it does not weaken before approaching the coast.

The typical simulated cases presented in this chapter represent three different background wind directions and three different wind speed regimes deduced by the observational analysis in Chapter 4. These simulations support the conclusions from the observational study regarding the location and intensity of interactions between the Sandhills front and the sea breeze front.
CHAPTER 6
SUMMARY AND CONCLUSIONS

Precipitation affects many aspects of the lives of people. During the summertime, convection and resultant precipitation, which is often intense, can have profound impact on personal endeavors and on various businesses and industries. Impacts can range from water resources management to crop damage. Some of the businesses and industries that are directly impacted by precipitation include tourism, transportation, and agriculture. These sectors are known to be important to the economy in the Carolinas (North Carolina and South Carolina). Reliable prediction of convective precipitation events can provide timely information which can aid in emergency management efforts that affect the safety of people and animals, and help mitigate the loss of property.

In the Carolinas, there are two key land-surface features over which convective precipitation often occurs during the summer months. These geomorphic features are the Sandhills and the coastline. Along the coastline, sea-breeze circulations regularly form during the summer months and are known to initiate convection. Inland, the Sandhills is known to be a zone of low-level convergence and origin of convective storms. The Sandhills is made up of sandy soils and its boundaries have a marked change in soil-type characteristics. This unique zone extends through the central part of the Carolinas and into Georgia and is oriented parallel to the coastline, at about 180 km inland. The height of the terrain of the Sandhills is approximately 150 m above sea level. It has an average width of
approximately 50 km. In the absence of synoptic forcing, summertime convective storms
often form over the Sandhills. This region has been observed to be an area of significant
precipitation. The interaction processes between the two mesoscale circulations that
develop over the region have been presented in this research. Although similar in concept
to converging sea-breezes from opposite coasts, the interaction between the sea-breeze
circulation and the Sandhills deep convection has been shown to be a completely different
mechanism.

The primary mesoscale driving force for the development of the sea breeze and the
convection over the Sandhills is the differential heating. During the early summer, the
ocean is still cool when compared to the heating of the land. Similarly, in the central part of
the Carolinas, the Sandhills heats quicker than the surrounding clay soil regions due to the
difference in soil heat capacities. The strong differential heating, induced by the differing
soil heat capacities over the Sandhills, causes strong surface convergence that can trigger
convection.

The sea-breeze circulation near the coast and the deep convection over the Sandhills
were generally hypothesized to interact in the same way as two sea-breeze circulations
converging across an island or a peninsula. However, a systematic investigation of this
phenomenon revealed a different mechanism of interaction. Low-level convergence over
the Sandhills initiates deep convection, which in turn generates a cold outflow air mass. This
air mass moves towards the coast as a shallow density current due to the gentle slope in the
topography. This shallow density current produces a front-like feature, “the Sandhills
front”. This front, about 500 m to 1000 m in depth, propagates eastward toward the coast and interacts with the westward propagating sea-breeze front. Merging or the interaction of these two mesoscale frontal features causes strong upward motion and initiates or enhances convective precipitation. This finding addresses the key scientific objective of this research, improving the understanding of the process through which these two mesoscale phenomena, the sea-breeze and the Sandhills convection interact.

An understanding of this interaction process is attained using observations and by utilizing numerical models to simulate the processes and resultant interactions. However, numerical models do not always accurately simulate locally-driven convective summertime precipitation, and are known to have deficiencies when simulating these events. Higher model resolutions have typically proven to be better at simulating precipitation maximums and are necessary to simulate weak convective events. Therefore, model resolution is an important factor to consider when simulating mesoscale-driven precipitation events. At coarser model resolutions, cumulus parameterization (CP) schemes are necessary to address the numerical model’s inability to resolve finer scale convective activity. However, the model resolution threshold for using a CP scheme has been arbitrary. For the simulation of these mesoscale interaction events, modifications have been incorporated to the Kain-Fritsch CP scheme. These modifications ramp down the contribution of the subgrid-scale convection in the CP scheme in a smooth and systematic physical manner. By incorporating these modifications, numerical simulations of these mesoscale interaction events between the sea-breeze front and the Sandhills front have improved.
The CP modifications include the incorporation of subgrid scale clouds in the radiation scheme which improves the radiative feedback processes. Subgrid scale clouds in turn affect the surface air temperatures and near-surface winds, which are important parameters in initiating and maintaining convection. Additionally, the introduction of a grid-independent scaling parameter modulates the impact of convective timescale and entrainment in the model. At higher resolutions, the CP scheme continues to activate but does not stabilize the atmosphere as quickly and hence does not produce excessive precipitation. This new formulation allows the moisture to be retained in the atmosphere, which in turn can increase the grid scale precipitation. These modifications to the cumulus physics thus provide a more realistic relationship between the subgrid-scale and grid-scale processes and are consistent with the physical representation of the convection. Benefits from these modifications in the model resulted in improved representation of the processes associated with the interaction between the Sandhills front and the sea-breeze front. The modifications help mitigate early development of convection during the daytime and improve the timing and strength of convection in the model thus mitigating the over-prediction of precipitation.

Careful observational analysis and simulations using an improved mesoscale numerical model led to the discovery of the Sandhills front and the evaluation of the key processes involved during its interaction with the sea-breeze front. However, additional characterization of these interactions is necessary to improve the understanding of their dependence on the ambient atmospheric conditions. These characteristics, including the
frequency of occurrence and the magnitude of the interactions, are determined by
categorizing these events by the background wind speeds, and wind directions. Twelve
years of data from multiple platforms including radar reflectivity, visible satellite data,
Landsat, MODIS, GPS-Integrated Precipitable Water, and near-surface in situ observations
were analyzed for the month of June.

An analysis of the frequency of occurrence of the interaction between the Sandhills
front and the sea-breeze front indicates that these events occur often. On average these
interactions occur on approximately 24% of all days in June and on 36% of days when
synoptic scale systems are absent. The frequency of occurrence of these events suggests
that interaction between the sea-breeze and the Sandhills circulation contributes a
significant amount of precipitation that this region receives during June.

For this analysis, the observations and modeling are performed over the region of
South Carolina where the coastline is straight and parallel to the Sandhills. Three regions,
the Sandhills zone, the Intermediate zone in central South Carolina, and the Coastal zone
are used to evaluate the precipitation on days when an interaction between the Sandhills
front and the sea-breeze front is likely to have occurred. The radar-derived Stage-IV
precipitation estimates indicate that the Intermediate zone has the highest total average
precipitation when compared to the other zones for all directions and speeds. However, an
analysis of the normalized total maximum precipitations indicates that largest precipitation
amounts tend to occur in the Sandhills zone.
Wind directions over the region are divided into three categories, onshore, offshore, and southwesterly flow. Wind speeds are also used to subdivide each of these wind direction categories using light (< 3 m s\(^{-1}\)) and moderate winds (\(\geq 3\) m s\(^{-1}\) and 6 m s\(^{-1}\)). Southwesterly flow has the highest total average and total maximum precipitation amounts. Moderate wind speeds between 3 m s\(^{-1}\) and 6 m s\(^{-1}\) account for the highest totals of average precipitation for southwesterly flow. These precipitation totals are believed to be due to the warm moist air advection from the Gulf of Mexico. For offshore flow, light wind speeds (< 3 m s\(^{-1}\)) produce the highest totals of average precipitation. The background flow opposes the inland-progressing sea-breeze front increasing convergence that results in large amounts of precipitation. Moderate offshore flow has reduced precipitation amounts since the background flow keeps the sea breeze front close to the coast reducing the frequency of strong interactions. Additionally, the Sandhills front is not as strong, as it gets moderated while advecting farther towards the coast. The least number of days with interactions occurred during onshore flow. When the flow is onshore, the sea-breeze front is the weakest resulting in less interactions and precipitation. Thus the background wind directions and associated wind speeds appear to influence the location of the interaction and the amount of resulting precipitation.

Evaluation of the vertical characteristics of these interactions including the depth of convection cannot be deduced exclusively from the near-surface observations in the region. Numerical simulations are used to further investigate the mesoscale processes for each of the wind regimes. In these simulations, the improved cumulus parameterization scheme in
the model presented in Chapter III is linked to the Mellor-Yamada-Nakanishi-Niino (MYNN) planetary boundary layer (PBL) scheme. For these cases, the CP scheme is updated using a subcloud velocity scale based on the turbulent kinetic energy (TKE) in the PBL. In the subcloud layer, during convective conditions, the TKE is the dominant force for buoyant transport and mixing; this linkage of the TKE in the PBL scheme to the CP scheme in the model has better representation of turbulent mixing in the subcloud layer. Numerical simulations are performed using the updated model for typical cases representing important wind regimes deduced from the observations analyzed in Chapter IV.

These different wind flow regimes have differing influences on the interaction between the sea-breeze front and the Sandhills front. The strength of the interaction, the intensity of convection, and the location and depth of convection are all influenced by the background winds. Southwesterly winds bring in moisture from the Gulf of Mexico and hence has the highest levels of atmospheric instability. The most widespread convection occurs across the Carolinas region during southwesterly flow. Additionally, interactions between the Sandhills front and the sea-breeze front that occur during moderate southwesterly winds tend to happen closer to the coast.

Light offshore winds produce the strongest interaction between the sea-breeze front and the Sandhills front due to the opposing background flow. Additionally, light offshore winds allow the sea-breeze to propagate far inland, towards the Sandhills. Therefore, interactions for this wind flow regime tend to occur farther inland where the Sandhills front is robust. Moderate offshore winds keep the sea-breeze near the coast. Interaction with
the Sandhills front can occur if the Sandhills front does not weaken before approaching the coast.

Onshore flow produces the least amount of convective precipitation. For light onshore flow, a weak sea-breeze can propagate far inland and interact with the Sandhills front. However, there is no opposing background flow which weakens the sea breeze front with reduced possibility for strong interactions to occur. For moderate onshore flow, there are no interactions due to the lack of sea breeze.

These interactions do occur during other summer months as well. In summary, mesoscale-driven interaction events between the sea-breeze front and the Sandhills front do occur regularly during the summer in the coastal Carolinas. The location and the intensity of these interactions depend on background wind speed and direction. The detailed evaluation of both observations and numerical simulations in this research have improved the understanding of the mesoscale processes involved in the interaction between the sea-breeze circulation and the Sandhills convection. This research also identified the key meteorological factors that influence the interaction between the sea-breeze circulation and the Sandhills convection.

6.1 Future Work

Additional study of other summer months when land-surface heating is stronger and near-coastal ocean temperatures are warmer will be helpful. The effects of these surface temperature changes on the interaction between the sea-breeze front and the Sandhills
front need to be investigated further. Increased resolution of surface and sub-surface properties such as the inclusion of subgrid scale land-use and soil characteristics may further improve the representation of these interaction events in numerical models.

It will be worthwhile to build on previous studies investigating the relative contribution of the soil and vegetation on the development of convection in the Sandhills. One possibility of process evaluation is to perform idealized studies comparing the heterogeneity of soil and land-use contributions to convection using these high-resolution subgrid scale land-surface properties. The advancements in numerical weather models and increased model resolution may improve the understanding of how the Sandhills initiates and enhances convection in this region. Another important factor to consider is moisture availability. Soil moisture is known to be an important ingredient in the partitioning of the surface sensible and latent heat fluxes. Investigation into improved estimation of soil moisture and the gradients associated with the different soil and land-use types could improve predictability of convection triggered in the Sandhills region.

Additional research into the modifications of the CP scheme to improve convection initiation may help simulations of weak sea-breeze fronts. Modifications to the CP scheme to include microphysical processes to account for subgrid-scale hydrometeors may further improve the representation of convection in the models. Also, development and intensification of convection during the night over the Sandhills has been observed. The initiation of nighttime convection over the Sandhills region, again due to differences in soil heat capacities causing a reversal of surface heat flux gradient, needs to be investigated.
Other considerations are to evaluate the land-use changes (deforestation, urbanization, and irrigation) over time and how these changes influence the development of the Sandhills convection and interaction with the sea-breeze circulation in the coastal Carolinas.
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