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RESEARCH ARTICLE

Interaction Between Two Distinct Mesoscale Circulations During Summer in the Coastal Region of Eastern USA

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Abstract The interaction of two phenomena, a sea-breeze front and a thermally-driven local circulation, is investigated during the summer season. The sea-breeze circulation in the coastal Carolinas (USA) can be quite strong and the sea-breeze front often propagates well inland. The Sandhills, an area of sandy soils, is oriented roughly parallel to the coast and is located approximately 180 km inland. Differential heating is a strong driving force for convective development in this coastal region and the Sandhills front develops from the thermally-driven circulation caused by the differential heating of differing soil types. The sea-breeze and the Sandhills circulations have been previously studied independently, however, the interaction of these two phenomena is not well known. A combination of remote sensing, in situ observations, and numerical simulations is used to examine the interaction of these two fronts with remote sensing and in situ observations revealing the differential heating that occurs along the Sandhills region. Radar reflectivity is used to identify the two frontal features that converge and result in enhanced convection. A modelling simulation reveals the vertical structure of the frontal features, their propagation, and interaction, highlighting the interaction of the two fronts that results in enhanced convection between the Sandhills and the coast. Over the Sandhills region, differential heating triggers convective storms. Radar reflectivity and numerical simulation indicate the outflows from these convective storms to produce a shallow Sandhills front that in turn propagates toward the coast. As the two opposing fronts, the Sandhills front and the sea-breeze front, converge and interact, intense convection occurs resulting in additional storms.

Keywords Circulations · Coastal Carolinas · Convection · Sandhills · Sea breeze

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1 Introduction

The multifaceted 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. Land-surface properties of 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 location of the Carolinas, and the dominant soil types of the Carolinas are shown in Fig. 1, with data obtained from the Digital General Soil Map of the USA (NRCS 2014).

The Sandhills is a region with a marked change in soil-type characteristics. Along the eastern edge of the Sandhills mixtures of different soil types exist that tend to be sandier in nature, particularly towards the coast, while 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 increased precipitation along this boundary (Raman et al. 2005). This boundary has been shown to exist nearly 40% of days during the summer and is convective in nature (Koch and Ray 1997); the feature is readily evident during summertime when surface heating is strong and synoptic forcing is weak. During other seasons, synoptic-scale processes tend to dominate weather events. Understanding the nature and frequency of convection in this region has implications for emergency preparedness, while precipitation monitoring and the prediction of convection is important for environmental, travel, and safety concerns.

The Carolinas have curved coastlines with a series of inlets and sounds that form several cusps along their length. Where these concave structures intersect, sea breezes that develop can converge and enhance precipitation (Gilliam et al. 2004). Another important factor in sea-breeze development is the speed and direction of the large-scale background flow, which influences the formation, intensity, and propagation of the sea breeze as it evolves (Helmis et al. 1995). In addition to the curved coastline, the warm Gulf Stream is in close proximity to the shoreline, and its meandering can generate horizontal eddies and advect 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).

During summer, and in the absence of large-scale synoptic forcing, mesoscale processes are often dominated 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 temperature gradient across the coast. As a result, sea-breeze-induced precipitation occurs during 40 % of the period from June through August and contributes to half of the average precipitation during the summer (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 Carolina Sandhills region can also exhibit 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 convergence boundary, often forms along the Sandhills during the summer and has been attributed to differences in the heating of the different soils (Koch and Ray 1997). When comparing the relative contribution of land use and soil types to differential heating in this region, the range of soil types has

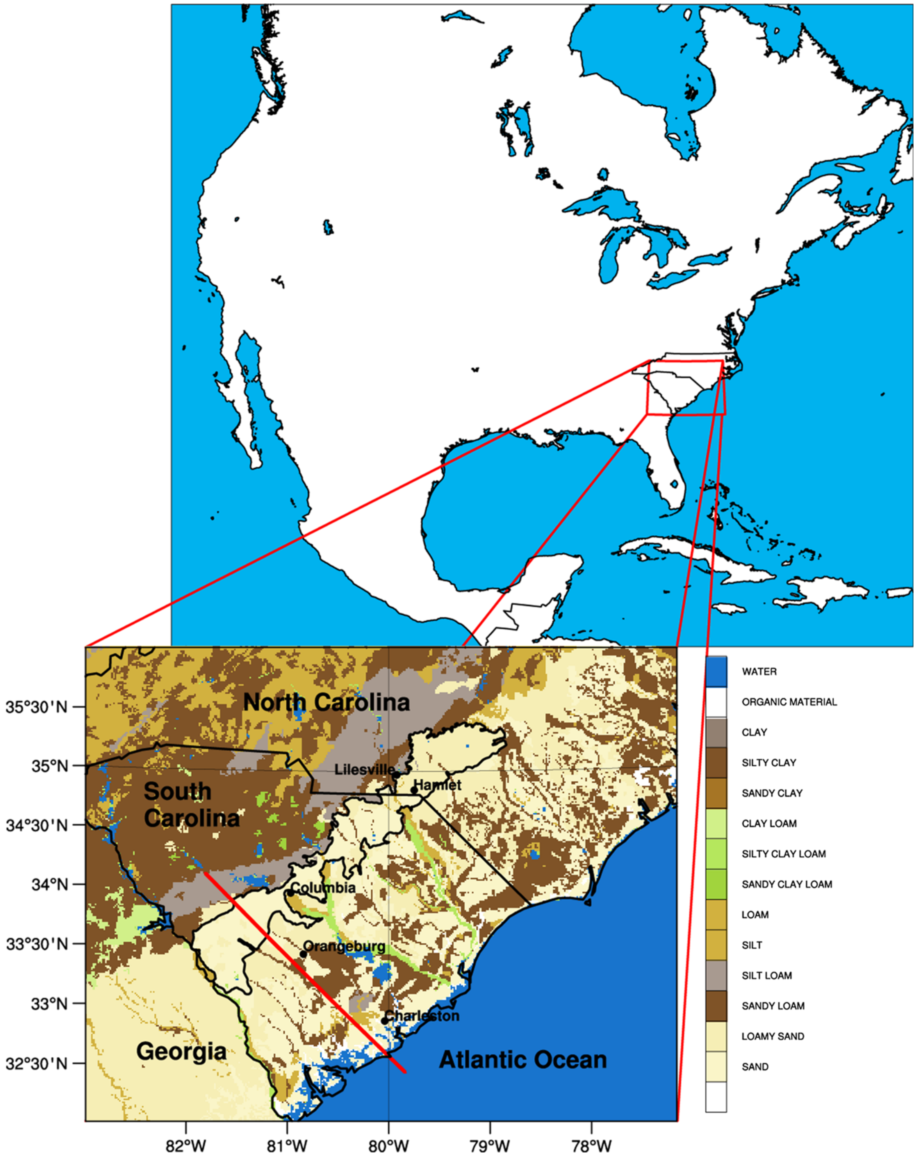

Fig. 1 Map of the study region showing the dominant soil-type categories for the Carolinas. The Sandhills is outlined in the central Carolinas. Observational station locations discussed are also depicted. The location of the cross-section used to present the modelling results is shown as a *red line*. 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, along the edge has clay soil

been shown to be the dominant factor (Boyles et al. 2007). Multiple factors can influence the magnitude and the rate of heating of the soils; moisture content, thermal conductivity, and heat capacity can all contribute to the relative heating of different soil types. The ground heat flux can be estimated using the diffusion equation for soil temperature (Chen and Dudhia 2001). A typical value of thermal diffusivity, α_h for sandy soil is 0.24 (dry) and 0.74 (wet) and for clay soils α_h ranges from 0.18 (dry) to 0.51 (wet) (Arya 1988). Therefore the Sandhills region heats more rapidly and tends to be warmer than the surrounding area during daytime. The differential heating of the surface can generate significant soil temperature differences, as noted with surface observations as well as satellite-derived surface temperatures (Doran et al. 1992).

Several modelling studies have shown that transverse vertical circulations develop along the Sandhills as a result of horizontal gradients in the surface heat fluxes (Sims 2001; Raman et al. 2005). Such gradients are attributed to the different surface characteristics and available soil moisture in the Sandhills region. These authors note that the resulting airflow circulations can often resemble that of a sea-breeze circulation, though smaller in horizontal and vertical extents. It has been shown that differing soil types are most likely the primary surface feature behind the development of surface temperature gradients as noted in an idealized modelling study (Boyles et al. 2007). These authors indicate that the local variations in soil characteristics are the dominant factor, when compared to land-use variability, in the development of the surface temperature gradients.

Surface and near-surface temperature differences can persist into the nighttime, with the sand cooling more rapidly than the clay. The differential cooling of the soils in the Sandhills is similar in nature to what would be expected along the coast, where the soil cools more rapidly than the ocean. Differences in soil characteristics may contribute to the development and enhancement of overnight convection over the Sandhills region (Wootten et al. 2010).

Past studies investigating climatological precipitation patterns based on in situ observations as well as radar-derived precipitation have shown increased precipitation in the coastal region and along the Sandhills region (Raman et al. 2005; Boyles 2006). Additionally, a climatology of average precipitation using Cooperative Observer stations from 1960–2015 was performed for the month of June as shown in Fig. 2. In June, the highest precipitation, in excess of 150 mm, occurred approximately 50 km inland from the coast in South Carolina. Additionally, higher precipitation, ranging from 130 mm to 140 mm, is shown to occur over and along the Sandhills. This region of increased precipitation correlates well with the location of the Sandhills convection and the location where interaction between the Sandhills and sea-breeze fronts occurs. These two phenomena are the likely candidates responsible for the increase in precipitation in this area. What is not well-known is how these two features interact and what role this interaction plays on precipitation patterns and amounts in the Coastal Carolinas.

Given favourable 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 breezes that converge across an island or a peninsula. Interaction of such circulations has been shown to produce enhanced convective precipitation along the intersection of the boundaries associated with sea-breeze formation along the east and west coasts of Florida (Blanchard and Lopez 1985; Xu et al. 1996), in the Italian Peninsula of Salento (Comin et al. 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. The objective of the present study is to investigate the role of the Sandhills convection, the development of the Sandhills front, and its interaction with the sea breeze. The following case study examines the interaction between the sea breeze and the Sandhills-induced convergence on a typical summer day.

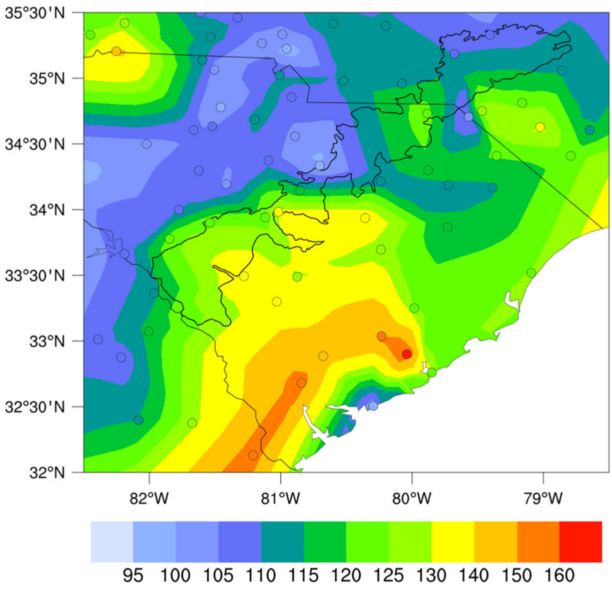

Fig. 2 Precipitation climatology (mm) from 1960–2015 for the month of June indicating higher amounts in the region between the Sandhills and the coast of South Carolina

2 Description of Observational Data and Numerical Modeling

A combination of surface observations, analyses, remote sensing, and numerical modelling 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 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 the different soil types. All station locations are indicated in Fig. 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. In the present case study, 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).

Table 1 WRF model set-up and physics packages used in the simulations. *CP* Cloud parametrization; *PBL* Planetary boundary layer; *LSM* Land surface model; *SST* Sea surface temperature

Domain	12 km	4 km	1 km
CP Scheme	KF	None	None
PBL Scheme	MYNN2.5	MYNN2.5	MYNN2.5
LSM	Noah	Noah	Noah
Microphysics	WSM6	WSM6	WSM6
Radiation	RRTMG	RRTMG	RRTMG
Initialization	GFS analysis	GFS analysis	GFS analysis
SST Data	GFS analysis	GFS analysis	GFS analysis
Horizontal Grid	250×250	421×421	1069×809
Vertical Levels	51	51	51

The model is initialized from the Global Forecast System (GFS). The physics packages used include: Kain–Fritsch cumulus parametrization (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

Additionally, remotely-sensed observations are used to examine the horizontal spatial structure of the mesoscale processes. Radar reflectivity data helps 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 throughout. 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-, 4-, and 1-km grid lengths (not shown). Additional model configuration information and model physics used are listed in Table 1. In the present paper, 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 datasets are on a 1-km grid. The location and formation of the Sandhills front is dictated by the sharp transition of the soil types. Qualitative comparison of simulated total precipitation of the intermediate domain and innermost domain indicates consistent results (not shown).

3 Convective Development and Sea-Breeze Progression

On 24 June 2009, the large-scale forcing was weak over the Carolinas, with the prevalent mesoscale processes largely responsible for the development of convective activity in the region. An area of weak low pressure existed off the coast of New England, advecting air into the region from the north-west, providing a weak to moderate offshore flow.

A sea breeze developed 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 Fig. 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 formed in the Sandhills region in central South Carolina as indicated in Fig. 3b. Henceforth, much of the discussion focusses on the South Carolina region where the interaction appears to be the strongest and the geography is simpler.

As the convective storms develop, the background flow from the north-west advects the Sandhills convection out towards the coast. Radar imagery during the afternoon indicates the strengthening sea-breeze circulation penetrating well inland for approximately 100 km and interacting with the Sandhills convection 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 Fig. 3c. Convergence of these two frontal features appears to enhance the formation of convection in the coastal plain as shown in Fig. 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 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 (not shown). However, it is interesting to note that the location of the last recognizable reflectivity signature of the sea breeze and its movement in North Carolina coincides with late-evening precipitation development in this region. The convection continues for several hours and moves towards the ocean due to north-westerly winds as nighttime progresses and is offshore by 0700 UTC (0200 EST).

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 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 Fig. 4a. The timing, location, and intensity of the simulated maximum convection are consistent with the radar reflectivity shown in Fig. 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 Fig. 3b) is also present in the maximum simulated radar reflectivity shown in Fig. 4b. The model simulation clearly reproduces the lines of convection associated with the sea breeze and the Sandhills region.

Observed total daily precipitation from precipitation gauges around the region are overlaid on the Stage IV precipitation estimates for 24 June 2009 as seen in Fig. 5. 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-

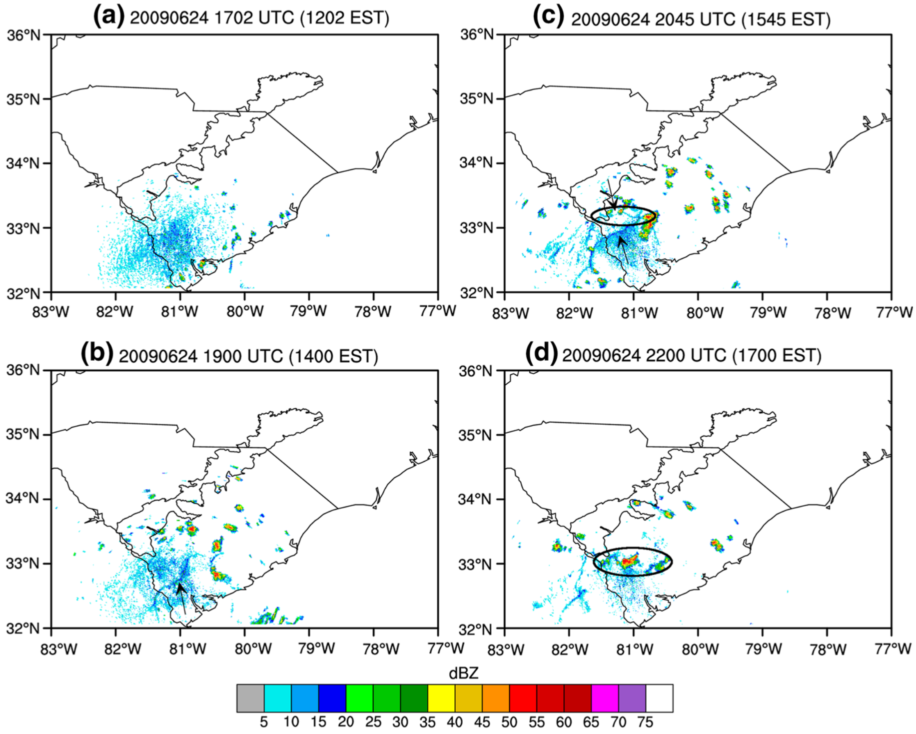

Fig. 3 Level-III base radar reflectivity on 24 June 2009. **a** Radar reflectivity indicates convection along the South Carolina coast associated with the sea breeze at 1702 UTC (1202 EST) on 24 June 2009. **b** Radar reflectivity at 1900 UTC (1400 EST) on 24 June 2009 indicates convection has formed 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 denote the frontal boundaries. **d** Development of enhanced convection indicated by the radar reflectivity in south-east South Carolina resulting from the interaction between the sea breeze and the Sandhills convection at 2200 UTC (1700 EST) on 24 June 2009

corrected using raingauge 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 to 10 mm in central South Carolina, but many of these stations are not located where the interaction and the most intense precipitation occurred.

4 Differential Heating of the Land Surface

Understanding the primary mesoscale forcing 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

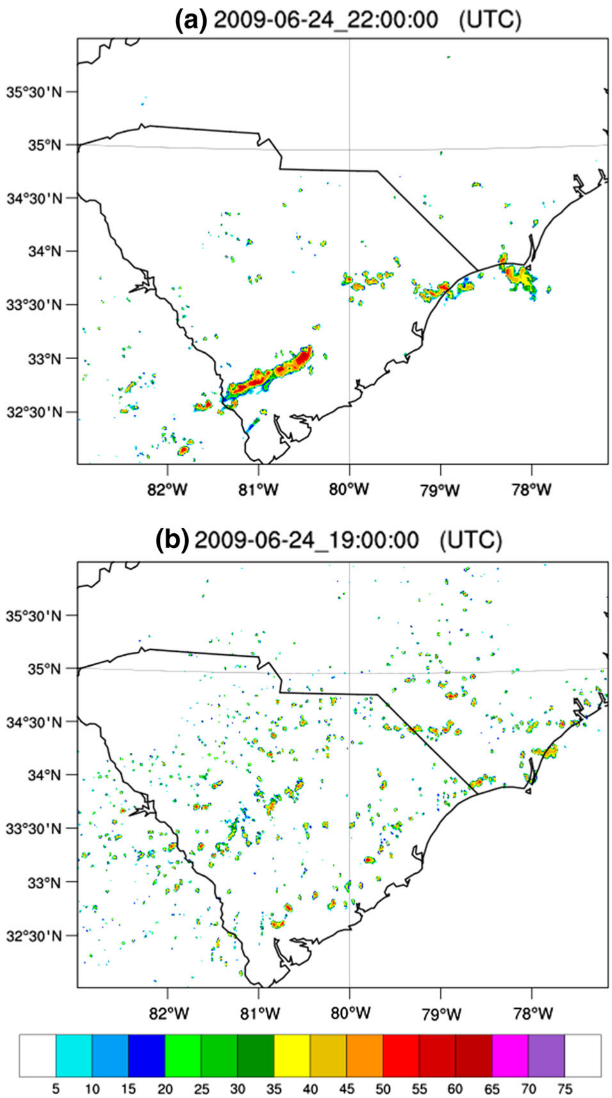

Fig. 4 **a** Simulated reflectivity at 2200 UTC (1700 EST) on 24 June 2009. Intense simulated reflectivity in southern South Carolina between the Sandhills and the coast as a result of the interaction between the Sandhills and sea-breeze fronts. **b** The model produces widely-scattered reflectivity values over much of the coastal region at 1900 UTC (1400 EST) and shows a line of convection along the coast and the Sandhills

shown in Fig. 6. The sharpest temperature gradients appear to occur on the western edge of the Sandhills, consistent with soil-type differences shown in Fig. 1. Surface temperatures over the Sandhills typically range between 35 and 45 °C. Surrounding area temperatures range anywhere between 30 and 35 °C.

Additionally, in situ observations of air and soil temperature are obtained from two ECONet stations. These two stations, shown in Fig. 1, are separated by a distance of approximately 22 km and are located near Lilesville, North Carolina (LILE) and Hamlet, North

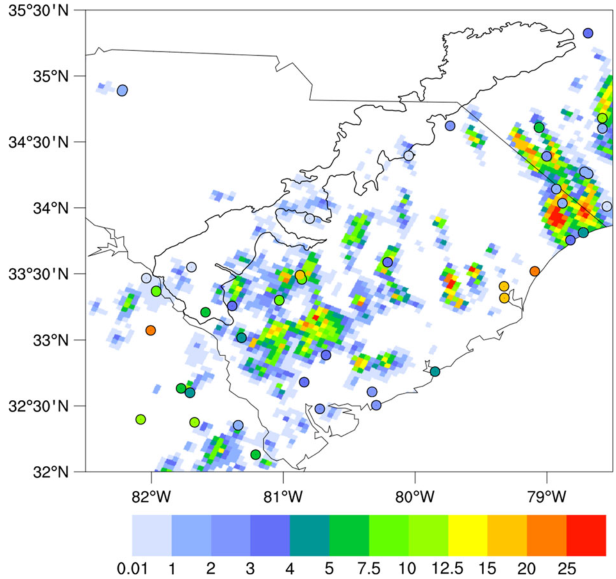

Fig. 5 Total daily precipitation (in mm) from gauge data overlaid on the gridded Stage IV precipitation estimates for 24 June 2009. Stage IV precipitation estimates indicate the precipitation patterns and the relative amounts

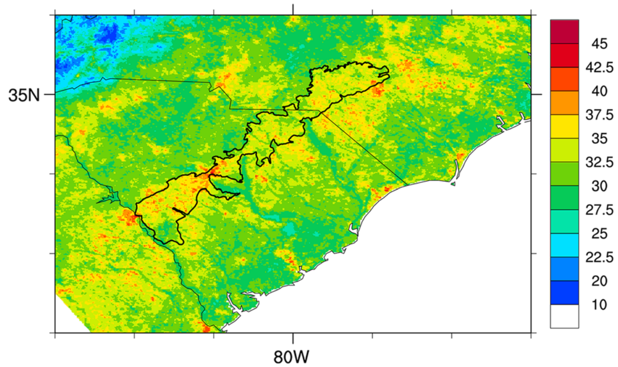

Fig. 6 Composite satellite land-surface temperatures (°C) based on data for eight days ending on 26 June 2009. Measurements taken at approximately 1600 UTC (1100 EST) averaged over 8 days showing strong heating in the central part of the Carolinas in and around the Sandhills area. Surface temperature differences in this region can vary from 5 °C to 15 °C

Carolina (HAML). The station LILE is located on clay soil, while station 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 stations.

Strong heating at the surface is also evident in the simulated surface skin temperature, and 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 (not shown). The sea-surface temperature off the coast is lower than the land surface and is approximately 27 °C. These

LST differences of almost 20 °C over approximately 100 km illustrate the heterogeneity of the heating and associated thermal gradients.

5 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 discussed below. Examination of the near-surface air temperature at 2 m and wind field at 10 m during the afternoon hours clearly shows 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 flow along the South Carolina coastline starts to develop around 1600 UTC (1100 EST) as shown in Fig. 7a. The sea-breeze circulation begins to strengthen with an onshore flow, and wind speeds ranging between 2 and 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 wind speeds 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 wind speeds between 5 and 7 m s^{-1}. Inland, to the east of Orangeburg, South Carolina, convergent flow is associated with the convective activity in the area as shown in Fig. 7b. This convergent flow corresponds well with the features observed in the radar reflectivity as was shown in Fig. 3b.

Closer examination of the timing of the sea-breeze progression and its potential interaction with the Sandhills convergence is essential to understanding 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 Fig. 8a. 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 1400 UTC (0900 EST) and 1800 UTC (1300 EST), but during this period convection in this area begins at approximately 1700 UTC (1200 EST), as shown by the radar reflectivity in Fig. 3a. Around 1800 UTC (1300 EST) the wind speed has increased to a maximum of 5 m s^{-1} with an 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 Fig. 8b. Between 2000 UTC (1500 EST) and 2200 UTC (1700 EST) there is a significant change in 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 is initiated, the sea-breeze front continues to move westward as indicated by the onshore flow observations at Orangeburg, South Carolina.

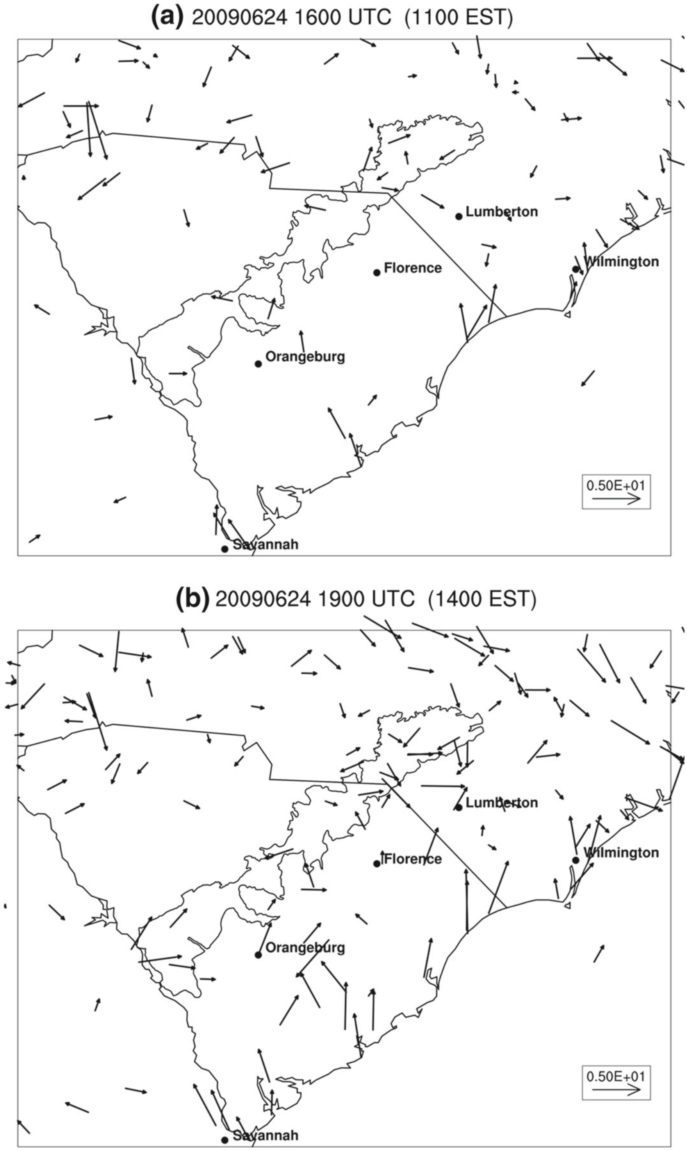

Fig. 7 Observed winds. The scale vector of 5 m s^{-1} is located in the box in the lower right. **a** Wind field (m s^{-1}) at 1600 UTC (1100 EST) on 24 June 2009. Winds are onshore along the coastline. Inland, winds are lighter and more variable. **b** Wind field at 1900 UTC (1400 EST) on 24 June 2009. Convergent flow near Orangeburg, SC is associated with convective activity in this area

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 airmass characteristics as seen in the near-surface air temperature and dew points at 2 m at Orangeburg, South Carolina, as shown in Fig. 8c. There is a sharp decrease in air temperature from about 29 °C at 1900 UTC (1400 EST) to 24 °C at 2000

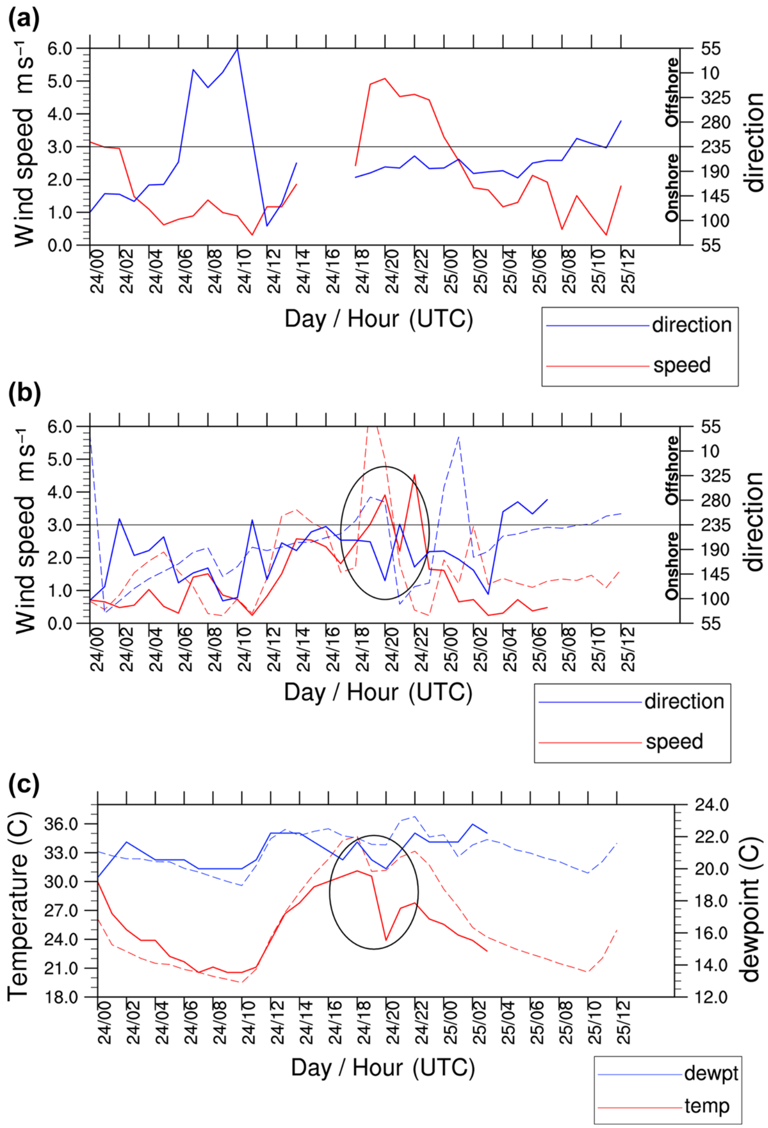

Fig. 8 **a** Time series of wind speed and direction from 0600 UTC (0100 EST) to 1200 UTC (0700 EST) in Charleston, South Carolina (KCHS). Winds are light and variable over the course of the night with the direction offshore. In the afternoon, the winds are onshore and speeds increase with the arrival of the sea breeze. **b** Observed (*solid*) and simulated (*dashed*) winds at Orangeburg, South Carolina (KOGB). The wind speeds (*red*) at night are low and variable. In the early to mid afternoon (*circled*), there is rapid variation in the wind speed and direction, likely associated with the frontal passage. **c** Observed (*solid*) and simulated (*dashed*) temperatures and dew points at Orangeburg, South Carolina. There is a sharp decrease in air temperature at 2000 UTC (1500 EST), *circled*. This rapid fall in the temperature (*red*) corresponds well with the changing winds during the same time reflecting the passing of the frontal feature associated with the Sandhills convection

UTC (1500 EST). The model numerical simulations also reveal this passing frontal feature and capturing the timing reasonably well.

Using the 2-m temperature from the RTMA, the location of the sea-breeze front at 2100 UTC (1600 EST) is shown in Fig. 9a. 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 temperature 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 temperatures 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 reduced 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 two hours as shown in Fig. 9b at 2300 UTC (1800 EST). By this time, the sea breeze is well developed and has propagated inland to the Sandhills, as is evident in the air temperature gradient and in the flow pattern. The air temperature along the Sandhills is still 4 to 6 °C higher 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 Carolina and Lumberton, North Carolina, located about 100 km from the coastline with flow generally from the coast (not shown).

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 (not shown). For the same time, model simulations show a temperature difference of approximately 6 to 8 °C and wind speeds 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 difference simulated inland across the edge of the Sandhills, is about 3 °C.

At 1800 UTC (1300 EST), the sea breeze has penetrated inland and is evident in the simulated near-surface 2-m air temperature in South Carolina as shown by a bold line in Fig. 10a. The wind vectors indicate an organized onshore flow with wind speeds of 3 to 4 m s^{-1} and the associated cooler, near-surface air at 2 m marks the edge of the sea-breeze front that 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 Fig 10b, indicates that the sea breeze has migrated 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, also 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 lower temperatures and the north-westerly flow with wind speeds of 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 lower by approximately 8 to 10 °C. By 2000 UTC (1500 EST) the model simulates cool-air advection from the north-west as noted by the wind vectors in this region. The sea breeze has strengthened with wind speeds increasing to about 5 m s^{-1} as the breeze front continues to penetrate inland by 90 to 100 km, as shown in Fig. 10c.

By 2100 UTC (1600 EST), the Sandhills front and the sea-breeze front have merged over central South Carolina as shown in Fig. 10d. The model clearly simulates the merging of these

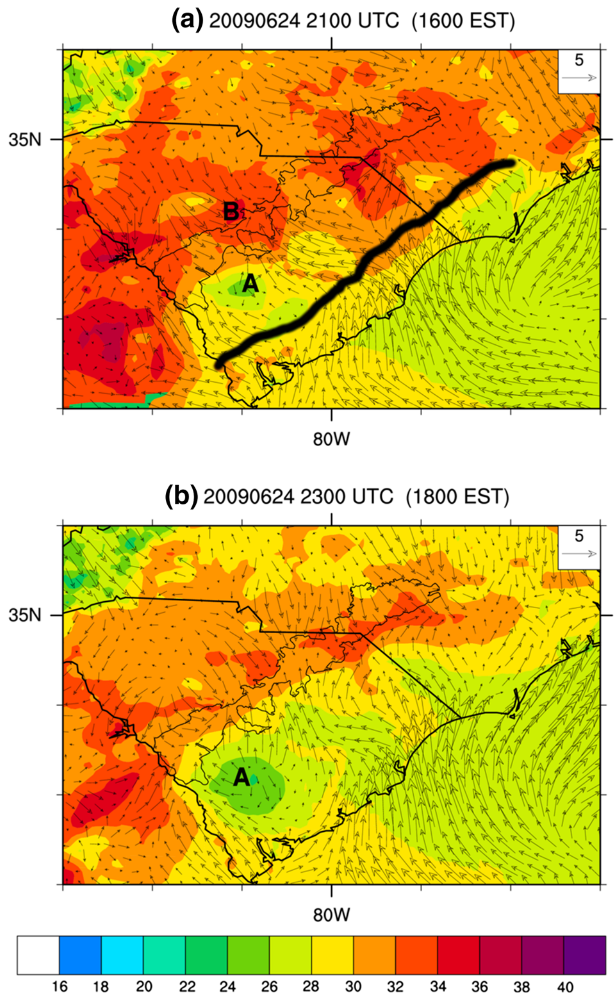

Fig. 9 **a** Gridded RTMA air temperature and winds at 2100 UTC (1600 EST) on 24 June 2009. A cold pool of air has formed just east of the Sandhills (*location A*) that can be attributed to rain-cooled downdrafts. In central South Carolina, the air is much warmer and the winds are from the north-west (*location B*). **b** The cold pool expansion and increase in size coupled with the divergent 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

two airmasses as indicated by the strong opposing flow near the surface at 10 m. Convergence of the two airmasses enhances the convection in this region.

6 Interaction of the Sea-Breeze and the Sandhills Fronts

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 Fig. 1. Several ASOS stations in South Carolina are located close by.

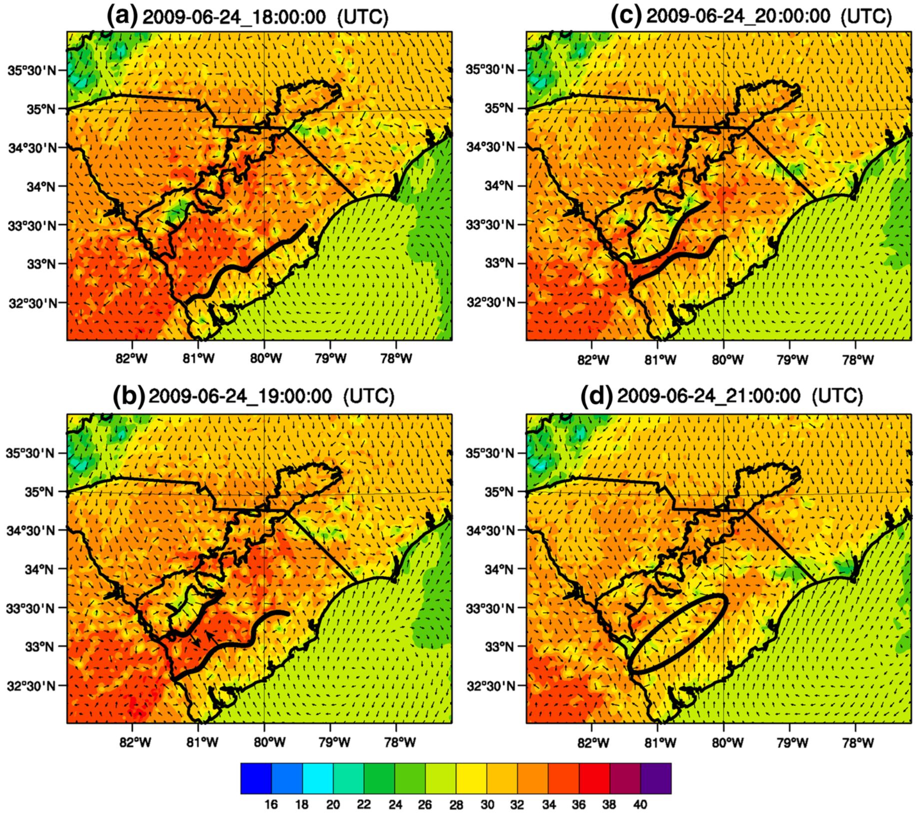

Fig. 10 Near-surface air temperature at 2 m and wind field at 10 m simulated at 1800, 1900, 2000, and 2100 UTC. (1300, 1400, 1500, and 1600 EST). **a** The sea breeze has penetrated inland along the coastline of South Carolina. The cooler near-surface air marks the edge of the sea-breeze circulation. 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 boundaries (*lines*) and their average directions are indicated with the *arrows*. **c** The Sandhills front is advancing towards the coast from the north-west. 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 airmasses are merging as indicated by the strong opposing flow depicted by the near-surface winds in the area encompassed by the *oval*

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 (not shown). The potential temperature near the surface has reached a minimum of 21 °C over land, with the stable layer extending up to about 200-m height near Columbia, South Carolina. At this time flow is onshore and light (wind speeds $\approx$3 m s^{-1}).

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 well-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 to a height of approximately 2 km as shown in Fig. 11a. 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

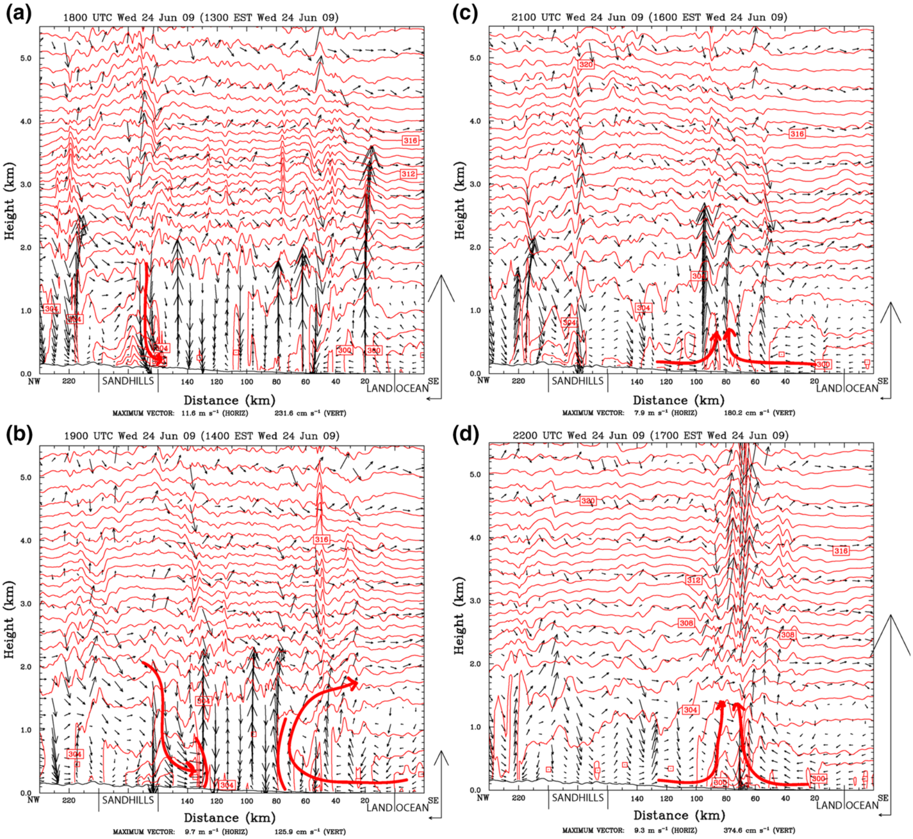

Fig. 11 **a** Well-developed convective boundary layer with strong upward vertical motions in the coastal region. A rain-cooled downdraft forms east of the Sandhills as indicated with the *red arrow*. **b** Along the eastern edge of the Sandhills, the Sandhills front is readily evident and is propagating toward the coast. The sea breeze is propagating inland. **c** The Sandhills front and the sea-breeze front converge, creating strong ascent as shown by the *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 to the generation of strong convection in this region

at approximately 1.5 km above the ground. Along the western side of this cross-section there is 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 Fig. 11b. There is still 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 region, the shallow cold airmass 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, with both showing a minimum near-surface air temperature of 27 °C. The Sandhills front is shallower

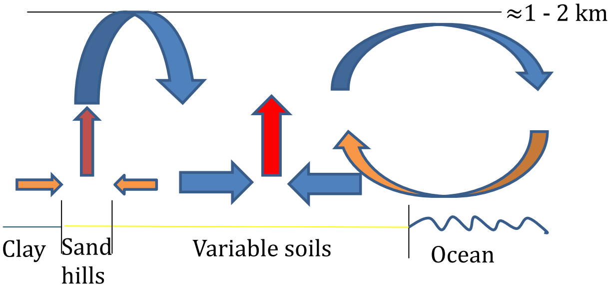

Fig. 12 Two mesoscale processes over the coastal Carolinas contribute to enhanced upward motion in the region. One is the convection over the Sandhills (*small red arrow*) causing a rain-cooled airmass from the downdrafts resulting in the formation of a shallow Sandhills front that propagates east toward the coast. The other is the sea-breeze front moving westward. The interaction between these two opposing mesoscale airmasses results in enhanced convection over the coastal Carolinas as indicated by the bright *red arrow*

in extent than the sea-breeze front and extends roughly 500 to 800 m in the vertical, compared to the depth of the sea-breeze circulation of roughly 1000 to 1200 m. The horizontal flow associated with the Sandhills front has wind speeds of approximately 10 m s^{-1}, with flow directed toward the coast. The inland propagation of the sea-breeze front is less rapid, with wind speeds of ≈5 m s^{-1}. As these two opposing fronts move towards each other, the convergent flow between the two frontal features favours an increased upward motion in the interior coastal plain on the order of 1 m s^{-1} vertical velocity, as shown in Fig 11b where no significant upward vertical motion existed earlier.

By 2100 UTC (1600 EST) the Sandhills front and the sea-breeze front are spatially close creating stronger ascent associated with their convergent airmasses, thus increasing the maximum vertical velocity to 2.3 m s^{-1} at 1 km above ground as noted in Fig. 11c. The simulated vertical updraft 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, and maximum horizontal wind speed 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 Fig. 11d. Model results also indicate the maximum vertical velocity of 20 m s^{-1} associated with the interaction to occur at an altitude of 6.4 km (not shown).

A schematic diagram depicted in Fig. 12 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, and 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 Sandhills front, with a sharp potential temperature gradient near the surface. There is a large horizontal temperature gradient between the Sandhills front and the region of the sea-breeze circulation; the depth of this contrast is about 1 km (Fig. 11a and Fig. 11b). This Sandhills front, propagating towards the coast, interacts with the approaching sea-breeze front. When these two opposing airmasses converge, additional strong convection develops.

7 Conclusions

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, and 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 south-eastern USA are caused by 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), though the interaction of these two features has not been previously explored.

The close proximity and parallel orientation of the Sandhills in relation to the coastline provides an opportunity 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 ($\approx$1 km) cool airmass producing a front-like feature (Sandhills front) propagating eastwards 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. A 20-year summer climatology is underway evaluating the frequency of occurrences of the interaction between these two fronts and the associated mesoscale processes.

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References

Ancell BC, Mass CF, Cook K, Colman B (2014) Comparison of surface wind and temperature analyses from an ensemble Kalman filter and the NWS real-time mesoscale analysis system. Weather Forecast 29:1058–1075

Arya SP (1988) Introduction to Micrometeorology. Academic Press Inc, San Diego, 307 pp

Blanchard DO, Lopez RE (1985) Spatial patterns of convection in South Florida. Mon Weather Rev 113:1282–1299

Boyles R (2006) Investigation of Mesoscale Precipitation Processes in the Carolinas Using a Radar- based Climatology. Doctoral Dissertation, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University. URL: http://www.lib.ncsu.edu/resolver/1840.16/3895

Boyles R, Raman S, Sims A (2007) Sensitivity of mesoscale precipitation dynamics to surface soil and vegetation contrasts over the Carolina Sandhills. Pure Appl Geophys 164:1547–1576

Chen F, Dudhia J (2001) Coupling an advanced land surface-hydrology model with the Penn State—NCAR MM5 modeling system. Part I: Model implementation and sensitivity. Mon Weather Rev 129:569–585
Cione JJ, Raman S, Pietrafesa LJ (1993) The effect of Gulf Stream-induced baroclinicity on the U.S. east coast winter cyclones. Mon Weather Rev 121:421–430
Comin AN, Miglietta MM, Rizza U, Costa CA, Degrazia GA (2015) Investigation of sea-breeze convergence in Salento Peninsula (southeastern Italy). Atmos Res 160:68–79
Crook NA (2001) Understanding hector: the dynamics of island thunderstorms. Mon Weather Rev 129:1550–1563
De Pondeca MSFV et al (2011) The real-time mesoscale analysis at NOAA's National Centers for Environmental Prediction: Current status and development. Weather Forecast 26:593–612
Doran JC et al (1992) The Boardman regional flux experiment. Bull Amer Meteorol Soc 73:1785–1795
Gilliam R, Raman S, Niyogi D (2004) Observational and numerical study on the influence of large scale flow direction and coastline shape on the sea breeze evolution. Boundary-Layer Meteorol 111:275–300
Helmis CG, Papadopoulos KH, Kalogiros JA, Soilemes AT, Asimakopoulos DN (1995) Influence of background flow on evolution of Saronic Gulf Sea Breeze. Atmos Environ 29:3689–3701
Jacobs NA, Lackmann GM, Raman S (2005) The combined effects of Gulf stream-induced baroclinicity and upper-level vorticity on U.S. East Coast extratropical cyclogenesis. Mon Weather Rev 133:2494–2501
Koch SE, Ray CA (1997) Mesoanalysis of summertime convergence zones in central and eastern North Carolina. Weather Forecast 12:56–77
Lin Y, Mitchell KE, (2005) The NCEP Stage II, IV hourly precipitation analyses: Development and applications. In:19th conference hydrology, American Meteorology Society 9–13 Jan, San Diego. CA, USA, Paper 1.2
Novak DR, Bailey C, Brill KF, Burke P, Hogsett WA, Rausch R, Schichtel M (2014) Precipitation and temperature forecast performance at the Weather Prediction Center. Weather Forecast 29:489–504
NRCS (2014) Natural resources conservation service, United States Department of Agriculture, web soil survey. http://websoilsurvey.nrcs.usda.gov. Accessed 5 Sept 2014
Pozo D, Borrajero I, Marin JC, Raga GB (2006) A numerical study of cell merger over Cuba—part I: implementation of the ARPS/MM5 models. Ann Geophys 24:2781–2792
Raman S, Sims AP, Ellis R, Boyles R (2005) Numerical Simulation of mesoscale circulations in a region of contrasting soil types. Pure Appl Geophys 162:1981–2004
Segal M, Avissar R, McCumber MC, Pielke RA (1988) Evaluation of vegetation effects on the generation and modification of mesoscale circulations. J Atmos Sci 45:2268–2293
Sims A (2001) Effect of mesoscale processes on boundary layer structure and precipitation patterns: a diagnostic evaluation and validation of MM5 with North Carolina ECONet observations. Master's Thesis, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University. URL: http://www.lib.ncsu.edu/resolver/1840.16/1075
Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang X-Y, Wang W, and Powers J (2008) A description of the advanced research WRF Version 3 NCAR/Tech Note 475, 113 pp
Wootten A, Raman S, Sims AP (2010) Diurnal variation of precipitation over the Carolina Sandhills Region. J Earth System Sci 119:579–596
Xu L, Raman S, Madala RV, Hodur R (1996) A non-hydrostatic modeling study of surface moisture effects on mesoscale convection induced by sea breeze circulation. Meteorol Atmos Phys 58:103–122