Numerical Simulation of the Interaction between the Sea-Breeze Front and Horizontal Convective Rolls. Part II: Alongshore Ambient Flow

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ABSTRACT

A three-dimensional, high-resolution model is employed to examine the interaction between the sea-breeze front (SBF) and horizontal convective rolls (HCRs) aligned parallel to the front. This study extends the perpendicular case that was the focus of Part I. In this situation, the SBF systematically encounters roll downdrafts and updrafts as it propagates inland.

The sea-breeze circulation is found to significantly influence HCR strength and development. In turn, the rolls are found to dramatically modulate the overall convective activity, alternately suppressing and enhancing SBF-associated convection. Suppression occurs as the SBF merges with a roll downdraft. This is in part due to the downdraft’s introduction of dry air into the mixed layer that becomes part of the SBF cloud’s inflow.

Following suppression, the SBF accelerates as convective heating above the frontal head diminishes. This leads to reinvigorated convection above the front prior to its contact with the next roll updraft, which itself sports a strong, deep cloud of its own by this time. This brings about two strong updrafts obscured by a single, merged cloud shield. During this time, a strong yet brief midlevel downdraft occurs in between the two updrafts; forcing mechanisms for this feature are discussed. The SBF propagation speed also declines significantly during this period; the near-surface portion of the front actually becoming retrograde for a period of a few minutes. Two other, less dramatic roll encounters are also examined.

1. Introduction

The sea-breeze circulation (SBC) is a locally induced flow driven by a thermal gradient that sets up along a shoreline. A long-standing interest with the SBC dates back to the late 1600s when its benefits to ocean navigation were first described (Dampier 1670). Even then it was known that the interface between warm continental and cool marine air contained within the SBC is associated with significant changes in temperature and wind direction. This transition region, at times very sharply defined, is referred to as the sea-breeze front (SBF). As with other frontal phenomena, the SBF comprises the region of strong horizontal density contrast and is often coupled with enhanced vertical lifting.

Much of the focus of contemporary research has been on the propagation speed and inland penetration of the SBF. Clearly, these investigations are critical to improving operational forecasts of localized SBF effects.

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Propagation speeds of 10–20 km h⁻¹ are common (e.g., Clarke 1955) with the greatest speeds normally occurring during the afternoon hours (Simpson et al. 1977). In extreme cases, the SBF has been known to penetrate over 300 km (Atkinson 1981) from the coast, though most SBFs do not reach more than 100 km inland. Propagation speed and inland penetration have been closely tied to the synoptic flow during SBF development (Arritt 1993; Atkins and Wakimoto 1997). It is known, for example, that opposing (offshore) flow impedes SBF speed and inland penetration, but it tends to sharpen frontal contrast. If the offshore flow is strong enough, the SBF may develop completely over water where the atmosphere is more stably stratified, thereby reducing frontal lift (Arritt 1993). In contrast, onshore flow tends to increase propagation speed and inland penetration, but in these cases the SBF is often disorganized and diffuse. Variability in propagation speed has also been tied to the presence of Kelvin–Helmholtz (KH) instability that can form at the head of the SBC. A slowing down of the SBF during periods of strong KH instability has been alluded to in observations (Simpson 1969) and studied using high-resolution 3D numerical models (Sha et al. 1991).
Another branch of SBF research has focused on the relationship between vertical lifting at the SBF head and associated convective initiation. The first numerical studies of SBC-induced convection were carried out by Pielke (1974) and Pielke and Mahrer (1978), though the model’s relatively coarse (≈11 km) grid was unable to resolve the SBF itself. These pioneering studies did reveal, however, that the convergence zone ahead of the SBF might play a key role in the initiation of daytime convection over the Florida peninsula. Since then, researchers have looked more closely at the positioning of convection along the front. Observations (Purdom 1982) and laboratory studies (Simpson and Britter 1980) have suggested that small-scale structures embedded within a convective convergence zone may play a role in the timing and positioning of convection. Investigations focusing on horizontal convective roll (HCR) activity have provided additional evidence that boundary layer variability may impact favored regions for convective development. HCRs are mesoscale features made up of counterrotating helices that commonly form over a heated land surface. Mason and Sykes (1982) have pointed to HCRs as an impetus to variability tied to gravity waves, and Balaji and Clark (1988) showed that the influence of this activity on convection is greatly influenced by the orientation of the waves relative to the convergence line. Hauf and Clark (1989) found that gravity waves generated in stable air near the top of the convective boundary layer can augment roll-type structures. If the wind shear inducing these waves is perpendicular to the wind direction within the planetary boundary layer (PBL), bands of convection can be produced roughly parallel to the mean PBL wind.

Numerical investigations of HCRs and their interaction with other boundary layer phenomena have emphasized two primary precursors for roll development: thermal forcing from the surface and wind shear. Some of the early numerical research focused on conditions of high winds and strong shear (e.g., Woodcock 1940; Grossman 1982), though more recently, shear profile inflection points (e.g., Asai 1972; Miura 1986) and the curvature of the wind speed profiles parallel to roll axes (e.g., Kuettner 1971) has been stressed. Weckwerth et al. (1999) have found that the magnitude of boundary layer shear is more critical to the evolution of roll convection than to the development of rolls themselves. In all cases, the production of roll vortices has been closely tied to the nature of flow in the boundary layer. Rao et al. (1999) used the Advanced Regional Prediction System mesoscale model with nested grids and resolutions as high as 100 m to simulate the SBC near Cape Canaveral, Florida. They found that both HCRs and the presence of KH instability in the vicinity of the front both impact the life cycle of the SBF. Intersections and mergers of the HCRs with the SBF lead to a vorticity signature within the SBC indicative of the interaction. Further, KH billows embedded within the front were associated with localized regions of enhanced vertical motion and preferred points of convection. As with the SBF, the evolution of HCRs is closely tied to airflow characteristics of the mesoscale and synoptic-scale environments.

Growing interest in all of these mesoscale phenomena—the SBF, frontal convective initiation, and HCRs—has led to new inquiry into how they all interact. Several studies have confirmed the ability of roll convection to modulate both clouds (e.g., Kuettner 1959; Streten 1975; LeMone and Pennell 1976) and precipitation (Kelly 1984; Rao and Agee 1996). More recent observations have suggested that HCRs can influence convection associated with the SBF, and are revealing that the orientation of HCRs with the front plays a key role in the timing and positioning of frontal convection. Wakimoto and Atkins (1994, hereafter WA94) and Atkins et al. (1995, hereafter AWW95) have observed the SBF and roll convection during the Convection and Precipitation/Electrification Experiment. SBF events are studied on 12 and 6 August 1991. On 12 August, the synoptic flow is nearly perpendicular to the coastline and preexisting HCRs developing out ahead of the front...
eventually interact normal to the SBF. WA94 and AWW95 report that convective “hot spots” occur along the frontal zone at the intersection points between the SBF and HCR updraft axes. WA94 and AWW95 report that these intersection points are favorable for convective initiation due to increased vertical lifting supplied by HCR updrafts. Indeed, detailed photogrammetric analysis reveals deep cumuli are collocated with these intersection points.

Part I of this study (Dailey and Fovell 1999, hereafter DF99) provides a detailed numerical investigation of this SBF–HCR interaction. A three-dimensional cloud model is initialized with a Florida sounding and offshore synoptic flow and produces HCRs perpendicular to a linear coastline. The SBF develops and eventually propagates inland to interact with the roll convection. The results reveal interesting alongfrontal structure closely tied to the evolution of HCRs. When HCRs are strong, during maximum daytime heating, their intersection points with the SBF provide enhanced lifting and initiate deep convection. Benchmark experiments in DF99 show that the SBF and HCRs modeled independently with the same initialization are unable to produce similar convection. DF99 also shows that convective suppression at the intersection of the front with HCR downdrafts is particularly striking.

On 6 August, WA94 and AWW95 observations reveal the interaction of the SBF with HCRs developing in a synoptic environment very different from the 12 August interaction simulated in DF99. In this case, synoptic flow is nearly parallel to the coastline. The resulting interaction of the SBF with roll convection is reported to episodically modulate the strength of the entire SBF. Because HCR lifting is aligned nearly parallel to the propagating SBF, this case is somewhat analogous to colliding convergence zones. Some work has been done in this area (e.g., Droegemeier and Wilhelmson 1985), but it has typically focused on thunderstorm outflows having thermal contrast and vertical motions that are much stronger than that of the SBF–HCR interaction.

In the front-parallel case described here, the balance of horizontal vorticity between the SBF and HCRs is dy-
namically more important since the vorticity axes are aligned. In a pioneering numerical modeling study, Rotunno et al. (1988) linked horizontal vorticity balance to convective efficiency, although again the analysis was aimed at much stronger convection than we typically see in the SBF. More recently, Wilson et al. (1992) have observed that the balance of vorticity on either side of a convergence line is critical to determining favorable conditions for convection.
regions of convective development. Rao et al. (1999) have shown with a 3D numerical model that vorticity within the SBF can be tied to the development of HCRs in the vicinity of the front.

DF99 focused on the interaction of HCRs aligned perpendicular to an evolving SBF. This paper laid the groundwork for the numerical formulation used to model the SBF and HCRs, both independently and simultaneously. DF99 discussed various dynamical components of the SBF–HCR interaction, including horizontal motion, vorticity, and the cloud field with particular emphasis on frontal modulation of convection. The purpose of this paper is to extend DF99 by reporting on the interaction of the SBF with roll convection aligned parallel to the front. Our goal is to discuss the same components of the interaction, comparing and contrasting the simulation with the results of DF99. The discussion is organized as follows. Section 2 provides a brief review of the numerical model used in this study. Section 3 provides the results and a discussion of the front-parallel simulation. Finally, section 4 provides a summary and a description of future work.

2. Model formulation

As in DF99, this study employs an enhanced version of the compressible, nonhydrostatic Klemp–Wilhelmson (Klemp and Wilhelmson 1978) 3D cloud model (see also Wilhelmson and Chen 1982; Dailey 1996) in a $180 \times 26 \times 18$ km domain. The vertical grid is again stretched, putting seven grid points into the lowest 1 km. The coastline is linear and aligned along the $y$ axis; the sea occupies the western 25% of the domain. Horizontal grid spacings are 0.5 and 1 km in the $x$ and $y$ directions, respectively, with the higher resolution assigned to the expected cross-roll direction. The lateral boundaries are open, the others are not.
Boundary layer fluxes are again handled using Blackadar’s (1976) “force–restore” slab model, as implemented in the Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model Version 4 (Zhang and Anthes 1982; Anthes et al. 1987). The land surface temperature is a prognostic function of several factors, including the surface moisture flux. This flux is itself a function of surface temperature and other factors, including the moisture availability fraction, which varies with land surface type. We have found both HCR strength and SBF evolution to be highly sensitive to the choice of moisture availability. For these simulations, we specifically selected a moisture fraction (15.4%) that yields weak, cloudless rolls in the absence of the SBC.

The simulations examined herein are again highly idealized, with Coriolis and precipitation terms deactivated, and topographic and coastline variations neglected. The sea and land subdomains are uniform with regard to surface temperature and surface type, respectively. Coarser horizontal spatial resolution is employed in the along-roll than across-roll directions for reasons of economy. While these simplifications tend to suppress along-roll variability that might otherwise develop, they also make the dynamics simpler and more tractable.

Figure 1 shows the idealized soundings used to initialize the model. Figs. 1a and 1b show the vertical profiles of potential temperature and water vapor mixing ratio, respectively. These profiles are derived from typical summertime conditions over Florida and are identical to those used in DF99. The ground temperature is initially set equal to the air temperature at the lowest model level. Figure 1c shows the \( u \) and \( v \) components of the mean horizontal wind used in this along-coastal experiment. Note that since the coastline is oriented along a north–south line, all flow is initially oriented along the coastline. That component possesses vertical shear of \( \frac{5}{3} \times 10^{-3} \) s\(^{-1}\) below 1 km and no shear farther above. Additional model setup and initialization details may be found in DF99.

### 3. Results and discussion

#### a. Overview of the simulations

As in Part I, three simulations were made, including sea-breeze only and roll-only control runs. A small amount of white noise was again added to the computed land surface heat fluxes in order to excite the rolls (Balaji and Clark 1988; DF99). As expected, the roll-only simulation (not shown) had generated organized rolls aligned parallel to the mean flow and vertical shear vectors by early afternoon. At 1400 local standard time (LST), the roll wavelengths varied between 5 and 7 km or so, roughly consistent with a \( \approx 2.5 \)-km deep convective boundary layer (Kuettner 1971) and comparable to the rolls generated in the DF99 roll-only run. Owing to the land surface’s greater moisture availability, the rolls in this simulation were less intense than their DF99 counterparts, with maximum roll updrafts never exceeding 1.9 m s\(^{-1}\). Indeed, these rolls were not strong enough to lift air to saturation, and thus no roll clouds were generated.

The sea-breeze only simulation (not shown) was fully three-dimensional, but roll generation was suppressed by removing the random surface heat flux perturbations. As the mean low-level flow was directed parallel to the coastline, the SBF was able to penetrate inland much faster (\( \approx 17 \) km h\(^{-1}\) at 1400 LST) than its counterpart in DF99 (\( \approx 13 \) km h\(^{-1}\)). Lifting at the SBF established a persistent
and appreciably deep cumulus cloud, but vigorous convection was never initiated.

Now we turn to the simulation incorporating both phenomena. For convenience, the afternoon portion of this simulation will be subdivided into three stages, each comprising an SBF–HCR encounter. The roll assimilated during the early stage, ending at 26,400 s after model start (1320 LST), was quite weak and exerted relatively little influence on the propagating SBF. In contrast, the roll encountered during the intermediate stage, ending at 29,100 s (1405 LST), was in the process of initiating deep convection as it was approached by the SBF. The influence of this roll on the SBF was dramatic. A third roll encounter occurred during the late stage, ending at 32,100 s (1455 LST). It is stressed that neither the SBF nor the rolls were able to provoke deep convection independently in the control simulations.

Most of the figures presented below are two-dimensional x–z cross sections consisting of fields averaged in the y direction, along the coastline, roll axes, and SBF. Especially during the early stage, the simulation is rather two-dimensional. During the intermediate stage, however, three-dimensional structures develop, though briefly, both along the SBF and the rolls. During this time, the two-dimensional averaging serves to emphasize the principal features associated with the SBF–roll interaction. In all cases, it is possible to find individual cross sections that bear a strong resemblance to the 2D averaged fields.

b. The early stage

Figure 2 presents 2D averaged fields made during the early stage. The subdomain depicted resides entirely over the land surface; the coastline is located at $x = 45$
The first three panels show the vertical velocity and cloud water fields at 10-min intervals. In this and subsequent figures, the location of the SBF will be taken to be where the 5 m s\(^{-1}\) contour of ground-relative cross-shore flow reaches the ground. Below this curve is onshore-directed air primarily of marine origin. The 5 m s\(^{-1}\) contour was also employed as the marine boundary proxy in Part I and appears to do a very good job of tracking the progress of the SBF.

In Fig. 2a, the SBF is located at \(x = 113\) km. The SBF-forced updraft is clearly visible, as is the associated SBF cloud. The location of the cloud water contours at the back edge of the SBF updraft (relative to its horizontal motion) marks the SBF cloud as the product of stable lifting. Several roll updrafts may be seen in the boundary layer, one of which is in the process of being assimilated by the SBF at the time shown (at \(x = 105\) km). Though weak, the rolls are clearly in the process of intensifying during this period.

The SBF propagation speed during this time is \(\approx 4.2\) m s\(^{-1}\), or 15 km h\(^{-1}\). After incorporating the weak roll updraft, the SBF encounters a weak roll downdraft by the time of Fig. 2b. This downdraft appears to get pushed along by the oncoming SBF during the next 10 min. The rolls farther upstream are also drifting slowly to the east with time. In the roll-only simulation, the rolls evinced no cross-roll translation.

The roll movement in this case is a result of the SBC’s mesoscale east–west circulation. Figure 2d presents the cross-shore wind field at 26 400 s (1320 LST), with the ground-relative vector airflow superposed. In the convective boundary layer (CBL), the flow is directed eastward (onshore); the flow farther aloft is directed offshore. Recall that there is no mean flow in the east–west direction.

At 26 400 s (Fig. 2c), roll updraft located at \(x = 121\) km has expanded vertically and has generated a weak roll cloud. In the roll-only simulation, no condensation ever occurred. In this case, it appears that enhanced horizontal convergence in the boundary layer owing to the superposed SBC mesoscale circulation has helped create the extra lifting required to create the roll cloud. Note that the cloud resides in the offshore flow above the CBL. As a result, the roll updraft has started leaning toward the oncoming SBF.
c. The intermediate stage

1) SBF CLOUD SUPPRESSION DURING ROLL APPROACH

Figure 3 presents fields every 5 min between 26 700 and 27 600 s (1325–1340 LST), composing the first portion of the intermediate stage. During this period, the SBF approaches the rapidly intensifying roll cloud. Note especially the dramatic suppression of the SBF cloud that occurs during the roll approach. As the SBF cloud weakens and drifts seaward, the SBF propagation speed increases, reaching 6.7 m s$^{-1}$ or 24 km h$^{-1}$ by 27 600 s (1340 LST). By the final time shown, there is virtually no cloudiness remaining directly above the SBF. Considering the simultaneous development of deep convection above the nearby roll, a sequence of satellite photographs might suggest that discrete propagation has occurred.

The suppression of the SBF cloud appears to result from roll-induced changes in the front’s upstream environment that affect the source and character of the air flowing over the SBF. Figure 4 presents the equivalent potential temperature ($\theta_e$) field at 27 000 s (1330 LST), just prior to the time when the SBF cloud suppression became especially pronounced. Also shown is the vector airflow field, which has been made SBF relative by subtraction of the front’s 5.9 m s$^{-1}$ (21 km h$^{-1}$) propagation speed at this time.

The CBL over land is marked by relatively high $\theta_e$, which typically decreases with height through the lower
troposphere. Note that the air being lifted over the SBF originates in both the marine and upstream environments. The roll downdraft has caused the high $\theta$, mixed layer just ahead of the SBF to become shallower, reducing the average $\theta$, in part of the SBF’s low-level relative inflow. Simultaneously, the development of the roll cloud farther upstream has induced enhanced flow of low $\theta$, air from above the CBL toward the SBF cloud. Both appear to contribute to the cloud’s ingestion of relatively drier air, bringing about a decline in the amount of cloudiness over the front.

2) SBF REINTENSIFICATION AND SLOWING PRIOR TO ROLL CONTACT

After 27 000 s, the SBF forced lifting intensifies (Fig. 3), perhaps owing at least in part to the accelerated frontal movement. This culminates in *reinvigorated SBF convection prior to the contact with the upstream roll*. This can be seen in Fig. 5, which spans the period between 27 900 and 29 100 s (1345–1405 LST). Note in particular the intensification and vertical expansion of the SBF-associated updraft that occurs between 27 900 and 28 800 s. By 28 200 s (Fig. 5b), a single cloud shield obscures the presence of two strong yet separate updrafts, those associated with the roll and the SBF, respectively. In between these updrafts, a relatively strong downdraft briefly appears. The downward motion is strongest at 28 500 s, the time of Fig. 5c. The forcing mechanism for this downdraft will be examined later.

This portion of the intermediate stage is marked by a substantial slowing of the SBF propagation speed, as well as the introduction of significant alongfrontal variability. The deceleration is particularly pronounced near the surface, leading to a temporary yet distinct alteration in the shape of the marine boundary, giving the SBF at least the appearance of an elevated “nose.” Between 28 200 and 28 800 s, in fact, the surface position of the 5 m s$^{-1}$ contour actually moves seaward (westward). Recall that these fields represent north–south averages; the retrograde motion is even more dramatic in some portions of the front, especially beneath the location of the most vigorous convection. This can be seen in Fig. 6, which provides a 3D perspective of the situation at 28 800 s.

Between the last two times shown, the SBF surges eastward yet again as the SBF and roll updrafts begin to merge. The temporal variation of the SBF propagation speed and low-level updraft intensity can also be seen in Fig. 7, which presents a Hovmöller diagram of vertical velocity recorded at 1.5 km above ground level (AGL) between 25 200 and 32 400 s, a time period spanning all three stages. Also shown are the locations of the ground-relative 5 m s$^{-1}$ contour in cross-shore horizontal wind at 500 and 50 m AGL, proxies for the marine boundary locations. The figure captures the SBF acceleration and updraft strengthening that occurred during the time period covered by Fig. 3, as well as the subsequent deceleration prior to the actual roll contact. The 10 m s$^{-1}$ contour at 500 m is included to show that the air behind the marine boundary exhibits significant temporal variation as well.

Behind the marine boundary, of course, air is flowing eastward (onshore). The propagation speed of the SBF, though, appears to be controlled primarily by whether that air is being accelerated or slowed as it approaches the front from behind. In the absence of mixing, the parcel horizontal acceleration in the east–west direction is a function of the cross-shore pressure gradient; that is,

$$\frac{du}{dt} = -\frac{1}{\bar{\rho}} \frac{\partial p'}{\partial x},$$

where $\bar{\rho}$ is the mean state density (a function of height alone) and $p'$ is the perturbation pressure computed relative to the horizontally homogeneous initial state. The
The DUDT field at the 50-m level is shown in the inset of Fig. 6. The subdomain depicted in the inset is indicated by the dashed box in the main figure.

Positive values of DUDT show where air is being accelerated eastward (onshore). During periods of SBF acceleration, the marine air behind the front is being accelerated toward the front. Soon after westward (offshore) accelerations appear in this air, however, the SBF starts slowing. At those times, the air is still progressing eastward, but it is being slowed as it approaches the front.

3) Convective feedback on the SBF propagation speed

The temporal variation in the SBF propagation speed is due to the effect of latent heat release above the front. During quiescent periods, the SBF progresses quickly eastward, but substantial slowing occurs once condensation above the front commences. The same process operates in midlatitude squall lines with evaporatively produced subcloud cold pools (e.g., Fovell and Tan 1998). The effect in those cases is typically much smaller, however, since the cross-frontal density contrasts tend to be much larger. In contrast, the SBF is rather weakly forced and thus quite susceptible to this convective feedback.

Figures 8 and 9 present the alongshore averaged DUDT field at the same times as shown in Figs. 3 and 5. The shaded field marks instantaneous latent heating release, with the darkest shading depicting the most intense condensation warming. At the first time shown, a small amount of latent heat release is occurring in the SBF cloud (see also Fig. 3a). Within and beneath the region warmed, westward accelerations are present. Thus, eastbound parcels directly behind the marine air boundary are being slowed as they approach the front.

During the period of SBF cloud suppression, however, latent heating wanes. By 27 300 s (Fig. 7c), the marine air behind the SBF is experiencing eastward acceleration. Following this time, the SBF propagation speed increases, at least until convection above the SBF reappears (Fig. 8a). The renewed latent heating is associated with the return of westward accelerations in the marine air and the pronounced frontal slowing that occurs during most of the balance of the intermediate phase.

To further this analysis, we employ the conventional partitioning of the pressure field into dynamic and buoyancy components. The dynamic and buoyancy pressures are associated with gradients in the wind and density fields, respectively. Fovell and Tan (1998) expressed these components as accelerations that sum to the total parcel acceleration. For the 2D averaged situation, the parcel acceleration equations (again, neglecting mixing) are

$$\frac{du}{dt} = -\frac{1}{\rho} \frac{\partial \rho'}{\partial x} - \frac{1}{\rho} \frac{\partial \rho''}{\partial x} + B',$$
$$\frac{dv}{dt} = -\frac{1}{\rho} \frac{\partial \rho'}{\partial z} - \frac{1}{\rho} \frac{\partial \rho''}{\partial z} + B',$$

where the subscripts $d$ and $b$ refer to dynamic and buoyancy components, respectively, and $B'$ is the perturbation buoyancy field (including water loading).

Figure 10 presents a schematic outline for this analysis. Figure 10a depicts the “background” situation. The colder marine air is more dense, and the density gradients across the SBF boundary induce a circulatory tendency that accelerates marine parcels eastward toward the front even as it accelerates parcels above the front westward. That is, $F_{dx} > 0$ within the marine air. Latent heat release above the front also induces a buoyancy-driven circulatory tendency, this one tending to lift air within the cloud and cause subsidence on the cloud’s flanks, as seen in Fig. 10b. This rotational tendency is associated with the establishment of low dynamic pressure on the cloud’s flanks, as shown in Fig. 10c. In this configuration, horizontal gradients of dynamic pressure tend to decelerate eastbound parcels located just behind the frontal boundary; that is, $F_{dx} < 0$. The total horizontal parcel acceleration, DUDT, is the sum of the dynamic and buoyancy horizontal acceleration components.

The $F_{dx}$ and $F_{dz}$ components of DUDT are presented in Fig. 11 for four times during the intermediate phase. The subdomains covered in the figure are indicated in Figs. 8 and 9 by the dashed boxes. Shown at left are the dynamic and buoyancy components of the total acceleration (DUDT) for a parcel indicated by the gray dot in the panels. This parcel’s location is 1 km behind the SBF’s surface position, at an elevation of 0.5 km.

At the first time shown, 27 600 s, there was little latent heating occurring over the SBF (see Figs. 3d and 8d). Figures 11a and 11c show that DUDT was dominated by the buoyancy component at this time. Parcels above the SBF were being accelerated westward by the buoyancy-induced background circulation. Air behind the SBF, including the highlighted parcel, was being accelerated eastward, toward the frontal boundary.

By 27 900 s (Figs. 11b,f), latent heating above the SBF has recommenced (see Figs. 5a and 9a). For the highlighted parcel, the net acceleration is now westward, causing slowing of its eastward progress. The buoyancy acceleration has weakened even as the westward-directed dynamic component has intensified. At 28 500 s (Figs. 11c,g), the dynamic acceleration component is particularly strong for the highlighted parcel and is directed toward the rotationally induced dynamic low at the rear flank of the growing
cloud and updraft (see Figs. 5c and 9c). By the final time, 29 100 s (Figs. 11d,h), latent heating has wanted substantially, and the background circulation has again become dominant.

4) FORCING OF THE BRIEF, INTENSE DOWNDRAFT

In Fig. 5, it was seen that a strong downdraft briefly appeared within the cloud shield, between the strong roll cloud updraft and the rapidly intensifying SBF updraft. The downdraft was positively buoyant (not shown), indicating that it was dynamically driven. This feature is due to the constructive superposition of buoyancy-induced circulations in the SBF and roll updrafts.

Parcel buoyancy acceleration vectors are shown for four times in Fig. 12. The components of these vectors are $F_{bx}$ and $F_{bz}$. In the first panel, the buoyancy-induced circulatory tendency associated with latent heat release in the roll cloud can be seen to be encouraging ascent within the cloud and descent on its west flank, facing

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**Fig. 11.** The $F_{dx}$ and $F_{bx}$ components of DUDT at four times during the intermediate phase of HCR interaction. The subdomains shown for each time correspond to the dashed boxes in Figs. 8 and 9. Shown to the left of each row are the dynamic and buoyancy components of total acceleration (DUDT) for a parcel indicated by the gray dot in the $F_{dx}$ and $F_{bx}$ plots. The contour interval on the dynamic and buoyancy plots is 0.002 and 0.001 m s$^{-2}$, respectively.
the oncoming SBF. As the SBF cloud subsequently intensifies (Fig. 12b), it begins generating its own buoyancy-induced circulation. These tendencies constructively combine to drive downward motion in between, above $x = 116$ km.

The downdraft is strongest at 28 500 s, the time of Fig. 12c. Soon thereafter, the SBF cloud in particular is swept westward, back toward the coast. The buoyancy accelerations above the marine air boundary have a significant westward component, itself a combination of the SBF cloud’s circulatory tendency with the background circulation owing to the buoyancy gradients across the SBF.

d. The late stage

After 29 100 s, the SBF overtakes and assimilates the boundary layer roll updraft. Figure 13 shows 2D averaged fields for six times composing the late stage. Between 30 300 and 31 200 s (1425–1440 LST), cloudiness above the SBF is again suppressed as the residual cloud mass from the previous convecting period is swept seaward. During this time interval, the buoyancy-induced circulatory tendency associated with the previous convection has served to cause the entrainment of low ($\theta_e$) air into the flow rising over the SBF. This is essentially the same “cut-off” process examined in multicellular squall line storms by Fovell and Tan (1998).
This sets the stage for the next, rather less dramatic roll encounter. Unlike its predecessor, this roll (located at $x \approx 132$ km) has not spawned an independent roll cloud. The SBF accelerates slightly prior to the encounter; the propagation speed at 31 020 s is about 5.6 m s$^{-1}$ (20 km h$^{-1}$). As it advances, the roll downdraft located in between the SBF and roll updrafts becomes squeezed. Enhanced horizontal convergence appears to explain the rising motion that appears just above the roll downdraft. This lifting is sufficiently strong to generate a shallow cloud (above $x = 130$ km in Fig. 11c) that slowly grows thicker as the storm-relative airflow subsequently carries it over the SBF updraft by 31 380 s (Fig. 13d).

This sequence of events appears qualitatively similar to the "daughter cloud" phenomenon that Fovell and Tan (1998) noted in their multicellular squall line simulations. In that study, the passage of shallow daughter clouds over the cold pool forced updraft resulted in the reinvigoration of convection and led to the establishment of another convective cell. In this case, however, the reinvigoration is very short lived. The newly established cloud is left behind as the SBF merges with the roll updraft after 31 380 s (Fig. 13d). The latter results in the independent generation of yet another cloud. The growth of this cloud is more rapid and successful, though it never attains the strength of that resulting from the previous roll encounter.

e. Summary of the three stages

Each of the encounters of the SBF with roll vortices is unique. The intermediate stage is certainly the most dramatic and stresses the importance of the circulations induced by SBF and HCR clouds. Yet in each stage, the modulation of the environment into which the SBF is propagating plays a critical role in the evolution of the front and frontal convection. The propagation speed, intensity of frontal lifting, and the character of frontal cloudiness can all be tied to the evolution of the front in the presence of HCRs. At the same time, the background circulation induced by the SBC impacts HCRs developing in its upstream environment. In this way, it is a distinctly two-way interaction, both features exhibiting characteristics that do not exist when they develop independently.

4. Summary

A simulation in which a sea-breeze front (SBF) and horizontal convective rolls (HCRs) evolve simultaneously has been presented. The mean ambient flow is directed parallel to the coast, setting up an SBF and roll axes aligned along the shoreline. In contrast to the cross-shore simulation presented in DF99, the SBF propagates inland, encountering a series of evolving HCRs aligned parallel to the front. The simulation is divided into three stages: early, intermediate, and late, each focused on the interaction of the SBF with an individual roll vortex.

In the early stage, several intensifying HCRs can be seen out ahead of the front propagating inland. In contrast to the roll-only simulation, the HCRs, including the roll downdraft just ahead of the front, appear to be pushed upstream by the front. This movement is attributed to the SBF’s mesoscale circulation. By the end of the early stage, the roll updraft has produced a rather
weak roll cloud. It is noted, however, that the roll-only simulation did not produce any condensation at all. The superimposed SBC has provided enough additional lift to produce a cloud in the offshore flow above the CBL.

As the intermediate stage begins, the HCR out ahead of the front is in the process of producing an intensifying roll cloud. The SBF cloud is suppressed during the approach as it encounters the roll downdraft and drifts seaward. At the same time, the SBF propagation speed increases by about 60% of its speed during early stage. By the end of the interaction with the downdraft, there is virtually no cloudiness above the SBF; owing to the simultaneous development of roll cloudiness, satellite pictures might suggest that discrete propagation is occurring. The drastic suppression of frontal convection results from roll-induced modulation of the SBF's upstream environment. Specifically, the downdraft has reduced the average \( \theta_r \) in the mixed layer ahead of the front, while roll convection has reduced the average \( \theta_r \) in the frontal cloud. These two effects contribute to reduced cloudiness over the frontal head.

Importantly, SBF convection is strikingly reinvigorated just prior to contact with the upstream roll. Two distinct updrafts appear, one associated with the front and the other with the HCR, separated by a strong albeit short-lived downdraft. The marked strength of the downdraft is attributed to the superposition of buoyancy-induced SBF and HCR circulations. Latent heat release encourages a downdraft in the west flank of the deep roll cloud, facing the oncoming front. At the same time, the SBF's own intensifying updraft is producing its own downdraft at its leading edge, facing the roll. These two effects combine to induce strong downward motion between the SBF and HCR that is hidden within the merged SBF and roll cloud shield. The downdraft is short-lived, however, since it depends on the existence of two quickly evolving features.

At this point in the intermediate stage, the front slows, and alongfrontal variation becomes noticeable. The slowing of the SBF is particularly dramatic near the surface below the deepest convection, where the front actually retrogrades briefly. The SBF then accelerates as the frontal and roll updrafts begin to merge. Modulation in the frontal speed appears to be controlled primarily by the relative acceleration of air behind the front, which itself is tied to convection occurring above the frontal head. The density gradient across the SBF boundary accelerates marine parcels toward the front. Latent heat release above the front results in a buoyancy-induced circulation characterized by rising air within the frontal cloud flanked by two downdrafts. As a result, dynamic low pressure is established on each side of the cloud. The total horizontal parcel acceleration is the sum of these dynamic and buoyant tendencies. During the period of strongest frontal convection, when the buoyancy acceleration has weakened and the dynamic acceleration has intensified, the net acceleration is westward, slowing the front's inland progress. Before and after convection is strong, the buoyancy-driven background circulation is dominant and the front proceeds inland.

The late stage SBF–HCR interaction is first characterized by the entrainment of dry air into the flow rising over the front. This HCR has not produced its own cloud. As in the previous encounter, the SBF accelerates prior to engagement with the roll updraft, and the strengthening of the downdraft between can be seen as well. Reinvigoration of SBF lifting is short lived as the SBF and roll updraft merge. Though this stage is qualitatively similar to the intermediate stage, the overall interaction and resulting intensity of convection are less pronounced.

Future work will focus on the combined findings of the cross-shore and alongshore experiments. It is hypothesized that, in an ambient flow having both cross-shore and alongshore components, the characteristics of both interactions may occur. Since real frontal interactions with roll convection are not purely parallel or perpendicular, a study of the two processes occurring in unison will further enhance the investigation.

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REFERENCES


