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1. INTRODUCTION

The mesoscale sea breeze has important consequences for many densely populated coastal environments, including convection initiation, aviation safety, and air quality. The sea breeze characteristics before and after sunset are markedly different (Sha et al 1993). A gravity current will form during the early afternoon due to the relatively large density difference between the land and sea air. During the afternoon, as the lighter land air is forced upward by the cooler dense sea air, Kelvin-Helmholtz (KH) billows often form along the interface, as well as thin regions of turbulent rising air, playing a crucial role in the mixing process (Simpson 1994). After sunset, the frontal zone expands as longwave radiation cools the surface which reduces vertical mixing. With further inland penetration, the sea breeze encounters increasingly stable air near the ground, resulting in the formation of an undular bore or cutoff vortex (Sha et al. 1993).

It has been demonstrated that large-scale winds have profound effects on both the strength and inland penetration of sea breezes (Arritt 1993, among others). In general, offshore flow results in a sharper frontal discontinuity and less inland penetration, while onshore flow produces weaker fronts which may penetrate further inland.

Most sea breeze studies have focused on its more dramatic daytime properties near the coast whereas inland nocturnal sea breezes have received much less attention. The reason for this neglect is a lack of good observational data in the boundary layer. Sha et al. (1991) note the necessity of high resolution data to capture the finer structures of the sea breeze.

A unique opportunity to examine the nocturnal sea breeze became available at the Savannah River Site (SRS, located roughly 150 km from the Atlantic Ocean in southwestern South Carolina) during the Stable Boundary Layer Experiment (STABLE), 12-17 April, 1988. Measurements were obtained from eight 61 m towers, a 300 m television tower (WJBF), instrumented at seven vertical levels, two sodars, a tether sonde, and a sonic anemometer (Weber and Kurzeja, 1991). This observational network captured many of the spatial characteristics of the inland nocturnal sea breeze on three nights of extensive data collection. Moreover, these three nights show a range of synoptic winds which have important qualitative effects on the sea breeze.

Numerical simulations using the Regional Atmospheric Modeling System (RAMS, Version 3a, developed at Colorado State University, Pielke et al. 1992) are performed to explain the unique observational data obtained from Project STABLE. Two separate nights are modeled and the results are compared with data obtained from the TV tower.

2. NUMERICAL MODEL

The atmospheric model (RAMS) used in this research has been in a continuous state of modification for over ten years. It has been used and verified as a viable tool in many numerical modeling efforts, including the sea breeze (Physick and Smith, 1985 and Xian and Pielke, 1991). Details regarding the model are not given here, but can be found in Pielke et al. (1992).

Three-dimensional initial conditions are obtained using the National Meteorological Center (NMC) Limited-area Fine-mesh Model (LFM), which contains horizontal wind components, geopotential heights, temperature, and humidity on a stereographic grid encompassing North America for five pressure levels at twelve-hour increments. In addition, archived upper air

soundings are used to modify these conditions. The LFM data are blended with the upper air data and then interpolated to the RAMS grid. These fields are used for the initial and boundary conditions. Time-dependent lateral boundary conditions are created from these fields, and the Davies relaxation technique is used to nudge the model results toward the lateral boundary conditions (Walko et al. 1993). At the surface, a soil model is used which incorporates data sets of vegetation and topography of varying resolution (Tremback and Kessler, 1985), while at the model top, a rigid lid is assumed.

A nested grid configuration is utilized in this study in which the coarse grid (10 km grid spacing on a domain of roughly 800 km x 800 km) covers the southeastern United States with finer grids (2.5 and 0.625 km grid spacing) centered over the SRS. The coarse grid contains both a significant portion of the Appalachian Mountains and the Atlantic Ocean, while the grid containing 2.5 km resolution nearly extends to the Atlantic coast, allowing for detailed study of the sea breeze as it traverses inland. The vertical coordinates (terrain-following) are stretched from the surface to a model top of ~15 km.

Simulations were performed for two different nights: 14-15 April, and 16-17 April, 1988. Since LFM data is available at 0 and 12 UTC, we began the simulations for each night at 12:00 UTC (8:00 EDT) to allow the model to 'spin up' and create a realistic boundary layer. The time period of interest is the 18-hour interval from 12:00 EDT to 6:00 EDT the following morning.

3. RESULTS AND DISCUSSION

As described in Weber and Kurzeja (1991), the night of April 14-15, 1988 was characterized by a low pressure center north of Lake Ontario with a cold front stretching southwest through the Ohio Valley to the Texas panhandle. Winds at 850 mb were 15-20 knots and southwesterly over inland South Carolina and west south-westerly at the coast.

By the night of April 16-17 the cold front had passed through South Carolina and become stationary over central Florida. A surface high pressure center was located over South Carolina and winds at 850 mb were west-northwesterly at around 20 knots.

The observed and predicted wind direction and temperature at the 300 m TV tower are shown in Figs. 1 and 2. The wind direction was significantly different on the two nights. On the first night the winds were parallel to the coast (southwest) while on the second night they were predominantly off-shore (northwest). The model wind directions are generally consistent with the observed directions (Figs. 1 and 2).

The temperature plots in Fig. 2 clearly show the frontal passage. The simulated frontal passage is 2 hours late on the first night (00:00 EDT on April 15 instead of 22:00 EDT on April 14) but simulated correctly on the second night (01:00 EDT on April 17).

Previous work, e.g., Reible et al (1993) and Arritt (1993), has shown that off-shore synoptic winds will both intensify frontal convergence and retard the inland penetration of the sea breeze. Thus, we would expect a narrower, slower moving, front on the second night than on the first night. The observations are consistent with the frontal speed expectation since the front arrives three hours later on the second night than the first. However, no difference is seen in the width of the frontal boundary on the two nights (Fig. 2). In contrast, the model shows a considerably sharper frontal boundary on the second night than the first, with a front arrival time only one hour later.

Further insight into the model simulation of the sea breeze front can be obtained from the 61 m streamlines (Fig. 3). This figure shows the front on the first night to be a broad confluence zone that dissipates as it propagates inland. It also exhibits uneven inland penetration and appears to rotate inland about a point south of the integration domain. The front on the second night is more concentrated and propagates inland parallel to the coast. Note that on the first night the wind backs with frontal passage at all points along the front. In contrast, on the second night the wind veers with frontal passage in the southern half of the domain and backs in the northern half. The occurrence of both veering and backing with frontal passage on the second night is caused by the formation of a deformation circulation along the front. Veering or backing will occur depending on the location with respect to the neutral point.

Despite the good general agreement between observations and model winds, there are some differences. The observations show gradual wind shifts in the hours between noon and the frontal passage whereas the model winds are fairly constant in direction. An important disagreement is seen on the second night where the observed temperature stratification is much greater below 50 m than in the model.

An interesting contrast between the observed fronts on the two nights is the sharper frontal gradient below 100 m on the second night (Fig. 2). While this feature was simulated by the model, a second temperature minimum, seen at the TV tower at 02:00 EDT on the second night, was not. In fact, the model did not simulate other observed small-scale features, such as the roll vortices preceding and following the front. The cross-sectional extent of these vortices is approximately 15 km, which should be resolvable by the model's fine grid (0.625 km). However, these vortices are probably not simulated by the model because they are initiated near the coast, where the model's grid spacing (10 km) is too coarse. This phenomenon is also noted by Lyons et al. (1995).

The differences between the two simulated nights can be further illustrated with a vertical cross-section normal to the coastline. In Fig. 4, a cross-section is taken through the second grid of the model running from the northwest to the southeast corner of the model domain. Contours of temperature ($^{\circ}\text{C}$) for two different times are shown for the two nights up to a height of ~ 850 m. (Note that local topography is also shown in the plots). On both nights at 20:00 EDT (parts a and c), a gravity current has formed, as illustrated by the sharp rise in temperature between $X = 50$ and 100 km. By 00:00 EDT on the first night, it is clear that longwave radiation cooling near the surface has weakened this gradient allowing temperature inversions to exist up to 400 m ASL. On the second night (part d), a more distinct break is seen at the leading edge of the advancing front which is also shallower than the previous night's inversion. The elevated peaks in temperature at two different horizontal locations was also evident in Fig. 2d.

4. CONCLUSIONS

Meteorological data collected during two separate nights of Project STABLE indicate the presence of nocturnal sea breezes at SRS. Numerical simulations showed that the major differences in the sea breeze on the two nights occur due to the influence of the large-scale winds and atmospheric stability. On nights when the flow is out of the southwest, a broad deep confluence zone occurs, which propagates quickly inland. However, when the synoptic flow is directly offshore, a sharp shallow convergence zone results accompanied by small-scale fine-structured vortices. Based on comparisons with observations, the model appears to capture the general features of the nocturnal sea breeze on both nights, but does not reproduce the variability in structure near the surface on the second night, most likely because of inadequate horizontal grid spacing along the coast.

ACKNOWLEDGMENTS

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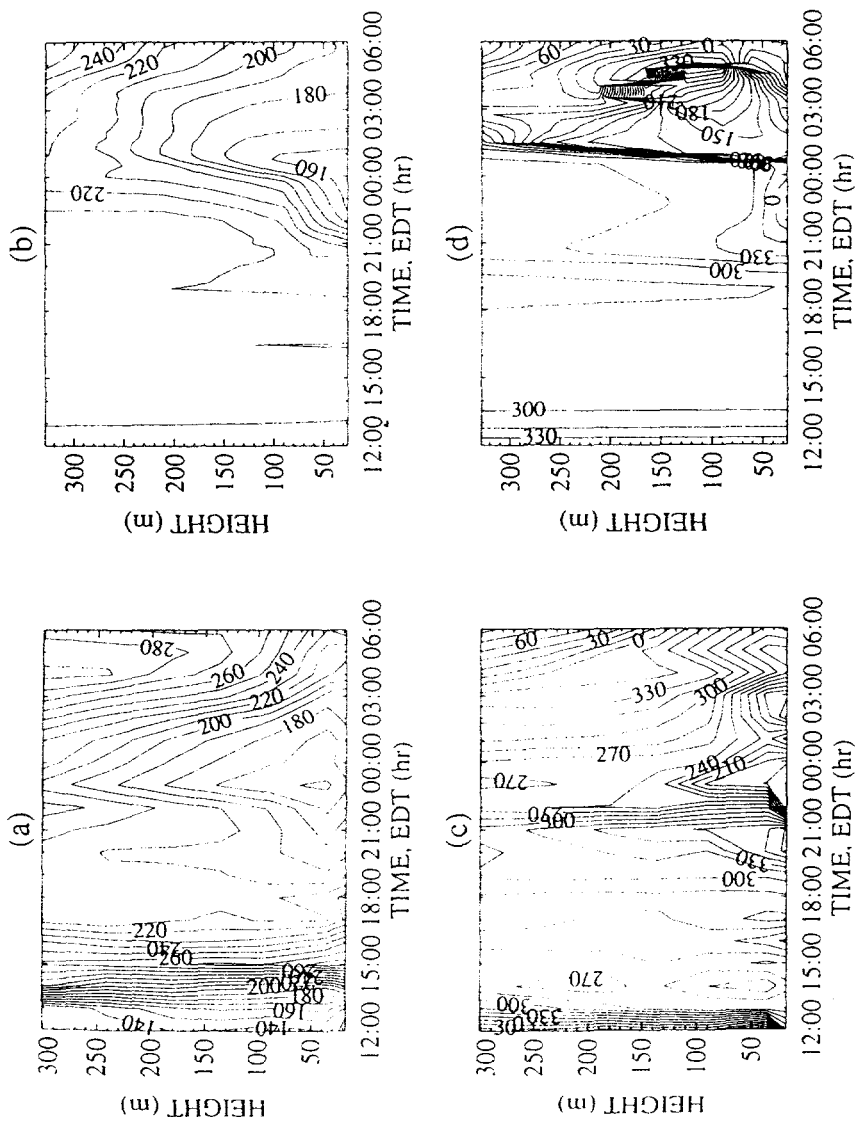


Figure 1. Wind azimuth contours (compass degrees) at the WJBF television tower for the 18 h period as: (a) observed on 14-15 April, (b) predicted on 14-15 April, (c) observed on 16-17 April, and (d) predicted on 16-17 April.

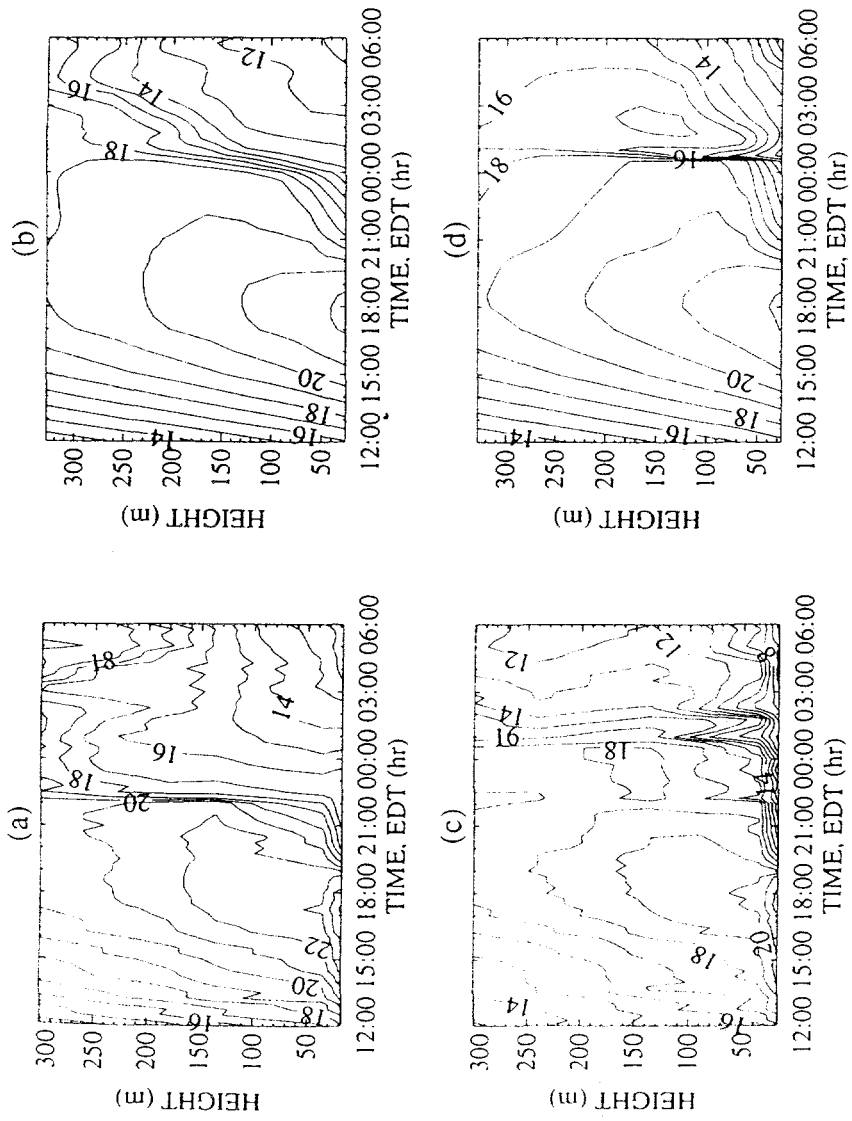


Figure 2. Temperature contours ($^{\circ}\text{C}$) at the WJBF television tower for the 18 h period as: (a) observed on 14-15 April, (b) predicted on 14-15 April, (c) observed on 16-17 April, and (d) predicted on 16-17 April.

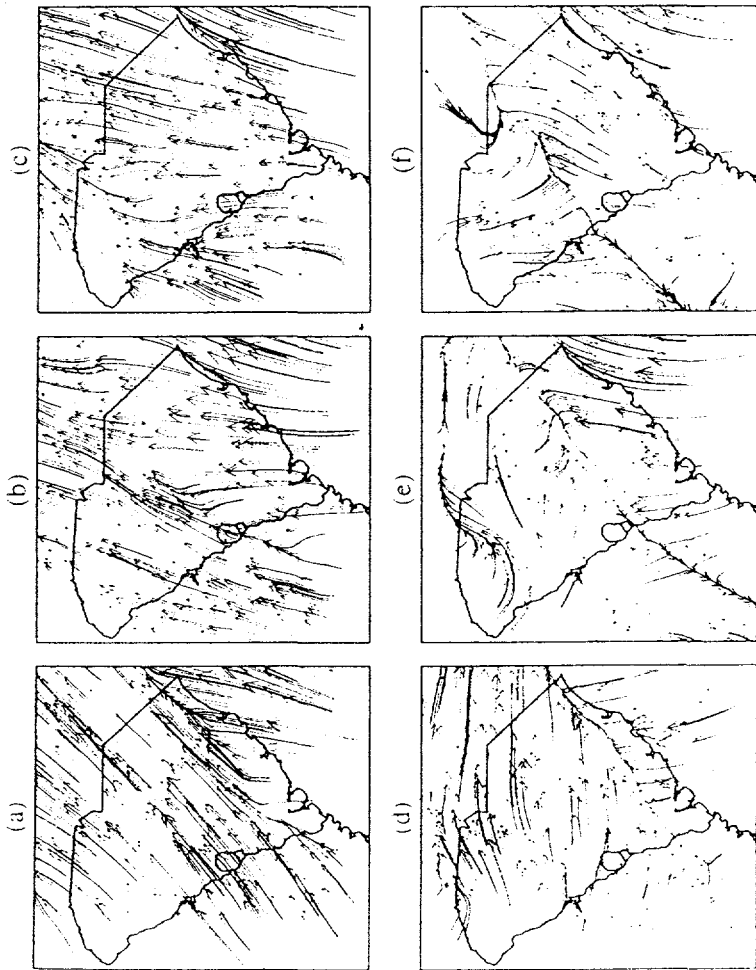


Figure 3. Predicted near surface streamlines (61 m AGL) in the model domain at a time of: (a) 18:00 EDT, 14 April, (b) 22:00 EDT, 14 April, (c) 02:00 EDT, 15 April, (d) 18:00 EDT, 16 April, (e) 22:00 EDT, 16 April, and (f) 02:00 EDT, 17 April.

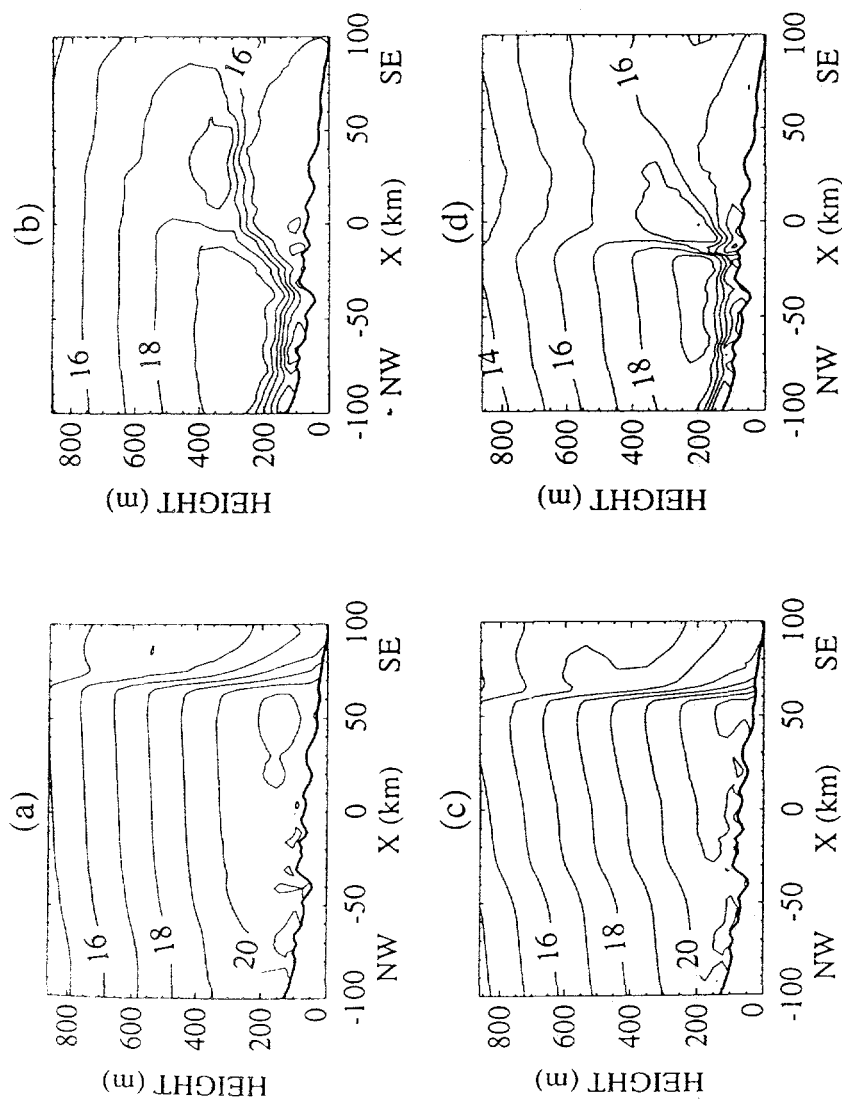


Figure 4. Vertical cross-section contours of predicted temperature ($^{\circ}\text{C}$) along a slice oriented normal to the coast where the furthest inland point is located in the northwest (NW) at a time of: (a) 20:00 EDT, 14 April, (b) 00:00 EDT, 15 April, (c) 20:00 EDT, 16 April, and (d) 00:00 EDT, 17 April.