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ABSTRACT

The 22–23 February 1998 central Florida tornado outbreak was one of the deadliest and costliest in Florida’s history; a number of long-track tornadoes moved across the Florida peninsula after 0000 UTC 23 February 1998. In the 12–24 h prior to 0000 UTC 23 February, a vigorous upper-level synoptic system was tracking across the southeast United States, and a north–south-oriented convective band located ahead of the cold front was moving eastward across the Gulf of Mexico. Strong vertical wind shear was present in the lowest 1 km, due to a low-level jet at 925 hPa and south-southeasterly surface flow over the Florida peninsula. Further, CAPE values across the central Florida peninsula exceeded 2500 J kg⁻¹. Upon making landfall on the Florida peninsula, the convective band rapidly intensified and developed into a line of tornadic supercells. This paper examines the relationship between a diabatically induced front across the central Florida peninsula and the rapid development of tornadic supercells in the convective band after 0000 UTC 23 February. Results suggest that persistent strong frontogenesis helped to maintain the front and enhanced ascent in the warm, moist unstable air to the south of the east–west-oriented front on the Florida peninsula, thus allowing the updrafts to rapidly intensify as they made landfall. Further, surface observations from three key locations along the surface front suggest that a mesolow moved eastward along the front just prior to the time when supercells developed. It is hypothesized that the eastward-moving mesolow may have caused the winds in the warm air to the south of the surface front to back to southeasterly and create a favorable low-level wind profile in which supercells could rapidly develop.

1. Introduction

On 22–23 February 1998, a deadly tornado outbreak struck the central Florida peninsula. The outbreak was confined to a relatively small geographic area (Fig. 1) and was short lived, lasting less than 4 h from the first tornado to the last (information online at http://www.srh.noaa.gov/srh/cwwd/serviceassessment/assessment/cntrfl.pdf). Nonetheless, the episode resulted in 42 fatalities and 260 injuries. A possible contributor to the large number of deaths and injuries may have been that the event occurred after sunset, when warning the public is more difficult than during the day (Fike 1993). Additionally, a large number of structures that sustained damage were mobile homes, which generally are not constructed to withstand the high wind speed of a tornado. The difficulty in warning the public was compounded by the very rapid increase of the tornado threat after a northeast–southwest-oriented con-
vective band moved across the Gulf of Mexico and made landfall on the Florida peninsula. Although soundings from 0000 UTC 23 February 1998 suggested that ample instability and vertical wind shear were present for supercell development, the rapid evolution of the system from a disorganized band of heavy precipitation into a line of tornadic supercells well after sunset made it difficult to warn the public, as this is a time when many people are not monitoring traditional media to stay up-to-date on evolving severe weather threats. The motivation behind this paper is to examine the event from a synoptic- and mesoscale perspective in order to gain a better understanding as to why the (apparently) weakening system rapidly evolved into numerous supercells after making landfall on the Florida peninsula. This paper will be organized as follows: data sources will be documented in section 2; the motivation for this study will be discussed and placed in the context of past research in section 3; the synoptic- and mesoscale aspects of the evolution of this episode are discussed in sections 4 and 5, respectively; the results of a special hindcast of the National Centers for Environmental Prediction (NCEP) Eta Model will be presented in section 6, and conclusions about the forcing mechanisms responsible for this tornado episode will be discussed in section 7.

2. Data sources and methodology

Data sources used in this study include storm reports [obtained from NCEP’s Storm Prediction Center (SPC)], surface (including ship and buoy) and upper-air observations from the SPC and the local University at Albany archive, the NCEP-National Center for Atmospheric Research (NCAR) reanalysis gridded dataset (2.5° × 2.5°; Kistler et al. 2001), the NCEP Aviation Model (AVN; 2.5° × 2.5°; Kanamitsu 1989; Kanamitsu et al. 1991), NCEP Eta Model (80 km; Black 1994; Rogers et al. 1995) output from the University at Albany archive, sea surface temperature data from the U.S. Navy Stennis Space Laboratory, cloud-to-ground lightning data from the National Lightning Detection Network (Cummins et al. 1998), and base reflectivity radar and velocity data obtained from the SPC. Surface observations were interpolated to a 0.25° × 0.25° grid via a Barnes interpolation scheme for calculations of two-dimensional frontogenesis as derived by Miller (1948) and absolute vorticity. A special hindcast of the 32-km NCEP Eta initialized with North American Regional Reanalysis (NARR) data (Mesinger et al. 2004) was completed to evaluate model performance at resolving the mesoscale features that became important to the evolution of this event. Both the Kain–Fritsch (KF; Kain and Fritsch 1993) and the Betts–Miller–Janjic (BMJ; Janjic 1994) convective parameterization schemes were used in the hindcasts.

3. Background synoptic climatology

Previous research has shown that there is a relatively high frequency of tornadoes in the overnight to early morning hours during the cool season in the southeastern United States, particularly in regions within close proximity to the Gulf of Mexico (e.g., Hagemeyer 1997; Mello et al. 2000; Knupp and Garinger 1993). These nocturnal tornado episodes can be particularly dangerous, with up to one-third of them associated with fatalities (Fike 1993). In fact, most strong and violent tornadoes (F2 or greater) in Florida occur during the cool season and are associated with extratropical cyclones (Hagemeyer 1997).

The return flow of tropical air across the southeast United States subsequent to the passage of cold fronts into the Gulf has been shown to be important in the development of severe weather scenarios along the Gulf coast (e.g., Crisp and Lewis 1992; Lewis and Crisp 1992; Weiss 1992). The warm Loop Current (LC) in the Gulf of Mexico can increase fluxes of heat and moisture into return-flow air and lead to rapid airmass destabilization (Molinari 1987). However, correctly forecasting the trajectories of return-flow air is difficult, and it has been shown that numerical prediction models are not able to accurately forecast the modification of the boundary layer, partially because of the lack of data.
over the Gulf (Weiss et al. 1998). Nevertheless, modification of air as it crosses the Gulf and moves onshore is an important factor in determining the severe weather potential across the southeast United States.

To conceptualize the synoptic-scale features associated with cool season (November–March) tornado episodes across the southeast United States (the area south of 36.5°N and east of 94°W), a total of 174 tornado episodes between 1950 and 2001 that began between 0000 and 0600 UTC were composited using the NCEP–NCAR reanalysis grids. A tornado episode was defined to be all tornado reports that occurred within 24 h of each other. The composite is “event relative”; each grid was translated prior to averaging so that the location of the first tornado report was at a common point (denoted by the asterisk in Fig. 2). Despite the large number of episodes in this composite and inherent smoothing in any compositing technique, a distinct large-scale signal appears. The tornado episodes occur downstream of a relatively potent 500-hPa trough, and on the southern edge of an area of warm-air advection at 850 hPa (Figs. 2a and 2b). Large-scale forcing for ascent is confirmed by the presence of a vertical motion maximum at 700 hPa (Fig. 2c). Additionally, low-level moisture is present in the composite, as a region of high equivalent potential temperature (θ_e) air and southwesterly flow at 850 hPa points directly toward the region where each tornado episode began (Fig. 2d). A very strong (greater than 44 m s⁻¹) upper-level jet streak is present at 200 hPa (Fig. 2e). The tornado episode begins in the warm sector of the surface low (Fig. 2f), and in the region of enhanced ascent in the equatorward-entrance region of the upper-level jet (Fig. 2e). A cross section through the jet entrance region confirms the presence of strong ascent over the location of the first tornado (Fig. 3).

4. Large-scale evolution

The 22–23 February 1998 central Florida tornado episode exhibits some large-scale similarities to the composite 0000–0600 UTC tornado episode shown in Fig. 2. NARR analyses for 0000 UTC 23 February show a surface low over Mississippi and Alabama (Fig. 4a), and a potent 500-hPa trough upstream of the Florida peninsula (Fig. 4b). Deepening of the surface cyclone from 1012 to 1004 hPa had occurred as this upper-level system moved eastward across the southeast United States in the 2 days prior to 23 February (not shown). There is a very strong southwesterly low-level jet at 850 hPa (greater than 23 m s⁻¹) in the warm sector ahead of the cold front (Fig. 4d). A jet streak was present in all model initial analyses just offshore east of the southern Florida peninsula, while a core of >60 m s⁻¹ winds at 175 hPa extended back to the west over south Florida at 0000 UTC 23 February (Fig. 4c). The upper-level jet strength over northeast Florida appears to have been underestimated in the model initial analysis, as evidenced by the 68 m s⁻¹ (136 kt) wind maximum at 175 hPa in the Jacksonville, Florida (JAX), 0000 UTC 23 February sounding (Fig. 5). The model wind speeds over northeast Florida at 200 hPa were only ~50 m s⁻¹ (Fig. 4c). These differences suggest that the placement and/or latitudinal extent of the upper-level jet core over south and/or central Florida may be poorly represented in the model analyses.

Although this event has many similarities to the large-scale composite southeast U.S. tornado episode shown in Fig. 2, there were considerable forecasting uncertainties developing as time progressed toward the beginning of the tornado episode (approximately 0000 UTC 23 February). While a large upstream 500-hPa trough was present, the primary region where cyclonic vorticity advection was increasing with height lay to the north and east of the Florida peninsula in South Carolina and Georgia at 0000 UTC 23 February (not shown). There was unstable air present over the Florida peninsula, as evidenced by the high surface-based convective available potential energy (CAPE) of 2891 J kg⁻¹ and the low lifted index value (−9°C) in the 0000 UTC 23 February Tampa Bay, Florida (TBW), sounding (Fig. 6a). Additionally, the TBW hodograph shows prominent clockwise turning and strong vertical shear (0–1-km shear was ~15 m s⁻¹ and 0–6-km shear was ~32 m s⁻¹), particularly below 700 hPa, as well as a very strong increase in wind speed between the surface (15 m s⁻¹) and 925 hPa (22 m s⁻¹; Fig. 6b). The high values of CAPE and 0–1-km shear over the Florida peninsula were conducive to supercell formation over the Florida peninsula at 0000 UTC 23 February.

The SPC had issued a tornado watch at 2200 UTC 22 February for the Florida peninsula valid through 0200 UTC 23 February based on favorable vertical wind shear profiles and moderate instability across the Florida peninsula. The decision whether or not to issue another tornado watch to become valid at 0200 UTC 23 February was decidedly difficult for SPC forecasters [S. Weiss and R. Johns 2002, personal communication (both were on shift during this event)]. There was concern that the primary threat was heavy rain/flooding associated with a broad area of rain continuing over parts of northern and central Florida. Since the late afternoon all warnings issued by the local weather forecast offices had been for flash flooding. Furthermore, a convective band advancing into the region from the Gulf of Mexico appeared to be weakening substantially.
Fig. 2. Storm-relative composite of tornado episodes beginning between 0000 and 0600 UTC. (a) The 500-hPa heights (solid, every 6 dam), vorticity (dashed, every $4 \times 10^{-3}$ s$^{-1}$), and vorticity advection (shaded every $2 \times 10^{-10}$ s$^{-2}$); (b) 850-hPa heights (solid, every 30 m), temperature (dashed, every 4°C), and temperature advection (shaded every $3 \times 10^{-5}$°C s$^{-1}$); (c) 700-hPa heights (solid, every 30 m) and vertical motion (dashed and shaded, every $0.5 \times 10^{-3}$ hPa s$^{-1}$); (d) 850–500-hPa lapse rate (dashed, every 1°C), 850-hPa $\theta_e$ (shaded every 5 K), and 850-hPa winds (barbs, m s$^{-1}$ but in kt convention); (e) 200-hPa heights (solid, every 24 dam) and isotachs (shaded every 4 m s$^{-1}$); and (f) 1000-hPa heights (solid, every 30 m), 1000–500-hPa thickness (dashed, every 6 dam), and 700-hPa relative humidity (%). The asterisk denotes the location of the first tornado. The black line in (d) denotes the cross section in Fig. 3.
with time in terms of intensity and organization, and the large-scale forcing for ascent associated with the upper-level system was shifting to the north and east. However, because of the high CAPE and strong vertical wind shear present in the 0000 UTC 23 February TBW sounding, it was determined that the potential for tornadoes was still present, and a new tornado watch was issued by the SPC to replace the earlier watch at 0113 UTC 23 February.

5. Mesoscale evolution

a. Convective band

A convective band ahead of the cold front was moving across the Gulf of Mexico between 1800 UTC 22 February and 0000 UTC 23 February 1998. The convective band formed in the warm sector, in association with a strong low-level jet and warm unstable air present over the Gulf of Mexico. The intensity of the
band varied widely as it moved across the Gulf. It appeared very intense and organized during the early afternoon of 22 February in the infrared satellite imagery (Fig. 7a). Subsequently, the convective band weakened substantially as it moved across the relatively shallow shelf waters off the west coast of Florida (Fig. 7b). Figure 8 shows the sea surface temperature (SST) and anomaly for 22 February. The SST anomaly is computed by subtracting a climatological field from the actual SST field (Fig. 8a). The climatological SST field is interpolated from the University of Wisconsin—Madison Comprehensive Ocean–Atmosphere Data Set 1° monthly sea surface temperature climatology (information online at http://www7320.nrlssc.navy.mil/altimetry/defs/def_frame.html). The LC and cooler shelf waters to its north and east are easily distinguishable in Fig. 8a. The already warm LC was +3°C warmer than normal, while the normal colder shelf waters west of the Florida peninsula were −3°C colder than normal (Fig. 8b). These SST anomaly patterns resulted in an enhanced SST gradient in the waters west of the Florida peninsula.

Cloud-to-ground (CG) lightning frequency was used as a proxy for convective band intensity to relate the intensity to the SSTs in the Gulf of Mexico. The system moved eastward across the Gulf from 1800 UTC 22 February to 0200 UTC 23 February, when it made landfall on the Florida peninsula. High CG flash counts (500–600 per 15 min) occurred while the convective band was over the anomalously warm waters of the LC (Fig. 9). As the system moved eastward and encountered the anomalously cool shelf waters, CG flash totals dropped off dramatically to less than 100 per 15 min (Fig. 9). The rapid reintensification of the system after it made landfall on the Florida peninsula is also evident in Fig. 9, as CG flash totals by 0200 UTC 23 February increased to levels seen earlier when the squall line was over the warm LC. As the system exited the Florida peninsula on the east coast and encountered the warm Gulf Stream, further reintensification is apparent based on the CG flash frequency. The results from Figs. 6–9 collectively suggest that the intensity of the prefrontal convective system is strongly tied to the enhanced surface heat and moisture fluxes over the LC and the Florida peninsula.
Figure 9 showed that CG flash frequency appears to be closely related to the SST anomalies in the Gulf of Mexico. What, then, led to the very rapid intensification of the convective band after it made landfall on the Florida peninsula? Earlier in the day, an intense bow echo embedded in a region of moderate to heavy precipitation had moved across the Florida panhandle and northern Florida during the morning hours of 22 February (not shown). As the region of precipitation moved eastward, it expanded across northern Florida northward into Georgia but made little southward progress into the central Florida peninsula. Evaporational cooling associated with this region of precipitation and inhibition of solar heating due to heavy cloud cover, in addition to daytime heating on the southern Florida peninsula, helped to set up a strong low-level baroclinic zone that persisted across the central Florida peninsula until after 0000 UTC 23 February.

At 1800 UTC 22 February, the high frequency of CG flashes associated with the convective system as it

Fig. 7. Infrared satellite images of convective band at (a) 1815 UTC 22 Feb and (b) 0015 UTC 23 Feb.
Fig. 8. SST (a) mean and (b) anomalies (°C) for 22 Feb 1998.
moves across the LC is overlaid on the surface analysis in Fig. 10a. Southerly flow of 15–20 kt and dewpoints above 20°C were present across the southern Florida peninsula. Partly sunny skies were allowing daytime heating to destabilize the air mass on the Florida peninsula (Fig. 10a). At the same time, moderate rain was being reported at stations across the Florida panhandle. Temperatures in the rain-cooled air across northern Florida remained about 10°C cooler than to the south. The associated front between rain-cooled air to the north and the clear air to the south helped to set the stage for frontogenesis associated with differential diabatic heating. The strength of the surface front increased in intensity to approximately 5°C (100 km)^{-1} by 0000 UTC 23 February as southerly flow persisted to the south of the front, while north to northeasterly winds continued to the north of the front (Fig. 10b). The temperature gradient along the front had increased sharply in 6 h as evidenced by the 7°C drop (≈3.5°C drop) in temperature at Gainesville, Florida (GNV) [Orlando, Florida (MCO)], between 1800 UTC February and 0000 UTC 23 February (Fig. 11). Further, the \( \theta_e \) gradient along the front had increased markedly as well, as \( \theta_e \) at GNV dropped off \( \approx \)16 K, while at MCO \( \theta_e \) stayed nearly stationary between 1800 UTC February and 0000 UTC 23 February (Fig. 11).

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Fig. 9. The 15-min lightning strike frequency from 1800 UTC 22 Feb to 0900 UTC 23 Feb. Red solid line indicates the transition longitude from warm (west) to cold (east) SST anomalies; dashed blue lines represent east and west coasts of the Florida peninsula.
Fig. 10. (a) Surface analyses of sea level pressure (solid, hPa), temperature (°C, dashed), and lightning at (a) 1800 UTC 22 Feb and (b) 0000 UTC 23 Feb. Lightning is all strikes in the half hour ending at the valid time of the map.
At 0000 UTC 23 February, the northern edge of the northeast-southwest-oriented convective band was beginning to make landfall in exactly the region where the front had formed (Fig. 10b). By 0200 UTC 23 February, the convective band had intersected the surface front [Brooksville, Florida (BKV), located approximately at the front, reported rain beginning at 0100 UTC February] and began to rapidly organize and intensify (Figs. 12a and 13a). Sustained easterly to northeasterly flow of 10 kt had developed to the north of the front, and southerly flow continued to the south (Fig. 12a). A mesolow developed on the west coast of the Florida peninsula at the surface front by this time, as evidenced by the >1 hPa drop in sea level pressure at BKV between 0100 and 0200 UTC 23 February (Fig. 13a). Melbourne, Florida (MLB), radar imagery from near this time shows individual cell elements within the line making landfall in the vicinity of the front (Figs. 14a and 15). Evidence of the southward movement of the front is present in the Leesburg, Florida (LEE), meteogram, where the temperature drops sharply and the wind shifts to easterly between 2300 UTC 22 February and 0000 UTC 23 February (Fig. 13b). As the surface wave develops and moves eastward between 0100 and 0300 UTC 23 February, the temperature at LEE rebounds to 20°C and the wind shifts back to southeast by 0300 UTC 23 February (Fig. 13b). At 0300 UTC 23 February, the mesolow along the front had further intensified (Fig. 12b), as the sea level pressure at LEE had dropped more than 2 hPa in 2 h (Fig. 13b). East of the mesolow the front had dropped to the south of Sanford Airport, Florida (SFB), as evidenced by the wind shift to the east-northeast and sharp drop in temperature and rise of ~1 hPa in pressure just after 0000 UTC 23 February (Fig. 13c). Just prior to the onset of convection at LEE at 0400 UTC 23 February, the front began to shift north of LEE as the temperature began to rise and the wind briefly shifted to southeasterly at 0330 UTC 23 February. It was approximately by this time that individual supercells were apparent along the convective band oriented northeast-southwest, each with mesocyclones as indicated in the storm-relative velocity imagery [Fig. 14b; see Lee and White (1998) for a description of the mesocyclone detection algorithm].

By 0400 UTC 23 February, the convective system had moved eastward across the Florida peninsula and individual elements along the line had developed supercellular characteristics. The surface mesolow had moved eastward to the east coast of the Florida peninsula along the front (Fig. 12c), as the pressure at SFB had begun to drop (Fig. 13c). As the front again shifted to the north of SFB, the temperature rebounded 5°C between 0300 and 0400 UTC 23 February as the winds at SFB shifted to southeasterly. Behind the mesolow, the wind at LEE had shifted to westerly (Fig. 13b). Figure 14c shows the convective line at its most intense stage between 0500 and 0600 UTC 23 February; close inspection of the radar reflectivity and storm-relative velocity imagery suggests the presence of supercells, many of which triggered the mesocyclone detection algorithm (Fig. 14c). Based upon this mesoscale analysis,
it appears that the first supercells developed near where the convective band intersected the surface front in association with the rapidly developing mesolow, which moved eastward along the front. Just prior to the onset of convection at LEE and SFB, the front briefly shifted back to the north of these stations as temperatures rapidly rebounded and the wind shifted to the southeast. It was in this environment that the first tornadic supercells developed. Subsequently, supercells developed to the south of the front in the warm air as cold outflow associated with the convective band itself set up a secondary (northeast–southwest oriented) boundary that moved across Florida between 0400 and 0700 UTC 23 February (Fig. 15). The supercellular structure of the convective band was maintained through approximately 0630 UTC 23 February, when the supercells began to merge into a contiguous squall line structure.

Fig. 12. Surface analyses of sea level pressure (solid, hPa) and temperature (°C, dashed) at (a) 0200, (b) 0300, and (c) 0400 UTC 23 Feb.

Fig. 13. Meteograms of temperature (°C, dashed), wind (kt), present weather, and sea level pressure for (a) BKV, (b) LEE, and (c) SFB.
Fig. 14. MLB (left) base reflectivity and (right) storm-relative velocity images at (a) 0156 UTC 22 Feb, (b) 0336 UTC 23 Feb, and (c) 0515 UTC 23 Feb. Radar-indicated mesocyclones are indicated by circles in the velocity panels.
b. Surface front

In this section the authors present a more detailed discussion of the evolution of the surface front that developed during the day across Florida and continued throughout the duration of the event. At GNV, north of the front, $\theta_e$ increased through 1800 UTC 22 February when precipitation moved into this region (Fig. 11a). Just prior to the onset of precipitation a wind shift to the north and a rapid decrease in $\theta_e$ occurred, due to both a drop in temperature and dewpoint (Fig. 11a). This decrease in $\theta_e$ was likely due to outflow from the precipitation to the north. By 0000 UTC 23 February the winds at GNV had begun to veer around to the northeast, and then to the east. At MCO, south of the front, $\theta_e$ increased steadily during the day, as winds remained southerly and allowed a fetch of warm, moist air up the peninsula (Fig. 11b).

Reverse surface trajectories were calculated from the gridded surface observations for parcels that had endpoints in the vicinity of the surface front as the line of convection was intensifying, at 0400 UTC 23 February (Fig. 16). Trajectories were calculated without accounting for the vertical motions of the air parcels. However, some useful information can still be obtained from them, particularly in areas far from the surface front where vertical motions are likely weak. These trajectories indicate that many of the air parcels to the south of the front had their origins due south of the Florida peninsula, where SSTs were more than 26°C (Figs. 8a and 16). Air parcels to the north of the front had their origins over the cooler shelf waters to the east of the Florida–Georgia coastline, where the usually cool SSTs were $\sim$16°C, more than 4°C cooler than normal (Figs. 8 and 16). The air in the easterly and southeasterly flow north of the front across north-central Florida is likely modified continental air that moved offshore in conjunction with an anticyclone to the north (Fig. 10a) and then became part of the return-flow airstream to the south and west of this anticyclone. The southeasterly flow offshore and relatively low dewpoints (note the 13°C report in Fig. 10a) are indicative of this modified continental air. The anomalously cold SSTs in the immediate coastal waters off northeastern Florida (Fig. 8) likely precluded significant warming and moistening of this modified continental air mass, resulting in surface dewpoints of approximately 15°C–20°C in direct contrast to the 20+°C dewpoints in the southerly flow moving up the Florida peninsula (Figs. 12a and 12b). Accordingly, a surface front could be maintained across north-central Florida, especially once precipitation began to fall and evaporate into the modified continental air moving onshore north of the front. The cold air to the north of the front may have also been maintained as cold downdrafts associated with the moderate to heavy precipitation transported relatively low $\theta_e$ air toward the surface.

c. Frontogenesis and vorticity analysis

Figure 17 shows Miller (1948) two-dimensional frontogenesis computed from the surface observations. Frontogenesis values are more accurate over the land,
where the observation network is quite dense, than over the water, where only a few buoys contribute to
the analysis. At 0000 UTC 23 February 1998, the front intensity is underestimated by the interpolated analysis
as compared with the surface observations, but the winds to the north and south of the front appear to be
representative of the observed winds (Figs. 10b and 17b). Frontogenesis had been present along the surface
front during much of the day of 22 February (Fig. 17a).
Winds to the north of the front strengthened out of the
east and northeast by 0000 UTC 23 February, while
winds south of the front were sustained southerly at
10–15 kt (Fig. 17b). Because of the increasingly conver-
gent flow around the front, frontogenesis persisted
throughout the interaction of the front with the convective line, through about 0400 UTC 23 February (Figs.
17b–d). After the passage of the convective line, the
front weakened in intensity. One would expect that this
persistent frontogenesis was associated with a thermally
direct secondary circulation, with warm air rising (cold
air sinking) to the south (north) of the front.
One factor that could have contributed to the rapid
evolution of supercells as cell elements interacted with
the surface front was the increase in streamwise vortic-
ity, which is the component of the vector vorticity in the
direction of the (three-dimensional) flow normalized by
the magnitude of the (three-dimensional) velocity. In-
dividual cells in the convective line may have ingested
air with relatively high streamwise vorticity as they in-
teracted with the low-level baroclinic zone on the
Florida peninsula. Figure 18 shows analyses of surface
absolute vorticity \( (\zeta + f) \) calculated from the gridded
surface observations for 0000 and 0400 UTC 23 Febru-
ary. As the winds to the north of the front strengthened
and veered to easterly between 1800 UTC 22 February
and 0000 UTC 23 February, the surface vorticity began
to increase on the Florida peninsula at the same time
convergent flow around the front was maintaining the

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**Fig. 17.** Surface frontogenesis [shaded, every 1°C (100 km)\(^{-1}\) (3 h)\(^{-1}\)], temperature (solid, every 4°C), and winds
(m s\(^{-1}\): half barb, 2.5 m s\(^{-1}\); full barb, 5 m s\(^{-1}\)] at (a) 2100 UTC 22 Feb, (b) 0000 UTC 23 Feb, (c) 0200 UTC 23
Feb, and (d) 0400 UTC 23 Feb.
frontogenesis in the same region (Figs. 17b and 18a). This increase in surface vorticity continued during the period of sustained frontogenesis until 0400 UTC 23 February (Figs. 17d and 18b), when values in the vicinity of the front itself exceeded $f (=6.8 \times 10^{-4} \text{s}^{-1}$ at 28°N). It is hypothesized that the mesolow that moved east along the surface front ahead of the convection prompted a response in the surface wind field; the winds ahead of this feature were backed, or more easterly, relative to the environmental winds to the south of the front. In particular, the winds at LEE and SFB show evidence of backing to southeasterly shortly before the onset of precipitation at those stations (Figs. 13a and 13b). Associated with this backing, the three-dimensional vorticity vector (which is likely dominated by the baroclinic generation of horizontal vorticity at the front) and the three-dimensional velocity vector are oriented in roughly the same direction (to the west or west-northwest). It is speculated that supercells at the front rapidly intensified and developed low-level rotation as the individual cell elements ingested air that had relatively high streamwise vorticity, which was then rapidly stretched and tilted in updrafts.

6. NCEP Eta Model hindcast

Hindcasts of the of the 32-km Eta Model initialized with NARR data at 1200 UTC 22 February were conducted in order to determine how well it resolved the surface front extending across the Florida peninsula, as well as to draw more definitive conclusions about the mechanisms responsible for the marked increase in low-level vorticity as the convective system made landfall. Hindcasts were completed using both the KF and the BMJ convective parameterization schemes in order to determine if either of the schemes were able to accurately represent the temperature and wind field in the vicinity of the front. As both convective schemes produced similar results, only figures for the KF run will be shown here, although discussion of results in the text applies to both hindcasts. Both the KF and BMJ runs accurately depicted the synoptic-scale warm and cold fronts at 2100 UTC 22 February, as well as capturing some of the temperature gradient present across the western Florida peninsula (Figs. 19a and 19c).

The Eta Model (using either the KF or BMJ convective scheme) was unable to accurately resolve or maintain the degree of diabatic cooling and easterly flow to the north of the front on the Florida peninsula that was a result of the ongoing precipitation on 22 February 1998. Low-level winds to the north of the front remain southerly in the model (Fig. 19a), although surface and radiosonde data from the north side of the front indicate northerly or northeasterly flow (Figs. 4 and 10). Although there is precipitation to the north of this front in the model (not shown), the cooling in the temperature field is underdone as compared with observations, and the northerly flow to the north of the front is not present in the model. The low-level front across the Florida peninsula is thus completely dissipated by 0000 UTC 23 February in the model (Figs. 19b and 19d). However, in reality this surface front strengthened during the day on 22 February in response to differential diabatic heating across the Florida peninsula (heating in the clear air over southern and central Florida and cooling over northern Florida associated with outflow-related precipitation), and maintained its intensity through 0400 UTC 23 February (Figs. 10 and 17).
12-h forecast cross section taken across the length of the Florida peninsula from Illinois to Cuba confirms that the observed temperature gradient and convergent flow at the front are not represented (Fig. 20a). There is also a region of strong frontogenesis sloping northward along the synoptic-scale warm front, and another region of much weaker low-level frontogenesis just south of the Florida peninsula (Fig. 20a). However, there is very little potential temperature gradient present across the Florida peninsula, and thus there is no strong frontogenesis in the 12-h forecast (which was previously inferred to be largely diabatically enhanced) as was observed (Fig. 17). The only region of ascent is associated with the larger-scale warm front in Georgia (Figs. 19c and 19d). The key point is that the Eta Model tested with two convective schemes was unable to generate and maintain the cold outflow to the north of the front.

As an additional test of the model’s ability to resolve the surface front, the Eta NARR initialized at 0000 UTC 23 February was examined. A cross section (as in Fig. 20a) shows that the initial analysis at 0000 UTC 23 February had a low-level front across the Florida peninsula embedded in a region of synoptic-scale ascent at ~600 hPa (Fig. 20b) and weak convective stability (not shown) at the same time. However, the strength of the surface front and the associated frontogenesis in the analysis are too weak when compared with the observations (Figs. 17 and 20b). The initial analysis also indicates that the strength of the synoptic-scale ascent south of the warm front is too strong in the 12-h forecast, and the 12-h forecast also missed a narrow band of
Fig. 20. Cross section of $\theta_v$ (K, blue solid), frontogenesis [°C (100 km)$^{-1}$ (3 h)$^{-1}$, warm colors shaded], isotachs (m s$^{-1}$, cool colors shaded), upward motion ($\times 10^{-3}$ hPa s$^{-1}$, red dashed), and wind in the plane of the cross section (brown arrows) for (a) 12-h forecast valid at 0000 UTC 23 Feb and (b) initial analysis at 0000 UTC 23 Feb. Horizontal reference vector is indicated in bottom left. Black triangle represents location of surface front on Florida peninsula.
ascent $< -18 \times 10^{-3} \text{ hPa}^{-1}$ centered at $\sim 600 \text{ hPa}$ over the northern Florida peninsula where the low-level surface front was situated (Figs. 20a and 20b).

As was noted in section 4, the northward extent of the core of the upper-level jet was underestimated in the initial analysis at 0000 UTC 23 February (Figs. 4c, 5, and 20b). While the upper-level jet core is located farther north in the 12-h forecast than in the initial analysis (Fig. 20), the 200–150-hPa wind speeds over north Florida still appear to be weaker than were observed (Fig. 5). While it is unclear what the role of the upper-level jet was in the evolution of this event and the maintenance of the narrow band of ascent located over the Florida peninsula at 0000 UTC 23 February (Fig. 20b), it is speculated that the placement of the upper-level jet kept synoptic-scale conditions neutral or weakly favorable for ascent over central Florida at that time. The surface front appears to have been located underneath the core of the entrance region of the upper-level jet based upon observations, whereas the model initial analysis would place it underneath the poleward entrance region of the upper-level jet (e.g., Fig. 4c), where synoptic-scale descent would be favored. Thus, despite the fact that the low-level warm-air advection and midlevel vorticity advection associated with the main short-wave trough had shifted to the north (Fig. 3), the synoptic-scale conditions do not appear to have been unfavorable for ascent over central Florida where the surface front developed.

A vorticity budget was calculated at 950 hPa using the NCEP Eta hindcast in an attempt to identify the mechanisms responsible for the rapid increase in low-level vorticity at the diabatically generated low-level front (which appeared to interact with the convective band as it made landfall and resulted in rapid intensification). However, because the low-level temperature and wind fields were not accurately represented in the model, calculation of a vorticity budget led the authors no closer to quantitatively identifying the primary mechanism of vorticity generation in the vicinity of this surface front, and will not be discussed here.

7. Discussion and conclusions

The 22–23 February 1998 central Florida tornado outbreak resulted in record loss of life and property damage for Florida tornadoes (Sharp et al. 1998). The high number of fatalities and injuries can be partially attributed to the fact that the outbreak occurred after dark, at a time when warning the public becomes increasingly difficult (Fike 1993). Numerical models for 12–24 h prior to the event varied widely in their forecasts of convective intensity over Florida (Baldwin et al. 1998). Although the primary region of quasigeostrophic forcing for ascent (i.e., cyclonic vorticity advection increasing with height and warm air advection) was moving away from the Florida peninsula, the synoptic-scale pattern showed distinct similarities to the 51-yr composite southeast U.S. cool season tornado episode and to previous climatological studies of synoptic-scale environments associated with tornadoes (e.g., Hagemeyer and Schmocker 1992; Hagemeyer 1997; Mello et al. 2000). However, it is unknown how many large-scale situations may look similar to the 51-yr composite, yet result in “false alarms.” This uncertainty can make a pattern-recognition tool such as the 51-yr large-scale composite difficult to use in real time. Additional difficulty was added to the forecast in real time because the convective system rapidly changed its intensity and organization as it moved across the Gulf, possibly due to the changing oceanic heat and moisture fluxes between the warm LC and the cooler shelf waters.

While the limitations of the available gridded data do not permit conclusively showing that the strong surface frontogenesis on the Florida peninsula contributed to enhanced ascent on the south side of the front, there is ample evidence that the mesoscale dynamics in the vicinity of this east–west-oriented surface front across central Florida became more important than synoptic-scale forcing for ascent (which had lifted well north and east of Florida by 0000 UTC 23 February) as the convective band made landfall and interacted with the surface front. The location of the upper-level jet core over south-central Florida did ensure the fact that the synoptic-scale forcing was, at the very least, not unfavorable for ascent. However, it is believed that the thermally direct circulation in the presence of strong frontogenesis at the surface front was a primary contributor to strong ascent south of the front, and to the rapid intensification of the convective band as it intersected with the front. Southerly return-flow air up the Florida peninsula helped to moisten and destabilize the boundary layer. Diabatically driven frontogenesis likely helped to create a strong surface front across the north-central Florida peninsula. Despite the fact that it was after dark and diurnal heating had ceased to destabilize the boundary layer when the convective line made landfall, unstable air was present on the south side of the surface front. Convergent/confluent winds on either side of the front were contributing to frontogenesis and, it is inferred, to baroclinic generation of vorticity near the surface. The ascent south of the front associated with strong frontogenesis helped to create a favorable environment in which the convection intensity could increase even after sunset. Additionally, a strong low-
level jet contributed to a favorable vertical wind shear profile for supercell development. Further research is needed to document the role that the subtropical jet at approximately 175–200 hPa over south-central Florida may have played in the evolution and/or maintenance of the diabatically generated front that interacted with the convective band.

Previous studies have documented the importance of low-level boundaries in serving as a focusing mechanism for the development of tornadic supercells (e.g., Maddox et al. 1980; Markowski et al. 1998; Rogash and Smith 2000; Rasmussen et al. 2000). In this case, the convective band intensified and individual cell elements rapidly became supercellular as they encountered the front and the strongly backed (southeasterly) surface flow just south of the front. This result is consistent with previous research that has shown that storms that move along thermal boundaries can produce long-lived tornadoes (e.g., Maddox et al. 1980; Langmaid and Riordan 1998). Maddox et al. (1980), in their study of interactions of tornadic storms with thermal boundaries, note that low-level convergence and cyclonic vertical vorticity are maximized within a narrow zone on the warm side of the boundary (between points B and C, see Fig. 21). Markowski et al. (1998) and Rasmussen et al. (2000) have shown that wind profiles on the cool side of thermal boundaries may be more favorable for long-lived supercells to develop. Wicker (1996, his Figs. 4a and 5b) showed that strong, long-lived low-level mesocyclones are most likely to develop when the hodograph is strongly curved in the lowest 100 m, so that the environmental vorticity vector points in the same direction as the (baroclinically generated) vorticity associated with the forward-flank downdraft. While surface observations from LEE and SFB do indicate that low-level winds were more backed (i.e., easterly) north of the surface front, observations from these stations also suggest that the winds south of the front may have backed to a more southeasterly direction as the weak mesolow moved eastward along the front. This, in effect, would increase the hodograph curvature near the surface in the warm air south of the front. It appears that as the convective line made landfall and the northern portion interacted with the front, a scenario similar to the one discussed in the conceptual model presented in Maddox et al. (1980) of flow near a boundary was in place (Fig. 21). It is hypothesized that this may have resulted in the extremely rapid intensification of the cell elements that interacted with the boundary, and the subsequent rapid development of low-level rotation in these cells.

In this case, storms to the south of the front along the convective line eventually became tornadic but took longer to do so. A key unanswered question is why there were several hours between the initial supercell development and tornado touchdown. While there was evidence in the MLB radar of increasing low-level vertical wind shear between 0300 and 0600 UTC 23 February (not shown), it is unclear what role this may have played in the system evolution, and should be the subject of further research.

The NCEP Eta Model (even using the KF convective parameterization with explicit convective downdrafts) did not accurately depict the intensity of the surface front, which likely was maintained because of diabatic effects. Thus, a vorticity budget calculated from these grids added little insight to the reasons for the large increase in cyclonic vorticity that was observed to occur at the surface between 2100 UTC 22 February and 0400 UTC 23 February. The inability of the model to maintain the cold pool is consistent with the findings of previous work (e.g., Stensrud et al. 1999).

This nocturnal cool season tornado episode highlights the importance of careful study of observational data (e.g., surface, radiosonde, and radar data) in real time to ascertain key features that numerical models often do not accurately depict. The SPC forecasters’ correct decision to issue a tornado watch at 0200 UTC 23 February is attributed to keen use of observations (e.g., the TBW sounding, surface observations). In particular, it is important to emphasize the role that dia-

![Fig. 21. Conceptual model of flow near a boundary (after Maddox et al. 1980).](image-url)
batically driven frontogenesis (due to diabatic heating and/or evaporative cooling) can play in the maintenance of these mesoscale boundaries, which become important players when they interact with a convective system.

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