Peninsular Florida Tornado Outbreaks

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ABSTRACT

An analysis of statistics for 1448 tornadoes documented by the National Severe Storms Forecast Center from 1950 through 1994 at, or south of, 30° latitude in Florida was completed to determine the definition of a peninsular Florida tornado outbreak and develop a tornado outbreak climatology. A peninsular Florida tornado outbreak was defined as the occurrence of four or more tornadoes in 4 h or less. Thirty-five outbreak cases were identified. After a review of all available synoptic data for each case, they were categorized into three basic types: 1) those associated with extratropical cyclones (27 cases), 2) those associated with tropical cyclones of tropical storm or hurricane strength (5 cases), and 3) those associated with hybrid cyclones having both tropical and extratropical characteristics (3 cases). A detailed climatology covering spatial and temporal aspects of outbreak characteristics was completed. Mean severe weather indices, thermodynamic soundings, and hodographs were produced for each outbreak type. Case studies of each type of outbreak are presented to complement the climatology and mean environment information.

It was found that tornado outbreaks account for 3.4% of all tornado days but caused 61% of all tornado deaths and 62% of tornado injuries. Most tornado deaths occurred in trailers or mobile homes. Extratropical outbreak tornadoes were most common from midmorning to early afternoon, while tropical outbreak tornadoes occurred mostly in the afternoon and evening. The outbreaks produced a much greater percentage of strong and violent tornadoes compared to the general tornado population. Hybrid outbreaks were the most consistently dangerous of the three types of outbreaks. Fundamental differences and similarities among the three outbreak environments are presented using mean soundings and case studies. The basic ingredients for tornado development in each type of outbreak were found to be the presence of strong low-level winds and shear, and enough instability to support thunderstorm development.

1. Introduction

In the summer of 1989 a new National Weather Service Office (NWSO) was opened in Melbourne, Florida (MLB), to provide forecasts and warnings of hazardous weather for east-central Florida. This office was part of the nationwide program for the Modernization and Associated Restructuring (MAR) of the NWS (Friday 1994) and was staffed with professional meteorologists who were largely new to the peninsular Florida environment. Tornado outbreaks in peninsular Florida are significant hazards to life and property, and the study of the characteristics of Florida tornadoes was identified as a high priority operational research project at the new office.

A large body of research had been accumulated regarding Great Plains or Midwestern tornadoes, but very little research had been done specifically on peninsular Florida tornado environments or their prediction. The exceptions were case studies of isolated wet season tornadoes by Hiser (1968), Gerrish (1969), and Holle and Maier (1980); studies of waterspouts by Golden (1971); one case study of a severe weather outbreak (Colin 1983); and general information on Florida tornadoes contained in large-scale climatologies such as Wolford (1960), Novlan and Gray (1974), Gentry (1983), Fujita (1987), Anthony (1988), and Grazulis (1990).

Rules designed for forecasting tornadoes in the central United States were being applied to Florida with limited success. It was suspected that significant differences might exist between the ''typical'' Midwestern tornado environment and that of Florida. For example, Johns and Sammler (1989) studied conditions associated with 77 violent tornado outbreaks (containing at least one tornado of F4 or greater intensity) between 1950 and 1988 and concluded that the elements that combine to produce tornado outbreaks vary with season and geography. However, only 1 of the 77 outbreaks in their study occurred in Florida; the majority were in the Great Plains and Midwest.

To improve regional knowledge and forecasting of severe weather in the peninsular Florida environment, and prepare for the implementation of the Weather Surveillance Radar-1988 Doppler (WSR-88D) in October 1991, a systematic investigation of tornado environ-

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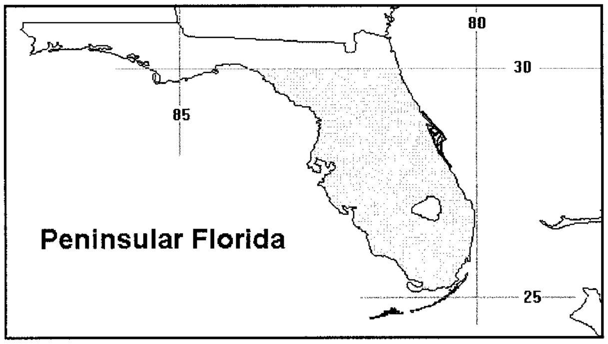

FIG. 1. Map of study area. Peninsular Florida is considered all of the peninsula south of 30°N latitude (shaded area).

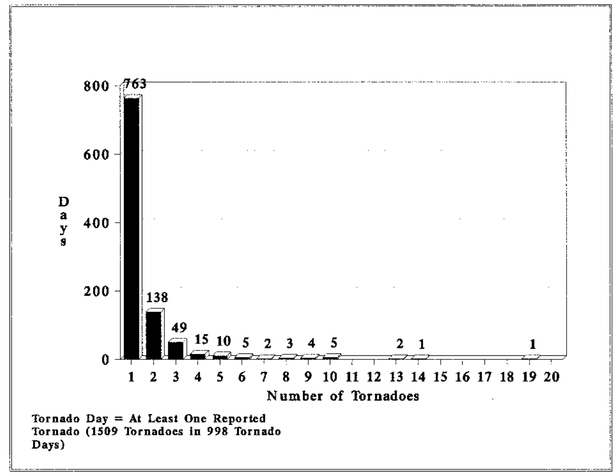

FIG. 2. Number of peninsular Florida tornadoes per tornado day (1950–94).

ments began in late 1989 at the Melbourne NWSO. Early research concentrated on establishing a basic tornado climatology (Schmocker et al. 1990) and investigating seasonal characteristics of tornado proximity soundings for east-central Florida (Hagemeyer and Schmocker 1991). Further analysis of the tornado forecast challenge concerned the general characteristics of east-central Florida extratropical tornado outbreaks (Hagemeyer and Schmocker 1992), the relationship of tornado outbreaks to common severe weather indices (Hagemeyer and Matney 1993a), and characteristics of hybrid (tropical–extratropical) tornado outbreaks (Hagemeyer and Matney 1993b). The investigation of tornado outbreaks was expanded to include all of peninsular Florida in the fall of 1993 (Hagemeyer and Matney 1994), and a climatology of Florida tropical cyclone tornadoes and outbreaks was completed in 1994 (Hagemeyer and Hodanish 1995).

Despite these incremental increases in knowledge, the recent hybrid cyclone, extratropical cyclone, and tropical cyclone killer tornado outbreaks of 2 October 1992 (DOC 1993), 12–13 March 1993 (DOC 1994), and 15 November 1994 (Spratt et al. 1997), respectively, illustrate the need to widely disseminate a comprehensive documentation of peninsular Florida tornado outbreak characteristics to the forecast community.

This paper will present a detailed peninsular Florida tornado outbreak climatology, including characteristics of the outbreak environments and their variability. Comparisons and brief case studies of each type of outbreak will also be presented. This information should result in a better understanding of peninsular Florida tornado outbreaks and improvements in their forecasting. It should also aid in community hazardous weather awareness and disaster preparedness efforts.

2. Tornado outbreak definition and categorization

The fundamental question of ''what is a peninsular Florida tornado outbreak?'' had to be answered before a study of outbreak characteristics could begin. In the 1940s the NWS and Air Weather Service (AWS) defined a ''family outbreak'' as five or more tornadoes associated with a weather system on a given day (Pautz 1969). Since then, the NWS Storm Prediction Center (formally called the National Severe Storms Forecast Center) has refined the definition to cover occurrences over a relatively small area of six or more tornadoes as a family outbreak, (6–10 tornadoes a small outbreak, 11–20 a moderate outbreak, and greater than 20 a large outbreaks). Galway (1977) addressed the need for a tornado outbreak definition that might apply to most of the nation east of the Continental Divide but came up with no definitive answer. Grazulis (1993) defined an outbreak as a group or family of six or more tornadoes spawned by the same general weather system. Based on the literature to date, there is clearly a need for more precise regional definitions of outbreaks based on climatological data.

A study by Fujita (1987) illustrated that peninsular Florida tornadoes are rarely associated with large-scale outbreaks affecting the rest of the nation. To determine the regional definition, an analysis of 1448 tornadoes documented by the Storm Prediction Center from 1950 through 1994 at, or south of, 30°N and east of 84°W in Florida was completed (shaded area in Fig. 1). The number of peninsular Florida tornadoes reported per tornado day is shown on Fig. 2 (a tornado day is any day with at least one tornado reported), similar to Fujita's (1987) analysis of the national tornado population. Figure 2 clearly shows that most tornadoes occur singly, and rarely are more than three tornadoes reported in a day. Only 48 (4.8%) of the 998 tornado days had four or more tornadoes reported. This threshold of four tornadoes per day provided a logical starting point in the regional definition of an outbreak. The next step was to establish an objective outbreak time limit.

A graph of the minimum time duration for at least four tornadoes to occur in the 48 cases of days with four or more tornadoes is shown as Fig. 3. The graph

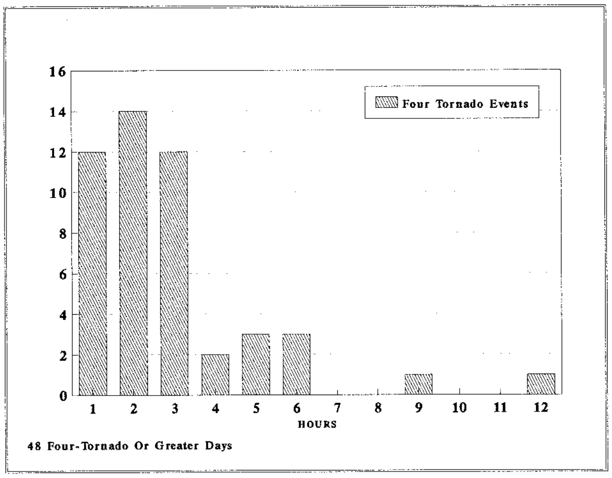

FIG. 3. Minimum duration of four-tornado occurrences on 48 days with four or more tornadoes (1950–94).

clearly shows that the great majority (83%) of the cases occur in less than 4 h (outbreaks stretching over 2 days, i.e., in progress at midnight, were allowed for). Thus, a peninsular Florida tornado outbreak was defined to be the occurrence of four or more tornadoes in 4 h or less at, or south of, 30°N. The beginning time of an outbreak was defined as the time of the first tornado, and the ending time was defined as the time of the last tornado before a minimum of a 4-h break in tornado activity. These criteria seem reasonable for the Florida peninsula that is only about 125 n mi across at its widest point. As will be shown in section 3, most synoptic systems that cause outbreaks are fast-moving extratropical cyclones. These temporal criteria eliminated 8 of the 48 candidate cases.

The remaining 40 candidate outbreak cases were then categorized into synoptic types by reviewing all available surface and upper air data from the National Climatic Data Center. Examination of these synoptic data for each outbreak case indicated they could be placed into four basic categories: 1) those associated with extratropical cyclones (27 cases); 2) those associated with tropical cyclones of hurricane or tropical storm intensity (5 cases); 3) those associated with hybrid cyclones (3 cases), having both tropical and extratropical characteristics (Neumann et al. 1993); and 4) those with no clearly defined synoptic triggering mechanism that were characterized by weak flow patterns (5 cases). An example typical of a weak-flow case is during the wet season when two tornadoes might occur in the afternoon near Tampa with the west coast sea breeze and two tornadoes might occur along the southeast coast with the east coast sea breeze, all within a few hours of each other. While this scenario meets the temporal criteria of four tornadoes in 4 h in peninsular Florida, it is not considered an outbreak. For the purpose of this study the tornadoes had to be related to the same forcing mechanisms associated with synoptic weather elements (i.e., a squall line in the warm sector of an extratropical cyclone) to be considered part of a true outbreak. The 5 weak flow cases were thus eliminated, leaving 35 outbreaks identified from 1950 through 1994.

The five tropical cases include three hurricanes and two tropical storms. There is no historical evidence of a tropical depression ever producing a tornado outbreak, although a few have produced tornadoes (Hagemeyer and Hodanish 1995). The three hybrid outbreaks were characterized by lower-tropospheric tropical or subtropical lows originating in the Gulf of Mexico and interacting with midlatitude upper troughs.

3. Tornado outbreak characteristics

a. General overview

A summary of *Storm Data* (NOAA 1959–94) and National Summary (DOC 1950–59) entries for each tornado outbreak are contained in Table 1. The outbreaks are listed by order of the day of the year that they occurred. Tropical cyclone and hybrid cases are shown by symbols (*) and (+) next to their dates, respectively. The rest are extratropical. Table 1 contains information on the duration of each outbreak, number and intensity [F scale, Fujita (1981)] of tornadoes, and whether reports were received of severe thunderstorm winds, hail, heavy rain or flooding, and lightning casualties or damage. All weather-related deaths and injuries and their causes during the outbreak are also listed.

The cyclones associated with the outbreaks were at times of such an intensity that they produced several hazardous weather elements besides tornadoes and have been directly responsible for 80 deaths and 1193 injuries. Tornado outbreaks account for only 3.4% of tornado days, but they have caused 61% of tornado deaths and 62% of tornado injuries. Killer tornadoes occurred in 10 outbreaks and accounted for 29 deaths. Tornado deaths and serious injuries were most often associated with occupants of trailers or mobile homes. The two deadliest outbreaks, 4 April 1966 and 12–13 March 1993, accounted for 43% of all outbreak deaths and 55% of tornado deaths. However, the most consistently deadly outbreaks occurred with tropical and hybrid cyclones. Seven of the 27 extratropical dry season (November–April) outbreaks (26%) caused fatalities, totaling 46, while seven of the eight (88%) tropical and hybrid outbreaks were killers, causing a combined total of 34 fatalities.

Drownings occurred in eight outbreaks and accounted for 39 deaths. They resulted from boats capsizing on lakes and coastal waters in high winds and seas, storm surge inundation, river flooding, and urban flooding of roadways and drainage ditches. The greatest number of drownings occurred in an extremely rare extratropical storm surge and in ships lost at sea during the ‘‘superstorm’’ of March 1993 (DOC 1994).

Severe thunderstorm winds are common with tornado

TABLE 1. Peninsular Florida tornado outbreak statistics (1950–94). *National Summary* data used for cases 20 and 25.

#	Date	Duration (EST)	Tornadoes F0	1	2	3	4	?	WND	HL	RN	LTG	▼Deaths/injuries
1.	3 January 1994	1445–1730	5	1					x				0/1
2.	6 January 1970	1005–1135		1	1			2	x				0/5
3.	19 January 1978	1350–1703	3	2					x				0/0
4.	24 January 1979	0200–0555						6	x				0/1
5.	28 January 1973	1135–1330		1	3								0/24
6.	2 February 1983	0430–1320	1	7	6				x				◆2/31◆
7.	3 February 1970	0730–0945	1	2	3			1	x				0/0
8.	23 February 1965	1050–1245		2	1	1			x				0/8
9.	3 March 1971	1431–1740	2	4	1				x				★1/1◆
10.	3 March 1978	1235–1504		5					x				0/1◆
11.	3 March 1991	0920–1450	5	3					x	x			0/1●
12.	12 March 1993	2338–0110	4	2	3				x	x			★23/91★◆
13.	14 March 1986	0617–1045	4	4	1				x			x	0/1↘
14.	17 March 1973	0300–0500		3	2				x				0/3◆
15.	31 March 1972	0415–0700	2	2	4				x	x			0/9◆
16.	4 April 1966	0815–1015			1		1	2@					11/530
17.	5 April 1993	0130–0430	8	1	1				x				0/5◆
18.	9 April 1984	1250–1400	2	2					x	x	x		0/0
19.	11 April 1975	0930–1520	1	4					x		x	x	0/1
20.	15 April 1958	1200–1309		1		2	1		x	x			†4/36
21.	23 April 1983	0830–1430		6					x				0/7
22.	25 April 1991	1417–1630	5	2					x	x			0/2◆
23.	4 May 1978	0800–1500	6	1		1			x		x		3/97
24.	8 May 1979+	0530–1630	15	3	1						x		★4/49
25.	8 June 1957*	1458–1715		1	4			1			x		★5/0
26.	17 June 1982+	1900–0309	3	5	2				x		x		★3/13
27	18 June 1972*	1255–1846	1	4	5				x				★◆8/67◆
28.	3 September 1979*	1800–2100	2	1	2								0/0
29.	3 October 1992+	0940–1740	3	4	1	1			x		x		4/77
30.	14 October 1964*	1510–2250		4	4			1					★2/48
31.	30 October 1993	0920–1119	7	2					x				0/1
32.	9 November 1968	1255–1900		6	3								2/29
33.	11 November 1968	1115–1330		1	2			1	x				0/3
34.	15 November 1994*	1853–0345	3	2	1				x		x	x	★8/41↘
35.	3 December 1971	1000–1345		2	3				x		x		0/10
		Totals:	83	91	55	5	2	14	28	6	9	3	80/1193 29/1122 tornado 39/2(★) drowning 8/66(◆) tstm wind 0/2(↘) lightning 0/1(●) hail 4/0(†) plane crash

▼ Includes: Thunderstorm wind, lightning, hail, drowning, and plane crash victims.
WND = thunderstorm wind ≥50 kt reported or inferred from damage.
HL = hail ≥ .75 in. reported.
RN = flooding rains reported.
LTG = lightning casualty or damage reported.
* Tropical cyclone case (5).
+ Hybrid case (3).
@ At least two more tornadoes indicated in *Storm Data.*

outbreaks (28 of 35 cases). Every tornado outbreak since 1979 has had severe thunderstorm winds reported. Only two tornado outbreaks had fatalities attributed to severe thunderstorm winds. Seven of the eight deaths attributed to severe thunderstorm winds occurred in ''windstorms'' associated with Hurricane Agnes that struck trailer parks near Lake Okeechobee in June 1972. These windstorms may have been tornadoes and are a subject of ongoing debate (Grazulis 1993).

Large hail was reported in only 6 of the 35 outbreaks, and all were in March and April. Based on a discussion of the thermodynamic environment to be presented later, hail is less likely in peninsular Florida outbreaks than in Midwestern tornado outbreaks.

Lightning reports are noticeably lacking in the outbreaks. Remarkably, only two injuries due to lightning and one instance of lightning damage were reported in the 35 outbreaks.

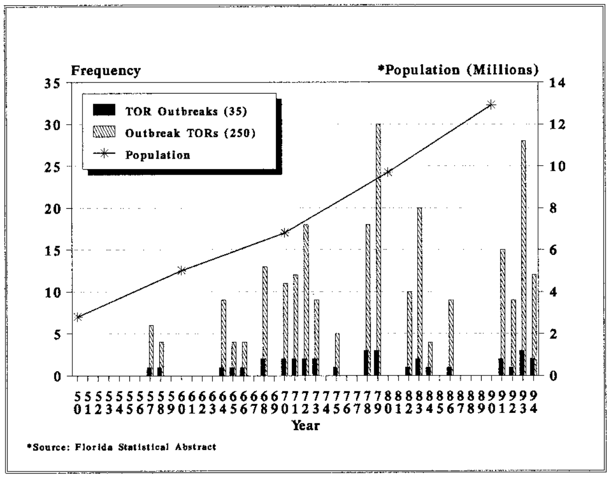

FIG. 4. Yearly distribution of tornado outbreaks, outbreak tornadoes (1950–94), and Florida population by decade.

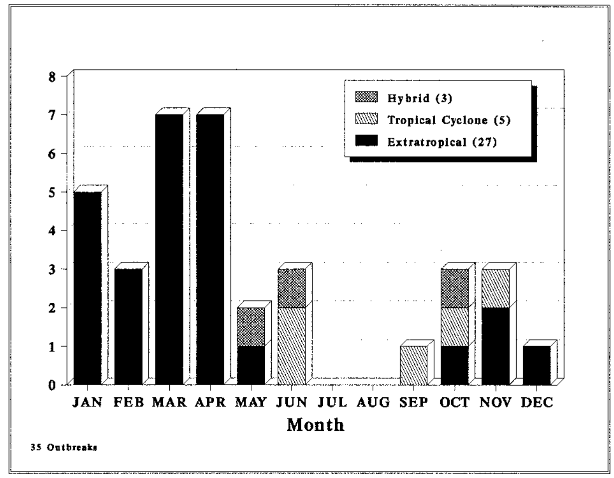

FIG. 5. Monthly distribution of peninsular Florida tornado outbreaks (1950–94).

Flooding rains were reported in 9 of 35 outbreaks. Five of the eight tropical–hybrid cases had flooding rains reported. Tropical–hybrid outbreaks last longer due to slower movement of parent cyclone allowing more opportunity for flooding than fast-moving extratropical cyclones. In addition, the tropical–hybrid atmosphere is much moister as will be discussed later.

This study was designed to concentrate on tornadoes, but knowledge of all weather-related hazards is crucial to completely forecasting cyclone effects and to conduct comprehensive preparedness and education efforts. Based on statistical evidence, populations at greatest risk from major outbreaks that can include high seas, coastal flooding, beach erosion, storm surge, local flooding rains, and river flooding as well as tornadoes and severe thunderstorms are occupants of mobile homes or trailers, mariners, and residents of the immediate coastal zone and many low-lying flood-prone areas.

b. *Climatology*

The yearly distribution of the tornado outbreaks, outbreak tornadoes, and Florida population by decade from 1950–94 is shown on Fig. 4. The scarcity of outbreaks before 1964 is probably related to lower population density and the tendency for only the most significant tornadoes to be reported before NWS emphasis on verification in the late 1970s (Grazulis 1993). Grazulis (1993) also provides a comprehensive discussion of the problems with the national tornado database and the challenges of accurate tornado documentation.

Although Florida's population has more than quadrupled since 1950, much of the growth has been along the coast and around Orlando. Fujita's (1987) national population index, community index, road index, forest index, and water index graphics show much of interior central and south-central Florida and the southwest coast is sparsely populated and swampy or forested. It remains difficult to obtain severe weather reports from these areas.

Detailed information on tornadoes before 1950 is difficult to obtain. A review of publications summarizing historical tornado data prior to 1950 (Wolford 1960; Grazulis 1993) indicated the earliest documented cases that probably met the definition of a peninsular Florida tornado outbreak occurred with tropical cyclones. Cases of four or more tornadoes occurred with tropical cyclones on 28 September 1929, 22 September 1947, and 5 October 1948. Based on descriptions in the literature, extratropical tornado outbreaks probably occurred over the northern peninsula on 26 February 1934 and 26–27 December 1940.

It is noteworthy that the longest period without an outbreak since 1964 was the 5-yr from March 1986 to March 1991. After this 5-yr absence, eight outbreaks occurred from March 1991 to November 1994. While some of this recent increase in outbreak activity may be due to new NWS offices being established in Florida as part of the MAR, and the deployment of new Doppler radars (WSR-88D), it may also reflect the influence of longer-term weather patterns. A discussion of the significance of the outbreak distribution since 1964 is beyond the scope of this paper, but it is reasonable to expect some identifiable relationship between active/inactive outbreak periods and changes in the general atmospheric circulation. Research into long-range prediction of tornado outbreak potential is planned.

The monthly distributions of the three categories of central Florida tornado outbreaks are shown on Fig. 5. Outbreaks are primarily associated with the warm sector of extratropical cyclones during the traditional dry season with peak occurrences in March and April. Tropical cyclones have caused outbreaks in June, September, October, and November. Hybrid cyclones have caused outbreaks in May, June, and October. May and October are typically the transition months between the dry season,

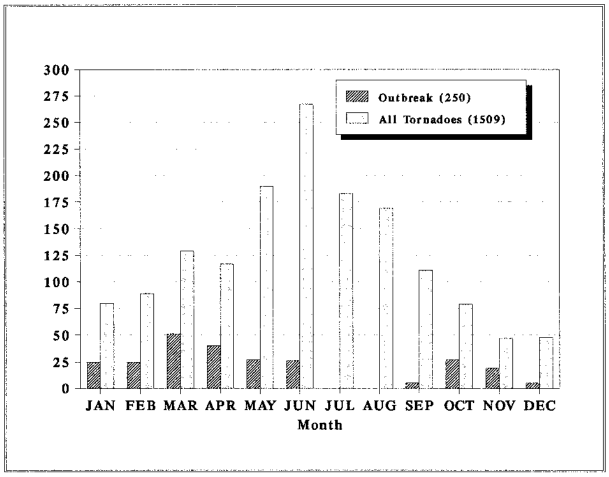

FIG. 6. Monthly distribution of all peninsular Florida tornadoes and outbreak tornadoes (1950–94).

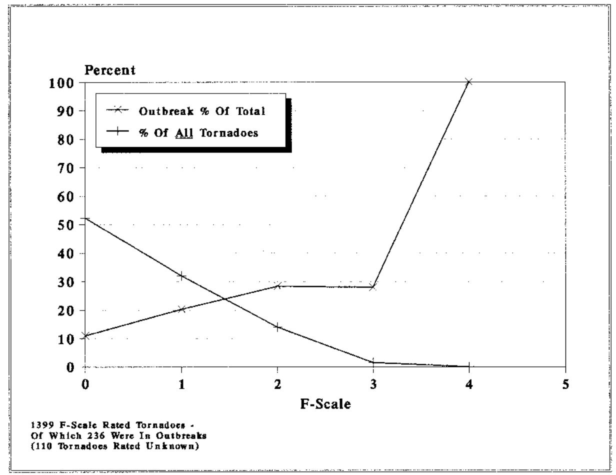

FIG. 7. Distributions of outbreak tornadoes by F scale as a percentage of all tornadoes, and all tornadoes by F scale (1950–94).

controlled by extratropical weather systems, and the wet season (May–October), characterized by weakly sheared tropical and subtropical air masses and infrequent organized weather systems. The sharp decline in outbreaks from April to May suggests the rarity of strong extratropical cyclones and associated fronts during the transition into the wet season as the subtropical ridge builds over the region (Hagemeyer 1991). It is in these transition months that tropical and extratropical interactions are most likely. Two of the hybrid outbreaks occurred in these transition months, the third occurred early in the wet season.

No outbreaks have occurred in July and August in the middle of the wet season. Hagemeyer and Schmocker (1991) found that the typical wet season tornado environment was characterized by weak lower-tropospheric winds and very low shear. This is a time when extratropical systems are least likely to affect the peninsula and tropical systems affecting Florida are at a minimum in July. These months are between the early hurricane season tendency for tropical and hybrid cyclones to develop in the northwest Caribbean and southern Gulf of Mexico and the primary peak of tropical cyclone development from African easterly waves in September (Neumann et al. 1993).

The monthly distribution of all peninsular Florida tornadoes and outbreak tornadoes from 1950–94 is shown as Fig. 6. The population of all tornadoes has a minimum in November and a very pronounced maximum in June. Outbreak tornadoes reach a maximum in March and a minimum in July and August. A secondary maximum occurs in October. Most peninsular Florida tornadoes occur from May to August during the peak thunderstorm season. These tornadoes are generally weak and make up much of the population of the cases with one tornado per day illustrated in Fig. 2.

The percent distribution of outbreak tornadoes by F scale as a percentage of all tornadoes and of all tornadoes by F scale is shown as Fig. 7. The distribution of outbreak tornadoes by F scale as a percentage of all tornadoes by F-scale increase from 12% for F0's to 100% for F4's (all F4's have occurred in outbreaks and there have been no F5's). In contrast, 50% of the all-tornado population are F-0's, decreasing to near 0% for F4's. This illustrates that the outbreaks contain a much greater percentage of F2 and stronger tornadoes than the general tornado population.

The monthly distribution of outbreak tornadoes by F scale is shown as Fig. 8. Strong (≥F2) tornadoes peak in February, March, and June. Almost as many strong as weak tornadoes occur in February and June. It is interesting that from March to May the ratio of strong to weak tornadoes decreases steadily as one might expect transitioning into the wet season. The increase of strong outbreak tornadoes in June, which is counter to the general tornado population, is due to the intensity

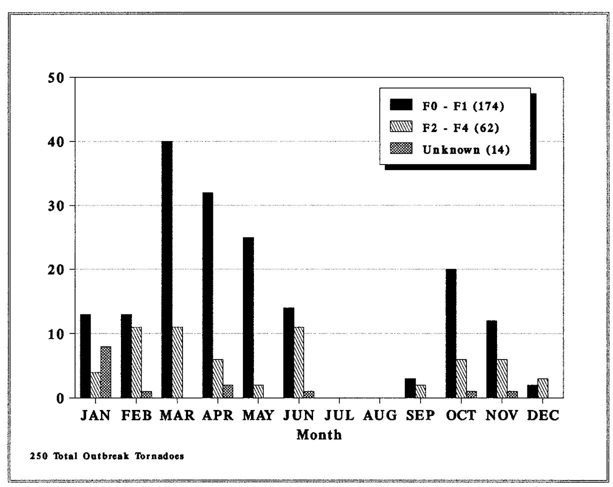

FIG. 8. Monthly distribution of outbreak tornadoes by F scale (1950–94).

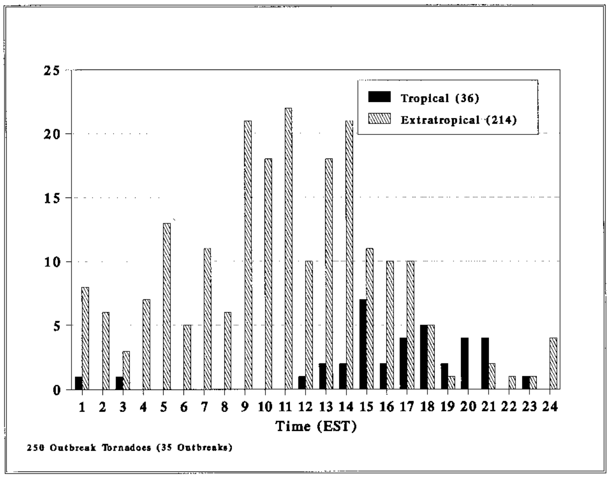

FIG. 9. Hourly distribution of peninsular Florida outbreak tornadoes (1950–94).

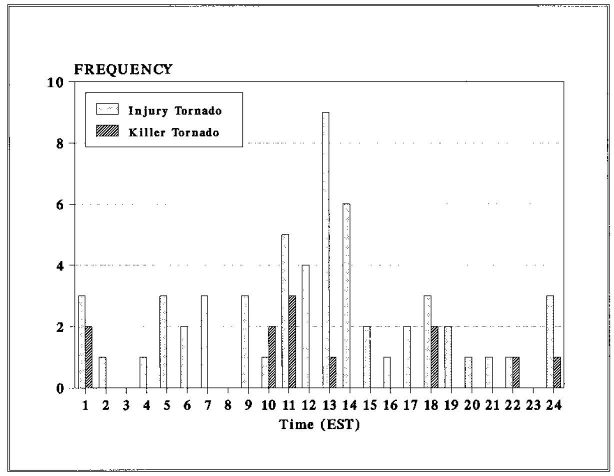

FIG. 10. Hourly distribution of peninsular Florida killer and injury outbreak tornadoes (1950–94).

of a small number of tropical/hybrid outbreaks that will be discussed later. Extratropical tornado strength peaks in the winter and decreases toward summer.

The hourly distribution of outbreak tornadoes is shown in Fig. 9. For the extratropical cases, tornadoes occur throughout the day and night, but most occur from 0900 EST through 1400 EST. A minimum of tornado activity occurs between 1900 and 2300 EST. Distinct diurnal differences in tornado occurrences have been noted between the southeast states and the Midwest, where tornadoes have a maximum in the late afternoon and evening, and a minimum in the morning (Wolford 1960 and Pautz 1969). The distribution of significant tornadoes in Grazulis (1993) also shows a peak in the morning for southeastern states. Anthony (1988) and Garinger and Knupp (1993) noted a secondary maximum of morning tornadoes in Florida. Schmocker et al. (1990) documented that most of the strong and violent tornadoes in central Florida occur during the dry season in the morning. The peninsular Florida morning tornado maximum is most striking. Of the 35 outbreaks, 21 (60%) began between 0000 and 1200 EST.

The extratropical cases cross the peninsula quite rapidly; thus, their tornado timing is more likely to be governed by synoptic-scale factors. However, why squall lines would show a tendency to begin crossing in the morning remains a subject for further research. Given the scale and strength of the parent midlatitude synoptic systems, it is unlikely the peninsula greatly affects their movement.

The five tropical cyclone cases have a distinctly different diurnal distribution than the extratropical cases. The tornadoes occurred mostly in the afternoon and evening and peak at 1500 EST. Often tornadoes occur either well removed from the cyclone center or well before cyclone landfall in Florida (Hagemeyer and Hodanish 1995). In these tropical cases, the cyclones move much more slowly and their convective bands affect the peninsula for a much longer time than the extratropical cases. This means tornado timing is less a function of cyclone timing as in extratropical cases, and diurnal peninsular scale factors such as surface differential heating may play a more significant role in producing rainband tornadoes. This finding is similar to that of Weiss (1987).

The hourly distribution of killer and injury outbreak tornadoes is shown in Fig. 10. A peak in killer tornadoes is evident in the late morning hours and injuries peak from late morning to early afternoon, generally corresponding to the major peak in the hourly tornado distribution. However, there are many environmental factors affecting deaths and injuries besides tornado occurrence. Note that in comparing Figs. 9 and 10, only one outbreak tornado has ever occurred in the 2100–2200 EST period and it was a killer. It is reasonable to assume that killer or injury outbreak tornadoes could occur at any time of day.

Figure 11 shows the location of the first tornadoes reported for the 27 extratropical outbreaks. The distribution is quite striking, with 25 outbreaks organized in a general north–south line from northeast to west-central Florida. The two exceptions (cases 1 and 8) were associated with northward-moving warm fronts. The distribution of the locations of the first tornadoes is perhaps not surprising when one realizes midlatitude extratropical cyclones and prefrontal squall lines all moved generally from west to east. Convective element movement obtained from coded radar observations ranged from south-southwest to north-northwest or about 160° of the western semicircle.

The distribution on Fig. 11 has important implications for forecasters. Clearly, with convection moving in from the Gulf of Mexico, western peninsula coastal counties have no possibility of upstream ground truth and more uncertainty about severe potential. Conversely, forecasters for the eastern counties of the Florida peninsula

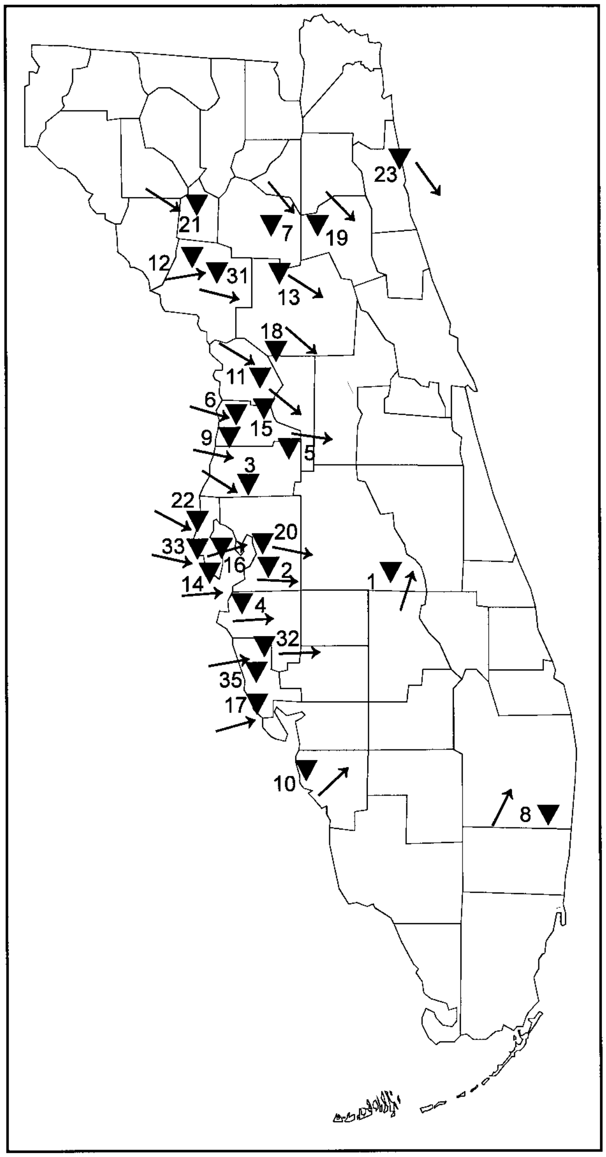

FIG. 11. Plot of locations of first tornadoes (▼) for 27 extratropical outbreaks. Numbers correspond to case numbers in Table 1. Arrows show general direction of movement of parent convective system.

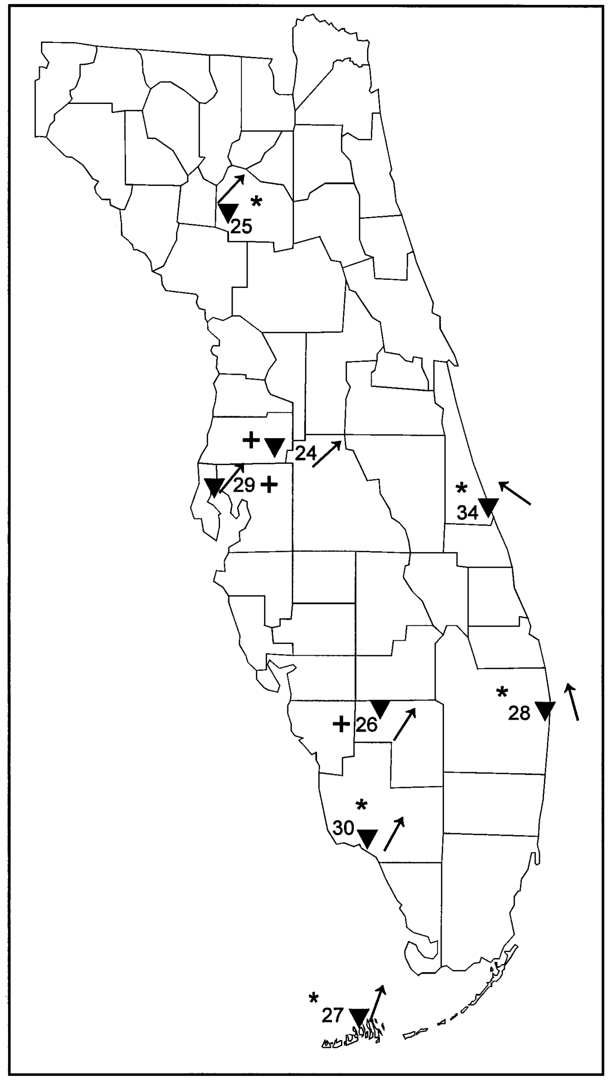

FIG. 12. Same as for Fig. 11 except for tropical cyclone (*) and hybrid (+) cases.

have a much greater chance to get ground truth and be prepared. Since these are generally fast-moving systems, intensive radar investigation of convection approaching the Gulf Coast is necessary. Tornadoes strike very soon after convection moves ashore, usually in the first tier of counties. It is debatable whether tornadic waterspouts are in progress offshore prior to landfall. Rapid tornado spinup in the coastal zone may be related to surface discontinuity and increased frictional convergence. This should be a subject for future research, especially now that a WSR-88D is operating at Tampa. Long-term study of rotation in offshore convection may help shed light on the issue.

Figure 12 shows the location of the first tornadoes reported for the eight tropical and hybrid cyclone outbreaks. There is considerable scatter among these cases and their distribution is markedly different from the extratropical cases. Both hybrid (+) and tropical case (*) convective systems have significantly, if not predominantly, northward components of motion and most began in the central and southern peninsula. This is understandable given the strong northward component of motion of their parent cyclones. Hurricane David (case 28) was the only outbreak associated with a cyclone in the Atlantic. The other seven cases were associated with cyclones in the Gulf of Mexico.

c. Environment

1) MEAN SEVERE WEATHER INDICES

To assess the thermodynamic and dynamic environment of the outbreaks, the upper-air sounding most rep-

TABLE 2. Mean values and standard deviations of 20 indices calculated from extratropical preoutbreak soundings and extratropical outbreak close proximity inflow soundings. The indices, from left to right, include temperature-based indices (*T*), lifted index (LI, °C), CAP strength (CAP, °C), freezing level (FZL, kft), 700–500-mb lapse rate (LR, °C/km), temperature- (*T*) and moisture- (T_d) based indices, theta-E index (TEI, °C), totals index (TT, °C) K index (K, °C), wet-bulb zero (WBZ, kft), precipitable water (PW, in.), B+ or convective available potential energy (CAPE, j kg^{-1}), B− or convective inhibition (j kg^{-1}), wind-based indices (wind), 0–6-km density-weighted mean wind (kt), 0–2-km and 0–3-km positive shear (SHR,10^{-3} s^{-1}), 0–2-km and 0–3-km storm-relative helicity (HEL, m s^{-2}), bulk Richardson number (BRN) shear (BRNSHR, m s^{-2}), and wind (wind), temperature (*T*), and moisture (T_d)–based indices: SWEAT index, BRN, and the energy–helicity index (EHI). Complete information about these parameters can be found in Hart and Korotky (1991).

	(*T*)				(*T*,T_d)							(Wind)						(Wind, *T*, T_d)		
	LI	CAP	FZL	LR	TEI	TT	K	WBZ	PW	B+	B−	0|6 k WND	0|2 k SHR	0|3 k SHR	0|2 k HEL	0|3 k HEL	BRN SHR	SWEAT	BRN	E/HI
Preoutbreak	−1	2.6	13.2	6.1	19	45	22	10.7	1.5	446	25	36	8.4	6.7	327	373	99	358	5	1.0
Std dev	4	1.6	1.3	0.9	8	6	13	1.4	0.3	402	61	7	2.4	1.9	148	158	43	82	5	1.0
Proximity	−3	1.5	13.4	5.4	19	46	31	11.4	1.8	995	200	45	11.7	7.6	400	405	95	324	14	2.3
Std dev	1	0.4	1.2	0.2	2	1	3	1.2	0.1	734	284	4	1.8	1.5	100	104	29	36	13	1.3

resentative of the severe weather environment was analyzed using the Skew*T*–Hodograph Analysis and Research Program (SHARP, Hart and Korotky 1991) for each outbreak case. Soundings were available from Tampa Bay (TBW), West Palm Beach (PBI), Miami (MIA, site deactivated and moved 60 n mi north to PBI in 1977), Key West (EYW), and Cape Canaveral (XMR). Preoutbreak soundings (last soundings released before beginning of an outbreak) were analyzed for the 33 cases from 1950 to 1993. Two of the cases had missing data, leaving 31 soundings. Proximity soundings (released within 2 h and 60 n mi of tornado touchdown) were also obtained for 11 cases and analyzed using SHARP. Five of these proximity cases were not representative of the storm inflow environment. They were released either in rain or in the wake of the parent convective system. This left six proximity inflow outbreak soundings. While this may seem like a small sample,

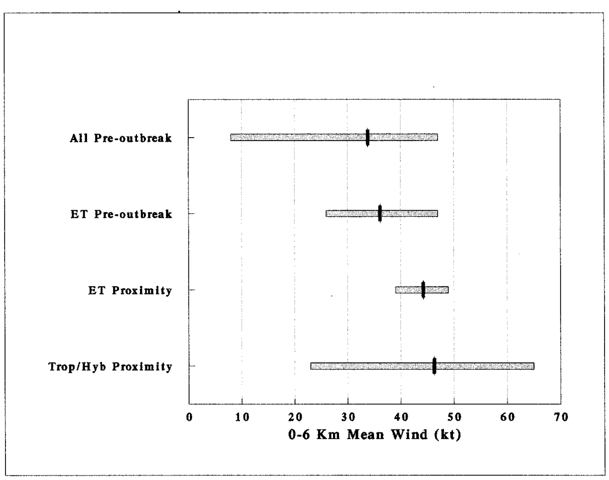

FIG. 13. High–low-average chart for 0–6 km mean wind computed with SHARP using all preoutbreak case soundings (All Pre-outbreak), extratropical preoutbreak soundings (ET Pre-outbreak), extratropical outbreak inflow proximity soundings (ET Proximity), and tropical/hybrid outbreak inflow proximity soundings (Trop–Hyb Proximity). Averages are indicated by the vertical lines.

McCaul (1991) used only 10 soundings in his study of the hurricane proximity inflow environment.

Mean values of 20 commonly used severe weather indices computed by averaging the indices of the individual preoutbreak extratropical and proximity inflow extratropical cases are shown on Table 2. The indices were calculated using the mean low-level lifted parcel and default storm motion (see Hart and Korotky 1991). Table 2 illustrates that in the mean there are considerable differences between some indices in the preoutbreak environment and close to tornadic storms. As expected, many indices change significantly in a direction favorable for tornadic production, especially wind-related variables when the proximity data are considered. This is useful climatological information, but the author is not in favor of purely index-based forecasting. An awareness of indices values and factors that affect their magnitude is crucial to their effective use in a comprehensive diagnosis of tornado potential. The most fundamental affect on indices or sounding representativeness is the population (environment) from which soundings are drawn.

An example of sounding representativeness is shown on Fig. 13, a high–low-average chart of 0–6-km mean wind for four different populations of soundings from this study. Charts like Fig. 13 were produced for the other 19 indices listed in Table 2 (not shown) and results were similar. In Fig. 13, the preoutbreak data for all outbreak cases (‘‘All Pre-outbreak’’ in Fig. 13) shows a wide range of values on either side of the average and skewed toward lower values. Here, the idea of an average sounding or index value has little meaning. This all-case population contains cases of mixed synoptic types: extratropical, tropical, and hybrid. When the data are limited to the same synoptic type, extratropical preoutbreak soundings (‘‘ET Pre-outbreak’’ in Fig. 13), the average wind is increased slightly, and the range of the data is considerably reduced and more evenly distributed. The dispersion of data or range is still affected by time and space variability in relation to the outbreak environment. Timing of tornado occurrence to sounding release time has considerable variability since soundings could precede tornado occurrence by as much as 12 h and be more than 125 n mi from touchdown.

When the population is restricted to only those cases with extratropical proximity inflow soundings (''ET Proximity'' in Fig. 13), where sounding differences are on the storm scale or mesoscale, the mean 0–6-km mean wind is increased significantly and the range is quite low. The 0–6-km mean wind increased further for the proximity inflow tropical/hybrid cases (''Trop–Hyb Proximity'' in Fig. 13), which are grouped together because of their similarity, but the wide range is due to including systems ranging from marginal tropical storms to hurricanes.

Clearly the forecaster should be alert to the fact that there is a variety of conditions that can lead to tornado outbreaks and the environment can evolve in a number of ways to reach favorable conditions for tornado formation.

Caution should be used in correlating sounding data to the tornado outbreak environment without allowing for time and space adjustments and completing a detailed diagnosis. For the March 1993 superstorm tornado outbreak, the 0–3-km storm-relative helicity computed from the 0000 UTC 13 March 1993 TBW sounding was 179 m s^{-2} several hours before the outbreak began. Helicity computed from an inflow proximity sounding constructed using estimated surface and upper-air data and Doppler wind data and observed storm motion from the Melbourne WSR-88D at 0530 UTC when an F2 killer tornado was within 60 n mi of the radar site was over 700 m s^{-2}.

It should be clear that upper-air soundings in close spatial and temporal proximity to peninsular Florida tornado outbreak environments have the greatest predictive value. However, until recently, forecasters had to rely on single station, 12-h soundings at widely spaced intervals to diagnose the outbreak environment, which is perhaps one reason skill for Florida has been relatively low (Anthony and Leftwich 1992; Crowther and Halmstad 1994). The increased availability of higher-resolution numerical model gridded data to forecasters now allows for construction of future proximity soundings to the extent model accuracy allows. Hourly model gridpoint soundings can now be input directly into the SHARP program (Nierow and Kane 1993). Meteorological conditions favorable for peninsular Florida tornado outbreaks often only exist for a few hours. The ability to observe the hourly evolution of important variables computed from a model gridpoint sounding processed via SHARP and in real time with WSR-88D velocity azimuth display (VAD) wind profiles (VWP) at frequent intervals may go a long way toward improving the prediction of tornado outbreaks.

2) MEAN SOUNDINGS

Given the discussion on the limitations of outbreak sounding data, it is now instructive to present mean soundings and hodographs that best represent the extratropical preoutbreak environment (Figs. 14a,b), the extratropical outbreak proximity inflow environment (Figs. 15a,b), and the tropical–hybrid outbreak proximity inflow environment (Figs. 16a,b). Tropical and hybrid cases were combined because of their general similarity below 500 mb and because there was not enough of each type of case to average separately. The mean soundings were produced by pressure averaging the individual soundings in the given population. Indices shown in Figs. 14a,b and 15a,b may differ slightly from those in Table 2, which were produced by averaging indices calculated from individual soundings.

In comparing the extratropical peninsular Florida tornado environments to those of the Midwest or Great Plains, it should be noted that there are fundamental climatological differences due to geography. Virtually all tornado proximity soundings used in studies of Great Plains and Midwest tornado environments are from 0000 UTC data and show a strong influence from diurnal heating (Maddox 1976; Johns and Sammler 1989; Schaefer and Livingston 1990). Likewise, nearly all Great Plains/Midwest preoutbreak or precedent soundings are from 1200 UTC data and show a strong influence of a diurnally fluctuating low level jet (LLJ) (Maddox 1993). This is the opposite of the situation in peninsular Florida, where most extratropical preoutbreak soundings are from 0000 UTC data and most proximity soundings are for 1200 UTC data. This results from the fact that the majority of peninsular Florida extratropical outbreaks begin in the morning and that strong advection of warm, moist low-level air was more of a destabilizing influence than diurnal heating. Even in those extratropical peninsular Florida outbreaks that began in the afternoon, diurnal heating was often not considered a major factor due to widespread cloud cover. One might expect some significant influence of diurnal heating in the primarily 0000 UTC preoutbreak soundings, but most extratropical outbreaks occur in the winter and early spring when daylight hours are relatively short. The Gulf of Mexico, with vastly different responses to solar heating, is upstream rather than the expanse of the Great Plains. However, the reason peninsular outbreaks tend to begin in the morning is a subject of continuing investigation.

The mean extratropical preoutbreak skew T–log$p$ (Fig. 14a) is significantly different from the typical Midwestern pretornado environment (Johns and Doswell 1992). In Fig. 14a instability is relatively weak and there is no sign of any capping inversion as is common in the Midwest preoutbreak environment. Inspections of all individual soundings that make up this mean sounding revealed none had a capping inversion. A distinct low-level moist layer overlaid by a very dry layer in the midtroposphere was common, but there were no capping inversions between these layers. The midtropospheric dry air, which provides a significant reservoir of potential convective instability, typically resulted

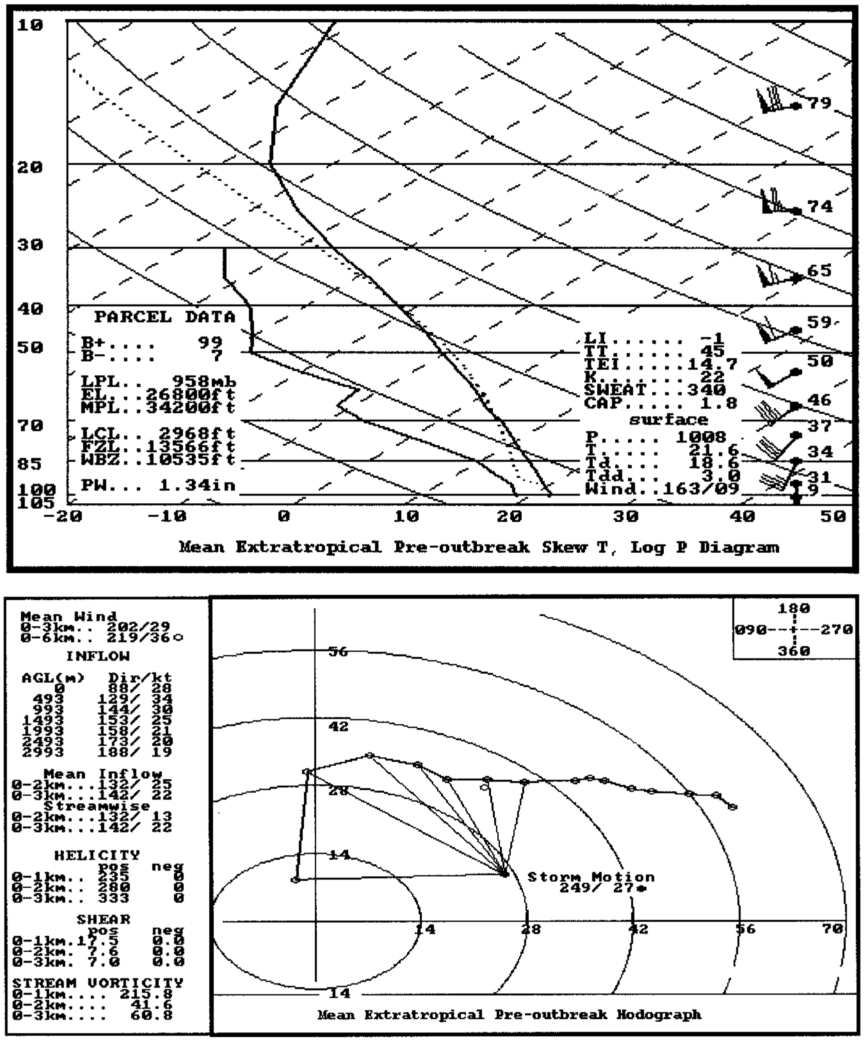

FIG. 14. Mean extratropical preoutbreak skew T–log$p$ diagram (a) and hodograph (b) produced from the SHARP workstation (Hart and Korotky 1991).

from subsidence in the subtropical upper anticyclone. The relative warmth of this air mass contributes to the weak static instability of the preoutbreak airmass. The Florida peninsula can on occasion be affected by an elevated mixed layer (EML) from an elevated heat source such as the desert southwest (Lanicci and Warner 1991; Hagemeyer 1991) from a very strong system or one that takes a more southward track. However, this air mass is usually out of phase with severe weather development and is seen over the peninsula after the cyclone passage. An EML air mass did not play a part in any of the 35 outbreaks in this study.

The extratropical preoutbreak hodograph (Fig. 14b) is similar in shape to that of the Midwest pretornado environment, but greater in magnitude (Taylor and Darkow 1982). Winds increase with height to a maximum in the upper troposphere. While instability is relatively weak in the mean, low-level shear and mean wind parameters are relatively strong.

Comparing the extratropical inflow proximity sounding (Fig. 15a) and hodograph (Fig. 15b) to the preoutbreak sounding (Fig. 14a) and hodograph (Fig. 14b) illustrates the changes that take place to produce an environment very favorable for tornado development. Comparing Fig. 14a to Fig. 15a, significant moistening and warming of the lower troposphere due to advection of tropical air, and moistening of the midtroposphere, take place. This results in a more unstable environment with positive buoyant energy between about 800 and 350 mb in Fig. 15a. The midlevel moistening in an area of strong low-level convergence associated with the warm sector of extratropical outbreaks also produces a favorable environment to sustain updrafts without detrimental entrainment (Darkow 1986).

Wet-bulb zero (WBZ) and freezing level (FZL) are relatively high compared to Midwest tornado environments, and this explains the general lack of large hail with outbreaks. Johns and Doswell (1992) note that su-

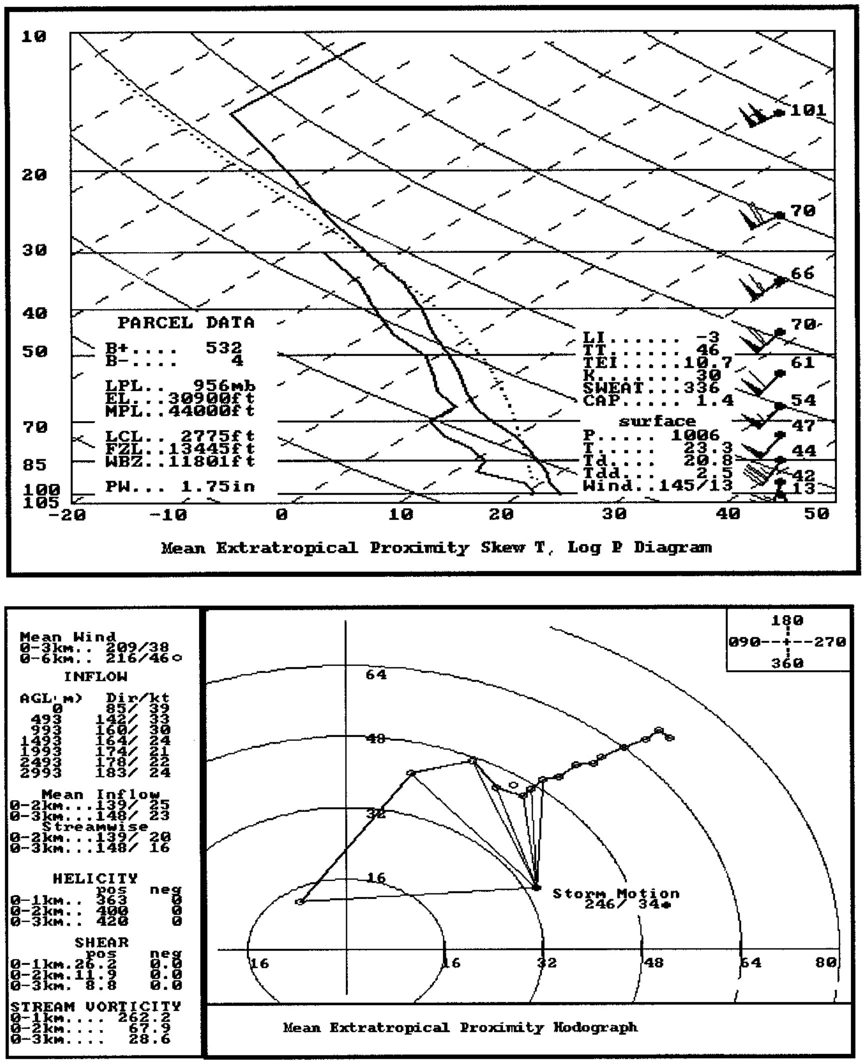

FIG. 15. Same as for Figs. 14a,b except for mean extratropical outbreak inflow proximity cases.

percells associated with relatively weak instability often do not produce large hail.

Comparing Figs. 14b and 15b illustrates that all wind-related parameters increase in the tornado proximity inflow environment. In particular, wind velocity and veering increase significantly in the first 1 km with a distinct LLJ indicated in the proximity hodograph (Fig. 15b). While there is a general increase in winds at all levels from Figs. 14b to 15b, the greatest changes are in the first 1 km in close proximity to outbreak tornadoes. Positive shear from the surface to 1 km is 66% higher in the proximity environment and 86% of the 0–3-km storm-relative helicity is generated in the first kilometer as compared to 70% for the preoutbreak environment. Upper-level winds increase considerably between the preoutbreak and close proximity environments, as in nearly every case a jet streak in the subtropical jet stream moved across or near the Florida peninsula during the outbreak. The mean proximity inflow hodograph (Fig. 15b) is similar in shape to that of the typical Midwest tornado environment but has greater low-level shear and helicity (Johns and Doswell 1992; Taylor and Darkow 1982).

Hagemeyer and Schmocker (1991) found that most east-central Florida *nonoutbreak* tornadoes in the dry season were also associated with extratropical cyclones and fronts. Their mean environment was characterized by a surface boundary across the peninsula for tornadoes occurring on the east side of the peninsula. Their proximity soundings were selected without regard for number of tornadoes and the proximity definition was less restrictive than in this study so they are not directly comparable to the outbreak cases. Nevertheless, it can be said with some confidence that the outbreak proximity environment is characterized by deeper moisture, and stronger lower-tropospheric winds and shear than the nonoutbreak tornado proximity environment (Hagemeyer and Schmocker 1991).

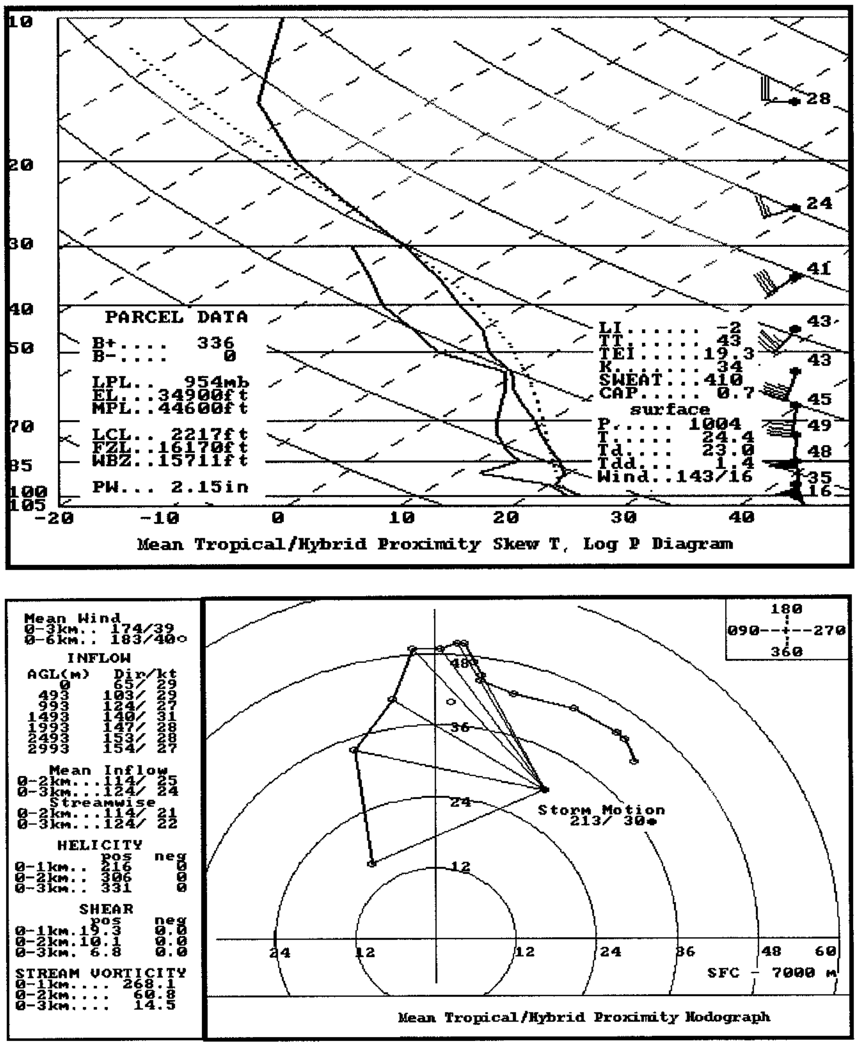

FIG. 16. Same as for Figs. 14a,b except for mean tropical/hybrid outbreak inflow proximity cases.

There are some significant differences and similarities between the extratropical proximity outbreak sounding (Fig. 15a) and hodograph (Fig. 15b) and the tropical/hybrid sounding (Fig. 16a) and hodograph (Fig. 16b). Comparing Figs. 15a and 16a, the most obvious difference is that where the extratropical wind increases with height to a maximum in the upper troposphere, the tropical–hybrid cases decrease with height from a maximum in the lower troposphere to a minimum in the upper troposphere. This is the fundamental difference between extratropical outbreaks with a strongly baroclinic environment and tropical–hybrid outbreaks with a quasi-barotropic environment. Yet each is capable of producing strong tornadoes.

The tropical–hybrid proximity sounding (Fig. 16a) is quite moist with precipitable water (PW) over 2 in. but shows a similar positive area to the extratropical proximity sounding (Fig. 15a) in the midlevels and similar values of convective available potential energy (CAPE). The tropical–hybrid sounding is considerably warmer at most levels aloft, which would tend to reduce the CAPE. However, it is also warmer and moister in the lower levels and reflects more of the influence of diurnal heating. Recall from the discussion of Figs. 9 and 12 that tropical–hybrid systems effect the peninsula for longer periods than extratropical systems and more of their tornadoes occur in the afternoon, indicating diurnal heating may be a significant factor as opposed to extratropical cases. The end result is that the thermodynamic environment of the two types of outbreaks is similar.

The mean tropical/hybrid hodograph (Fig. 16b) displays a ‘‘loop’’ or ‘‘horseshoe’’ shape found in hurricane close-proximity cases described by McCaul (1991) due to winds decreasing with height above the low-level maximum and gradually veering in the tropical tornado environment. On average, dynamic parameters such as storm-relative (SR) helicity, positive shear, and mean

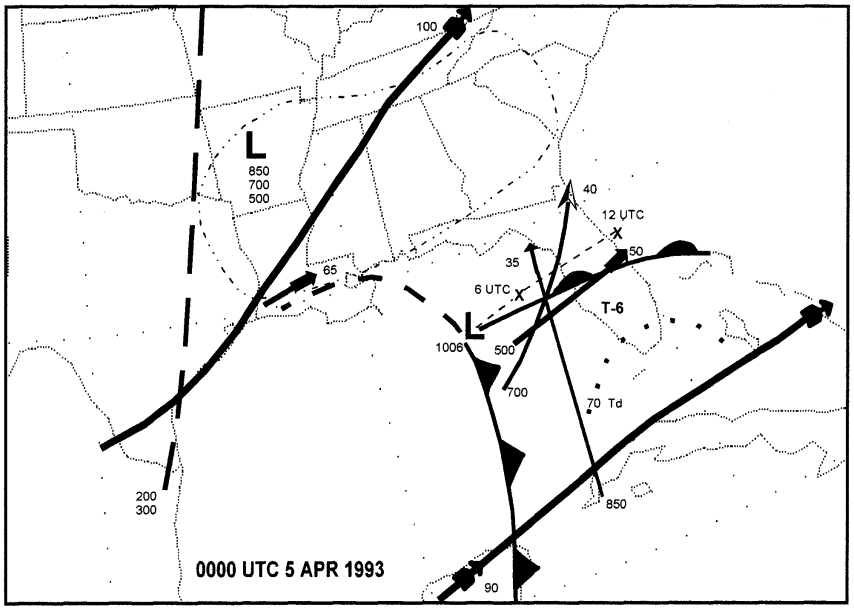

FIG. 17. Composite synoptic analysis for 0000 UTC 5 April 1993. Surface fronts, surface and upper troughs, and areas of high and low pressure are shown by conventional notation with levels in mb indicated. Axes of maximum winds at 850, 700, 500, and 250 mb are indicated by the symbols →, ⋗, ➡, and ➧➧, respectively. Maximum winds are indicated in knots. The track of the surface low is indicated by the light-dashed line. The leading edge of the highest values of low-level moisture (surface dewpoint T_d in °C) is indicated by the heavy-dotted line over south Florida. The approximate location of the first tornado is indicated by "*T*," 6 h after map time.

wind are less for the tropical–hybrid proximity environment than extratropical. However, it should be noted that tropical–hybrid cases display greater variability in wind-related parameters compared to extratropical cases (see Fig. 13) but are still capable of producing supercell thunderstorms and strong tornadoes. Mean inflow and streamwise vorticity are nearly identical in the two environments. Mean wind and storm motion are considerably more southerly for the tropical–hybrid cases than the extratropical cases. This relates to the discussion of Figs. 11 and 12 regarding tornado location and movement.

4. Synoptic case studies

Case studies of each type of outbreak—extratropical, tropical, and hybrid—are presented to supplement the information on climatology of peninsular Florida tornado outbreaks and their mean environments. Three recent case studies were selected because they serve to clearly illustrate the fundamental characteristics of, and differences between, the different outbreak types. Melbourne, Florida, WSR-88D data will be presented for each of the case studies; however, detailed interpretation of radar data is beyond the scope of this paper. Explanations and examples of WSR-88D products can be found in Klazura and Imy (1993).

a. Extratropical outbreaks

The tornado outbreak that occurred early on the morning of 5 April 1993, less than a month after the March 1993 superstorm (see DOC 1994; Kocin et al. 1995), is typical of peninsular Florida extratropical tornado outbreaks.

Figure 17 shows the preoutbreak composite synoptic analysis for 0000 UTC 5 April 1993. A surface low pressure center in the eastern Gulf of Mexico is beginning to deepen and accelerate as a strong short wave rotates through the base of a trough extending from a 500-mb low centered over Arkansas into the western Gulf of Mexico. A split jet stream flow is present at 250 mb with jet streaks approaching the Florida Straits from the Yucatan Peninsula and exiting to the north over the Tennessee Valley. This upper-level flow pattern resulted in strong upper diffluence over the central peninsula. A warm front extended eastward across central Florida from the low and a cold front trailed south from the low to the Yucatan Peninsula. Surface observations over the western peninsula indicated pressure falls of 2.4 mb in 3 h. An 850-mb jet axis and moist axis in the warm sector intersected the warm front west of the Florida peninsula. Jet axes at 700 and 500 mb overlaid the LLJ, resulting in significant veering and a favorable environment for rotating thunderstorms. At this time a prefrontal squall line was developing in the warm sector a few hundred miles west of the Florida peninsula.

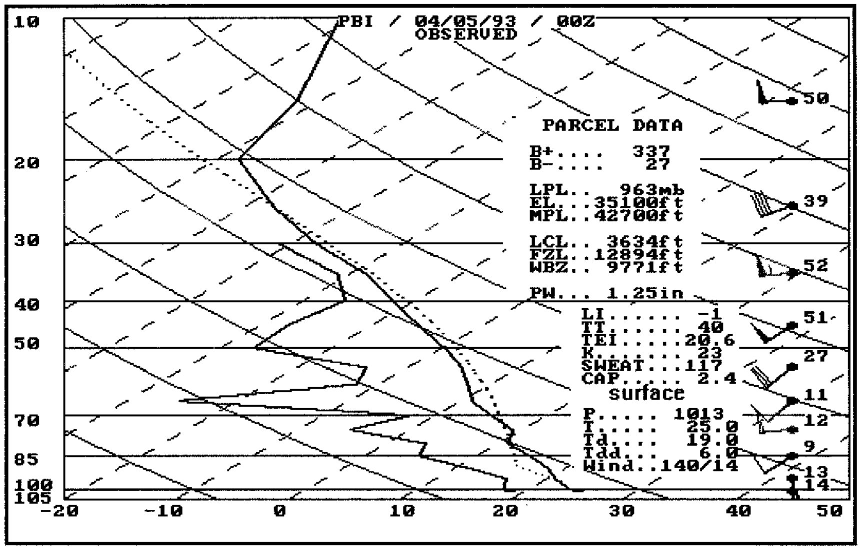

FIG. 18. The skew *T*–log*p* diagram for West Palm Beach, Florida, at 0000 UTC 5 April 1993.

It is likely a strong 500-mb jet maximum was over the central Gulf of Mexico and approaching the Florida peninsula at 0000 UTC. The often complete lack of upper-air data over the Gulf of Mexico makes for a difficult analysis, but with 65 kt (32.5 m s^{-1}) at 500 mb over Lake Charles and already 50 kt (25 m s^{-1}) above Tampa, it was likely at least a 70 kt (35 m s^{-1}) jet maximum existed over the central gulf. The diagnosis of jet streaks in the data-sparse gulf is crucial to successful extratropical outbreak forecasting. An analysis combining continuity, knowledge of dynamic and conceptual models, and using all available observational data including radar and satellite data is essential to diagnose the preoutbreak environment.

The 0000 UTC 5 April 1993 Tampa Bay skew *T*–log*p* was not representative of the warm sector air mass, as the warm front was in the vicinity and the hodograph contained negative shear and streamwise vorticity in the lowest kilometer. The next best warm sector sounding was West Palm Beach (PBI, Fig. 18), about 125 n mi east-southeast of Tampa. The Key West sounding, 215 n mi south-southeast of Tampa, was similar to the PBI sounding, but slightly more unstable and with less low-level shear and wind velocity. The PBI sounding (Fig. 18) is typical of preoutbreak extratropical cases in the warm sector: marginally unstable with dry air in midlevels. The hodograph (not shown) had begun to develop a favorable veering profile in the lower levels, but low-level winds had not yet increased significantly in response to the approaching low. Storm-relative helicity from 0–3 km was 42 m s^{-2}, and 0–3-km positive shear was 4.1 10^{-3} s^{-1}.

By 0553 UTC the Melbourne WSR-88D indicated that the prefrontal squall line was south of Tampa Bay (''A'' to ''B'' in Fig. 19) and was racing eastward toward the southern peninsula. The line was moving eastward at speeds exceeding 40 kt (20 m s^{-1}) with individual cells moving east-northeastward at near 50 kt (25 m s^{-1}) at times. A distinct bowing or comma-head feature was evident at the northern end of the squall line (Przybylinski 1995; Weisman 1993). Most of the tornadoes were associated with this feature. The occurrence of tornadoes with bow echoes in prefrontal squall lines in recent outbreaks is common, and this case is not unlike that for the March 1993 superstorm (DOC1994).

Figure 20 shows the tornadoes and severe thunderstorm wind reports for this outbreak. Four reports of tornadoes and four reports of severe thunderstorm wind damage were received between 0630 and 0645 UTC in the heavily populated coastal area from Sarasota south to Fort Myers as the north end of the squall line hit land.

Figure 21 shows the squall line about midway across the peninsula at 0751 UTC. The northern bow-echo feature (''A'' in Fig. 21) caused two more tornadoes at 0800 and 0815 UTC before weakening. The northern bow echo had dissipated by 0900 UTC. A second bow echo (''B'' in Fig. 21) developed on the squall line to the south of the first and produced two more tornadoes at 0905 and 0915 UTC before moving into the Atlantic. The trailing squall line south of the bow echo passed on a more east or east-southeastward track through south Florida and produced severe thunderstorm winds as far south as Key West and another weak tornado near Fort Lauderdale at 0930 UTC.

It is useful to note that there were eight severe weather reports in 15 min when the squall line first hit the west coast and seven reports in 15 min when it exited the east coast and only six reports in the 2½ h it took the squall line to cross the interior. Both coasts have a narrow, heavily populated zone; in the interior it is very sparsely populated.

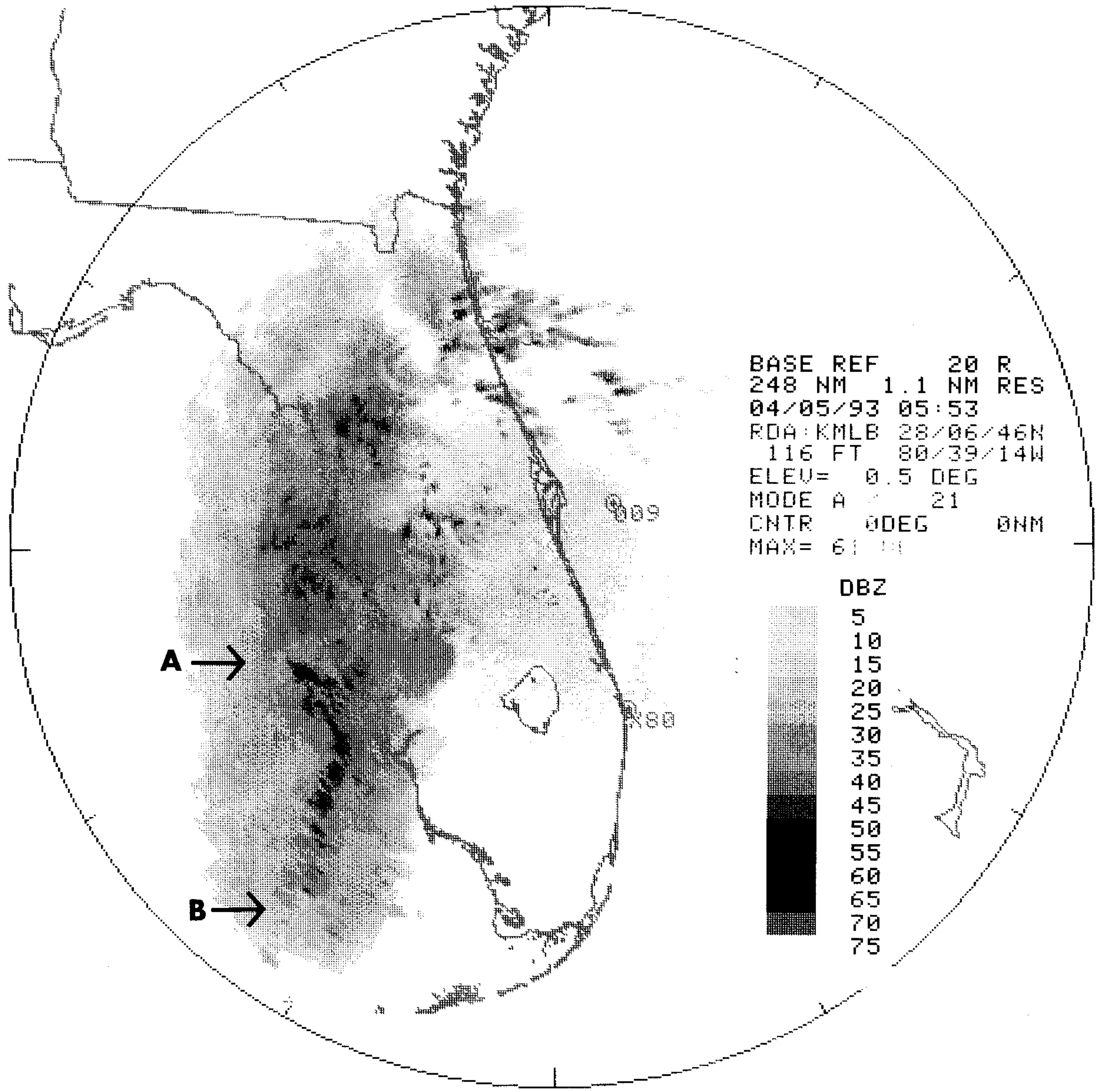

FIG. 19. Base reflectivity product (0.5° elevation, 248 n mi range) from Melbourne, FL, WSR-88D showing prefrontal squall line from "A" to "B" approaching the southwest Florida coast at 0553 UTC 5 April 1993.

Figure 22 shows the proximity hodograph for 0900 UTC as the northern end of the squall line approached the Melbourne WSR-88D site and the major bow echo was about 30 mi south of Melbourne. Figure 22 was constructed using 0900 UTC surface reports, WSR-88D VWP winds, and observed storm motion from the WSR-88D. It is quite similar to the mean inflow proximity hodograph (Fig. 15b). A distinct LLJ and strong low-level shear are evident, and 0–3-km storm-relative helicity has increased to 523 $m\ s^{-2}$. The WSR-88D VWP showed an 80-kt (40 $m\ s^{-1}$) maximum from 35 to 40 kft (10.6–12.2 km) passing over the area between 0800 and 0900 UTC. This was likely a reflection of the jet streak moving toward the Florida Straits at 0000 UTC shown in Fig. 17. Jet streaks were also evident at 1200 UTC across the southern peninsula at 700 and 500 mb in the wake of the squall line.

By 1030 UTC the squall line was already well offshore in the Atlantic. A deep, dry air mass in the lower and midtroposphere was evident in the TBW sounding at 1200 UTC (not shown), indicating a dry intrusion may have played a role in this outbreak. The surface low tracked farther south than in most extratropical cases, moving rapidly just north of east, to offshore Daytona Beach by 1200 UTC. This outbreak lasted exactly 3 h. All severe weather reports were in the warm sector.

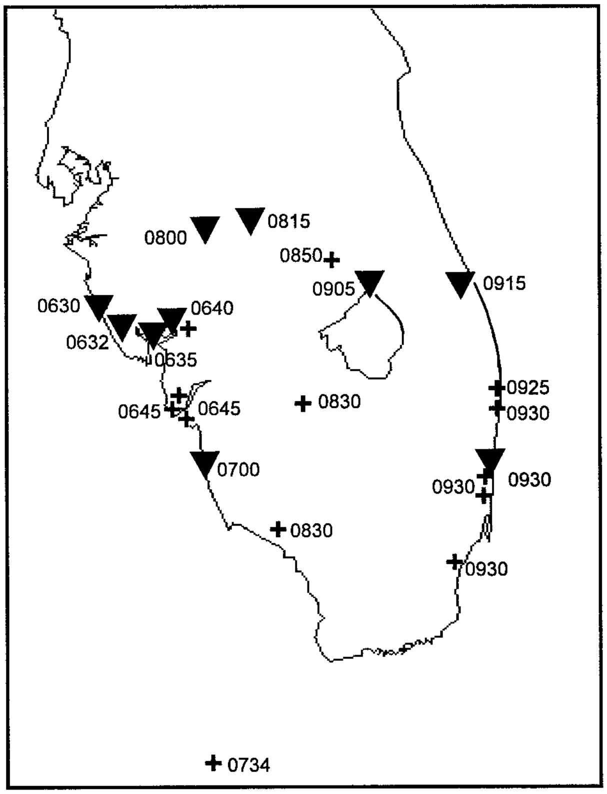

FIG. 20. Plot of tornadoes (▼) and severe thunderstorm winds (+) reported for the 5 April 1993 outbreak. Times are in UTC.

b. Tropical cyclone outbreaks

1) DISCUSSION

To expand our knowledge beyond the data search discussed in section 2, the publications *Significant Tornadoes 1680–1991* (Grazulis 1993) and *Tornado Occurrences in the United States 1916–1958* (Wolford 1960), and *Storm Data* (1959–94) were reviewed for all documented tornadoes in peninsular Florida associated with tropical cyclones, tropical disturbances, and hybrid cyclones. Historical tropical cyclone track information was obtained from the CD-ROM, *Global Tropical/Extratropical Cyclone Climatic Atlas* (USN and DOC 1994). The review yielded nine cases of tropical cyclones causing four or more tornadoes in the recorded history of peninsular Florida. Three cases (two hurricanes and one tropical storm) that occurred before 1950 were discussed briefly in section 3b. The remaining six cases (four hurricanes and two tropical storms) occurred between 1950 and 1994. Of these six, five also met the rigorous outbreak test of at least four tornadoes in 4 h or less and are shown in Table 1. Only Hurricane Elena in August 1985 (four tornadoes in 10:50 h) did not meet the rigorous temporal criteria of the outbreak definition. This case caused no injuries or deaths.

Of the nine tropical cyclones that produced at least four tornadoes, four produced all their tornadoes before the center made landfall. In eight of the nine cases, tornadoes occurred in the right-front quadrant of the cyclone. This is consistent with previous research such as Novlan and Gray (1974) and Gentry (1983). Only two of the nine cases had tornadoes near the center. Tornadoes associated with Hurricane Isbel (case 30 in Table 1) occurred both in the right-front sector before landfall and continued near the center as Isbel crossed the peninsula from southwest to northeast.

Seven of the nine tropical cyclones approached Florida from the Gulf of Mexico. Only Hurricane David in September 1979 and the hurricane of September 1929 approached from the Atlantic Ocean. September is also the most likely month for tropical cyclones to strike Florida from the Atlantic (Neumann et al. 1993). Only two outbreak cases (34 and 28) were associated with convection moving in from the Atlantic Ocean. The tropical cyclone storm tracks generally had a predominantly northerly component when producing multiple tornadoes. Elena (August 1985), which underwent several loops in the gulf was the only exception. Killer tropical cyclone tornadoes have occurred in only two cases (June 1972 and November 1994) and both were outbreaks included in this study. In each case all tornado deaths occurred in trailers or mobile homes.

There appears to be much more variability in the manner in which tropical cyclone tornado outbreaks might develop compared to extratropical cyclone cases, which are remarkably similar to each other. The essence of the tropical cyclone tornado forecast challenge is predicting the occurrence of tornadoes *outside* the area where people are prepared for the maximum winds from a landfalling cyclone and predicting tornadoes from weaker cyclones where tornadoes may pose the greater threat.

2) CASE STUDY

Tropical Storm Gordon is an example where tornadoes, rather than winds associated with the circulation, were the greater threat. Gordon passed through the Florida Straits on 14 and 15 November 1994, bringing flooding rains and gusty winds to Miami and southeast Florida. At 0000 UTC 16 November 1994 Gordon was centered just north of Key West and moving slowly north. The composite synoptic analysis for this time is shown as Fig. 23. The analysis was produced by analyzing 0000 UTC observational datasets and Nested Grid Model gridded data. Gordon's development into a tropical storm may have been influenced by a persistent upper low and old frontal boundary that reached the Caribbean Sea several days earlier. However, by 0000 UTC 16 November, Gordon was clearly a warm-core tropical system detached from any midlatitude influence. A symmetrical circulation of greater than 30 kt (15 m s^{-1}) was evident at the surface and 850 mb, but winds were significantly higher on the east side of Gordon where a LLJ of 50 kt (25 m s^{-1}) had developed. The cyclonic circulation was evident at 700, 500, and 300 mb,

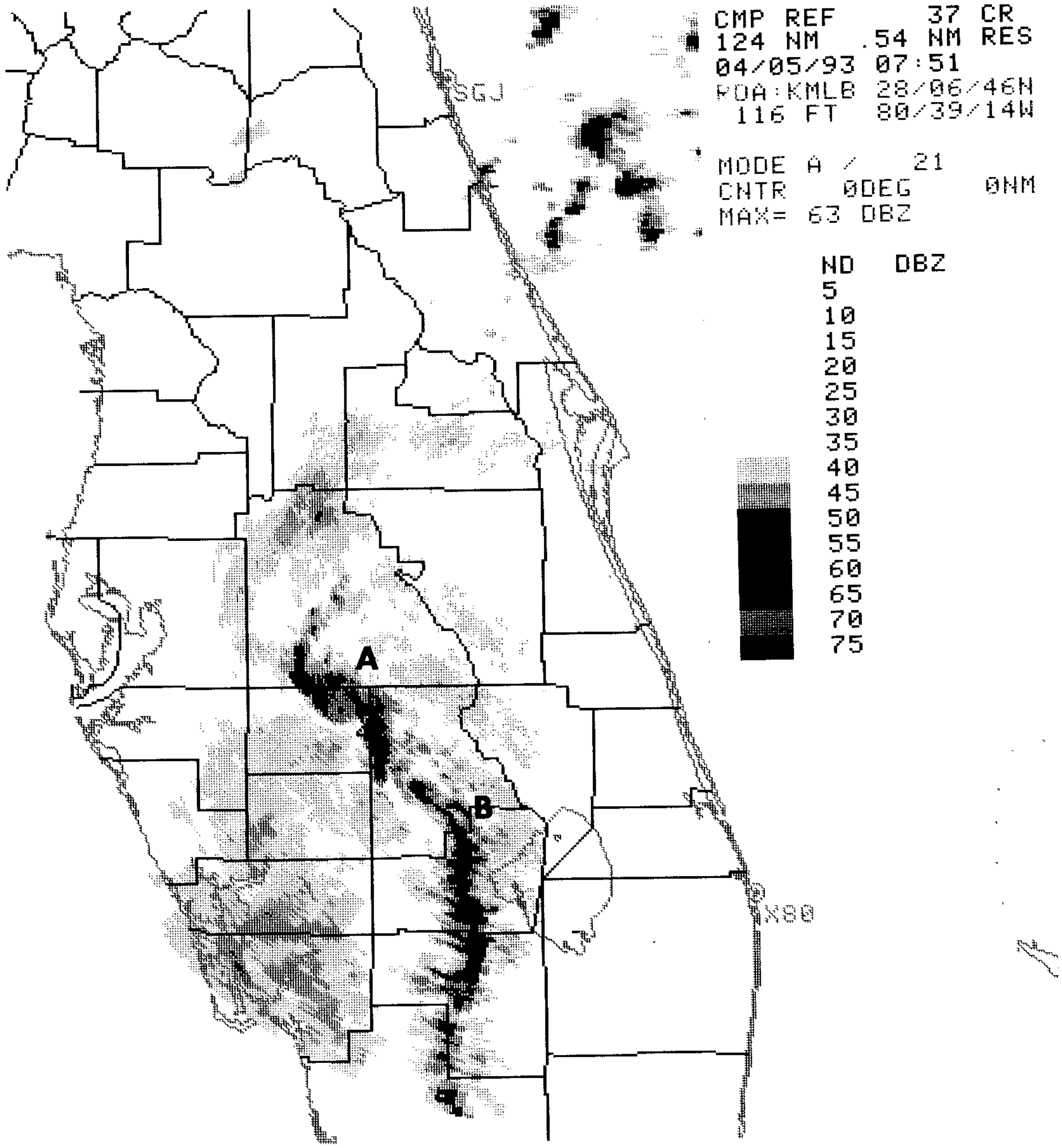

FIG. 21. Composite reflectivity product (.54 n mi resolution, 124 n mi range) from Melbourne, FL, WSR-88D for 0751 UTC 5 April 1993 showing prefrontal squall line midway across the peninsula. Bow echo at northern end of squall line with associated WSR-88D-detected mesocyclone is indicated at "A"; developing bow echo to the south is indicated at "B."

but the isotach pattern was discontinuous, as strong winds were indicated on the east side and the west side of the low, with lower wind speeds north and south. Deep tropical moisture was pulled north over the Atlantic coastal waters east of the center, while drier air was pulled down the backside of the large circulation center. The interaction of Gordon with a high pressure center off the Carolinas caused the development of a low-level northeastery flow of 25–30 kt (12.5–15 m s $^{-1}$) off northeast Florida and low-level southeasterly flow off southeast Florida. This resultant pattern produced an area of very strong low-level convergence and upward vertical motion offshore of east-central Florida (shaded area in Fig. 23), and an asymmetrical convective pattern around Gordon as detached rainbands spiraled around the northeast quadrant.

The 2352 UTC 15 November 1994 base reflectivity product from the MLB WSR-88D (Fig. 24), at about the time the first of six tornadoes was reported, shows the convective bands rotating around Gordon southwest of the line from "A" to "B." The large area of convection northeast of line "AB" was earlier associated with Gordon but at this time was moving to the north, away from the influence of the circulation.

The skew T–log$p$ from PBI for 0000 UTC 16 No-

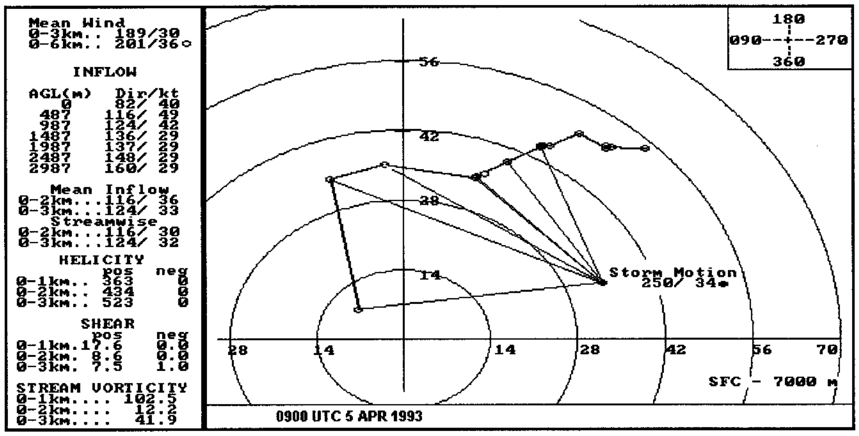

FIG. 22. Close proximity hodograph constructed from Melbourne, FL, WSR-88D VWP data, observed storm movement, and surface data for 0900 UTC 5 April 1993.

vember 1994 is shown as Fig. 25a (0000 UTC Cape Canaveral sounding not available). The sounding is quite moist with PW of 2.33 in., but still contains a relatively large positive area in the midlevels. In fact, the mean low-level lifted parcel does not intersect the temperature profile at high levels, resulting in an indeterminate CAPE. Warm 500-mb temperatures of −5°C are offset by warm and very moist low-level conditions enhanced in this case by the contribution of diurnal heating. Recall that in discussions of Figs. 9, 12, and 16a, the tropical/hybrid cases are more likely in the afternoon and evening.

The 0000 UTC proximity hodograph constructed from the MLB WSR-88D VWP and Melbourne International Airport (MLB) surface wind is shown as Fig. 25b. The hodograph displays a horseshoe or loop shape described by McCaul (1991) for hurricane proximity soundings and is very similar in magnitude to the mean

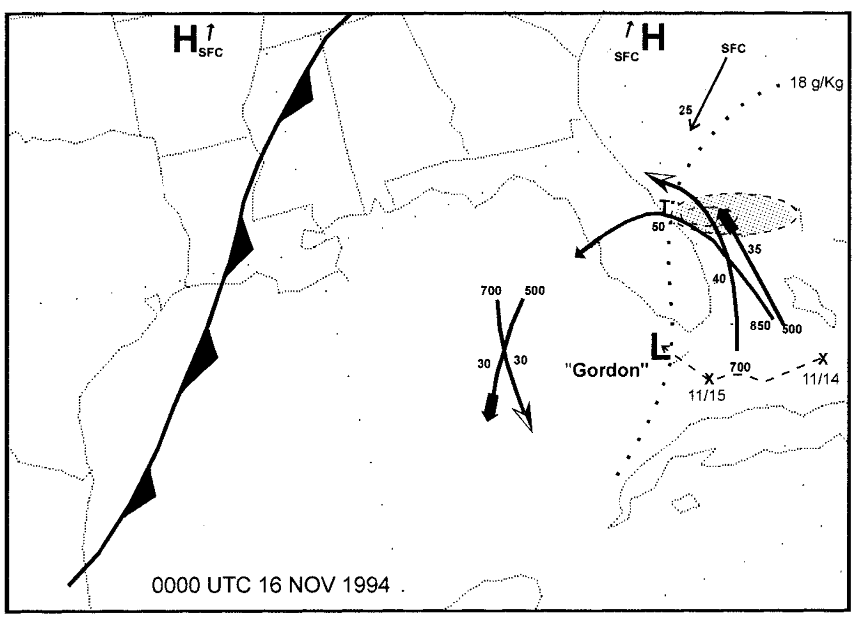

FIG. 23. Composite synoptic analysis for 0000 UTC 16 November 1994. Surface fronts and areas of high and low pressure are shown by conventional notation. Gordon was a vertically stacked low from the surface to 300 mb. Axes of maximum winds at 850, 700, and 500 mb are indicated by the symbols →, ⪢, and ➡, respectively. Maximum winds are indicated in knots. The past track of the surface low is indicated by the light-dashed line. The leading edge of the highest values of low-level moisture (surface mixing ratio in g kg^{-1}) is indicated by the heavy-dotted line. The approximate location of the first tornado is indicated by "T," at about the same time as map time. An area of strong low-level moisture convergence and upward vertical motion is indicated by the shaded area off the east coast of Florida.

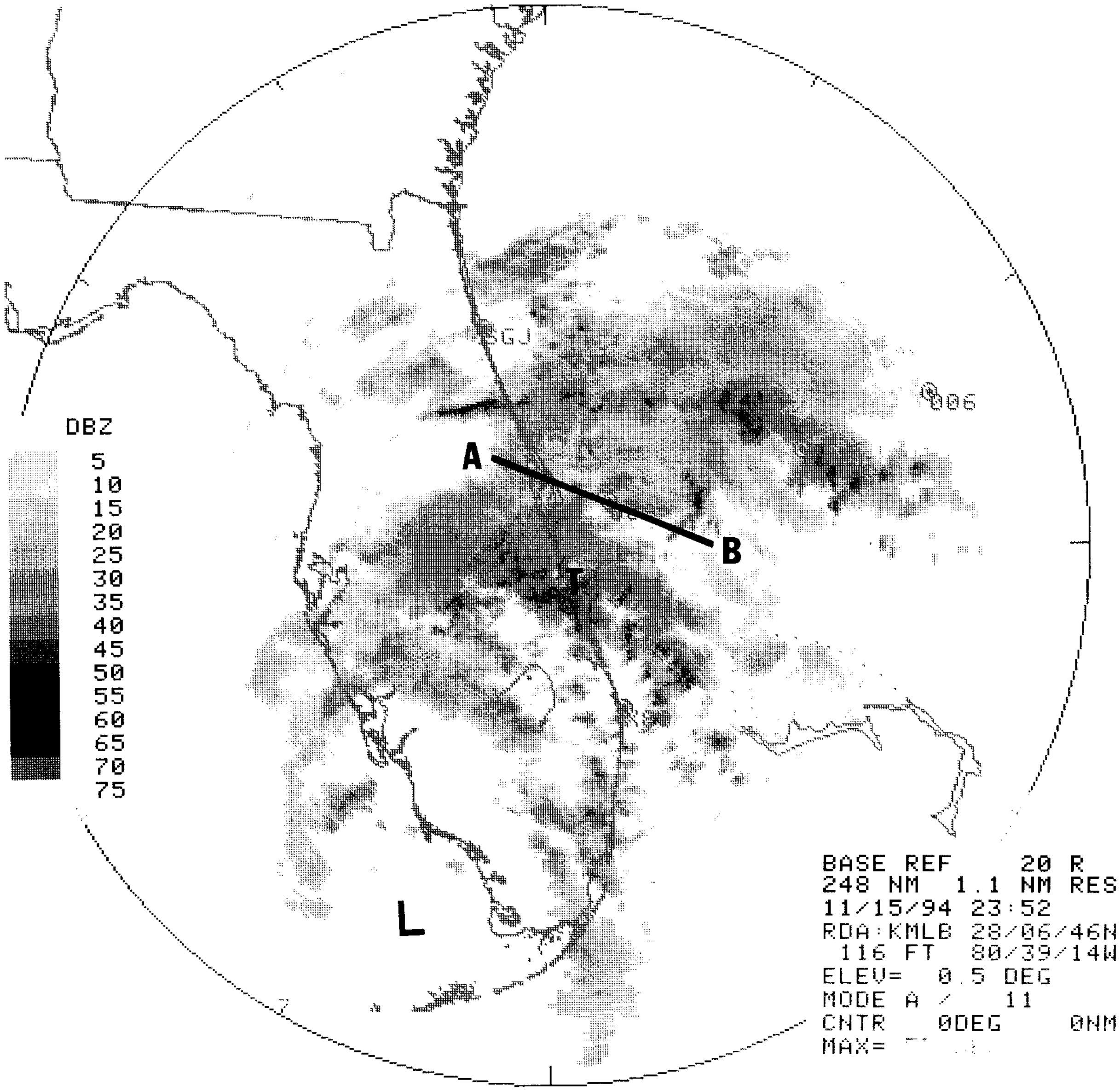

FIG. 24. Base reflectivity product (0.5° elevation, 248 n mi range) from Melbourne, FL, WSR-88D for 2352 UTC 15 November 1994. Rainbands associated with Gordon are shown at, and southwest of, line ''AB''; the large precipitation area northeast of line ''AB'' is moving north, away from Gordon's influence. The center of Gordon is indicated by ''L'' north of Key West. The location of the first tornado touchdown at 2356 UTC is indicated by ''T.''

hodograph (Fig. 16b) but has an easterly mean wind. Note that this outbreak case is one of only two that had convective elements move in from the Atlantic Ocean, most moved in from the gulf with a strong southerly component (see Fig. 12). The hodograph in Fig. 25b was taken within a few minutes and 20 n mi of the first tornado to occur in this outbreak. Because of the 50-kt (25 m s^{-1}) LLJ from 1 to 1.5 km, with winds decreasing, and gradually veering with height above it, most of the shear was in the lowest 1 km. The 0000 UTC PBI hodograph (not shown) released about 2 h before the second outbreak tornado occurred in Palm Beach County was very similar in shape to Fig. 25b but had a southerly mean wind illustrating the strongly cyclonically curved flow between PBI and MLB.

As early at 2030 UTC the MLB WSR-88D detected low-level rotation in rainbands that formed off east-central Florida in an area of strengthening convection associated with the strong low-level convergence zone. The first tornado (F2) touched down at 2353 UTC, striking the Barefoot Bay manufactured housing development on the coast south of Melbourne. The tornado

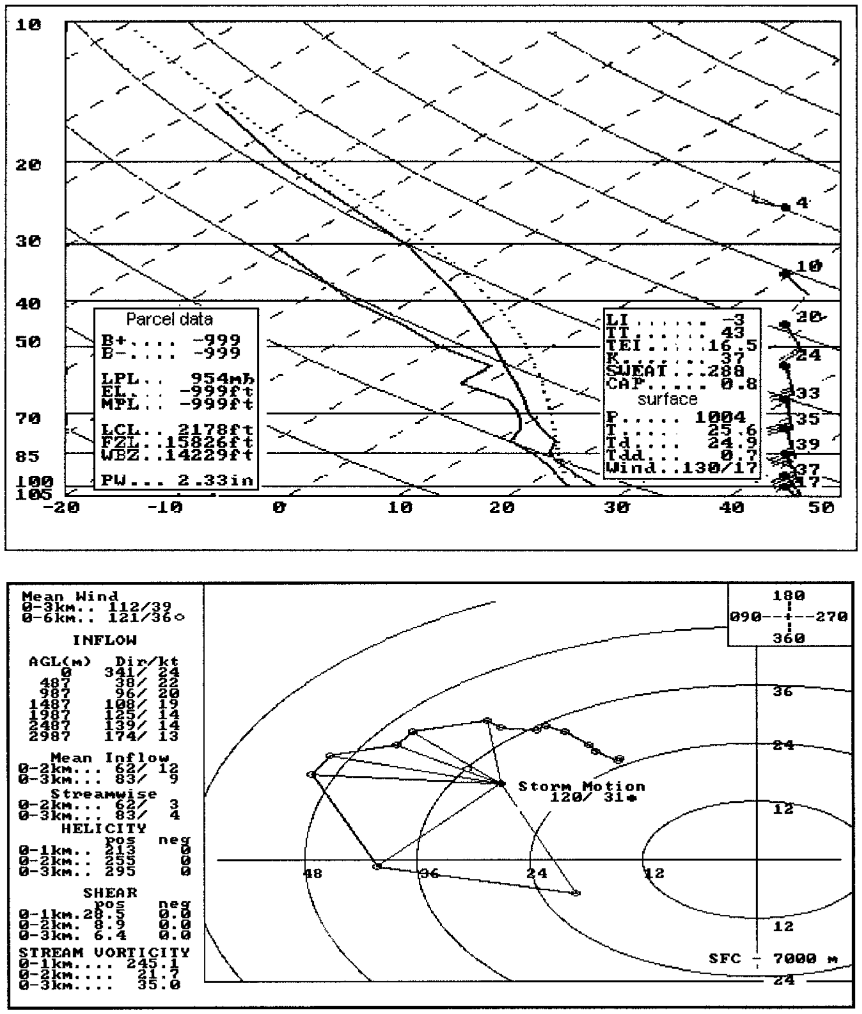

FIG. 25. Skew *T*–log*p* (a) for West Palm Beach, FL, at 0000 UTC 16 November 1994 and hodograph (b) constructed from 0000 UTC MLB WSR-88D VWP.

destroyed 62 homes, injuring 40 and killing one man before quickly dissipating.

Figure 26 shows the locations of tornadoes reported during this outbreak. Tropical Storm Gordon produced the second longest peninsular Florida tornado outbreak on record. For more than 8 h, showers and isolated thunderstorms formed in bands over the Atlantic coastal waters and moved onshore, occasionally producing tornadoes near the coast that dissipated after moving inland. Twice, gaps of more than 2 h occurred between tornado reports. Except for a few reports of waterspouts over the coastal waters, there were no other reports of severe weather, but flooding rainfall was widespread from 14 through 16 November in south Florida and from Daytona Beach to Orlando (Choy et al. 1996). Seven deaths were attributed to drowning.

The MLB WSR-88D detected shallow cyclonic shear or rotation in many of the rainbands and was used effectively to issue severe thunderstorm and tornado warnings to alert coastal residents. However, many more rotating storms were observed than tornadoes reported, and several false alarms were given. At times rotational velocities in rainbands would decrease as they approached land, at other times they would increase upon landfall. Since warnings had to be issued with lead times, these trends were often not observed until after decisions to warn or not warn were made. Spratt et al. (1997, this issue) provide a discussion of the storm-scale and mesoscale aspects of several of the tornadoes in this outbreak using WSR-88D data.

Based on peninsular Florida climatology, it is likely that if a tropical cyclone does produce multiple tornadoes, they may be spread over a relatively long period of time over a small area. This is considerably different from most outbreaks in the Midwest, which may last for an extended period but can occur over an area the size of several states. In the tropical cyclone cases, there is a risk of not issuing a tornado watch or canceling a

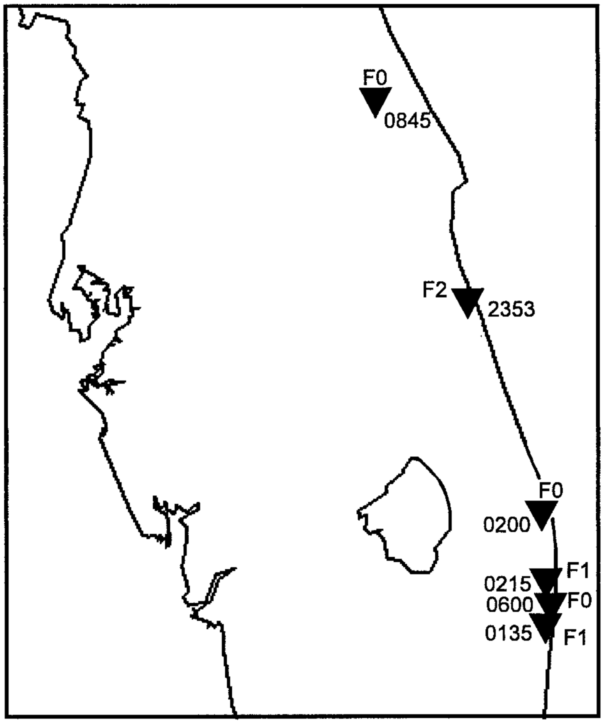

FIG. 26. Plot of tornadoes (▼) with F scale indicated for the 15–16 November 1994 outbreak. Times are in UTC.

watch too soon if reports do not come in after several hours and/or cease for several hours. Weiss (1985) discussed tornado watch forecast implications of multiple tornadoes associated with tropical cyclones but did not address temporal issues. In cases like Gordon, it is debatable whether a strategy of posting tornado watches for a narrow coastal zone for up to 12 h is preferable to issuing local statements of tornado potential and individual warnings as needed and including statements of tornadic potential in National Hurricane Center advisories. In the author's opinion, there is little doubt that tornado watches raise public awareness, especially with weaker tropical cyclones such as Gordon where general high winds are not a serious concern. Overwarning may be justified due to the rarity of tropical cyclone tornado outbreaks and the fact that residents in mobile homes and trailers are at the greatest risk. In any case, the NWS office with warning responsibility must intensively investigate storms with the WSR-88D and collect spotter reports during a protracted tropical event.

c. Hybrid outbreaks

1) DISCUSSION

Forecasters expect the possibility of tornadoes with any landfalling hurricane, although they are rare events, because research into their nature has been widely promulgated (Novlan and Gray 1974; Gentry 1983; McCaul 1991). The diagnoses of the hybrid cases, which have tropical and extratropical characteristics of varying degrees, are not nearly as clear due to their complexity and rarity. Indeed, as the hybrid killer tornado outbreak that struck the Tampa Bay area on 3 October 1992 (DOC 1993) illustrates, they can strike without any watches or warnings in effect.

Until the late 1960s only tropical and extratropical terms were used to describe cyclones, although some cyclones were suspected to be hybrids (Neumann et al. 1993). In 1972 the term ''subtropical storm'' was officially designated to describe hybrid cyclones that reach tropical storm strength ($\geq$34 kt or 17 m s^{-1}). However, hybrid cyclones below this threshold are not always specifically identified. Five hybrid cyclones (two subtropical storms and three unnamed cyclones) have spawned tornadoes in peninsular Florida in recorded history, none are documented before 1976. Four of the five produced killer tornadoes, and all five produced tornadoes that caused injury. Three of these five also met the definition of an outbreak and are included in this study. Of the two that did not meet the rigorous outbreak criteria, one produced three tornadoes in 2½ h, including a killer tornado, and the other produced four tornadoes in 9 h.

Hybrid cyclone tornado outbreaks are of great concern because they are the rarest and most consistently dangerous of the outbreaks types. All three hybrid outbreaks included in this study produced F2 or greater killer tornadoes and flooding rains that caused as many deaths by drowning as by tornadoes. The May 1979 outbreak produced 18 in. of rain in the St. Petersburg area, leading to three drownings, while tornadoes killed 1 and injured 49. Excessive rainfall with the June 1982 outbreak flooded six rivers in west-central Florida and caused widespread urban flooding that led to three drownings. Tornadoes killed 1 and injured 13. The October 1992 outbreak produced tornadoes of up to F3 intensity that killed four people west of Tampa, and excessive rainfall caused record flooding in northeast Florida leading to a presidential disaster declaration. The stronger hybrid cyclones of June 1982 and October 1992 (lower central pressures) caused significant coastal flooding and beach erosion along Florida's gulf coast.

One of the most significant aspects of these outbreaks is their longevity. The May 1979 (case 24), June 1982 (case 26), and October 1992 (case 29) hybrid outbreaks are the first (11:00 h), third (8:09), and fourth (8:00) longest, respectively, of the 35 outbreaks. Due to their longevity, they produced a higher than normal number of tornadoes. The May 1979 (19 tornadoes), June 1982 (10 tornadoes), and October 1992 (9 tornadoes) outbreaks rank first, third (tie), and fourth (tie), respectively, for number of tornadoes in peninsular Florida outbreaks. All three exceed the ''major'' hurricane tornado outbreak criteria set by McCaul (1991).

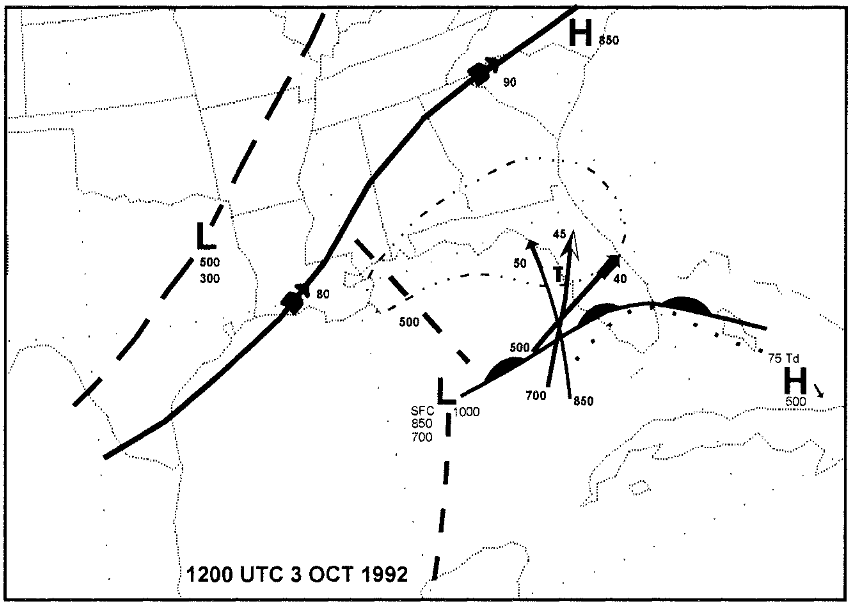

FIG. 27. Composite synoptic analysis for 1200 UTC 3 October 1992. Surface fronts, surface and upper troughs, and areas of high and low pressure are shown by conventional notation with levels in mb indicated. Axes of maximum winds at 850, 700, 500, and 250 mb are indicated by the symbols →, ⋗, ➡, and ➽ respectively. Maximum winds are indicated in knots. The leading edge of the highest values of low-level moisture (surface dewpoint T_d in °C) is indicated by the heavy-dotted line over south Florida. The approximate location of first tornadoes is indicated by "T," 2 h after map time. The dash–dot line encloses the rain shield, or rain-cooled air mass associated with the cyclone.

2) HYBRID OUTBREAK CASE STUDY

In late September 1992 a surface low began to develop near the Yucatan Peninsula on an old frontal boundary across the southern Gulf of Mexico. As the low deepened and moved northeast toward Florida, it evolved into a hybrid cyclone outbreak. Figure 27 shows the synoptic composite analysis for 1200 UTC 3 October 1992. The surface low in the east-central gulf has deepened to 1000 mb with a surface trough trailing south into the southern gulf. Closed lows at 850 and 700 mb existed above the surface low. Above 700 mb a broad trough extended from Illinois to south Texas. A weak 500-mb short wave was rotating up the front of the trough over the north-central gulf. The subtropical jet stream extended from south Texas to North Carolina with a jet streak approaching the Southeast. Strong upper diffluence was over the northern peninsula.

As the southerly flow on the east side of the low increased, a surge of tropical moisture south of an old frontal boundary moved northward similar to a warm front, resulting in overrunning rainfall over Florida early in October. This rain-cooled air mass enhanced the temperature contrast across the boundary. By the time of Fig. 27, an LLJ of 50 kt (25 m s^{-1}) at 850 mb was intersecting the warm front southwest of Tampa, maximizing vertical velocity and overrunning while winds at 700 and 500 mb were increasing and veering over the area in response to the approaching subtropical jet streak and short wave.

The cyclone's interaction with the midlatitude trough approaching from the west and surface high pressure over the mid-Atlantic states resulted in an asymmetric wind flow with the only strong low-level flow in the northeast quadrant, well east of the center. The result was a setting much like the warm sector of a strong extratropical cyclone even though the environment was weakly baroclinic. The cyclone was not specifically identified as having tropical characteristics in real time but was later called a tropical disturbance in DOC (1994).

The 1200 UTC TBW sounding (Fig. 28a) and hodograph (Fig. 28b) terminated prematurely at 400 mb. The sounding is characterized by very high PW values and moderate instability typical of hybrid and tropical outbreaks. The hodograph is quite similar to the mean tropical–hybrid proximity sounding (Fig. 16b) and displays strong low-level shear and veering (storm-relative parameters were computed using 1500 UTC observed storm motion from the MLB WSR-88D rather than default storm motion). The winds decrease with height above a maximum at 850 mb resulting in a horseshoe-shaped wind profile similar to tropical cyclone tornado cases of McCaul (1991). One of the basic differences between the hybrid and tropical cyclone cases is that

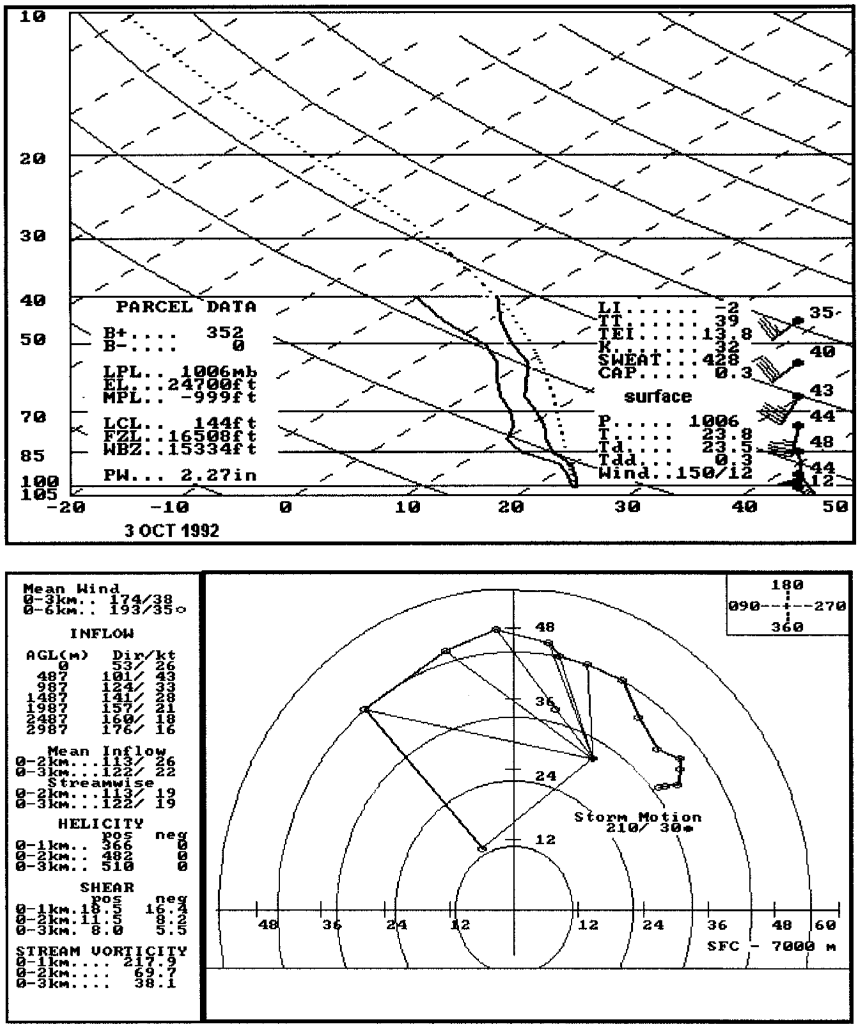

FIG. 28. Skew *T*–log*p* (a) and hodograph (b) for Tampa, FL, at 1200 UTC 3 October 1992. Storm-relative parameters on the hodograph (b) where computed using observed tornadic storm motion from the MLB WSR-88D instead of default storm motion.

because of the interaction of a midlatitude trough and a subtropical jet in the hybrid cases, winds are southwest at 35–40 kt (17.5–20 m s^{-1}) above 500 mb. More detailed discussions of the dynamic and thermodynamic nature of the Tampa sounding can be found in Anthony (1993) and Davies (1993).

The 1204 UTC Melbourne WSR-88D base reflectivity image (Fig. 29) shows the precipitation pattern associated with the low and warm front. Figure 29 is fundamentally different from the tropical case (Fig. 24). The large overrunning precipitation area north of the warm front is similar to that of an extratropical cyclone, even though in this case the cyclone developed in the Tropics. Strong thunderstorms are developing in the Gulf of Mexico southwest of Tampa Bay at ''A'' in Fig. 29, just north of where the LLJ is intersecting the warm front and maximizing upward vertical velocity and overrunning.

Figure 30 shows the tornadoes and severe thunderstorm wind reports for this outbreak. The first tornado (F2) struck Pinellas County at 1440 UTC, killing an elderly woman in a mobile home. The third tornado of the outbreak was an F3 that struck Pinellas County at 1530 UTC, killing three before quickly dissipating. The focus of severe weather shifted steadily northward with the warm front as the day progressed. The trend was for thunderstorms to move onshore, produce brief severe weather within 50 mi of the coast and weaken.

The base reflectivity product from the Melbourne WSR-88D for 1743 UTC (Fig. 31) shows another cluster of strong thunderstorms approaching shore north of TBW at ''A.'' The thunderstorm complex at ''B'' earlier

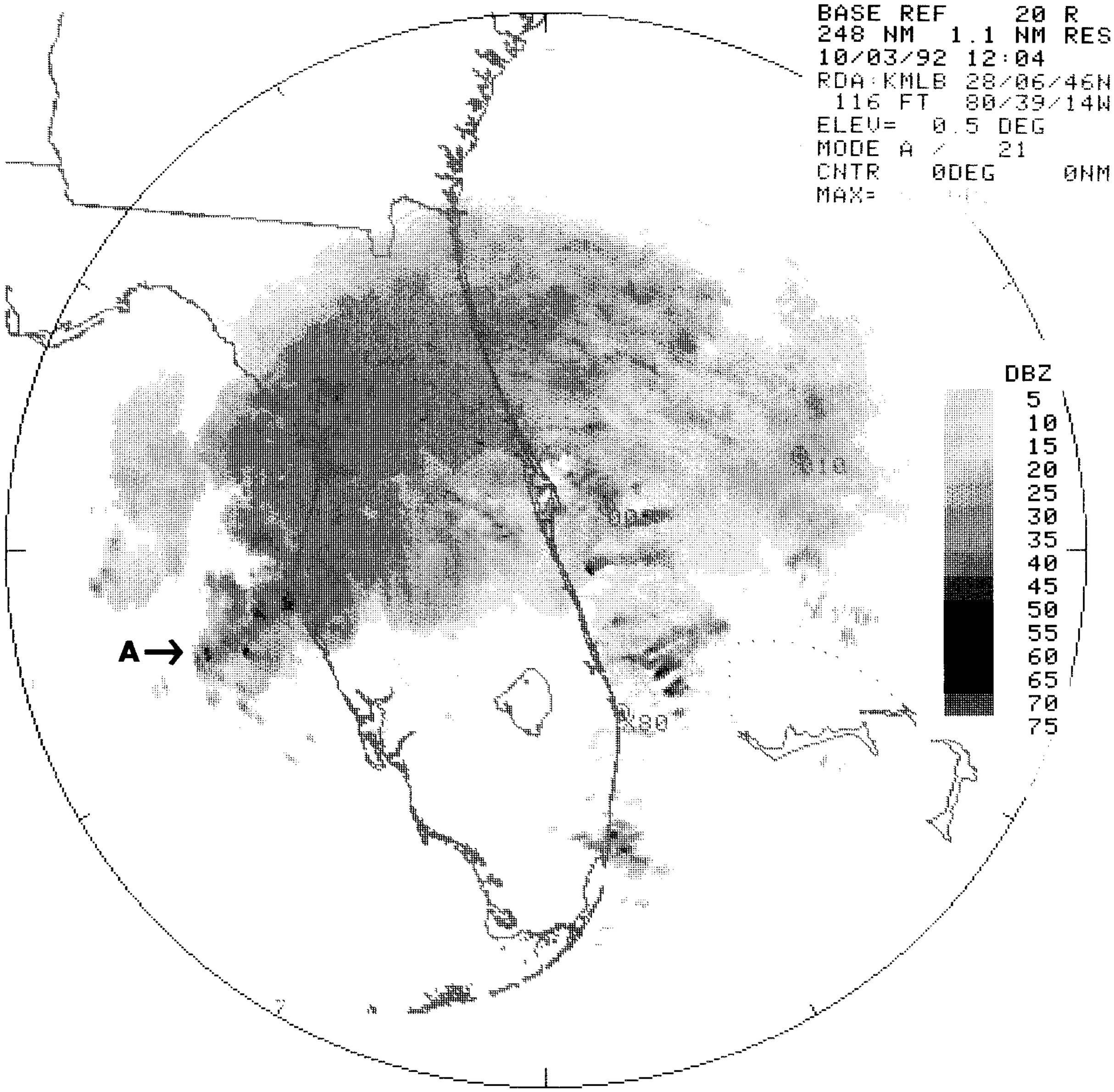

FIG. 29. Base reflectivity product (0.5°, 248 n mi range) from Melbourne, FL, WSR-88D for 1204 UTC 3 October 1992. The area of developing strong thunderstorms southwest of Tampa is indicated at "A."

produced tornadoes at 1707 and 1720 UTC. The remains of the thunderstorms that had produced the first round of tornadoes are now at "C."

This hybrid scenario is fundamentally different from the extratropical outbreaks that cross the peninsula quickly. There are general similarities to the tropical case study in that there the severe weather was also limited to the coastal sections with a long duration of onshore flow. As in both the tropical and extratropical cyclone cases, severe weather occurred when convective cells moved onshore and then weakened after moving inland. The killer tornadoes in this case and Tropical Storm Gordon affected the immediate coastal area and then dissipated.

In the hybrid cases, as in the previous tropical outbreak case study, the outbreaks are long-term events that require intensive radar interpretation of every thunderstorm or heavy rainshower moving onshore. Many convective cells will come ashore, but only a fraction will produce severe weather.

As near as can be determined from sparse historical synoptic data over the Gulf of Mexico and Latin America, all three hybrid outbreak cases began when weak lows developed along old frontal boundaries that had

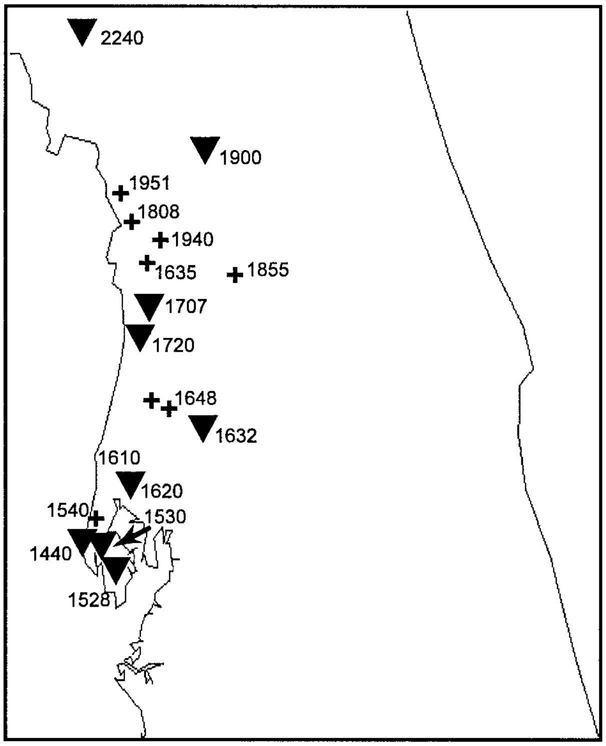

FIG. 30. Plot of tornadoes (▼) and severe thunderstorm winds (+) reported for the 3 October 1992 outbreak. Times are in UTC.

largely lost their thermal features over the southern or southwestern Gulf of Mexico. Subsequently surges of tropical moisture moved north toward the Florida peninsula on the east side of the developing lows. These tropical surges could generally be identified by characteristics similar to warm fronts with a very shallow slope. Showers and thunderstorms then spread over the peninsula well ahead of the approaching lows, leading to the development of a rain-cooled air mass that enhanced the weak overrunning pattern. As the lows moved northward and gradually deepened, the low-level pressure gradient increased between the lows and the subtropical ridges to their northeast creating an asymmetrical wind pattern. Low-level winds increased significantly east of the lows, and a favorable shear environment for tornadogenesis developed well east of the lows in the overrunning zone. In each case the orientation and slow movement of the hybrid cyclones caused peninsular Florida to be in a favorable shear and moisture environment for tornado and excessive rain production for 12–18 h.

Most of the tornadoes occurred in the overrunning zone very near or north of where a strong low-level jet (LLJ $\geq$ 35 kt or 17.5 m s^{-1}) intersected the surface warm front, maximizing moisture convergence in a highly sheared, moist environment with diffluence at high levels. In each case the heavy rain phase began before the severe weather phase and continued during, and well after, the tornado outbreak phase. The tornadic phases appeared to be associated with the approach of an upper short wave, an increase in the 850–500-mb wind speeds, and maximum shear and overrunning.

Unless a hybrid cyclone has reached, or is predicted to reach, subtropical storm intensity (sustained surface winds $\geq$ 34 kt or 17 m s^{-1}) it is not particularly critical to belabor its categorization. Forecasters are better served by concentrating on a detailed diagnosis of the important elements that can come together to produce severe weather without forcing them to fit a generic tropical or extratropical conceptual model.

Experience with hybrid outbreaks is limited. Because of their extent and duration, they present major challenges to NWS offices that rival or exceed those of a ‘‘typical’’ hurricane. NWS offices should assume a proactive posture similar to that for hurricanes. The public can be properly alerted to the dangerous potential of these hybrid cyclones via timely statements and warnings. Emphasis should be placed on preparedness and safety advice relating to coastal zone impacts, flooding, and boating and drowning hazards as well as tornadoes and severe thunderstorms.

5. Concluding remarks

A comprehensive study of peninsular Florida tornado outbreaks has been presented. This is an important forecast problem, presented completely for the first time. The climatology, mean environment, and synoptic-scale aspects of these outbreaks are now available as tools for forecasters to use and build upon to improve forecasts of hazardous weather. The importance of a detailed diagnosis of the outbreak environment and construction of future tornado proximity environments cannot be underestimated.

This study has also revealed important information that can be used in community education and preparedness efforts. However, more study is needed in this area for a state with 13 million people, most of whom live in the fragile coastal zone. For example, are tornado deaths related more to shelter quality than tornado strength? Initial evidence would tend to support the former. Especially in the case of tropical cyclone tornadoes outside the eyewall, it appears most are survivable if people are in substantial structures. Cyclones that produce tornado outbreaks can rival the effects of some hurricanes. NWS offices, the media, and public officials should consider preparing for some extratropical and hybrid cyclones in a manner similar to tropical cyclones.

A number of key relationships between the regional environment and tornado outbreak characteristics were revealed in this study. The exploitation of this information with evolving technology should result in a better understanding of the physical processes at work and, ultimately, improvements in our ability to more accurately predict tornado outbreaks on a smaller scale.

There appears to be a fundamental similarity in the

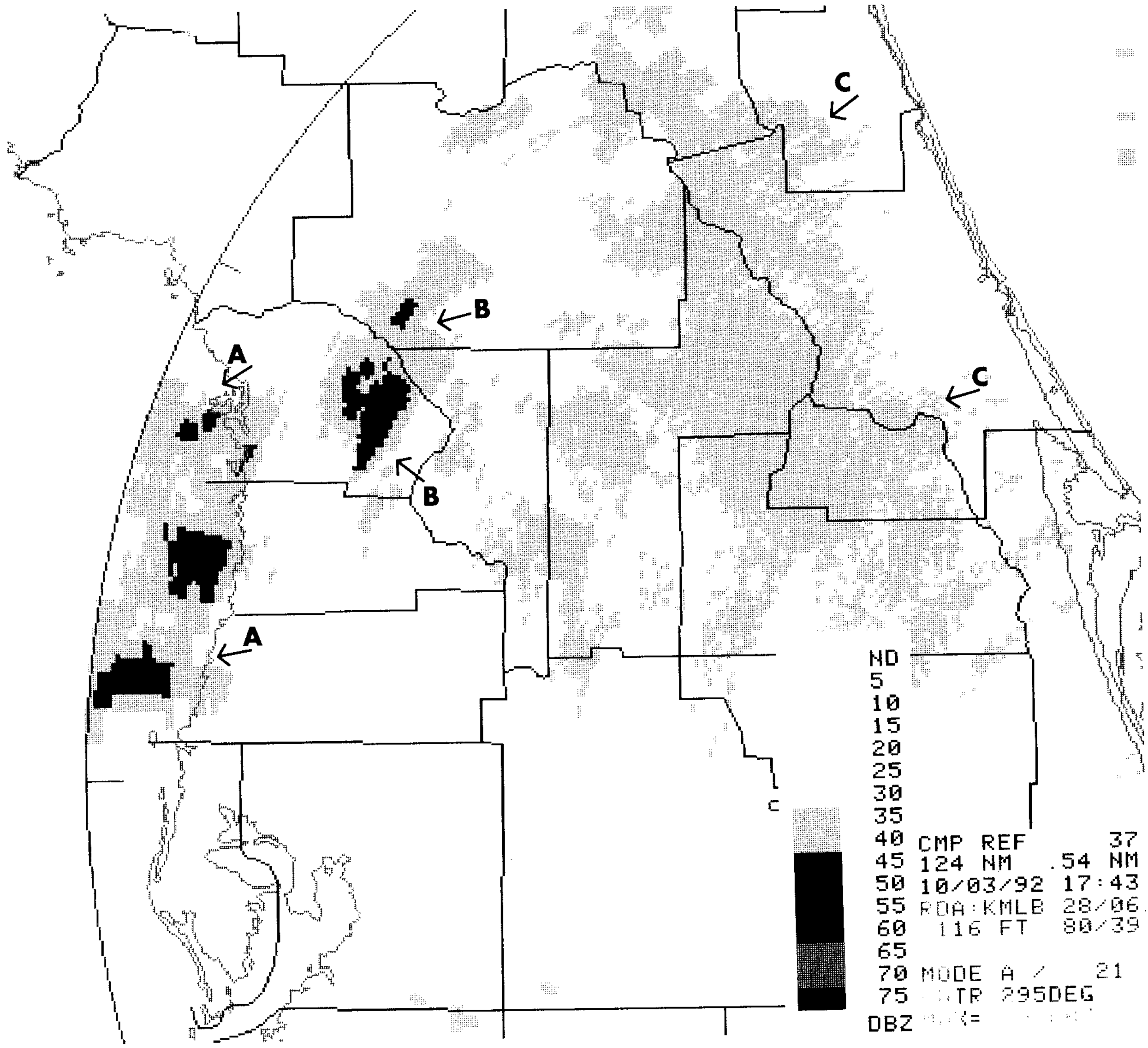

FIG. 31. Composite reflectivity product (0.54 n mi resolution, 124 n mi range) from Melbourne, FL, WSR-88D for 1743 UTC 3 October 1992. Returns below 35 dB*Z* have been filtered out. Cluster of severe thunderstorms is about to move onshore north of Tampa at ''A.'' Thunderstorms at ''B'' earlier produced tornadoes at 1707 and 1720 UTC. The large area of rain at ''C'' is the remains of thunderstorms that produced tornadoes early in the outbreak.

three peninsular Florida tornado outbreak environments and in tornado environments in other areas such as the Midwest, especially regarding shear and instability relationships. However, storm-scale morphology and mesoscale knowledge of tornadic convective initiation is still in its infancy in Florida. Nearly all recent research in severe storms in Florida has taken the case study, or mean condition, approach. This is understandable, given that only in recent years has work began on the problem in earnest. A climatological or case study approach is the logical way to begin. What is needed now is the development of rigorous conceptual models of the mesoscale environment and storm structure of the whole spectrum of convection that can produce tornadoes and tornado outbreaks. The dense network of WSR-88D Doppler radars that now exist around Florida should be turned to this task.

Complete coastal coverage by the WSR-88Ds has already improved the ability to issue timely watches and warnings. However, even with the WSR-88D, issuing tornado warnings will remain difficult due to the lack of offshore ''sea truth'' and an incomplete understanding of the air–sea–land interactions. A common element in all three types of outbreaks is the apparent rapid spinup of tornadoes in the coastal zone and often weakening inland. This phenomenon could also be due, in part, to population density. This is a critical research area ripe for investigation.

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