Characteristics of East-Central Florida Tornado Environments

BARTLETT C. HAGEMEYER AND GARY K. SCHMOCKER

National Weather Service Office, Melbourne, Florida

(Manuscript received 25 April 1991, in final form 16 August 1991)

ABSTRACT

Climatological analyses indicate that strong morning tornadoes in the dry season, and weak afternoon tornadoes in the wet season, are significant forecast problems in east-central Florida. To address this issue, an analysis of upper-air soundings for Tampa Bay, West Palm Beach, and Cape Canaveral, Florida, released within ±2 hours of tornado touchdowns in the County Warning Area (CWA) of future National Weather Service (NWS) Weather Forecast Office (WFO), Melbourne, Florida, was completed. Mean dry- and wet-season tornado-proximity soundings to 200 mb were produced, and selected mean diagnostic parameters and variance statistics computed.

Both dry- and wet-season tornado environments were associated with deep moist layers overlain by dry air, but no capping inversions. Dry-season cases were characterized by lower-tropospheric θ_W values well above normal, very low Convective Available Potential Energy (CAPE) and Bulk Richardson Number (BRN), strong speed and directional shear at low levels, a strong midlevel dry intrusion, and a maximum wind at 200 mb. The thermodynamic environment of the wet-season cases under westerly flow was close to mean seasonal values, but U increased steadily above 650 mb to a mean westerly maximum wind at 275 mb. These middle and upper-level winds, greatly exceeding mean seasonal values, allow thunderstorms developing along low-level convergent boundaries to be organized and sustained by the production of strong, persistent, tilted updrafts and continued low-level inflow of high θ_W air.

1. Introduction

The diagnosis of the dynamic and thermodynamic structure of the environment in which tornadic thunderstorms develop, as well as potential mechanisms to initiate intense convection, are crucial to severe-storm forecasting. Over the years, researchers such as Showalter and Fulks (1943), Fawbush and Miller (1952), Beebe (1958 and 1963), Darkow (1969), Wills (1969), Darkow and Fowler (1971), Lustig (1973), Maddox (1976), and Taylor and Darkow (1982) have used mean upper-air sounding data to investigate the structure of the atmosphere in proximity to tornadic thunderstorms. Recent studies indicate renewed interest in the use of tornado-proximity soundings to relate thermodynamic and dynamic variables to tornado intensity (Riley and Colquhoun 1990; Johns et al. 1990), the examination of the structural characteristics and evolution of different types of tornado-proximity soundings (Schaefer and Livingston 1988; 1990), and the characteristics of hurricane-tornado environments (McCaul 1991).

Characteristics common to all these studies is that they combine data collected from a large area of the country, contain little data (in most cases none) from peninsular Florida, and, with the exception of McCaul (1991) and Wills (1969), tend to focus on the Midwest. A recent study using tornado-proximity data (Johns et al. 1990) is a case in point: of the 242 cases in the dataset, only two were in peninsular Florida, and cases were selected to minimize inclusion of nonsupercell tornadoes (Wakimoto and Wilson 1989).

There are two basic reasons for a study of tornado soundings restricted by geographic area to central Florida: 1) Peninsular Florida is a unique environment, and averaging soundings collected over a large portion of the eastern United States would tend to mask the uniqueness of the diurnal, seasonal, and synoptic characteristics of the Florida tornado environments; and 2) the modernization and associated restructuring of the National Weather Service (NWS) will result in the early deployment of sophisticated Doppler weather-radar [NEXRAD/WSR-88D (Weather Surveillance Radar—1988 Doppler)] and Doppler profiler technology in the area, and the development of a highly trained professional meteorological staff to use these tools to improve forecasts and warnings of severe weather in the region.

Byers and Rodebush (1948) recognized the uniqueness of the peninsular Florida environment and the need for investigation of dynamic mechanisms that result in a United States maximum of thunderstorms in central Florida. However, little in the way of specific, systematic study of the environment of central-Florida tornadoes and damaging tornadic waterspouts has been done despite their significance and relatively frequent

Corresponding author address: Bartlett Hagemeyer, National Weather Service, 421 Croton Road, Melbourne, FL 32935

© 1991 American Meteorological Society

occurrence (Kelley et al. 1978). Recently, Golden and Sabones (1991) investigated two tornadic waterspouts near Cape Canaveral in east-central Florida, using Doppler radar and mesonet data. Past work has been primarily confined to case studies of tornadoes in *south* Florida in the wet season. Gerrish (1967) produced a mean tornado sounding for Miami for the wet season, and case studies of wet-season tornadoes in south Florida were investigated by Hiser (1968), Gerrish (1969), Golden (1971), and Holle and Maier (1980).

These researchers have documented that low-level convergent boundaries, particularly intersecting outflow boundaries, are a triggering mechanism for tornadic thunderstorms in the wet season. Wakimoto and Wilson (1989) have proposed a model to explain nonsupercell tornado development in which low-level boundaries play a crucial role in tornadogenesis. This theory may have important applications in central Florida.

The tracking of boundaries with Doppler radar, satellite, and mesonet data aids in the short-term prediction of potentially tornadic thunderstorms, but few boundaries, or boundary intersections, actually result in tornadic development (Holle and Maier 1980). Better information concerning the characteristics of the overlying dynamic and thermodynamic structure of the atmosphere that might aid forecasters in determining whether tornadic-thunderstorm development is likely on a given day is needed for the whole range of tornado scenarios, including significant dry-season cases that are responsible for most of the deaths and injuries in central Florida (Schmocker et al. 1990).

The current situation is one where tornado-forecast techniques and conceptual models developed from mean upper-air data over the Great Plains and Midwest are applied in central Florida with limited success. This study is a response to an assessment of high-priority operational forecast problems to be addressed by the new Weather Forecast Office (WFO) being formed at Melbourne, Florida, as part of the modernization of the NWS (Schmocker et al. 1990) and consists of the determination of the mean atmospheric structure of two significant central-Florida tornado environments. The results presented should result in improved severe-weather forecasts for central Florida and also illustrate how new WFOs with severe-weather forecast responsibility might work toward a better understanding of the characteristics of their *regional* tornado environments.

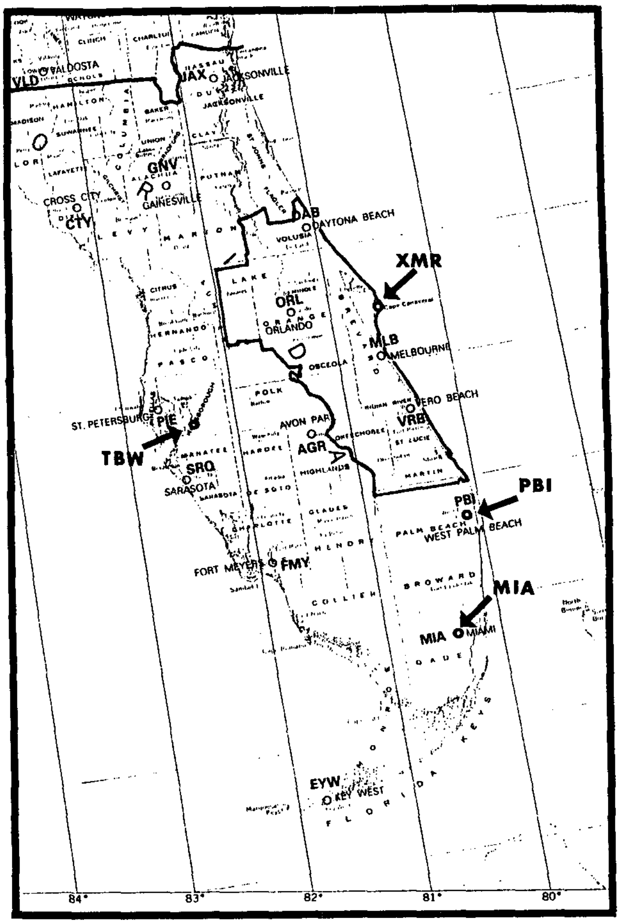


FIG. 1. Peninsular Florida. The CWA of future WFO Melbourne in east-central Florida is enclosed by the bold line. Upper-air stations are indicated by bold arrows: Cape Canaveral (XMR), West Palm Beach (PBI), Miami (MIA, moved to PBI in 1977), and Tampa Bay (TBW).

2. Methodology of case selection

This study is unique in that the area of investigation was restricted to the ten County Warning Areas (CWA) of future NWS WFO Melbourne in east-central Florida. The location of the Melbourne CWA and upper-air stations used in this study are shown on Fig. 1.

The first task was to develop proper seasonal divisions and terminology to be used in this paper. The terms "cool" and "warm" season (November–April and May–October, respectively; Gerrish 1969) and "dry" and "wet" (or rainy) season are often used interchangeably in Florida. The distinction between cool and warm seasons is often blurred in central Florida. A regional temperature and precipitation analysis by Schmocker et al. (1990) indicated a division based on rainfall, rather than temperature, was more appropriate. Based on these results, tornado characteristics were divided into two seasons: dry season (November through April) and wet season (May through October).

The regional hourly distribution of tornadoes within a 125-n mi radius of Melbourne by season (Fig. 2a,b) clearly shows a diurnal afternoon maximum in the wet season (Fig. 2b), while the dry season (Fig. 2a) is characterized by many fewer tornadoes, but a more-even hourly distribution with significant morning activity.

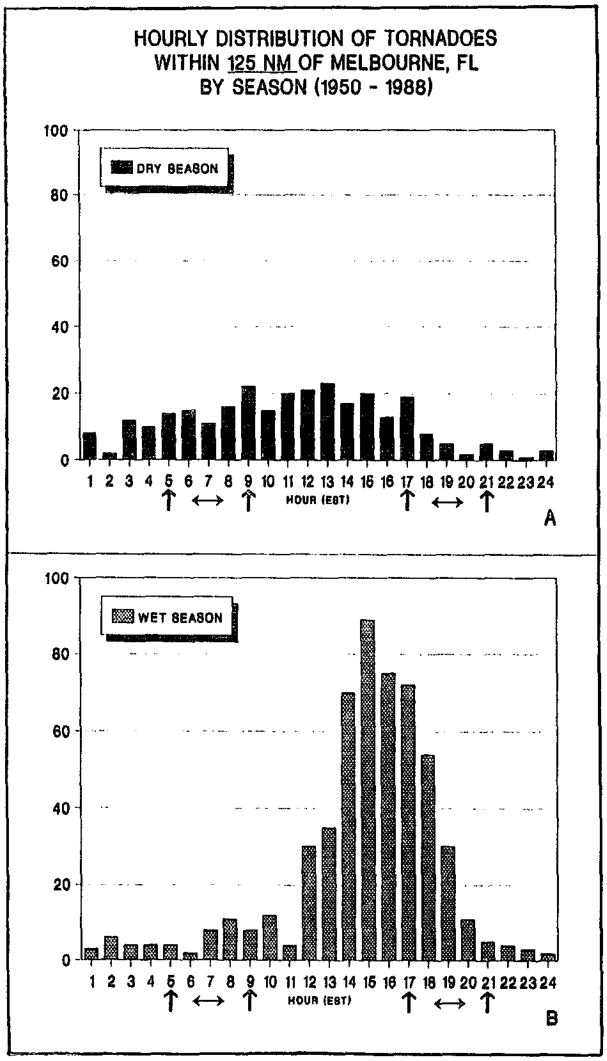


FIG. 2. Hourly distribution of dry-season (a) and wet-season (b) tornadoes within 125 n mi of future WFO Melbourne. The time intervals of this study (1200 UTC [0700 EST] and 0000 UTC [1900 EST] ±2 h) are shown by the arrows along the x axis.

The distributions of strong and violent tornadoes (F2–5; Fujita 1981) and those that have caused injury and death, reported specifically in future WFO Melbourne's CWA, are shown on Fig. 3. As can be seen, most of the F2–5 tornadoes occur in the dry season, and half of these have been found to occur in the morning (Schmocker et al. 1990). This relatively high percentage of strong and violent dry-season *morning* tornadoes in east-central Florida (50% of total; Schmocker et al. 1990) is unusual when compared to studies done in other parts of the country, and represents a unique regional-forecast problem. For example, Maddox (1976) considered only afternoon (0000 UTC) tornado-proximity cases (159), all 161 proximity soundings used by Taylor and Darkow (1982) were for 0000 UTC, and all but 5 of 134 and 1 of 85 proximity soundings used by Schaefer and Livingston (1989, 1990) were for 0000 UTC.

Strong tornado activity drops off sharply in May (Fig. 3) as the influence of vigorous midlatitude disturbances diminish and the transition from dry to wet season takes place. The increase in August and September is due to tornadoes associated with tropical cyclones. Climatological analyses indicate an attack on the tornado-forecast problem by seasonal and diurnal divisions is necessary.

Since the criteria used for proximity-sounding selection can greatly influence results (Taylor and Darkow 1982), the basic approach of this study was to get as much relevant information as possible about seasonal tornado environments for use by forecasters.

Upper-air data was available for 0000 and 1200 UTC for Tampa Bay (TBW), Palm Beach (PBI), and Miami (MIA) (note: MIA site deactivated and moved 100 km north to PBI in 1977). Only 1200 UTC soundings since 1980 were available for Cape Canaveral (XMR). With these data limitations in mind, tornado candidate cases were considered by looking first at spatial, then temporal, selection criteria. Printouts of all tornadoes reported in Florida supplied by the Verification Section, National Severe Storms Forecast Center (NSSFC), were reviewed for cases of tornado touchdowns in the Melbourne CWA (Fig. 1) that occurred within ±2 h of standard observation times [0000 UTC (1900 EST) and 1200 UTC (0700 EST)] from 1980 to 1988. This resulted in sixteen 0000 UTC cases and seven 1200 UTC cases, and reflects the fact that many fewer tornadoes occur at 1200 UTC compared to 0000 UTC (see Fig. 2a,b). Because the 1200 UTC tornadoes are

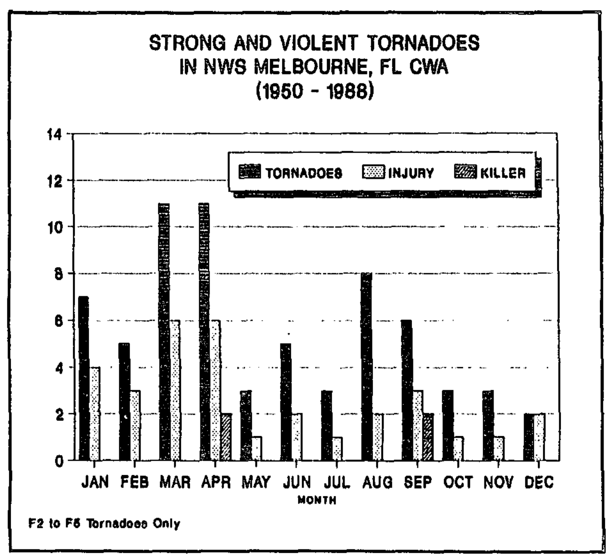


FIG. 3. Monthly distribution of strong and violent tornadoes, and killer and injury tornadoes, reported within future WFO Melbourne's CWA.

typically the most significant, five additional cases were added by searching the tornado records back to 1975 to get a larger sample, even though XMR data would not be available.

Twenty-eight candidate cases were thus identified (sixteen 0000 UTC and twelve 1200 UTC) and soundings obtained. Each sounding was then examined for data quality and contamination by precipitation or convective debris. Tropical-cyclone cases were removed for a separate research project. This selection criteria yielded nine 1200 UTC dry-season cases and nine 0000 UTC wet-season cases. These small sample sizes are deemed sufficient, considering this study is concentrating on a specific forecast area. Additionally, despite limitations, this is the best data available.

The upper-air station closest to a reported tornado was designated the proximity sounding for each season. Since 0000 UTC wet-season proximity data was not available for Cape Canaveral, but 1200 UTC data was, a wet-season 1200 UTC XMR wet-season precedent sounding (12 h prior to tornado touchdown, ±2 h) was developed to provide useful information on tornado-precursor conditions. Precedent soundings for the dry season were unavailable. Soundings were then pressure-averaged at 50-mb intervals to 200 mb. Mean soundings and diagnostic parameters for the seasonal atmospheres were computed, and vertical profiles from the surface to 200 mb of θ, θ_W, U and V, and their standard deviations were constructed for dry- and wet-season tornado-proximity and wet-season tornado-precedent atmospheres. These seasonal profiles were then compared to seasonal mean atmospheres.

3. Results

a. *Tornado case characteristics*

The locations of the dry- and wet-season tornadoes, and summaries of tornado case characteristics, are shown on Figs. 4a,b. Most of the tornadoes in both seasons are found clustered around the Orlando area west of Cape Canaveral, which corresponds to the general area of greatest overall frequency of reported tornadoes and population density (Schmocker et al. 1990).

b. *Mean soundings and diagnostic parameters*

Skew T–log p plots and hodographs of the dry- and wet-season mean tornado-proximity soundings, and of the wet-season mean tornado-precedent and -proximity soundings, are shown as Figs. 5a and 5b. A detailed discussion of the physical structure of these seasonal environments will be presented in following sections. A summary of diagnostic parameters derived from the mean soundings are shown as Table 1.

The general structure of the dry-season sounding and hodograph (Fig. 5a) is similar to the strongly sheared, classic Midwest tornadic supercell environment (Doswell 1982). The most notable difference is the lack of any mean capping inversion overlying a well-mixed

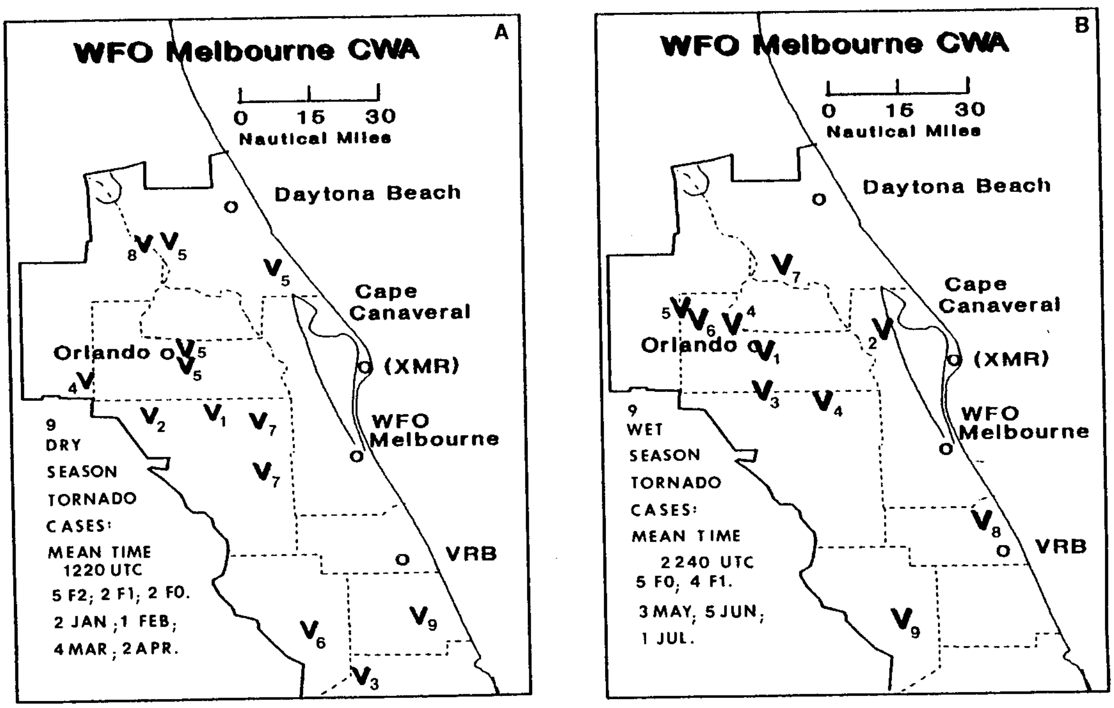


FIG. 4. Locations of tornadoes (V) reported in dry-season (a) and wet-season (b) cases, and summary of case characteristics. Each tornado is identified with its case number (1–9).

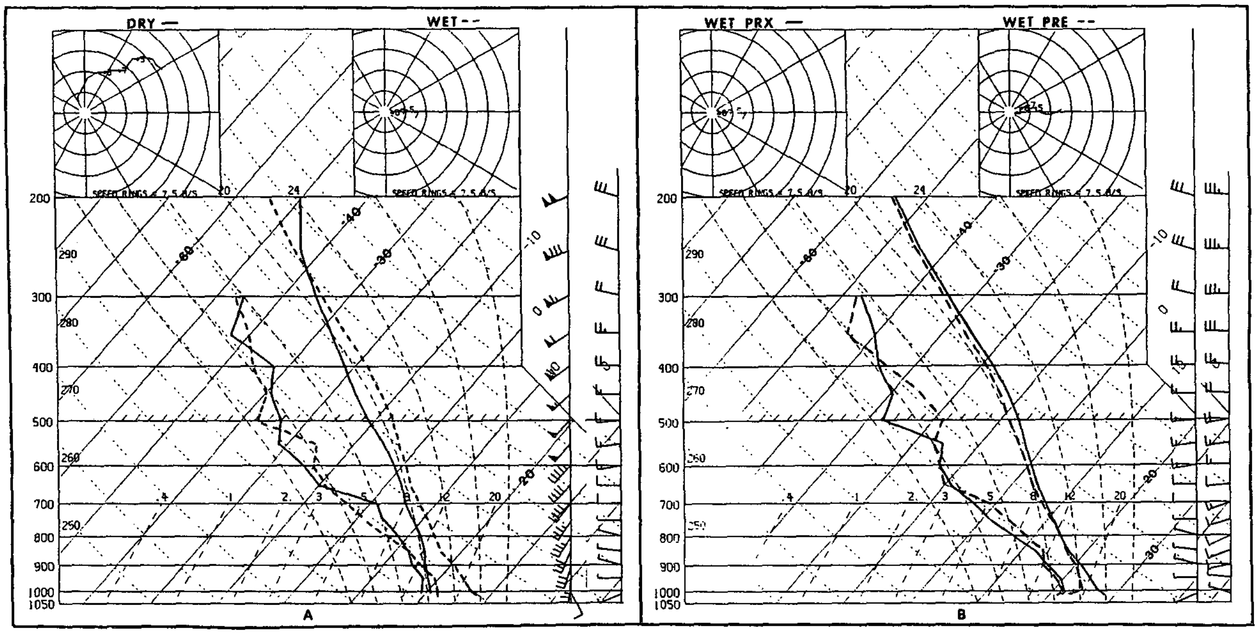


FIG. 5. Skew T–log$p$ diagrams and hodographs for mean dry- and wet-season proximity (a) and mean wet-season proximity and precedent (b) tornado environments. Half wind barb is 2.5 m s^{-1}, full wind barb 5 m s^{-1}, and pendant is 25 m s^{-1}.

low-level moist layer. An inspection of all individual soundings (dry and wet) revealed the presence of a stable layer above the moist layer, but none of the low-level moist layers were truly capped by an inversion.

TABLE 1. Mean diagnostic parameters computed from mean dry- and wet-season proximity and mean wet-season precedent tornado atmospheres.

	Dry Prx	Wet Pre	Wet Prx
Freezing Level (m AGL)	4104	4351	4477
Wet-bulb Zero (m AGL)	3360	3410	3419
Showalter Index (°C)	−0.8	−1.1	1.5
Lifted Index (°C)	−1.8	−3.5	−3.4
Totals Index (°C)	48	48	43
Cross Totals Index (°C)	23	22	19
Vertical Totals Index (°C)	25	26	24
K Index (°C)	33	31	26
SWEAT Index	325	194	168
Precipitable Water (cm)	3.8	4.2	3.9
LCL Height (m)	386	596	882
LCL Mixing Ratio (g kg^{-1})	13.9	15.8	16.1
LFC Height (m)	2584	2109	1484
CCL Height (m)	631	1187	1236
EL Temperature (°C)	−26.2	−51.1	−55.0
EL Level Height (m)	8150	11 727	12 346
Convective Temperature (°C)	24.1	30.6	31.2
CAPE (J kg^{-1})	164	904	1683
Bulk Richardson Number	1.5	166	576
Mean 0–6-km wind (m s^{-1})	215/19	260/06	267/04
Assumed Storm Motion	245/14	290/04	297/03
Absolute Helicity (m^2 s^{-2})	250	10	06
Mean 3–10-km wind (m s^{-1})	230/28	268/12	271/09
Mean Shear 850–200 mb (m s^{-1})	34	14	13

Environmental dynamics are quite strong and the Bulk Richardson Number (BRN; Weisman and Klemp 1982) is very low (1.5). Absolute helicity of 250 m^2 s^{-2} is within the range of strong and violent tornado-producing supercells documented by Leftwich (1990).

Conventional instability indices (Table 1) indicate less instability present than for typical Midwestern tornado cases (see Miller 1972). This is probably because midtropospheric temperatures are generally warmer over Florida, and, because these are *morning* tornado cases, there isn't much contribution to destabilization from diurnal heating. This, and the fact that the equilibrium level is low, explains in part the low Convective Available Potential Energy (CAPE) of the dry-season tornado environment.

The wet-season mean sounding and hodograph are unlike any of the classic tornado environments (Miller 1972) and represent a regional hybrid. There is a general similarity to the mean dry-season sounding in that a distinct dry layer overlies the moist layer, and thus it is most unlike Newton's Type C (1980) and Miller's Type II (1972) for the Gulf Coast and southeastern regions, which are typified by high moisture through the troposphere.

c. Relative atmospheric profiles

To determine what, if anything, is unusual about the dry- and wet-season proximity and wet-season precedent tornado atmospheres, profiles of θ, θ_W, U, and V are compared to each other and seasonal means (DOD 1983).

1) Dry to wet

Comparisons of dry- and wet-season proximity soundings are shown as Figs. 6a–d. The wet-season θ profile (Fig. 6a) is warmer than the dry season at all levels below 300 mb. Potential temperature values are very close between 700 and 600 mb, but because of increased warmth at both low and high levels, the dry static instability (Darkow 1986) of the wet season is only slightly greater than the dry.

Wet-bulb potential-temperature profiles (Fig. 6b) clearly indicate greater potential convective instability (θ_W decreasing with height) in the wet-season environment, as θ_W is much higher at lower levels and nearly identical at the minimum around 650 mb. Indeed, θ_W values are very close between 800 and 650 mb, indicating that while instability and dynamics may vary, the presence of an overlying dry air mass with minimum θ_W is a fundamental aspect of many tornado environments (Newton 1963).

Wind component U increases steadily with height, reaching maximums at 300 and 200 mb in the wet and dry environments, respectively (Fig. 6c), but is much higher in the dry season above 900 mb. The most notable difference between the two environments is the large V component of the dry-season profile (Fig. 6d). Wind component V is near zero through the depth of the troposphere in the wet season, but exhibits very strong surface-to-950-mb shear, and exceeds 15 m s^{-1} above 900 mb with distinct maximums between 600 and 400 mb and at 200 mb in the dry season.

2) Dry season

Comparisons of mean dry-season profiles to adjusted seasonal means (average for all months with cases, January through April) are shown on Figs. 7a–d. Potential temperature values are significantly higher than mean values below 800 mb and above 400 mb, but are only slightly above mean between about 700 mb and 450 mb, indicating greater-than-normal dry static instability below 700 mb. More notable is θ_W greatly exceeding normal values below 650 mb (Fig. 7b). The mean atmosphere has a degree of potential convective instability with a θ_W minimum around 800 mb, but the depth of the moist layer in the mean tornado atmosphere is about twice as deep, and potential convective instability much greater.

The high U values of the mean tornado profile, reaching a maximum of 45 m s^{-1} at 200 mb, are not significantly higher than seasonal means (Fig. 7c). Indeed there are only minor differences (<5 m s^{-1}) from the surface to 250 mb. This is not the case with the V components (Fig. 7d), where mean seasonal V is nearly zero and is greatly exceeded by V in the mean tornado environment at all levels. Very strong shear of V is found in the lowest 100 mb, and there is clear indication of a midlevel southwest jet between 600 and 400 mb, and an upper jet at 200 mb.

3) Wet season

Comparisons of the mean wet-season precedent and proximity profiles to adjusted seasonal means (average for months with cases, May through July) are shown as Figs. 8a–d. Except for differences at the surface due to diurnal heating, the potential-temperature values of the precedent and proximity atmosphere are very close to the mean seasonal values (Fig. 8a), indicating there is little difference in the vertical temperature structure between a nontornado and tornado day in the wet season. Comparisons of θ_W profiles (Fig. 8b) show that the depth of the moist layers are nearly the same, with θ_W minima around 650 mb in all three atmospheres. Proximity wet-bulb potential-temperature values are two degrees greater at the surface and the same at 650 mb when compared to the tornado-precedent sounding taken 12 h earlier. This indicates a much greater degree of potential convective instability, and illustrates how diurnal heating can nearly double CAPE (see Table 1) between 1200 UTC (904 J kg^{-1}) and 0000 UTC (1683 J kg^{-1}). This agrees with Taylor and Darkow (1982), who also found a large increase in low-level energy between precedent (1200 UTC) and proximity (0000 UTC) soundings.

However, the most outstanding feature of the wet-season tornado environment was found to be the existence of significantly increasing shear, and westerly winds greatly exceeding seasonal means, in the mid- and upper-troposphere (Fig. 8c). In contrast, the trend and magnitude of the V component is generally close to seasonal means (Fig. 8d).

(i) *Discussion.* All nine wet-season cases had westerly winds in the mid- and upper-troposphere, and eight cases were westerly from the surface to 200 mb. This dominance of westerly flow cases has several causes. Hagemeyer (1991) found that lower-tropospheric flow is westerly over central Florida into June and persistent easterly flow does not appear until well into the wet season. Most cases presented here occurred early in the wet season, when westerly disturbances are more likely, compared to late in the wet season, when easterly flow dominates. Additionally, undisturbed easterly flow early in the wet season tends to be drier and have a shallower moist layer than later in the wet season (Hagemeyer 1991) and is less likely to produce strong thunderstorms and tornadoes.

There is also a bias toward west-flow cases on the east coast, in the ±2 h from 0000 UTC selection criteria used in this study, that can be explained by reviewing a study of spatial patterns of south Florida convection, without regard to severity, done by Blanchard and Lopez (1985). They identified three basic patterns of convection over south Florida during the summer: Type I, weak southeast flow with *early development* of convection along the east-coast sea breeze (ECSB), which moves inland and merges with the west-coast sea breeze (WCSB) west of the central peninsula; Type

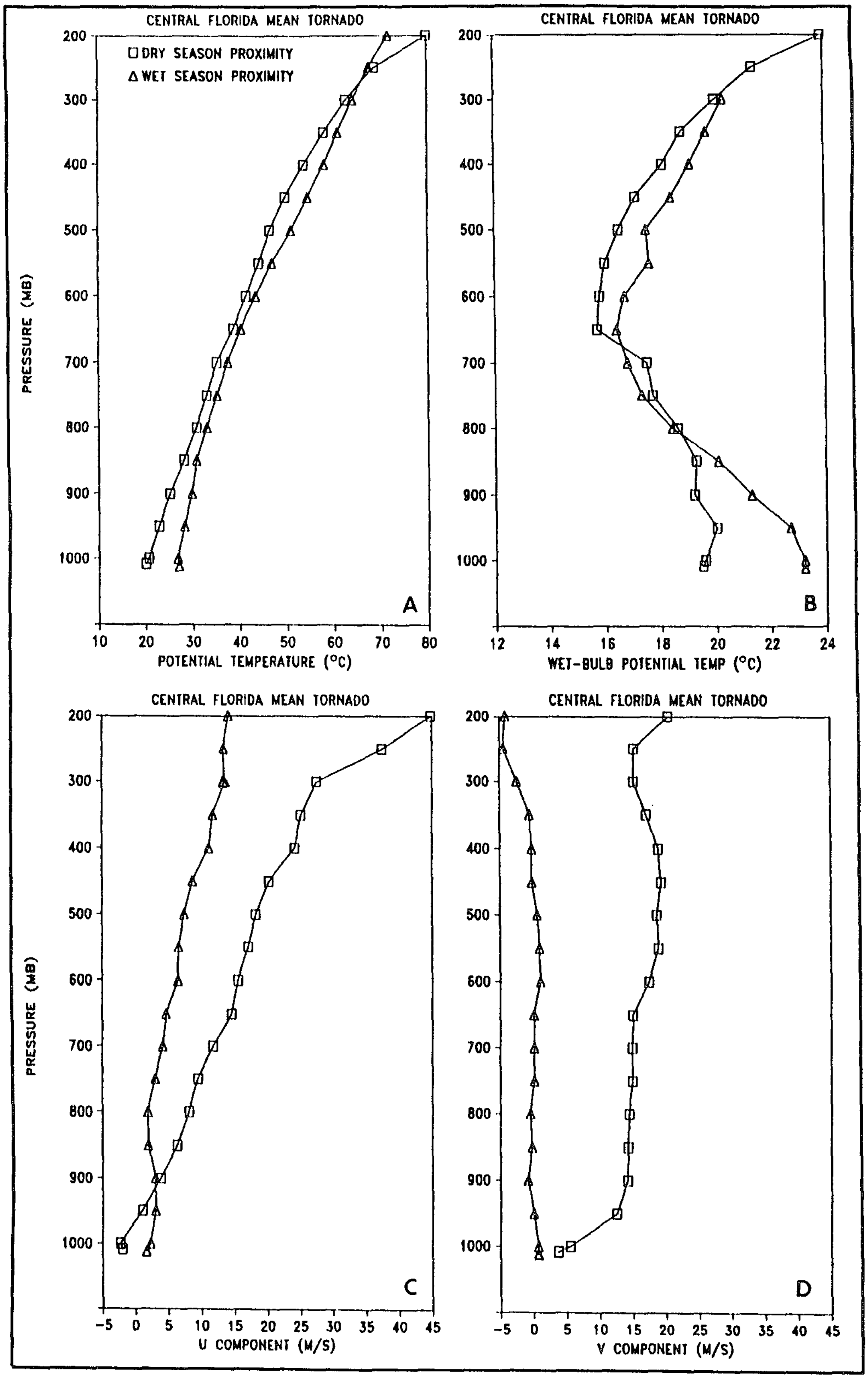


FIG. 6. Mean vertical profiles of θ (a), θ_W (b), U (c), and V (d) to 200 mb for mean dry- and wet-season tornado-proximity cases.

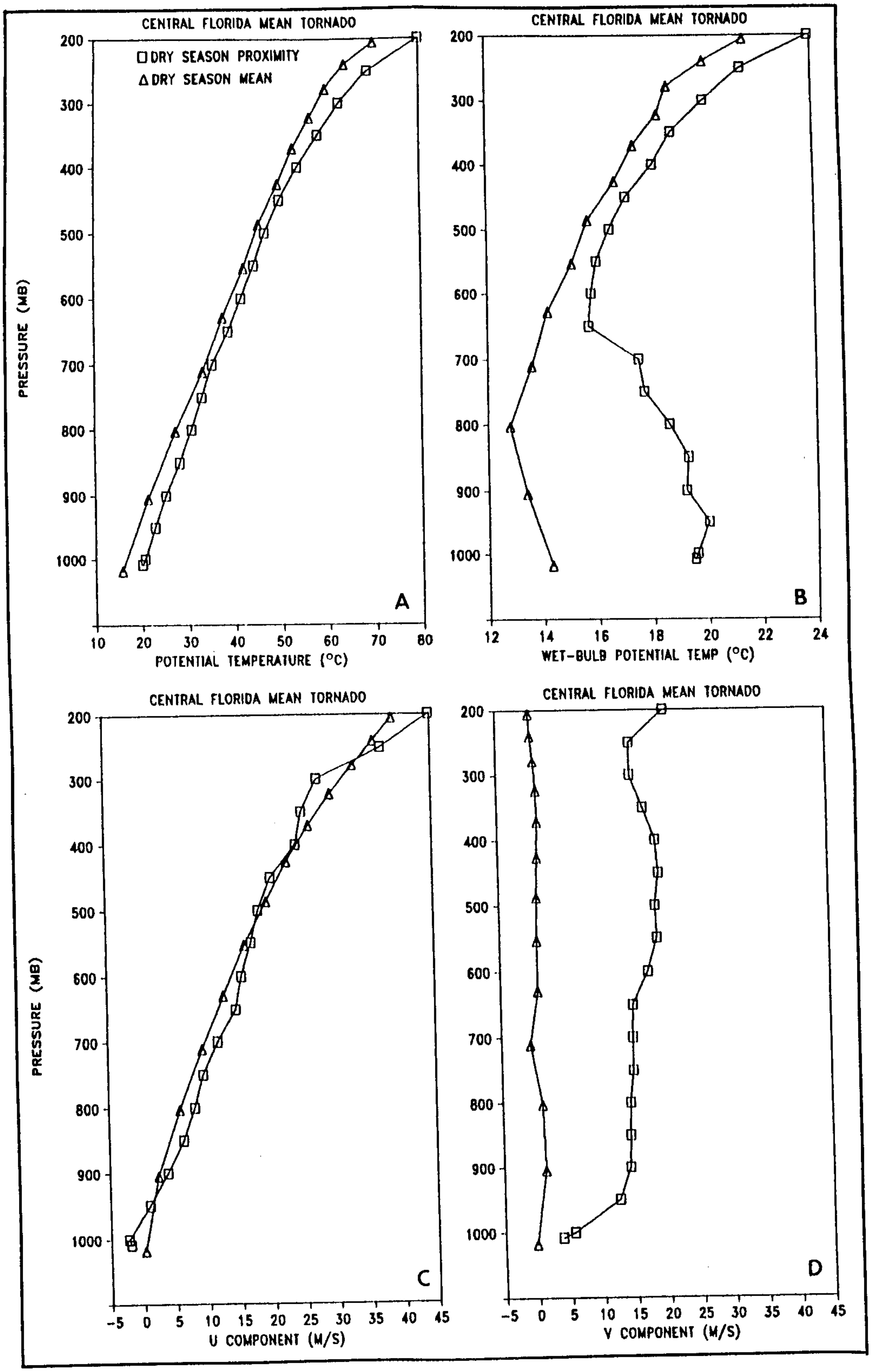


FIG. 7. Mean vertical profiles of θ (a), θ_W (b), U (c), and V (d) for mean dry-season tornado-proximity cases and the mean dry-season environment.

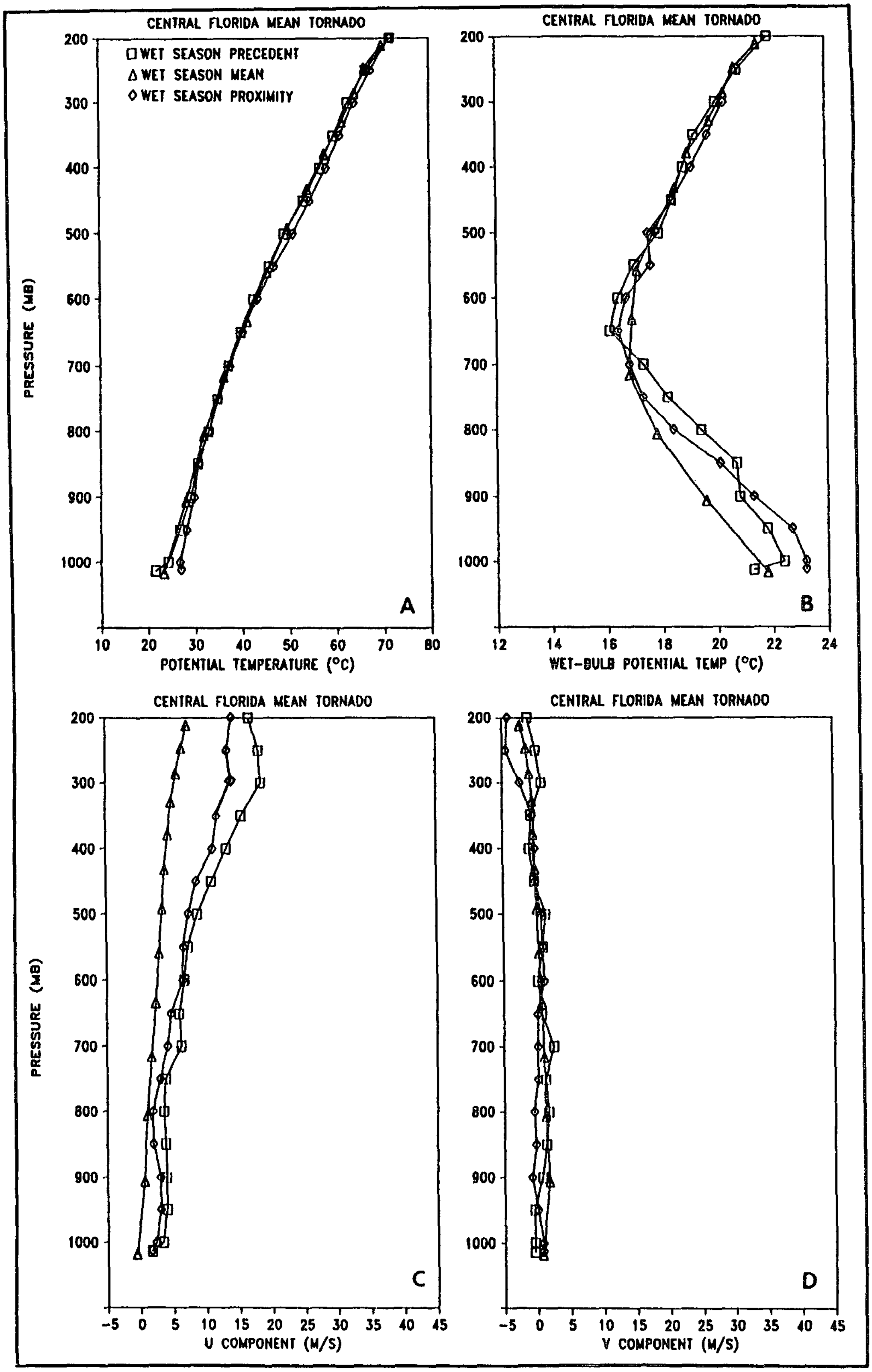
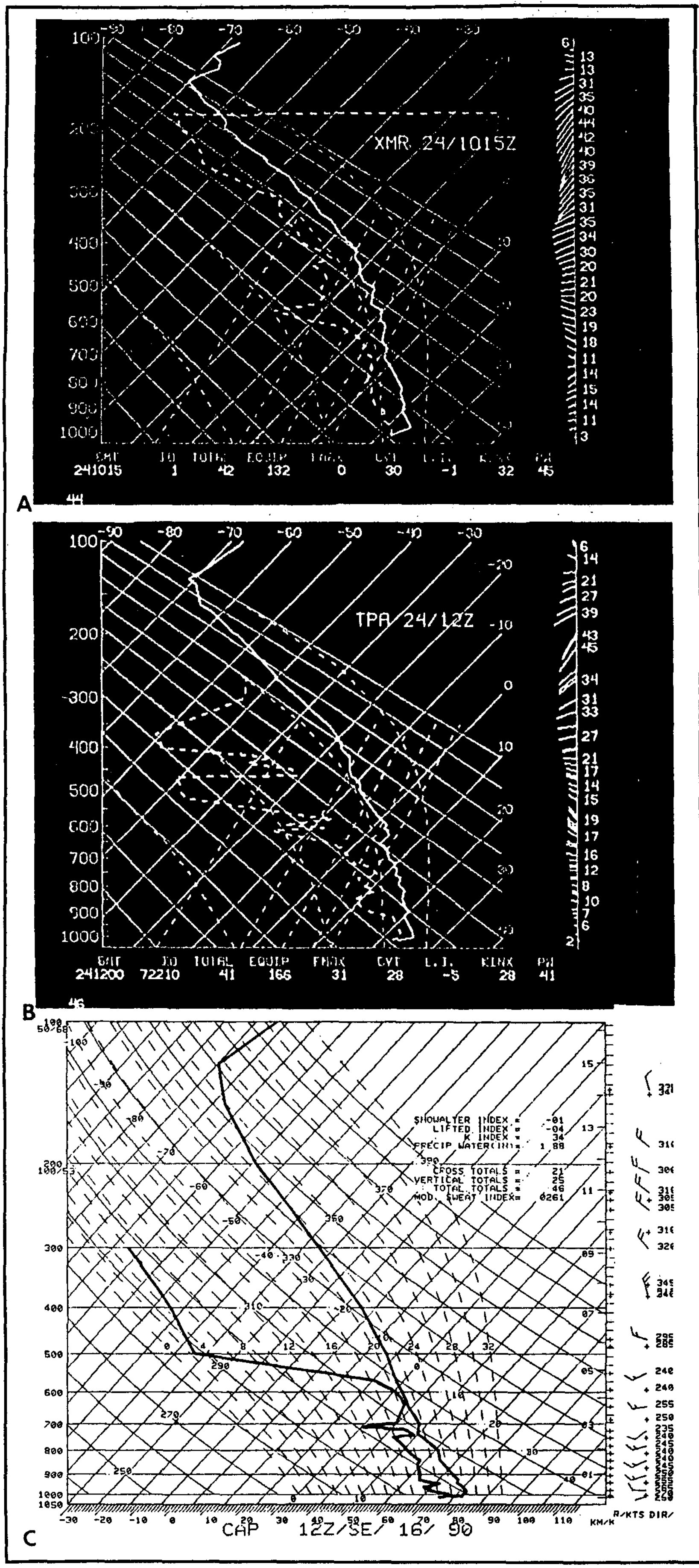


FIG. 8. Mean profiles of θ (a), θ_W (b), U (c), and V (d) for mean wet-season tornado-proximity and precedent cases, and the mean wet-season environment.


A
XMR 24/1015Z
241015 1 42 132 0 30 -1 32 45
B
TPA 24/12Z
SAT ID TOTAL EQUIP FMAX CVT L.I. KINX PW
241200 72210 41 166 31 28 -5 28 41
C
SHOWALTER INDEX = -01
LIFTED INDEX = -04
K INDEX = 34
PRECIP WATER(IN)= 1.88
CROSS TOTALS = 21
VERTICAL TOTALS = 25
TOTAL TOTALS = 46
MOD. SWEAT INDEX= 0261
CAP 12Z/SE/16/90

II, stronger, dry, east flow with *early passage* of the ECSB with limited convection, which is quickly advected to the west coast to merge with the WCSB and move out into the Gulf; and Type III, southwest to northwest flow over central Florida with the westerly flow advecting the WCSB inland, while the ECSB remains anchored along the east coast by ambient flow, causing stronger circulations and convergence. Outflow boundaries from the WCSB convection in the central peninsula interact with the ECSB and other outflow boundaries to enhance convection before dissipation during the evening. Type III days exhibit greater echo coverage, and dissipation takes place much later in the day, while on Type I and II days, convective activity moves through east-central Florida before the 0000 UTC (±2 h) selection criteria.

The wet-season tornado cases presented here are clearly Type III cases, *but it is important to note that the wind speeds between 500 and 200 mb on the mean wet-season tornado-precedent sounding are twice as strong as those of the mean Type III day sounding for MIA and PBI produced by Blanchard and Lopez (1985).*

These stronger upper-level wind velocities and shear appear to be an important factor in significant wet-season tornado cases. The strong, damaging tornado that struck Miami on 17 June 1959 developed in the evening under westerly flow, and Hiser (1968) found that the *most outstanding synoptic weather feature at the time of the tornado was a 47-kt westerly wind-speed maximum at 12 km.* Hiser noted a rapid eastward "explosion" of the high-level storm echo prior to and during the tornado, which he thought indicative of strong storm-top divergence and ascribed this as a primary contributor of the tornadoes.

Detailed radar and mesoscale analyses of cases are beyond the scope of this paper, but recently Golden and Sabones (1991) studied two 1990 wet-season tornado and tornadic-waterspout events near Cape Canaveral using Doppler radar and mesonet data (not included in this study) that serve to illustrate the results of this study. The XMR precedent sounding for the 24 June 1990 event, when a documented *supercell* thunderstorm with a mesocyclone produced an F1 tornado in Cape Canaveral and a huge tornadic waterspout offshore Cocoa Beach between 2155 and 2230 UTC, is shown as Fig. 9a. There is considerable speed shear between low and high levels on Figs. 9a and 9b. The dry layer is relatively shallow over XMR (Fig. 9a), but there is a significantly deeper dry layer upstream at TBW (Fig. 9b). The XMR precedent sounding for 16 September 1990, when a documented *nonsupercell* tornadic thunderstorm, triggered by colliding outflow

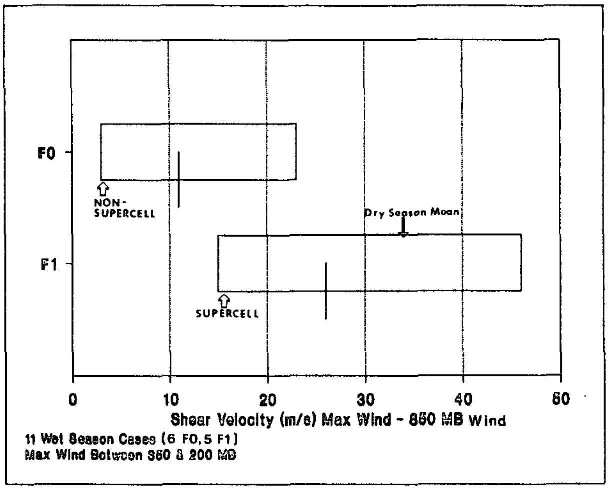


FIG. 10. Box and whisker diagram illustrating the range of shear velocities (m s^{-1}) between the maximum upper-tropospheric wind (350–200 mb) and 850-mb wind for six F0 and five F1 wet-season tornado cases (including two from Golden and Sabones 1991). Confirmed supercell and nonsupercell maximum shear values of the two Golden and Sabones (1991) cases are indicated by arrows. Mean shear of F0 and F1 cases indicated by vertical lines. Mean shear of dry-season proximity cases indicated by arrow.

boundaries, produced an F0 tornadic waterspout near Cape Canaveral in westerly, but very weakly sheared, flow between 1950 and 2004 UTC, is shown as Fig. 9c.

The environments of both of these cases resemble the general characteristics of the mean wet-season tornado-precedent sounding presented in this study in that they display a deep moist layer capped by dry air, and have westerly or northwesterly wind maximums in the upper troposphere and westerly winds through the depth of the troposphere. However, the maximum wind of the September case was half as strong, and shear between 850 mb and the maximum upper-tropospheric wind one-sixth as great, when compared to the June case. The tornadoes in the June case were much larger, stronger, and longer-lived than in the September case.

Although the wet-season data sample is small (five F0, four F1 cases), there does appear to be a relationship between higher mid- and upper-tropospheric wind speeds and shear, tornado strength, and possibly the transition from nonsupercell to supercell thunderstorms that needs further research.

A graph of shear between 850 mb and the maximum upper-tropospheric wind (350–200 mb) for F0 and F1 west flow, wet-season tornado cases (Fig. 10), which includes the two recent cases (one F1, one F0) of Golden and Sabones (1991), serves to illustrate this

FIG. 9. Tornado precedent skew T–log$p$ soundings (wind speed in knots) for 24 June 1990 for XMR (a) at 1015 UTC, and TBW (upstream) at 1200 UTC (b), and for 16 September 1990 for XMR at 1200 UTC (c).

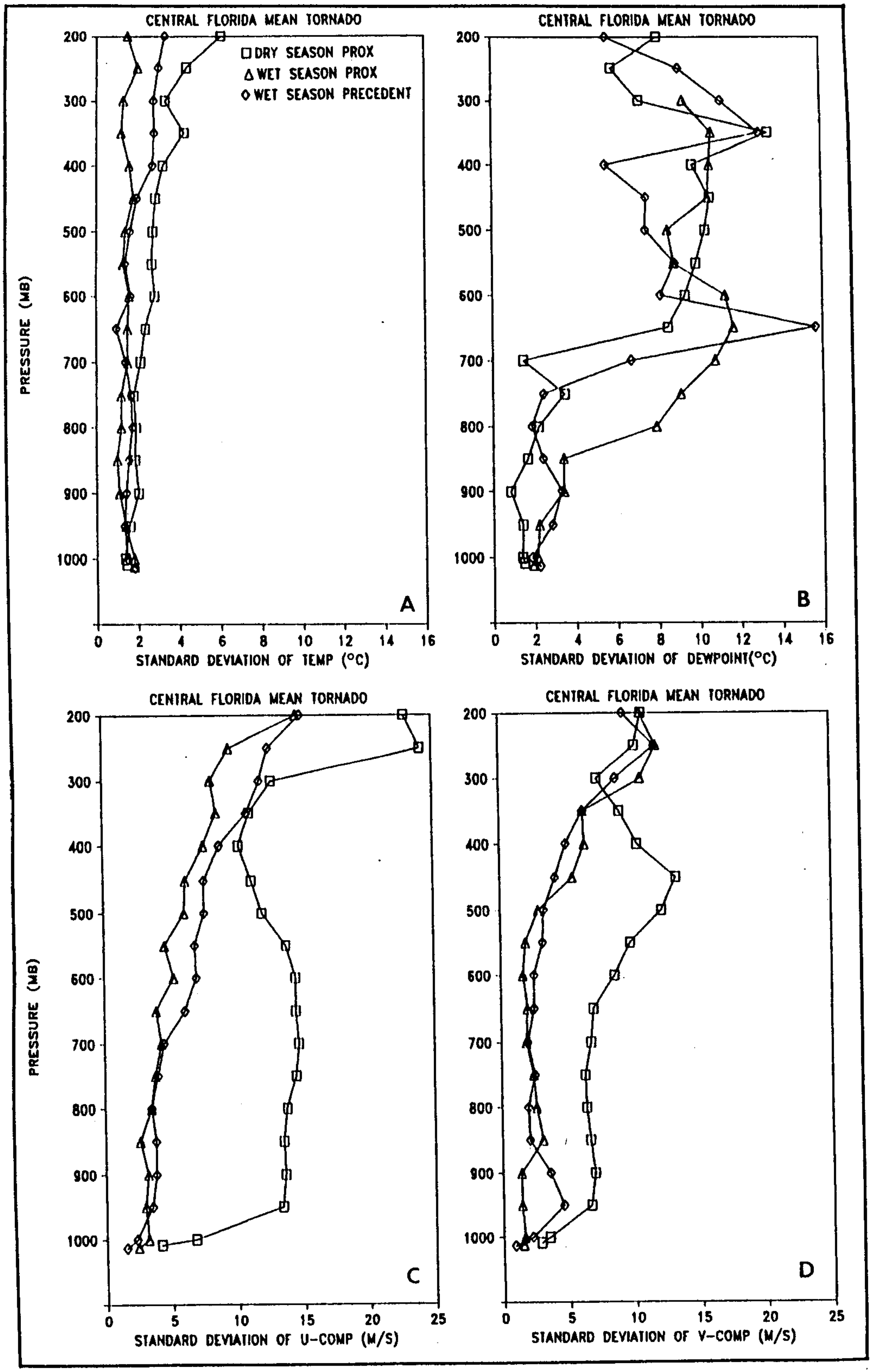


FIG. 11. Mean vertical profiles of standard deviation of T (a), T_d (b), U (c), and V (d) for mean dry- and wet-season tornado-proximity cases and mean wet-season precedent cases.

point: The shear for F0 tornadoes ranges from 3 to 23 m s^{-1}, with a mean of 11 m s^{-1}, while shear for F1 tornadoes ranges from 15 to 46 m s^{-1} with a mean of 26 m s^{-1}. The nonsupercell tornado case of 16 September 1990 had a shear value of 2.5 m s^{-1} and the supercell case of 24 June 1990 had a shear value of 15 m s^{-1}. Both of these cases were at the lower end of their respective F-scale categories. While the high 850–200-mb shear values of the dry-season cases (mean 34 m s^{-1}, shown by dark arrow on Fig. 10) typically result from high 850-mb flow and very high 200-mb flow, the higher values of wet-season shear are due to unusually high upper-tropospheric winds and low 850-mb winds (which didn't equal 10 m s^{-1} in any case).

While shear values appear to be critical to the type of thunderstorms that develop and how strong tornadoes may be, there is a wide range of shear values associated with tornadoes and tornadic waterspouts, and more research is planned.

Tornadoes and waterspouts also occur in weakly sheared and/or easterly flow, but no east-flow wet-season cases are included in this study, because, as stated

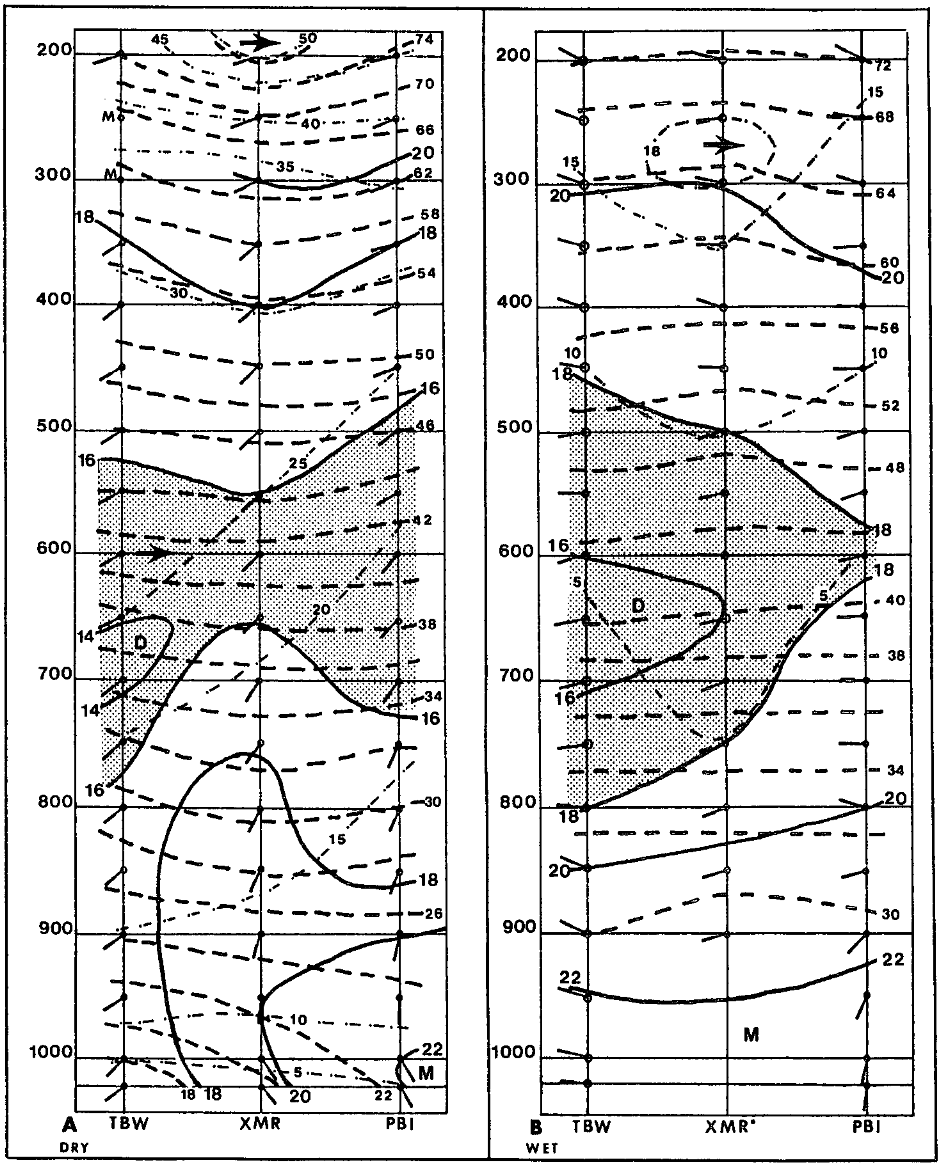


FIG. 12. Schematic representations of mean environmental conditions in the vicinity (XMR), upstream (TBW), and downstream (PBI) of central-Florida tornadic thunderstorms for the dry season (a, all 1200 UTC data) and wet-season (b, TBW & PBI 0000 UTC, XMR 1200 UTC). Bold lines (θ_W, °C), dashed lines (θ, °C), and small dash-dot lines wind speed (m s^{-1}). Wind maxima are indicated by bold arrow and wind direction by conventional direction shafts. θ_W minimums are indicated by (D) and maximums by (M). Layers of low θ_W are shaded.

earlier, they would tend to occur in east-central Florida before 2 h prior to 0000 UTC. Research is planned on these types of events in the future.

d. Standard-deviation analyses

Because of the small sample sizes used in this study, analyses of standard deviation of temperature (T), dewpoint (T_d), U, and V for the dry- and wet-season proximity and wet-season precedent atmospheres (Fig. 11a–d) are presented to aid in the interpretation of the results.

Standard deviation of T (Fig. 11a) is below 2°C to 700 mb for all three atmospheres, and remains below 2°C for the wet-season precedent and proximity to 450 mb. Most noteworthy is standard deviation for the wet-season proximity, which remains below 2°C to 200 mb. Standard deviation of T_d (Fig. 11b) remains below 4°C for all three atmospheres to 850 mb. The most striking feature in the analyses of T_d is the sharp increase in standard deviation occurring in the lower midtroposphere of all three atmospheres near the top of the mean moist layers. This probably results from variability in the depth of the moist layer and the magnitude of the overlying dry air mass. These results are similar to those of McCaul (1990) for hurricane tornadoes and Bluestein and Jain (1985) for the Oklahoma severe squall-line environment.

The most outstanding features of the standard deviation of U (Fig. 11c) are the significant increases at the levels of the low-level jet (LLJ) and upper-level jet (950 and 350 mb) in the dry-season proximity profile. The maximum of U standard deviation in the southerly LLJ is significant to forecasters. Note that mean U is nearly zero at 950 mb (Fig. 6c), while standard deviation is 13 m s^{-1} (Fig. 11c). This indicates that the LLJ, while dominated by the V component, would typically contain a significant U component and be either southeasterly (negative U) or southwesterly (positive U). In the mean, however, they are canceled out.

The most interesting feature of the standard deviation of V (Fig. 11d) is the peak in the dry-season proximity environment at 450 mb at the level of the mid-level southwesterly jet. Standard deviation of wet-season proximity and precedent V peaks at 250 mb (12 m s^{-1}), where mean V is near zero (Fig. 8d). This indicates that the upper-level westerlies could have a significant V component and be either northwesterly (negative V) or southwesterly (positive V). However, in the mean they are likewise canceled out.

4. Summary of mean atmospheric structure

We have examined dry- and wet-season tornado-environment profiles relative to each other and seasonal means. We now summarize the features of the atmospheric structure of the regional seasonal tornado environments in the proper geographic and synoptic context, by presenting mean "cross sections" of individual mean soundings across central Florida (Figs. 12a,b) rather than blended proximity soundings. These are really schematic representations of conditions in the vicinity of CWA tornadic-thunderstorm development (XMR), upstream (TBW), and downstream (PBI).

a. Dry season

The dry-season environment (Fig. 12a) is characterized by a distinct low-level convergent boundary between TBW and XMR, and significant θ and θ_W discontinuities across the central peninsula. High values of θ_W (>22°C) are feeding into the boundary, and the moist layer has increased greatly in depth over XMR, while a dry air mass with low values of θ_W (<14°C) centered around 650 mb is injected into the storm environment. *Despite the lack of diurnal heating, which would further destabilize the environment, the existence of a strong convergent boundary and significant potential convective instability in the presence of strong dynamics and shear give rise to tornadic-thunderstorm development.*

Morning tornadic thunderstorms forming in this environment would tend to be low topped, fast moving, and very difficult to detect with conventional radar. At present, there is seldom any lead time for this type of tornado, unless they are spotted and reported in time to warn downstream counties. The results presented here could lead to a better chance of detection if used in combination with detailed radar analysis. The NEXRAD/WSR-88D's high-resolution reflectivity, combined with the ability to slice through a storm and diagnose the mesoscale dynamic environment, offers a real promise of improving detection of this type of storm.

b. Wet season

The wet-season mean tornado environment (Fig. 12b) is characterized by a distinct peninsula-scale convergent boundary between PBI and TBW. This is really a reflection of the passage of the WCSB well east of TBW (west winds) and the lack of deep inland penetration of the ECSB at PBI (south winds) due to the influence of ambient westerly flow. Because only 1200 UTC soundings were available for XMR, the data below 900 mb was omitted, and for our purposes it is assumed the atmosphere over XMR above this level is indicative of the prevailing conditions later in the day.

In contrast to the dry season, there are no significant low-level thermal or moisture differences across the peninsula, and winds are uniformly weak (<5 m s^{-1}) below about 650 mb. However, two significant features stand out in the wet-season environment: 1) The existence of a deep dry layer of low θ_W (<16°C) air in the midtroposphere upstream of the tornado-threat area, and 2) a wind maximum (>18 m s^{-1}) at 275 mb over the threat area.

The ECSB and WCSB are present almost daily in the wet season to provide low-level forcing mechanisms. Cooper et al. (1982) found that the sea breezes are responsible for forcing early in the day, and then convective-scale forcing dominates after convection is initiated. Gerrish (1969) was one of the first to speculate that the subcloud layer contains the key mechanism for at least some wet-season tornadoes in Florida. Wakimoto and Wilson (1989) demonstrated how vorticity concentrated in low-level boundaries could interact with updrafts in developing nonsupercell thunderstorms along boundaries to spinup tornadoes by vortex stretching. But, to put these concepts to good use operationally, forecasters must diagnose the whole picture in detail and understand the interactions and physical processes involved to the degree that technology allows. Key factors that effect whether thunderstorms on one day may be tornadic or not depend on the characteristics of the overlying air mass, as well as the probable existence, and strength, of low-level triggering boundaries.

This fundamental issue is addressed in the following conceptual model of west flow, wet-season tornadic-thunderstorm development, which appears to have a degree of predictability:

> Weak synoptic low-level westerly flow over the peninsula permits the diurnal development of distinct mesoscale circulations (sea/lake breezes). Weak shear in the lower- to midtroposphere allows convection initiated by low-level thermal circulations to readily modify the atmosphere to that favorable for rapid growth of developing storm towers. Then, increasing shear from the mid- to upper-troposphere results in tilted updrafts and increased high-level divergence, which, in turn, causes more-vigorous updrafts. At the same time, the existence of a deep layer of low θ_W (potentially cool) air (Normand 1946) in the midtroposphere allows for the development of strong, evaporatively cooled downdrafts that reach the ground considerably cooler than the air feeding the storm. These downdrafts, the strength of which are related to the magnitude of θ_W in the midtroposphere, are essential to production of thunderstorm outflow boundaries, which can trigger further convection. The thunderstorms begin to be established with vigorous, sustained, tilted updrafts, strong downdrafts, and significant convectively induced boundaries, some of which eventually interact with each other and the ECSB, further intensifying convection before diminishing during the evening.

Thus, while low-level boundaries are necessary for convective initiation, the overlying atmosphere plays an important role in organizing, sustaining, and initiating subsequent convection. The NEXRAD/WSR-88D, with its ability to detect, track, and possibly quantify the strength of low-level boundaries, as well as diagnose the dynamic environment at much higher spatial and temporal resolutions than the current synoptic upper-air network, offers the promise of greatly improving the detection of wet-season tornadic thunderstorms.

Acknowledgments. Cape Canaveral data was provided by Hal Herring, Computer Sciences, Raytheon Corporation. Daniel Smith provided Tampa Bay and Palm Beach sounding data. Barry Schwartz provided skew T–log p plots of mean soundings and computations of diagnostic parameters. Preston W. Leftwich, Jr., provided calculations of helicity. Jo Ann Carney and Karen Hileman assisted in data tabulation and figure preparation. Thanks to Joe Golden for his advice and encouragement to continue the study. Paul Hebert and Mike Sabones provided helpful reviews of the paper. Special thanks to Ron Holle, Irv Watson, and Raul Lopez for providing an extensive collection of papers relating to Florida convection for our use. Financial support for this paper was provided by the National Weather Service Southern Region, and Harry Hassel, its regional director.

REFERENCES

Beebe, R. G., 1958: Tornado proximity soundings. *Bull. Amer. Meteor. Soc.*, **39**, 195–201.

——, 1963: Tornado proximity soundings. Preprints, *3rd Conf. on Severe Local Storms*, Urbana, IL, Amer. Meteor. Soc., 6 pp.

Blanchard, D. O., and R. E. Lopez, 1985: Spatial patterns of convection in south Florida. *Mon. Wea. Rev.*, **113**, 1282–1299.

Bluestein, H. B., and M. H. Jain, 1985: Formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during the spring. *J. Atmos. Sci.*, **42**, 1711–1732.

Byers, H. R., and H. R. Rodebush, 1948: Causes of thunderstorms of the Florida Peninsula. *J. Meteor.*, **5**, 275–280.

Cooper, H. J., M. Garstang, and J. Simpson, 1982: The diurnal interaction between convection and peninsular-scale forcing over south Florida. *Mon. Wea. Rev.*, **110**, 486–503.

Darkow, G. L., 1969: An analysis of over 60 tornado proximity soundings. Preprints, *6th Conf. on Severe Local Storms*, Chicago, Amer. Meteor. Soc., 218–221.

——, 1986: Basic thunderstorm energetics and thermodynamics; Thunderstorm: A social, scientific and technological documentary, *Vol. 2, Thunderstorm Morphology and Dynamics, 2nd Ed.* E. Kessler, Ed., Univ. of Oklahoma Press, 59–73.

——, and M. G. Fowler, 1971: Tornado proximity sounding wind analysis. Preprints, *7th Conf. on Severe Local Storms*, Kansas City, Amer. Meteor. Soc., 148–151.

DOD, 1983: Cape Canaveral, Florida Range Reference Atmosphere 0–70 km altitude. Published by Secretariat, Range Commanders Council, White Sands Missile Range, NM, 203 pp.

Doswell, C. A. III, 1982: The operational meteorology of convective weather, Vol. 1: Operational mesoanalysis. NOAA Tech. Memo. NWS NSSFC-5.

Fawbush, E. J., and R. C. Miller, 1952: A mean sounding representative of the tornado airmass environment. *Bull. Amer. Meteor. Soc.*, **33**, 303–307.

Fujita, T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.*, **38**, 1511–1534.

Gerrish, H. P., 1967: Tornadoes and waterspouts in the south Florida area. *Proc. 1967 Army Conf. on Tropical Meteorology,* Coral Gables, FL, 62–76.

——, 1969: Intersecting fine lines and a south Florida tornado. Preprints, *6th Conf. on Severe Local Storms,* Chicago, Amer. Meteor. Soc., 188–191.

Golden, J. H., 1971: Waterspouts and tornadoes over south Florida. *Mon. Wea. Rev.*, **99**, 146–154.

——, and M. E. Sabones, 1991: Tornadic waterspout formation near intersecting boundaries. Preprints, *25th Conf. on Radar Meteorology*, Paris, Amer. Meteor. Soc.

Hagemeyer, B. C., 1991: A lower-tropospheric thermodynamic climatology for March through September: Some implications for thunderstorm forecasting. *Wea. Forecasting*, **6**, 254–270.

Hiser, H. W., 1968: Radar and synoptic analysis of the Miami tornado of 17 June 1959. *J. Appl. Meteor.*, **7**, 892–900.

Holle, R. L., and M. W. Maier, 1980: Tornado formation from downdraft interaction in the FACE mesonetwork. *Mon. Wea. Rev.*, **108**, 1010–1028.

Johns, R. H., J. M. Davies, and P. W. Leftwich, 1990: An examination of the relationship of 0–2-km AGL "positive" wind shear to potential buoyant energy in strong and violent tornado situations. Preprints, *16th Conf. on Severe Local Storms*, Alberta, Canada, Amer. Meteor. Soc., 593–598.

Kelley, D. L., J. T. Schaefer, R. P. McNulty, C. A. Doswell, and R. F. Abbey, 1978: An augmented tornado climatology. *Mon. Wea. Rev.*, **106**, 1172–1183.

Leftwich, P. W., 1990: On the use of helicity in operational assessment of severe local storm potential. Preprints, *16th Conf. on Severe Local Storms*, Alberta, Canada, Amer. Meteor. Soc., 306–310.

Lustig, J. C., 1973: A comparison of tornado proximity and precedent soundings. M.S. thesis, University of Missouri–Columbia, 120 pp.

Maddox, R. A., 1976: An evaluation of tornado proximity wind and stability data. *Mon. Wea. Rev.*, **104**, 133–142.

McCaul, E. W., Jr., 1991: Buoyancy and shear characteristics of hurricane-tornado environments. *Mon. Wea. Rev.*, **119**, 1954–1978.

Miller, R. C., 1972: Notes on analysis and severe storm forecasting procedures of the Air Force Global Weather Central. Tech. Rep. 200 (Rev.), Air Weather Service, Scott AFB, IL, 190 pp.

Newton, C. W., 1963: Dynamics of severe convective storms. *Meteor. Monogr.*, **5**, 33–58.

——, 1980: Overview on convective storm systems. *Proc. of CIMMS Symposium*. Y. K. Sasaki, N. Monji, and S. Bloom, Eds., Norman, OK, 3–107.

Normand, W. W. B., 1946: Energy in the atmosphere. *Quart. J. Roy. Meteor. Soc.*, **64**, 47–66.

Riley, P. A., and J. R. Colquhoun, 1990: Thermodynamic and wind related variables in the environment of United States tornadoes and their relationship to tornado intensity. Preprints, *16th Conf. on Severe Local Storms*, Alberta, Canada, Amer. Meteor. Soc., 599–602.

Schaefer, J. T., 1990: The evolution of tornado proximity soundings. Preprints, *16th Conf. on Severe Local Storms*, Alberta, Canada, Amer. Meteor. Soc., 96–101.

——, and R. L. Livingston, 1988: Structural characteristics of tornado proximity soundings. Preprints, *15th Conf. on Severe Local Storms*, Baltimore, Amer. Meteor. Soc., 537–540.

Schmocker, G. K., D. W. Sharp, and B. C. Hagemeyer, 1990: Three initial climatological studies for WFO Melbourne, Florida: A first step in the preparation for future operations. NOAA Tech. Memo. NWS SR-132, 52 pp.

Showalter, A. K., and J. R. Fulks, 1943: A preliminary report on tornadoes. U.S. Weather Bureau, Washington, D.C.

Taylor, G. E., and G. L. Darkow, 1982: Atmospheric structure prior to tornadoes derived from proximity and precedent upper-air soundings. NUREG/CR-2359, U.S. Nuclear Regulatory Commission, Washington, D.C., 95 pp.

Wakimoto, R. M., and J. Wilson, 1989: Nonsupercell tornadoes. *Mon. Wea. Rev.*, **117**, 1118–1140.

Weisman, M. L., and J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.*, **110**, 504–520.

Wills, T. G., 1969: Characteristics of the tornado environment as deduced from tornado proximity soundings. Preprints, *6th Conf. on Severe Local Storms*. Chicago, Amer. Meteor. Soc., 222–228.