The 13 March 1993 Severe Squall Line over Western Cuba

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(Manuscript received 24 January 1994, in final form 14 November 1995)

ABSTRACT

On 13 March 1993 a powerful prefontal squall line hit western and central Cuba. At 0000 UTC, a fast-developing extratropical cyclone with a well-defined cold front was located in the northeast Gulf of Mexico. Over the eastern Gulf of Mexico there was a 300-hPa jet streak interacting with a low-level jet. A hodograph typically associated with supercells or severe squall lines was observed at Key West, Florida. The air mass over the eastern Gulf of Mexico, Florida, and Cuba was conditionally unstable. Instability was enhanced by moist air at the surface interacting with a dry intrusion in the midtroposphere from the Mexican Plateau. Lifting induced by a strong short-wave trough favored the formation a compact squall line with embedded bow-echoes and line-echo wave patterns. Damaging winds were widespread with the squall line. Thus, the event fits the definition of a serial derecho. One of the two bow echoes that affected Cuba included a small but strong mesocyclone in its forward flank, as detected by radar and surface observations. The mesocyclone caused great damage in a 20-km-wide strip over the Havana and Havana City provinces, producing a family of downbursts in its southern portion. Estimated damage up to F2 on the Fujita scale was experienced in the effected area. Another bow echo struck the central region of Cuba producing similar damage. The squall line event described in this study is the most damaging one ever recorded in Cuba.

1. Introduction

Alfonso (1988) has shown that severe local storms (SLS)[1] can occur in every month of the year in Cuba but that a period with more frequent SLS extends from March to September. The SLS events observed during the early part of the active season (March to May) are generated by extratropical systems (e.g., cold fronts and short-wave troughs). Tropical synoptic systems (e.g., upper cold lows, tropical waves, and tropical cyclones) and mesoscale forcing (as described by Garinger and Knupp 1993) produce the majority of SLS events from July to September. Since both types of systems can occur in June, it is the month with maximum frequency of occurrence of SLS. However, the most damaging SLS events observed in Cuba have occurred in the cool season, from late December to March. These events are produced by prefrontal squall lines. For example, on 26 December 1940, an SLS squall line, which included a severe tornadic storm, devastated the town of Bejucal, near Havana City (Ortiz and Ortiz Jr. 1940). Twenty people died and approximately 200 were injured in that event. More recently, on 16 February 1983, a severe squall line with strong mesocyclones affected broad areas in the Havana province (Alfonso and Córdoba 1987). These examples illustrate the importance placed on the study of prefrontal squall lines in Cuba (e.g., Alfonso 1986).

Córdoba and Alfonso (1992) have pointed out that the SLS-producing prefrontal squall lines studied to date in Cuba were linked to slow-moving extratropical lows associated with short-wave troughs in the southern branch of a split polar jet (SBPJ). The conditions were similar to central U.S. squall environments (Hane 1986) except that the Cuban events occurred with weak, cold fronts of Pacific maritime, rather than continental, origins.

On 13 March 1993 a very strong extratropical storm hit a broad area of the United States and Cuba, causing considerable damage and casualties. In Cuba, total fatalities were relatively low (10), but economic losses amounted to more than U.S. $1 billion. A significant portion of these losses were caused by a prefrontal SLS squall line with severe weather that swept the whole country, bringing straight-line winds over 55 m s^{-1} and hail to the western provinces. Rains over 100 mm in 24 h fell over eastern provinces. Although the observed severe phenomena were not the most intense ever recorded in Cuba, the extent of the area affected by significant SLS phenomena was greater than that of any other severe prefrontal squall lines previously studied.

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[1] For purposes of the Institute of Meteorology of Cuba, the definition of an SLS is a storm that produces one or more of the following phenomena:

- tornado
- hail, any size
- damaging winds, or measured winds $\geqslant$ 25 m s^{-1}
- waterspout

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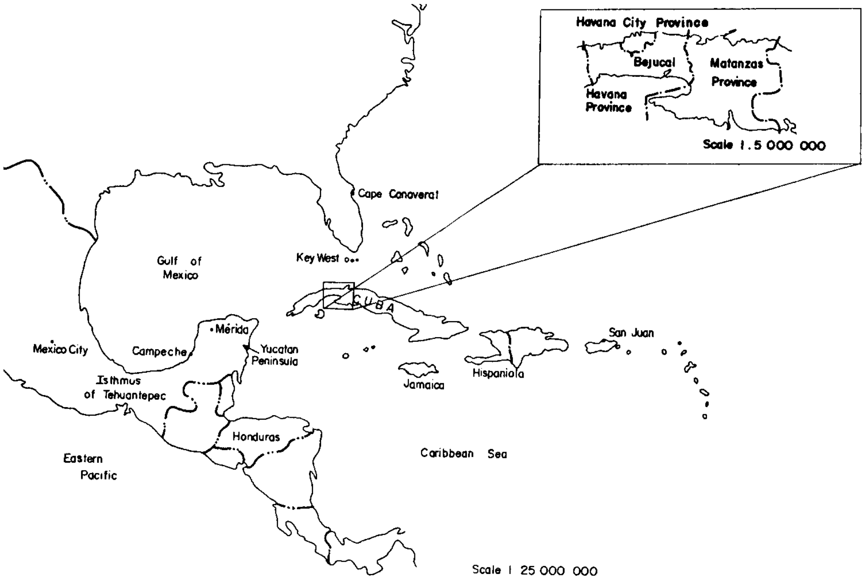

FIG. 1. Key locations over Cuba and adjacent areas.

The 13 March 1993 squall line formed in a synoptic environment quite different from formerly reported cases in Cuba (Córdoba and Alfonso 1992). It was distinguished by an exceptionally strong polar outbreak over the central United States and the Gulf of Mexico, with a pronounced cold front along the forward boundary of this air mass. These features were associated with a deep, long-wave trough in the midtroposphere that extended from polar latitudes down to the Tropics. The object of this paper is to report on a detailed analysis of this case in order to contribute to the current knowledge of the behavior of severe weather–producing squall line systems in low latitudes, and especially in the vicinity of Cuba (Fig. 1).

2. Synoptic analysis

a. General description[2]

A strong polar outbreak over the central United States brought on sustained surface pressure rises in that area on 11 and 12 March. At the same time, an extratropical low pressure center began to develop over Mexico. At 0000 UTC 12 March, the low started to move east along a quasi-stationary front that had remained over the northern part of the Gulf of Mexico during the preceding 48 h. An increase in contrast between cold continental air and maritime air from the Atlantic Ocean covering the Gulf of Mexico south of the quasi-stationary front was clearly observable. By 2300 UTC 12 March the continental high pressure center had reached a value of 103.1 kPa over Kansas. Meanwhile, the low pressure center had moved into the Gulf and was located near 25°N, 93°W and had a surface pressure of 100.4 kPa at its center.

Above the surface, these events were initially associated with a period of quasi-zonal flow over the central and eastern United States, the Gulf of Mexico, and even the Caribbean Sea. By 1200 UTC 12 March, a strong short-wave trough in the SBPJ began supporting rapid cyclogenesis in the Gulf of Mexico. A powerful cold outbreak in the midlevels spread to the south over the Great Plains, and a short-wave trough in the northern branch of the polar jet (NBPJ) came quickly into phase with the southern current, resulting in the deep, long-wave trough shown in Fig. 2.

The low pressure center deepened rapidly, and at 0000 UTC on 13 March it was located near 29°N and 89°W with a central pressure of 99.1 kPa. The cold front associated with the SBPJ was already strong and well defined, extending from the low center down to the Isthmus of Tehuantepec (Fig. 3). During the following hours, the low pressure center continued deepening and moving east-northeastward. An intensifying low-level jet (LLJ) was located over western Cuba and the eastern Gulf of Mexico. A maximum speed of 19 m s^{-1} at 85 kPa was observed at Key West at 0000 UTC 13 March. Winds continued increasing at the surface until the squall line arrived. Thermal analyses indicated strong baroclinity associated with this jet, that is, an intrusion of warm and humid air into Florida and the eastern portion of the Gulf of Mexico. These features are shown in Fig. 4. The LLJ had in this case a purely dynamical origin (Uccellini 1990).

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[2] The synoptic analyses used in this study are based on surface and upper-air charts and atmospheric soundings, subjectively analyzed by the staff of the Weather Forecast Department, Meteorological Center, Matanzas, Cuba (FDMCM).

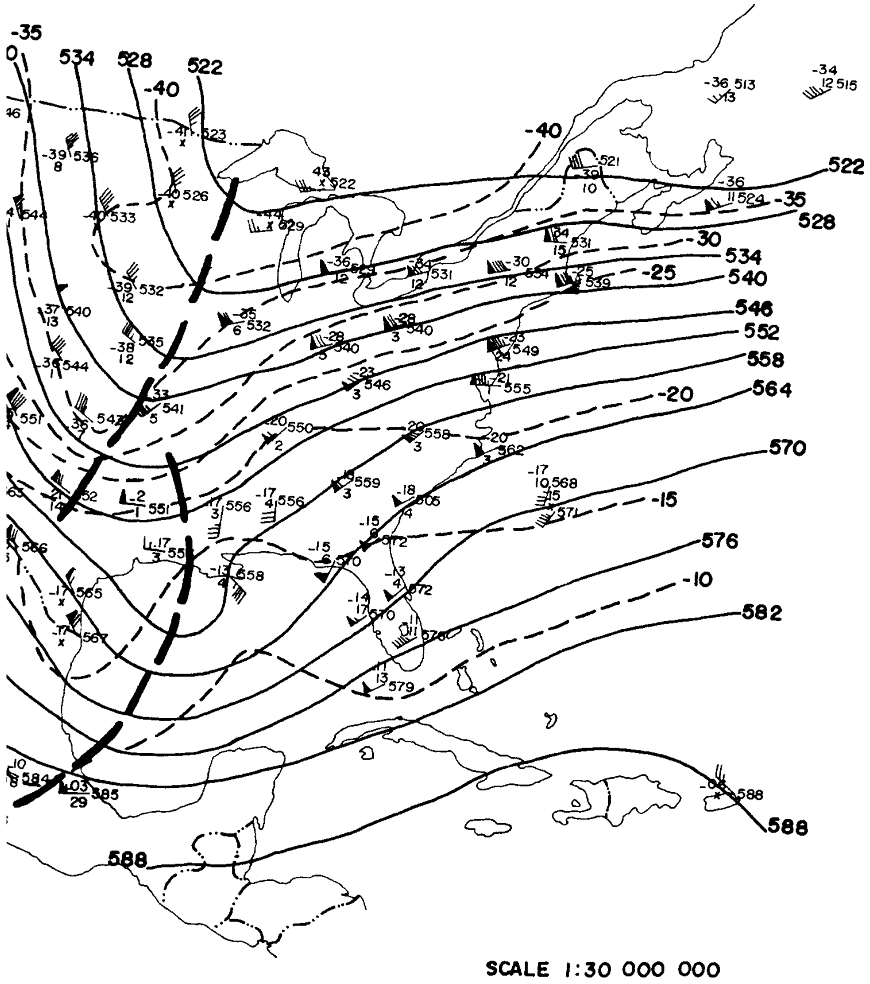

FIG. 2. FDMCM subjective 50-kPa analysis for 0000 UTC 13 March 1993. Geopotential heights (solid) every 6 dam and temperatures (dashed) every 5°C. Station model temperatures (top) and dewpoint depressions (bottom) in Celsius. Each full-wind barb equals 10 kt, and each flag equals 50 kt.

In the upper troposphere (i.e., the 30-kPa level shown in Fig. 5) it is evident that the intense cyclogenesis in the Gulf of Mexico was associated with a pronounced zone of difluence. Strong ageostrophic flow components were indicated over the U.S. gulf coastal region, with the flow becoming perpendicular to the height contours over Louisiana and the nearby gulf. This development was a consequence of the rapid intensification of the low pressure center that was being built up from the lower atmospheric layers and was also related to deep convection over the Gulf of Mexico and the southeast United States (Keyser and Carlson 1984). This situation was coincident with the SBPJ exit region over the central gulf. Figure 5 also illustrates the intense split in the polar jet.

No data were received from radiosonde stations in Central America and the Caribbean Sea (except San Juan, Puerto Rico) at 0000 UTC 13 March, but satellite imagery at 0201 UTC indicated that the subtropical jet stream (STJ) was far to the south, emerging from the eastern Pacific across eastern Honduras and continuing east-northeastward across Jamaica and Hispaniola.

b. Factors related to deep convection and associated severe weather

Doswell (1987) has stated that many severe weather phenomena, as defined in section 1, are related to deep convection and that there are three necessary elements for their occurrence. The first of these elements is the presence of a deep moist layer in the lowest levels. In the 13 March case an abundant supply of moisture at the surface is apparent, with mixing ratio (q) values reaching up to 16 g kg^{-1} over eastern Yucatán and adjacent waters and high values extending to the north over the eastern Gulf of Mexico (Fig. 6). This is more than twice the 7 g kg^{-1} average value found by McNulty (1978) to be associated with cases of severe

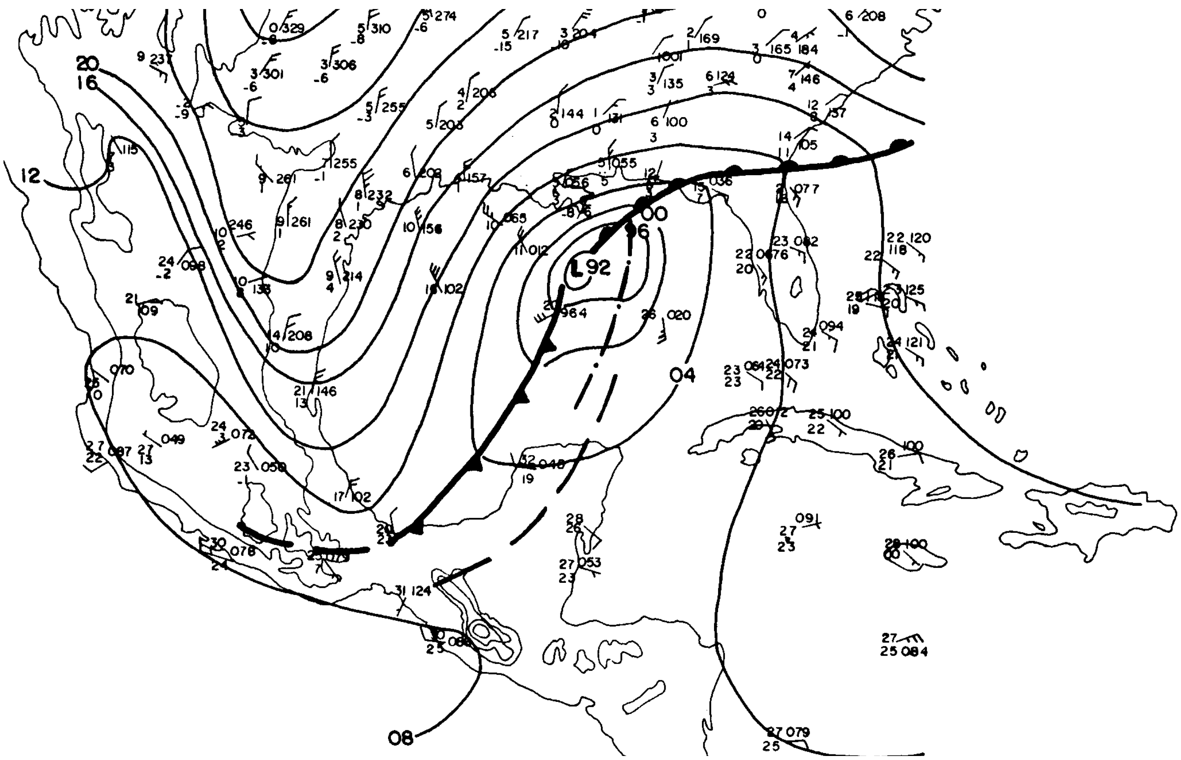

FIG. 3. FDMCM sea level pressure analysis for 0000 UTC 13 March 1993. Isobars every 4 hPa. Temperature (top) and dewpoint (bottom) in Celsius. Each full-wind barb equals 10 kt.

weather outbreaks occurring during March in the United States.

A strong *q* gradient existed over Yucatán between very humid air to the east and relatively dry air to the west over the Yucatán Plateau and the western Gulf of Mexico. Further, at 0000 UTC 13 March the temperature in both Merida and Campeche on the west Yucatán coast was 32°–33°C in contrast to 28°C on the eastern coast of the peninsula. The moisture and temperature distribution over the Yucatán Peninsula resembles the pattern that Miller (1972) described as very favorable to SLS development, that is, the low-level heat axis located west (upstream) of the moisture axis. Observational evidence obtained from SLS squall line forecasting in Cuba suggests that most of the time, when squall lines develop in the Gulf of Mexico, they extend south only to about 25°N latitude as they traverse the northwest and central gulf. As they reach the eastern gulf, squall lines typically expand rapidly southward over the southeast gulf and western Cuba. Since the *q* distribution over Yucatán in this case is typical of most spring afternoons, it is possible that this regional aspect of the heat and moisture distributions is responsible for the behavior of squall lines in this area. The satellite picture sequence included in the paper by Nielsen and Igau (1993) showed very rapid building to the south of the squall line over the eastern Yucatán Peninsula. Figure 4 shows this development coincident with the moisture axis at 85 kPa. Soundings over Florida, as shown by the Cape Canaveral, Florida, sounding, for example (Fig. 7), indicated that the moist layer extended to about 70 kPa at 0000 UTC 13 March.

The second necessary element for the development of deep convection is a sufficiently steep lapse rate above the moist layer. In this case, conditionally unstable air covered Florida and western Cuba, as shown in Fig. 7. Lifted index values (Galway 1956) between −3 and −5 and total totals indices (Miller 1972) between 48 and 50 were observed in soundings of Florida at 0000 UTC 13 March. However, these very moist sounding do not appear typical of soundings usually associated with very strong and spatially extensive downbursts.

The 50- (Fig. 2) and the 70-kPa (Fig. 8) analyses show the existence of very strong winds blowing from the Mexican Plateau to the eastern Gulf of Mexico. Hot, dry, and high-lapse-rate air forming over Mexico (as shown by Mexico City sounding at 0000 UTC 13 March, Fig. 9) was advecting eastward over the Gulf of Mexico (indicated by the analysis in Fig. 8). Consequently, a very strong capping inversion also extended eastward over the moist gulf air at low levels. The process of lid formation in this case was somewhat different from the classical process in the central United States, as described by Lannicci and Warner (1991). The hot, dry, and high-lapse-rate air from the Mexican Plateau was advecting from the rear of the short-wave trough and merging both with the warm and humid

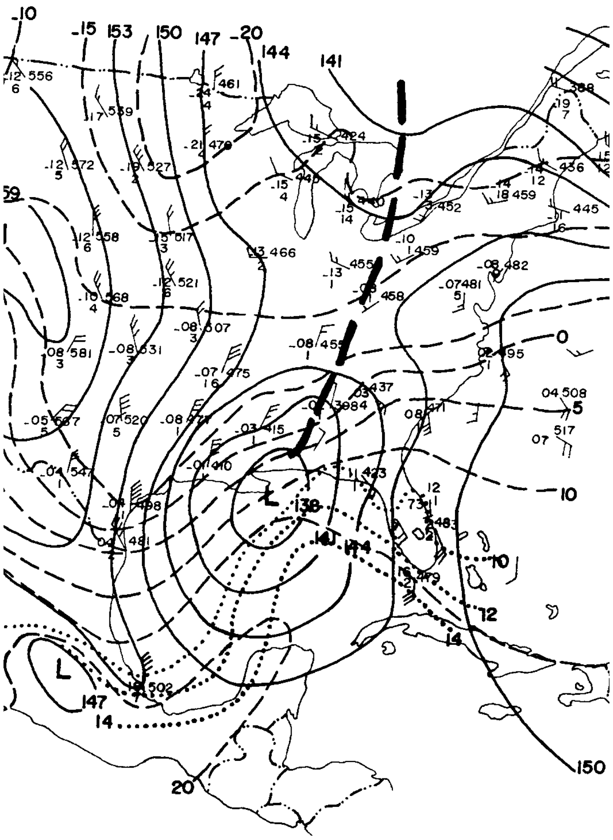

FIG. 4. Same as Fig. 2 except for 85 kPa. Isodrosotherm (dotted line) every 2°C over the eastern Gulf and Florida.

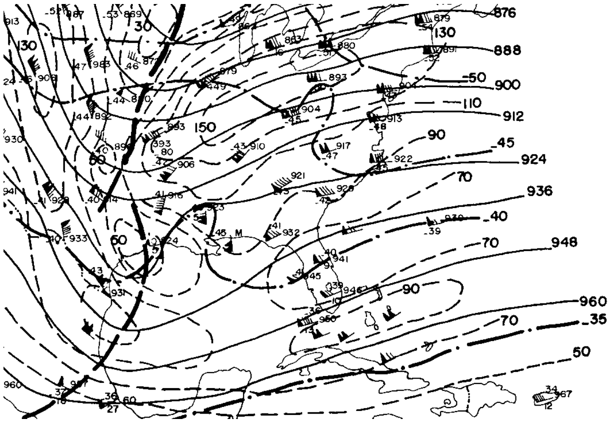

FIG. 5. Same as Fig. 2 except for 30 kPa. Isotachs (dashed) every 20 kt, isotherms (dotted and dashed), and geopotential heights (solid) every 12 dam.

airstream from the south and with the cold and relatively moist airflow from the north. Thus, a strong moisture gradient to the south and a strong baroclinic zone to the north existed at the edges of the hot and dry air plume from the Mexican Plateau. Thus, this led to a narrow dry intrusion from the Mexican gulf coast eastward. As a result, convective instability and conditions favorable for intensification of downdrafts in cumulonimbus and consequently for the development of SLS were intensifying east of 90°W, where the hot and dry air advected over the moisture axis in low levels.

The third necessary ingredient, the lifting mechanism, was provided by the leading, strong southern short-wave trough. As shown by Nielsen and Igau (1993), the squall line was clearly a prefrontal squall line across the entire Gulf of Mexico, and this behavior was maintained across Cuba. The squall line preceded the polar front passage by several hours, producing only wind shifts from S to SW and no significant change in temperatures. Light rain showers and a wind shift to NW with a rapid drop in temperature characterized frontal passage. Typical pressure changes were recorded by barographs in western Cuba. The pressure trace of Union de Reyes, Matanzas, (78327) (Fig. 10) shows the pressure jump associated with the squall line (A) and the rapid rise that followed polar frontal passage (B).

Doswell (1982) also suggests that two primary factors favoring development of severe weather are convergence in low levels and moisture supply (i.e., pronounced moisture convergence). The analysis of the moisture convergence field at the surface, objectively performed, with a grid length of 2.5°, is shown in Fig. 11. It is evident that a moisture convergence zone lies over the northeast Gulf of Mexico and the western half of Cuba and surrounding waters. Since this variable is highly scale dependent, it might be expected that on a smaller scale, with a higher data density than was available for this study, values should be considerably greater. Thus, one may assume that these values indicate substantial moisture convergence over the affected area, favorable to SLS development.

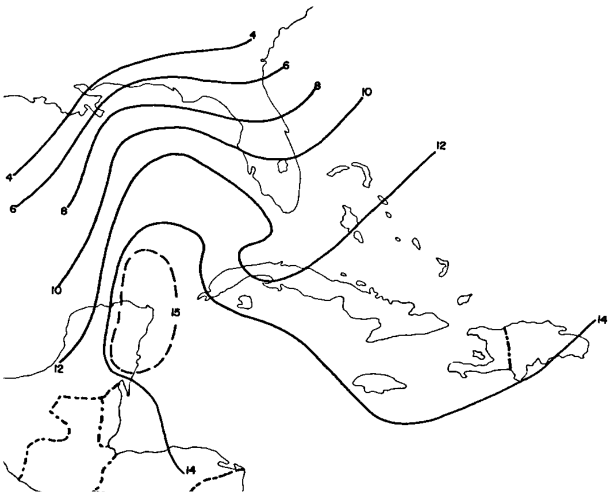

FIG. 6. Mixing ratio (q) analysis at surface for 0000 UTC 13 March. Contours every 2 g kg^{-1}.

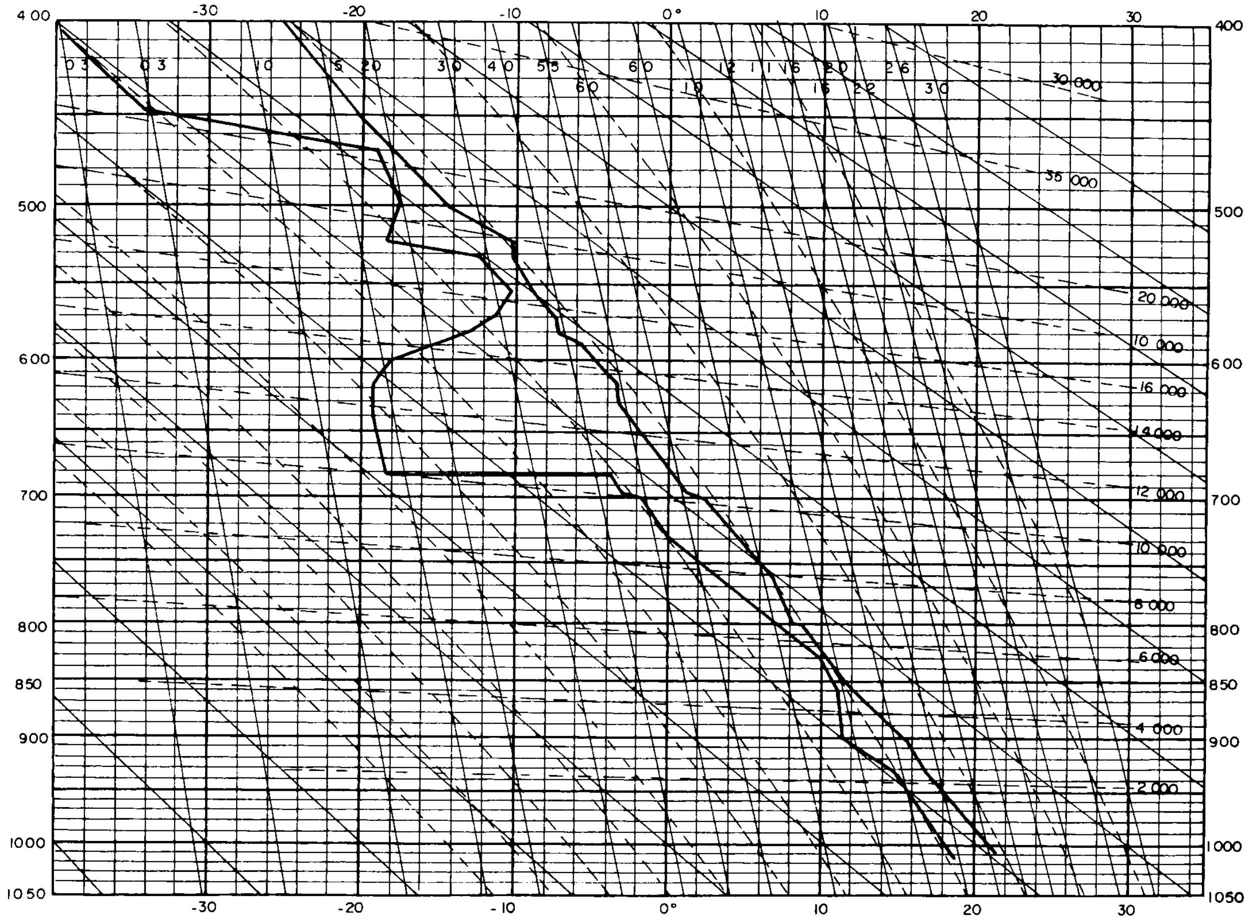

FIG. 7. FDMCM Stuve diagram of sounding for 0000 UTC 13 March 1993 at Cape Canaveral (74794).

All of the elements identified in this section are illustrated in a composite chart (Fig. 12). The relative positions of the surface low, fronts, and jets resemble the idealized pattern of a midlatitude synoptic-scale situation favorable for development of SLS, including supercell thunderstorms and tornadoes (Barnes and Newton 1986). However, in this case the role of the SJ does not seem significant since it was located far to the south. Although the exact positioning of the leading edge of hot and dry air in midlevels is difficult to determine, it is likely that the intrusion of this current was a key element in the SLS development over the eastern Gulf of Mexico, Florida, Cuba, and the extreme northwestern Caribbean. Local conditions over the Yucatán Peninsula and adjacent waters contributed to the rapid southward growth of the line from 0000 UTC 13 March.

In brief, the synoptic environment was highly favorable for the development of very deep convection and related severe weather on the eastern side of the Gulf of Mexico at 0000 UTC 13 March 1993, including most classical elements associated with severe weather development common to midlatitudes during winter or spring. However, because of the latitude, available humidity in the lowest layer was higher than usual for the time of year, and the air was considerably unstable ahead of the squall line.

3. Development and structure of the squall line

a. Formation

The squall line appeared to form by a back-building process (Bluestein and Jain 1985). Building to the south was rapid after the squall line passed to the north of the Yucatán Plateau, such that when the line reached western Cuba it already extended into the northwestern Caribbean Sea and its southward growth continued for several hours. At 0000 UTC 13 March the environment into which the squall line was moving was typical of that associated with the back-building process. The Key West, Florida, hodograph was sharply curved with anticyclonic veering in levels below 70 kPa, as shown in Fig. 13. It is similar to the mean sounding for this type of squall line (Bluestein and Jain 1985).

Another typical characteristic of back-building lines, also described by Bluestein and Jain (1985), very evident in this case, is the displacement by virtue of continuous cell propagation, as also suggested by Fig. 13. The discrete propagation vector had an almost null value. Conversely, the continuous propagation vector at the height of 2 km reached 27 m s^{-1} in the opposite direction to the surface wind. The individual cells were moving from 257° at 28 m s^{-1}, while the flow in the cloud layer was from 242° at 34 m s^{-1}.

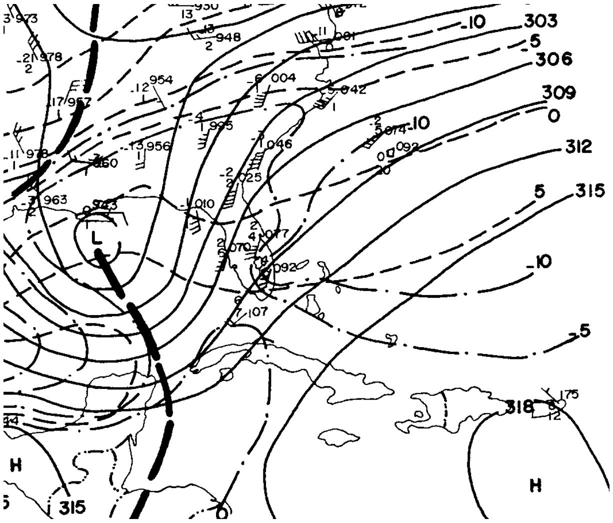

FIG. 8. Same as Fig. 2 except for 70 kPa. Isodrosotherm (dotted and dashed) every 5°C over the Gulf of Mexico and adjacent areas.

b. Structure

The Havana radar (MRL, 10 cm) plan position indicator sequence from 0500 to 1000 UTC 13 March indicated that the squall line consisted of a line-echo wave pattern (Nolen 1959) with a series of bow echoes (Fujita and Caracena 1977). A similar structure was observed by radars over Florida (STORM DATA 1993). These echoes were very persistent and intense. The two bow echoes that affected western Cuba and the Isle of Youth–central Cuba retained their comma shape and identity during the entire 5 h they were observed by Havana radar (Fig. 14). The echoes reached heights up to 16.3 km and intensities as high as 70 dBZ during the period of maximum intensity over the westernmost provinces of Cuba.

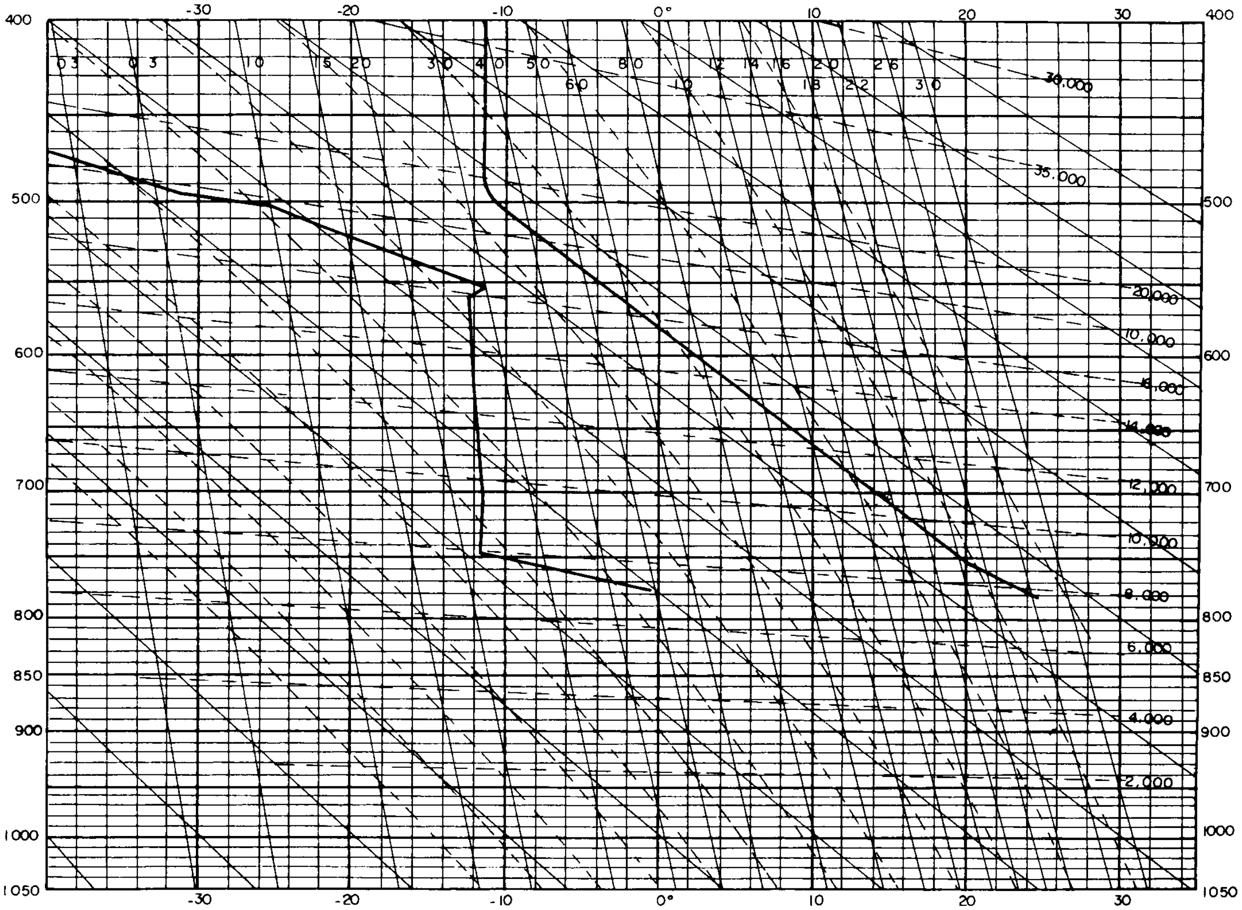

FIG. 9. Same as Fig. 6 except at Mexico City (76679).

The Key West hodograph (Fig. 13) might also be considered typical for supercells. In fact, in the lowest layer (specifically at the surface) a wind with an easterly component is present resembling soundings associated with supercells, and the cell motion is clearly to the right of all winds shown, also characteristic of supercells. As stated by Johns and Doswell (1992), supercell circulations ''can occur within a broad range of storm structures.'' Several tornadoes were observed in Florida north of 27°N. One of the tornadoes attained F3 intensity, and the other traversed a 30-mile-long path. This second event was within the range of the Melbourne, Florida, Doppler radar and exhibited a mesocyclone circulation. The tornadoes were apparently related with supercell thunderstorms embedded in a large bow echo that rapidly moved over Florida (STORM DATA 1993). Farther to the south, over south Florida and Cuba, no tornadoes occurred but very strong damaging winds were recorded.

Storm-relative helicity (*H*) (Davies-Jones et al. 1990) is considered a crucial parameter for supercell thunderstorm occurrence. At 0000 UTC 13 March high *H* values were indicated by Florida soundings in relationship with later observed storm motions. In particular, *H* computed from the Key West sounding for the bow-echo movement over Cuba reached 402 $m^2 s^{-2}$. Therefore, the squall line structure resembles those corresponding to the ''dynamic pattern'' described by Johns (1993) with the parameters that promote mesocyclone development sufficiently strong to produce isolated supercell circulations associated with a portion of the bow-echo structure.

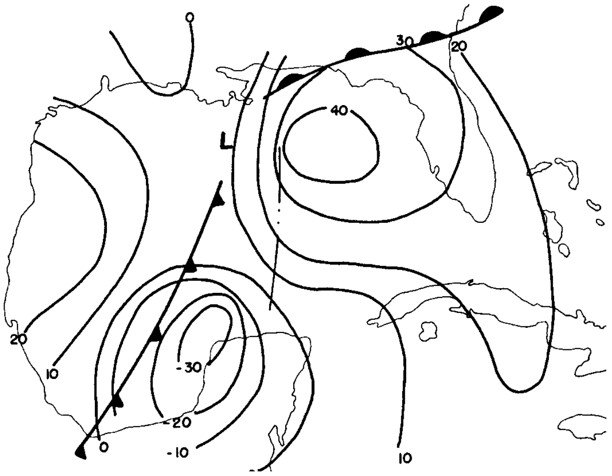

FIG. 11. Surface moisture convergence in g kg^{-1} h^{-1} times 10 for 0000 UTC 13 March 1993.

4. Storm-scale analysis

Figure 15 shows the geography, topography, and key locations of the area of western and central Cuba affected by squall line. The direction, speed, and time of the highest gusts recorded during squall line passage are shown in Fig. 16. Except for the stations of Bauta and Santiago de las Vegas (discussed later in this section), there were no indications that wind gusts were associated with mesoscale cyclones at the surface but rather with a typical pressure jump line, clearly reflected by 0.2–0.5-kPa pressure rises in 15-min periods on the barograph traces (as shown in Fig. 10). The 25 m s^{-1} threshold value for an SLS was greatly exceeded at most of the meteorological stations. Thus, most of the individual local storms in the line fit the SLS category. Stations with gusts under 25 m s^{-1} were located near the southern end of the northern bow echo.

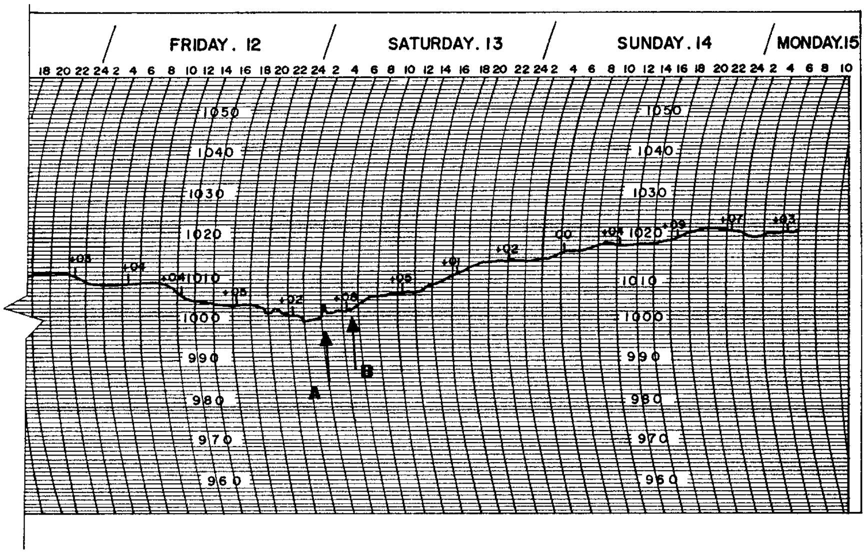

FIG. 10. Barograph trace for 12–14 March 1993 at Union de Reyes, Matanzas. Pressure jump line passage, A. Polar front passage, B.

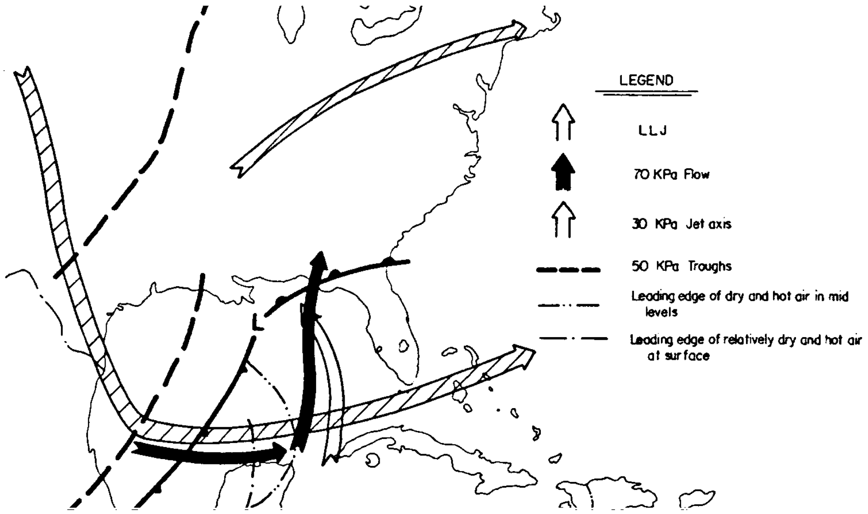

FIG. 12. Composite chart for 0000 UTC 13 March 1993.

A research team from the Institute of Meteorology of Cuba, led by the first author, did an on-site evaluation and analysis of the most damaged area in relation to meteorological characteristics of the phenomenon. A large number of eyewitnesses in the Havana, Havana City, and Matanzas provinces were interviewed. Valuable information was also gathered from professional and amateur meteorologists residing in the damage area, who also examined the damage immediately after the storms passed by.

Damage was assessed using the Fujita scale (*F*) and also the TORRO scale (Elsom and Meaden 1982). The use of both scales allowed for more detailed assessment of damage patterns displayed by trees and different types of man-made construction. The results of this assessment, in terms of *F* scale, are presented for the Havana and Havana City provinces (Fig. 17), where

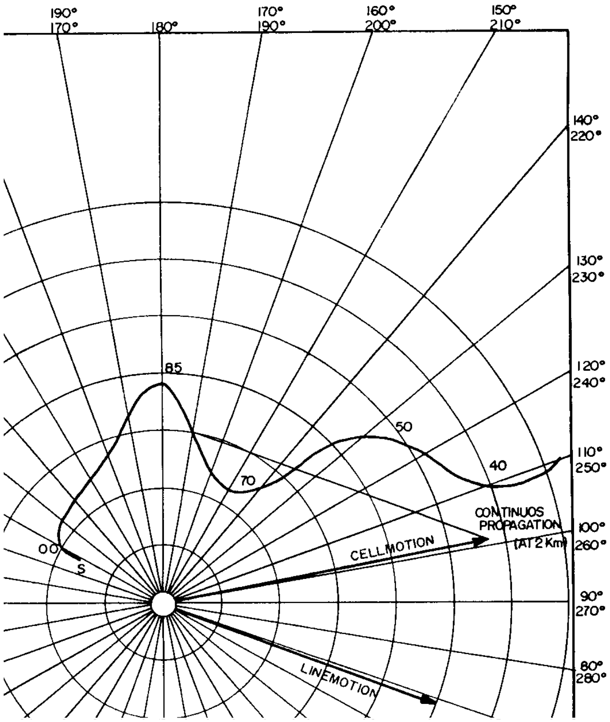

FIG. 13. Hodograph of Key West for 0000 UTC 13 March 1993. The vectors related with cell and squall line motions, and continuous propagation are shown. Rings every 5 m s^{-1}.

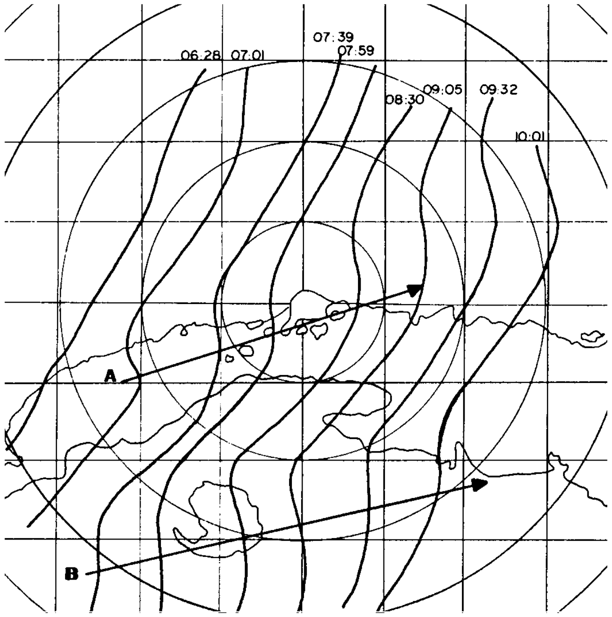

FIG. 14. Successive positions of the prefrontal squall line leading edge. UTC time is indicated at the northern end of the Havana radar image of the squall line. Trajectories of most intense portions of both northern (A) and southern (B) bow echoes are indicated.

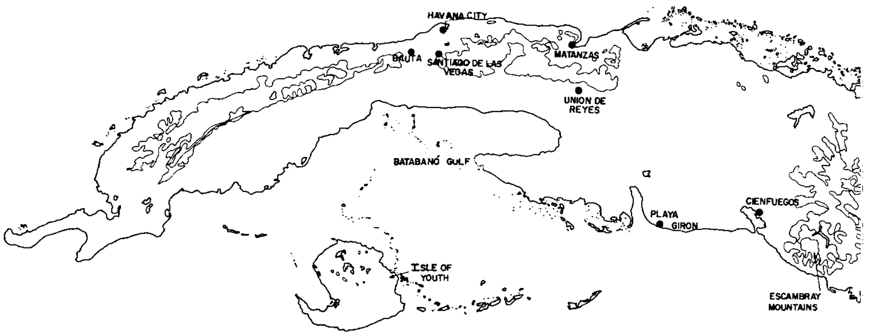

FIG. 15. Key locations over western and central Cuba. Contours indicate elevation every 100 m MSL.

the most intense damage took place and where the meteorological network (Fig. 18) allows for meteorological field analyses on scales near that of storm scales. A swath of F2 damage 10–20 km wide was observed. Maximum estimated gusts ranged up to 60 m s^{-1}. Several engineering calculations agree with these estimated values. This damage occurred between 0730 and 0900 UTC.

For the purpose of determining the type of mesoscale phenomenon responsible for this main damage swath, mesoscale analyses, 15 min apart from 0745 to 0845 UTC, were carried out. An intense mesoscale system is shown over the western portion of the Havana province at 0815 UTC (Fig. 19). The strongest element was a mesocyclone, only 5 km in diameter, with a minimum pressure of 99.9 kPa. The pressure gradient in its central zone reached 0.1 kPa km^{-1}. This feature was followed by an intense mesohigh (more than 100.9 kPa), also with very sharp pressure gradients. The combination of both of these features explains the very strong SW winds that swept the most damaged area. Meanwhile, the presence of the mesohigh explains less strong west wind gusts recorded to the south, because of the resultant weakened pressure gradient.

No evidence of a wind circulation related to the mesocyclone appeared in the damage pattern, but strong convergence was present according to recorded winds at Bauta and Santiago de las Vegas. Barnes (1978) also found this strong convergence in a mesocyclone associated with the Oklahoma storm of 29–30 April 1970 in its early stage of development. This strongly convergent but nonrotational characteristic might be due to the system's rapid translation. To obtain additional insight, storm-relative winds were calculated and plotted on time–space conversion lines passing through the Bauta and Santiago de las Vegas weather stations (Fig. 20). A marked inflow toward the mesocyclone in the Bauta region is observed, while in Santiago de las Vegas relative winds are more intense after the mesocyclone has passed. Thus, the wind increase at Bauta was directly related to the mesocyclone, while Santiago de las Vegas experienced a downburst.

The radar picture at 0759 UTC (Fig. 21) shows a well-defined bow echo, with the comma head very close to the north coast of Cuba and its southern end in Batabano Gulf. The most severe portion was over the western Havana province, where an indentation with a weak-echo region existed, surrounded by a high-

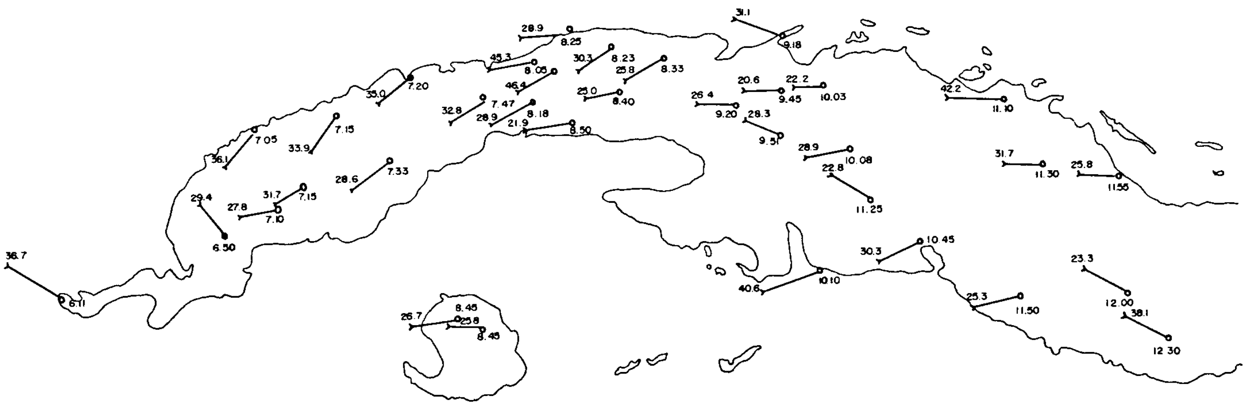

FIG. 16. Highest convective gust observed at Cuban meteorological stations on 13 March 1993. Gusts in m s^{-1}. UTC occurrence time is indicated.

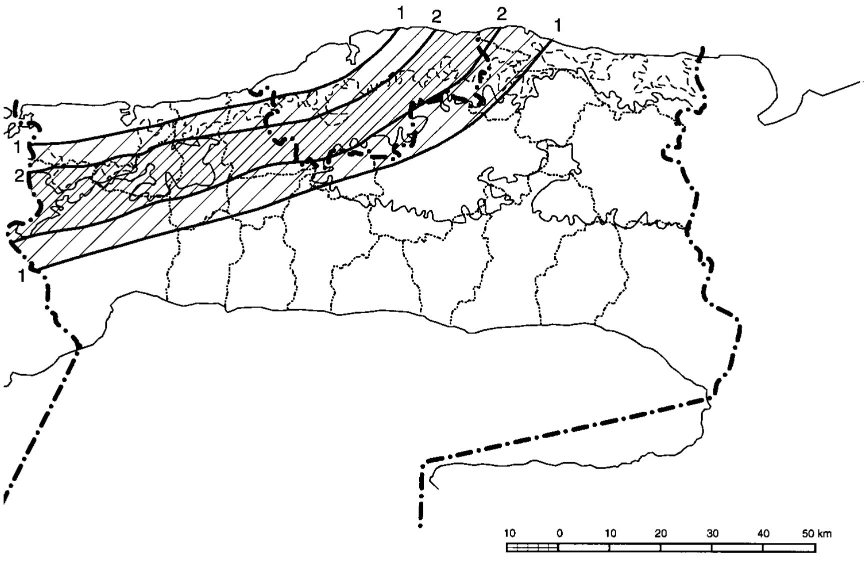

FIG. 17. The *F*-scale assessments for damage experienced over the Havana and Havana City provinces.

reflectivity area, suggesting the presence of extreme inflow and a mesocyclone at the leading edge of the bow echo. Stumpf and Burgess (1993) reported the presence of mesocyclones related with bow echoes in a similar location. The position of indentation corresponds very well with the estimated location of surface mesocyclone at 0800 UTC, west-southwest of Bauta. Strong winds affected Bauta before any rain was recorded. Thus, the major damage was attributable to the mesocyclone of a supercell embedded in the bow-echo structure. There also appears to be a rear-inflow notch (or weak echo region) to the south of the inflow notch (Fig. 21), and it was likely associated with the most intense downburst winds (Przybylinski and Decaire 1985), as observed in Santiago de las Vegas, where strong winds followed a hail and rain episode.

Another area of very significant damage was related to the bow echo that affected the Isle of Youth and afterward reached Playa Giron and Cienfuegos City, where damaging gusts corresponding to F2 scale (in excess of 50 m s^{-1}) were reported. In Cienfuegos City damage was very similar to that found in the destruc-

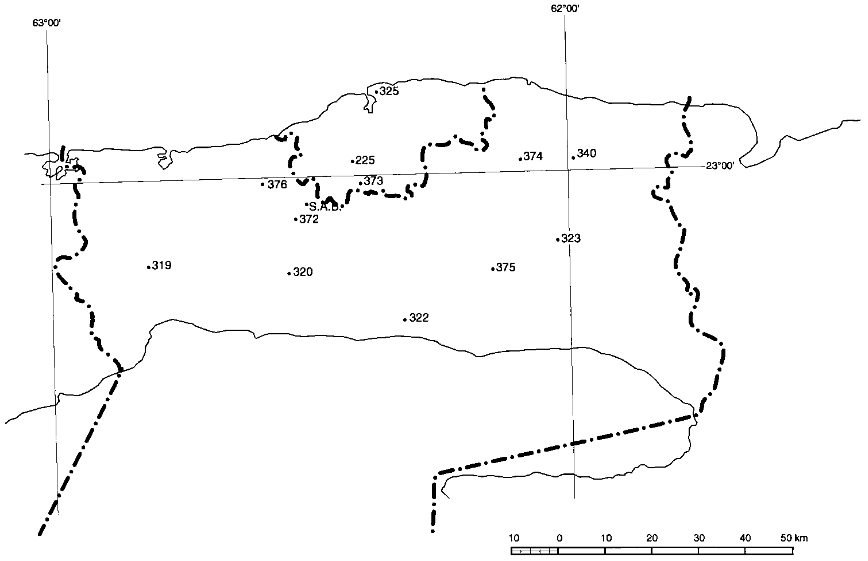

FIG. 18. Locations of the meteorological stations of the Havana and Havana City networks. Block 78 numbers are indicated.

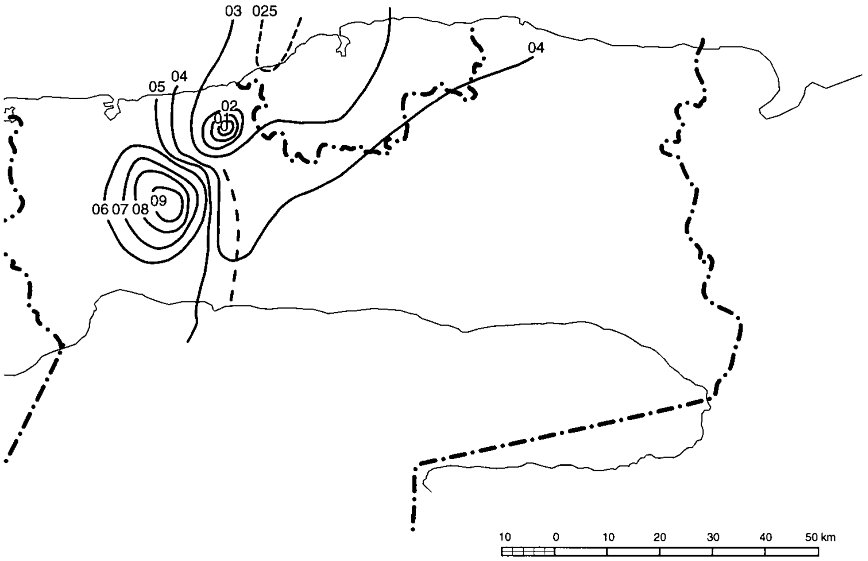

FIG. 19. Mesoscale pressure analysis every 0.1 kPa for 0815 UTC 13 March 1993 over the Havana and Havana City provinces.

tion swath in the Havana province. There are no indications of mesocyclone development in the records of wind and pressure of meteorological stations in this area. The strongest damage in the Isle of Youth was located in the extreme northeast portion of the island. Apparently, the strongest portion of the second bow echo produced a family of very strong downbursts.

The extent of the area covered by 26 m s^{-1} gusts appears to include all of central and southern Florida and all of the western and the northern coast of Cuba. The southernmost intense damage swath in Cuba (Isle of Youth to Cienfuegos City) appears to be connected to the aforementioned 26 m s^{-1} area. Therefore, the large-scale event could be considered a ''serial derecho'' (Johns and Hirt 1987).

5. Conclusions

An intense, prefrontal squall line formed over the Gulf of Mexico on the afternoon of 13 March 1993 in a very favorable synoptic environment related to a well-defined polar outbreak and strong cyclogenesis.

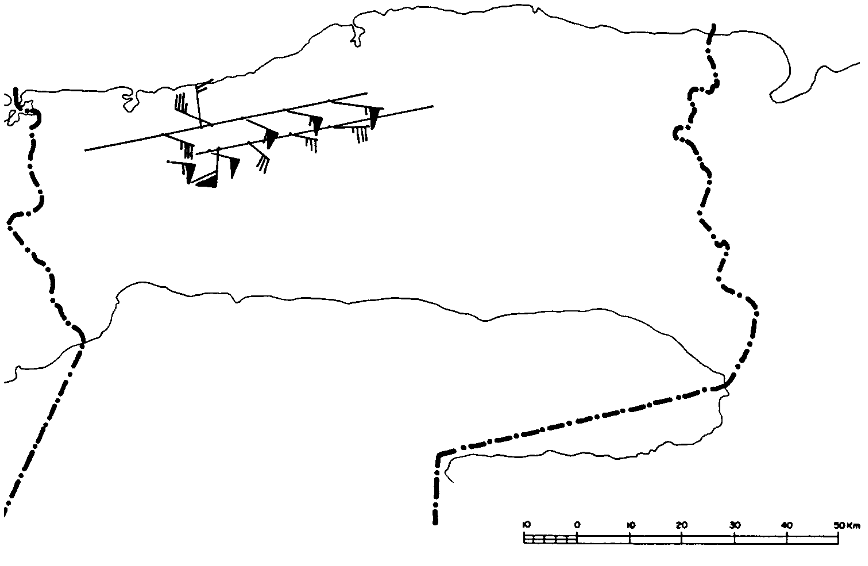

FIG. 20. Storm-relative winds at 0800 UTC 13 March 1993. The upper section corresponds to the Bauta meteorological station, and the lower section to the Santiago de las Vegas meteorological station. Winds with one flag, full-barb, and half-barb denote 25, 5, and 2.5 m s^{-1}, respectively.

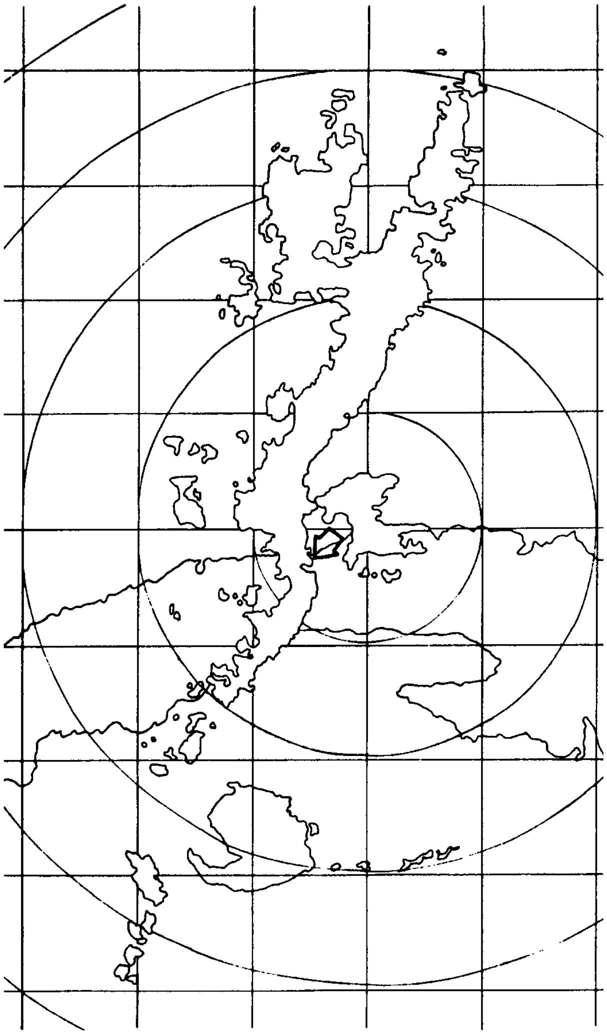

FIG. 21. Digitized Havana radar reflectivity depiction for 0759 UTC 13 March 1993. The arrow denotes possible mesocyclone, inflow region shown as an indentation at the leading edge of the developing bow echo.

The event exhibited similar characteristics with the classic Great Plains tornado outbreak (Barnes and Newton 1986). Nevertheless, the structure of squall lines resembles rather than corresponds to the dynamic pattern described by Johns (1993). Apparently, this case corresponds to a blend of the two types of synoptic patterns. Further, the differences of both patterns appear to be rather subtle. Such events may affect the southern Great Plains and gulf coastal states but rarely hit Cuba.

Significant differences from the most common patterns and behavior reported in other severe weather outbreaks in Cuba in the cool season (Córdoba and Alfonso 1992) were found:

- The cold front was strong and well defined, related to a deep long-wave trough. Short-wave troughs in the NBPJ and SBPJ came into phase.
- There was a nonoccluded low center that developed and moved rapidly.
- The role of STJ in the process was unclear, since the line formed far north of the STJ axis.

Necessary conditions for deep convection were present, and moisture convergence showed its effectiveness to indicate the areas where SLS development should be expected. Due to the geographical location, moisture availability was high for the time of year.

The squall line was a back-building type and formed in a very favorable environment for such events. A possible explanation for the rapid expansion of the prefrontal squall lines, frequently observed in the southeastern Gulf of Mexico, can be given. The Yucatán Plateau is a source of very warm and dry air, extending into the Gulf of Mexico when the steering flow is from south to southwest. This situation seems to have some correlation with the arrival in Texas of dry air formed over the northern Mexico Plateau. Thus, it might be analogous to the development of the dryline frequently observed over the southern plains of the United States.

Additionally, in this case, dry, hot, and high-lapse-rate air from the Mexico Plateau was advected eastward by strong winds in the layer 70–50 kPa from its source across the Gulf of Mexico. The movement of this air current at midlevels over the eastern gulf was considered a key element for the development of the LS that affected Florida and western and central Cuba.

The most intense phenomena were associated with bow echoes, with their central portion characterized by quasi-linear, very intense winds from the southwest. Further, the most significant damage in the Havana province was along the track of a mesolow circulation embedded in the northern part of the bow echo. A very intense pressure gradient was associated with the mesocyclone circulation and with its interaction with a powerful mesohigh. The intensity of the mesocyclone may be considered strong, and the helicity value of Key West ($402\ \mathrm{m^2\ s^{-2}}$) appears to support this assessment.

Based on the National Meteorological Center's Nested Grid Model forecasts for 24 and 48 h, and on the previous knowledge acquired in Cuba regarding prefrontal squall line formation and displacement over the Gulf of Mexico, meteorologists at the Forecast Center of Matanzas issued a special warning on the possible occurrence of the squall line at 2000 UTC 12 March. This warning had a lead time of up to 13 h, since the squall line reached Matanzas at 0900 UTC of the following day.

The reported damage was the largest ever attributed to a squall line in Cuba, and the extent of the damage area was greater than ever before. However, the local severe weather phenomena were not as intense as those observed in other cases.

Acknowledgments. This work is part of the research program ‘‘Very Short-Range Forecast of Dangerous Phenomena Related with Convective Clouds’’ of the Institute of Meteorology, Ministry of Science, Technology and Environment, Cuba. We are very grateful to Dr. Robert Maddox, Dr. Robert Johns, and Dr. Oswaldo García for their interest, comments, and suggestions and for providing us with valuable materials. Dr. Maddox also assisted by making the drafting facilities of NSSL available to us. We would also like to express our thanks to Dr. John P. Monteverdi for his encouragement and support during the reviewing process of the manuscript. Jorge Rodriguez gave drafting assistance.

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