AN OVERVIEW OF A STRONG WINTER LOW IN THE GULF OF MEXICO 12–13 MARCH 1993

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Abstract

Rapid and intense cyclogenesis occurred during 12–13 March 1993 in the northwest Gulf of Mexico. The event was the result of a baroclinic zone and an anomalous sea-surface temperature field combining with a "classic" upper-level synoptic pattern. The upper-level pattern displayed vigorous dynamics such as short-wave phasing and negative tilting, dramatic pressure height falls, upper-level jet placement and polar air intrusion. The effects in the marine boundary layer were atypical as anomalous warm eddies in the northwest Gulf of Mexico acted as heat sources for the baroclinic system.

The extratropical cyclone developed with force and inflicted major damage to the Gulf Coast area. Quickly after the storm developed it was predicted by many to be the "Storm of the Century" for the East Coast of the United States.

1. Introduction

During the period 12–13 March 1993, a combination of upper-level dynamics and an existing baroclinic zone in the western Gulf of Mexico produced an intense extratropical cyclone. This system was comparable in strength to a Category 1 hurricane, and was dubbed by many as the "Storm of the Century." Along the storm's path winds reached 70 kt, generating seas more than 25 ft high, and producing storm surges more than 10 ft along parts of the northeast Gulf Coast (Fig. 1). This storm system was also significantly enhanced by a southward moving cold air outbreak. The result was unusually heavy snowfall and extremely cold temperatures over the Gulf Coast States. Though a limited climatology investigation was done, the combination of upper-level dynamics and air-sea interactions produced pressure falls and storm central pressures not observed for an extratropical cyclone in more than ten years (Johnson et al. 1984).

This paper will provide an overview of the synoptic scale and marine boundary layer features during this storm's development. The performance of the National Weather Service (NWS), National Meteorological Center's (NMC) models will also be discussed as the storm developed and traveled across the Gulf of Mexico. Lastly, storm impact over several Gulf Coast States and the northern Gulf of Mexico will be mentioned.

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2. Synoptic Features

At 0000 UTC on 12 March, the southern stream of the polar jet (110 kt) was progressing southward over Utah and Arizona into Mexico. During this same time, a subtropical jet was observed over the northern Gulf of Mexico and northeast Florida (Fig. 2a). The 500-mb pattern showed a series of short-wave troughs and associated vorticity maxima (Fig. 2b). Two short waves were significant. One was entering Wyoming and was associated with a strong surge of cold air ($-40°C$) at 500 mb; the second extended from Colorado and New Mexico south into Mexico. An 850-mb low (not shown) developed about this time over the Sierra Madre, south of Del Rio, Texas.

The stationary front over the northern Gulf of Mexico had persisted for several days (Fig. 2c). The Gulf surface analysis done at the NWS Forecast Office at Slidell, Louisiana at 0000 UTC (not shown) indicated tight packing of isotherms across the northwest Gulf in the warm sector of the stationary front. A strong baroclinic zone was established over this area with moist, warm maritime tropical air (temperatures ranging from 20 to 24°C and equivalent potential temperature (θ *e*) approximately 324 K) over the northwest Gulf and drier continental polar air moving southward into north Texas (temperatures ranging from 10 to 12°C and θ *e* approximately 316 K). Over the northwest Gulf coastal waters, east to southeast winds of 30 kt and 5–7 ft seas were occurring.

By 1200 UTC on 12 March, the axis of the upper-level trough over Colorado shifted slightly southeastward, but remained oriented southwest-northeast. The polar jet now extended from Idaho and the Rocky Mountains southeastward and further south into Mexico (Fig. 3a). Two other wind maxima were observed. One jet extended northeastward across the Ohio Valley and eastward off the Mid-Atlantic States. An apparent subtropical jet extended from lower Mexico across Cuba to the southern tip of Florida. NMC's initialized Nested Grid Model (NGM) and ETA model gridded data for this period (not shown) indicated a maximum 250-mb divergence value of 60 (6×10^{-5} s^{-1}) extending over the northwest Gulf as the jet max rotated northeastward towards the Louisiana coast. High divergence values were forecast to continue over the Gulf Coast States between Mississippi and Florida for the next 12 hours. As the 250-mb jet recurved, the two significant 500-mb short waves continued to progress downstream. The vorticity maximum associated with the southern short-wave trough had increased in intensity over 12 hours and was moving off the Mexican Plateau into the Gulf (Fig. 3b). At the 850-mb level (not shown), the closed low was also just east of Brownsville, Texas.

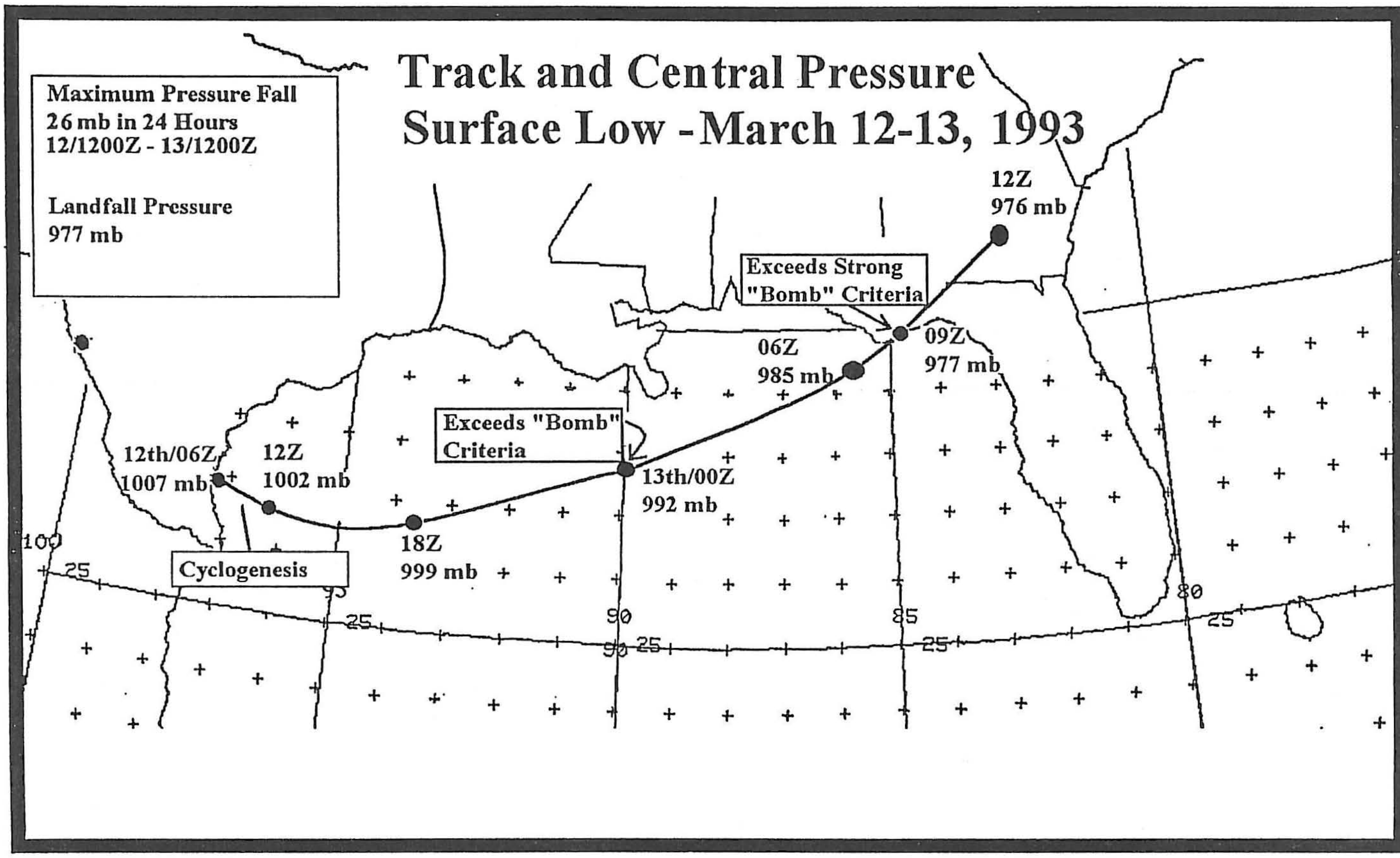

Fig. 1. Surface low center track across Gulf of Mexico.

Surface cyclogenesis became evident at 1200 UTC when a closed 1002-mb low moved into the Gulf from the Texas coast (Fig. 3c). Southeast winds near the low were approaching 40 kt, with seas of 7–9 ft in the northwest Gulf of Mexico. The strength of the surface cold outbreak advancing southward was well indicated with cold 1000-mb temperatures moving south across the midwest and a 1044-mb high center moving southward over Wyoming.

By 0000 UTC on 13 March, the 250-mb jet axis had shifted east with discontinuous segments on either side of the upper tropospheric trough. Jet wind speeds had increased to more than 140 kt over the Ohio Valley and Mid-Atlantic States (Fig. 4a). The subtropical jet was depressed farther south and was difficult to distinguish without satellite observations. Over the northern Gulf of Mexico the southernmost, 500-mb, shortwave trough deepened, with a doubling of the vorticity maximum from 12 hours earlier. An intense area of 500-mb PVA was indicated over the northeast quadrant of the Gulf of Mexico (Fig. 4b). Upstream in the northern trough axis, the second strong vorticity maximum continued advancing southward into north Texas, along with a reinforcing continental polar air mass. Cold 500-mb temperatures (−30°C) continued southeastward across Oklahoma and Texas. Modest height falls (7–10 dm) at the 500-mb level were noted during the preceding 24 hours over the lower Mississippi Valley and northern Gulf Coast. These height falls and cold-air advection, indicated the trough would continue to deepen and move.

Figure 4c shows a pressure fall of 10 mb in 12 hours (compared to Fig. 3c) associated with the surface low (992 mb at 0000 UTC on 13 March). Offshore oil rigs approximately 30 meters above the water surface on the northwest side of the low reported sustained winds near 70 kt. Sea heights increased to 15–20 ft over a large area of the northwest Gulf of Mexico. Minimum pressure at Moisant International Airport (MSY) in New Orleans reached 1003.6 mb, with winds around the metropolitan area gusting to 55 kt for several hours.

Twelve hours later, at 1200 UTC, the 250-mb trough (not shown) had a pronounced negative tilt, extending from Wisconsin southeast into the northern Gulf of Mexico. Winds at the 250-mb level moving out of the upper trough over northwestern Florida were 140 kt and continued north over the Ohio Valley, then northeastward into New England (Fig. 5a). The 500-mb trough was also negatively tilted with the main vorticity maximum over southern Georgia. A second maximum was located near the 500-mb trough south of the Mississippi coast (Fig. 5b). Cold air had continued southward into Arkansas and Mississippi. At 1200 UTC on the 13th, the surface low was over southeast Georgia with a pressure of 976 mb and the cold front was crossing Florida (Fig. 5c). During the previous 24 hours the storm's central pressure at the surface fell 26 mb.

When the bitter cold surge entered the nearly frictionless northern Gulf, the wind force showed incredible strength again. The northern Gulf of Mexico buoy data indicated northerly winds of 50–70 kt from 90°W eastward to Florida. Seas reached 30 ft at the middle Gulf of Mexico buoy 42001 (at 25.9°N, 89.7°W), and there were numerous buoy and C-MAN reports of 20–25 ft seas over the north-central and east Gulf of Mexico.

The advancing cold air and increased upward vertical motion (synoptic scale) were very intense over the southeast States especially from Alabama northeastward and contributed to

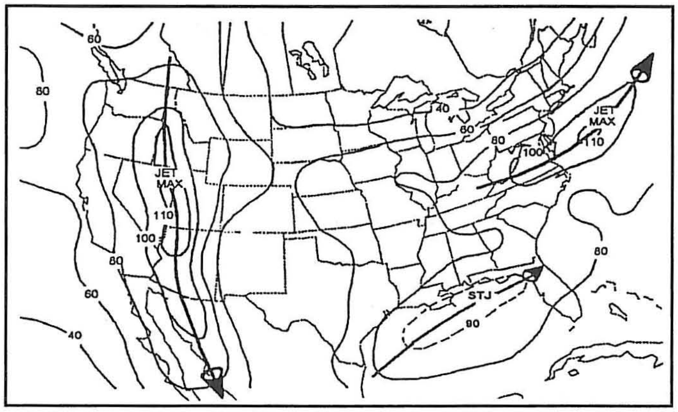

Fig. 2a. 250-mb isotachs (solid, kt) and jets (heavy solid) for 0000 UTC 12 March 1993.

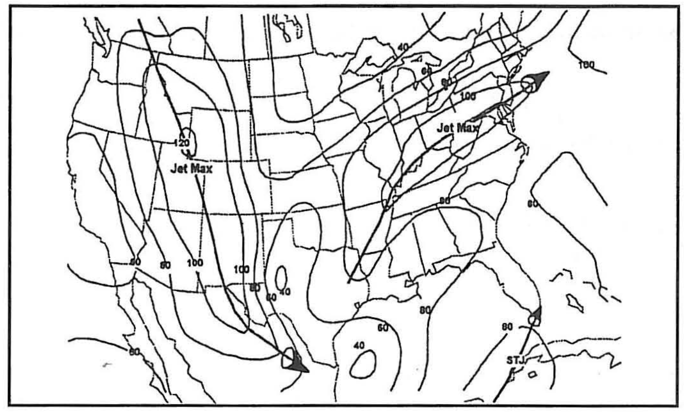

Fig. 3a. 250-mb isotachs (solid, kt) and jets (heavy solid) for 1200 UTC 12 March 1993.

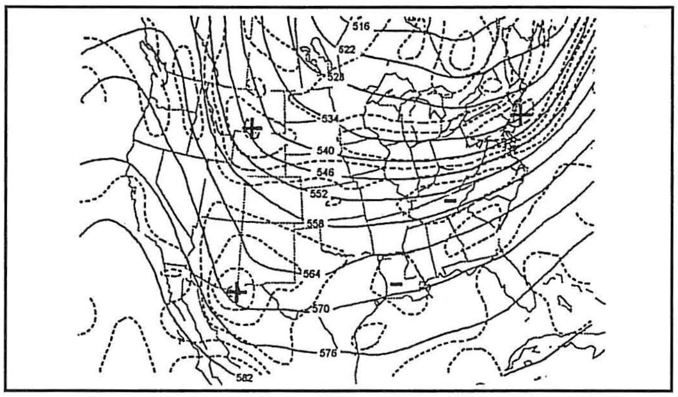

Fig. 2b. 500-mb heights (solid, dm) and vorticity pattern (dashed) for 0000 UTC 12 March 1993.

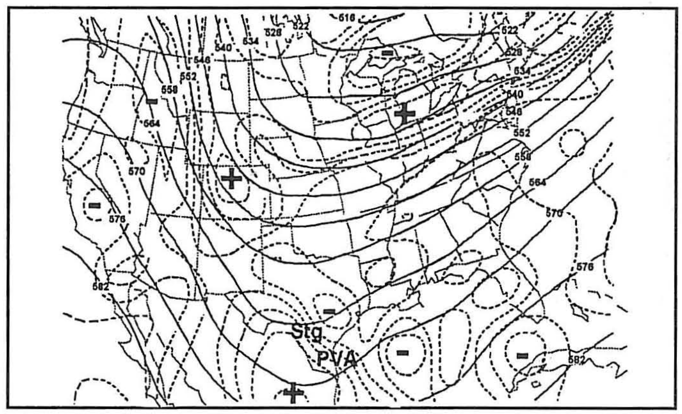

Fig. 3b. 500-mb heights (solid, dm) and vorticity pattern (dashed) for 1200 UTC 12 March 1993.

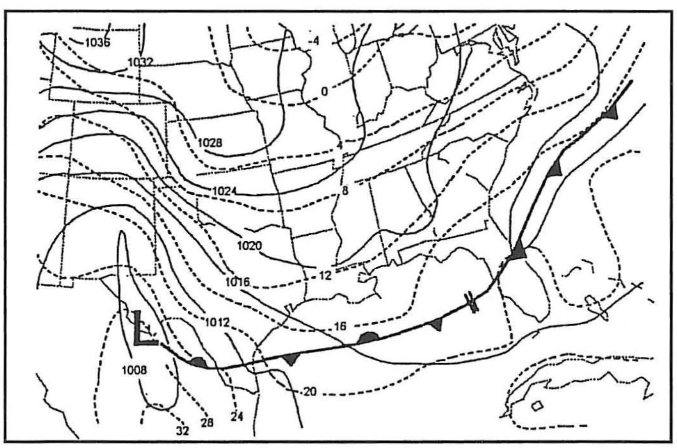

Fig. 2c. Surface fronts (heavy solid), isobars (solid, mb) and 1000-mb temperatures (dashed, °C) for 0000 UTC 12 March 1993.

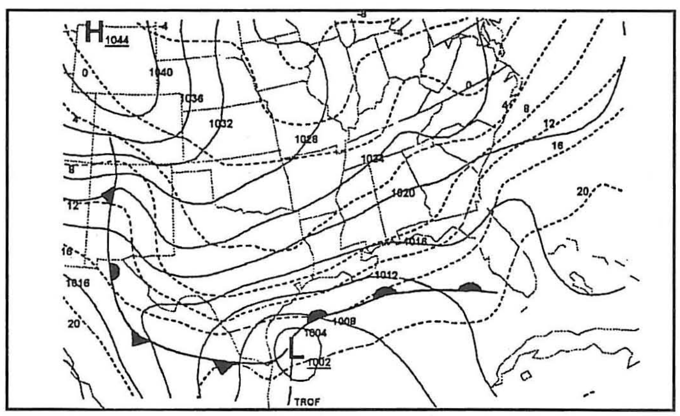

Fig. 3c. Surface fronts (heavy solid), isobars (solid, mb) and 1000-mb temperatures (dashed, °C) for 1200 UTC 12 March 1993.

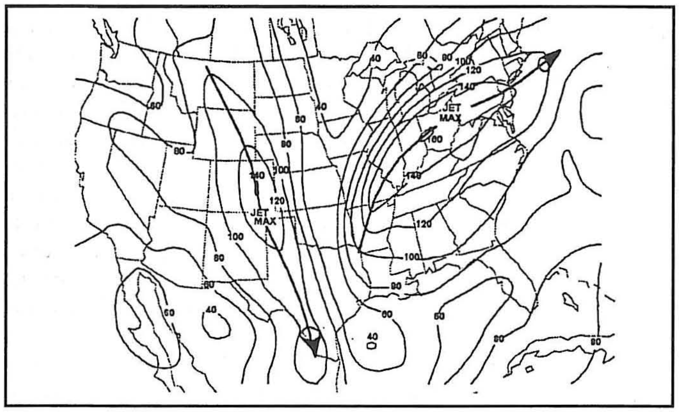

Fig. 4a. 250-mb isotachs (solid, kt) and jets (heavy solid) for 0000 UTC 13 March 1993.

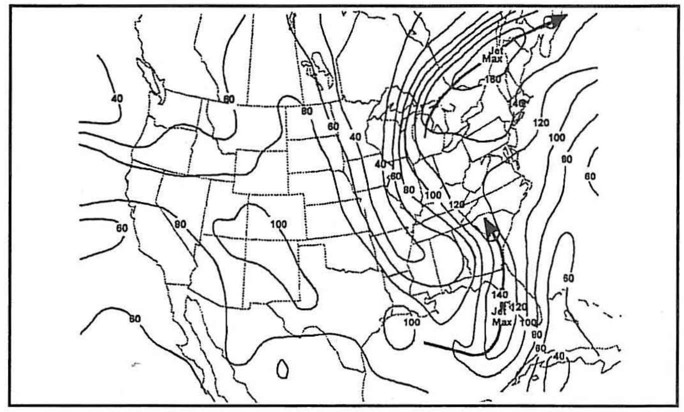

Fig. 5a. 250-mb isotachs (solid, kt) and jets (heavy solid) for 1200 UTC 13 March 1993.

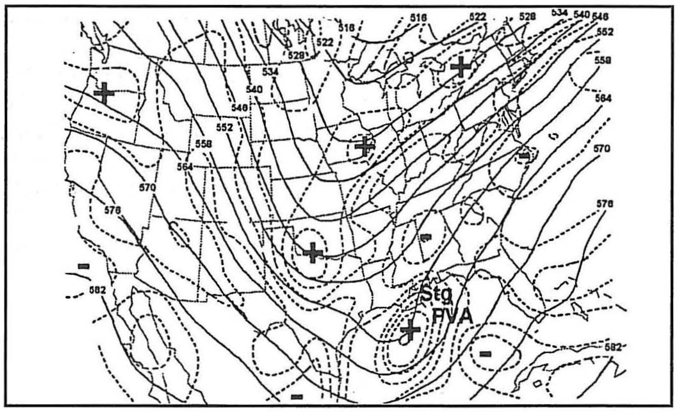

Fig. 4b. 500-mb heights (solid, dm) and vorticity pattern (dashed) for 0000 UTC 13 March 1993.

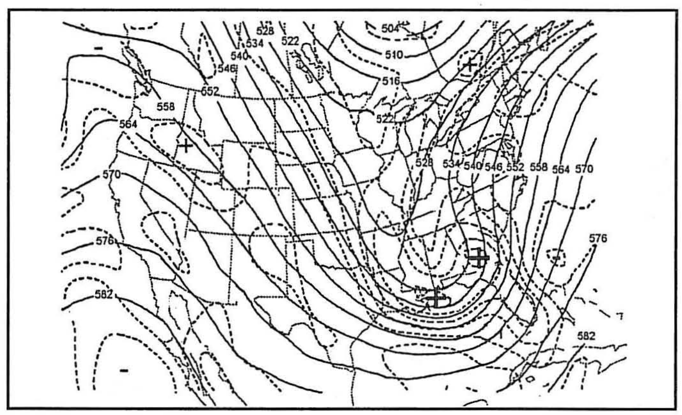

Fig. 5b. 500-mb heights (solid, dm) and vorticity pattern (dashed) for 1200 UTC 13 March 1993.

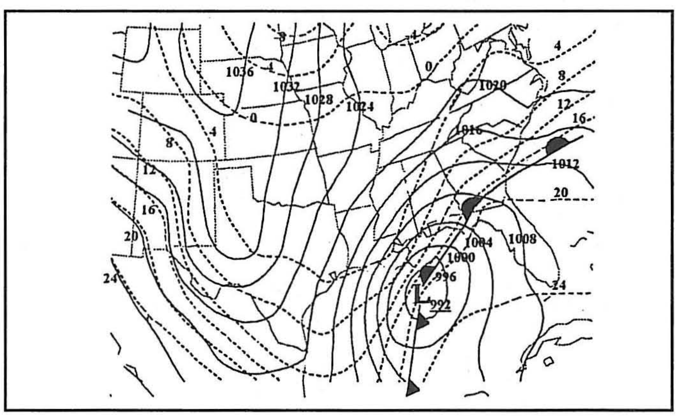

Fig. 4c. Surface fronts (heavy solid), isobars (solid, mb) and 1000-mb temperatures (dashed, °C) for 0000 UTC 13 March 1993.

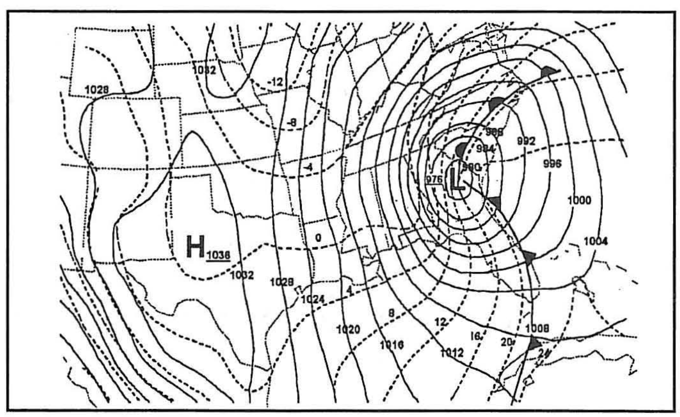

Fig. 5c. Surface fronts (heavy solid), isobars (solid, mb) and 1000-mb temperatures (dashed, °C) for 1200 UTC 13 March 1993.

record snows as well as mixed precipitation. As the 1000–500 mb layer thickness decreased significantly so did 500-mb heights (Fig. 5d). During the 12-hour period ending at 1200 UTC on the 13th, 500-mb height falls approaching 30 dm were observed from central Mississippi east to northern Florida (Fig. 5e). A time section from the Winnfield, Louisiana wind profiler also reveals the depth of the cold air and the backing of low-level winds with height (indicating cold air advection) (Fig. 5f).

An indicator often used to visualize the strength of such dramatic pressure falls is a barograph trace. Figure 6, taken from Apalachicola (AQQ), Florida which was just west of the storm track clearly reflects the intensity of this winter storm. A minimum pressure of 977 mb was recorded about 0240 LST as the storm center made landfall.

3. Air-Sea Interactions

Rapid cyclogenesis occurred over waters of the northwestern Gulf of Mexico and deepening of the system continued as the storm tracked across the northern Gulf of Mexico. Air-sea interactions, pertinent to storm development and intensification, are discussed in this section.

The smoothed sea surface temperature (SST) distribution on 9 March 1993, 3 days before storm formation, is indicated in Fig. 7a. During this time, Eddy Vasquez, a warm water eddy which had been shed from the clockwise Loop Current that is present over the southern Gulf of Mexico, was situated in the northwestern Gulf of Mexico near the Texas continental shelf (Walker 1993). Surface temperatures of 22–23°C were observed within the Eddy which measured 283 km x 335 km as revealed by NOAA-12 Advanced Very High Resolution Radiometer (AVHRR) data of 9 March 1993 (1353 UTC) (Fig. 7b). Although the Eddy had resided in the northwest Gulf of Mexico for several months, during the second half of February its surface temperature increased due to the advection of warmer water from another detached Loop Eddy, further south. The satellite image revealed that the Loop Current had intruded far north in the eastern Gulf of Mexico and was characterized by surface temperatures above 24°C. As a result, SSTs seaward of the continental shelf were 1–2°C higher than average. These higher temperatures extended over large portions of the northern Gulf of Mexico (Ford et al. 1988). The presence of anomalous warm water would have produced a less stable marine boundary layer through the processes of ocean to atmosphere fluxes of heat and water vapor.

In contrast to the Loop Eddies and Loop Current which are hundreds of meters deep and serve as reservoirs of heat and moisture for the overlaying atmosphere, shallow coastal and continental waters lose heat rapidly. The winter-time succession of cold-air outbreaks results in strong latent (evaporative) and sensible heat fluxes and active Ekman pumping. During this cyclogenesis event, continental shelf temperatures along the Texas coast were depressed below 17°C on 9 March. Louisiana coastal and continental shelf temperatures were even lower, particularly where the Mississippi and Atchafalaya Rivers discharge into the Gulf of Mexico. SSTs near the Mississippi River mouth were as low as 8°C (Fig. 7b). The close proximity

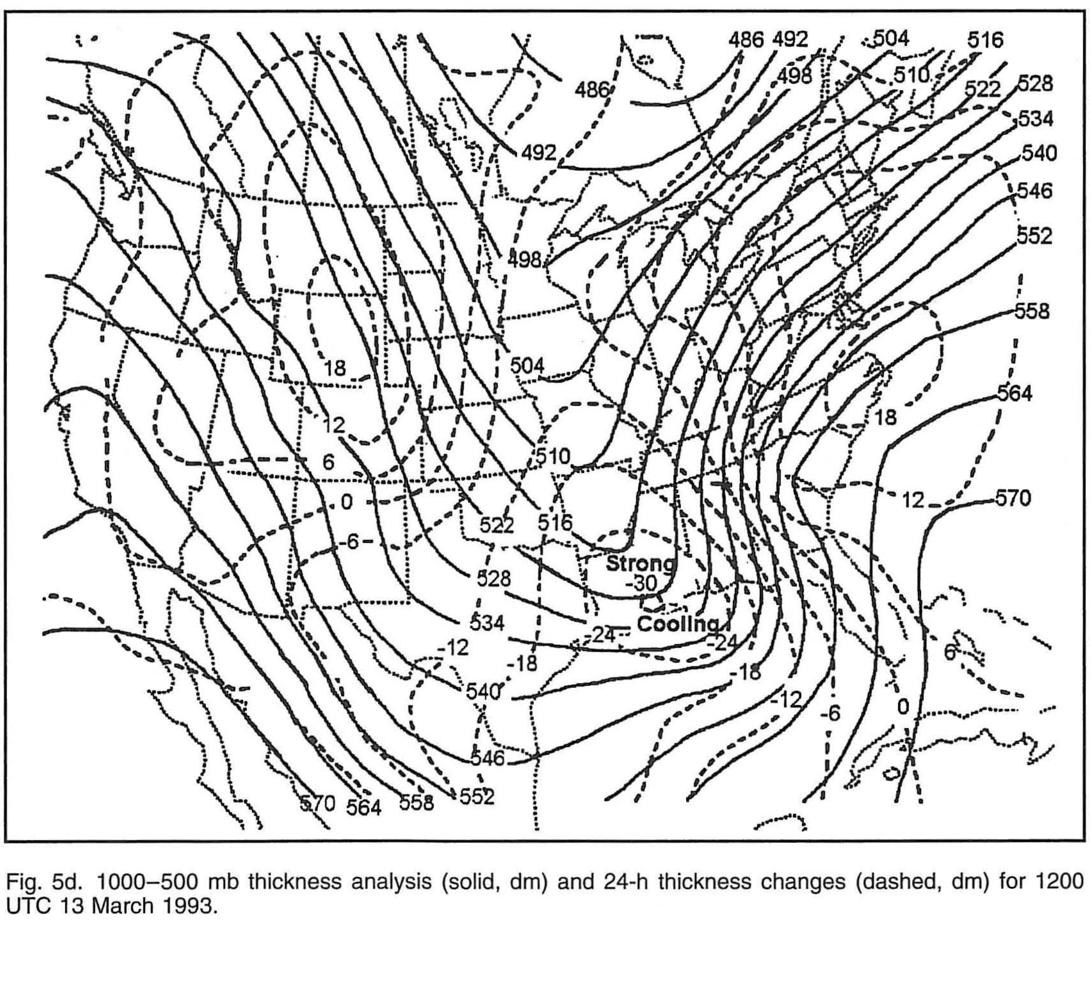

Fig. 5d. 1000–500 mb thickness analysis (solid, dm) and 24-h thickness changes (dashed, dm) for 1200 UTC 13 March 1993.

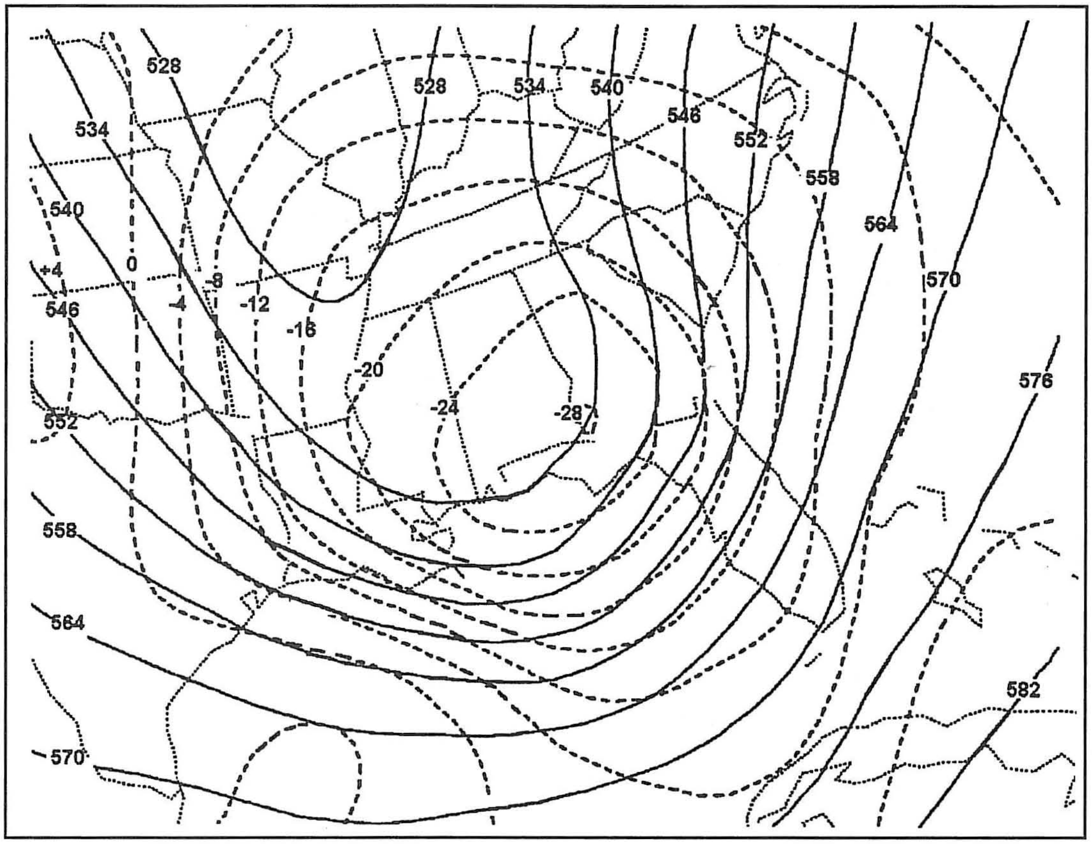

Fig. 5e. 500-mb heights (solid, dm) and 12-h height falls (dashed, dm) for 1200 UTC 13 March 1993.

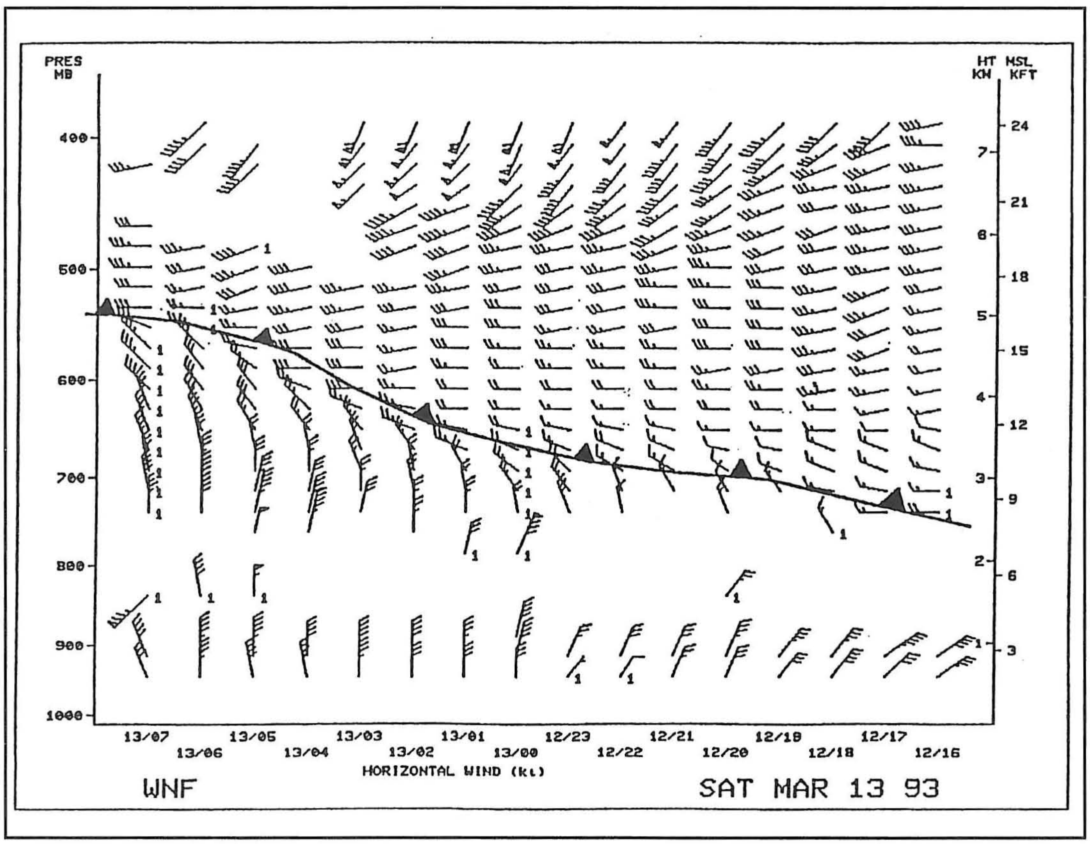

Fig. 5f. Wind profiler time-height cross section from (right to left) 1600 UTC 12 March 1993 to 0700 UTC 13 March 1993 for Winnfield, Louisiana (WNF).

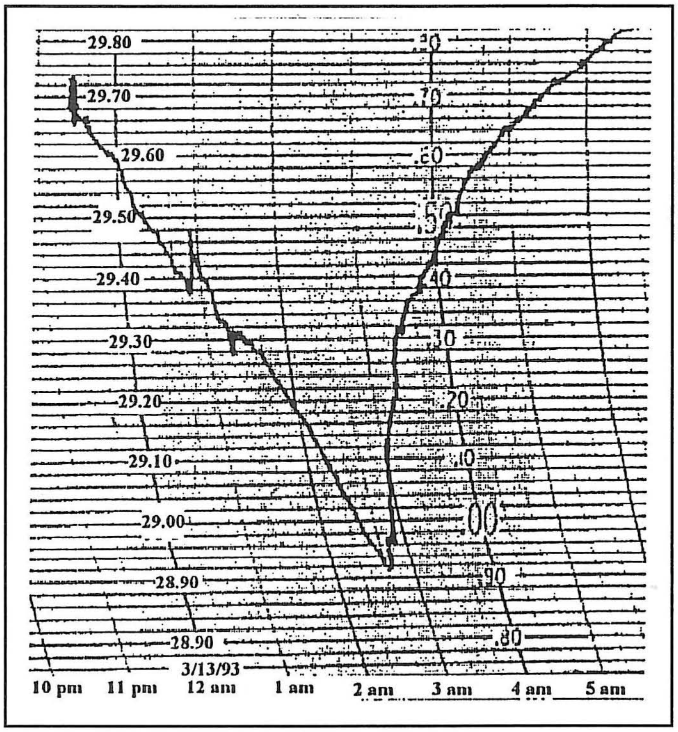

Fig. 6. Unofficial barograph trace from Appalachicola, Florida, NWS office from (left to right) 2200 LST 12 March 1993 to 0600 LST 13 March 1993.

of cold Texas and Louisiana shelf waters to warm waters of Eddy Vasquez created strong surface temperature gradients in the northwestern Gulf of Mexico. Maximum SST gradients of 1°C/2 km were observed along the western flank of Eddy Vasquez (Fig. 7b, Point A), where SSTs ranged from 18°C on the shelf to 23°C within the Eddy. Similar surface temperature ranges were observed north of the Eddy; however, the gradient magnitude was somewhat weaker (1°C/5 km to 1°C/10 km) (Fig. 7b, Point B). Thus, it has been shown that two conditions necessary for surface cyclogenesis were met in the northwestern Gulf of Mexico in early March 1993: (1) strong low-level atmospheric baroclinicity and (2) low static stability within the marine boundary layer (Reed and Albright 1986; Nuss and Anthes 1987).

Rapid cyclogenesis is a common occurrence off the East Coast of the U.S. (Sanders and Gyakum 1980) in fall and winter when frontal waves encounter strong SST gradients associated with the Gulf Stream and winter-chilled shelf waters along the coast. Bosart (1981) gives evidence that the Presidents' Day snowstorm of 1979 occurred in association with SST gradients 2°C greater than normal. Hsu (1992) and Lewis and Hsu (1992) have shown that cyclogenesis in the northwestern Gulf of Mexico during the winter is strongly related to the magnitude of coastal-offshore SST gradients. These gradients can be approximated by the surface temperature gradient between Lake Charles and buoy station 42002 (at 25.9°N, 93.6°W). During winter, SST gradients are favorable for cyclogenesis as they serve to intensify the local geostrophic vorticity field. During March 1993, an enhanced baroclinic zone was present and

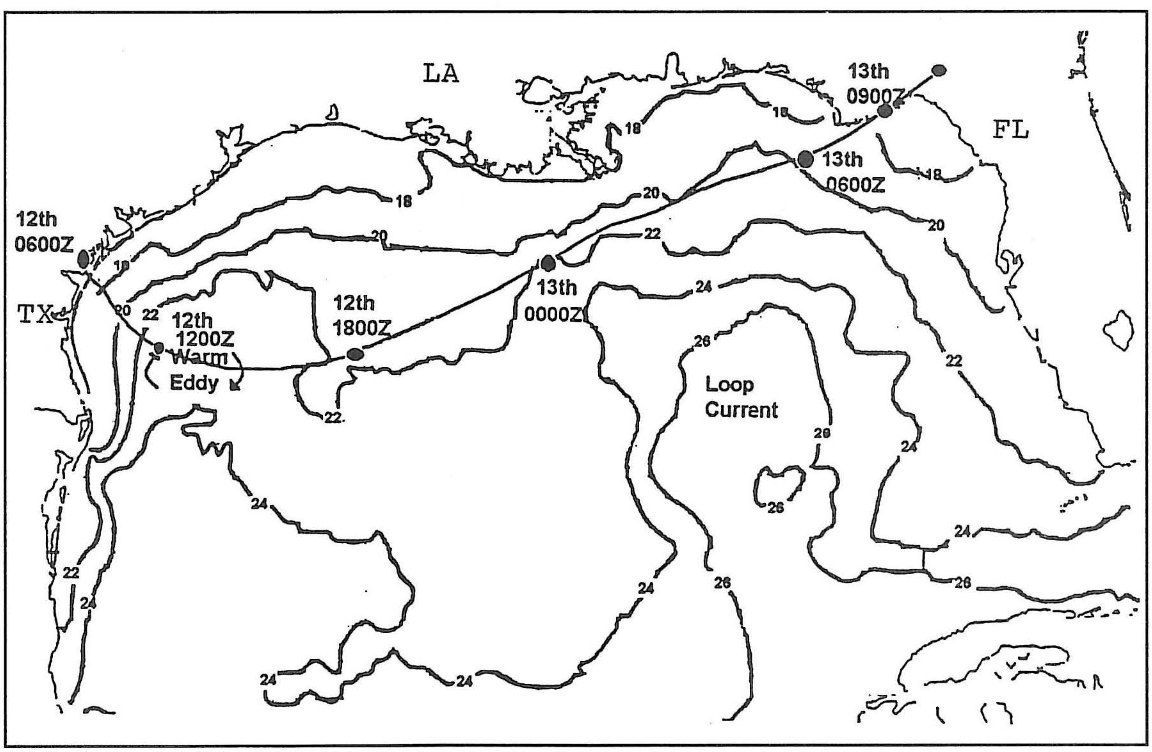

Fig. 7a. Smoothed 7-day average of sea surface temperatures (°C), 9 March 1993. Surface low center track from Fig. 1.

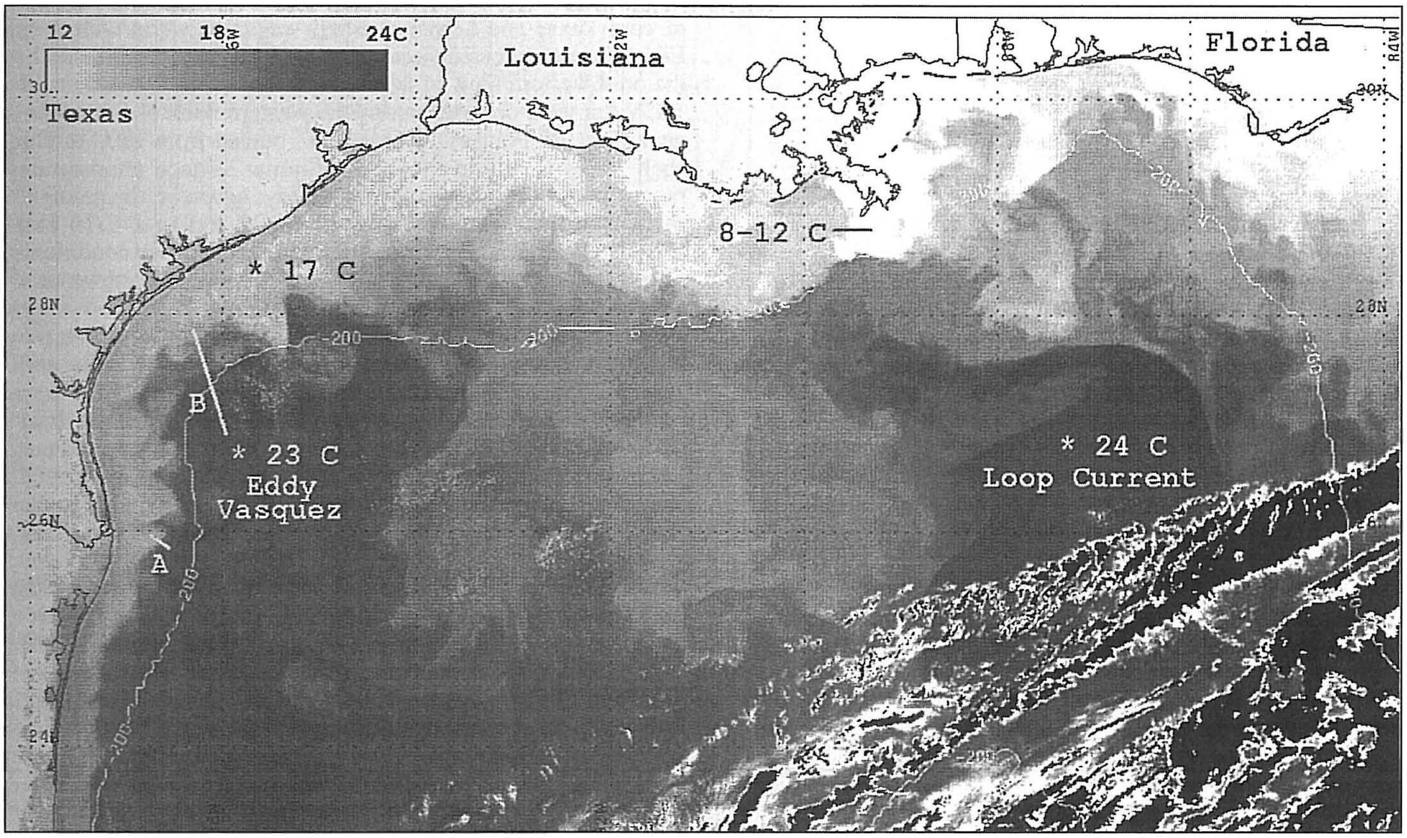

Fig. 7b. Analysis of NOAA-12 Advanced Very High Resolution Radiometer (AVHRR) satellite imagery of sea surface temperatures (SST), 1353 UTC 9 March 1993. Lighter grey shades represent lower SST.

surface air temperature differences between Lake Charles and the deep Gulf of Mexico were 8–10°C above the climatic mean. Nuss and Anthes (1987) suggest that phasing of the SST pattern with the low-level atmospheric thermal pattern can further enhance storm development. By 1200 UTC on March 12, cyclogenesis had occurred over the northwestern Gulf of Mexico, as a low-level (1000-mb) baroclinic zone had become aligned with the strong SST gradients in the northwestern Gulf of Mexico. Surface baroclinic conditions were thus optimized for rapid deepening of the storm, given the appropriate upper-level dynamics that had developed.

An analysis of cloud top temperatures from NOAA AVHRR satellite data available every 4–6 hours confirms the presence of strong vertical motion over the northwestern Gulf of Mexico between 0200 and 1400 UTC on 12 March 1993. One indication of significant vertical motion is the large increase in cloud cover over the northwest Gulf between these periods. A second indication is seen by comparing 12-hour changes in cloud top temperatures. Cloud top temperatures cooled 20°C over the northwest Gulf of Mexico (Figs. 7c and d). These colder temperatures indicate convection above the tropopause (tropopause approximated between 250–300 mb at a temperature of −45°C) and confirm the occurrence of rapid cyclogenesis. Thus, the superpositioning of an enhanced surface baroclinic zone and the low-level heat and moisture source (Eddy Vasquez) with upper-level dynamics maximized storm development over the northwestern Gulf of Mexico. The storm continued to be fueled by these processes as it traversed the northern Gulf of Mexico over anomalous warm waters with strong surface temperature gradients along its northern margin.

4. Rating The Storm

Studies of cyclogenesis including Sanders (1986) and Johnson et al. (1984), describe the primary weather features of rapid marine cyclogenesis along the East Coast and over the Gulf of Mexico. The upper-level dynamics and air-sea interaction associated with the March 1993 Gulf storm corresponded well with features cited in earlier studies. The pressure falls associated with this storm can be expressed in bergerons, where 1 bergeron is equivalent to a 24-h pressure fall of 24 mb at 60°N and varies with latitude (1 bergeron at latitude θ is equivalent to a 24-h pressure fall of 24 mb $\times$ sin θ /sin 60). Therefore, based on a 24-h surface pressure fall of 26 mb and using an average latitude of 28.5°N, the rating for the March storm is 1.97 bergerons, which puts this storm in the strong "bomb" category (see Sanders 1986). Dolan and Davies (1992) also studied Atlantic Coast storms (Northeasters) and developed a 1 through 5 scale based on storm impact from beach erosion to property damage. They characterized Extreme or Class 5 storms as having extreme beach erosion, massive overwash in channels, deep-water significant wave heights of 23 ft, and damages in millions of dollars. Despite the fact the March storm was within an entirely different geographical area, this storm met the extreme case early on along the Gulf Coast States.

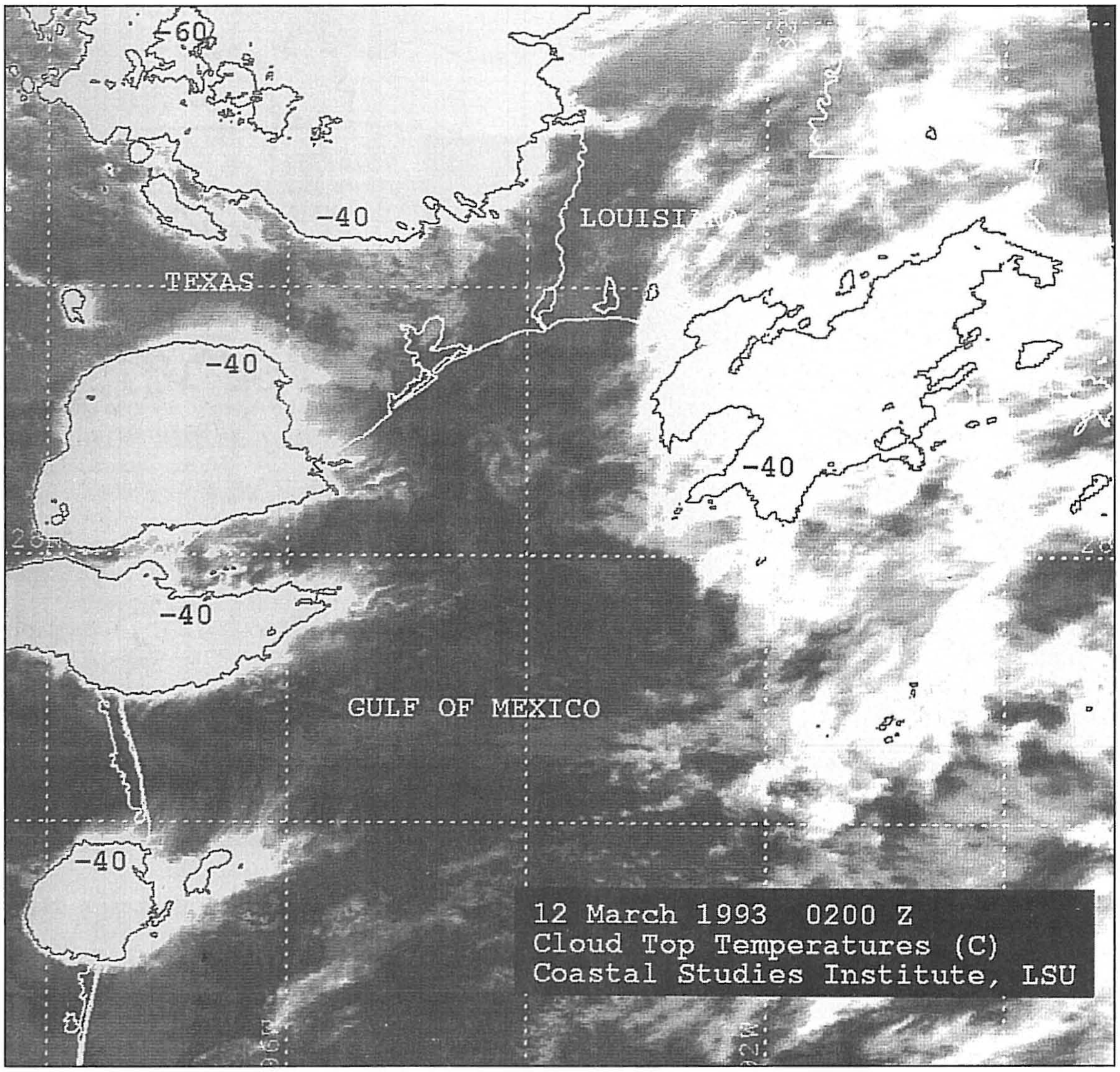

Fig. 7c. Analysis of NOAA-12 AVHRR satellite imagery of cloud-top temperatures (°C) over Texas and Louisiana coast, 0200 UTC 12 March 1993.

5. Impact On The Gulf Coast Area

Along the Gulf Coast the storm's rapid development produced events that were extraordinary and devastating. There was loss of life and considerable property damage. The major areas of impact along the storm track and well inland are depicted in Fig. 8. High winds with gusts to 55 mph were observed over most of southeast Louisiana during 12–13 March. Damage was mainly to mobile dwellings and electrical utilities. Three inches of snow fell over parts of southeast Louisiana, mainly north of Lake Pontchartrain. Damage from the 2-day storm was estimated to be less than $250,000. The major economic impact came during 14 March when the secondary surge of colder air invaded the area. Agricultural losses from freezing conditions alone amounted to more than $5 million, and one death in New Orleans was due to the cold.

In Mississippi the storm had less of a reported impact. One to three inches of snow fell over southern and central portions of the state.

Record-breaking heavy snowfall was observed over parts of central and northeast Alabama with areas around Birmingham receiving 8 to 13 inches. The impact was crippling for parts of that state. Two to four inches of snow fell as far south as Mobile. The economic impact of the storm on Alabama alone was at least $75 million.

Florida was hit the hardest. Taylor County, in the Panhandle, reported 10 drownings due to a 13 ft storm surge, and beach erosion occurred with tides 5 ft above normal. A similar storm surge in Dixie County destroyed more than 500 homes and caused major damage to another 700 structures, mostly mobile homes and businesses. Numerous tornadoes were spawned over north and central Florida affecting some 10 counties. Up to 5 inches of snow were observed over areas of the Panhandle. The death toll in Florida reached 27 as a result of drownings and severe weather associated with the storm. Financial losses were estimated at $1.5 billion.

The storm dealt a devastating blow to vessels across both the offshore Gulf of Mexico and coastal waters. Coast Guard

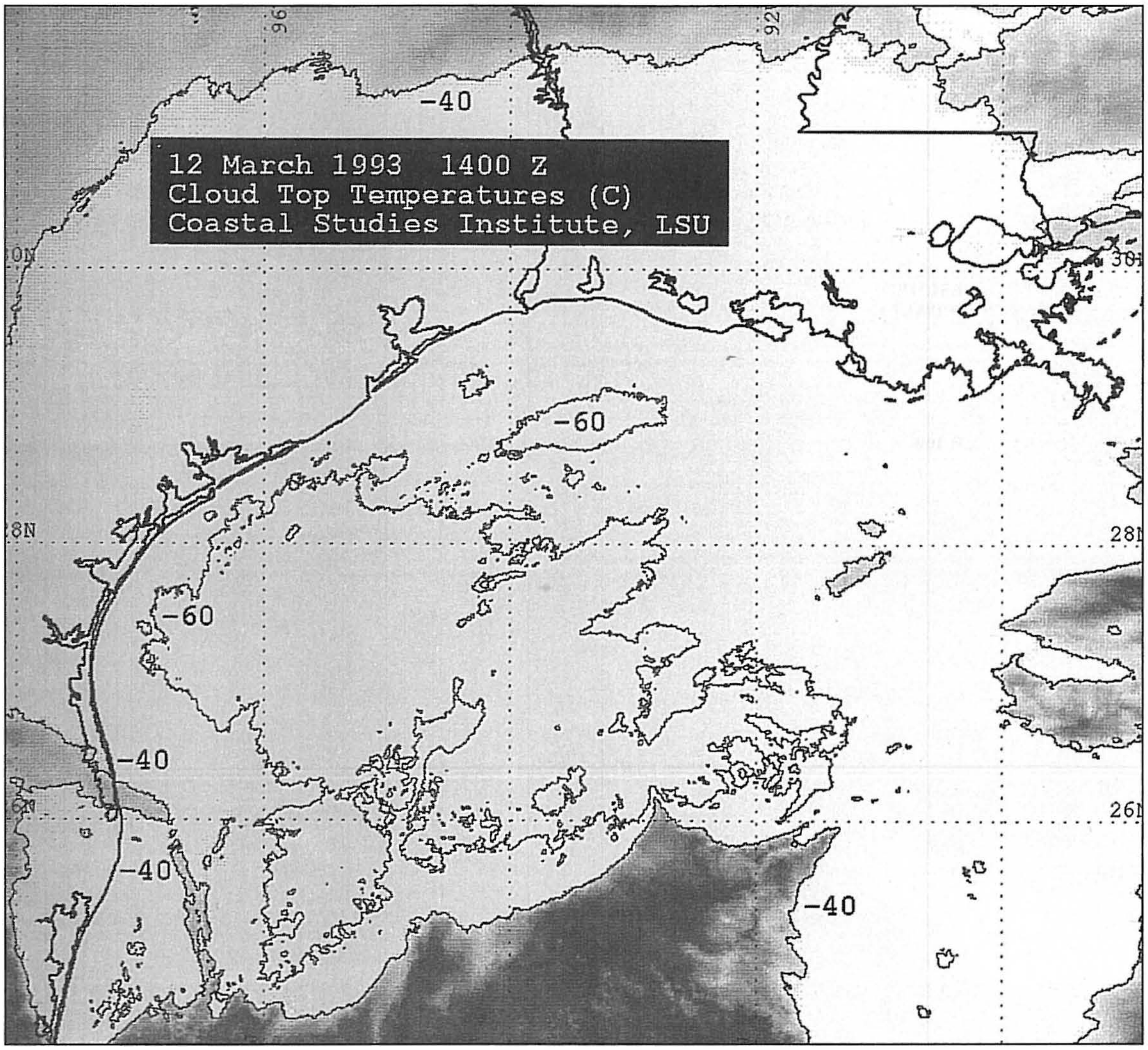

Fig. 7d. Same as Fig. 7c. except for 1400 UTC 12 March 1993.

units from New Orleans and Miami responded to a combined 226 search and rescue missions over the Gulf of Mexico and Florida coastal waters. Their actions resulted in 191 lives saved and dozens of vessels assisted. Casualties included 7 deaths and 15 people determined missing.

6. Model Performance

Deepening winter cyclones present many challenges to the operational forecaster. For major storms, longer lead times are necessary. With longer lead times needed, the dependance on numerical models and their performance is vital. For the winter storm some initial areas a forecaster needs information on are:

1) expected storm intensity (storm central pressure),
2) expected storm track (with regard to temperature and moisture pattern), and
3) the strength of the cold air mass (advection) following the passage of the low pressure center.

These facets of atmospheric model performance will be depicted in associated graphics which display:

1) forecast central pressure of the surface low,
2) forecast position accuracy of the surface low,
3) low-level wind forecast,
4) thickness forecast, and
5) jet forecast.

Factor number one above, is depicted in Figs. 9a-c. In Fig. 9a, the NMC Limited-area Fine Mesh Model (LFM) had the smallest error for the central pressure of the storm for the 12, 24 and 36-hour forecasts with mixed results at 48 hours. The NMC aviation run (AVN) and ETA model performance improved at 48 hours. Contrary to this, the NGM missed the central pressure at 48 hours by 18 mb. It must be pointed out that nearly all models forecast a central pressure that was too high. In Fig. 9b, results were similar but with smaller errors. However, a trend began to appear in the 48-hour forecast for Fig. 9b and is easily seen in Fig. 9c. At 48 hours in Fig. 9b, all models except the LFM forecast a central pressure that was too low. This continued in the forecast made from the initial time 0000 UTC 13 March 1993 as depicted in Fig. 9c. Nearly all models at the 24, 36 and 48-hour points forecasted a central pressure that was as much as 9 mb too low. AVN model data was not available at 36 and 48 hours.

Factor two considers the forecast accuracy of the surface low pressure system. In Fig. 9d, the error pattern for the forecast

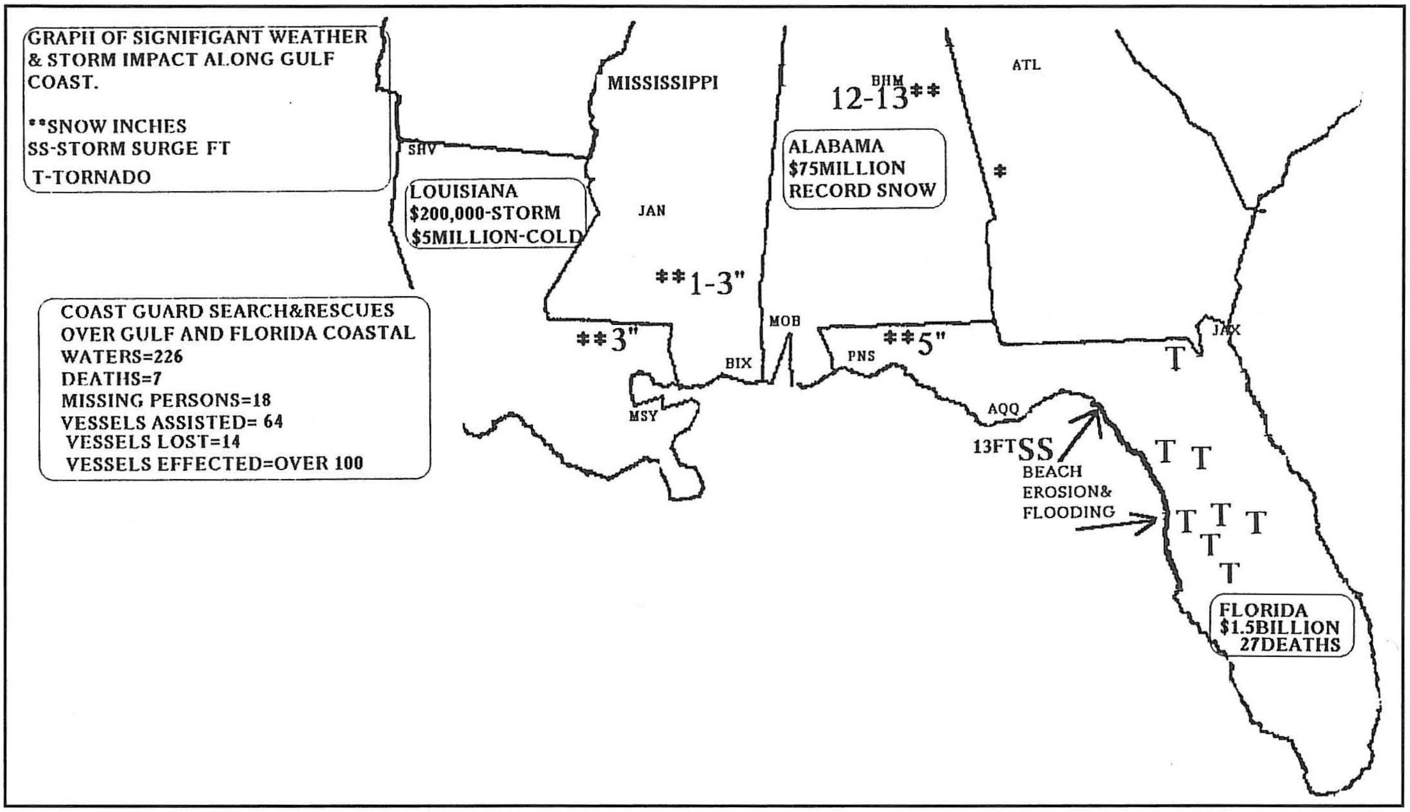

Fig. 8. Storm damage and significant snow amounts over Gulf Coast area.

is reversed from what most meteorologists would consider a typical pattern of largest errors as forecast times increased. Possible reasons follow. First, the surface low was just forming (0000 UTC 12 March) in an area (Texas Big Bend/northern Mexico) where the surface data field is sparse and upper-air data becomes non-existent. Thus, with initialization, the forecast would have had a large built-in error. The models, however, began to recover from this error through 36 hours. In Fig. 9e, it can be seen that a "normal" error pattern begins to assert itself. (i.e., larger errors at longer forecast times). This continues in Fig. 9f. It could be argued that the Gulf of Mexico is every bit as big a data-void area as the formation area noted above. While this may be true, most of the surface data from the Gulf of Mexico undergo high quality control by the NOAA Data Buoy Office. This fact, leads to the possibility that the NMC models were able to recover from our suggested poor initialization at 0000 UTC 12 March. It can also be seen by inspecting the Total Error Figures (summations of 12 to 36-h position

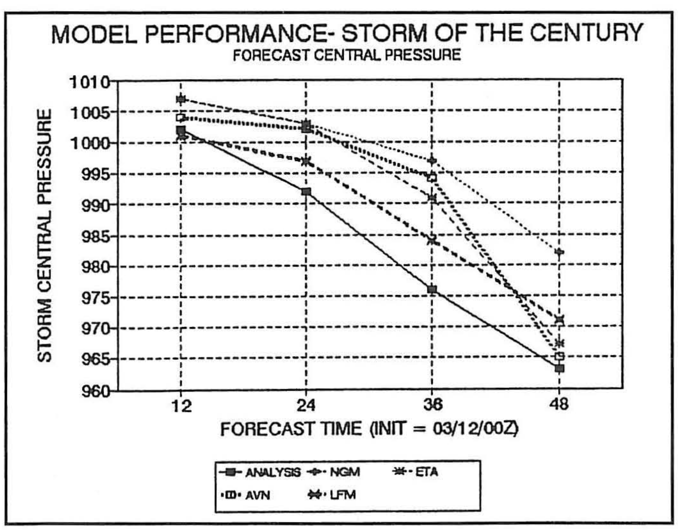

Fig. 9a. Performance of NMC models in forecasting central pressure of the surface low for the initial time of 0000 UTC 12 March 1993.

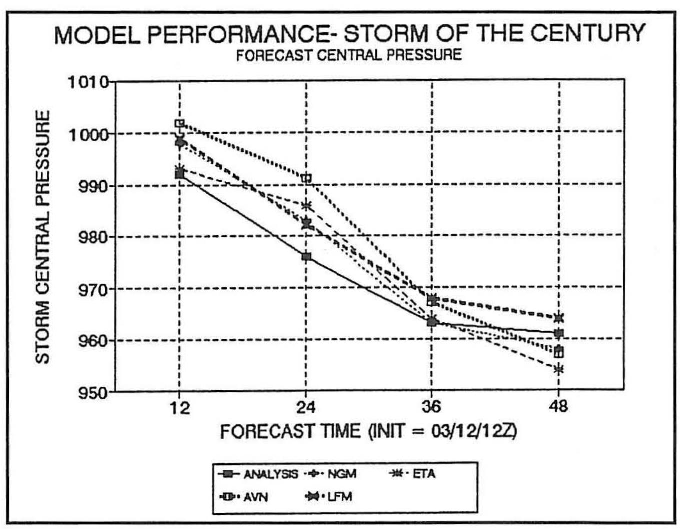

Fig. 9b. Same as Fig. 9a with initial time of 1200 UTC 12 March 1993.

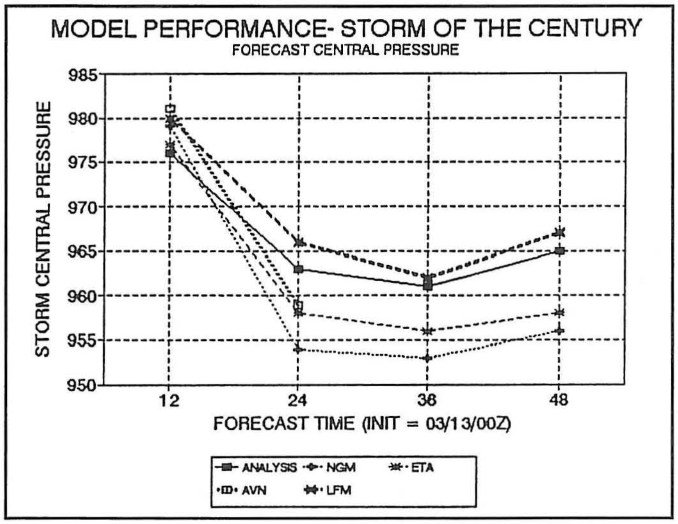

Fig. 9c. Same as Fig. 9a with initial time of 0000 UTC 13 March 1993.

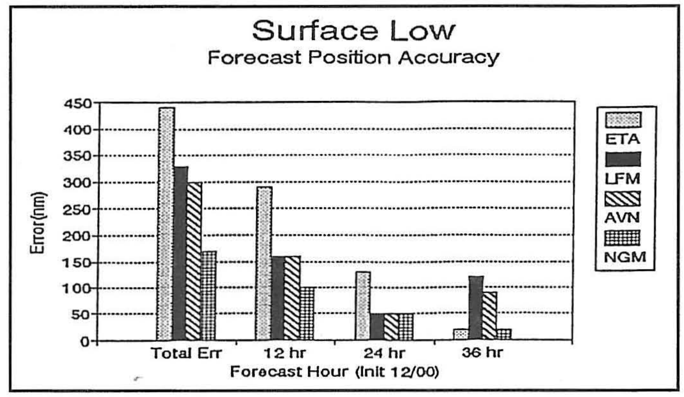

Fig. 9d. Performance of NMC models in forecasting position of the surface low center with initial time of 0000 UTC 12 March 1993. Total Err (nm) equals the sum of 12-h + 24-h + 36-h errors.

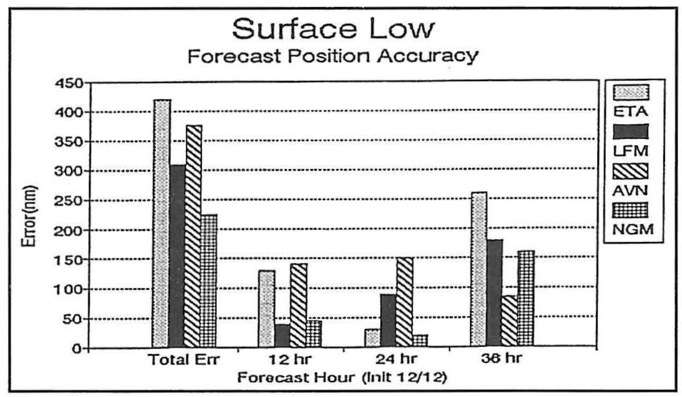

Fig. 9e. Same as Fig. 9d with initial time of 1200 UTC 12 March 1993.

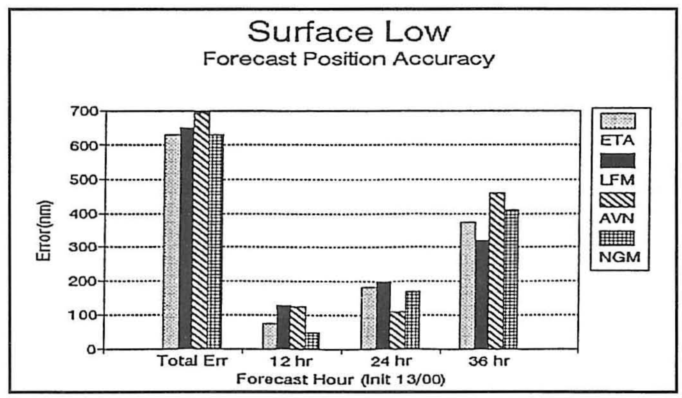

Fig. 9f. Same as Fig. 9d with initial time of 0000 UTC 13 March 1993.

errors) from Figs. 9d-f that the NGM had the lowest forecast position error. This trend is difficult to explain since the ETA model has a higher spatial resolution.

An important factor in the marine forecast for the Gulf of Mexico is the low-level wind forecast, since wind speed is a major factor on the wave forecast. Because Gale Warnings are expected to be posted 24 hours in advance, the most critical prediction was the 24-hour forecast made from the initialization on 0000 UTC 12 March 1993. Figure 10 is the isotach analysis of the surface winds across the Gulf of Mexico for the morning of the 13th. The figure indicates a broad area of 60+ kt surface winds. Sea heights in the Gulf of Mexico eventually reached 25 to 30 ft following the passage of the surface low. Figures 11a-c show the 24-hour, 1000-mb NMC model wind forecast for 1200 UTC 13 March 1993. Maximum winds forecast over the area are 40–45 kt. To understand what this 20 kt error means to the sea height forecast, one only has to consider that sea heights are tied directly to the square of the wind speed. This means that forecast model winds rendered wave heights that were in error by more than 100 percent.

In attempting to forecast precipitation type associated with any developing winter storm system the 1000–500 mb thickness forecast is often a first guess. In Figs. 12a-c a thickness error (observed minus forecasted) developed in the western Gulf of Mexico and southern tip of Texas that was west and southwest of the surface low pressure area. This error field maximized for the 24-h forecast from 1200 UTC 12 March 1993 valid 1200 UTC 13 March 1993. The thickness error (observed minus forecasted) ranged from 90 meters for the AVN model to 120 meters for the NGM model to 180 meters for the ETA model. After the surface low had moved out of the Gulf of Mexico and had been over land for over 12 hours, the models recovered somewhat with errors in the NGM and ETA models diminishing to 80–90 meters respectively. Despite the large error in thickness value, the storm was recognized early as a major snow producer and snowfall forecasts over the Gulf Coast States were excellent.

The last area of model performance is the forecast for the upper-level (200–300 mb) jet. Areas of wind speed maxima (jet max) are important in synoptic development as they carry with them a pattern of concentrated mass divergence/convergence which is important in the development of the vertical motion field. The performance of the NGM model is presented in Figs. 13a-c. The 250-mb isotach analysis for 0000 UTC 13 March 1993 indicated two jet maxima; one in the lee of the Rocky Mountains and another over the Ohio Valley. The 24-hour isotach pattern forecast for these features captured the axis but underforecast the maximum wind speed by 40 kt. As the jet max in the lee of the Rockies dove into the base of the trough over the Gulf of Mexico and re-entered the data field over Florida the maximum speed in this feature continued to be in error by 40 kt. The forecast for the jet maximum over the

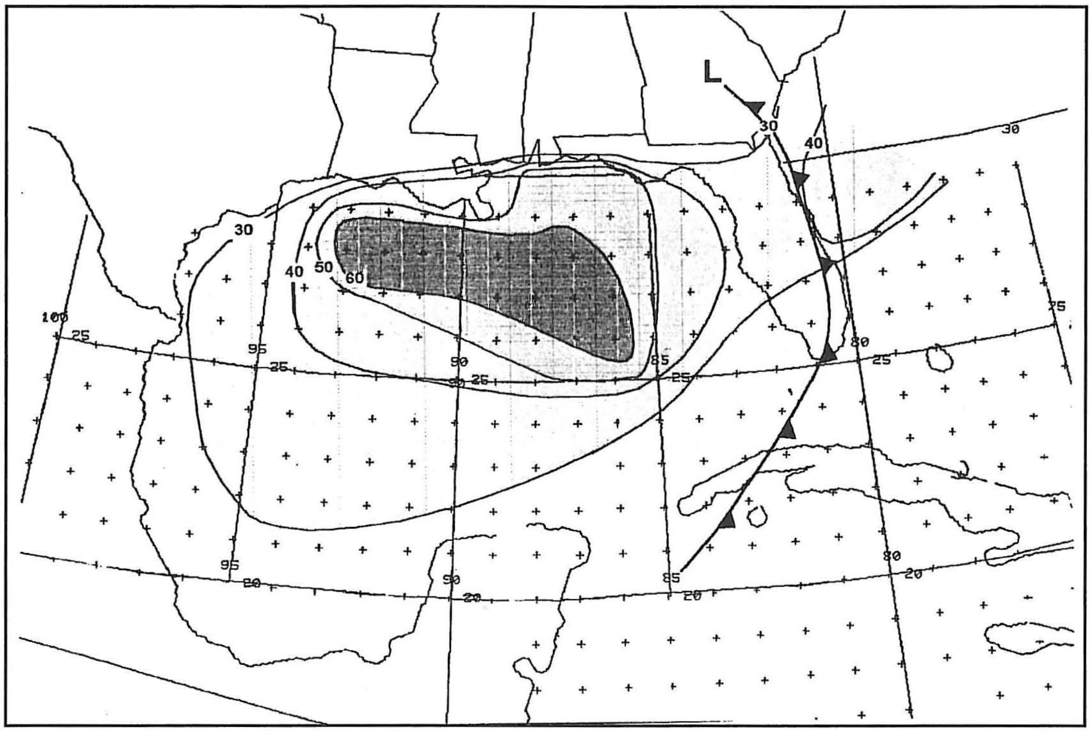

Fig. 10. Isotach (kt) analysis of Gulf of Mexico area surface wind data at 1200 UTC 13 March 1993 (from NWS Forecast Office New Orleans).

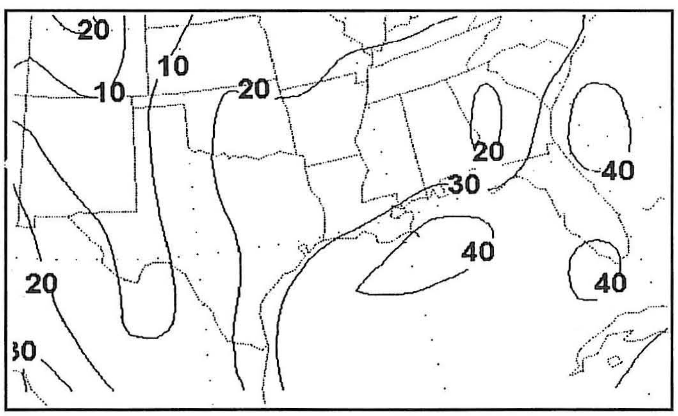

Fig. 11a. NMC NGM 1000-mb, 24-h forecast isotach (kt) pattern valid 1200 UTC 13 March 1993.

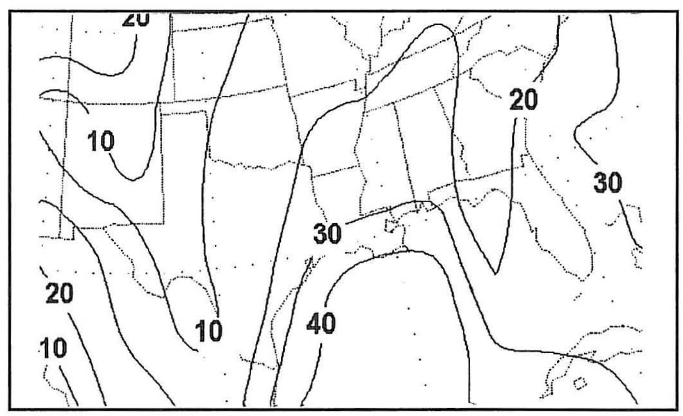

Fig. 11b. NMC Eta model 1000-mb, 24-h forecast isotach (kt) pattern valid 1200 UTC 13 March 1993.

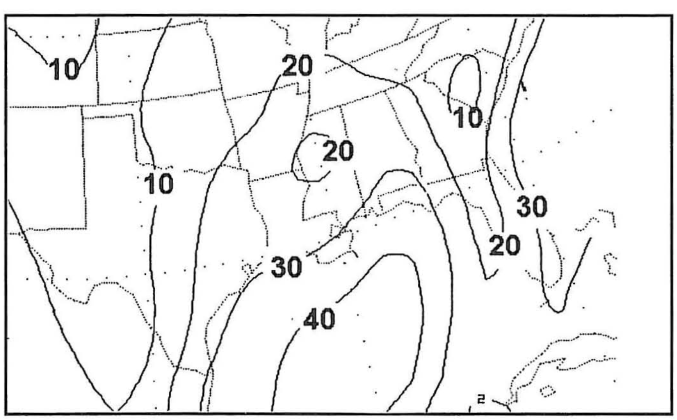

Fig. 11c. NMC AVN model 1000-mb, 24-h forecast isotach (kt) pattern valid 1200 UTC 13 March 1993.

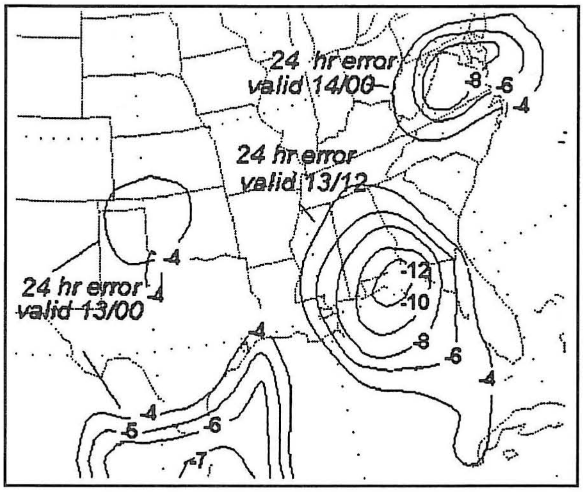

Fig. 12a. Errors (observed—forecast) in the NMC NGM 24-h, 1000-500 mb thickness (dm) forecasts from model initial times of 0000 UTC 12 March, 1200 UTC 12 March and 0000 UTC 13 March 1993.

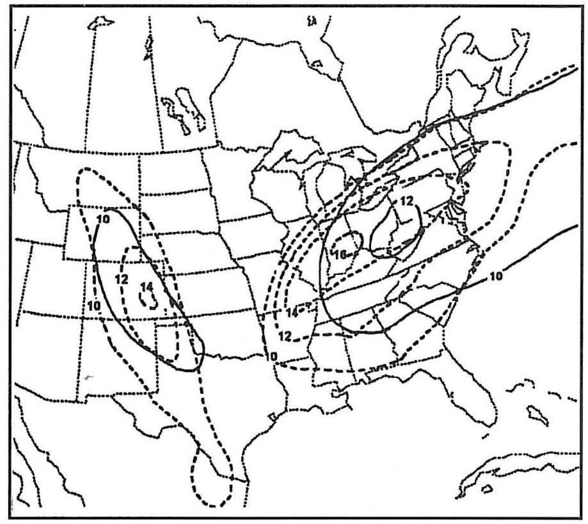

Fig. 13a. NMC NGM 250-mb, 24-h isotach forecast (solid, kt x 10) valid 0000 UTC 13 March 1993 and the verifying NGM analysis (dashed, kt x 10).

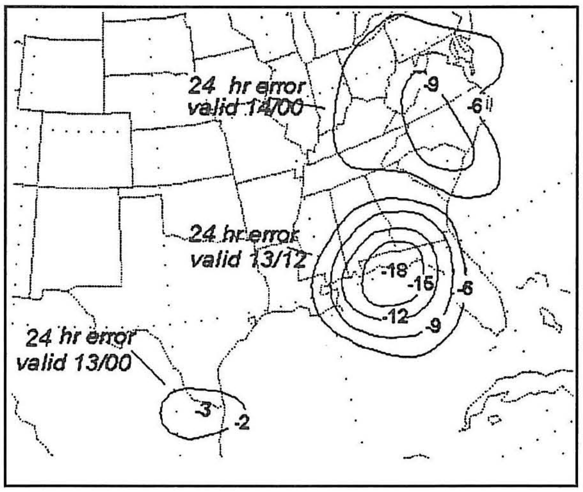

Fig. 12b. Same as Fig. 12a for NMC Eta model performance.

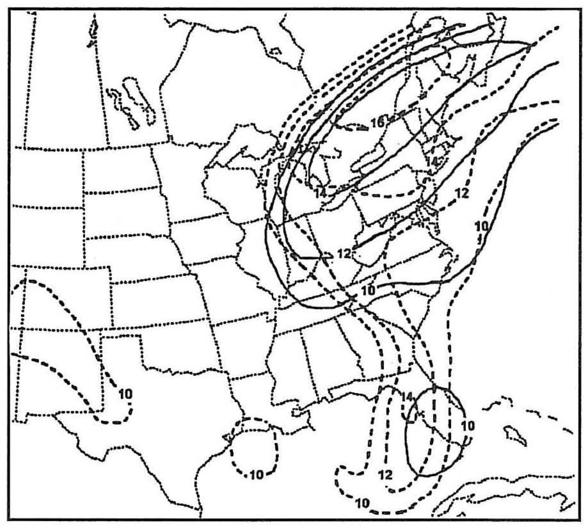

Fig. 13b. Same as Fig. 13a with valid time 1200 UTC 13 March 1993.

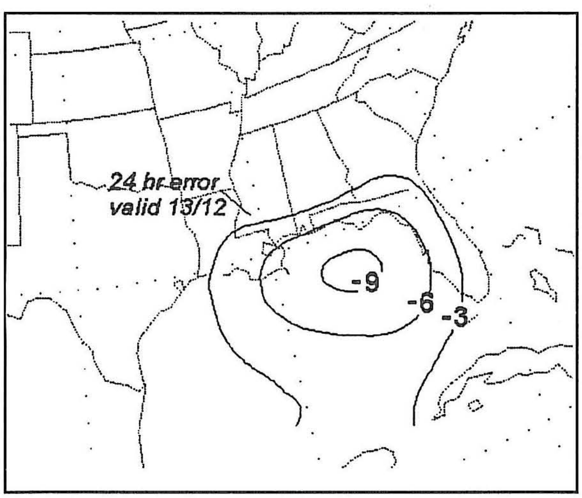

Fig. 12c. Same as Fig. 12a for NMC AVN model performance. (Forecasts from initial times of 0000 UTC 12 March and 0000 UTC 13 March were not available.)

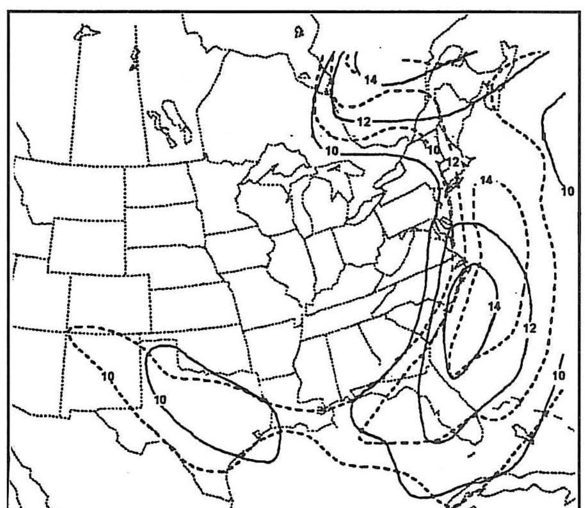

Fig. 13c. Same as Fig. 13a with valid time 0000 UTC 14 March 1993.

Ohio Valley, which had pushed northeast over the St. Lawrence River Valley, had improved with only a 20 kt deficit. By 0000 UTC 14 March 1993, the isotach forecast had continued to improve with the jet axis and the maximum speed close to observed.

Five areas of model performance for the March 1993 "superstorm" have been covered pointing out several fields where the model forecast was significantly in error. Much of this error occurred during the developmental stages of the storm. Due to the lack of detailed knowledge of the numerical models by the authors, only the model errors and not the specific causes of these errors have been discussed.

6. Summary and Conclusions

The March 1993 winter storm demonstrated the potential for, and impact of, rapid cyclogenesis over the Gulf of Mexico. An important factor in the initiation of strong cyclogenesis was the presence and proximity of a strong, low-level baroclinic zone (stationary front) coinciding with a strong SST gradient. As the low moved northeast across the Gulf of Mexico, upper-level features produced the necessary strong dynamics for development. In particular, a strengthening jet streak as well as a negatively tilted short-wave trough produced areas of strong vertical motion and upper-level divergence necessary for rapid development. This episode displays all five criteria associated with strong cyclogenesis described by Lyons (1992):

1) mid-level negative tilt trough,
2) upper-level jet streak in the back side of the trough,
3) strong convection near the surface low,
4) strong baroclinicity in the lower levels, and
5) strong upper-level divergence in concert with strong low-level convergence.

Acknowledgments

The authors wish to thank the staff of the Scientific Services Division at NWS Southern Region Headquarters for obtaining the necessary data to conduct this study and providing editorial assistance. Thanks also to Dave Gilhousen of the NOAA National Data Buoy Center for providing data buoy observations. SST analyses were provided by Dr. Steven Baig of the NWS/National Hurricane Center. Gulf of Mexico search and rescue information was provided by the U.S. Coast Guard Eighth District, New Orleans, and Seventh District, Miami. Thanks also to NWS Forecast Offices in Jackson MS, Birmingham AL and Miami FL. Many thanks to Frank Revitte for his positive comments and suggestions for improvement on this paper. The NOAA AVHRR satellite imagery was captured and processed at the Earth Scan Laboratory, Coastal Studies Institute, Baton Rouge, Louisiana. This work was partially funded by the Minerals Management Service through the Texas-Louisiana (LATEX) contract 14-35-001-30632 and 14-35-001-30509.

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