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SURFACE AND NEAR-SURFACE OBSERVATIONS DURING HURRICANE ANDREW

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U.S. DEPARTMENT OF COMMERCE
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TECHNICAL NOTE*

SURFACE AND NEAR-SURFACE MARINE OBSERVATIONS DURING HURRICANE ANDREW

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OPC CONTRIBUTIONS

No. 1. Burroughs, L. D., 1986: Development of Forecast Guidance for Santa Ana Conditions. National Weather Digest, Vol. 12 No. 1, 8pp.

No. 2. Richardson, W. S., D. J. Schwab, Y. Y. Chao, and D. M. Wright, 1986: Lake Erie Wave Height Forecasts Generated by Empirical and Dynamical Methods -- Comparison and Verification. Technical Note, 23pp.

No. 3. Auer, S. J., 1986: Determination of Errors in LFM Forecasts Surface Lows Over the Northwest Atlantic Ocean. Technical Note/NMC Office Note No. 313, 17pp.

No. 4. Rao, D. B., S. D. Steenrod, and B. V. Sanchez, 1987: A Method of Calculating the Total Flow from A Given Sea Surface Topography. NASA Technical Memorandum 87799., 19pp.

No. 5. Feit, D. M., 1986: Compendium of Marine Meteorological and Oceanographic Products of the Ocean Products Center. NOAA Technical Memorandum NWS NMC 68, 93pp.

No. 6. Auer, S. J., 1986: A Comparison of the LFM, Spectral, and ECMWF Numerical Model Forecasts of Deepening Oceanic Cyclones During One Cool Season. Technical Note/NMC Office Note No. 312, 20pp.

No. 7. Burroughs, L. D., 1987: Development of Open Fog Forecasting Regions. Technical Note/NMC Office Note. No. 323., 36pp.

No. 8. Yu, T. W., 1987: A Technique of Deducing Wind Direction from Satellite Measurements of Wind Speed. Monthly Weather Review, 115, 1929-1939.

No. 9. Auer, S. J., 1987: Five-Year Climatological Survey of the Gulf Stream System and Its Associated Rings. Journal of Geophysical Research, 92, 11,709-11,726.

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No. 11. Esteva, D. C., 1987: The Editing and Averaging of Altimeter Wave and Wind Data. Technical Note, 4pp.

No. 12. Feit, D. M., 1987: Forecasting Superstructure Icing for Alaskan Waters. National Weather Digest, 12, 5-10.

No. 13. Sanchez, B. V., D. B. Rao, S. D. Steenrod, 1987: Tidal Estimation in the Atlantic and Indian Oceans. Marine Geodesy, 10, 309-350.

No. 14. Gemmill, W.H., T.W. Yu, and D.M. Feit 1988: Performance of Techniques Used to Derive Ocean Surface Winds. Technical Note/NMC Office Note No. 330, 34pp.

No. 15. Gemmill, W.H., T.W. Yu, and D.M. Feit 1987: Performance Statistics of Techniques Used to Determine Ocean Surface Winds. Conference Preprint, Workshop Proceedings AES/CMOS 2nd Workshop of Operational Meteorology. Halifax, Nova Scotia., 234-243.

No. 16. Yu, T.W., 1988: A Method for Determining Equivalent Depths of the Atmospheric Boundary Layer Over the Oceans. Journal of Geophysical Research. 93, 3655-3661.

No. 17. Yu, T.W 1987: Analysis of the Atmospheric Mixed Layer Heights Over the Oceans. Conference Preprint, Workshop Proceedings AES/CMOS 2nd Workshop of Operational Meteorology, Halifax, Nova Scotia, 2, 425-432.

No. 18. Feit, D. M., 1987: An Operational Forecast System for Superstructure Icing. Proceedings Fourth Conference Meteorology and Oceanography of the Coastal Zone. 4pp.

ABSTRACT

Hurricane Andrew was a relatively small but intense hurricane that passed through the Bahamas, across the Florida Peninsula, and across the Gulf of Mexico between 23 and 26 August 1992. This paper summarizes the characteristics of this hurricane using observations only. These include (1) marine observations from two NDBC buoys and two C-MAN stations close to the storm track, (2) water levels and storm surge at 15 locations in the Bahamas, around the coast of Florida and along the northern coast of the Gulf, (3) currents, temperature and salinity at a depth of 11 meters in the northern Gulf, and (4), difference maps of sea surface temperature before and after the passage of Andrew, for the Bahamas, the Straits of Florida and the Gulf. Sea level pressure, wind direction, wind speed, wind gust, air temperature and SST were strongly influenced by the hurricane in most cases. Water level was strongly affected by the storm at North Miami Beach where a record high occurred. Major decreases in water level occurred along the west coast of Florida with a maximum surge of -1.2 meters at Naples. Major increases in water level occurred at several locations along the Gulf coast between the Florida panhandle, and Louisiana. At Bay Waveland, Mississippi, for example, a storm surge of +1.2 meters was observed.

Significant changes in other environmental parameters were also produced by the passage of Andrew. Current meter data at one location along the hurricane track in the northern Gulf (28.4°N, 90.5°W) indicated that current speeds at a depth of 11 meters increased from ~15 cm/sec to almost 140 cm/sec during passage of the storm. Temperature at this depth decreased by almost 4°C and salinity increased by 2.0 to 3.0 ppt. Finally, difference maps of satellite-derived SST for the period 18 to 29 August showed decreases of 1-2°C at various locations along, and just north of, the storm track.

1. INTRODUCTION

Although Hurricane Andrew was relatively small, it was intense with a minimum central pressure of about 926 mb and maximum sustained winds of almost 72 m/sec (Rappaport, 1992). This hurricane was extremely destructive, devastating portions of the Bahamas, southern Florida and southern Louisiana. Estimates of damage from Hurricane Andrew have reached at least 15 billion dollars in the U.S. alone.

Hurricane Andrew originated as a tropical wave off the west coast of Africa on 14 August 1992 and initially moved to the west. By 16 August, Andrew became a tropical depression, and on 17 August it was classified as a tropical storm. At this stage in its development, Andrew moved rapidly continuing to the west and then to the WNW. From 17 to 20 August, the forward speed of tropical storm Andrew slowed as it turned to the NW. By 20 August, Andrew had weakened somewhat, but by 21 August, it rapidly intensified and again turned to the west. Andrew continued to intensify and by 22 August had reached hurricane strength. Hurricane Andrew reached its maximum intensity on 23 August, while it was still in the Bahamas, approximately one day before reaching the east coast of Florida.

Hurricane Andrew weakened slightly over the Great Bahamas Bank but reintensified just before reaching the southeast coast of Florida. The hurricane came ashore near Homestead Air Force Base with sustained winds of about 65 m/sec, with gusts of up to about 78 m/sec (Churchill, 1992). The arrival of Andrew in southeast Florida coincided approximately with local high tide, producing a large storm surge in this area although not as large as it might have been due to its relatively small size and rapid movement.

After landfall, Andrew continued to move westward over the southern Florida peninsula and weakened slightly. After reaching the Gulf of Mexico (hereinafter called the Gulf), the hurricane reintensified and picked up forward motion as its direction changed from westward, to WNW, and finally to NW as it approached the coast of Louisiana. Before reaching the northern Gulf coast on 25 August, Andrew began to slow down and weaken. At this point in it's evolution, Andrew had maximum winds in the neighborhood of 31 m/sec[5]; it finally reached landfall in southern Louisiana on 26 August and rapidly weakened once it moved inland.

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[5]The highest wind reported through the C-MAN network at BUSL1 in the Northern Gulf was 27 m/sec. Continuous recordings on the platform showed winds of 29.5 m/sec at one anemometer and 34.8 m/sec on the other. One of the aircraft recons had wind speeds in the storm near the surface of 50 m/sec. (Forristall, personal communication).

It is the purpose of this study to document the impact of Hurricane Andrew on the near-surface marine environment across the Bahamas and the Gulf through observations of sea level pressure, surface winds, surface air temperature, sea surface temperature, water level, near-surface currents, temperature and salinity. It was fortuitous that a number of National Data Buoy Center (NDBC) environmental data buoys, Coastal Marine Automated Network (C-MAN) stations, and a Louisiana-Texas Shelf Physical Oceanography Program (LATEX) current meter mooring were located close to Andrew's track during its passage across the Bahamas and the Gulf. These data naturally take the form of time series and thus characterize the intensification and decay of Andrew at specific locations along its track. Also, we include several difference maps of satellite-derived sea surface temperature (SST) to provide an alternate perspective of the ocean's response to this hurricane.

2. DATA SOURCES AND SENSOR CHARACTERISTICS

A. NDBC Buoys and C-MAN Station Data

Two NDBC buoys and two C-MAN stations provided observational data for this study.[6] The buoys are located near Eleuthera in the Bahamas (41016) and in the eastern Gulf (42003). The C-MAN stations are SANF1, a stationary platform off Sand Key, Florida and BUSL1, an oil platform called Bullwinkle Block owned by Shell Offshore, Incorporated. Information about the sensor packages on the two NDBC buoys and SANF1 is available from Gilhousen (1992) and NDBC (1989, 1992a, 1992b). Information about the sensor package on BUSL1 is available from Shell Development Corporation (Heckler, personal communication; see also Swanson and Baxter, 1989).

Table 1 gives the position of each station, hull type for buoys or location description (onshore/offshore) for C-MAN stations, and the types of instrumentation employed. Table 2 presents the sensor elevations for each platform. Table 3 provides descriptions of the sensors including type of sensor, sampling range, averaging frequency and averaging period.

The NDBC buoy and C-MAN station data are transmitted to the GOES geostationary satellite which then relays it to a ground receiving station where it is routed to the National Weather Service Telecommunications Gateway which in turn routes it to the National Meteorological Center.

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[6]Marine observations from a C-MAN station at Fowey Rocks about 25 km north of the storm track near Miami were also acquired during the passage of Andrew (Meindl, 1993). We did not have access to the data at this location because of equipment failure at the height of the storm. Meindl's results are summarized in a forthcoming article by us.

Table 1. NDBC Buoy and C-MAN Stations Selected During Hurricane Andrew.

Station ID	Platform Description	Latitude (degrees)	Longitude (degrees)
41016	12 m discus	24.6°N	76.5°W
SANF1	offshore C-MAN	24.5°N	81.9°W
42003	10 m discus	25.9°N	85.9°W
BUSL1	offshore C-MAN	27.9°N	90.9°W

Table 2. NDBC Buoy and C-MAN Sensor Heights Above and Below Sea Level (in meters).

Station ID	Barometer	Wind Sensor	Air Temperature	SST
41016	0.0	10.0	10.0	-1.0
SANF1	6.4	13.1	12.8	-1.5
42003	0.0	10.0	10.0	-1.0
BUSL1	20.1	93.6	21.3	-3.0

Table 3. Instrument descriptions - only information for the measurements presented in this study are included.

Measurement	Sensor Type	Sampling Range	Sampling Freq. (Hz)	Averaging Period
Wind direction (vector avg. in deg.)	Vane & digital Magnetic Compass/Vane & fluxgate compass/Vane & resistance potentiometer	0 to 355/ 0 to 360/ 0 to 355	1.28/ 1.00/ 0.50	2 min */ 8.5 min/ 2.0 min
Wind speed (unit scalar avg. m/sec)/(vector avg. m/s)/(unit scalar avg. in m/sec)	Vane-directed impeller	0 to 61.8/ 0 to 80.0/ 0 to 59.9	1.28/ 1.00/ 0.50	2 min */ 8.5 min/ 2.0 min
Wind gust (m/sec)	Vane-directed impeller	0 to 81.4/ 0 to 80.0/ 0 to 59.9	1.28/ 1.00/ 0.50	5 sec 8 sec **/ 3 sec ***/
Air temperature (°C)	Thermister	-40 to 50/ -15 to 50/ -1.1 to 37.8	1.28/ 0.01/ 0.50	2 min */ 90 sec/ 2.0 min
SST (°C)	Thermister	-5 to 40/ -15 to 40/ -1.1 to 37.8	1.28/ 1.00 ****/ 0.50	2 min */ 1 sec/ 2.0 min
Barometric Pressure (kPa)	Variable capacitance/ Variable capacitance/ pressure transducer	80 to 110/ 90 to 110/ 91.4 to 106.7	1.28/ 0.25/ 0.50	2 min */ 8.5 min/ 2.0 min

* Averaging period for sensors on the NDBC buoys is 8 min.

** Highest 8 sec window retained
*** Highest 3 sec window retained

**** Sampled only once during acquisition period using time constant

B. Coastal Tide Station Data

The National Ocean Service (NOS) of NOAA manages the National Water Level Observation Program. As such, it collects, processes and analyzes water level data from approximately 190 continuously operating tide stations in U.S. coastal waters, the Great Lakes, and U.S. territories and possessions.

The NOS tide stations presently use a stilling well with an analog-to-digital recorder (ADR) float driven gauge that records data at 6-minute intervals. The ADR timing is controlled by solid-state timers accurate to one minute per month. Each ADR measurement is an instantaneous discrete value measured with a resolution of 0.003 meters. There is a backup instrument which consists of a nitrogen gas pressure driven bubbler gauge. Timing is controlled by a spring-wound clock mechanism accurate to several minutes per month.

The NOS has implemented a Next Generation Water Level Measurement System (NGWLMS) which is being operated side-by-side with present systems to provide datum ties and data continuity with the historical time series at each tide station. These NGWLMS field units consist of a data collection platform and a downward looking acoustic sensor that sends shock waves down a sounding tube housed in a protective well. The leveling reference point is a known distance from the calibration point on the sounding tube. These known and measured distances are used to refer the data to station datum. The timing of the system is controlled by an oscillator located in the GOES satellite transmitter and is accurate to 2 seconds per month. The data are stored in memory and transmitted via the GOES satellite every three hours. Measurement samples consist of 181, one-second water level observations which are averaged; these samples are recorded at 6-minute intervals. The reported measurements have a resolution 0.001 meters. The characteristics of the instruments that are used to measure water level are given in Table 4.

The NOS tide stations located around the coasts of Florida and the rest of the Gulf coast are generally equipped with the ADR and backup bubbler gauges. The NGWLMS system has also been installed at many of these stations with dual data collection presently in effect. The specific locations, and sensor and measurement types for the water level data presented in the next section are given in Table 5.

C. Current Meter Data

In April 1992 a number of moored current meters were deployed on the Texas-Louisiana continental shelf as part of the Louisiana Texas Shelf Physical Oceanography Program (LATEX; Guinasso, 1992). Data from one particular instrument (mooring 14) acquired during the passage of Hurricane Andrew are reported here. Mooring 14, located at 90.493°W, 28.395°N in a water depth of 48 m, is a taut

Table 4. Instrument Descriptions.

Measurement	Sensor Type	Vertical Sampling Range (meters)	Sampling Period (minutes)	Averaging Period
Water Level	Analog-to-Digital Recorder	0-30	6	None
Water Level	Bubbler	0-6	Continuous	None
Water Level	Acoustic Sensor	0-15	6	1/sec burst for 3 min.

subsurface mooring with about 180 kg of flotation. An ENDECO Type 174SSM vector-averaging current meter was attached at 11 m below the surface on this mooring. This instrument samples current speed and direction approximately once per second, and every 30 minutes, records a vector-averaged current speed and direction plus instantaneous values of temperature and salinity. The time associated with one ensemble of observations is the time that corresponds to the end of that sequence. Data are recorded internally with a solid state memory and are retrieved each time the current meter is recovered and serviced.

D. Satellite Data

Satellite-derived SST analyses produced by NESDIS were used in constructing SST difference maps. In particular, high-resolution regional SST analyses produced on a ⅛° x ⅛° grid covering the SE Atlantic and Gulf areas were employed. The SSTs that enter these analyses are calculated from AVHRR satellite data using the NOAA/NESDIS multichannel SST retrieval technique (e.g., Walton, 1988). These analyses are produced twice per week using observations composited over an approximate 3½-day period. During periods of cloud cover, these analyses relax back to previous cloud-free values at the affected grid points until the next cloud-free observations are obtained. For additional details see McClain et al. (1985).

The particular SST difference fields presented in this study were calculated by simply subtracting the analyzed values for two successive analyses at each grid point over the analysis domains and then contouring the results. In each case, the earlier analysis has been subtracted from the subsequent analysis.

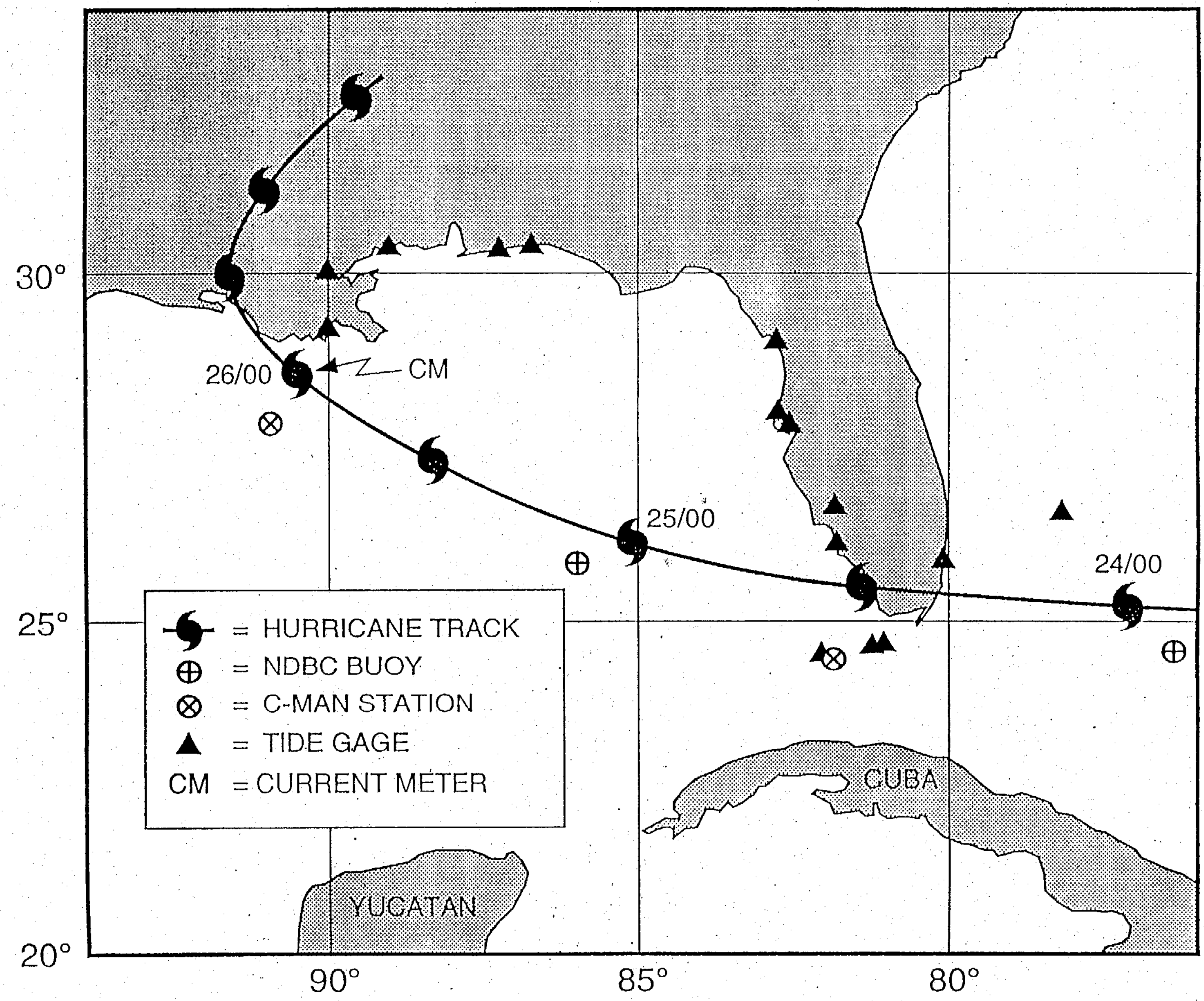

Figure 1: Track chart of Hurricane Andrew plus locations of NDBC buoys, C-MAN stations, NOS tide gage locations, and LA.TEX current meter.

Table 5. NOS Water Level Station Locations with Sensor and Measurement Types.

STATION	LATITUDE	LONGITUDE	SENSOR*	MEASUREMENT TYPE
SETTLEMENT POINT, BA	26.70°N	79.00°W	ADR**	DISCRETE
HAULOVER PIER, FL	25.90°N	80.12°W	ADR	DISCRETE
KEY COLONY BEACH, FL	24.72°N	81.02°W	ADR	DISCRETE
VACA KEY, FL	24.71°N	81.11°W	ADR	DISCRETE
KEY WEST, FL	24.55°N	81.81°W	ADR	DISCRETE
NAPLES, FL	26.13°N	81.81°W	ADR	DISCRETE
FORT MYERS, FL	26.65°N	81.87°W	ADR	DISCRETE
ST. PETERSBURG, FL	27.77°N	82.62°W	ACOUSTIC	AVERAGE
CLEARWATER BEACH, FL	27.98°N	82.83°W	ADR	DISCRETE
CEDAR KEY, FL	29.14°N	93.03°W	ADR	DISCRETE
PANAMA CITY BEACH, FL	30.21°N	85.88°W	ACOUSTIC	AVERAGE
PENSACOLA, FL	30.40°N	87.21°W	ADR	DISCRETE
BAY WAVELAND YACHT CLUB, MS	30.33°N	88.33°W	ADR	DISCRETE
GRAND ISLE, LA	30.12°N	89.22°W	ADR	DISCRETE
NEW CANAL, LA	30.03°N	90.11°W	ADR	DISCRETE

* This sensor provided the water level measurements presented in this study

** ADR = Analog-to-digital recorder

3. RESULTS

A. NDBC Buoy/C-MAN Observations

Sea level pressure, wind speed and direction, wind gust, air temperature and sea surface temperature (SST) data were acquired at four locations close to the track of Hurricane Andrew (Fig. 1) with the exception of BUSL1 (27.9°W, 90.0°W) where only wind speed and direction, wind gust and SST were available over the C-MAN network.[7] The approximate distance of each buoy or C-MAN station from the track is given in Table 6. Time series plots of sea level pressure, wind direction, wind speed, wind gust, air temperature, SST and sensible heat flux are presented for each location in Figs. 2-5. These parameters, with the possible exception of wind gust and sensible heat flux, are self-explanatory.

A wind gust corresponds to a brief (usually less than 20 seconds in duration) increase in wind speed and is usually followed by a lull or slackening in wind speed (Huschke, 1959). Wind gust as it is measured at the NDBC buoys and C-MAN stations represents the highest mean wind speed recorded for any 8-second window. For the BUSL1 station (27.9°N, 90.9°W), wind gust represents the highest mean wind speed recorded for any 3-second window. In Figs. 2-5, data on wind gust have only been included for the period surrounding the peak winds associated with the passage of the hurricane (i.e., ± 24 hours of the maximum value of wind speed).

For each location, the sensible heat flux (SHF) has also been calculated from the corresponding sea-air temperature difference and wind speed. A standard bulk aerodynamic formulation was used to perform these calculations (e.g., Kraus, 1972), where

$$SHF = c_p \rho_a \zeta (T_o - T_{10}) U_{10}$$

c_p is the specific heat of air, ρ_a is the air density, and ζ is a constant drag coefficient of the order of 2.0 x 10^{-3} (the value used here). T_o and T_{10} are the SST, and air temperature at a height of 10m, respectively, and U_{10} is the wind speed at 10m. When the SHF is positive, a transfer of heat from the ocean to the atmosphere is indicated, and vice versa. Although SHF is a derived rather than a measured quantity, it is a parameter which often represents an important source of energy for hurricane development and maintenance (e.g., Ooyama, 1969).

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[7]The barometric pressure is recorded at BUSL1, but is not transmitted over the C-MAN network. However, according to G. Forristall (personal communication), the minimum pressure on the platform was 29.50 in Hg.

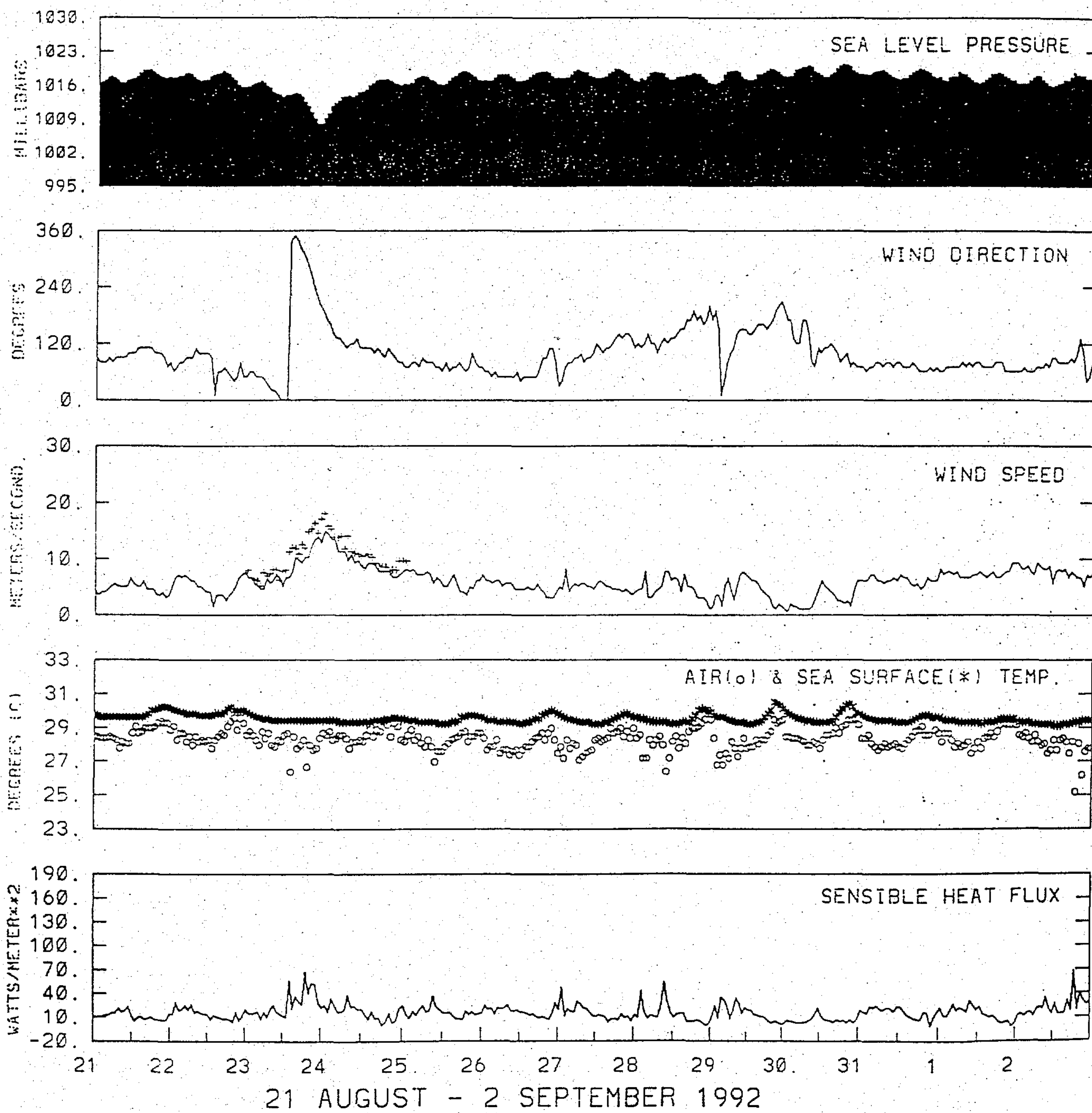

Figure 2. Hourly time series for sea level pressure, wind speed, wind direction, air temperature, SST, and sensible heat flux for 8/21/92 through 9/2/92. Buoy location is 24.6°N, 76.5°W.

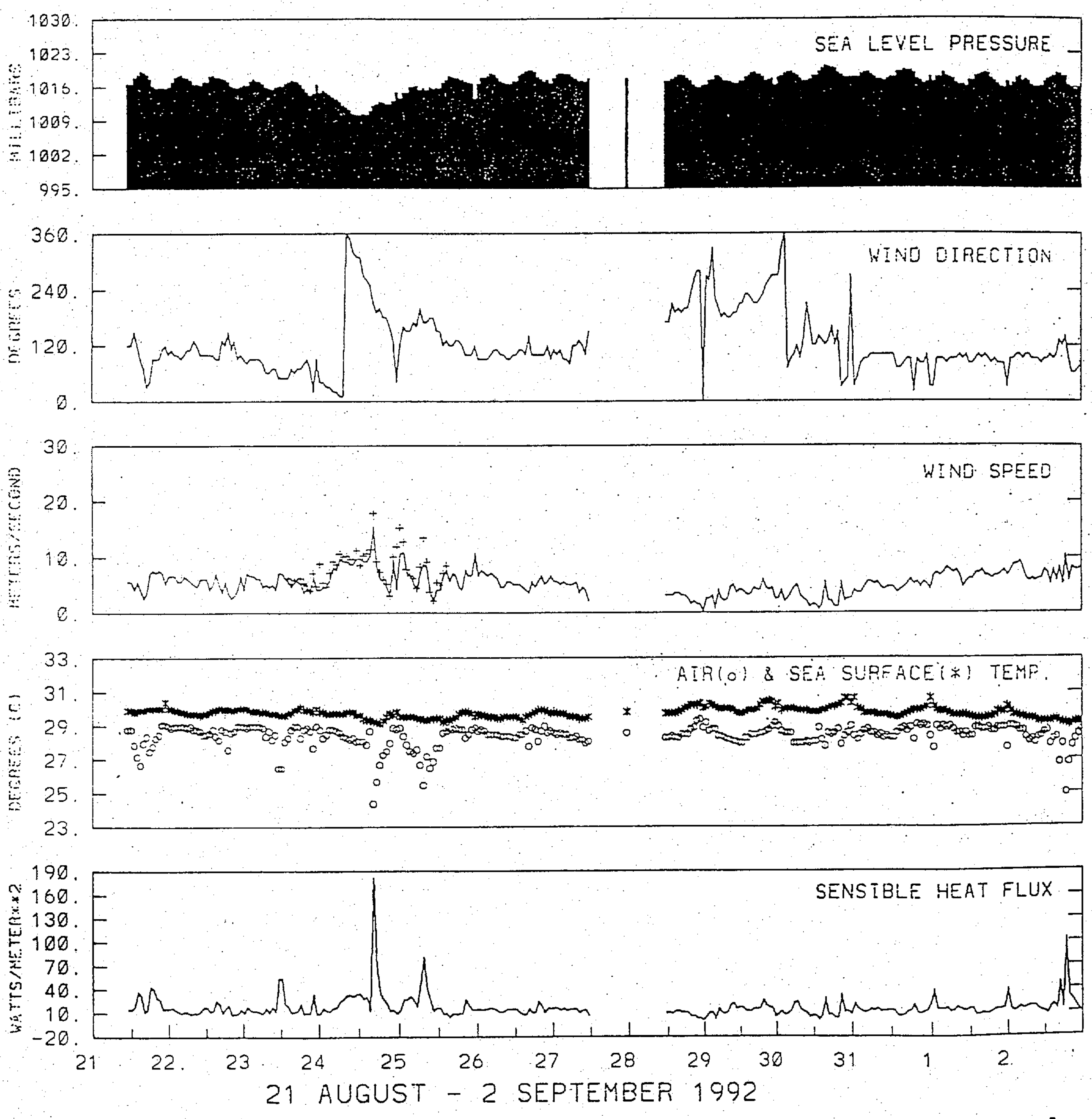

Figure 3. Hourly time series for sea level pressure, wind speed, wind direction, air and SST, and sensible heat flux for 8/21/92 through 9/2/92. C-MAN location is 24.5°N, 81.9°W.

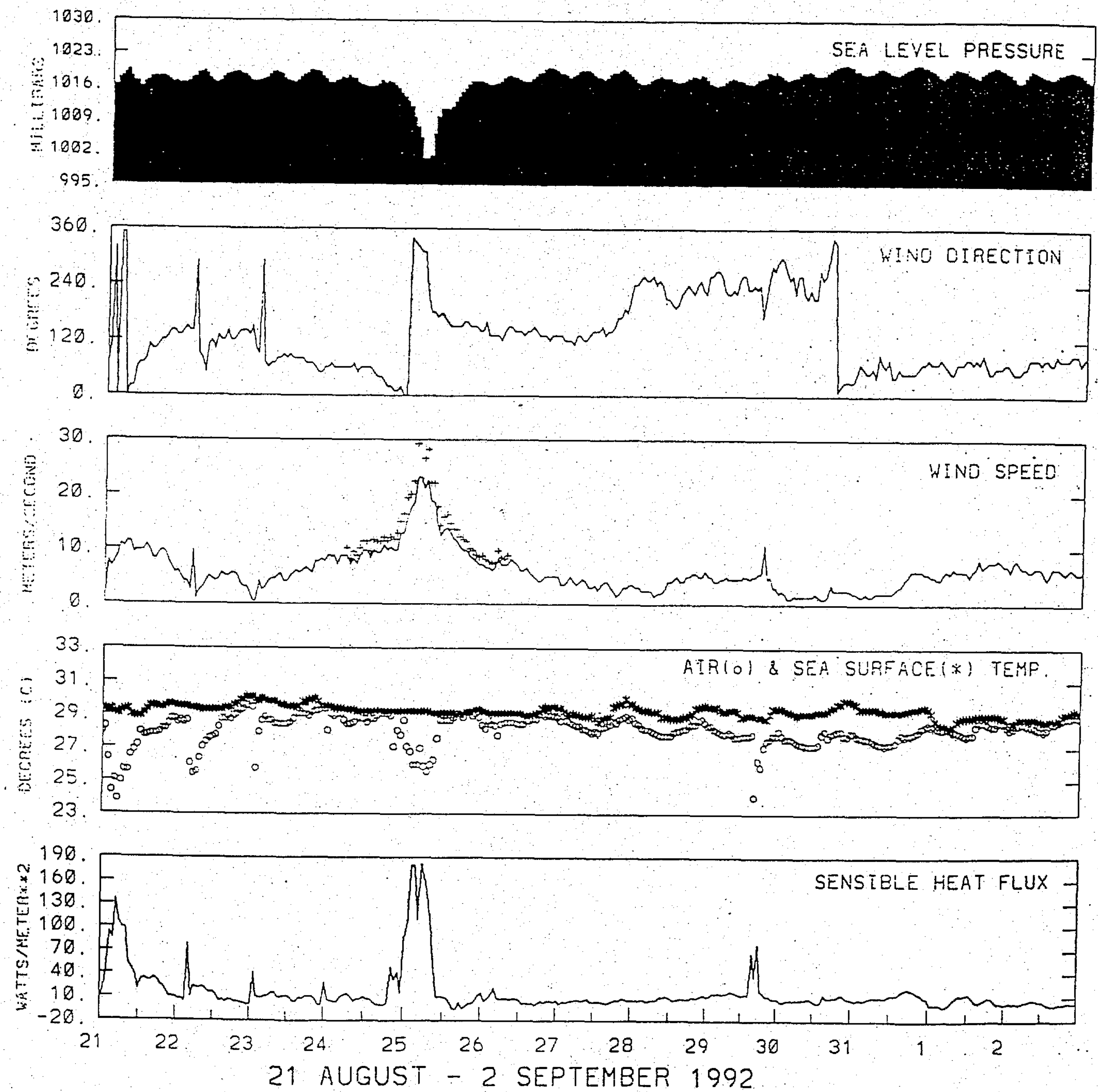

Figure 4. Hourly time series for sea level pressure, wind speed, wind direction, air temperature, SST, and sensible heat flux for 8/21/92 through 9/2/92. Buoy location is 25.9°N, 85.9°W.

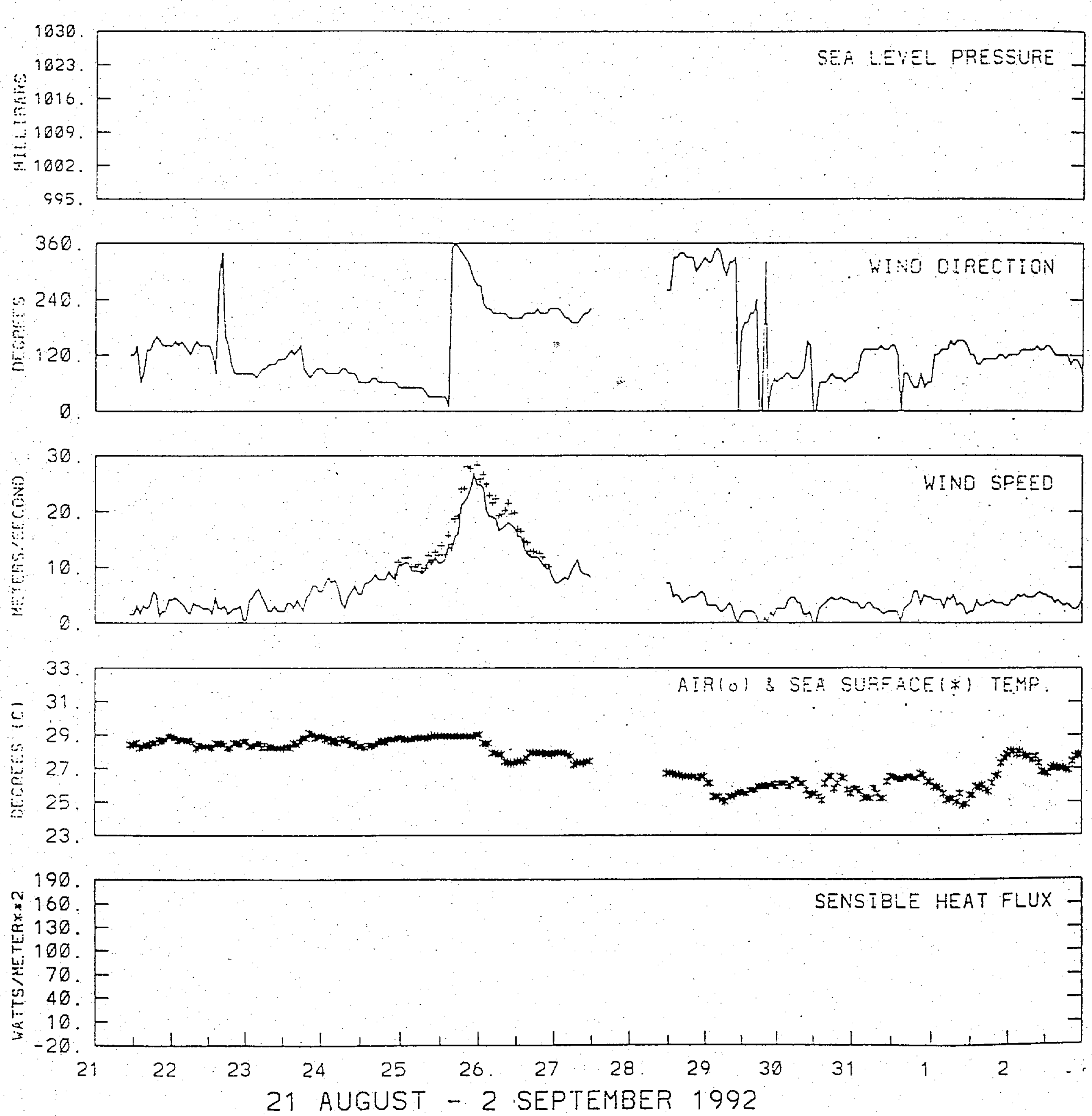

Figure 5. Hourly time series for wind speed, wind direction and SST for 8/21/92 through 9/2/92. C-MAN location is 27.9°N, 90.9°W. (Sea level pressure and air temperature were not available at this location and since air temperature was not available sensible heat flux could not be calculated.)

In addition to the distances between measurement location and the hurricane track, extreme values for sea level pressure, wind speed, wind gust and SHF are included. Also, the estimated maximum decrease in air temperature during the storm period is given. No measure of the change in SST is presented because this parameter showed only very small changes during the periods associated with the hurricane (<1°C).

From Table 6, there is at least a weak dependence on distance from the hurricane, for both the extreme values of sea level pressure and wind speed. The lowest sea level pressure (997 mb) and the highest wind (27 m/sec) were recorded at buoys 42003 and BUSL1, respectively, which were only about 63 and 97km from the track.[8] Even the maximum wind gust at BUSL1, however, did not approach the maximum winds reported for Hurricane Andrew elsewhere along its path (e.g., wind gusts of up to 78 m/sec were reported near Homestead Air Force Base in South Florida). Distance from the hurricane plus the fact that the wind observations were acquired at 10m, well below the level where wind maxima usually occur for hurricanes, most likely account for this apparent discrepancy.

Air temperature for the three locations where air temperatures were available dropped significantly in each case in contrast to SST which showed almost no change during the period of maximum winds. Thus, it was the decrease in air temperature (plus the increase in wind speed) that primarily contributed to the brief but large increases in SHF.

B. Water Levels

The water level response of the various NOS tide stations in operation during Hurricane Andrew vary in time and magnitude depending on the geographic location of the station in relation to the storm track. Figure 1 shows the tide station locations. Predicted water levels were computed using standard harmonic analysis and tide prediction algorithms (Shureman, 1958; Zetler, 1982). All elevations are relative to Mean Lower Low Water (MLLW), or chart datum, at each station. Table 7 shows the extreme water level elevations recorded during Hurricane Andrew compared with the historical extremes at each station. Storm surges were generated by subtracting the predicted water levels (i.e., the tides) from the observed water levels. Table 8 shows the extreme storm surge values for each station. The time series plots of hourly predicted and observed water level and of hourly storm surge are shown in Figs. 6-11.

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[8]The anemometers at BUSL1, however, are mounted at a height of approximately 94m, and so it is difficult to compare the wind speeds at this location with those at the other locations (since no adjustment to a standard height of 10m was made).

Table 6. Selected Statistics from NDBC buoys and C-MAN Stations Associated with Hurricane Andrew.

Station ID	Distance from Track* (km)	Min. Sea Level Pressure (mb)	Max. Wind Speed (m/sec)	Max. Wind Gust (m/sec)	Estimated Drop in Air Temp. (°C)	Maximum Sensible Heat Flux (W/m^2)
41016	78	1007.9	14.7	18.1	2.0	68
SANF1	133	1010.2	15.6	17.9	4.0	183
42003	63	997.4	23.4	30.6	3.5	183
BUSL1	97	**	26.6	32.3	**	**

* Estimated
** Not available; see footnote 5 in the text for additional information on the winds in the Gulf of Mexico

Table 7. Extreme Observed Water Level Elevations and Historical Data Comparison

	Hurricane Andrew Elevation Above MLLW (Meters)		Historical Elevation Above MLLW (Meters)	
STATION	DATE/TIME	ELEV.	DATE	ELEV.
Settlement Point, BA	*		1/87	1.38
Haulover Pier, FL	8/24 0854	1.65	11/84	1.43
Key Colony Beach, FL	*		10/90	1.05
Vaca Key, FL	8/24 1212	0.48	10/74	0.80
Key West, FL	*		9/65	1.21
Naples, FL (-)	8/24 1442	-0.84	3/88	-0.71
(+)	8/25 1424	1.11	12/72	1.87
Fort Myers, FL (-)	8/24 1812	-0.32	1/72	-0.62
(+)	8/25 1730	0.65	11/88	1.47
St. Petersburg, FL (-)	8/24 2206	-0.28	1/77	-0.69
(+)	8/25 1254	1.15	8/85	1.97
Clearwater Beach, FL (-)	8/24 1912	-0.61	1/77	-0.73
(+)	8/25 1254	1.37	8/85	1.86
Cedar Key, FL (-)	8/24 2212	-0.36	9/47	-1.24
(+)	8/25 1518	1.67	6/72	2.48
Panama City Beach, FL	8/25 1324	0.83	10/92	1.02
Pensacola, FL	8/26 1400	0.81	9/26	2.69
Bay Waveland, MS	8/26 1436	1.37	1/83	2.03
Grand Isle, LA	8/26 0054	1.16	10/85	1.46
New Canal, LA	8/26 2036	0.96	1/83	1.08

NOTES:

MLLW is Mean Lower Low Water, Times are UTC

- * Maximum water level elevations not significantly effected by Hurricane Andrew.
- (+) Extreme maximum water level.
- (-) Extreme minimum water level.

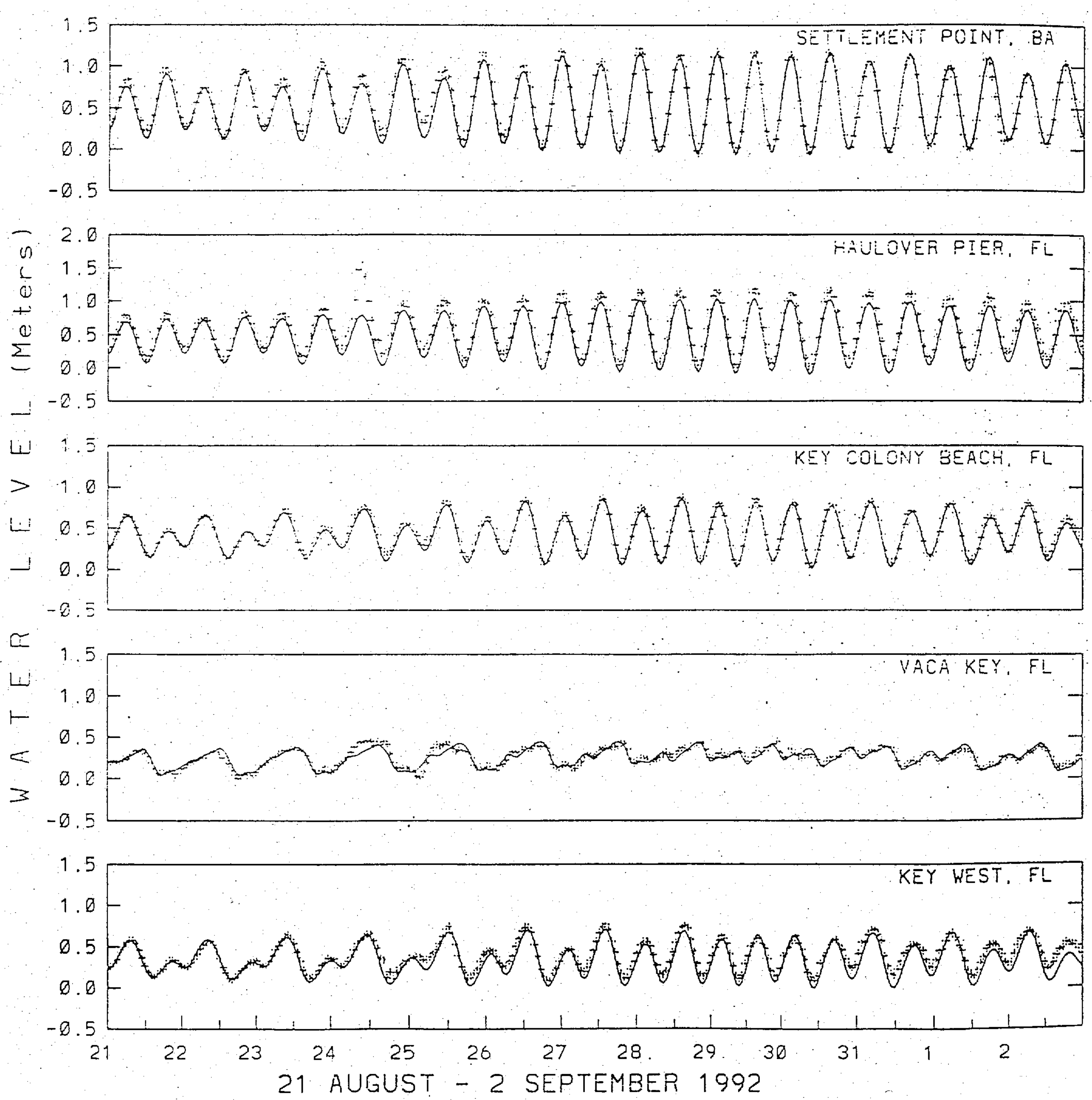

Figure 6. Observed and predicted hourly water level along the Florida east coast, Florida keys and Bahamas from 8/21/92 through 9/2/92 (see Table 4 for exact station locations).

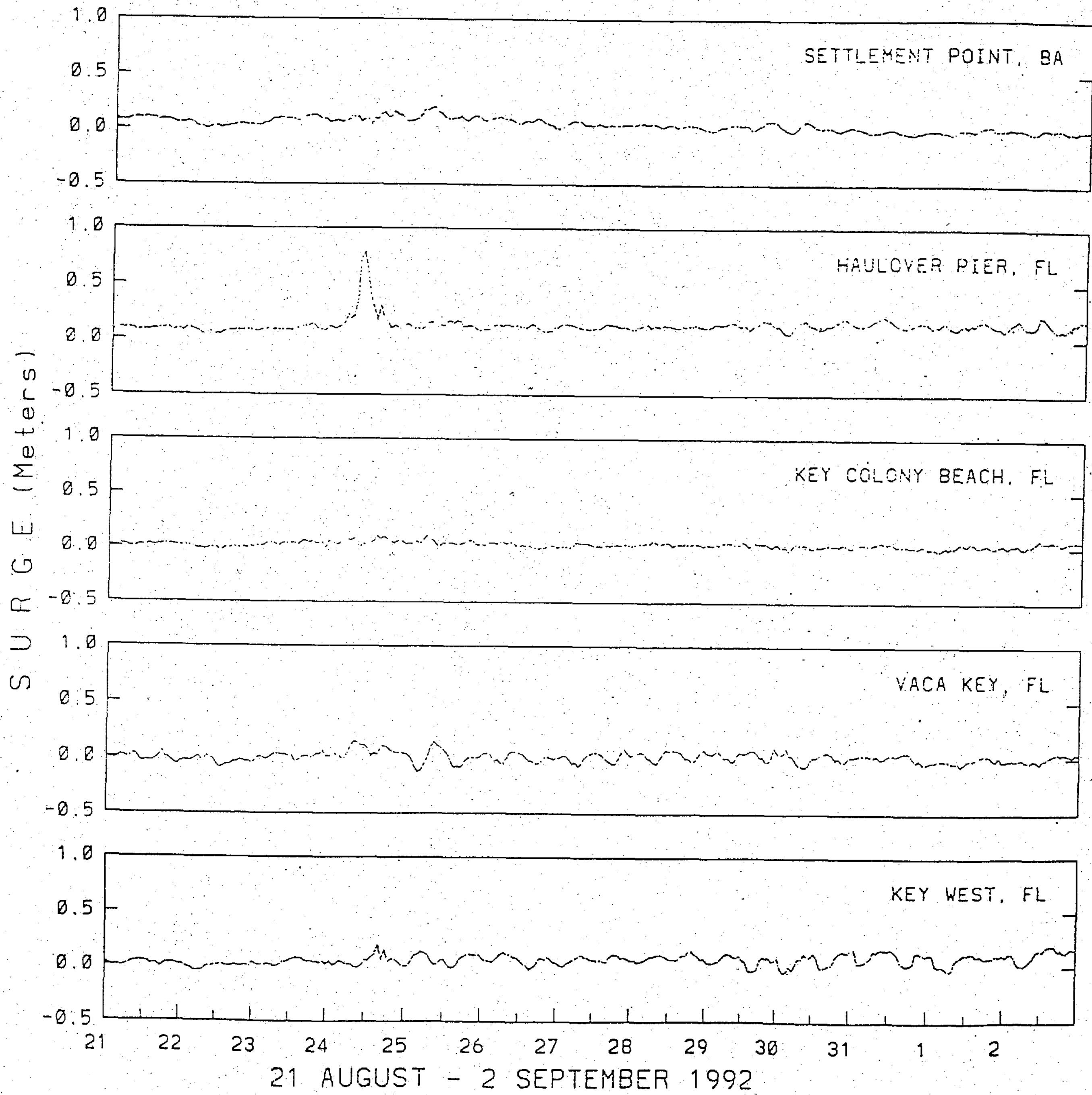

Figure 7. Storm surge along the Florida east coast, Florida keys and Bahamas from 8/21/92 through 9/2/92 (see Table 4 for exact station locations).

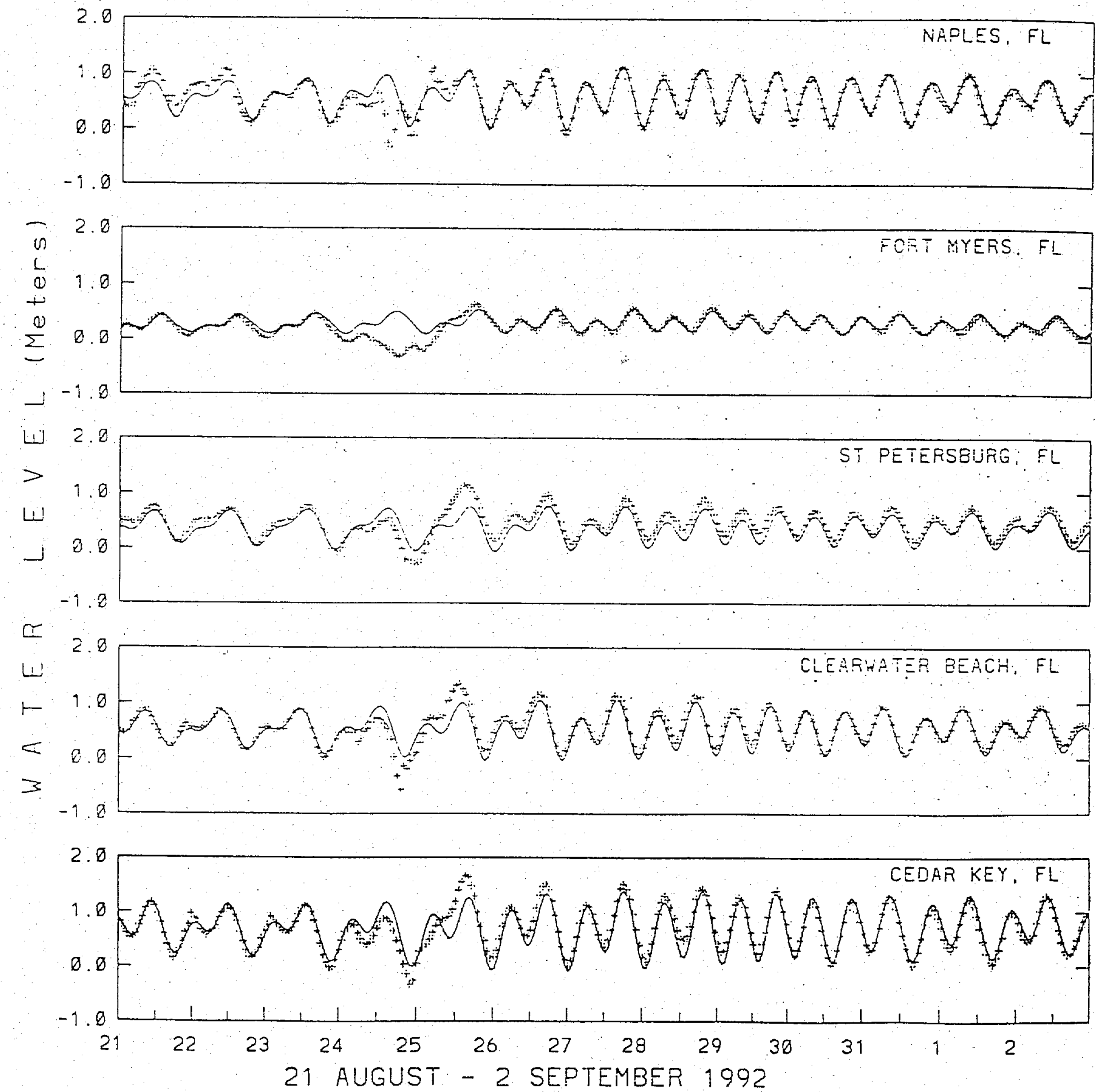

Figure 8. Observed and predicted hourly water level along the Florida west coast from 8/21/92 through 9/2/92 (see Table 4 for exact station locations).

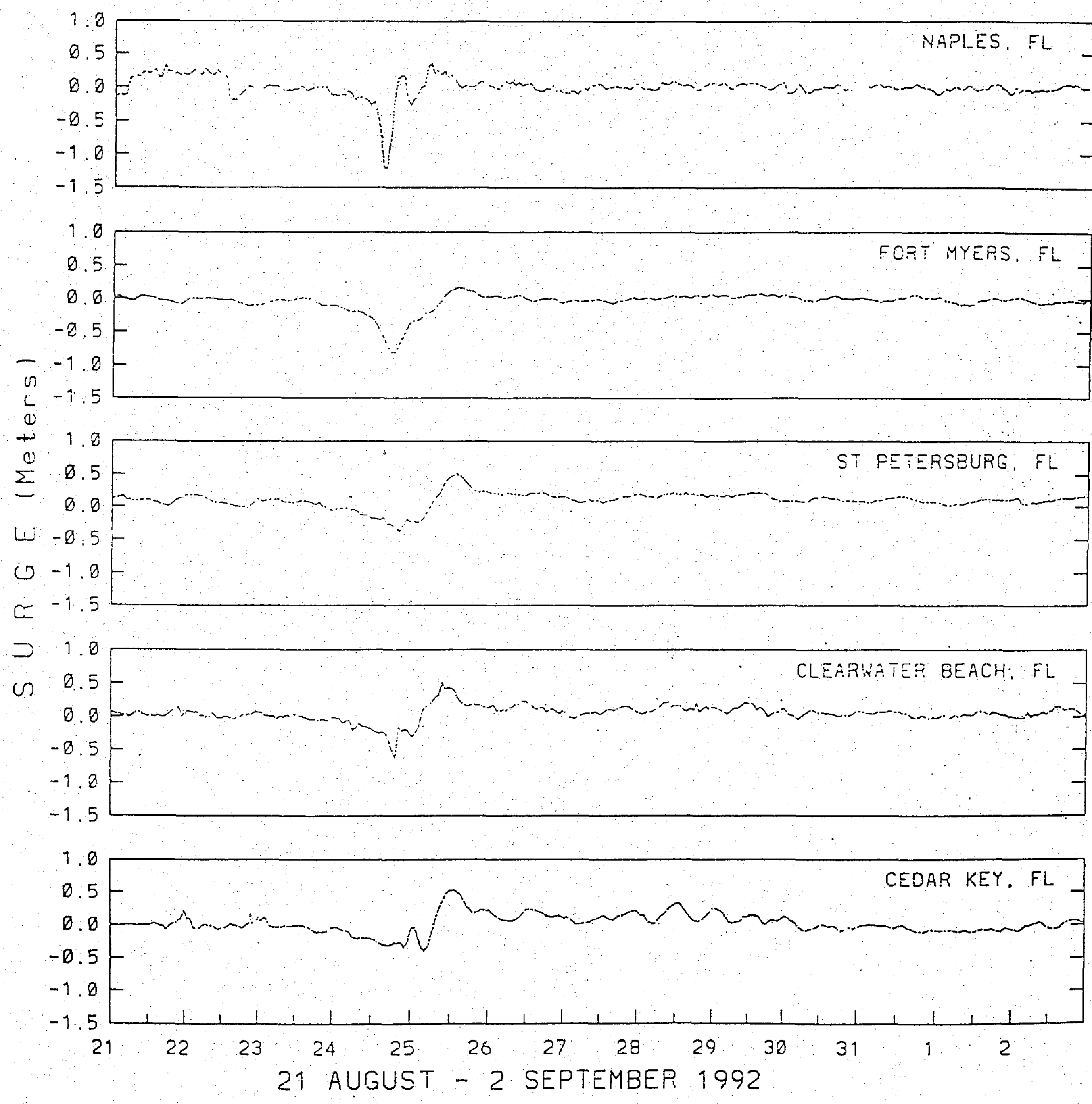

Figure 9. Storm surge along the Florida west coast, from 8/21/92 through 9/2/92 (see Table 4 for exact station locations).

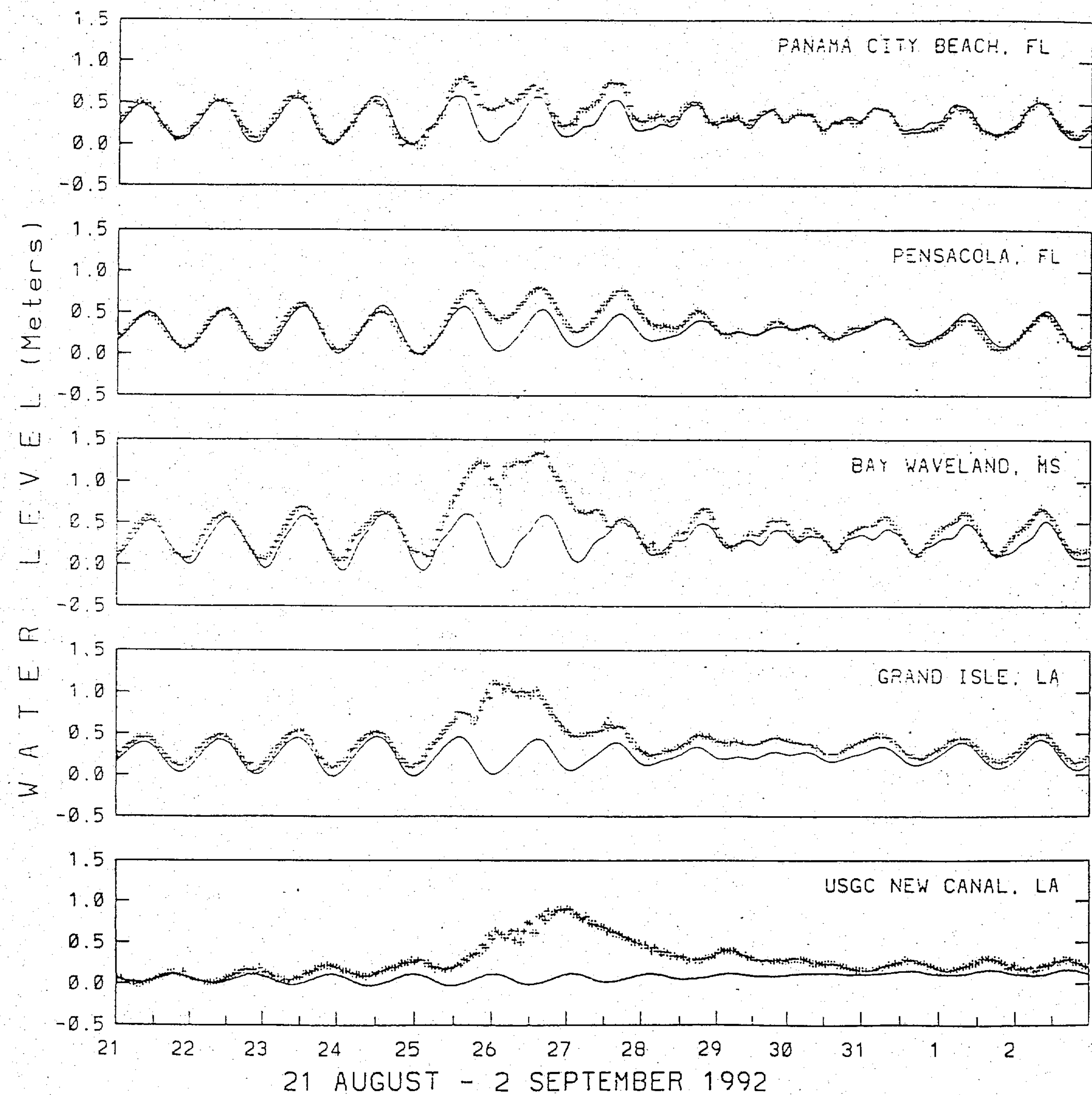

Figure 10. Observed and predicted hourly water level along the Florida panhandle and north gulf coast from 8/21/92 through 9/2/92 (see Table 4 for exact station locations).

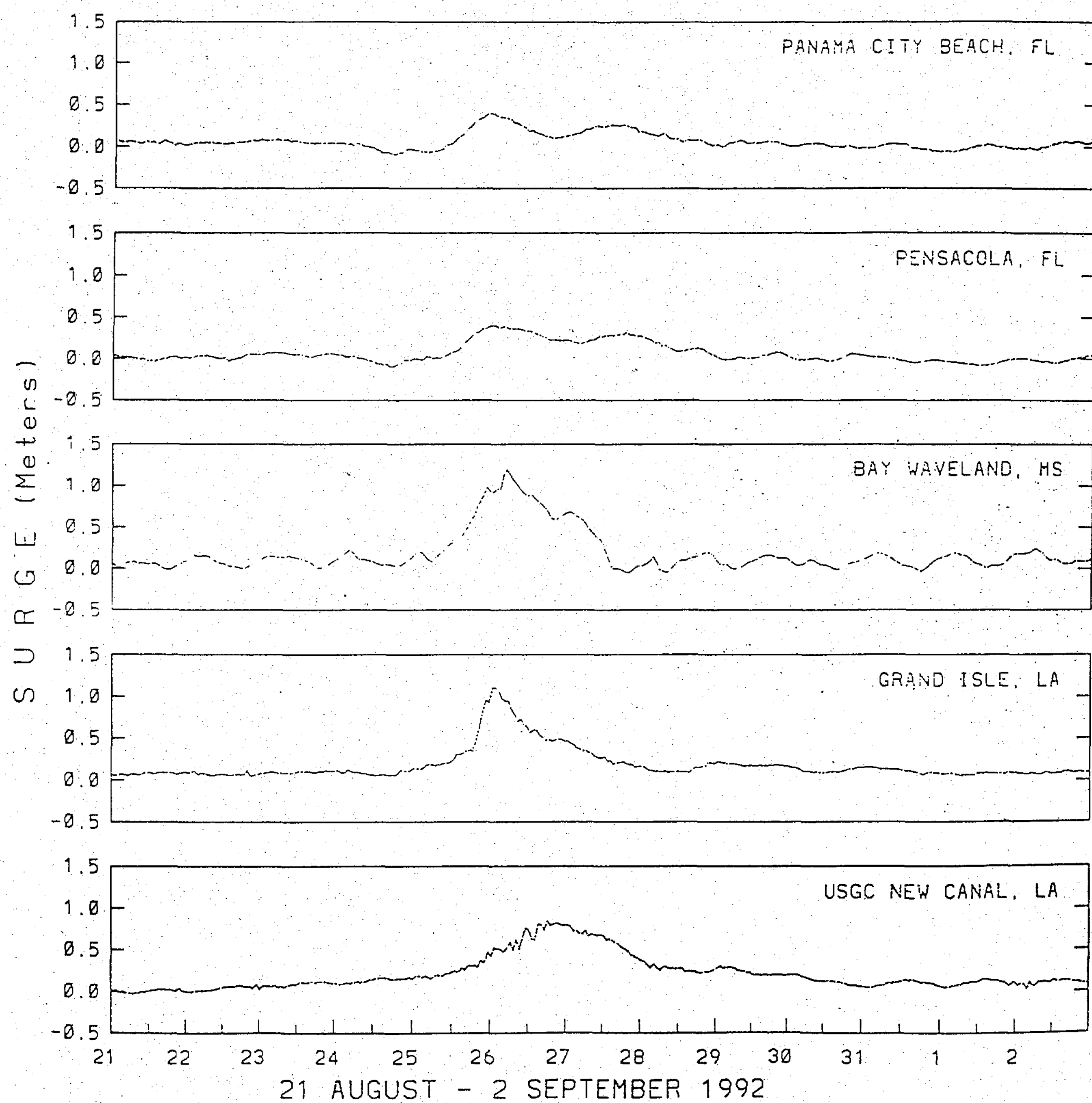

Figure 11. Storm surge along the Florida panhandle and north gulf coast from 8/21/92 through 9/2/92 (see Table 4 for exact station locations).

Early on 24 August 1992, Hurricane Andrew passed somewhat south of the Bahamas. No significant effect on water levels was observed at the Settlement Point tide station (Figs. 6 and 7). Andrew struck Florida on 24 August 1992 at approximately 0900 UTC. The tide station at Haulover Pier, in North Miami Beach, located approximately 50 km north of the point where the hurricane made

landfall, recorded a maximum water level of 1.65 m above MLLW, exceeding the historical maximum by 0.22 m (Fig. 6; Table 7). The maximum storm surge, 0.79 m above MLLW (Fig. 7; Table 8), occurred at 0900 UTC near the expected time of high water.[9]

Data received from NOS tide stations in the Florida Keys show that as the eye of Andrew crossed Florida, storm effects on water level south of the hurricane track were small (Figs. 6 and 7). The record for Key Colony Beach does, however, show slightly elevated water levels for the day immediately following the hurricane. Also, the Vaca Key record shows that high waters on 24 and 25 August 1992 were earlier than predicted.

Along the Florida west coast, negative elevations in water level were observed near the hurricane track while the storm center was still located over land (Figs. 8 and 9). Naples, the closest station to the eye of the hurricane, recorded a drop in elevation that exceeded the lowest historical elevation by 0.13 m. The drop in water level occurred at the predicted high water, resulting in a negative surge of -1.21 m.

A comparison of Clearwater Beach, located on the Gulf coast, and St. Petersburg, located on the western shore of Tampa Bay, shows the varying effects of the hurricane on two stations located at approximately the same latitude, but geographically different in relation to the storm track (Figs. 8 and 9). Clearwater Beach shows a more intense negative surge (-0.62 m) and lower water level elevations than St. Petersburg (-0.34 m). Although St. Petersburg was actually closer to the storm center, the restricted flow within Tampa Bay moderated the response to the storm.

After Hurricane Andrew entered the Gulf of Mexico, a moderate increase in water level and surge was observed along the Florida panhandle (Figs. 10 and 11). Storm surge plots for the Florida panhandle also show a secondary maximum on 27 August 1992.

After landfall in Louisiana, Hurricane Andrew proceeded north and then NE passing to the west of Lake Pontchartrain. The tidal records at New Canal, on the eastern shore of Lake Pontchartrain,

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[9]The pier and the tide gauge sustained considerable damage from the hurricane, and data transmissions ceased at ~0900 UTC on 24 August 1992, but subsequent data were acquired and retrieved from internal storage.

Table 8. Storm Surge Elevation Above MLLW (Meters)

STATION	DATE/TIME	OBSERVED	PREDICTED TIDAL AMPLITUDE	SURGE
Settlement Point, BA	*			
Haulover Pier, FL	8/24 0900	1.59	0.80	0.79
Key Colony Beach, FL	*			
Vaca Key, FL	8/24 0800	0.44	0.29	0.15
Key West, FL	*			
Naples, FL (+)	8/24 0400	1.12	0.74	0.38
(-)	8/24 1400	-0.24	0.97	-1.21
Fort Myers, FL (-)	8/24 1700	-0.30	0.50	-0.80
(+)	8/25 1300	0.45	0.27	0.18
St. Petersburg, FL (-)	8/24 1900	0.00	0.34	-0.34
(+)	8/25 1300	1.09	0.58	0.51
Clearwater Beach, FL (-)	8/24 1900	-0.55	0.07	-0.62
(+)	8/25 0900	1.05	0.53	0.52
Cedar Key, FL (-)	8/25 0400	0.52	0.80	-0.27
(+)	8/25 1300	1.42	0.76	0.66
Panama City Beach, FL	8/25 1800	0.61	0.20	0.41
Pensacola, FL	8/26 0200	0.44	0.05	0.39
Bay Waveland, MS	8/26 0400	1.19	0.00	1.19
Grand Isle, LA	8/26 0000	1.12	0.01	1.11
New Canal, LA	8/26 1800	0.89	0.05	0.84

NOTES:

Storm surge = Observed minus predicted elevations
MLLW is Mean Lower Low Water datum; Times are UTC
*   No tidal surge effect by Hurricane Andrew.
(-) Negative tidal surge.
(+) Positive tidal surge.

indicate that highest water and maximum surge did not occur until the evening of 26 August 1992 (Figs. 10 and 11). High water and surge were sustained through 27 August 1992 at this location.

C. Current Meter Observations

The ENDECO current meter attached to LATEX mooring 14 (Fig. 1) at 11m below the surface responded dramatically to the passage of Hurricane Andrew (Fig. 12). Mean current speeds at this location averaged about 9 cm/sec and did not exceed 19 cm/sec during the period from 21 to 24 August. The eye of the storm passed about 10 km east of the mooring at about 2300 UTC on 25 August. Current speeds began increasing shortly after 1200 UTC on the 25th with a direction of flow to the southwest approximately parallel to the local bathymetric contours. Current speeds of 134 cm/sec were reached as the eye passed, and current speeds greater than 100 cm/sec to the southwest were maintained for three hours after passage of the eye although the direction of the prevailing wind had changed such that it opposed the current. A slight decrease in current speed occurred at the time when the eye passed closest to the current meter and may have reflected the effect of the opposing wind stress.

Following passage of the eye, currents rotated clockwise producing a series of oscillations that continued for the next 4 to 5 days. The period of these oscillations is approximately 24 hours, consistent with an inertial response at this latitude (i.e., 28°N). Current speeds decreased rapidly from their maximum value at about 0000 UTC on the 26th, reaching a minimum value at about 1200 UTC on the same day. From about 1300 to 1900 UTC on the 26th, the currents were directed offshore at about 190 degrees (SSW). At 1900 UTC, currents again increased and flowed approximately parallel to the local bathymetric contours. The strong southwesterly flow reached a second maximum of 88 cm/sec at 0000 UTC on the 27th.

The current velocities resulting from the passage of Andrew were most likely produced by (1), the superposition of a large-scale southwesterly flow parallel to the local bathymetry and driven by the cross-shelf pressure gradient, (2), inertial oscillations generated by the impulsive nature of the storm passage, and (3), to a lesser extent, flow driven by the local wind stress.

As the eye of Hurricane Andrew approached mooring 14, the temperature decreased and the salinity increased (Fig. 12, lower two panels), most likely caused by vertical mixing and upwelling of deeper, colder and higher salinity water with the overlying warmer and fresher waters. Finally, the initial maximum in current speed associated with the passage of Andrew coincided closely with the time of high water at Grand Isle (Figs. 10 and 11).

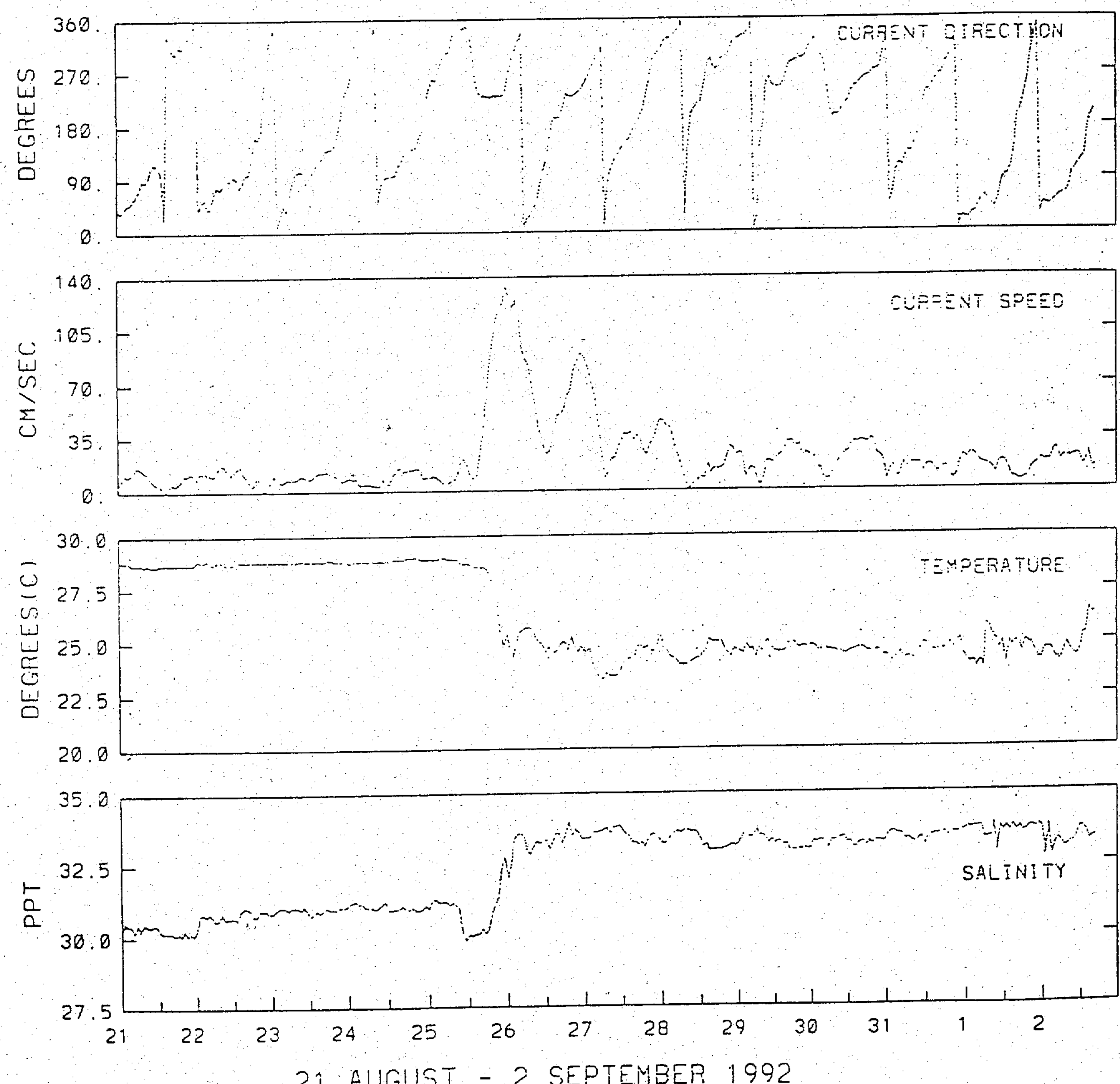

Figure 12. Current speed and direction, temperature and salinity at a depth of 11 meters. Bottom depth is 47 meters. Location is 90.49°W, 28.39°N.

D. Satellite SST Differences

Fig. 13 shows the change in SST between 18 and 29 August 1992 (i.e., 8/29/92 minus 8/18/92) for the SE Atlantic region (18°-32°N, 70°-85°W). Since the hurricane did not pass through the region until 24 August, most of this change occurred between 24 and 29 August. SSTs were generally isothermal prior to the passage of Andrew with temperatures off the east coast of Florida and in the Bahamas averaging around 30°C (not shown), about 1°C warmer than climatology for this area (Robinson et al., 1979). Andrew moved westward between 25°N and 26°N as it approached Florida. SSTs cooled by as much as 2°C in areas which were generally north of Andrew's track (Fig. 13). This cooling was undoubtedly related to the processes of mixing and upwelling which are normally associated with hurricanes (e.g., Black et al., 1988; Black, 1983; Leipper, 1972). The appearance of pockets or local areas of cooler water rather than a more continuous band of cool water may have been due to intermittent cloud cover which affected the satellite based SST analyses.[10]

SSTs in the Gulf also tended to be isothermal with temperatures averaging close to 30°C at this time. The observed SSTs were generally 0.5-1.0°C higher than climatology. The greatest cooling between 18 and 29 August 1992, occurred along, and just north of, the hurricane track (Fig. 14). Most of this cooling undoubtedly took place between 25 and 29 August. Again, the cooling is not continuous along the track but appears as pockets of cooler water which, as indicated before, may have been due to partial cloud cover. Surface temperatures were reduced by as much as 2°C in some areas. Also of interest in this case, is the rather linear boundary of no change (i.e., the 0°C contour) which extends from Yucatan, Mexico to the south Texas coast (25°-26°N). Surface waters south of this line generally increased in temperature suggesting a prevailing southward transport together with an accumulation of warmer surface waters due to the hurricane-related winds.

4. DISCUSSION

We include in this section a discussion of several topics related to the results of the previous section to improve our understanding of the impact of Hurricane Andrew on the near-surface marine environment. A number of dynamical and thermodynamical processes

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[10]Although clouds may have hidden some of the cooling which occurred near the hurricane track, areas where significant decreases are indicated (i.e., -1 to -2°C), are most likely representative due to the conservative nature of the cloud screening algorithms employed in producing these SSTs (e.g., McClain et al., 1985).

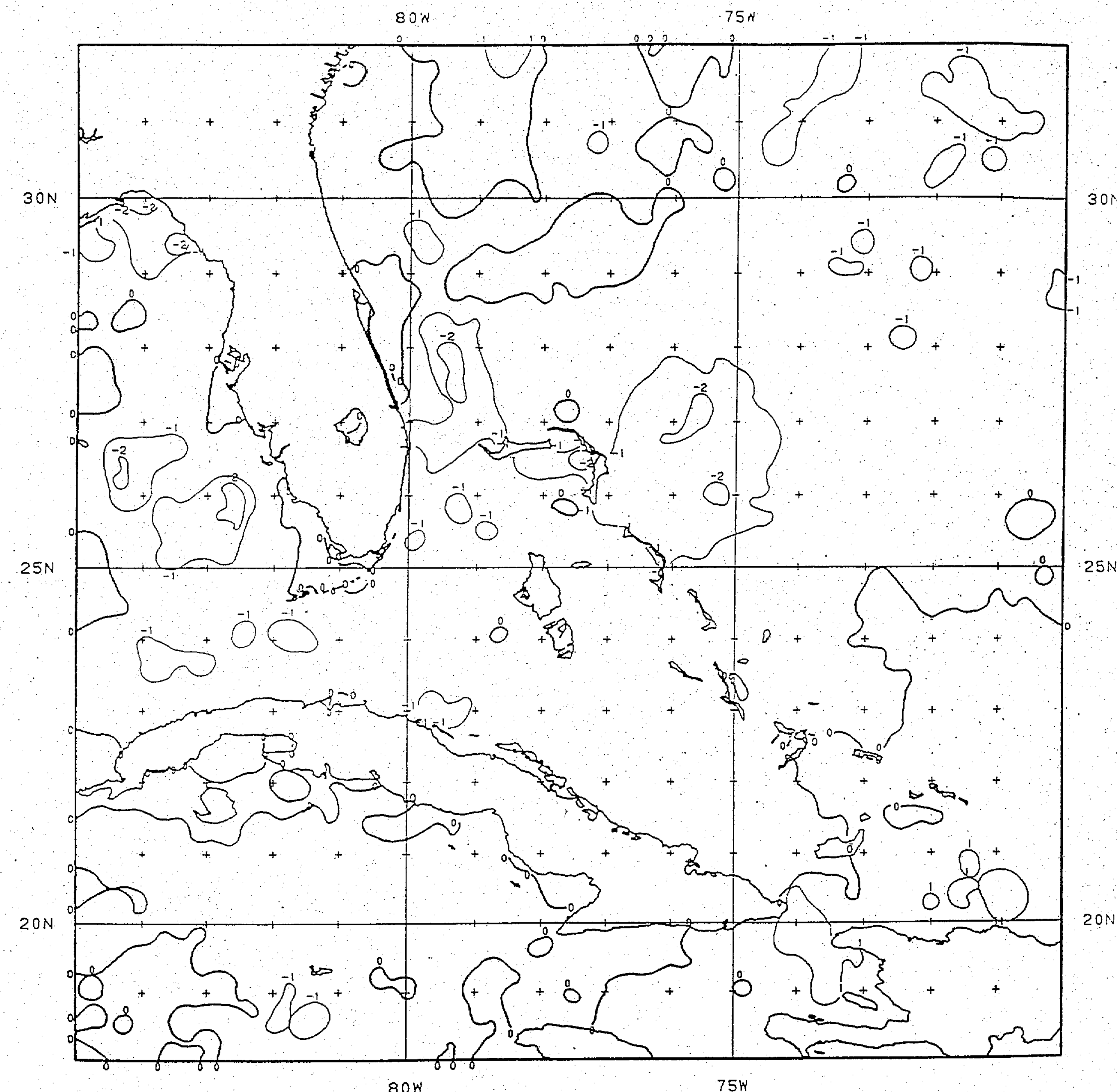

Figure 13. Difference in SST (satellite-derived) between 8/29/92 and 8/18/92 for the SE Atlantic region.

lead to cooling at the sea surface due to the passage of a hurricane. For example, mixing in the oceanic surface layer may produce cooling at the surface since temperatures at depth (within the layer) may be slightly lower than temperatures at the surface. Entertainment of cooler waters at the bottom of the surface layer together with mixing also causes SST to decrease as a result of strong wind forcing at the surface. Upwelling in the thermocline due to rotational wind motion in the hurricane raises deep cooler waters to shallower levels and thus can also contribute to cooling at the surface. The loss of heat across the sea surface from the ocean to the atmosphere due to the sensible and latent fluxes of heat also contributes to lowering SST.

Thus, it was initially surprising that the SST at each of the buoy and C-MAN stations remained virtually unchanged during the passage of Hurricane Andrew. However, upon closer inspection we note that each of the measurement sites was located south, or to the left, of the hurricane track. Both observations and theory clearly indicate that maximum reductions in SST occur to the right of hurricanes (e.g., Chang and Anthes, 1978; Price, 1981). Also, Hurricane Andrew was a relatively small [maximum winds occurred 15-20 km from the center of the storm (E. Rappaport, personal communication)], rapidly-moving storm and consequently might have been expected to have less effect on SST than a larger, slower-moving storm particularly at sites located well beyond the radius of maximum winds. Even to the right of the storm the maximum reductions in the satellite-derived SSTs were only about 2°C (Figs. 13 and 14). The apparently strong response in temperature (a decrease of ~4°C) and salinity (an increase of 2-3 ppt) at the current meter mooring reflects not only its close proximity to the storm track but also that hurricane-forced upwelling may have reached the level of the current meter (11 meters) but not the surface (or at the surface with much less effect).

Water levels provide another indication of the somewhat spatially restricted influence of Hurricane Andrew. Andrew had little effect on water levels at most tide stations along the east coast of Florida down to the Florida Keys. The only site where a significant increase in water level was observed was at North Miami Beach located about 50 km north of the storm track. However, land survey information from the Hurricane Response Team of the Army Corps of Engineers, indicated much higher storm surges near the location where the eye made landfall.

At Naples, on the west coast of Florida, a record decrease in water level was observed. The negative surge was caused by surface winds which transported water away from the coast while the eye of the hurricane was still over land. The marked decrease in water levels along the west coast of Florida was greatest near the storm track and diminished rapidly with distance to the north.

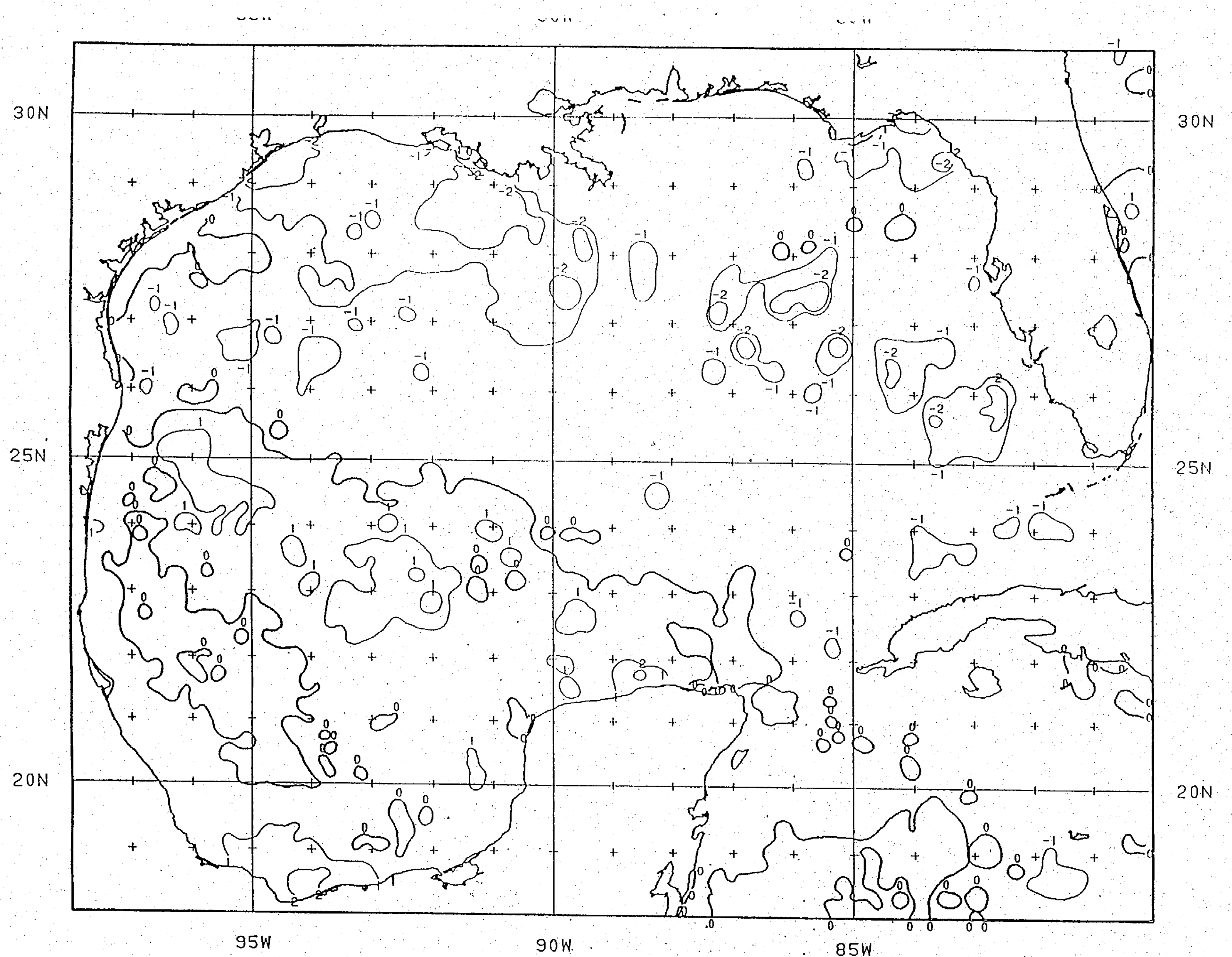

Figure 14. Difference in SST (satellite-derived) between 8/29/92 through 8/18/92 for the Gulf of Mexico.

Along the Florida panhandle westward to Louisiana, significant increases in water level were observed, but in no case did they exceed historical maxima. Water levels were elevated for several days during and after the storm, however, resulting in an extended surge from western Florida through eastern Louisiana. The direction of the sustained winds plus a shallow shelf together with the physical barrier effect of the Mississippi delta caused an accumulation of water along the northern Gulf coast and the Mississippi Sound area.

The secondary maximum in storm surge observed along the Florida panhandle on August 27 was most likely due to a basin oscillation (i.e., seiche) generated after passage of the hurricane.

Hurricane Andrew made its second landfall on August 26, 1992 at 0830 UTC in south-central Louisiana. The tide station closest to the hurricane was at Grand Isle. Lower storm intensity together with low tide at the time of landfall limited water elevations and storm surges from exceeding historical maxima; however, tide stations south of Grand Isle, at Cocodrie and South Pass (not shown) were inundated and ceased operation before the peak of the storm. Incomplete water level records indicated that historical maxima had been exceeded at both stations.

Water levels in Lake Ponchartrain were strongly influenced by the passage of Andrew. The hurricane-related winds forced waters on the western side across the Lake and to the eastern shore. The ensuing rainfall and winds were responsible for the prolonged elevated water level and surge at this location.

5. SUMMARY

Various oceanographic and meteorological data have been presented to demonstrate the impact of Hurricane Andrew on surface and near-surface conditions in the Bahamas, around the coast of Florida, and in the Gulf of Mexico and along its borders. Sea level pressure, wind direction, wind speed, wind gust, and air temperature were significantly influenced by the hurricane in most cases. SST at the buoy and C-MAN station locations, however, experienced virtually no change during passage of the storm. The degree of impact on the parameters that were affected was somewhat related to the distance between the hurricane and the observing site. In this regard, maximum buoy and C-MAN-reported winds never approached the maximum winds reported near the center of the hurricane. Maximum wind speeds of approximately 27 m/sec with maximum gusts of up to 32 m/sec, for example, were reported in the northern Gulf of Mexico (27.9°N, 90.9°W) at a distance of about 100 km from the storm track.

Water levels were not strongly affected by the storm in the Bahamas and along most of the east coast of Florida; however, a record high water level was observed at North Miami Beach during passage of the hurricane. Major decreases in water level were observed along the west coast of Florida with a maximum surge of -1.2 meters occurring at Naples. Conversely, major increases in water level occurred at several locations along the Gulf coast between the Florida panhandle, and Louisiana. At Bay Waveland, Mississippi for example, a storm surge of +1.2 meters was observed. Also, water levels were almost certainly higher than historical maxima along the western shore of the lower Mississippi delta.

Current meter data at one location along the hurricane track in the northern Gulf of Mexico (28.4°N, 90.5°W) indicated that current speeds at a depth of 11 meters increased from ~15 cm/sec to almost 140 cm/sec during passage of the storm. Temperature at this depth decreased by almost 4°C and salinity increased by 2.0 to 3.0 ppt. Finally, difference maps of satellite-derived SST for the period 18 to 29 August showed decreases of 1-2°C at various locations along, and just north of, the storm track.

6. ACKNOWLEDGMENTS

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