HURRICANES ANITA AND BABE

BY

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ABSTRACT

Hurricane Anita formed in the central Gulf of Mexico on August 29, 1977, and strengthened as she moved westward to a landfall on the northern coast of Mexico on September 2. Although Anita was never very close to the Ocean Current Measurement Program stations, she caused a long period of gale force winds at the stations and a maximum wave of 38 feet at Station 2. A complete set of current data was not obtained, but the maximum recorded current speed was 1.2 ft/sec. Shortly after Anita moved ashore, hurricane Babe formed in the central Gulf and passed very close to Station 2 before going ashore near Morgan City on September 5, 1977. Babe was a weak storm. The maximum wave recorded at Station 2 before the batteries failed near the center of the storm was 20 feet. Only the deepest current meter at Station 2 was recorded during Babe and the maximum current speed there was 1.4 ft/sec.

KEY WORDS: Hurricane Anita, 1977, hurricane Babe, 1977, meteorology, wave height, wave period, wave spectrum, water current, data analysis, Mexico Gulf, measuring, salinity, temperature, barometric pressure, digitization, current meter, oceanography, wind.

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PURPOSE AND SCOPE

The Ocean Current Measurement Program (OCMP) was begun with a pilot station at the Buccaneer platform south of Galveston (OCMP 1 in Figure 1) in 1971. The following year, the program was extended to three stations which were operated more or less continuously through the end of 1976. In the summer of 1977, Stations 2 and 3 were reactivated for the hurricane season. Although Station 1 was not officially part of the program for 1977, some special measurements were also made there for various purposes.

The OCMP instrumentation system was designed primarily for the study of wind generated currents, particularly those caused by hurricanes. However, auxiliary wind, wave, and barometric pressure instrumentation has greatly added to the usefulness of the measurements. The instrumentation system is described in References 1 and 2. Important data were obtained by the project in tropical storm Delia in 1973,[3] hurricane Carmen in 1974,[4] and hurricane Eloise in 1975.[5] In late August of 1977, hurricane Anita formed in the central Gulf of Mexico and affected the OCMP stations as she moved westward to a landfall in northern Mexico as shown in Figure 1. Shortly thereafter, weak hurricane Babe formed almost in the wake of Anita and eventually made landfall on the central Louisiana coast.

The main purpose of this report is to describe the measurements made by the OCMP stations in hurricanes Anita and Babe. The scope of the report is specified and limited by its function as the storm report mentioned in the contract with the OCMP outside participants. In order to make the report as useful as possible, we have also included in it a large amount of data collected by others. The report begins with a description

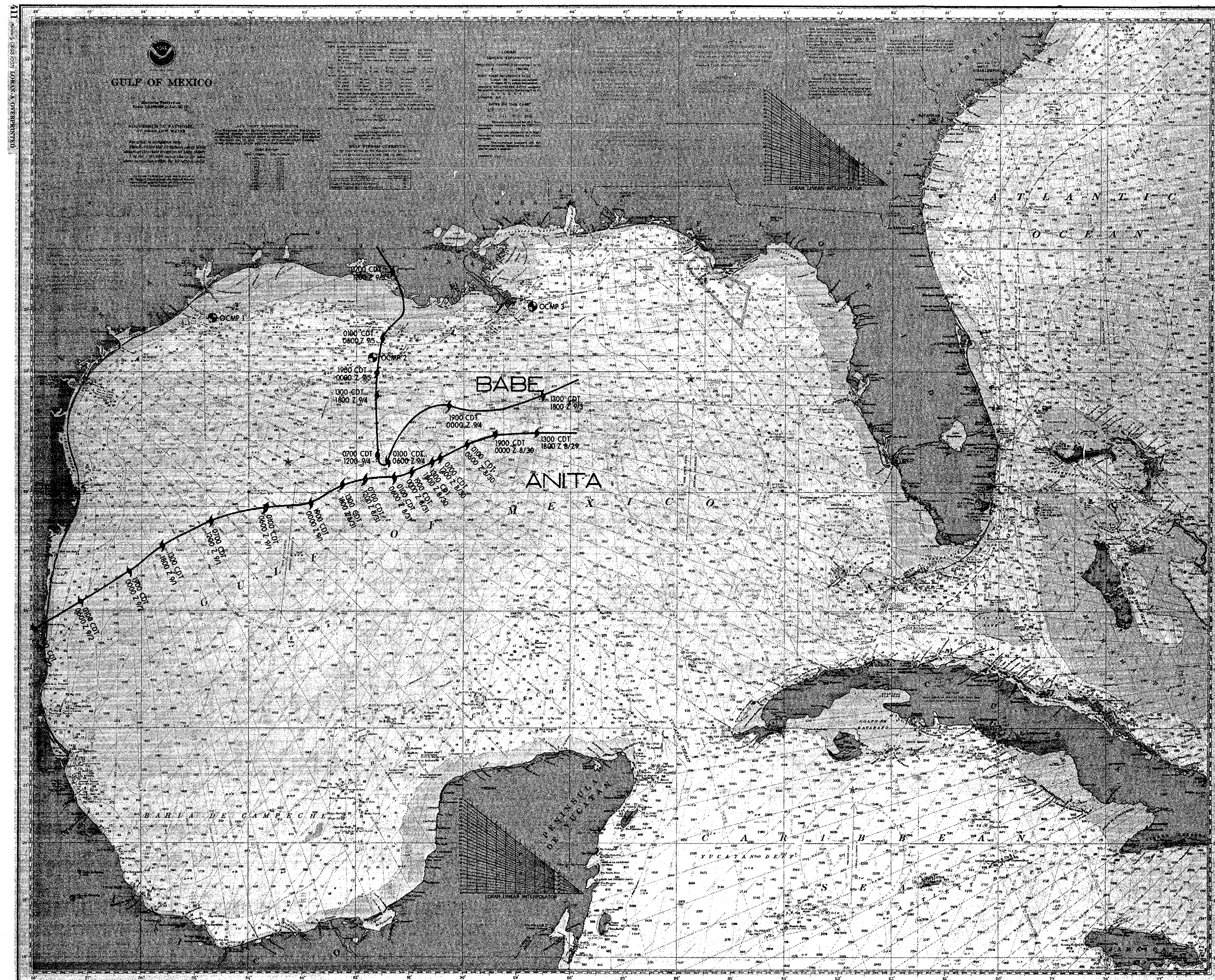

Fig. 1 - Storm tracks of hurricanes Anita and Babe.

of the meteorology of the storms. The operation of the measurement stations during the storms is then discussed and the methods of data analysis used are described. Finally, the analyzed measurements are presented and described.

Very little interpretation of the results is given in this report. Our intent has simply been to present the data in a readily usable form. The description of the station operation and data reduction techniques should aid data users in understanding the records presented.

METEOROLOGY OF HURRICANE ANITA

The origin of hurricane Anita can be traced to a tropical disturbance which moved off the African coast on August 16, 1977. The system did not look very important until it crossed the Florida penisula on August 26, 1977, as a strong tropical easterly wave with associated heavy rains and gusty surface winds. As the wave moved into the central Gulf of Mexico, a tropical depression and a closed wind circulation formed in the wave. This development was first evidenced by the report of a brisk westerly wind from NOAA buoy EB04 located 26N 90W (see Figure 2) at 1200Z (0700 CDT) on August 29.

The first cyclone classification and location report was issued by the NOAA field satellite services (SFSS) meteorologist at the National Hurricane Center (NHC) at 1230Z, August 29. The first Air Force reconnaissance aircraft to investigate the system reached the depression center at 1640Z on August 29.

The apparent center of the depression drifted very slowly and erratically as it intensified to tropical storm strength. The depression was named Anita at 1000Z on August 30. At this time, a research flight showed two distinct areas of convection in the storm located south and east of the low level circulation center. The storm then included a large area of 50-knot winds with no distinct maximum.[6] About 12 hours later, Anita strengthened further to hurricane force. The intensification on August 30 may have been aided by the presence beneath the circulation of a persistent warm eddy which had been detected a few days earlier by the NOAA ship, Researcher.[7]

The daily satellite views of Anita in Figures 3-7 show that by 1800Z on August 31, the storm had become much better organized with an easily recognizable eye, but most of the convection remained in

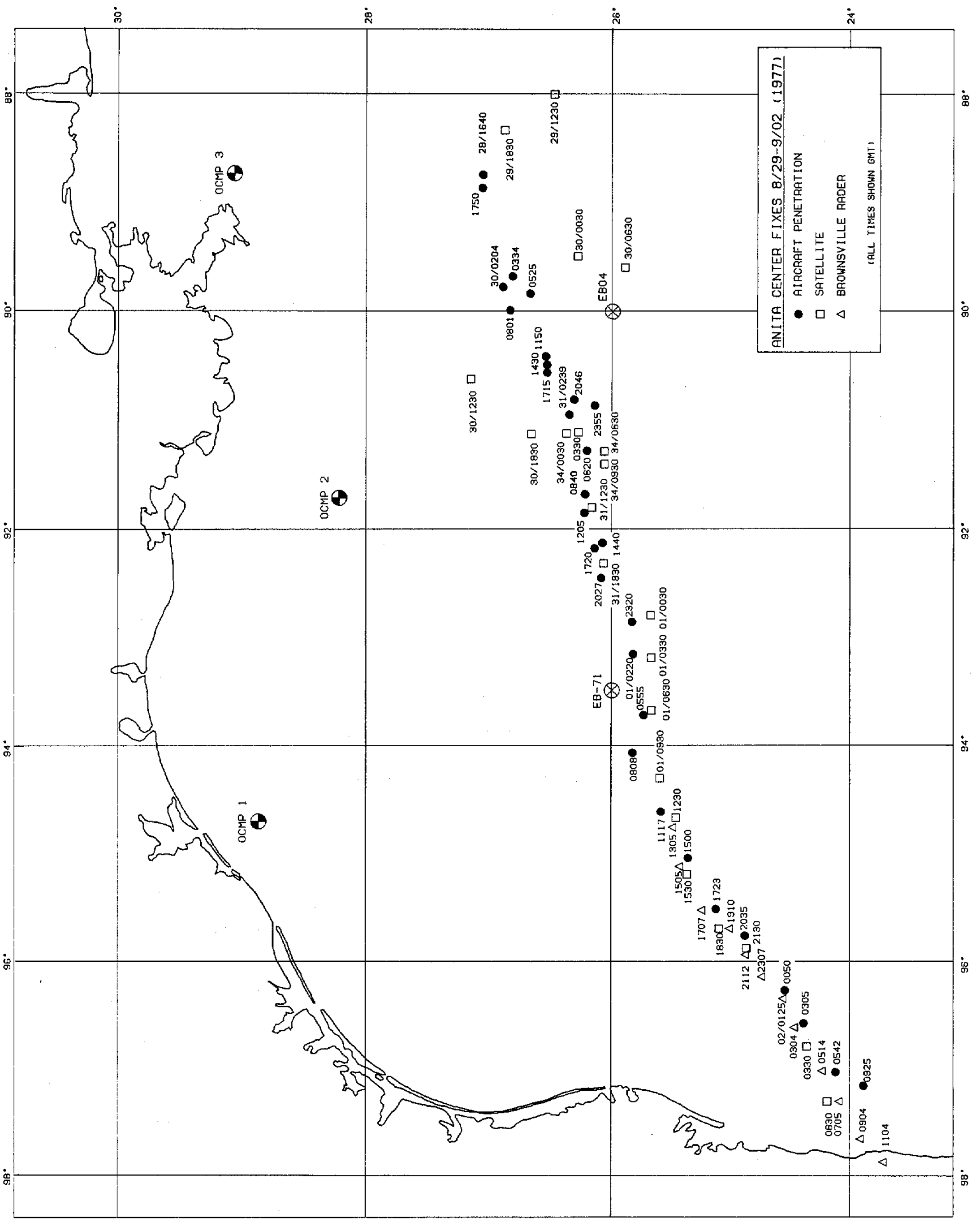

Fig. 2 - Center fixes for hurricane Anita.

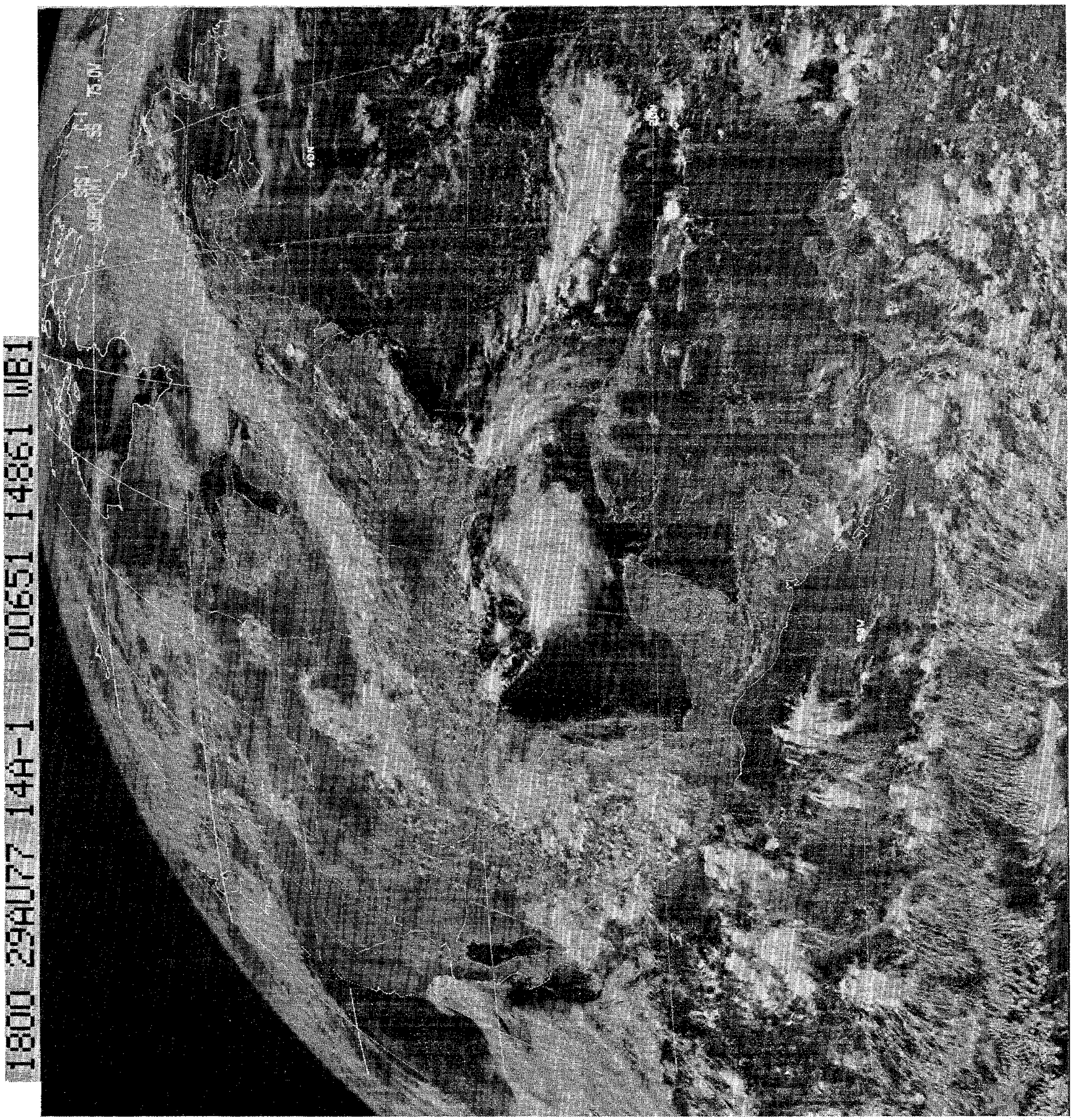

Fig. 3 - NOAA GOES satellite image, 1800Z, August 29, 1977.

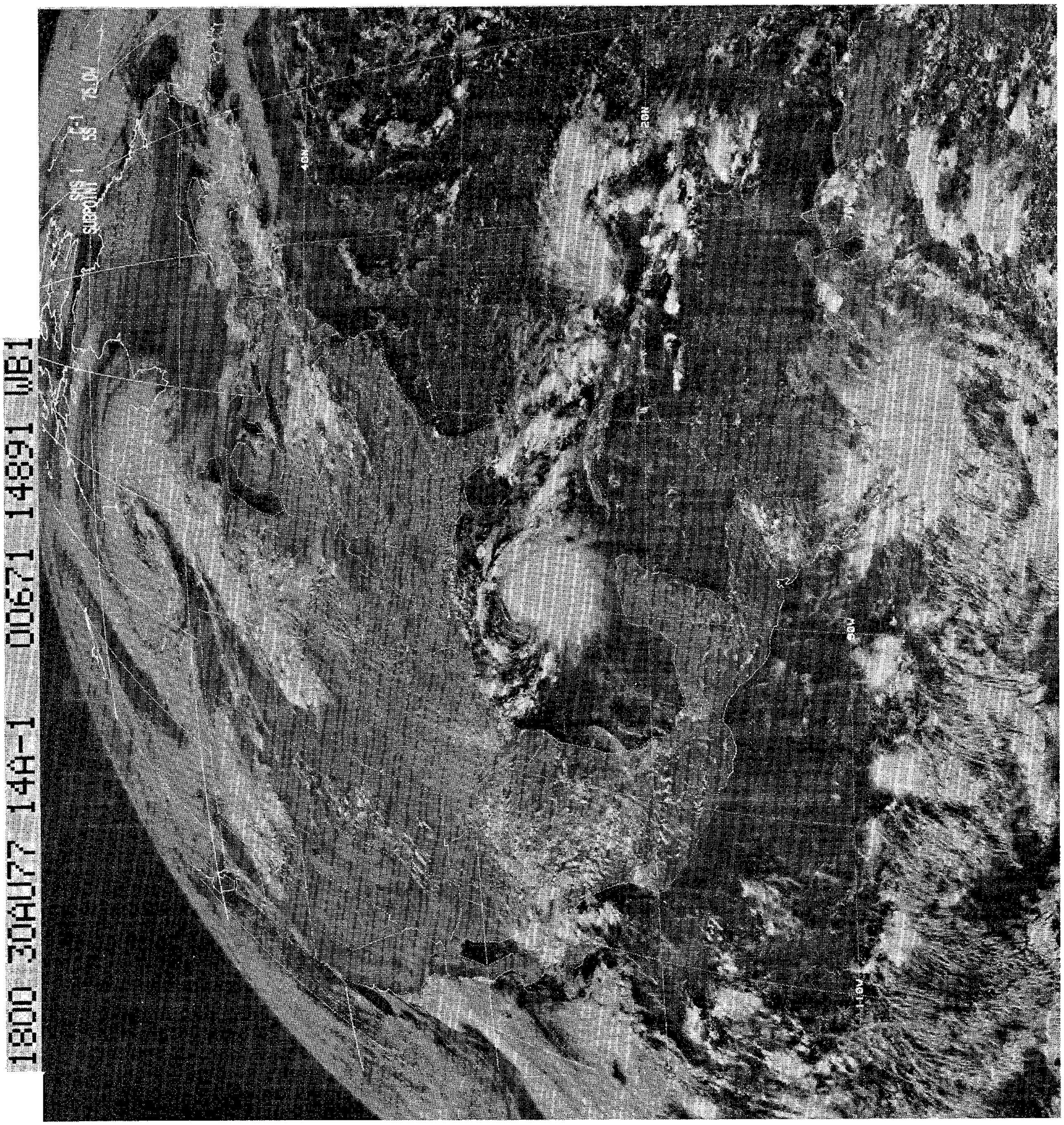

Fig. 4 - NOAA GOES satellite image, 1800Z, August 30, 1977.

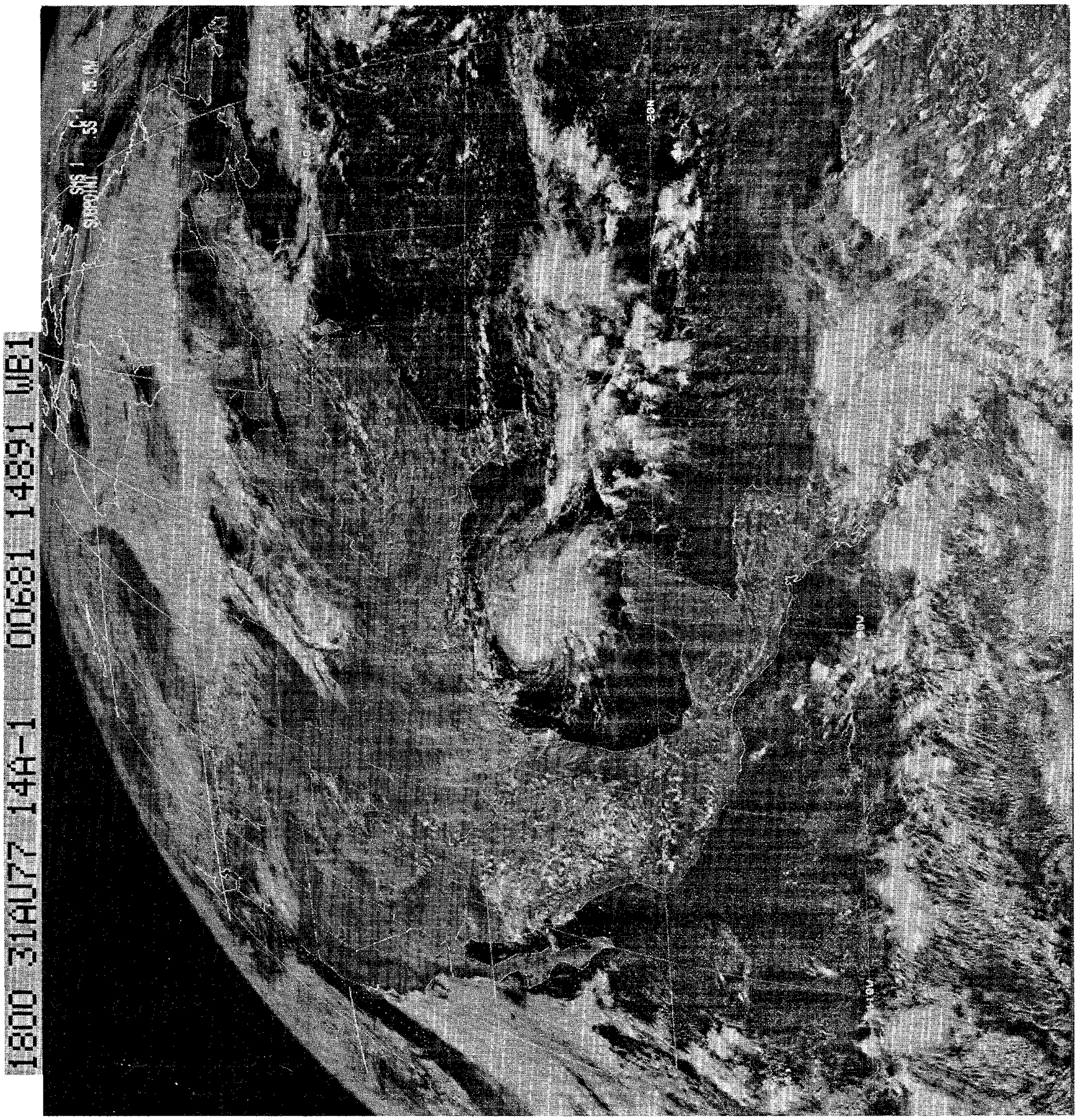

Fig. 5 - NOAA GOES satellite image, 1800Z, August 31, 1977.

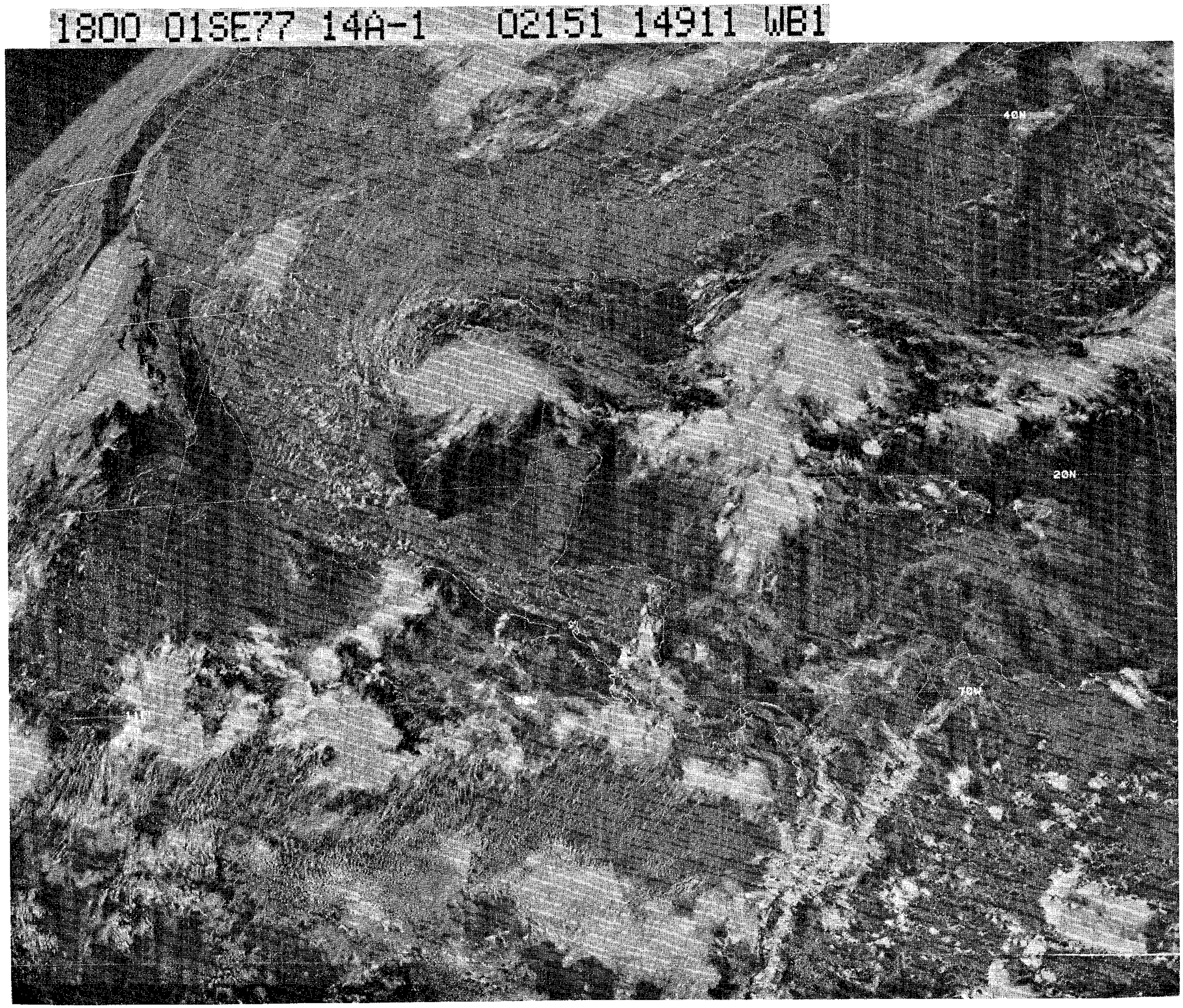

Fig. 6 - NOAA GOES satellite image, 1800Z, September 1, 1977.

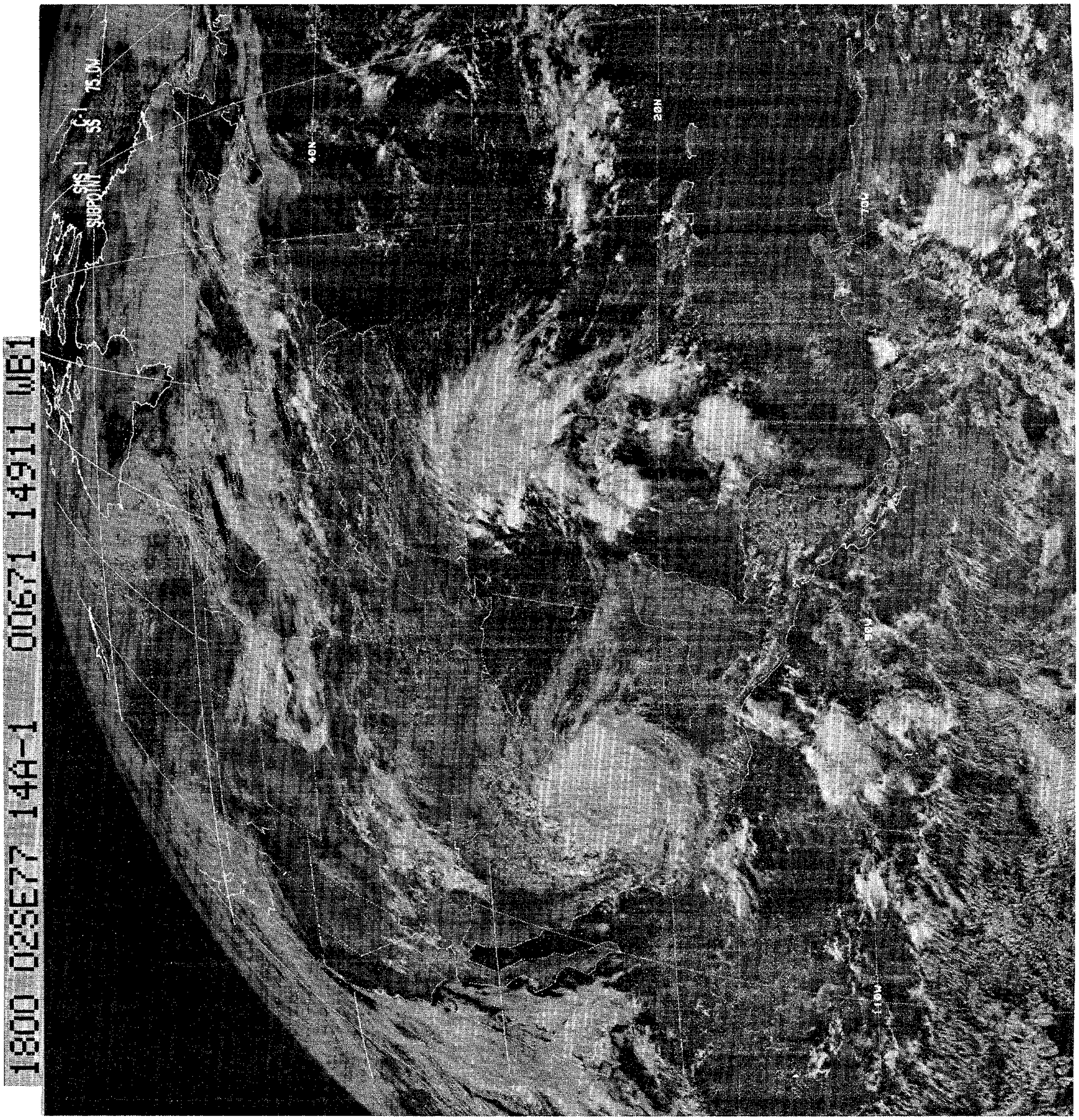

Fig. 7 - NOAA GOES satellite image, 1800Z, September 2, 1977.

the southeast quadrant. On September 1 (Figure 6), Anita continued to strengthen as she moved toward a landfall about 120 miles south of the Rio Grande River on September 2 (Figure 7). On the afternoon of September 1, the structure of Anita began to be clearly visible on the Brownsville weather radar and selected photographs of the radar are shown in Figures 8-14. The well defined, small eye and eye wall typical of intense hurricanes are shown particularly well in Figures 9, 10, and 11, taken at 2200Z, September 1, 0000Z, September 2, and 0600Z, September 2.

Figure 2 shows the aircraft, satellite, and radar center fixes on Anita between her formation and landfall on the Mexican coast. The source data for the fixes are recorded in Tables 1-4, with Table 1 giving the vortex/center data messages filed by the aircraft, Table 2 the GOES satellite classification and location reports, and Tables 3 and 4 the radar observer reports from Brownsville and Corpus Christi, respectively.

Retrospectively, Anita's track reveals a determined and rather unusual southwestward drift. In real time, however, short term trends in the track were not as definitive and the various climatological, statistical, and dynamical hurricane track forecast methods used at the NHC often produced conflicting forecast guidance. Official NHC forecasts repeatedly called for the storm to turn westward and then northwestward. These forecasts, coupled with the fact that strong winds were never far from the coast, caused most of the area from Mobile to Brownsville to be put on hurricane watch sometime between August 29 and September 2. An estimated 35,000 people were evacuated from the Texas and Louisiana coasts.

The threat from Anita forced offshore oil operators to begin evacuating personnel from the Gulf on August 29. Almost as soon as the platforms were remanned on September 1 and 2, hurricane Babe (next section) forced another evacuation. Estimates of the total work force evacuated ranged from 4500 to 7500 and the U.S.G.S. estimated that three million barrels of oil production were deferred.[8] However, there was only minimal damage to exploration and production equipment.

The central pressure measurements plotted in Figure 15 show that Anita deepened steadily during her last two days to become an extremely severe storm. The central pressure of 926 mb recorded as the eye closed to within 30 miles of the Mexican coast early on September

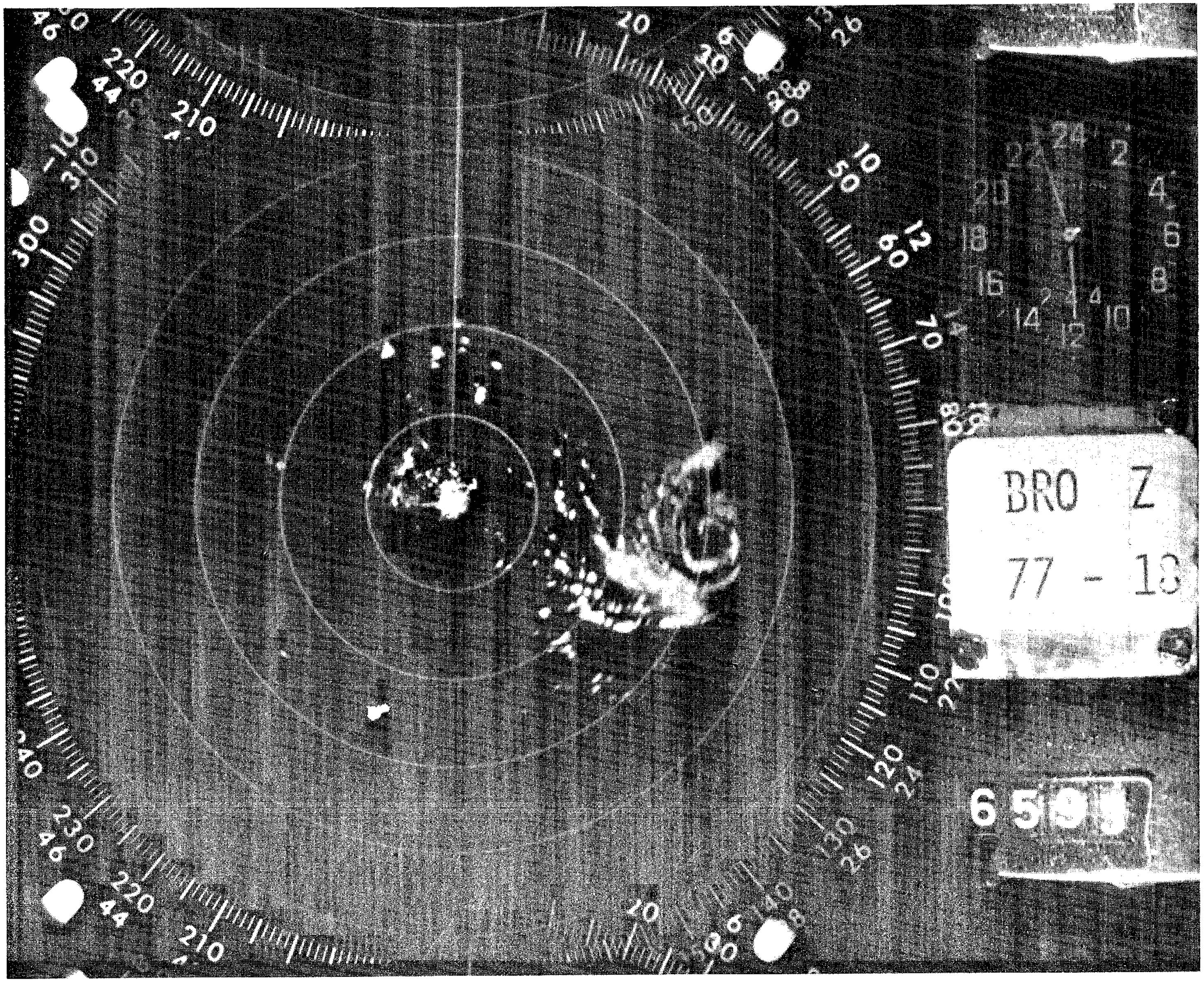

Fig. 8 - Brownsville weather radar plan position indicator at 1200Z, September 1, 1977.

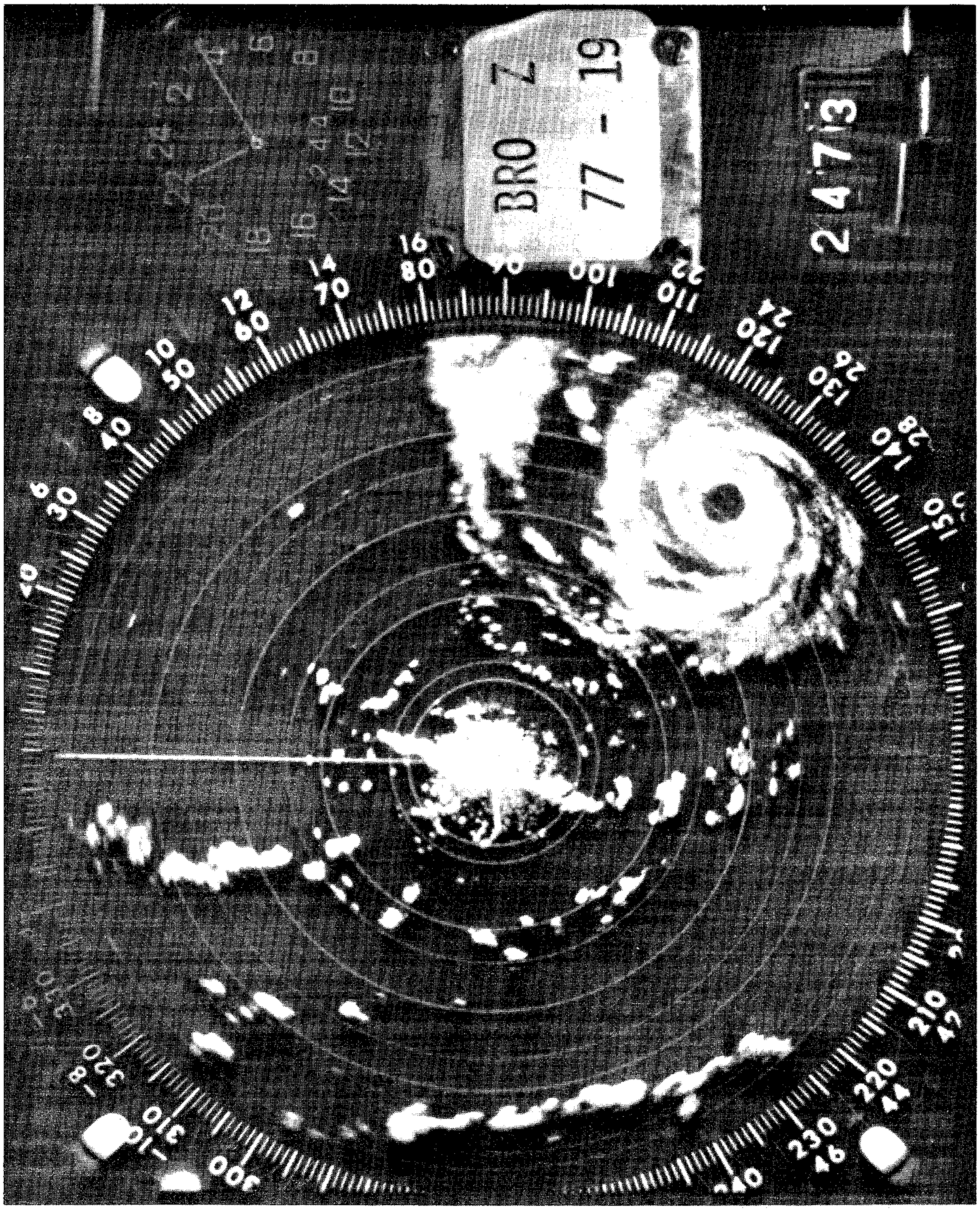

Fig. 9 - Brownsville weather radar plan position indicator at 2200Z, September 1, 1977.

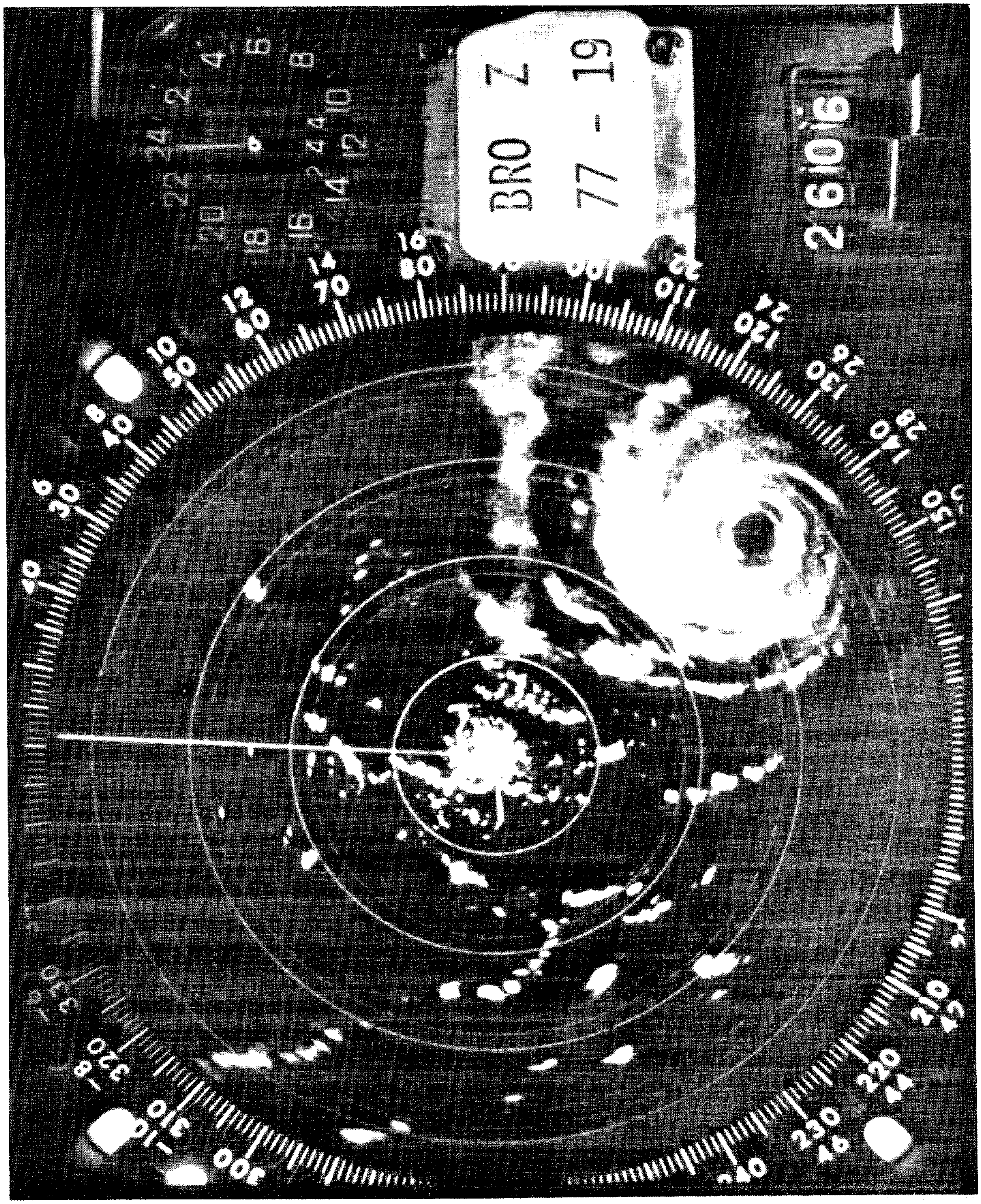

Fig. 10 - Brownsville weather radar plan position indicator at 0000Z, September 2, 1977.

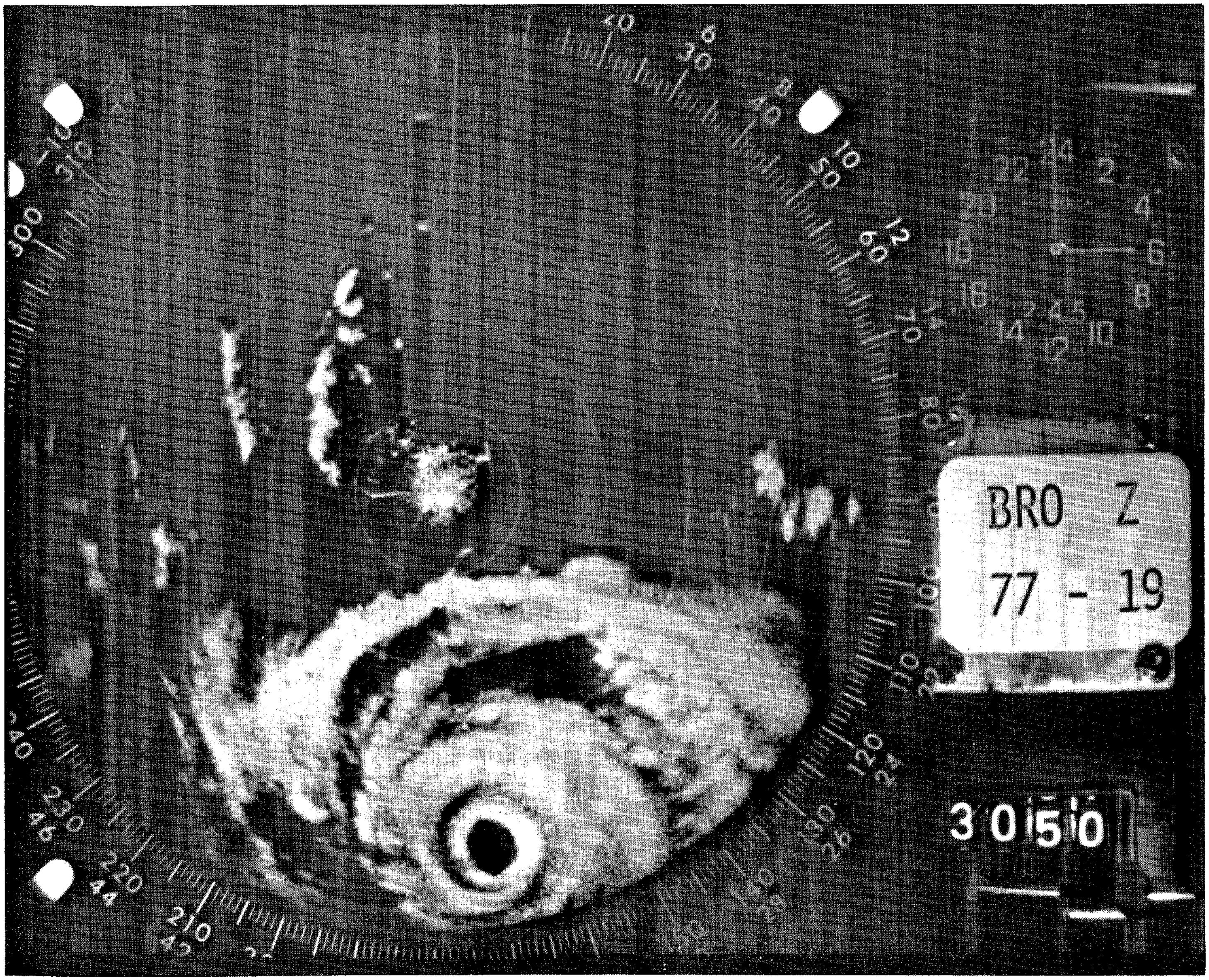

Fig. 11 - Brownsville weather radar plan position indicator at 0600Z, September 2, 1977.

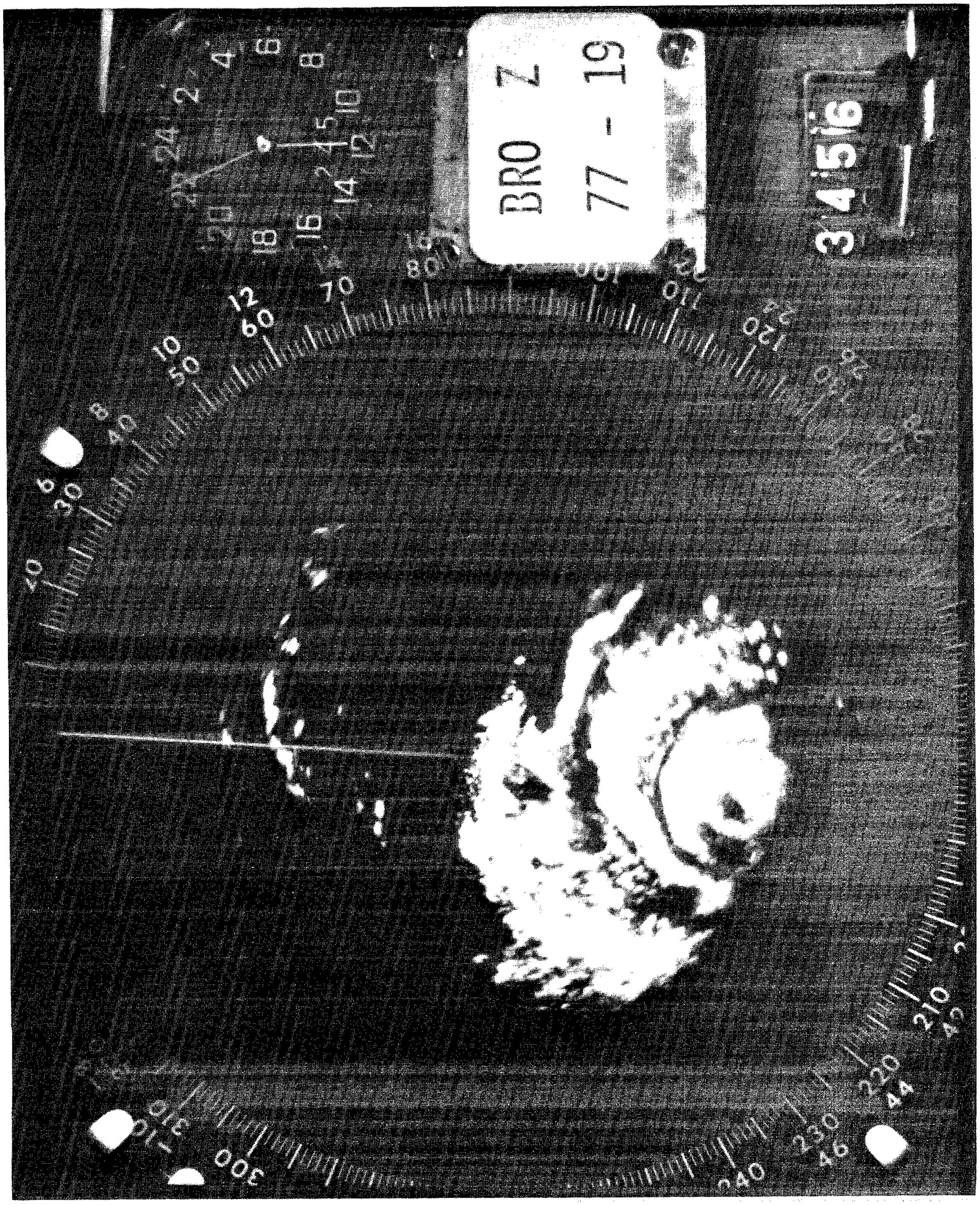

Fig. 12 - Brownsville weather radar plan position indicator at 1200Z, September 2, 1977.

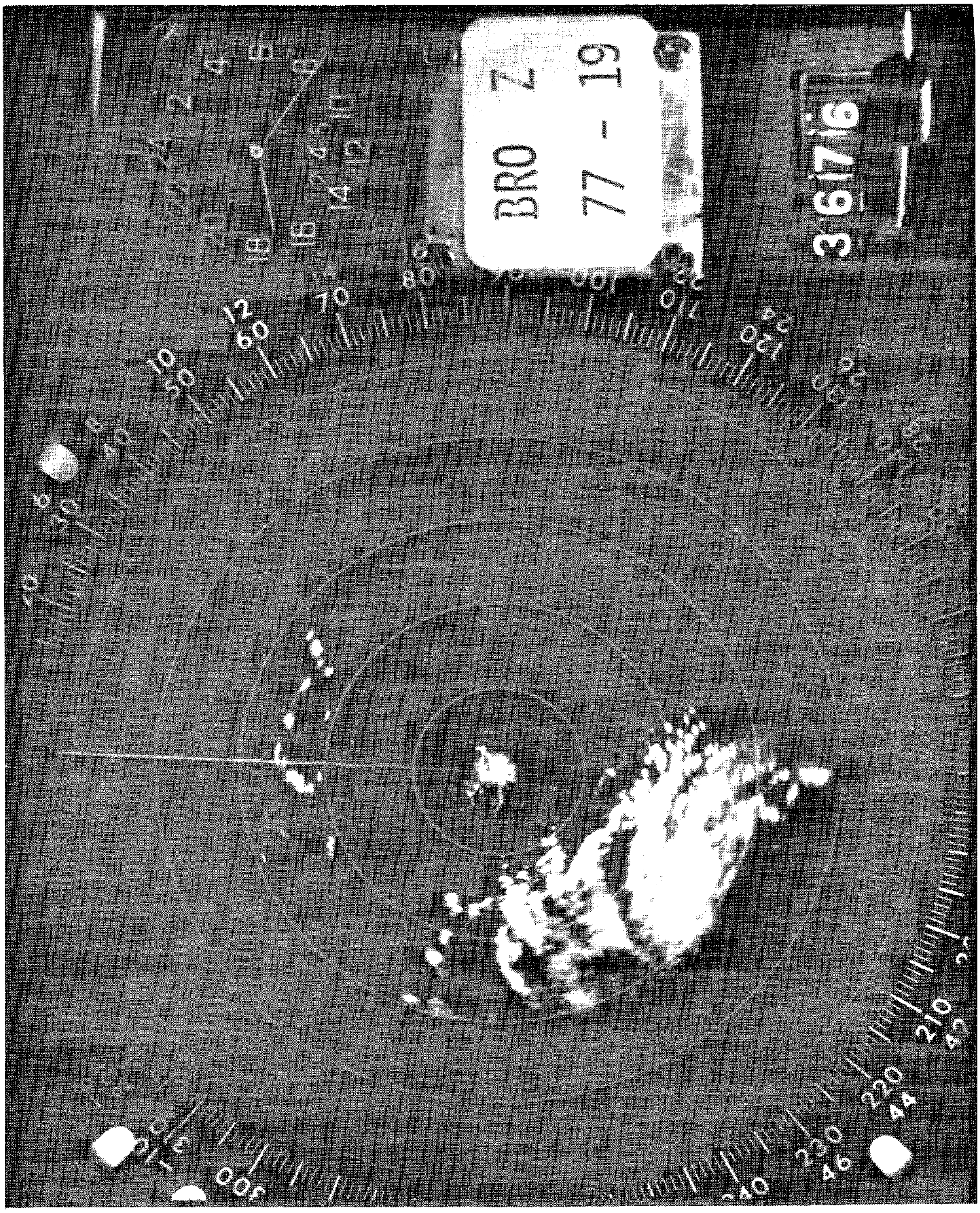

Fig. 13 - Brownsville weather radar plan position indicator at 1800Z, September 2, 1977.

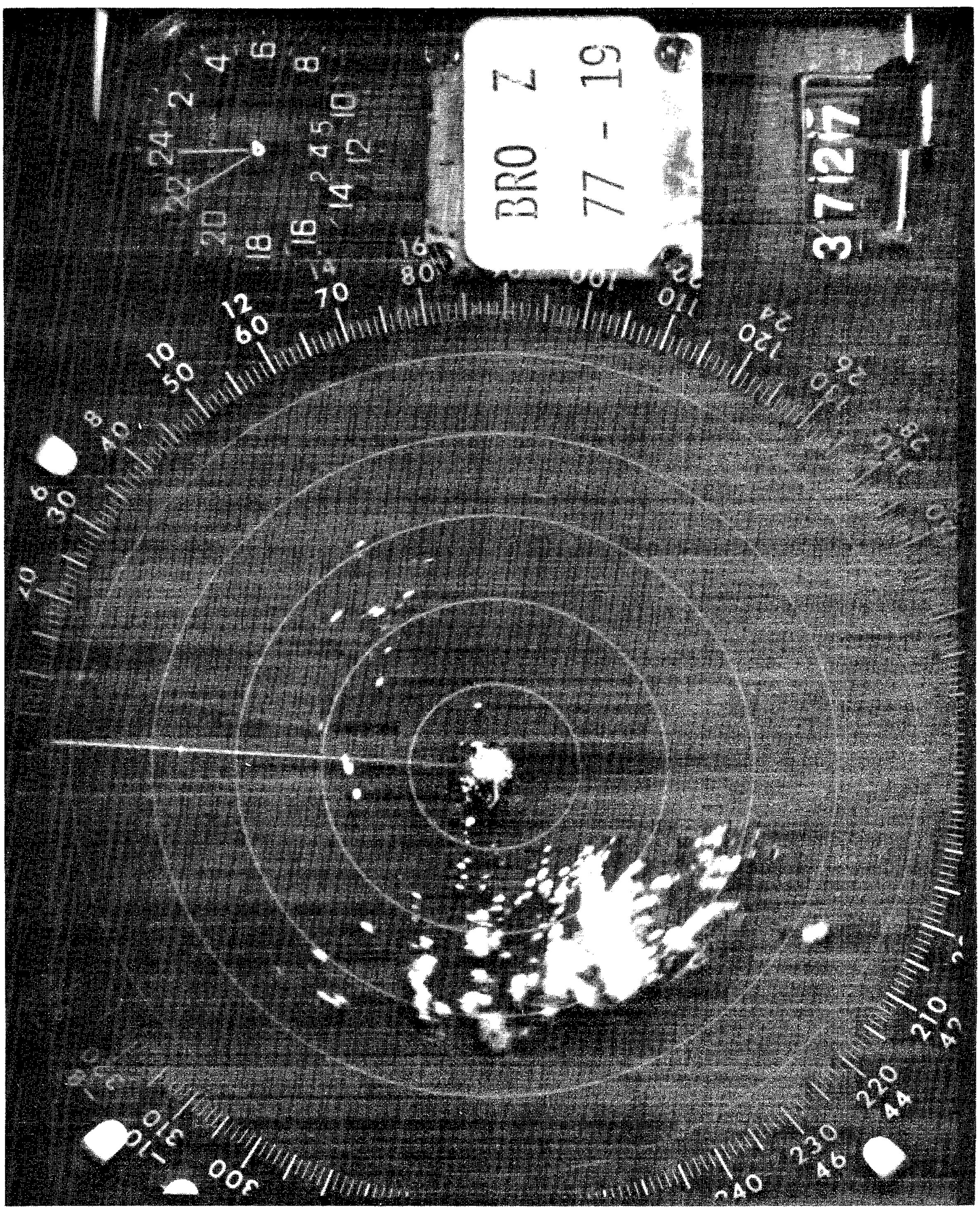

Fig. 14 - Brownsville weather radar plan position indicator at 0000Z, September 3, 1977.

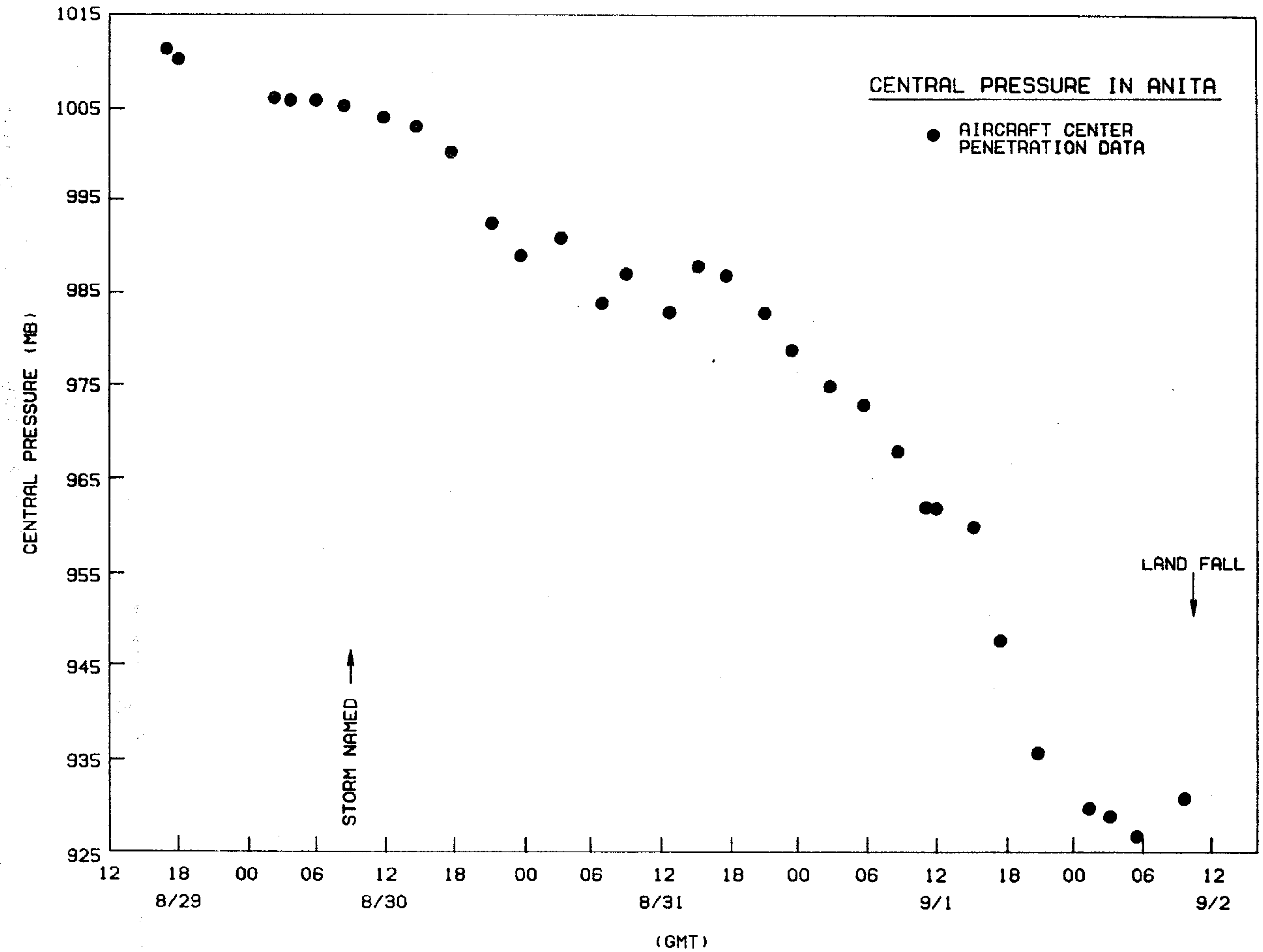

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Fig. 15 - Variation of central pressure with time in Anita.

Table 1

SUMMARY OF DATA CONTAINED IN DETAILED VORTEX/CENTER DATA MESSAGE FILED BY AIRCRAFT IN ANITA

		A	B		C	D	E	F	G	H	I	J	K	L
Aircraft	Mission	Date and Time of Fix	Latitude (deg./min.)	Longitude (deg./min.)	Ht. of Isobaric Sfc	Maximum (kts.)	Surface Wind deg./n.mi.	Maximum deg./kts.	Flight Level Wind deg./n.mi.	Minimum Pressure (mb)	Eye Character	Eye Stage	Fix Method/ Level	Accuracy n.mi.
AF967	0101 Cyclone	29/1640	27 05	88 45	N/A	20	080/70	170/25	107/120	1011.4 (est.)	N/A	N/A	12345/1	5/5
AF967	0101 Cyclone	29/1750	27 05	88 50	N/A	25	075/20	140/25	075/20	1010.3 (est.)	N/A	N/A	12345/1	5/5
AF365	0201 Cyclone	30/0204	26 55	89 47	N/A	N/A	N/A	190/33	160/82	1006.	N/A	N/A	1345/1	3/10
AF365	0201 Cyclone	30/0334	26 51	89 40	N/A	N/A	N/A	020/16	270/35	1006.	N/A	N/A	1345/1	3/10
AF365	0201 Cyclone	30/0525	26 43	89 52	N/A	N/A	N/A	100/35	360/65	1006.	N/A	N/A	1345/1	3/10
AF365	0201 Cyclone	30/0801	26 53	89 59	N/A	N/A	N/A	040/23	300/95	1005.	N/A	N/A	1345/1	3/10
NOAA2	0301 Anita	30/1150	26 35	90 20	N/A	50	050/30	150/54	050/30	1004.	Undefined	N/A	134/1	2/5
NOAA2	0301 Anita	30/1430	26 35	90 24	N/A	65	090/30	140/60	090/30	1003.	Open west	N/A	134/1	2/5
NOAA2	0301 Anita	30/1715	26 35	90 32	N/A	70	360/20	110/60	360/20	1000.	Poorly defined	N/A	134/1	2/5
NOAA1	0401 Anita	30/2046	26 20	90 48	N/A	100	360/25	110/107	360/25	992.3	N/A	N/A	N/A	N/A
AF977	0501 Anita	30/2355	26 11	90 51	700/2990	80	340/15	050/16	330/15	989.	Open SW	N/A	12345/7	10/10
AF977	0501 Anita	31/0239	26 22	90 58	700/2995	N/A	N/A	010/40	310/45	991.	Poorly defined	C 30	12345/7	10/10
AF977	0501 Anita	31/0620	26 14	91 15	700/2972	N/A	N/A	270/46	210/35	984.	Open west	C 30	12345/7	10/10
AF980	0601 Anita	31/0840	26 15	91 40	700/2968	N/A	N/A	180/62	070/20	987.	Poorly defined	Circular	1345/7	10/10
AF980	0601 Anita	31/1205	26 17	91 50	700/2939	65	080/20	070/68	080/20	983.	Poorly defined	Circular	1235/7	5/5
NOAA2	0701 Anita	31/1440	26 07	92 08	N/A	90	360/20	090/85	360/20	988.	Open west	C 35	12345/1	2/4
NOAA2	0701 Anita	31/1720	26 10	92 10	N/A	105	360/25	100/100	360/25	987.	Open NW	E 45/30	12345/1	2/4
NOAA1	0801 Anita	31/2027	26 07	92 25	N/A	85	350/25	085/85	350/25	982.8	Closed wall	E 29/40/30	1/1	N/A
AF976	0901 Anita	31/2320	25 50	92 50	700/2871	65	035/40	170/60	060/12	979.	Open S	C 35	123/7	5/3
AF976	0901 Anita	01/0220	25 50	93 10	700/2889	N/A	N/A	030/75	300/20	975.	Open NE	C 35	12345/7	5/5
AF976	0901 Anita	01/0555	25 45	93 45	700/2858	N/A	N/A	310/75	040/20	973.	Poorly defined	C 35	12345/7	5/5
AF964	1001 Anita	01/0808	25 51	94 04	700/2828	N/A	N/A	020/68	108/20	968.	N/A	Irregular 15	12345/7	5/1
AF964	1001 Anita	01/1117	25 37	94 36	700/2774	N/A	N/A	037/85	300/10	962.	N/A	Irregular 15	12345/7	5/1
AF964	1001 Anita	01/1146	25 37	94 36	700/2774	75	040/10	037/85	300/10	962.	Closed wall	C 20	12345/0	5/1
AF492	1101 Anita	01/1500	25 22	95 03	700/2749	90	240/10	130/85	020/20	960.	Open E-S	C 20	12345/7	1/1
AF492	1101 Anita	01/1723	25 09	95 30	700/2670	110	240/10	190/90	130/15	948.	Closed wall	C 15	12345/7	1/1
AF492	1101 Anita	01/2035	24 54	95 45	700/2549	115	150/10	040/115	30/15	936.	Closed wall	C 15	12345/7	1/1
NOAA2	1201 Anita	02/0050	24 34	96 16	700/2512	N/A	N/A	005/125	270/15	930.	Closed wall	C 20	12345/7	2/4
NOAA2	1201 Anita	02/0305	24 24	96 34	700/2511	N/A	N/A	100/115	360/13	929.	Closed wall	C 08	12345/7	2/4
NOAA2	1201 Anita	02/0542	24 09	97 02	700/2482	N/A	N/A	120/150	020/12	927.	Closed wall	C 17	12345/7	2/4
AF972	1401 Anita	02/0925	23 55	97 10	700/2475	N/A	N/A	N/A	N/A	931.	Closed wall	C 12	12345/7	5/2

Explanation of table entries:

A. Date and time of fix (Greenwich mean time).
B. Latitude and longitude of eye.
C. Standard level flown (e.g., 700 millibars) and minimum isobaric height (m) observed.
D. Maximum surface wind estimated from aircraft visually (knots).
E. Bearing and range from center of maximum estimated surface wind (deg./n.mi.).
F. Maximum observed flight level wind direction (degrees) and speed (knots).
G. Bearing and range from center of maximum flight level winds (deg./n.mi.).
H. Minimum sea level pressure (mb) computed unless otherwise stated.
I. Eye character (e.g., closed, open, poorly defined).
J. Eye shape (e.g., C 20--circular 20 n. mi. diameter; E 29/40/30--elliptical major axis along 290°, 40-mile major axis, 30-mile minor axis).
K. Fix level: 0--surface, 1--1500 feet, 8--850 mb, 7--700 mb, 5--500 mb, etc.
L. Fix accuracy: navigation fix accuracy/meteorological accuracy n. mi.

Table 2

SUMMARY OF MIAMI SFSS/NHC TROPICAL CYCLONE CLASSIFICATION AND LOCATION REPORTS SUBMITTED TO THE NOAA NATIONAL HURRICANE CENTER ON THE BASIS OF ANALYSIS OF GOES VISIBLE AND INFRARED IMAGERY OF ANITA

Month/Day	Time (GMT)	Center Location		C.I.*	V_{max} (knots)	Mean Motion		Averaging Interval	Remarks
		Latitude	Longitude			Hdg	Spd (knots)		
8/29	1230	26.5	88.0	1.5	25				Low cloud cumulus line center near dense overcast.
8/29	1830	26.9	88.3	1.5	25	325	5	6	Circulation center poorly defined. Development has continued with good upper outflow to E and S.
8/30	0030	26.3	89.5	2.0	25	270	5	11	Circulation center continues poorly defined and hard to locate.
8/30	0630	25.9	89.6	2.0+	32	220	8	11.5	System getting better organized. Upper outflow SE-SW.
8/30	1230	27.2	90.6	2.5	35	285	6	24	Cumulus line center clearly visible near dense overcase. Upper outflow confined to east and south of center.
8/30	1830	26.7	91.1	3.0	45	270	6	24	Center appears in cmulus lines with tight curvature at edge of dense overcast. Development is more rapid than normal in last three hours.
8/31	0030	26.4	91.1	3.5	55	212	5	12	Central dense overcase better defined. Band of convection developing over area SE-E of center.
						275	4	24	
8/31	0330	26.3	91.1	3.5	55	180	3	9	
						290	4	21	
8/31	0630	26.1	91.3	4.0	65	280	4	24	Outflow evident NE-S.
						200	3	12	
8/31	0930	26.1	91.4	4.0	65	235	3	6	Outflow somewhat inhibited in NW quadrant. Ragged eye trying to form.
						215	4	21	
8/31	1230	26.2	91.8	4.0+	70	230	3	18	BC enhancement shows pattern evolution to be covered by circular cold overcast which indicates bursting. Usually, this is associated with arrested development until the burst subsides or a comma configuration appears.
8/31	1830	26.1	92.3	4.5	77	260	4	6	Emergence of an embedded eye indicates development was resumed following short period of bursting.
9/01	0030	25.7	92.8	4.5	77	228	7	6	Eye becoming more evident. Strong outflow NE-SE.
9/01	0330	25.7	93.2	4.5	77	245	6	9	
9/01	0630	25.7	93.7	4.5	77	270	8	6	Development has slowed past 24 hours. Seems to be undergoing bursting. Dim and ragged eye visible.
						255	7	12	
9/01	0930	25.6	94.3	4.5+	83	265	11	3	Average total rain potential is 4.76 inches for storm moving at seven knots, 6.67 inches at five knots, and 3.33 inches at ten knots. Ragged eye dimly visible.
						268	9	9	
9/01	1230	25.5	94.7	5.0	90	265	9	9	
						255	7	18	
9/01	1530	25.4	95.2	5.0+	95	255	9	3	
						255	9	6	
9/01	1830	25.1	95.7	5.5	102	245	10	6	Development has continued with the embedded eye becoming more distinct.
						255	8	24	
9/01	2130	24.9	95.9	6.0	109	230	8	6	
						240	8	9	
9/02	0030	24.4	96.3	6.0+	121	218	9	6	
						233	9	12	
						250	8	24	
9/02	0330	24.4	96.8	6.5	127	240	10	6	Eye diameter increasing past three hours.
						240	9	12	
9/02	0630	24.2	97.3	6.5	127	250	10	3	Last official classification.
						260	9	6	

*Cyclone intensity, see Dvorak, NOAA Technical Memorandum NESS 45, February 1973.

Table 3

ANITA EYE FIXES - BROWNSVILLE WEATHER RADAR

Date/Time (GMT)	Latitude degrees/minutes		Longitude degrees/minutes		Remarks
01/1205	25	27	94	34	D20--good fix
01/1233	25	28	94	43	D18--good fix
01/1305	25	29	94	44	D18--good fix
01/1330	25	30	94	50	D20--good fix
01/1408	25	28	94	59	D20--good fix
01/1440	25	25	95	01	D18--fair fix
01/1505	25	27	95	07	D14--good fix
01/1533	25	22	95	11	D18--good fix
01/1606	25	22	95	20	D14--good fix
01/1633	25	18	95	25	D14--good fix
01/1707	25	14	95	31	D12--good fix
01/1731	25	09	95	35	D13--good fix
01/1805	25	05	95	37	D12--good fix
01/1831	25	02	95	40	D12--good fix
01/1910	25	00	95	41	D10--good fix
01/1938	24	57	95	49	D12--good fix
01/2006	24	56	95	46	D12--good fix
01/2036	24	56	95	48	D12--good fix
01/2112	24	54	95	55	D10--good fix
01/2135	24	52	95	57	D10--good fix
01/2211	24	45	96	01	D14--good fix
01/2230	24	47	96	01	D12--good fix
01/2307	24	44	96	08	D12--good fix
01/2333	24	43	96	08	D10--good fix
02/0008	24	37	96	12	D15--good fix
02/0030	24	37	96	16	D15--good fix
02/0125	24	34	96	20	D15--good fix
02/0202	24	32	96	24	D17--good fix
02/0231	24	32	96	30	D16--good fix
02/0304	24	28	96	37	D18--good fix
02/0331	24	29	96	41	D18--good fix
02/0402	24	25	96	49	D16--good fix
02/0430	24	22	96	56	D15--good fix
02/0514	24	14	97	01	D15--good fix
02/0530	24	14	97	03	D15--good fix
02/0612	24	11	97	08	D15--good fix
02/0630	24	10	97	14	D15--good fix
02/0705	24	06	97	18	D18--fair fix
02/0730	24	04	97	22	D15--fair fix
02/0810	24	03	97	26	D17--fair fix
02/0830	24	01	97	30	D17--fair fix
02/0904	23	55	97	40	D20--good fix
02/0935	23	52	97	43	D20--good fix
02/1005	23	49	97	47	D22--fair fix
02/1035	23	44	97	49	D18--good fix
02/1104	23	43	97	50	D18--fair fix
02/1130	23	40	97	55	D17--poor fix
02/1209	23	37	98	30	D16--poor fix
02/1233	23	38	98	30	D13--poor fix
02/1308	23	36	98	11	Poor fix
02/1330	23	36	98	11	Diffuse

Table 4

ANITA EYE FIXES - CORPUS CHRISTI WEATHER RADAR

Date/Time (GMT)	Latitude degrees/minutes		Longitude degrees/minutes		Remarks
01/1630	25	08	95	19	15° overlay--fair fix
01/1805	25	04	95	39	15° overlay--good fix
01/1909	24	58	95	45	Good fix
01/2010	24	54	95	48	Good fix
01/2110	24	50	95	56	Good fix
01/2210	24	48	95	57	Good fix
01/2308	24	39	96	04	
01/2345	24	43	96	09	15° spiral--poor fix
02/0008	24	94	96	15	15° spiral--poor fix
02/0033	24	50	96	16	15° spiral--poor fix
02/0110	24	30	96	16	15° spiral--poor fix
02/0135	24	30	96	22	15° spiral--poor fix
02/0232	24	29	96	31	Good fix
02/0310	24	22	96	38	Good fix
02/0332	24	24	96	47	Good fix
02/0408	24	22	96	52	Good fix
02/0434	24	16	96	58	Good fix
02/0508	24	12	97	05	Good fix
02/0533	24	09	97	07	Good fix
02/0610	24	06	97	11	Good fix
02/0634	24	03	97	15	Good fix
02/0710	24	00	97	20	Good fix
02/0732	23	58	97	13	Fair fix

2 was the third lowest pressure ever recorded for a landfalling storm in the Gulf of Mexico. At that same time, the NOAA research aircraft measured a 155-knot flight level wind and a 26-knot vertical windspeed.[6] It is fortunate that Anita made landfall on a sparsely settled portion of the coast and apparently did not cause great loss of life or property, although no reliable damage reports seem to be available.

The NOAA data buoys EB04 and EB71 were in excellent positions to make observations of the storm as shown in Figure 2. At the request of the NHC, the buoys transmitted hourly rather than the usual three hourly meteorological measurements starting at 0000Z, August 29. The buoys also obtained wave spectrum measurements from hull mounted accelerometers on a three hourly cycle. It should be noted that some questions have recently been raised concerning the effect of the buoy hull response on these measurements. Anita's center passed within 60 miles of EB04 on August 30 and within 20 miles of EB71 on September 1. Figures 16 and 17 show the reported measurements of pressure, wind speed and direction, and spectrally computed significant wave height from the two buoys. Figures 18 and 19 show selected spectra obtained at or near the peak storm conditions. More extensive reprocessed buoy data sets will probably be published by the NOAA Data Buoy Office in the near future.

Smith[9] has reported on current measurements from two meters moored two and ten meters above the bottom in 17 meters of water off the coast near Port O'Connor, Texas. The currents during the storm were predominantly longshore and his graph of the longshore current components is reproduced here as Figure 20. The longshore current speed reached a maximum of 80 cm/sec on September 1 and the current was reasonably constant with depth.

METEOROLOGY OF HURRICANE BABE

Almost as soon as Anita crossed the Mexican coast, weather activity began to increase again in the central Gulf. Although the formation of Babe was essentially unrelated to the recent passage of Anita, the oceanographic effects of the two storms were closely coupled.

The disturbance which spawned hurricane Babe was not entirely tropical in origin, but rather resulted from the combination of a weak

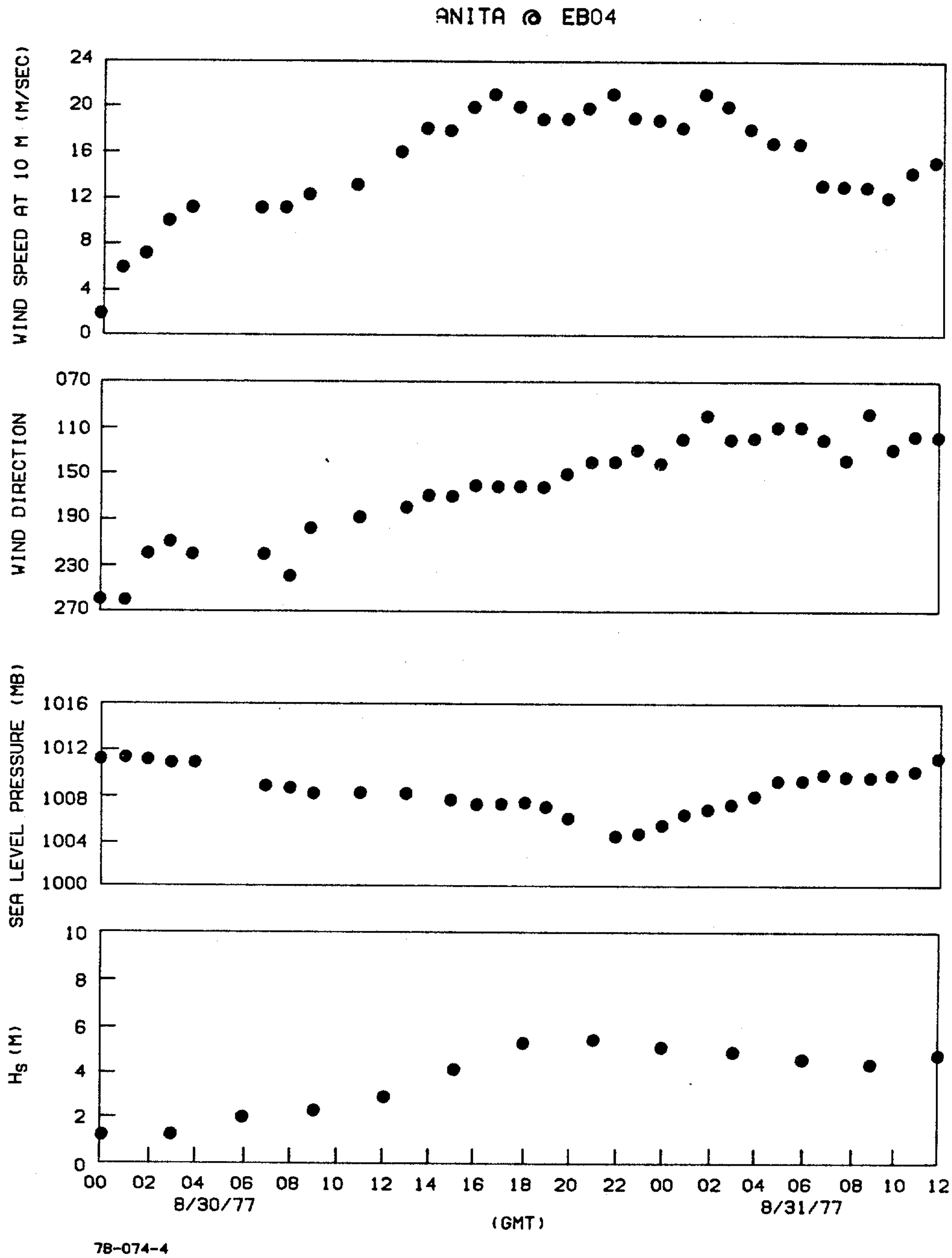


Fig. 16 - Measurements at NOAA data buoy EB04 during Anita.

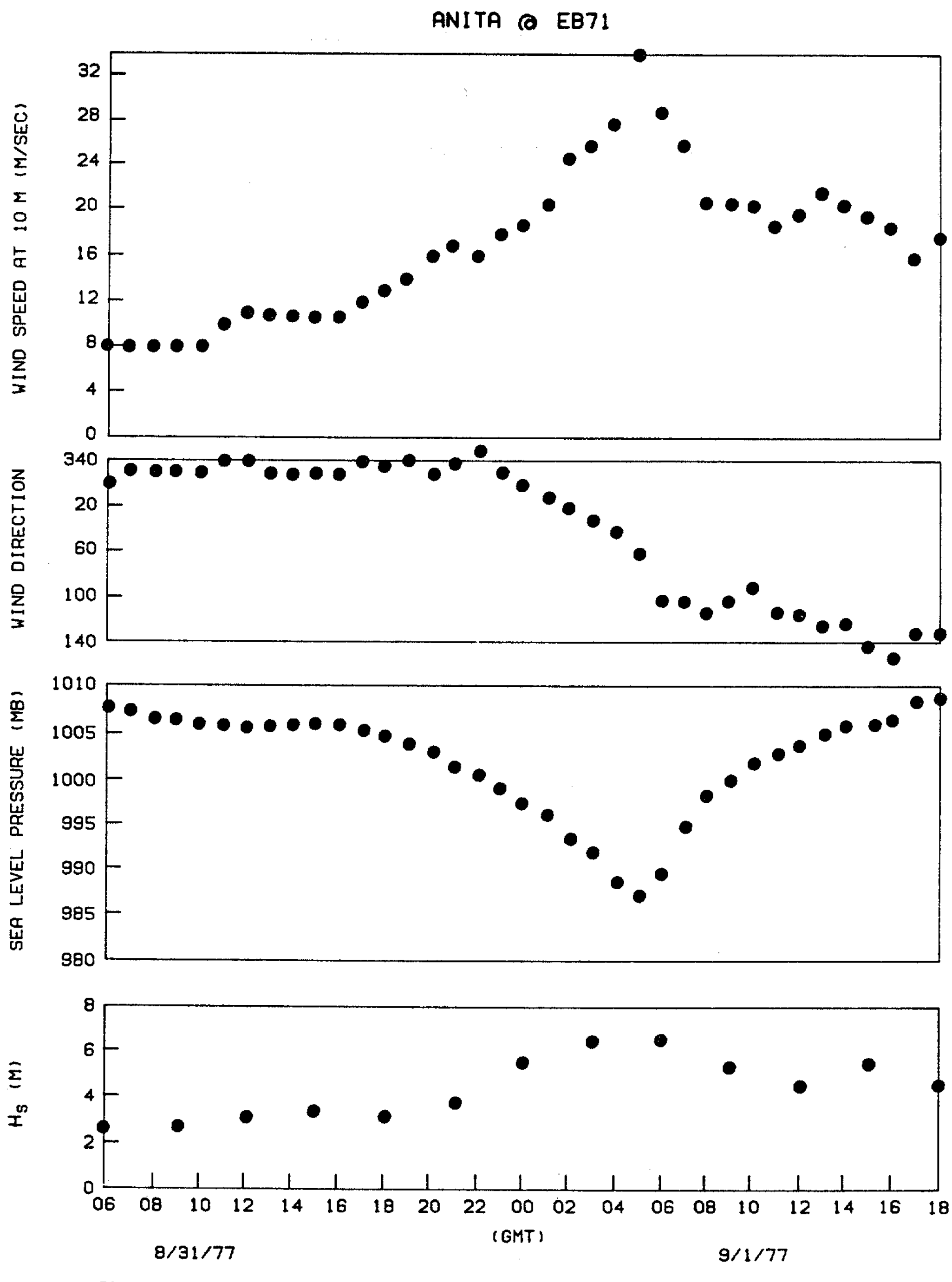


Fig. 17 - Measurements at NOAA data buoy EB71 during Anita.

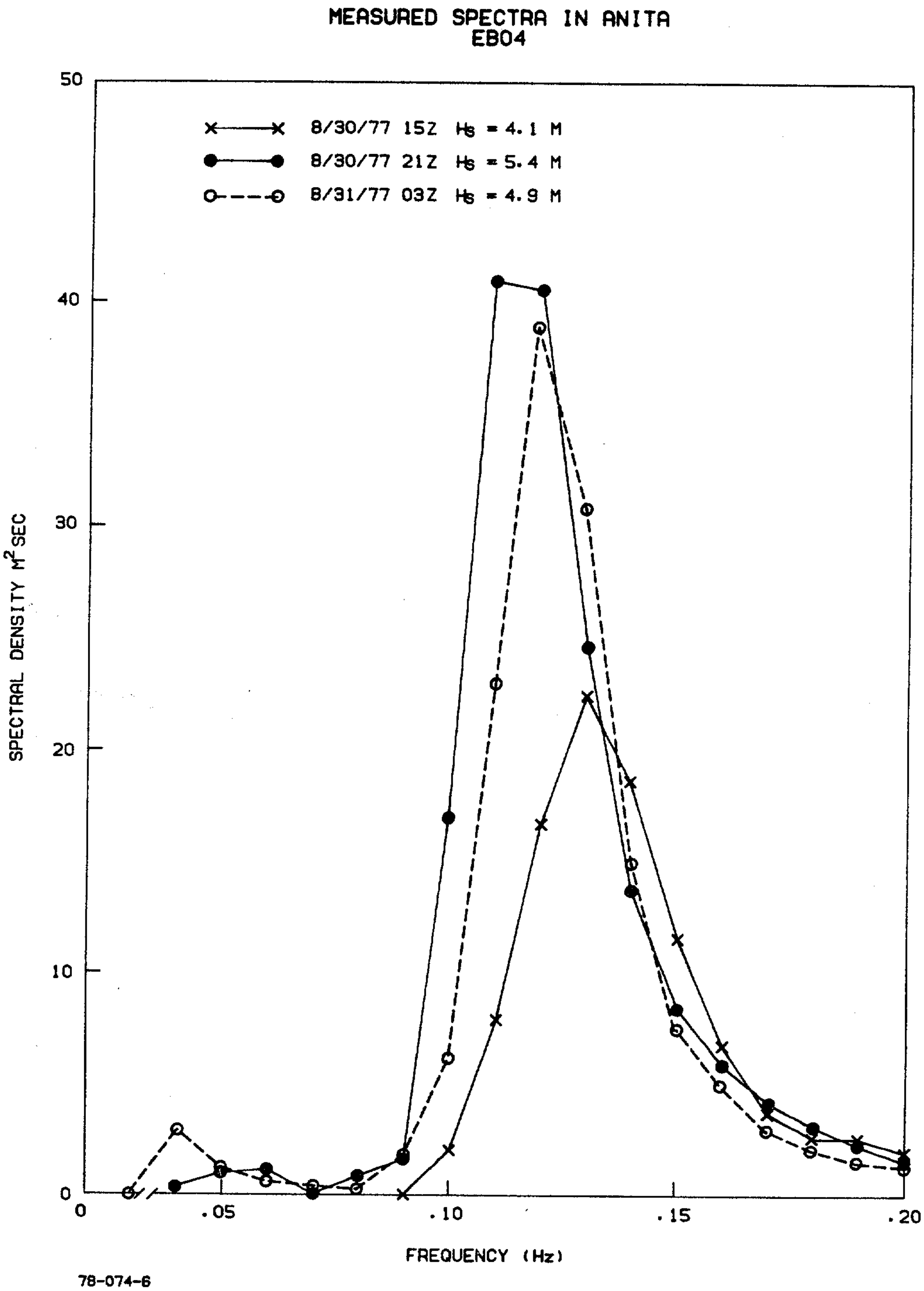
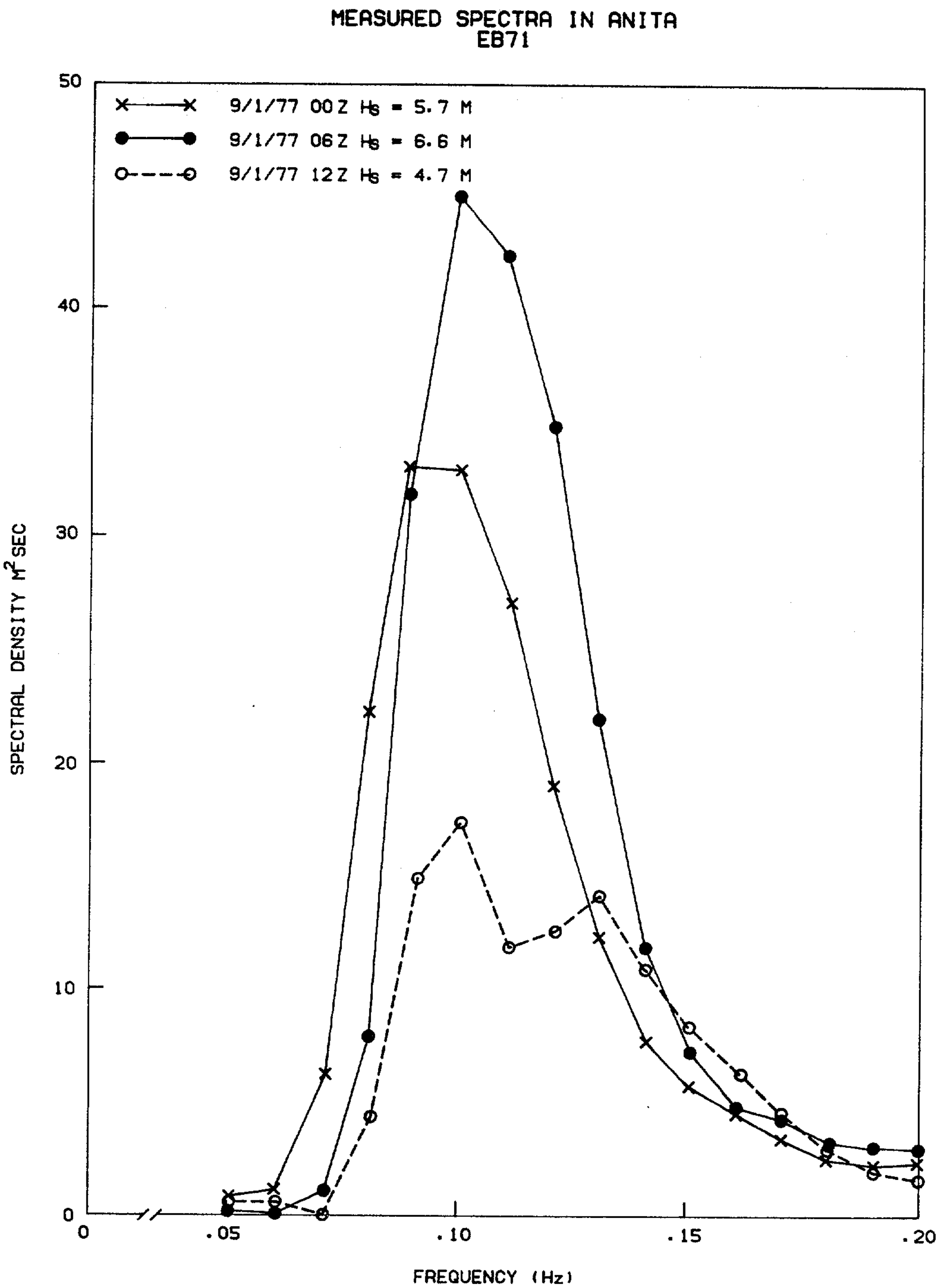
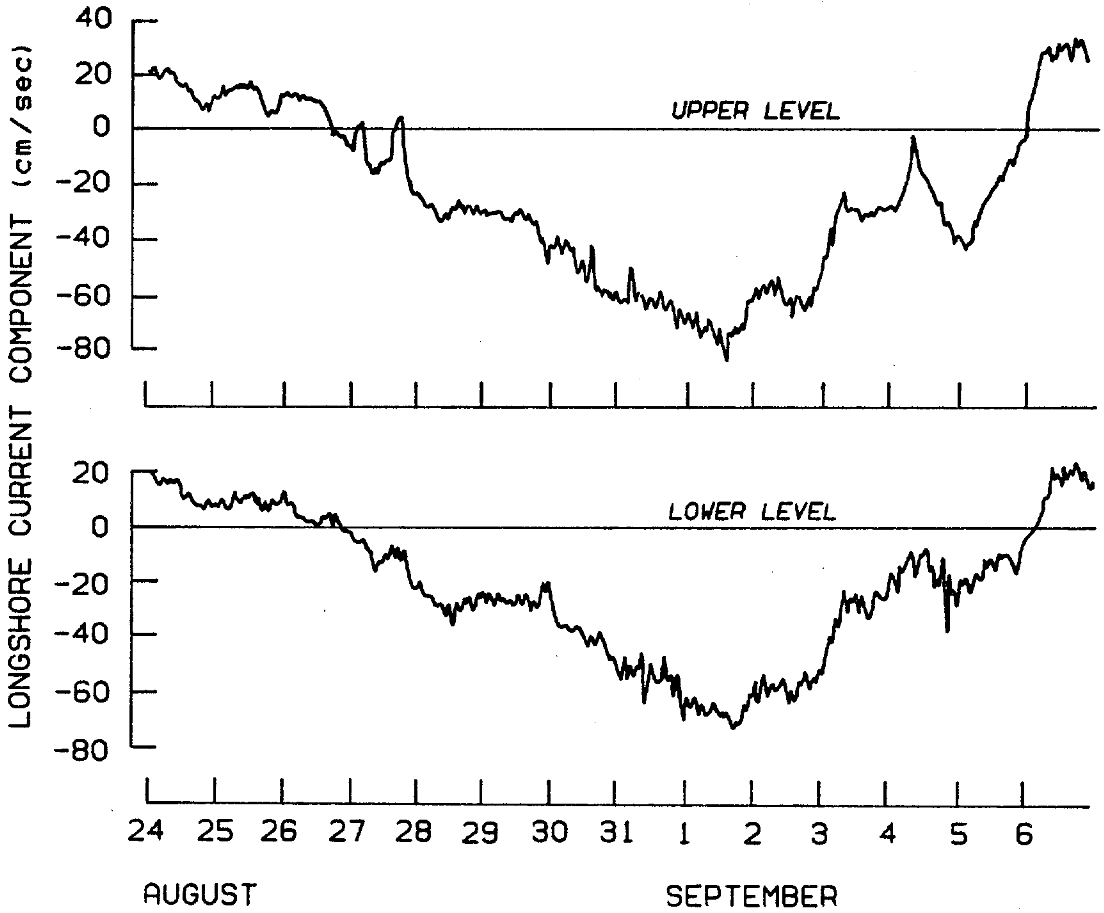


Fig. 18 - Selected wave spectra from EB04 in Anita.



78-074-7

Fig. 19 - Selected wave spectra from EB71 in Anita.



78-111-1

Fig. 20 - Current measurements near Port O'Connor during Anita (after Smith[9]).

tropical wave which had been tracked from the African coast on August 23 to the Gulf of Mexico on September 2 and an upper atmospheric extratropical cyclone which was positioned over the northeast Gulf of Mexico during the first few days of September. By September 3, this combination of systems was associated with a wide band of convective cloudiness and squalls from the middle Gulf of Mexico northward to the central Gulf coast and then eastward to the Florida panhandle. These cloud patterns can be clearly seen in the satellite photograph reproduced in Figure 21.

Though only a weak tropical depression was evident in the tropical wave drifting westward in the central Gulf, the existence of gale force winds in the convective band of clouds prompted the issuance of gale warnings from Morgan City, Louisiana, to Pensacola, Florida, at 1600Z on September 3 and the upgrading of the depression to tropical storm status as Babe.

The west-east convective band moved inland on September 4 as shown in Figure 22 and weakened. However, the disturbance still in the Gulf strengthened slowly and began to assume some of the characteristics of a tropical storm. An Air Force reconnaissance flight reported 70-knot winds southeast of the center of the storm.[10] A synopsis of vortex/center message filed by aircraft reporting from Babe is given in Table 5.

Babe turned northward early on September 4 and at 2200Z a hurricane watch and gale warnings were posted west of Mobile to Galveston. At 0100Z on September 5, Babe was upgraded to hurricane status and a hurricane warning was issued for the Louisiana coast from the mouth of the Mississippi River to Vermillion Bay. Babe made landfall about 25 miles east of Morgan City around 1000Z on September 5.

As shown in the satellite photograph (reproduced as Figure 23) for September 5, the cloud formations in Babe looked most like a typical tropical storm only after the center of the storm had moved inland. The images on the Slidell, Louisiana, NOAA weather radar, some of which are reproduced in Figures 24-28, never showed much organization in the convective structure of the storm. Table 6 gives the information on Babe deduced from the GOES satellite imagery and Table 7 gives the comments of the Slidell radar observer. The center fixes from all sources are plotted in Figure 29, where the lack of a clearly defined eye in Babe is reflected in the scatter of the reported positions.

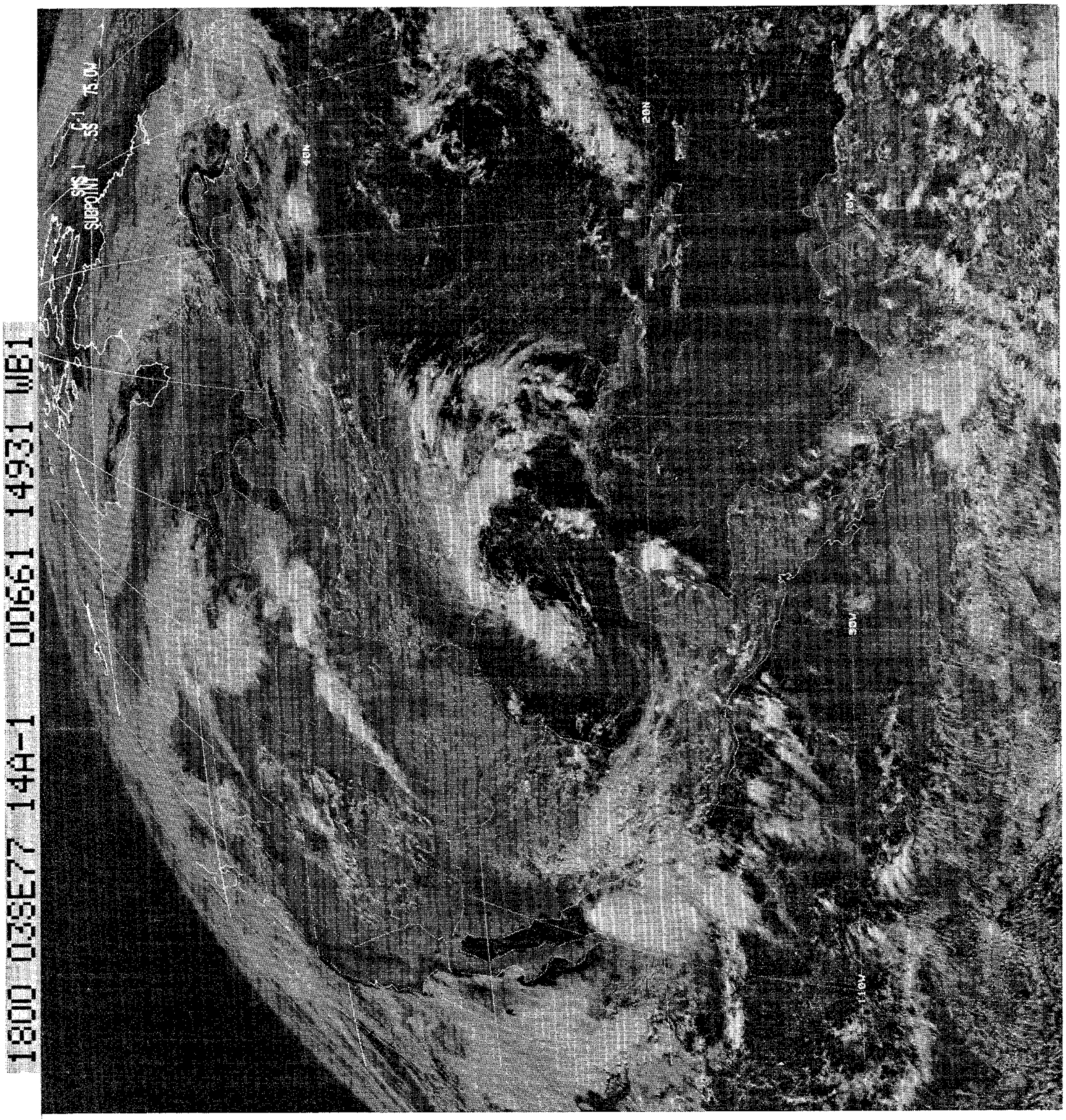


Fig. 21 - NOAA GOES satellite image, 1800Z, September 3, 1977.

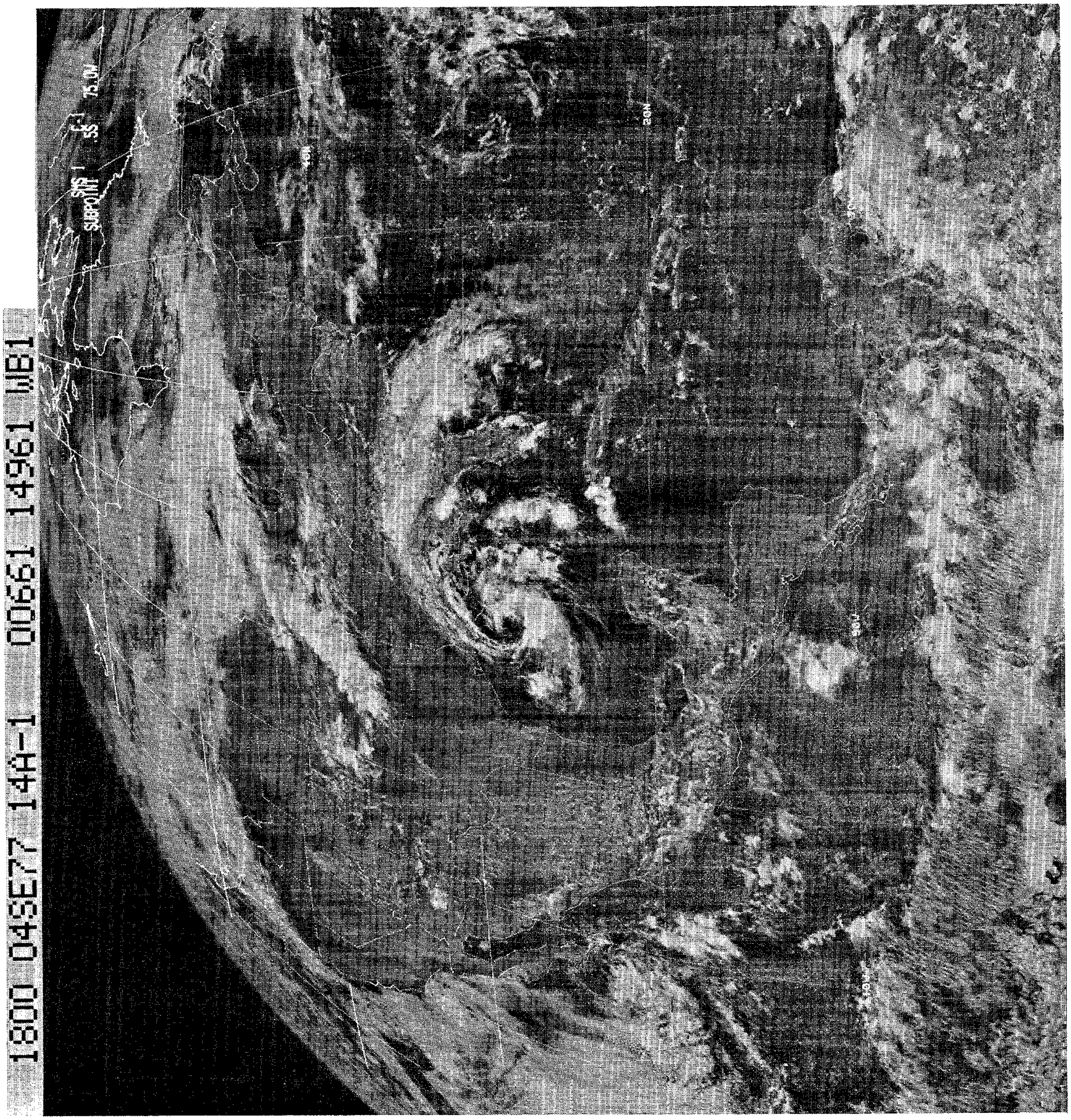


Fig. 22 - NOAA GOES satellite image, 1800Z, September 4, 1977.

Table 5

SUMMARY OF DATA CONTAINED IN DETAILED VORTEX/CENTER DATA MESSAGE FILED BY AIRCRAFT IN BABE

Aircraft	Mission	A Date and Time of Fix	B Latitude (deg./min.)		B Longitude (deg./min.)		C Ht. of Isobaric Sfc	D Maximum (kts.)	E Surface Wind deg./n.mi.	F Maximum deg./kts.	G Flight Level Wind deg./n.mi.	H Minimum Pressure (mb)	I Eye Character	J Eye Stage	K Fix Method/ Level	L Accuracy n.mi.
AF980	0202 Cyclone	03/1543	28	01	87	55	N/A	40	300/45	30	300/45	1006.8	Poorly defined	E 01/60/20	1/1	5/5
NOAA1	0302 Babe	03/1750	27	30	88	50	N/A	35	290/50	35	290/50	1005.3	Poorly defined	N/A	1/1	5/5
NOAA1	0302 Babe	03/1907	27	21	89	00	N/A	N/A	N/A	N/A	N/A	1004.8	N/A	N/A	N/A	N/A
AF967	0402 Babe	03/2130	27	25	89	25	N/A	15	130/30	20	130/30	1006.	Poorly defined	C 10	1/1	2/2
AF967	0402 Babe	03/2322	27	30	90	02	N/A	30	240/20	20	240/20	1006.	Poorly defined	C 10	1/1	2/2
AF967	0402 Babe	04/0200	27	21	90	25	N/A	N/A	N/A	20	160/20	1005.9	Poorly defined	C 15	1/1	2/2
AF365	0502 Babe	04/0608	26	35	91	25	N/A	N/A	N/A	30	080/40	1005.2	Open NE	C 06	1/1	3/4
AF365	0502 Babe	04/0804	26	42	91	30	N/A	N/A	N/A	33	060/25	1003.	Open NNW-E	C 09	1/1	3/5
AF365	0502 Babe	04/1100	26	23	91	37	N/A	N/A	N/A	38	240/20	1004.	Open NW-NE	C 09	1/1	5/5
AF964	0602 Babe	04/1434	27	23	91	42	N/A	50	030/50	50	030/50	1003.	Easily defined	C 20	1/1	5/5
AF964	0602 Babe	04/1703	27	30	91	28	N/A	40	240/45	28	240/45	1003.	Easily defined	C 30	1/1	5/5
AF964	0602 Babe	04/1903	27	41	91	43	N/A	70	140/55	70	140/55	1000.	Banded	C 30	1/1	5/5
AF964	0602 Babe	04/2011	27	46	91	40	N/A	25	330/30	20	330/30	999.	Banded	C 30	1/1	5/5
AF967	0702 Babe	05/0006	27	59	91	37	3060	45	180/40	40	180/40	1000.1	Closed wall	C 20	1/7	2/2
AF967	0702 Babe	05/0304	28	30	91	29	3050	N/A	N/A	40	160/10	999.	Open West	C 15	1/7	3/3
AF967	0702 Babe	05/0513	28	29	91	32	3053	N/A	N/A	25	220/30	996.	Poorly defined	C 15	1/7	4/5
AF365	0802 Babe	05/0805	28	49	91	15	3041	N/A	N/A	46	130/63	995.	N/A	N/A	1/7	6/6
AF365	0802 Babe	05/1100	29	25	91	17	N/A	N/A	N/A	26	180/36	N/A	N/A	N/A	1/7	N/A

Explanation of table entries:
A. Date and time of fix (Greenwich mean time).
B. Latitude and longitude of eye.
C. Standard level flown (e.g., 700 millibars) and minimum isobaric height (m) observed.
D. Maximum surface wind estimated from aircraft visually (knots).
E. Bearing and range from center of maximum estimated surface wind (deg./n.mi.).
F. Maximum observed flight level wind direction (degrees) and speed (knots).
G. Bearing and range from center of maximum flight level winds (deg./n.mi.).
H. Minimum sea level pressure (mb) computed unless otherwise stated.
I. Eye character (e.g., closed, open, poorly defined).
J. Eye shape (e.g., C 20--circular 20 n. mi. diameter; E 29/40/30--elliptical major axis along 290°, 40-mile major axis, 30-mile minor axis).
K. Fix level: 0--surface, 1--1500 feet, 8--850 mb, 7--700 mb, 5--500 mb, etc.
L. Fix accuracy: navigation fix accuracy/meteorological accuracy n. mi.

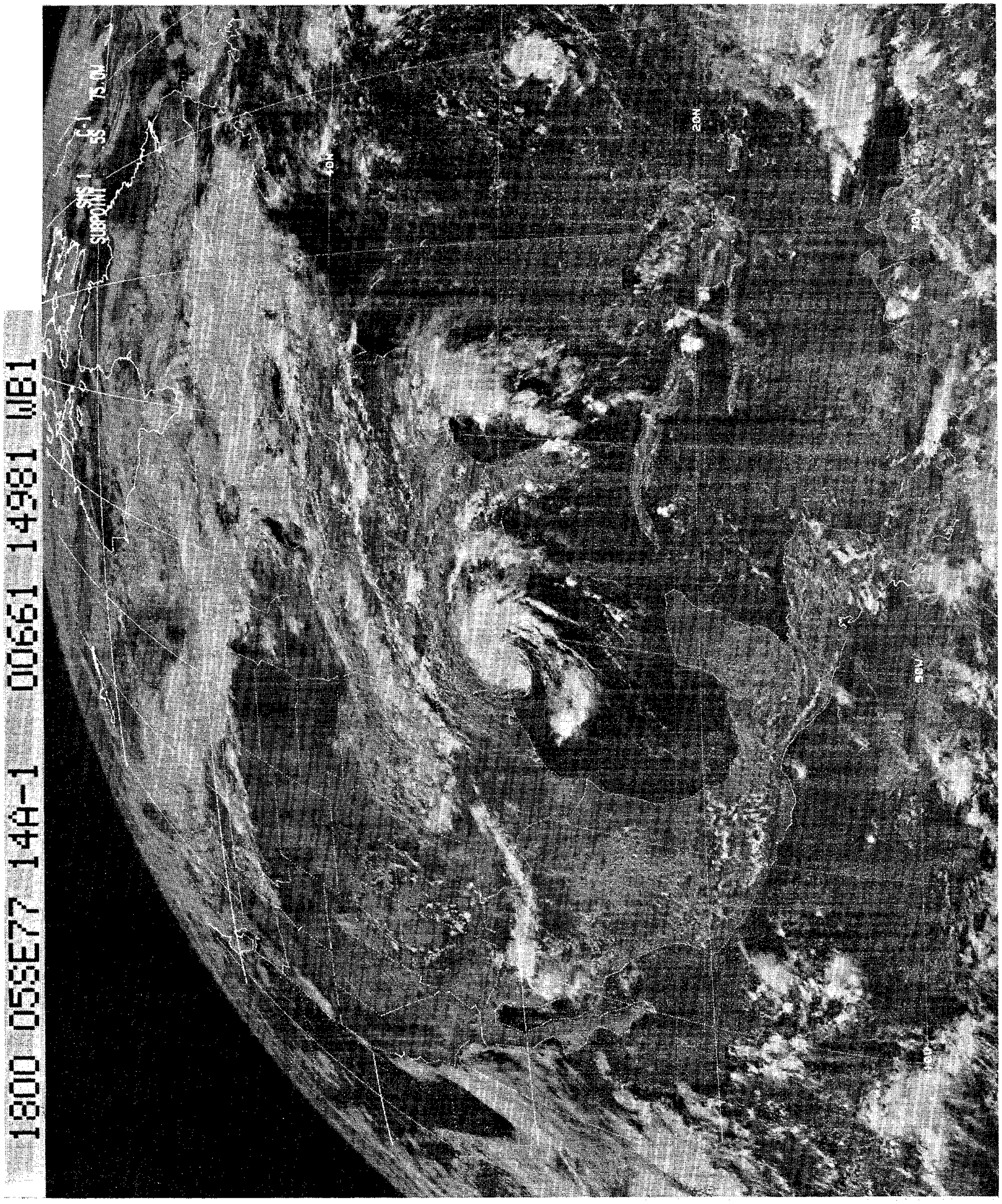


Fig. 23 - NOAA GOES satellite image, 1800Z, September 5, 1977.

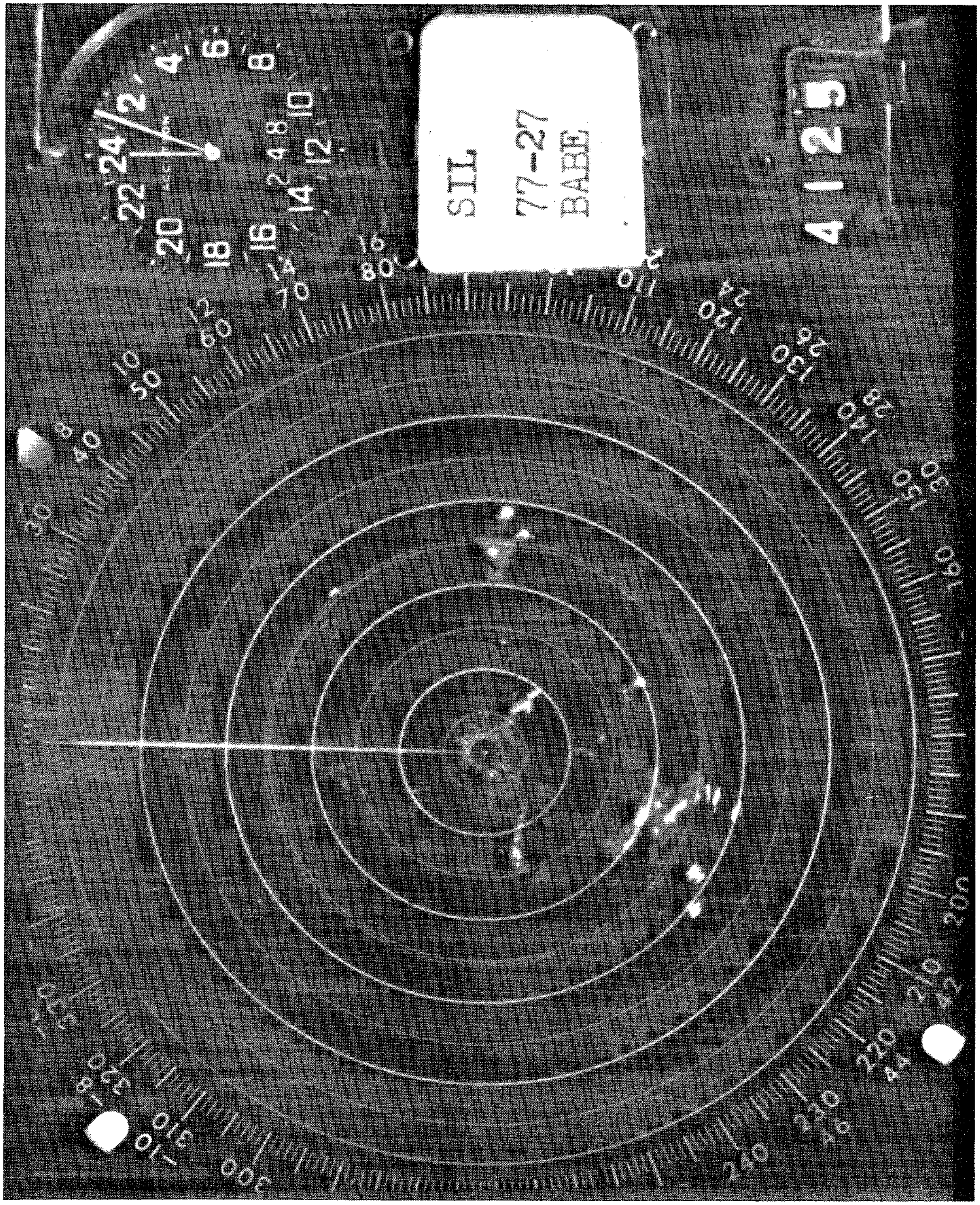


Fig. 24 - Slidell weather radar plan position indicator at 0000Z, September 5, 1977.

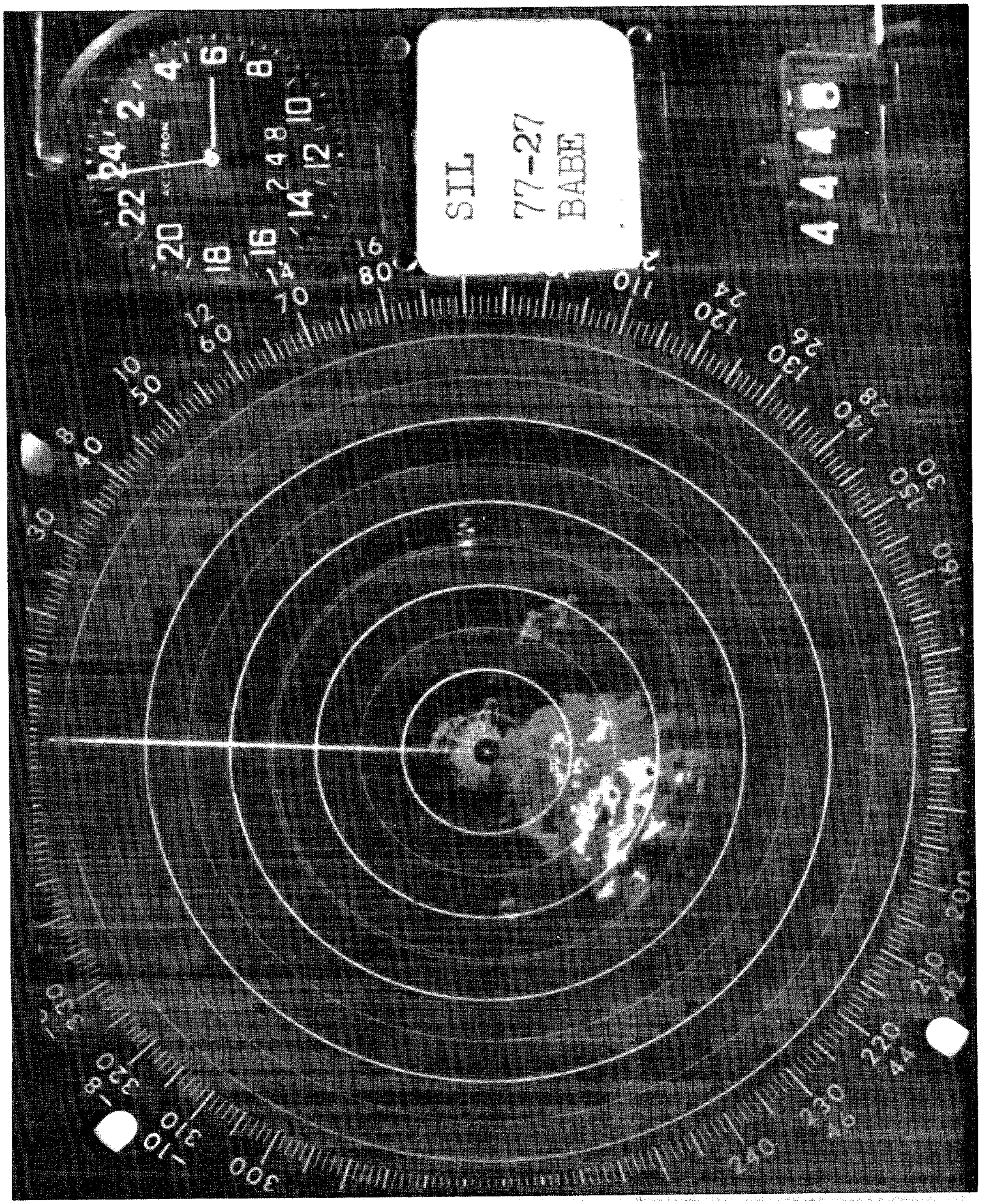


Fig. 25 - Slidell weather radar plan position indicator at 0600Z, September 5, 1977.

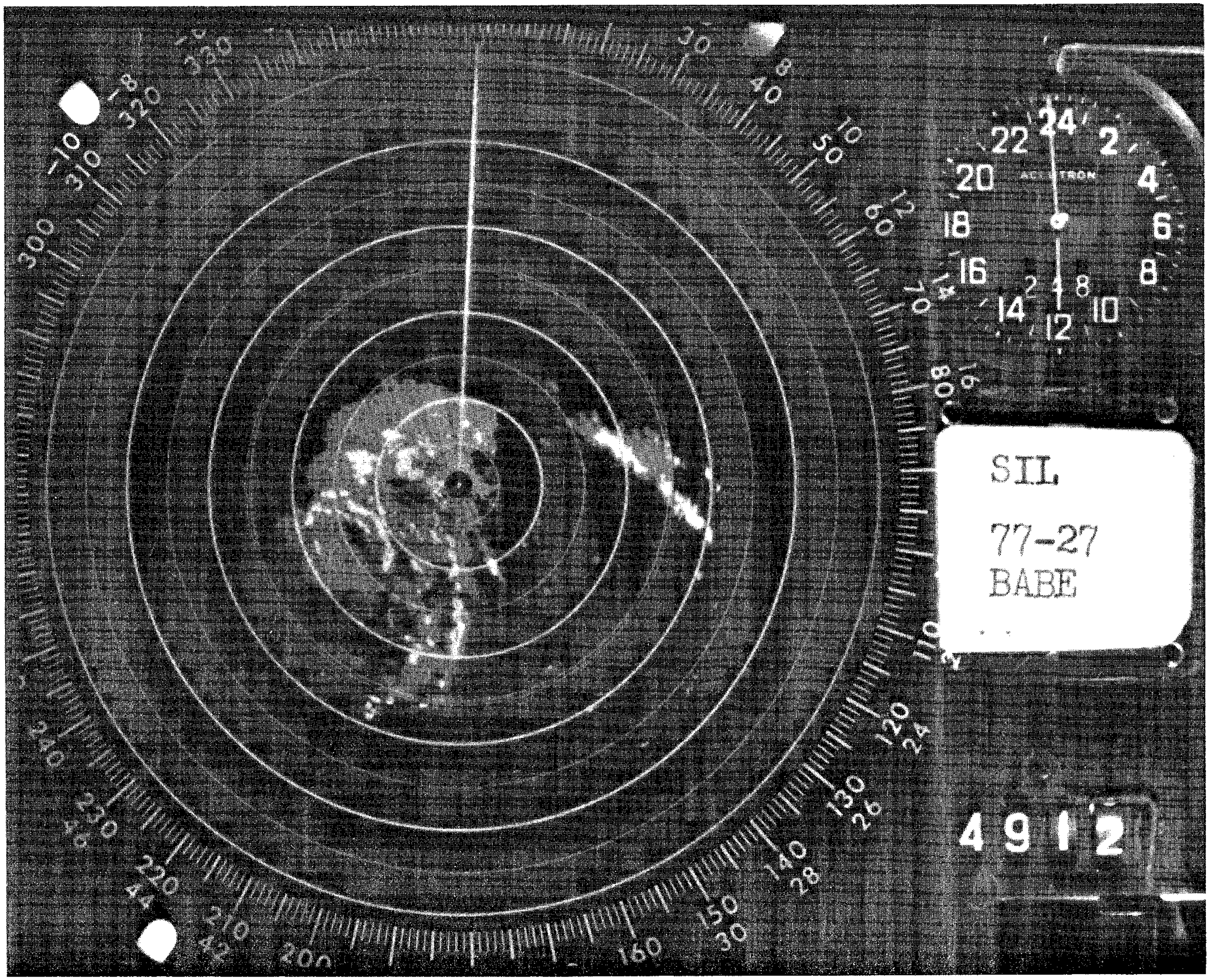


Fig. 26 - Slidell weather radar plan position indicator at 1200Z, September 5, 1977.

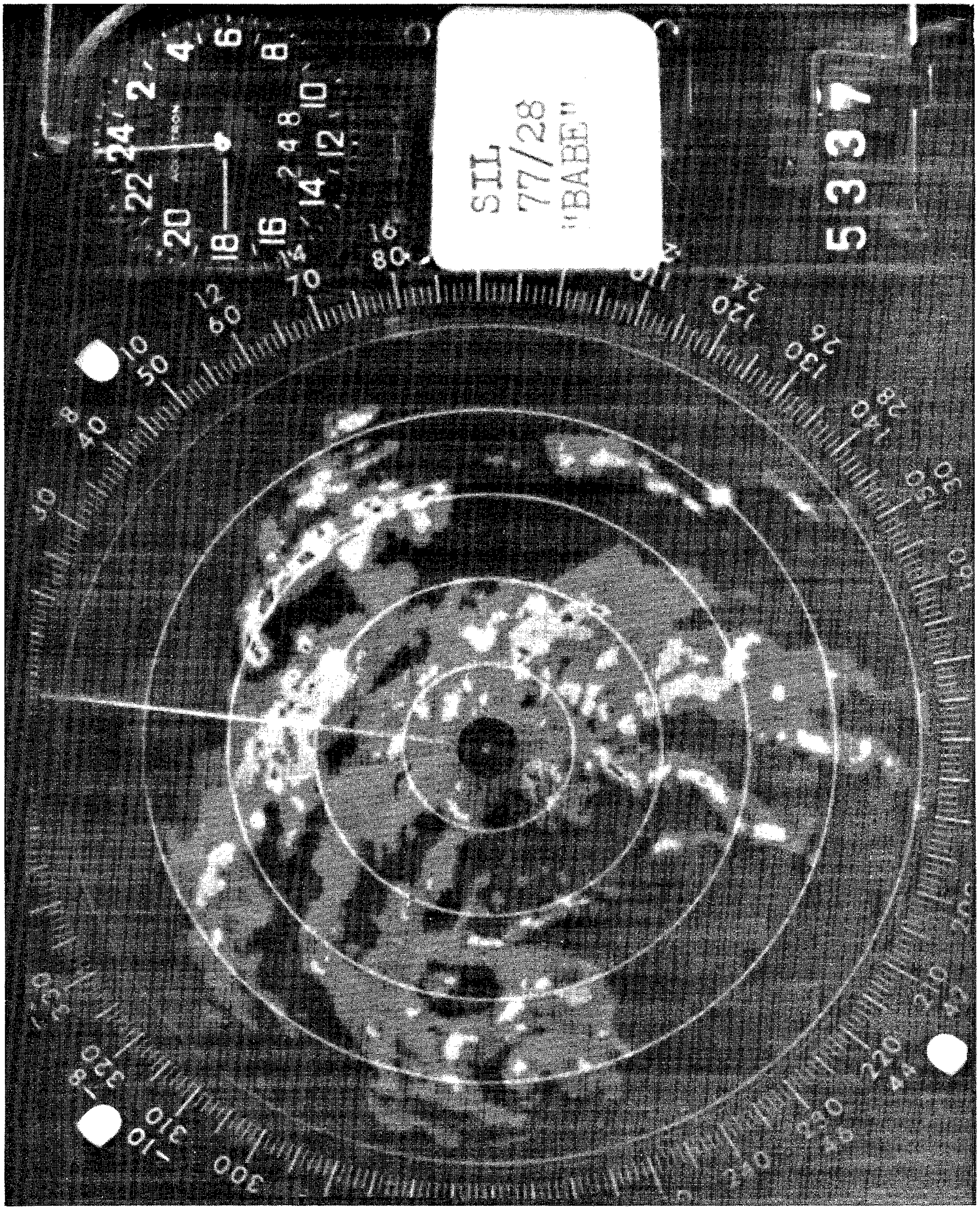


Fig. 27 - Slidell weather radar plan position indicator at 1800Z, September 5, 1977.

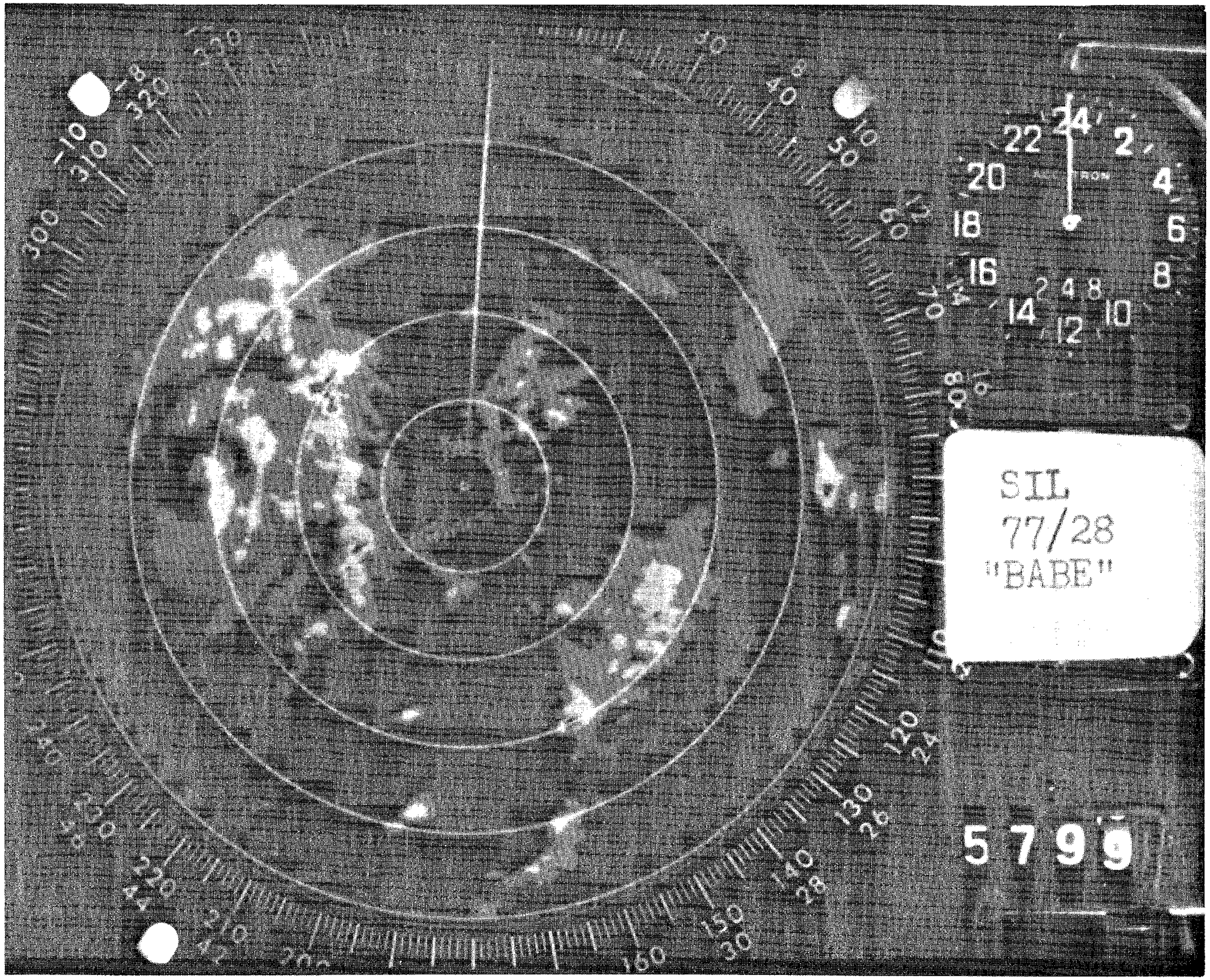


Fig. 28 - Slidell weather radar plan position indicator at 0000Z, September 6, 1977.

Table 6

SUMMARY OF MIAMI SFSS/NHC TROPICAL CYCLONE CLASSIFICATION AND LOCATION REPORTS SUBMITTED TO THE NOAA NATIONAL HURRICANE CENTER ON THE BASIS OF ANALYSIS OF GOES VISIBLE AND INFRARED IMAGERY OF BABE

Month/Day	Time (GMT)	Center Location		C.I.*	V_{max} (knots)	Mean Motion		Averaging Interval	Remarks
		Latitude	Longitude			Hdg	Spd (knots)		
9/03	1430	27.6	87.8	1.5	30	290	7	22	Poorly defined low level circulation.
9/03	1830	27.8	88.3	2.5	35	290	10	4	Convective band E-N-W has become better organized around low level center.
						290	7	25	
9/04	0030	28.1	89.5	2.5	35	285	11	6	System is minimal 2.5. Cold upper center appears 200 miles S of low level center. Troughing in low level center extends to Florida coast to ENE.
9/04	0630	27.3	90.2	2.5	35	240	12	12	System making transition from subtropical to tropical as cloud system is isolated from others.
9/04	1230	27.0	91.4	2.5	35	236	10	12	Circulation center is now closer to convective area. Convective area more clearly defined.
						256	10	6	
9/04	1830	27.6	91.5	3.5	55	353	5	6	System mean motion vectors unreliable due to erratic motion.
						283	5	12	System has now assumed more definitive storm characteristics.
9/05	0030	28.1	91.5	3.5	55	360	5	6	
						350	5	12	
9/05	0630	28.6	91.5	3.5	55	360	5	6	
						360	5	12	

Table 7

BABE EYE FIXES - SLIDELL, LOUISIANA WEATHER RADAR

Date/Time (GMT)	Latitude degrees/minutes		Longitude degrees/minutes		Remarks
05/0132	27	51	90	48	Poor fix, possible center
05/0233					No fix
05/0335					No fix
05/0431	28	19	91	00	D50--fair fix
05/0502	28	29	91	18	15° spiral--poor fix
05/0532	28	30	91	18	15° spiral--poor fix
05/0632	28	42	91	00	15° spiral--poor fix
05/0641	28	42	91	18	Eye--good fix
05/0700	28	45	91	05	Eye--good fix
05/0735	28	50	91	12	Possible center--poor fix
05/0800	28	49	91	12	Eye--good fix
05/0833	29	06	91	20	15° spiral overlay, eye, fair fix
05/0859	29	09	91	22	Possible center--fair fix
05/0932	29	13	91	23	Possible center--fair fix
05/1002	29	20	91	24	15° spiral overlay, fair fix
05/1032	29	23	91	11	Eye D9, good fix, relocated
05/1057	29	23	91	10	Eye D9, good fix
05/1133	29	22	91	09	Eye D8, good fix
05/1209	29	30	91	08	Possible center
05/1236	29	28	91	06	Possible center
05/1307	29	42	91	06	Possible center
05/1340	29	47	91	18	Possible center
05/1405	29	51	91	24	Possible center
05/1434	29	48	91	24	Fair fix--center
05/1508	29	48	91	24	Possible center
05/1535	29	44	91	25	Good fix
05/1635	29	51	91	30	Good fix
05/1736	29	49	91	37	Good fix
05/1800	29	49	91	32	Fair fix
05/1834	29	51	91	30	Fair fix
05/1907	29	59	91	33	Possible center
05/1937	29	57	91	35	Good fix, open SE
05/2001	30	06	91	17	D15 Open W, good fix
05/2032	29	52	91	34	D10 Open W, fair fix
05/2100	29	50	91	26	D15 Open W, good fix
05/2133	29	55	91	22	D12 Open W, fair fix
05/2205	29	45	91	16	Poor fix
05/2231	29	57	91	26	Possible center
05/2300	29	57	91	29	Possible center
05/2332	30	00	91	32	Possible center
06/0001	30	00	91	30	Possible center
06/0701	30	38	91	00	Good fix--D9
06/0731	30	45	90	54	Good fix--D8
06/0802	30	43	90	49	Good fix-D6
06/0832	30	44	90	44	Good fix--D2
06/0912	30	45	90	34	Good fix
06/0932	30	45	90	34	Good fix--D5, 15° spiral overlay
06/1007	30	54	90	28	Fair fix--D6
06/1035	30	54	90	15	Poor fix
06/1100	31	02	90	06	Poor fix
06/1131	31	09	90	00	Good fix
06/1209	31	03	89	56	Fair
06/1235	31	08	89	48	Possible center
06/1310	31	18	89	48	Possible center

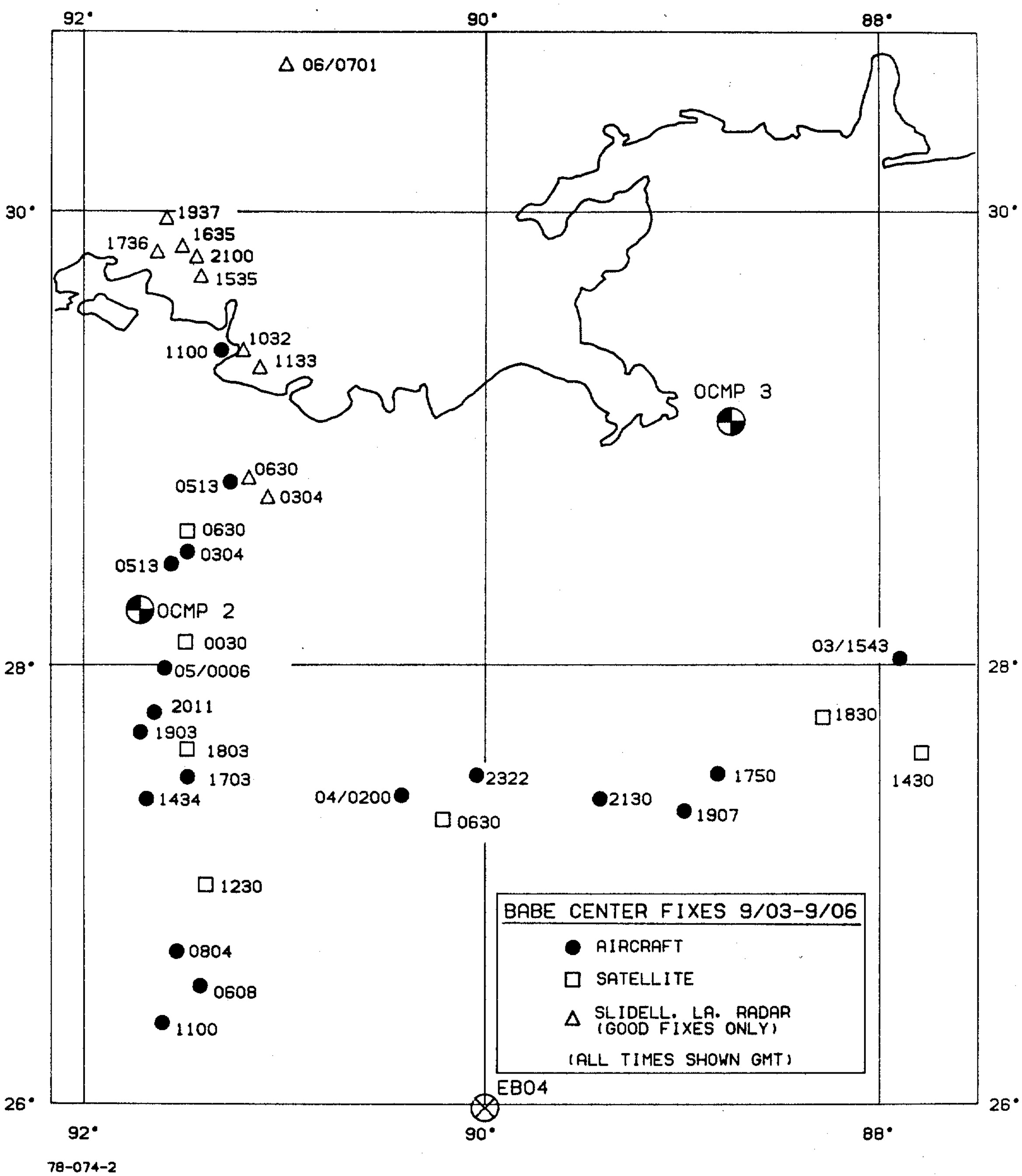


Fig. 29 - Center fixes for hurricane Babe.

Babe was a minimal hurricane and it is likely that hurricane force winds existed only over the water in squalls mainly east of the center and only during the four-six hour period before landfall. No hurricane force winds were reported on land. The lowest pressure of 995 mb was reported by Air Force reconnaissance just before landfall. The highest reported winds were a 46-knot gust at the Coast Guard station at Grand Isle, a 38-knot gust at the New Orleans lakefront airport, and a 34-knot gust at Morgan City. The highest tides were reported to be four to five feet above normal in southeastern Louisiana. A preliminary estimate of property damage due to Babe was $10 million,[10] in addition to the deferred oil and gas production mentioned in the previous section. No serious injuries or fatalities were reported.

MEASUREMENT STATION OPERATION

The locations and water depths of the three OCMP stations are listed below and the station locations are plotted in Figures 1 and 2.

Station 1 - Galveston Area 288A (Buccaneer)
- Latitude - 28°53'28" N
- Longitude - 94°41'42" W
- Water Depth - 68 feet

Station 2 - Eugene Island 331A
- Latitude - 28°14'8" N
- Longitude - 91°42'34" W
- Water Depth - 246 feet

Station 3 - South Pass 62C
- Latitude - 29°05'15" N
- Longitude - 88°44'2" W
- Water Depth - 325 feet

The current meters at all stations are numbered from the top (nearest the surface) meter downward. The meters are aligned so that the x-channel measured true north-south current speed and the y-channel measures true east-west current speed. Currents setting toward the north and toward the east give positive outputs.

Each station contains two 7-channel FM magnetic tape recorders. The recorder designated "current" contains data from Current Meters 1, 2, and 3, plus time. The recorder designated "weather" contains wind, wave, barometric pressure, and time data and data from Current Meter No. 4.

Channel seven of all recorders contains the time signal which consists of a low frequency pulse every minute and a high frequency pulse every hour. The clock also triggers the automatic calibration circuit once every 24 hours. The automatic calibration circuit is triggered manually at the start and end of the tapes to synchronize the station clock with absolute time.

A more detailed description of the instrumentation system is given in the reports by Forristall[1] and Hamilton.[2]

The OCMP stations had been turned off at the end of 1976. The current meters were returned to Marsh-McBirney, Inc., where they were repaired as necessary, recalibrated, and covered with a new layer of No-Foul. In May of 1977, the refurbished current meters were installed at OCMP Stations 2 and 3 and the stations were made operational again with few problems.

Station No. 1 at Buccaneer was not scheduled to be operational for the 1977 phase of the OCMP. However, on August 2, 1977, the station was turned on with a special suite of instruments in hopes of obtaining some data on wave kinematics in the splash zone above mean water level. The details of this attempt and of the operation of the two other stations before and during the storms are given below.

Station 1 (Buccaneer A)

On August 2, 1977, the instrumentation system at Station 1 was turned on with the current meter taut wire system raised so that the second current meter was approximately seven feet above mean water level. Previous laboratory tests and some limited field trials had shown that the electromagnetic current meters responded very rapidly when immersed in a moving stream. The response time seems limited only by the output time constant of the meter--in this case, a 0.2 second simple low pass filter. The meters were thus positioned so that there would be some possibility of recording wave particle velocities above mean water level in hurricane waves. Current Meter 1 was left off since it had failed some months previously. Current Meter 3 was turned on, but was noisy due to probe leakage. The positions of the current meters at Station 1 on August 2 were:

Meter	Depth Below Top of Wave Staff	Nominal Distance from MWL	Rotation
1	Off		
2	56 feet	+7 feet	13.6°
3	81 feet	-18 feet	19.6°

The rotation of the current meters refers to the fact that the anchor holding the taut wires at Station 1 has rotated, twisting the taut wires so that, for example, indicated north is actually 13.6° true for Current Meter 1.

Since the top current meter was not on, the wave staff and barometer were wired to the two recorder channels which would normally have recorded current data and only one tape recorder was operated at the station.

The conversion of the station to the new configuration could not be finished on August 2 and we returned on August 11 to complete the work. On August 31, with Anita crossing the Gulf and the tape about to run out, we made a trip to Station 1 to change the tape. The station was operating correctly at that time although Current Meter 3 was still noisy.

The clock at Station 1 stopped due to battery failure a few hours after the August 31 station check and Current Meter 3 remained noisy and had two severe level shifts. Otherwise, the instrumentation worked well during the storm and a number of waves high enough to immerse Current Meter 2 were recorded. The standby batteries ran down on the morning of September 2 and platform power was restored early on September 3.

The storm tapes were recovered and the station checked on September 30. We then noticed that the taut wire array had slipped down about 16 inches from the position it had on August 2. The two operating current meters were thus also lower by that amount. The exact time of the movement is not now known, although it was most probably during the storm.

Detailed examination of the wave kinematics may indicate the time of movement.

Station 2 (EI331A)

The refurbished current meters were installed and the station became operational on May 31, 1977. The positions of the four current meters at Station 2 are:

Meter	Depth Below Top of Wave Staff	Nominal Distance from MWL
1	55 feet	- 12 feet
2	90 feet	- 47 feet
3	145 feet	-103 feet
4	220 feet	-177 feet

The y-axis of Current Meter 3 became noisy soon after its installation and continued to be noisy throughout the storm period. The cause of the noise has not been identified, but data from the meter should be used with caution.

A regularly scheduled station check was made on August 16 and the station was left in excellent operating condition. On August 28, the bearings of the current recorder drive motor froze and the recorder stopped. However, the recorder started again for two periods of about 1 1/2 hours each at 0635 on August 30 and 1600 on September 1. These times have been accurately determined by the cross-correlation analysis described in the next section.

The rapid development of Anita in the central Gulf precluded any special station checks before the storm. The platform was evacuated on the morning of August 30 and the station ran on back-up battery power until 1900 CDT on September 1, when the battery voltage dropped too low to power the station inverter. The platform was remanned on the morning of September 2 and the power from the generators started the station again at 1245 CDT on September 2. With Babe developing rapidly near the station, the platform was again evacuated at noon on September 3. By then, the batteries had been sufficiently recharged so that the station continued to run until about 1710 CDT on September 4. The platform was again remanned on the afternoon of September 6.

The storm tapes were recovered and the station calibrated on the morning of September 9, 1977. Casts with a Beckman Model RS-5 salinometer were made during the station checks on August 16 and September 9.

Station 3 (SP62C)

The refurbished current meters were installed and the station became operational on May 26, 1977. The positions of the four current meters at Station 3 are:

Meter	Depth Below Top of Wave Staff	Nominal Distance from MWL
1	65 feet	- 15 feet
2	124 feet	- 74 feet
3	202 feet	-152 feet
4	302 feet	-252 feet

A regularly scheduled station check was made on August 16 and the station was found and left in perfect condition. The platform was evacuated on the morning of August 30 and the station ran on backup battery power until 0215 CDT on September 1, when the battery voltage dropped too low to power the station inverter. Although the platform was remanned on September 2, the generators could not be restarted and no data was recorded during hurricane Babe. The platform was again remanned and the generators started on September 6.

The storm tapes were recovered and the station calibrated on the afternoon of September 9, 1977. Casts with a Beckman Model RS-5 salinometer were made during the station checks on August 16 and September 9.

METHODS OF DATA ANALYSIS

The major results presented in this report are strip charts of the current meter signals, accurately calibrated and filtered to remove particle velocities due to wind-waves. They are accompanied by strip charts of wind speed and direction, barometric pressure, and wave height which were similarly filtered. Wave height statistics and spectra are also given. All calculations were performed in the digital mode which meant that the first step in the analysis had to be the digitization of the FM analog field tapes.

Digitization

During digitization, the field recorded tapes were played at 7 1/2 ips, giving a playback/field speed ratio of 250. The digitization rate was 500 Hz per channel at playback speed or two Hz field speed. To avoid aliasing, the analog signals (except Channel seven, the clock) were filtered by a four-pole, 24 db/octave Butterworth filter with a cutoff frequency of 200 Hz at playback speed or 0.8 Hz at field speed.

Calibration and Filtering

The field data tapes include automatic calibration records written on the tapes every 24 hours.[2] For most channels, the calibration mark is simply a constant voltage applied to the recorder. However, the current meters include an internal calibration circuit which also permits a check on the operation of most of the meter's amplification stages. Since the digital tapes also include the calibration marks, it is possible to calibrate the digital tapes to engineering units without detailed knowledge of the performance of all the recorders and amplifiers upstream from the digital tape.

The current meters used in the program do not have a perfect cosine response; i.e., for constant flow speed, the measured velocity is a nonconstant function of azimuth. The maximum error, for a current at 45° to the current meter axes, is eight percent. According to Marsh-McBirney, Inc., the response curve is fully repeatable for all meters of the design used in the program for all flow velocities. Thus, the correct velocity $\underset{\sim}{V}_1$ can be found through use of the formula:

$$\underset{\sim}{V}_1 = \underset{\sim}{V} \left(1 - .08 \left|\sin 2\theta\right| \right)^{-1} , \qquad (1)$$

which was applied to all the digitized and calibrated current meter records.

As mentioned in the previous section, the current meters at Station 1 (Buccaneer) are no longer precisely aligned with geographic coordinates. To correct this problem, it was necessary to make a coordinate rotation which was done rather easily in the digital mode.

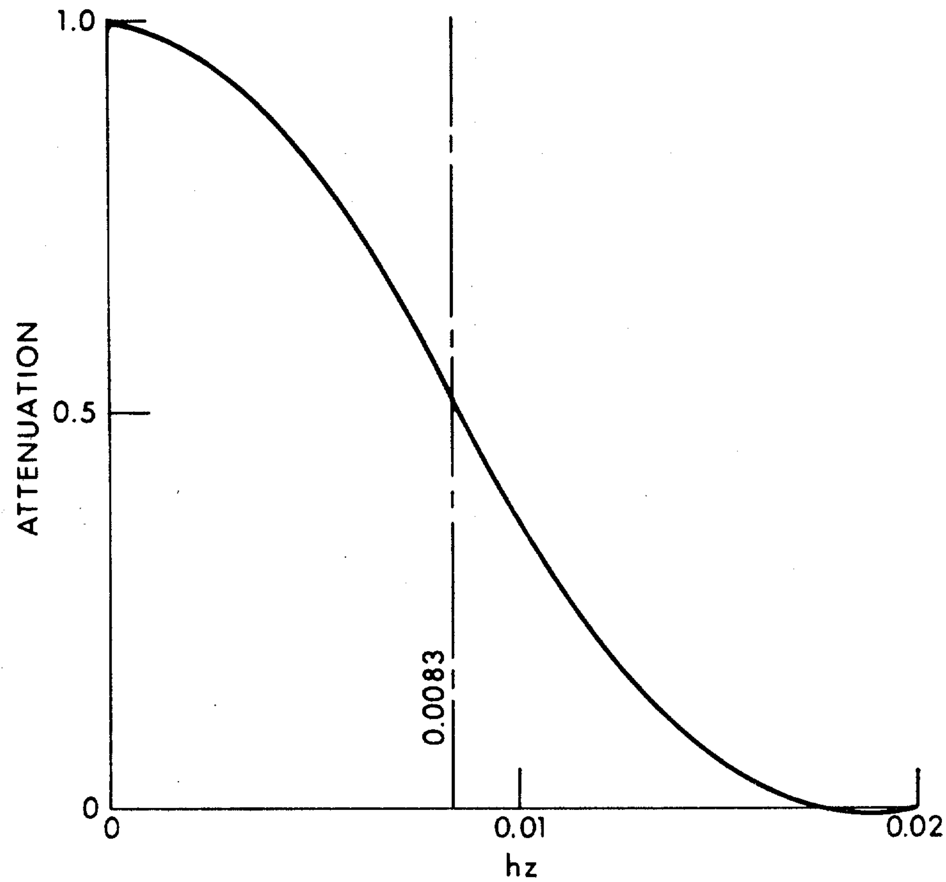
The records from the current meters include motions of two time scales: oscillatory motion associated with the waves and much more slowly varying currents. To separate these effects, some sort of averaging is required and to avoid the side lobes which simple averaging creates, a 383-point numerical filter with a two-minute cutoff was used. The characteristics of the digital filter are shown in Figure 30. The filter is not very sharp and it might be thought that the cutoff frequency is too high to properly filter out wave velocities. In fact, over a wide range the choice of digital filter has very little effect on the resulting currents. Aside from being convenient, this fact confirms the assumption that the separation of the water velocity into wave effects with time scales of a few seconds and currents with time scales of a few hours is a rational method of analysis. The wind speed and direction, barometric pressure, and wave record were filtered in the same way.

Wave Heights and Periods

The surface of the sea during a hurricane is quite complex, consisting of irregular waves of various heights and periods. The best description of the sea state thus is given by calculating various statistical properties of the wave time history. A great many such descriptors are in use and none is intrinsically more correct than any other, although some are certainly more useful. It is therefore very important to explicitly define what descriptors and methods of calculation are used in any particular study.

The analyses in this report were done for consecutive 30-minute segments of data beginning at each hour and half hour. The mean sea level for each segment was calculated and defined as the zero level. A wave was then defined as the part of the record between two consecutive passages of the trace down across the zero level. This definition is sometimes referred to as the zero downcrossing method. The 30-minute records were thus divided into a number of consecutive sections, each of which constitutes a wave. The period of each wave is then the time between downcrossings and the height of the wave is the difference between the highest and lowest elevations during the wave, that is, the distance between the crest and the preceding trough. These concepts are illustrated for two waves in Figure 31.

Given a list of the waves in a 30-minute segment, the significant wave height, $H_{1/3}$, is defined as the average height of the highest one-third



75-0024-2

Fig. 30 - Digital filter characteristics.

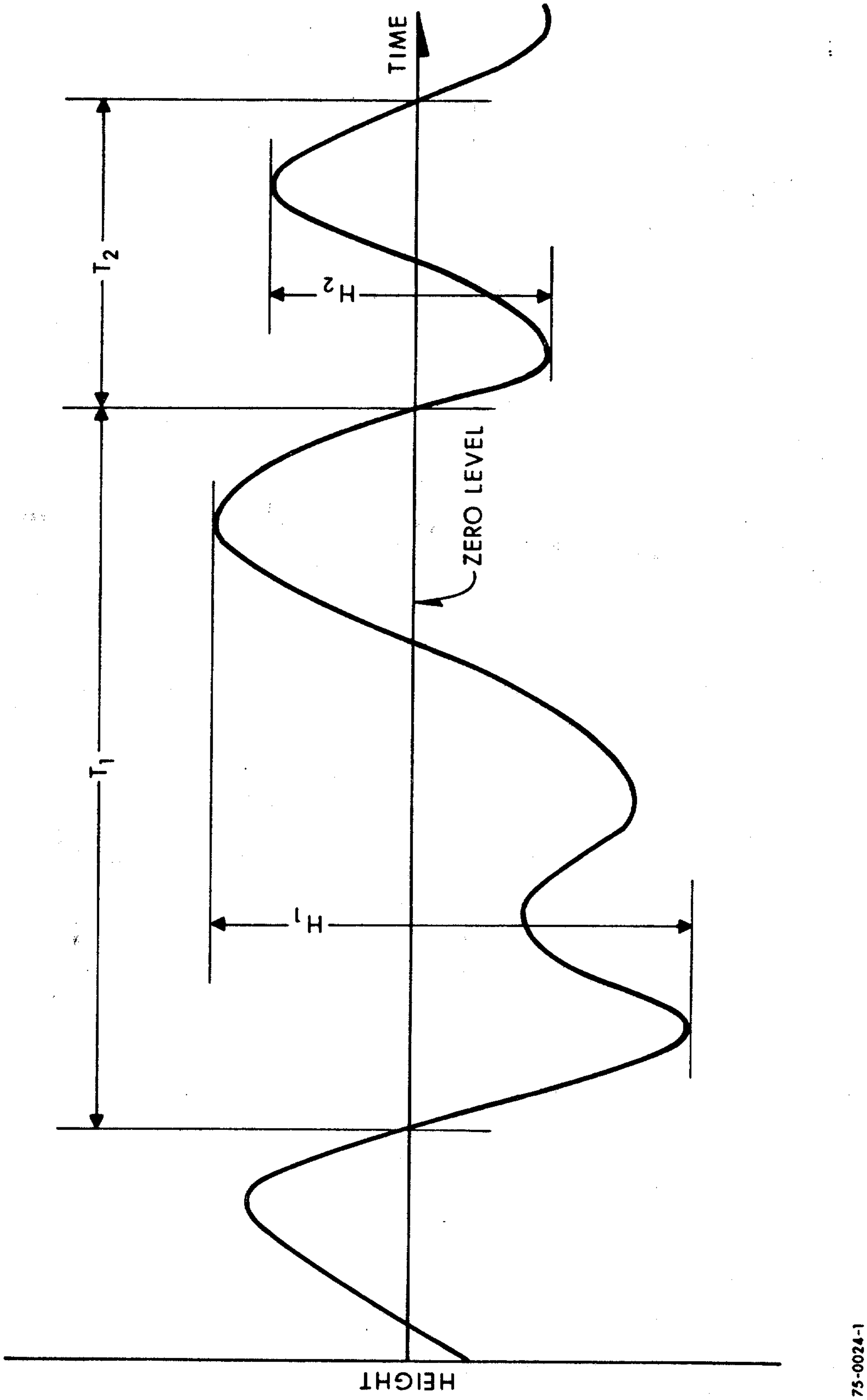


Fig. 31 - Wave definitions.

of the waves. The significant wave period, $T_{1/3}$, is defined as the average of the periods of those waves. The significant wave height thus defined should correspond to the average wave height reported by an expert making visual observations.

Spectra

A much more complete description of the sea state is given by its spectra. A large number of techniques for calculating spectra exist, each of which is recommended by various authors for various situations and which give slightly different results. Fortunately, the wave time histories are sufficiently long and well behaved that the choice of method is not critical. For consistency, we have used the same method as in previous OCMP reports.[4,5]

The spectra were computed over the consecutive 30-minute intervals using Fast Fourier Transform (FFT) techniques. Since the 30-minute record contains 3600 samples and the FFT demands a sample length which is a power of two, the records were augmented with 248 zeros at each end. This zero filling actually aids the analysis by sharpening the spectral window.

The FFT yields 2048 real and imaginary Fourier components $a_i\ (f_i)$ and $b_i\ (f_i)$, where the frequencies f_i are equally spaced between 0 and 1.0 Hz. The raw power spectral estimates are then defined by:

$$S_i = (a_i + b_i^2)/(3600)(2048) \quad . \tag{2}$$

The division produces a variance spectra with units of feet-squared. The spectra were then smoothed using a 20-point boxcar window, so that:

$$S_k = \sum_{i = 20k + 1}^{20k + 21} S_i \quad . \tag{3}$$

Each of the smoothed estimates will then have approximately 35 degrees of freedom. To produce a power density spectra with units of ft^2-sec, each S_k is divided by the width of the smoothed frequency band, $\Delta f = 20/2048$. If the wave heights were distributed according to a Rayleigh distribution, the significant wave height could be derived from the spectrum through the relation:

$$H_s = 4M_o^{1/2} \quad , \tag{4}$$

where

M_o is the total variance of the spectrum.

Note that the significant wave height calculated from (4) is distinguished by a different symbol than that calculated from the original definition, since it will, in general, have a different value.

The mean was removed from the wave trace prior to taking the FFT, but no trend removal was attempted. Some extraneous energy thus sometimes appears in the lowest smoothed band. Since this band contains only waves with periods longer than 100 seconds and should have nearly zero energy, it was not included in the calculation of M_o or H_s.

Correlation of Wave Staff and Current Meter Records

As mentioned in the previous section, the current recorder at Station 2 ran for only two brief periods during hurricane Anita. Study of some characteristic noise spikes on the analog tapes indicated the probable time of those periods, but it was important to accurately verify this timing.

The verification was done by calculating the coherence between the signals from the current meters and the wave staff, for which the timing was known. The coherence is defined as:

$$\gamma^2 = \frac{(\sigma_{wv})^2}{\sigma_{ww}\,\sigma_{vv}} \quad , \tag{5}$$

where

$$\sigma_{wv} = \frac{1}{2048} \sum_{i=1}^{2048} W_i V_i , \tag{6}$$

and W_i and V_i are successive digitized measurements from the wave staff and one current meter axis, respectively. If linear wave theory holds, the coherence should be unity when the two signals have the same time base.[11] If the time base of the signals differs by more than a few seconds, the coherence should approach that of two random noise signals which is zero.

The current tape did have hour marks from the clock recorded during the two intervals in question. Thus, each hour in turn of the wave trace was correlated with the current meter traces and the best fit found. For the correct timing, the coherence on the best current meter channel was 0.76, which was at least two orders of magnitude higher than the coherence for any other timing. We are thus quite confident in the timing presented for the current records.

RESULTS

Figure 32 is a strip chart of the measurements recorded at Station 1. Strip charts of the wind, waves, and barometric pressure recorded at Stations 2 and 3, respectively, are given in Figures 33 and 34 and strip charts of the currents recorded at those stations are displayed in Figures 35 and 36. On each strip chart, the bottom trace gives thehour pulses from the station clock, to which noon and midnight CDT and dates have been added. Each 24 hours, calibration records appear as spikes on the data traces. Information concerning station operation and malfunctions has been added to the charts. Below, we discuss some significant features of the measurements with particular emphasis given to extremes.

Wave Height and Period

The fifth trace down in Figure 32 and the top traces in Figures 33 and 34 are the calibrated--but unfiltered--output from the wave staff. The time scale is far too compressed for individual waves to be distinguished, but some idea of the severity of the sea state can be estimated from the breadth of the trace. More detailed information on wave heights and periods is given in Figures 37-40. In these figures, CDT is plotted as the abscissa and the heights and periods are reported for 30-minute data sections. Occasional noise spikes or gaps in the data have been edited out or interpolated across. In the wave height graphs, the solid line shows the maximum height during each data segment, the dashed line shows $H_{1/3}$, and the dash-dot line shows H_s. In the wave period graphs, the dashed line shows the period of maximum energy from the spectral computations and the dash-dot line shows $T_{1/3}$.

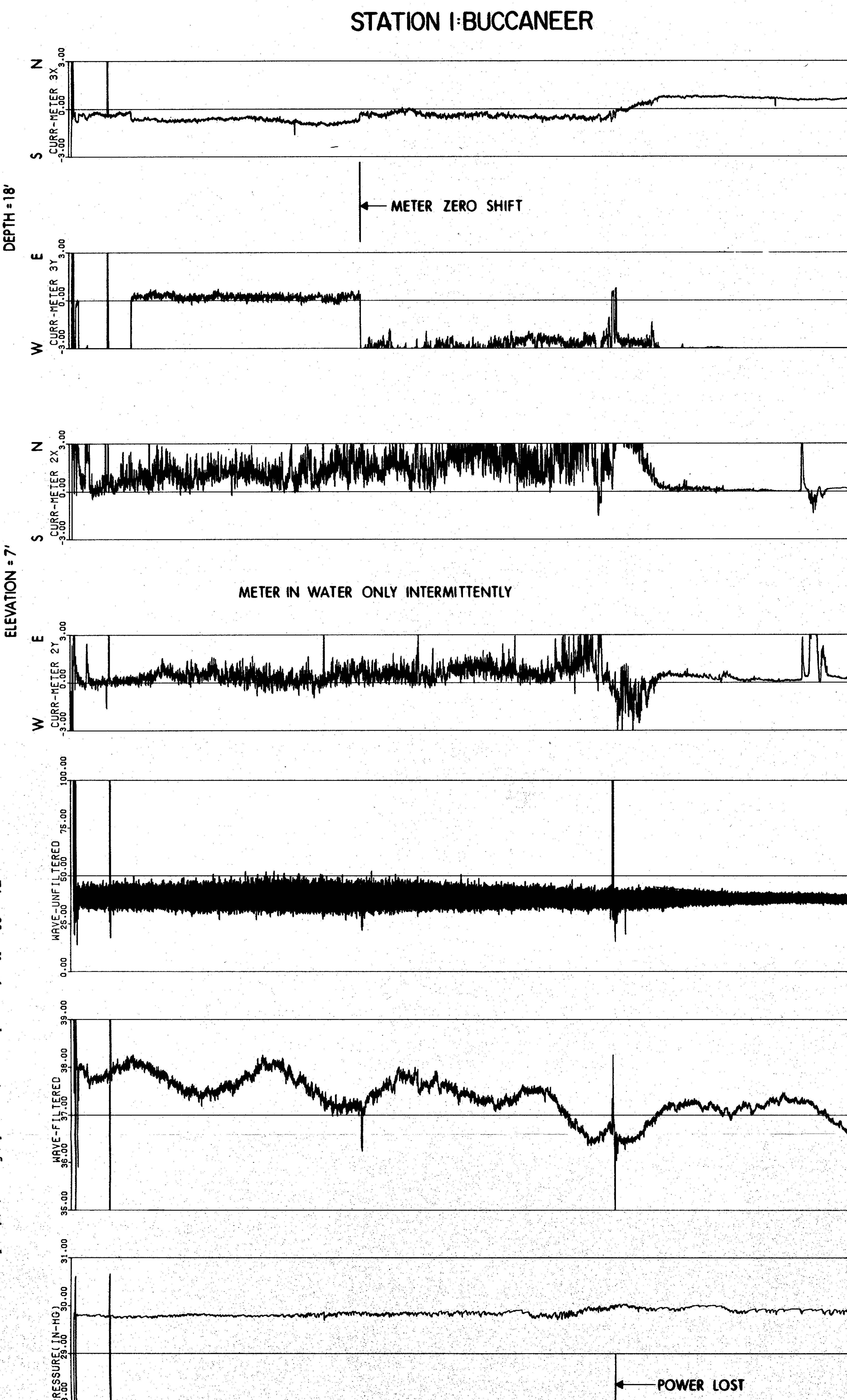


Fig. 32 - Weather and current records from station 1.

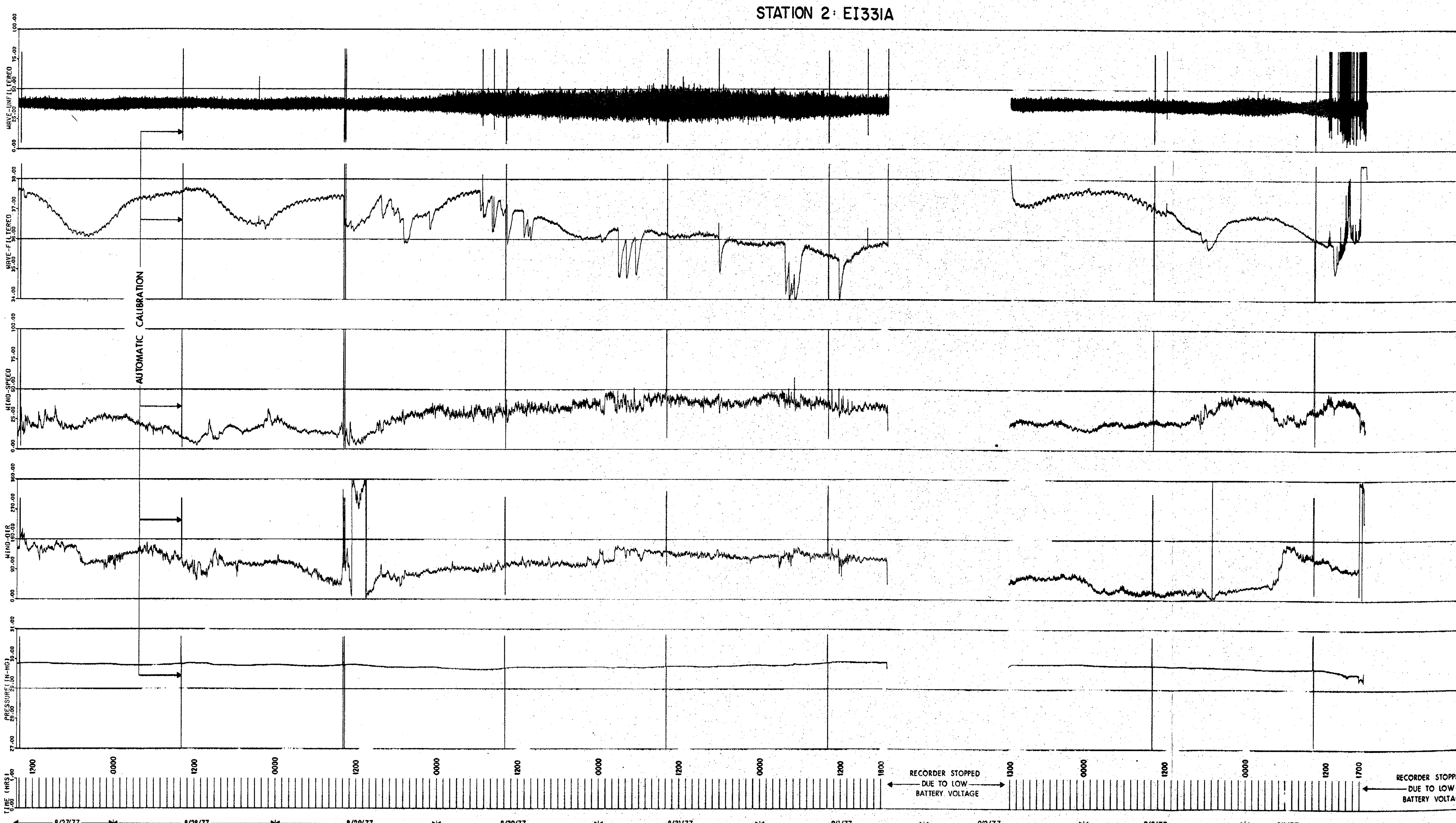


Fig. 33 - Weather records from station 2.

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STATION 3: SP62C

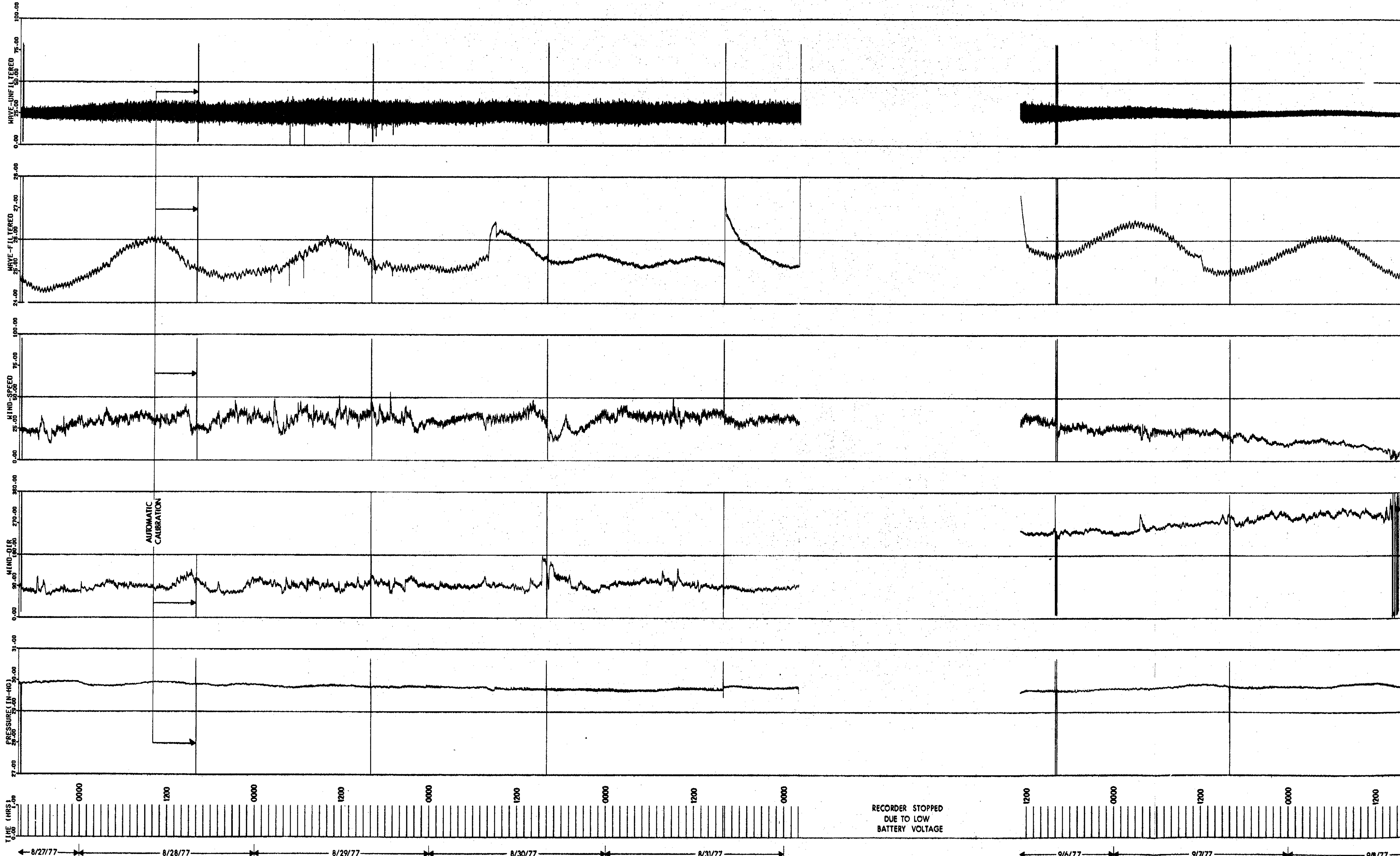

Fig. 34 - Weather records from station 3.

STATION 2: EI33IA

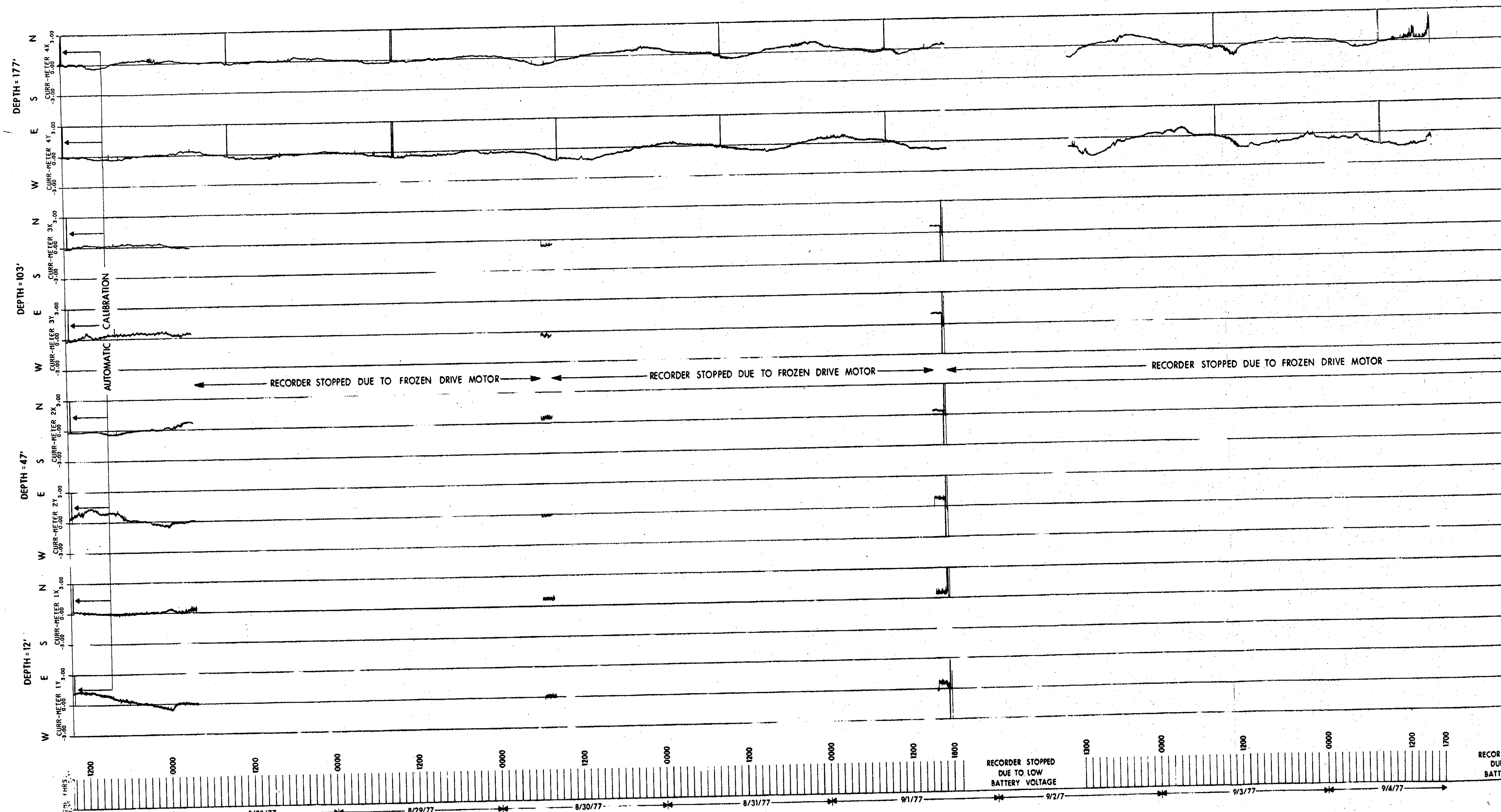

Fig. 35 - Current records from station 2.

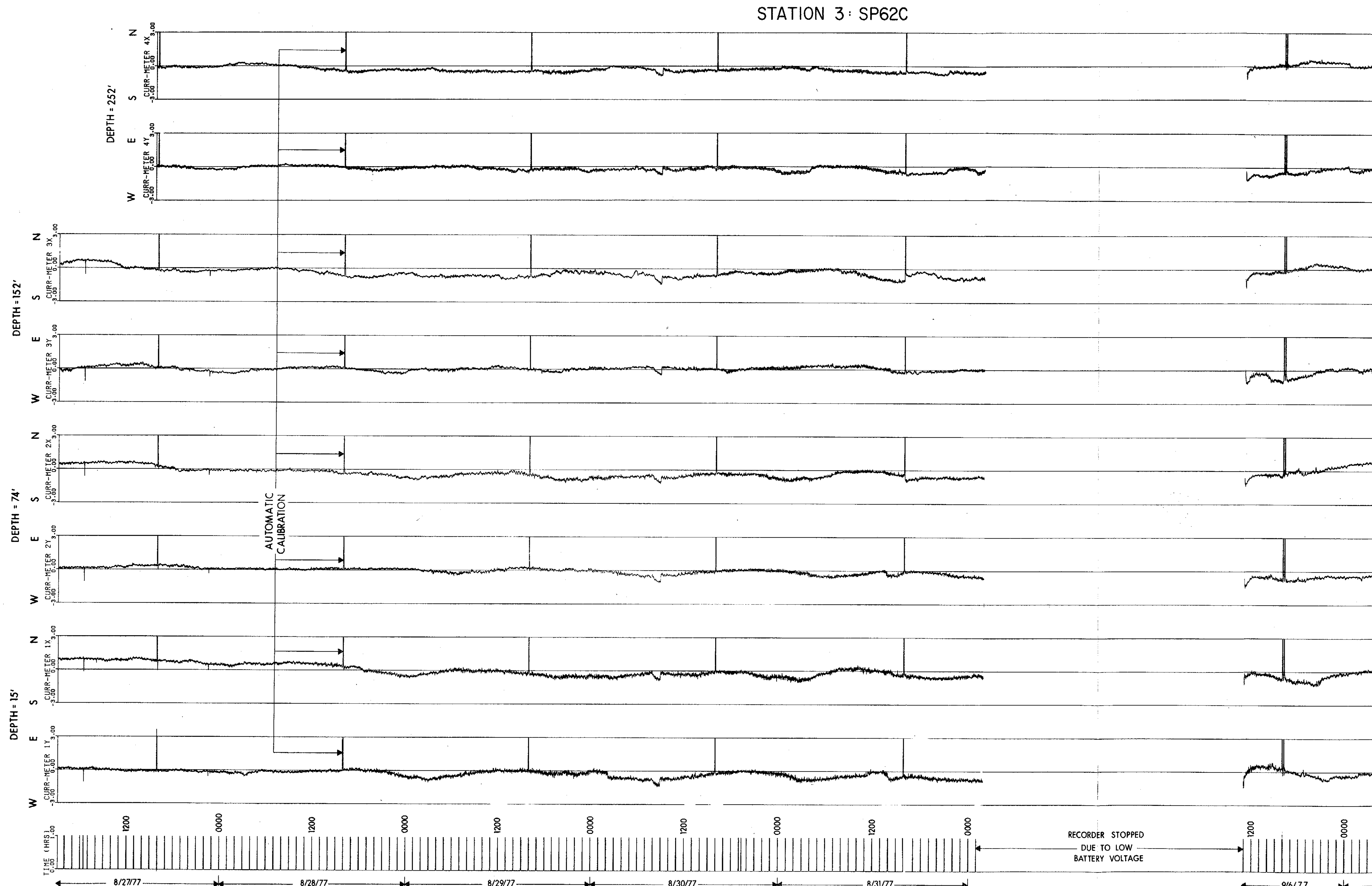

Fig. 36 - Current records from station 3.

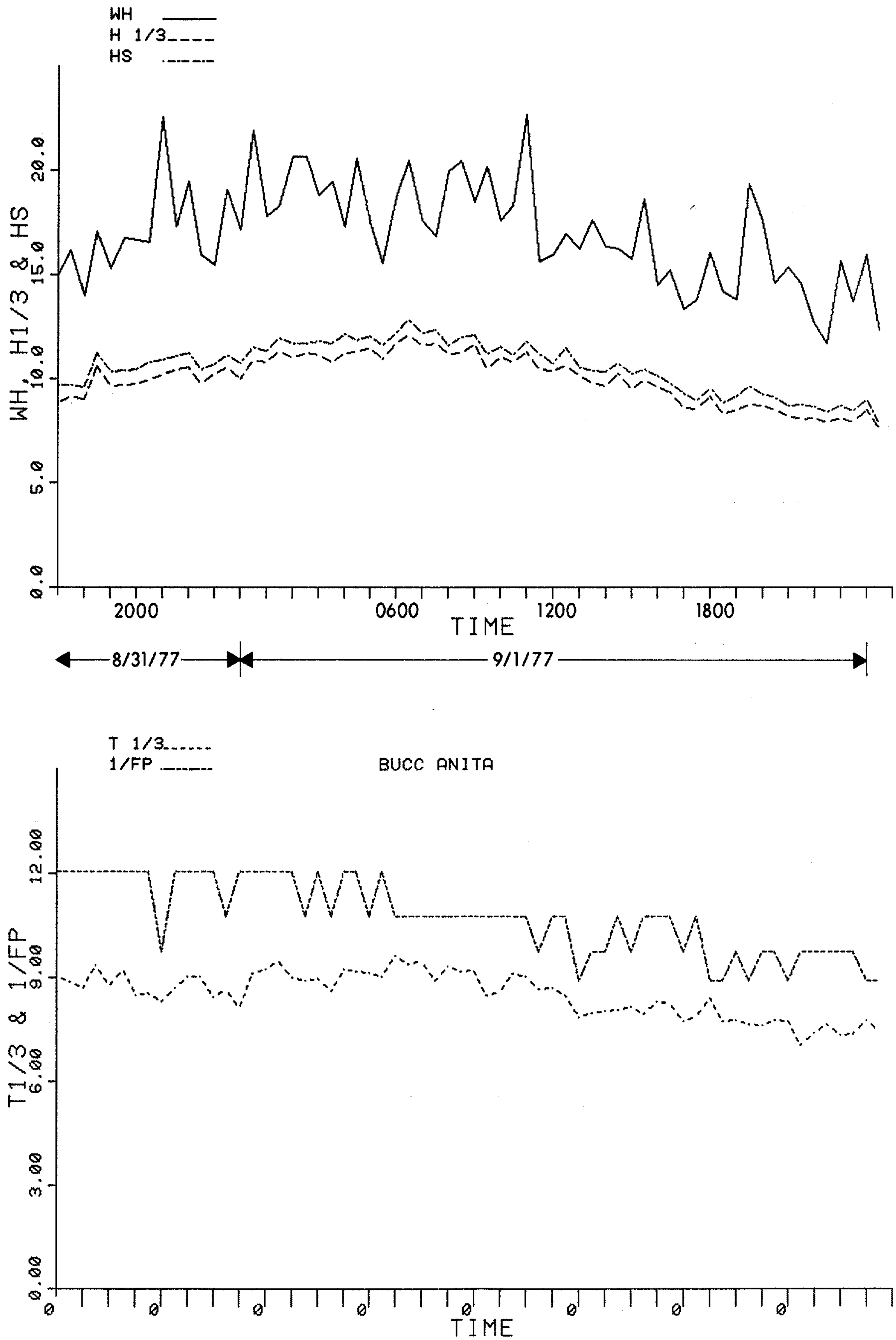

Fig. 37 - Wave heights and periods from station 1 during Anita.

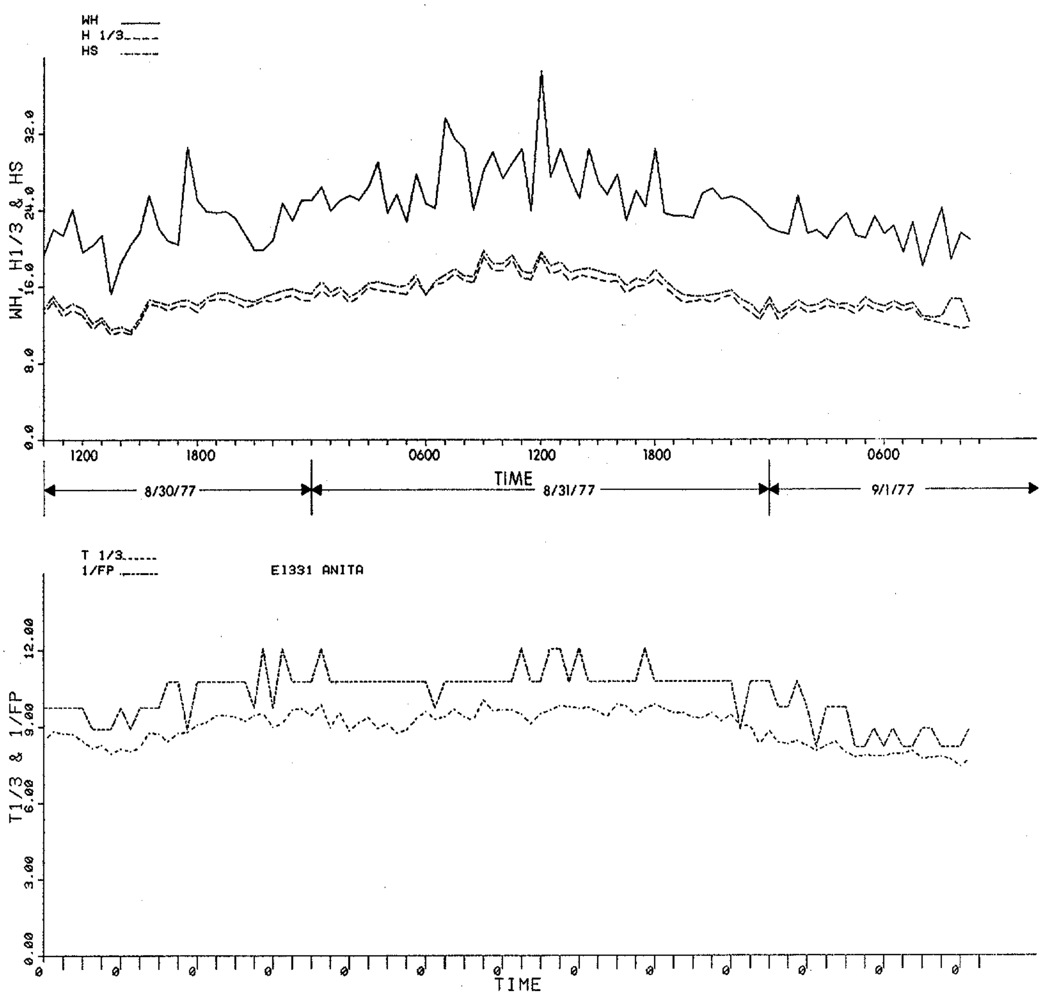

Fig. 38 - Wave heights and periods from station 2 during Anita.

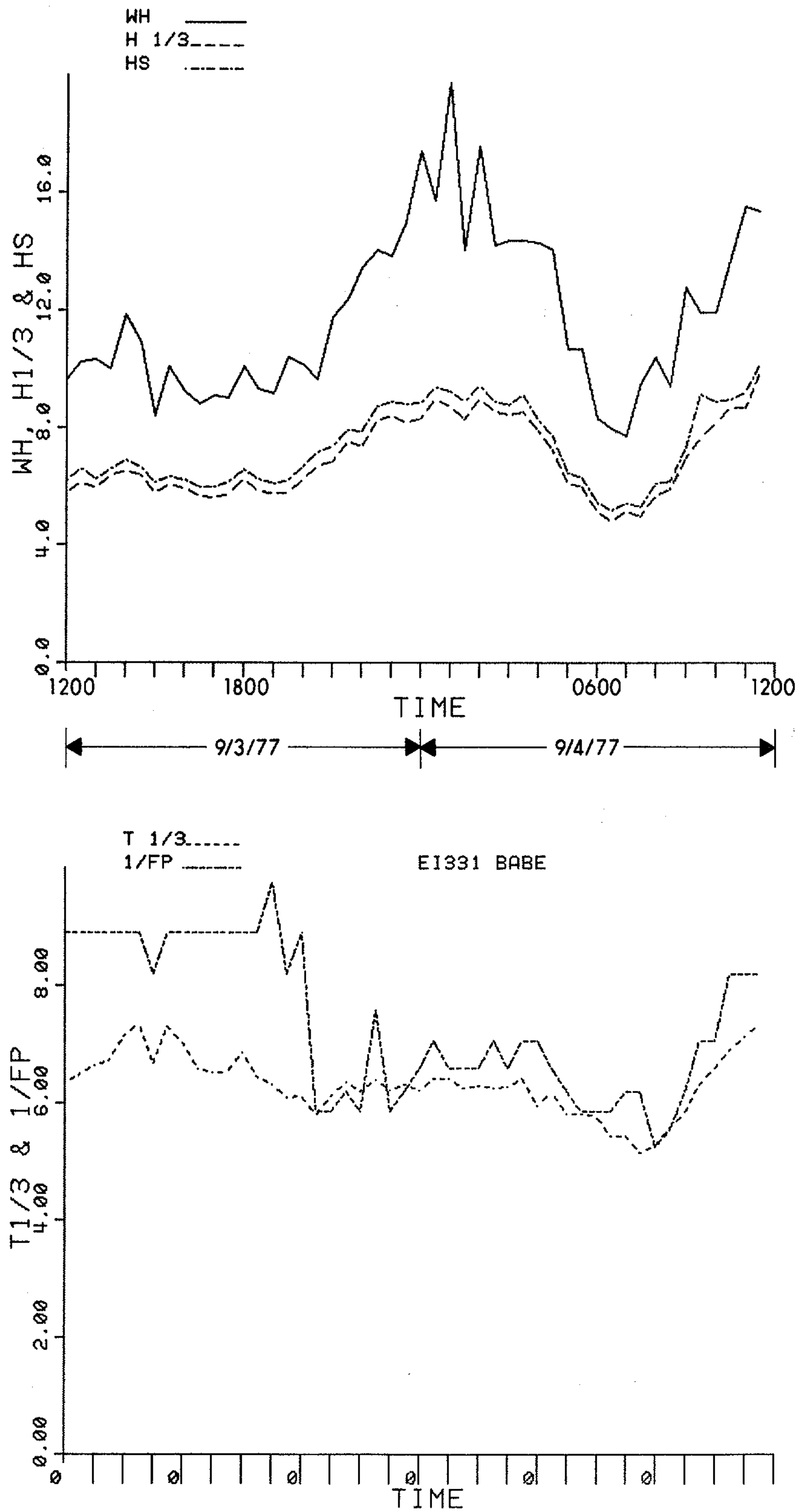

Fig. 39 - Wave heights and periods from station 2 during Babe.

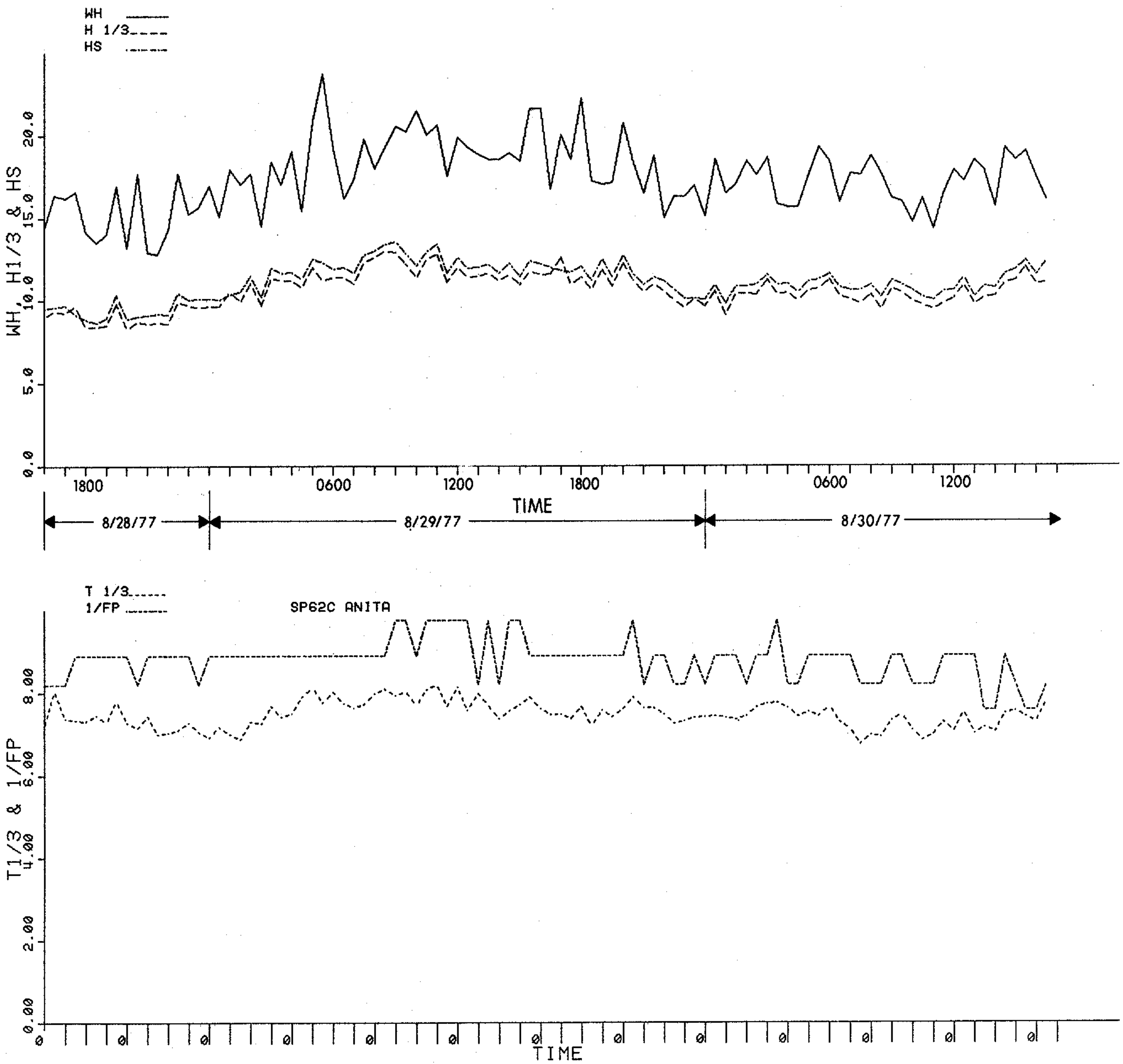

Fig. 40 - Wave heights and periods from station 3 during Anita.

At Station 1, the highest wave was 22.7 feet with a 10.5-second period, recorded at 1100 CDT on September 1. A 22.6-foot wave with a 9.5-second period was recorded at 2100 on August 31. Throughout the time period shown in Figure 37, there were a great many waves high enough to immerse the top current meter. The maximum of the significant wave height, $H_{1/3}$, was 12.11 feet at 0630 on September 1 and the maximum of H_s was 12.85 feet at the same time. At this station as well as the others, H_s from the spectral energy consistently exceeded $H_{1/3}$ from the zero downcrossing method by about five percent. This discrepancy is a symptom of the failure of the actual wave height probability distribution to match the Rayleigh distribution.[12] The significant wave height remained near ten feet at Station 1 from 1830 on August 31 to 1500 on September 1. As shown in Figure 2, Anita made her closest approach south of the station during this time interval, strengthening as she moved away farther to the south. During the large waves, the period of maximum energy was 11-12 seconds and the average period of the significant wave was nine seconds.

Figure 38 shows the wave heights and periods recorded at Station 2 during the influence of Anita. The highest wave was 38.5 feet, recorded at 1200 CDT on August 31. The period of this wave was 10.0 seconds. This high wave was quite rare in the sense that it was 7.85 times the square root of the spectral variance.[12] The highest values of $H_{1/3}$ and H_s, 19.17 feet and 19.64 feet, respectively, also occurred at 1200 CDT. Because of the slow passage of Anita to the south of the station, the waves remained relatively high for a long time; the significant wave height was over 15 feet from 2300 on August 30 to 1900 on August 31. During this time, the period of maximum energy in the spectrum was usually 10.9 seconds and the average period of the significant waves was near nine seconds.

Wave data were also collected at Station 2 during hurricane Babe as shown in Figure 39. The highest individual wave recorded during Babe was 19.7 feet with a 6.0-second period, at 0100 CDT on September 4. The values of $H_{1/3}$ and H_s at that time were 8.74 and 9.23 feet, respectively. The wave heights then declined before again building to a recorded peak of 9.87 feet for $H_{1/3}$ and 10.17 feet for H_s at 1130 CDT on September 4. As shown in Figure 33, the recorder

Anita

Babe

continued to work with some dropouts due to low voltage until shortly after 1700 on the fourth. The noise spikes on the wave channel made the standard statistical analysis of the wave data impossible from 1230 to 1700. However, examination of the unfiltered wave trace in Figure 33 indicates that the significant wave height declined slightly during this time period. It is interesting to compare the wave data with the center fixes for Babe in Figure 29. The first wave height peak at midnight September 23-24 was due to the passage of the east-west convective band which can be seen moving onshore in Figure 22. The next peak, apparently reached between 1200 and 1700 on the fourth, is due to the northern half of the hurricane proper. At 1500 CDT, Figure 29 shows the center of Babe about 30 miles south of the station. The eye of the ill defined storm was apparently moving over the station as the power failed. Since reconnaissance flights reported that the southwest quadrant of Babe was the strongest, it is quite likely that the wave heights increased to another, higher maximum later in the day after the power failed. No data during Babe were recorded at the other two OCMP stations.

Figure 40 shows the wave heights and periods recorded during Anita at Station 3. The storm was weak when it was due south of the station and then moved away as it strengthened. As a result, the significant wave height grew slowly to ten feet early on August 29 and then remained near that level until the end of the recording on September 1. The maximum values of $H_{1/3}$ and H_s were 13.01 feet and 13.41 feet, respectively, recorded at 0900, August 29. The highest individual wave was 23.7 feet with an 8.5-second period at 0530 on August 29. The period of maximum energy was usually 9.0 seconds and the average period of the significant waves was about 7.5 seconds.

Wave Spectra

A selection of the calculated wave spectra are shown in Figures 41-45 for Station 1 during Anita, Figures 46-52 for Stations 2 during Anita, Figures 53-57 for Station 2 during Babe, and Figures 58-63 for Station 3 during Anita. The abscissa in each plot is frequency in Hz and the ordinate is energy density in ft^2-sec. An effort was made to keep the ordinate scale uniform, but the wide range of energies made

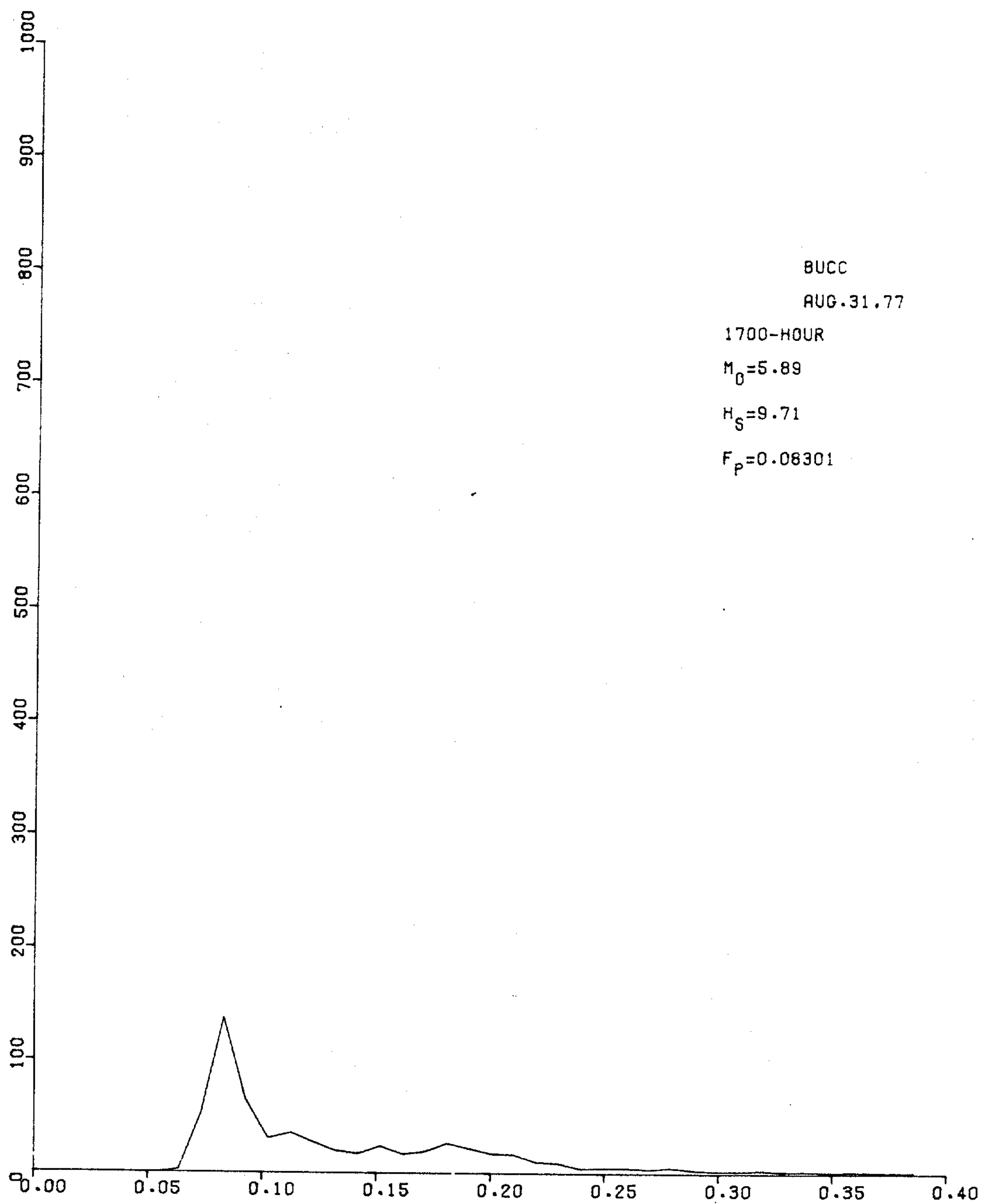

Fig. 41 - Wave spectrum from station 1, 1700 CDT, August 31, 1977.

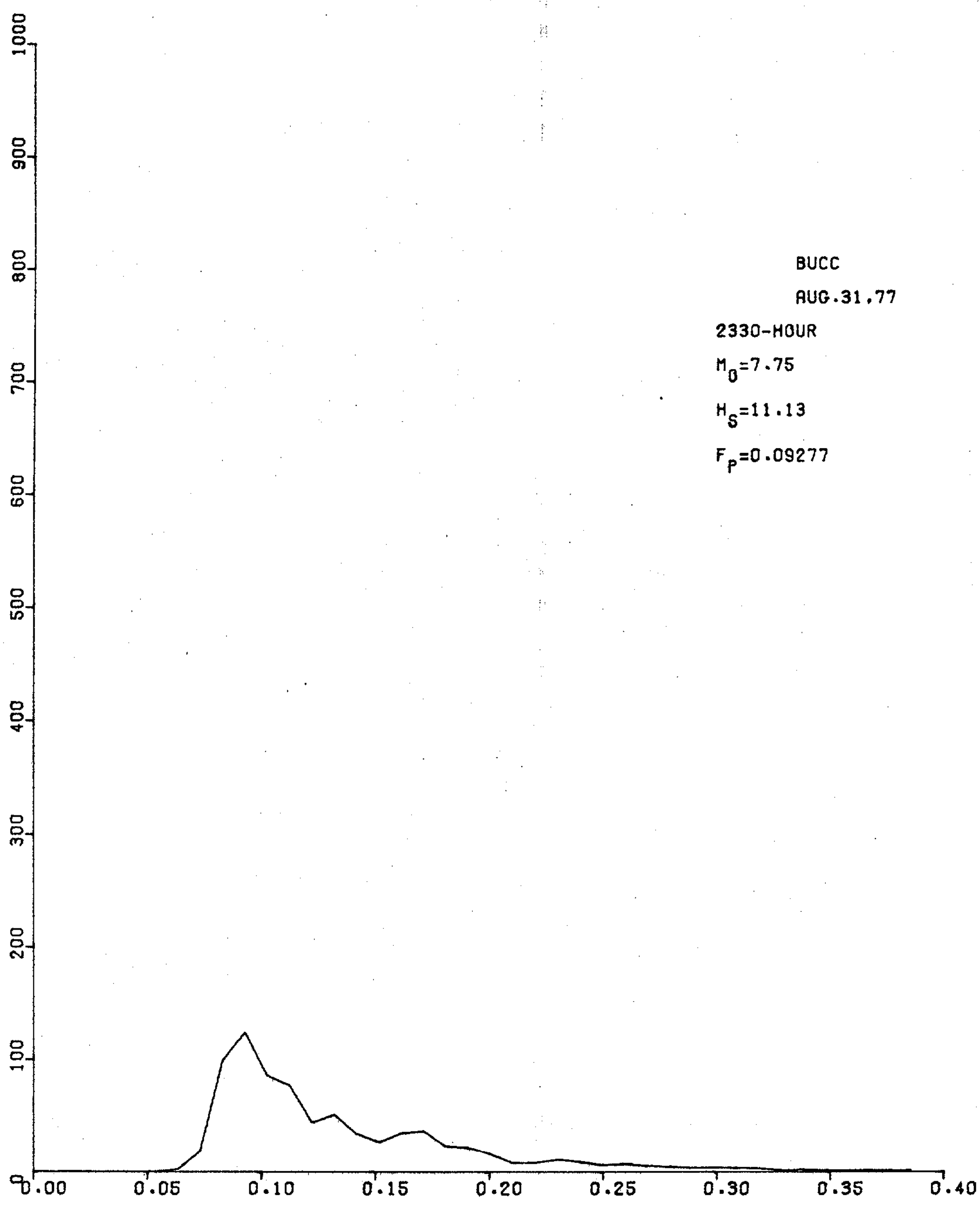

Fig. 42 - Wave spectrum from station 1, 2330 CDT, August 31, 1977.

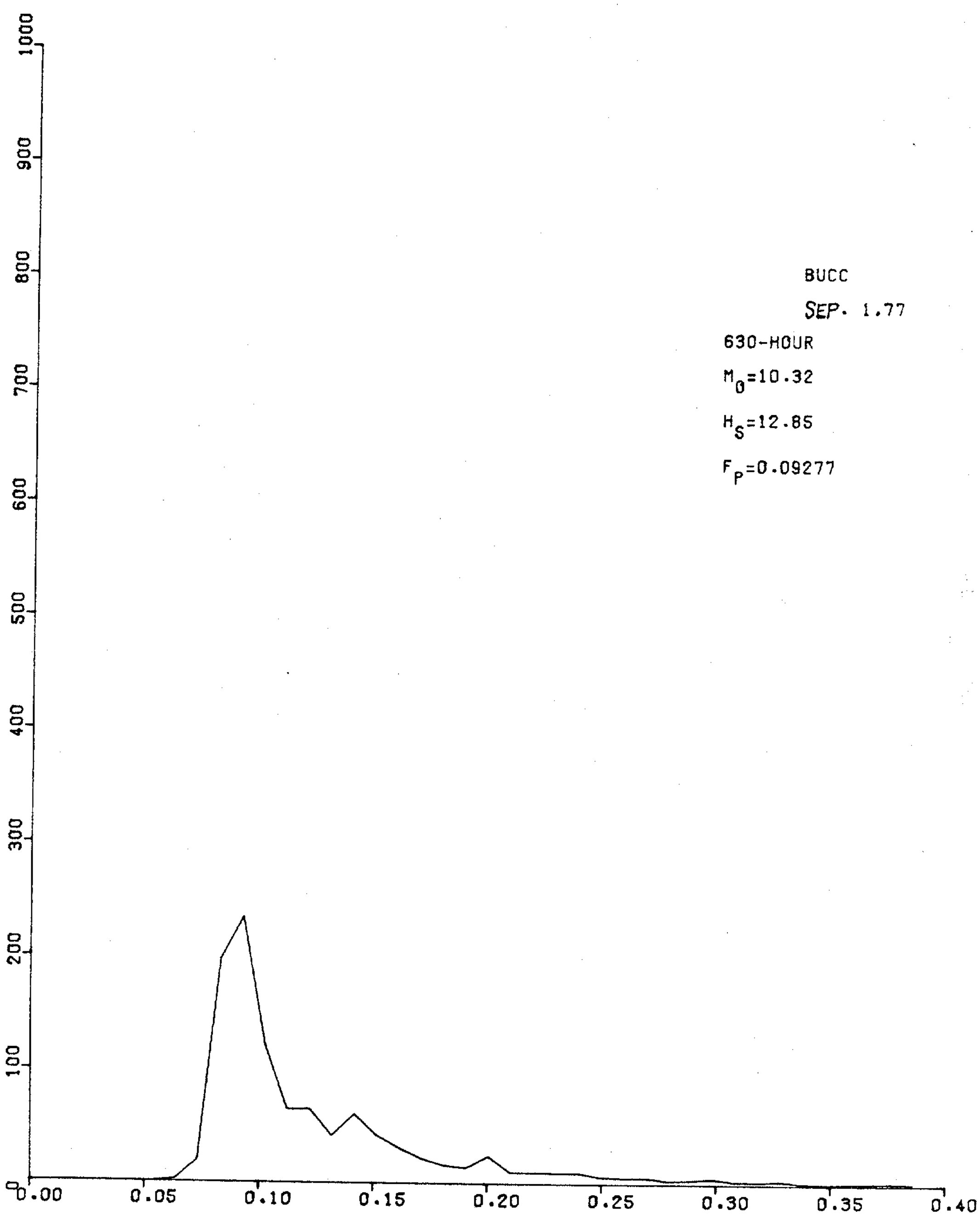

Fig. 43 - Wave spectrum from station 1, 0630 CDT, September 1, 1977.

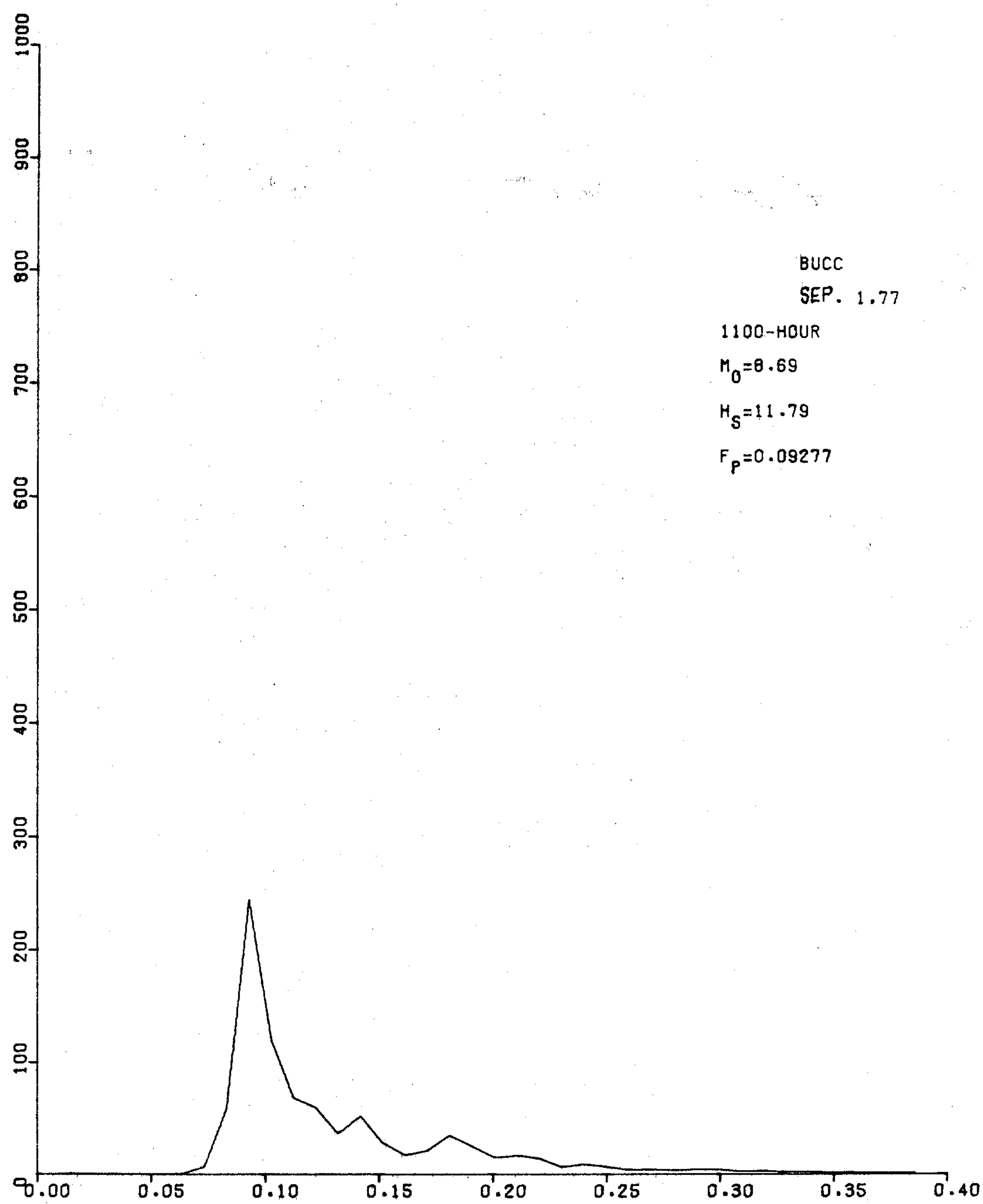

Fig. 44 - Wave spectrum from station 1, 1100 CDT, September 1, 1977.

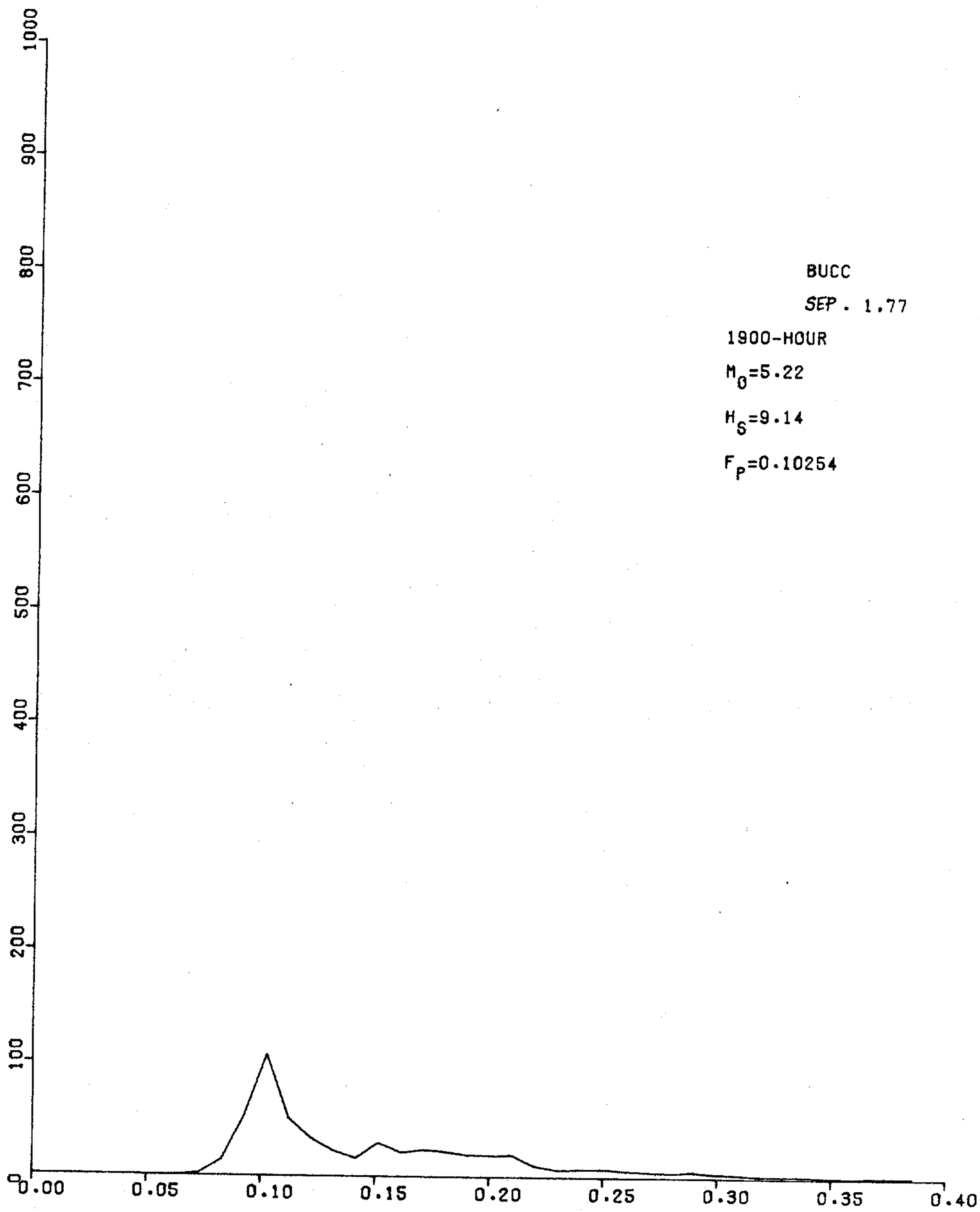

Fig. 45 - Wave spectrum from station 1, 1900 CDT, September 1, 1977.

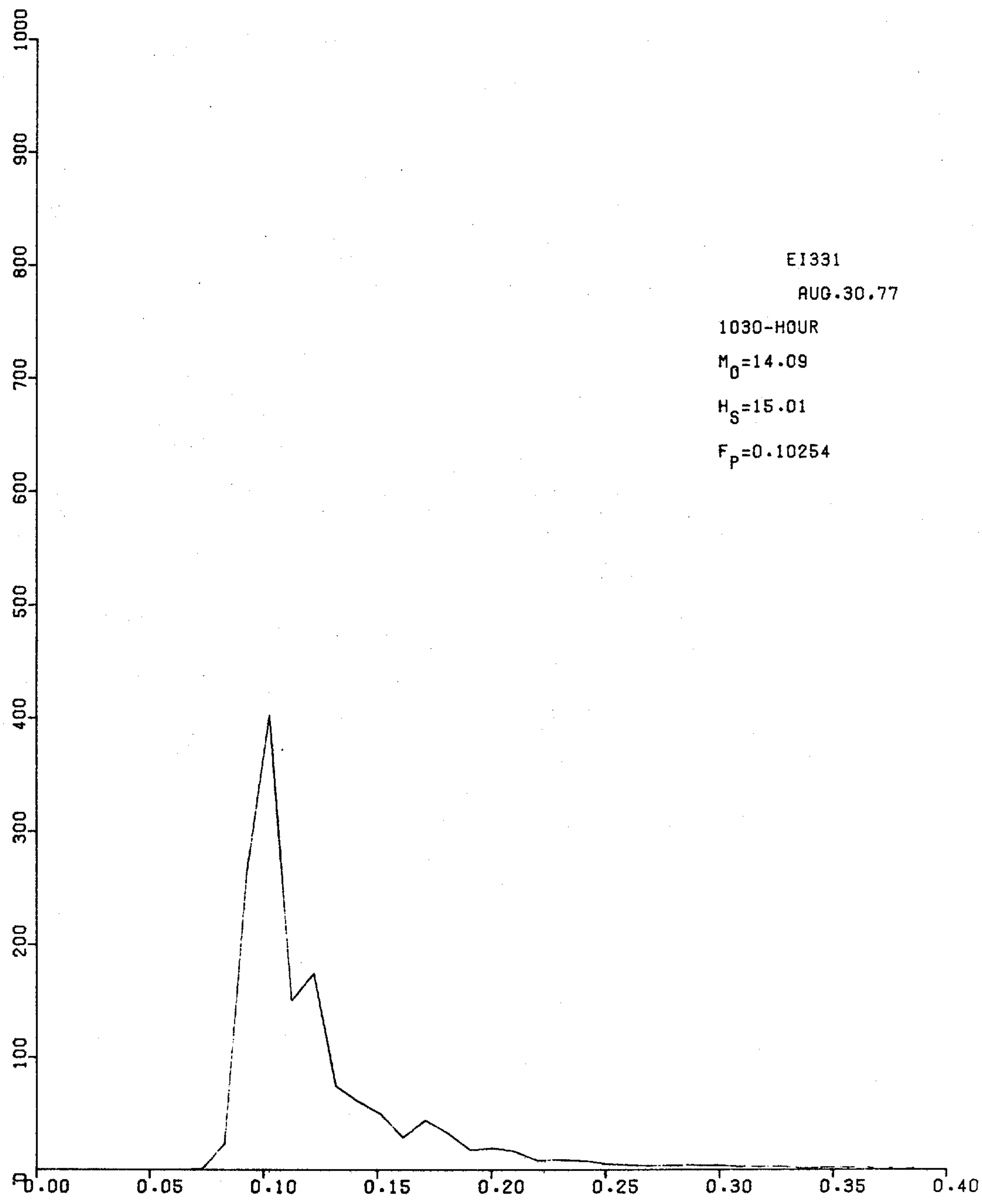

Fig. 46 - Wave spectrum from station 2, 1030 CDT, August 30, 1977.

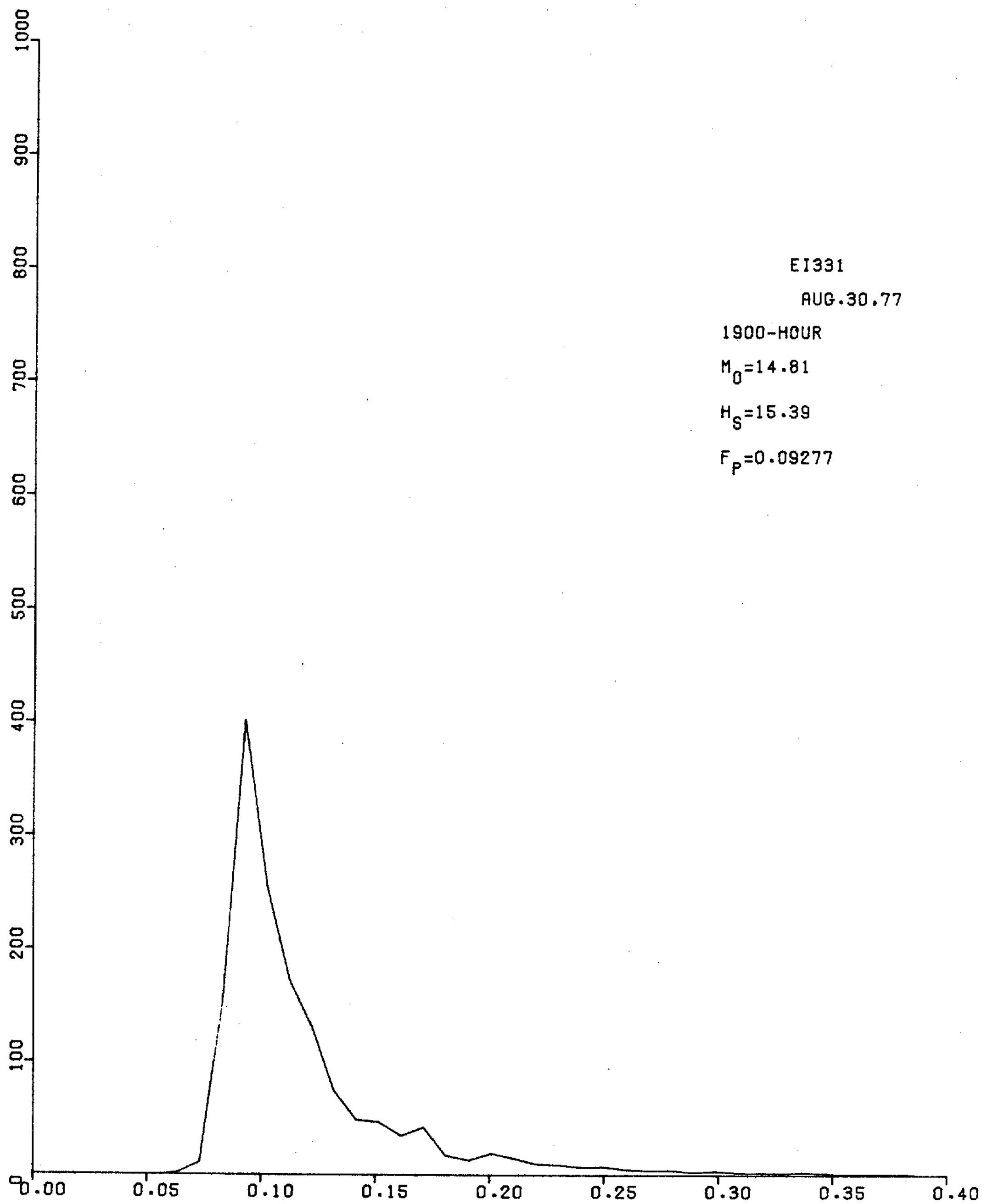

Fig. 47 - Wave spectrum from station 2, 1900 CDT, August 30, 1977.

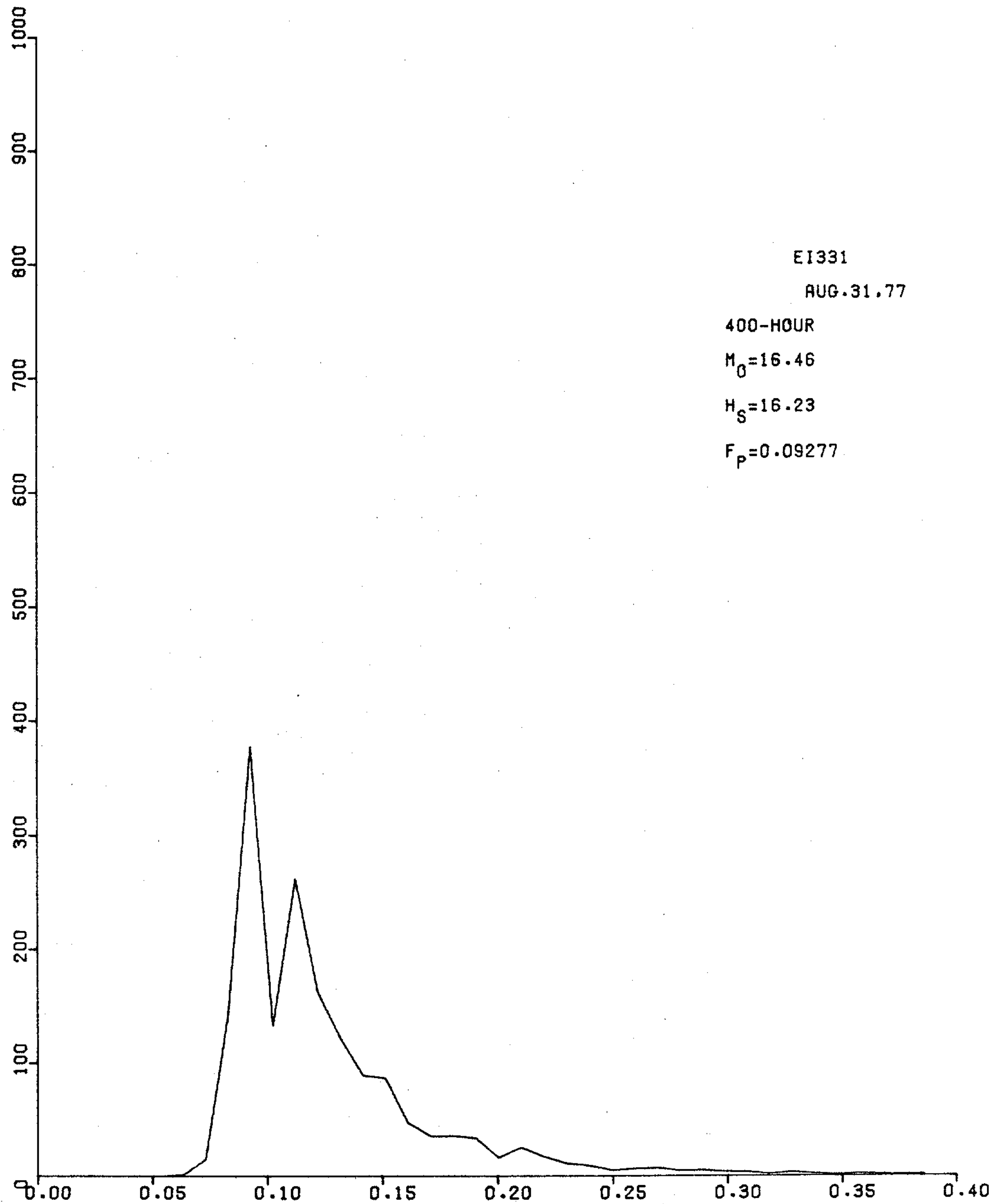

Fig. 48 - Wave spectrum from station 2, 0400 CDT, August 31, 1977.

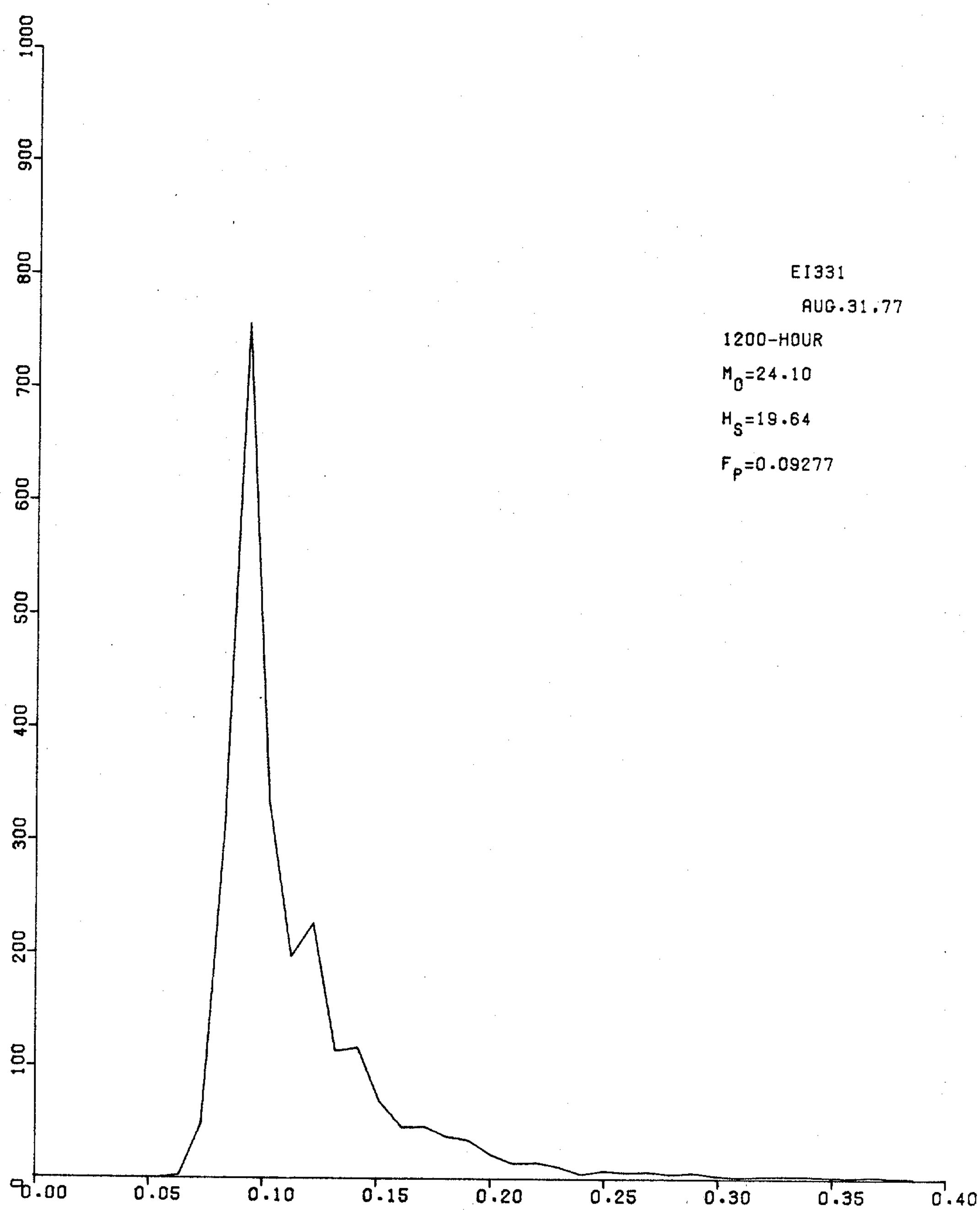

Fig. 49 - Wave spectrum from station 2, 1200 CDT, August 31, 1977.

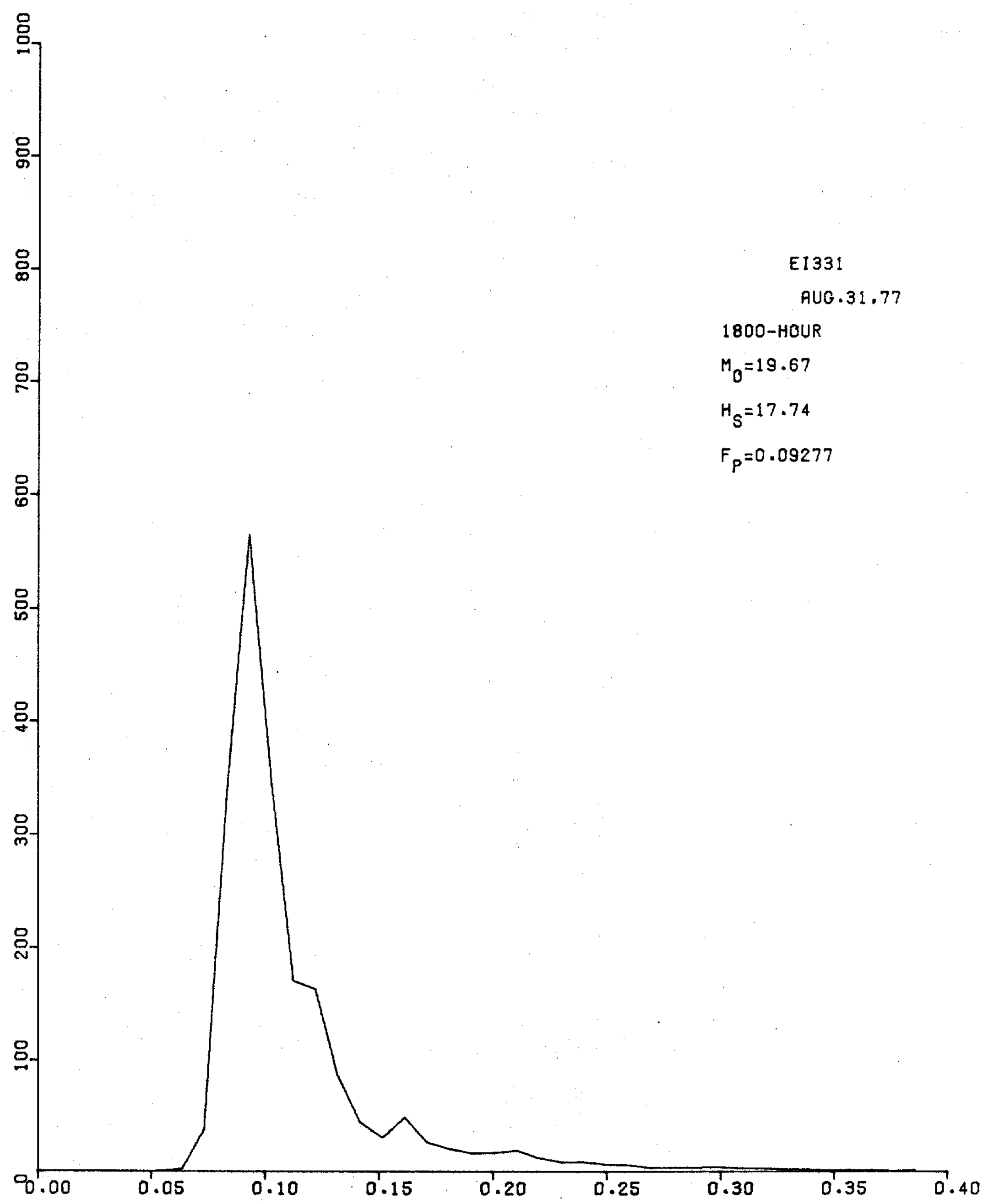

Fig. 50 - Wave spectrum from station 2, 1800 CDT, August 31, 1977.

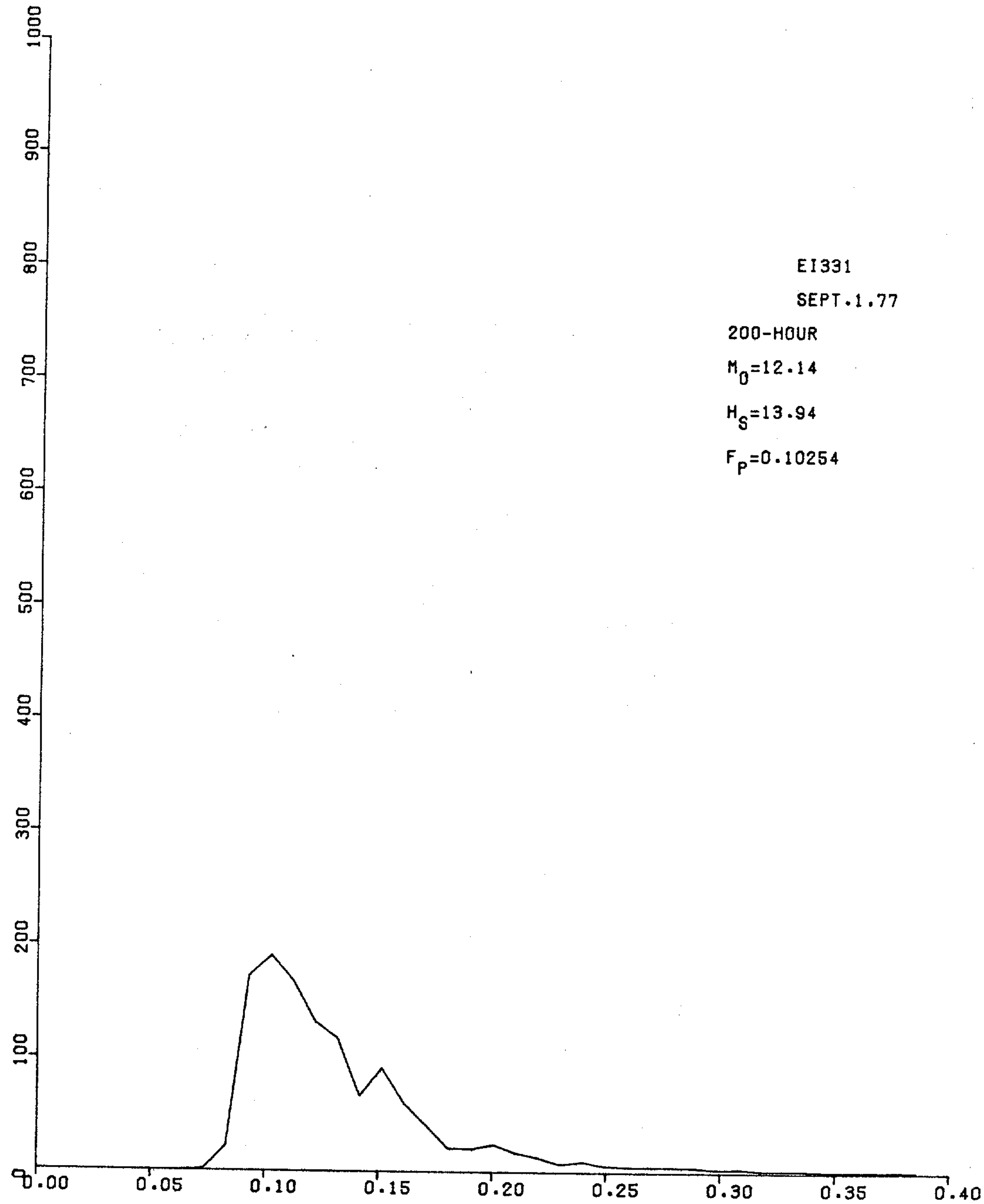

Fig. 51 - Wave spectrum from station 2, 0200 CDT, September 1, 1977.

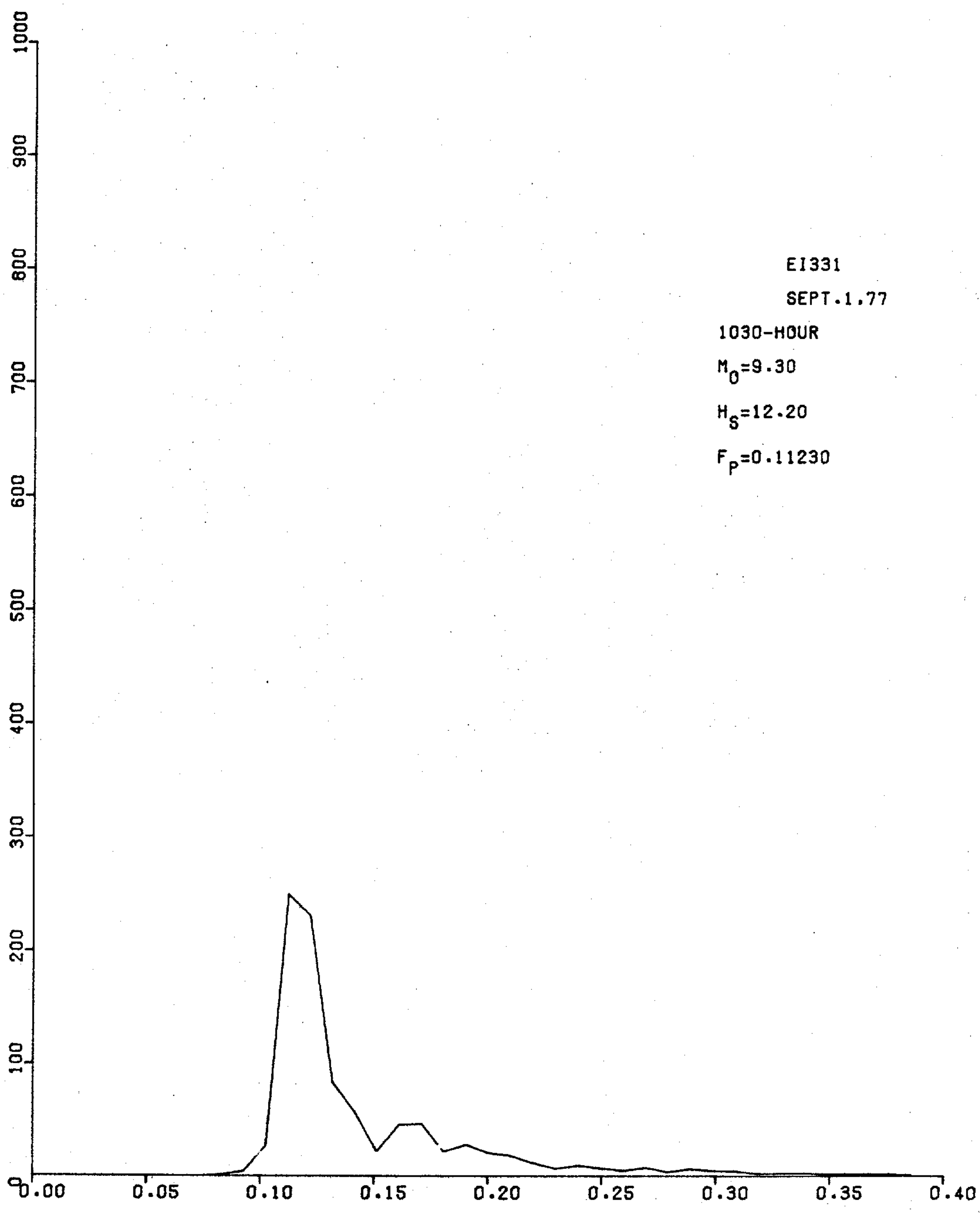

Fig. 52 - Wave spectrum from station 2, 1030 CDT, September 1, 1977.

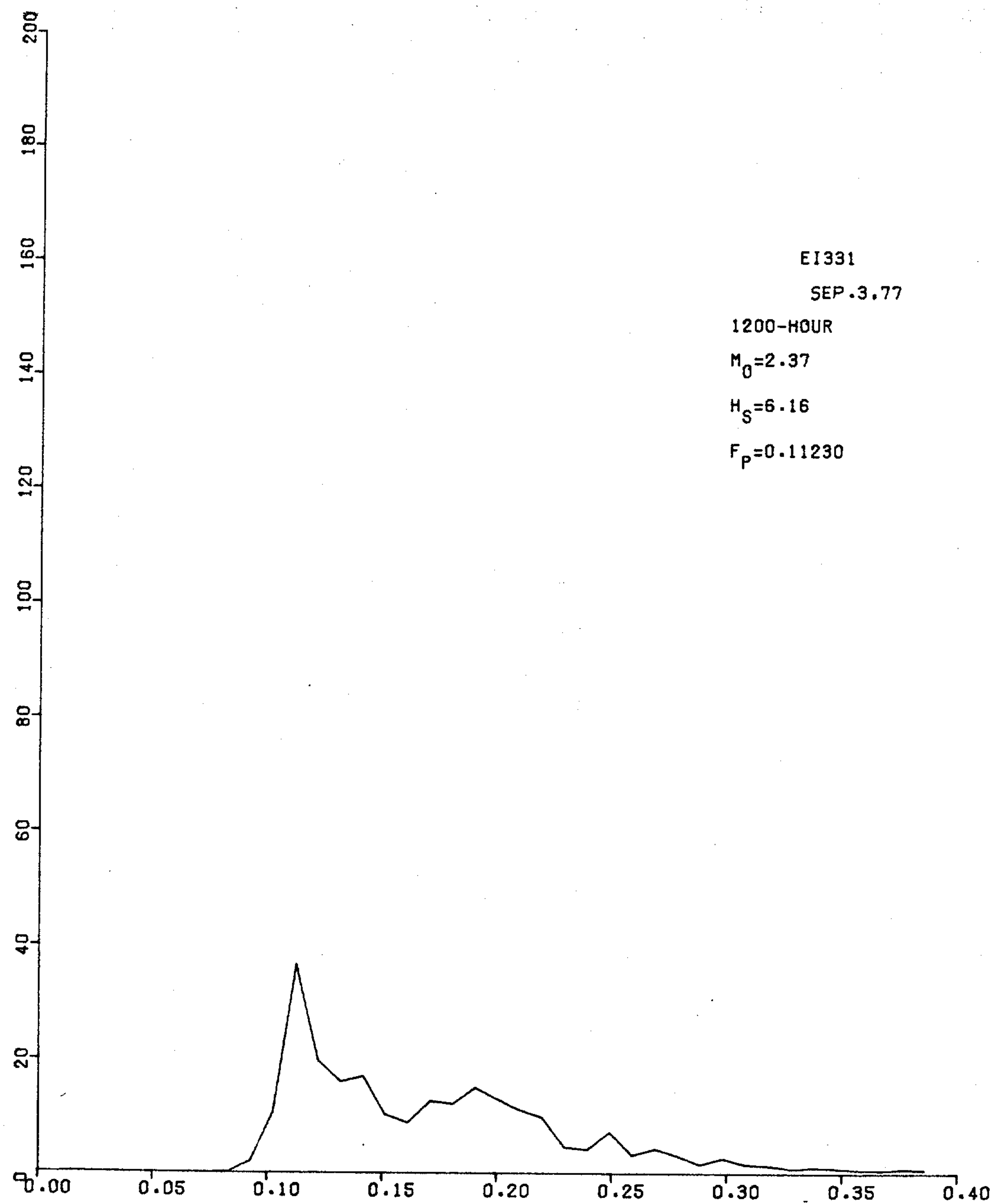

Fig. 53 - Wave spectrum from station 2, 1200 CDT, September 3, 1977.

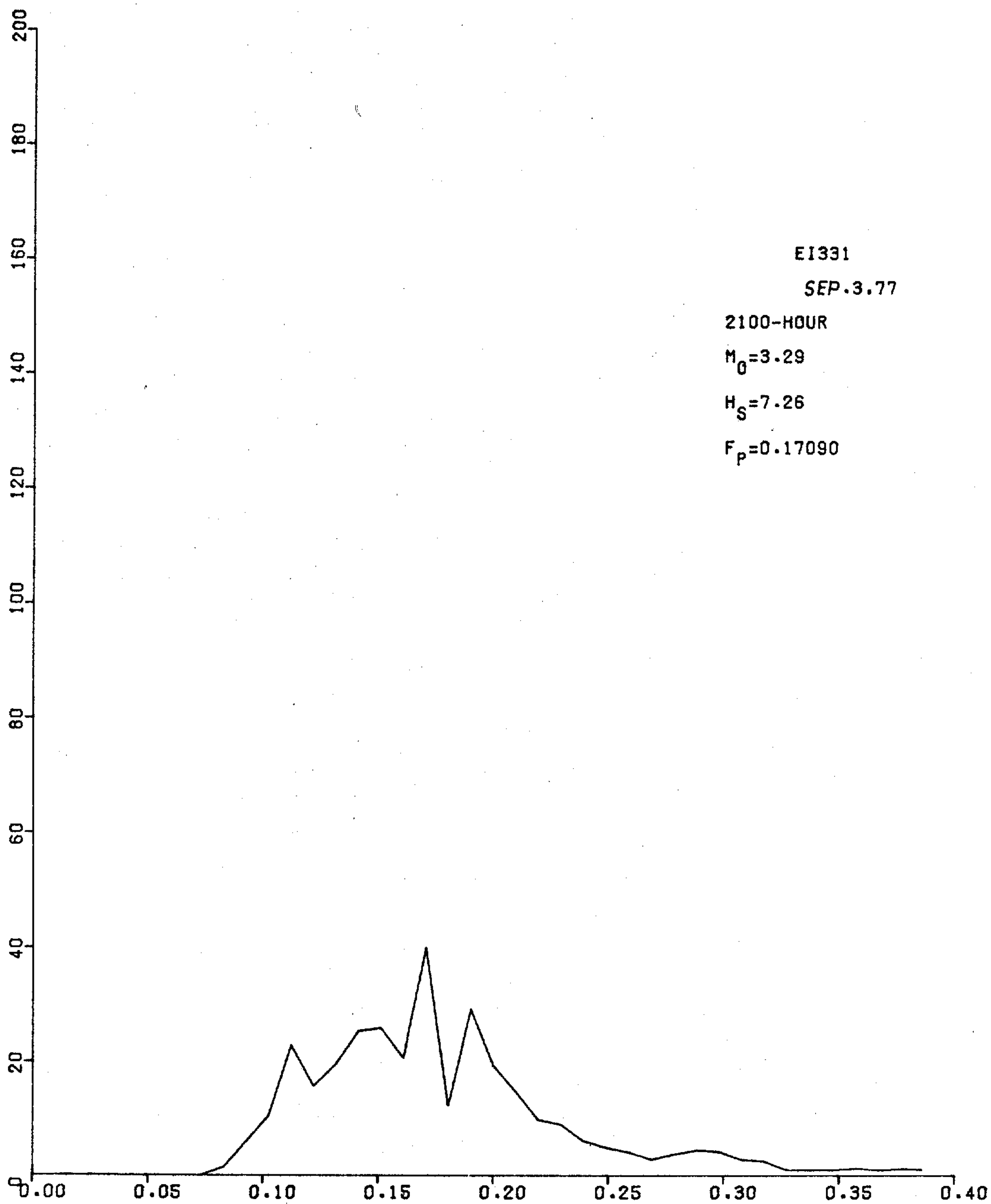

Fig. 54 - Wave spectrum from station 2, 2100 CDT, September 3, 1977.

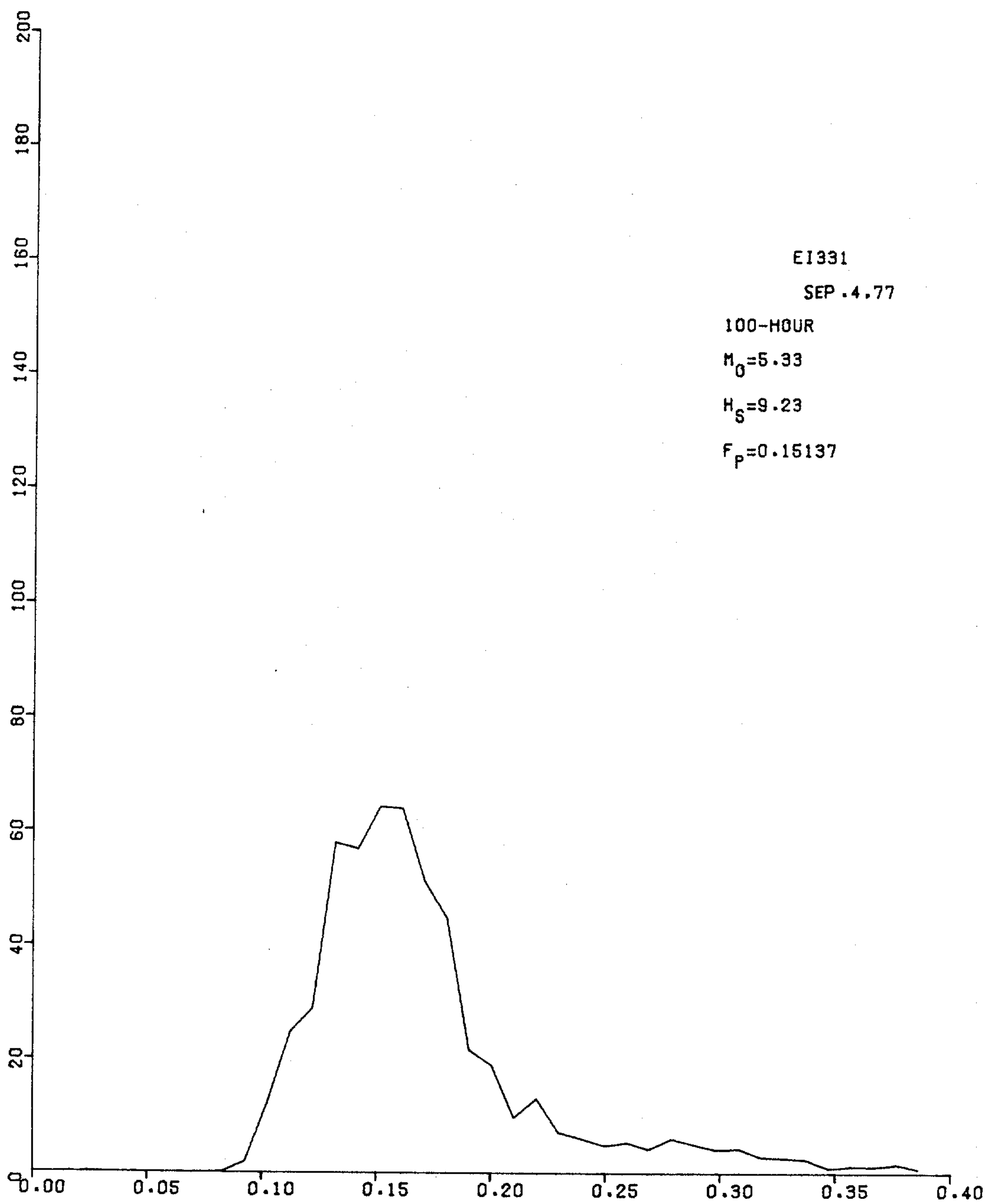

Fig. 55 - Wave spectrum from station 2, 0100 CDT, September 4, 1977.

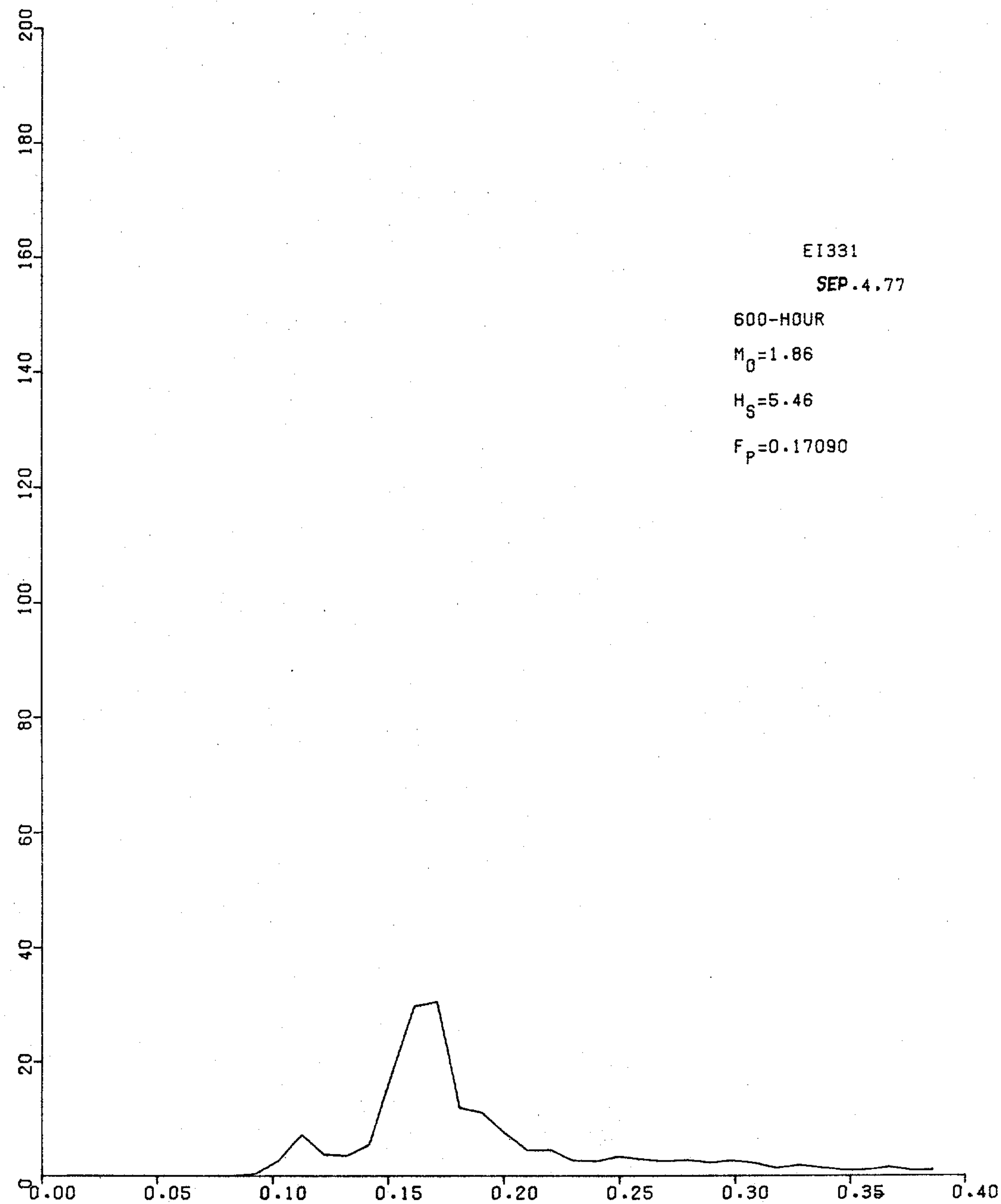

Fig. 56 - Wave spectrum from station 2, 0600 CDT, September 4, 1977.

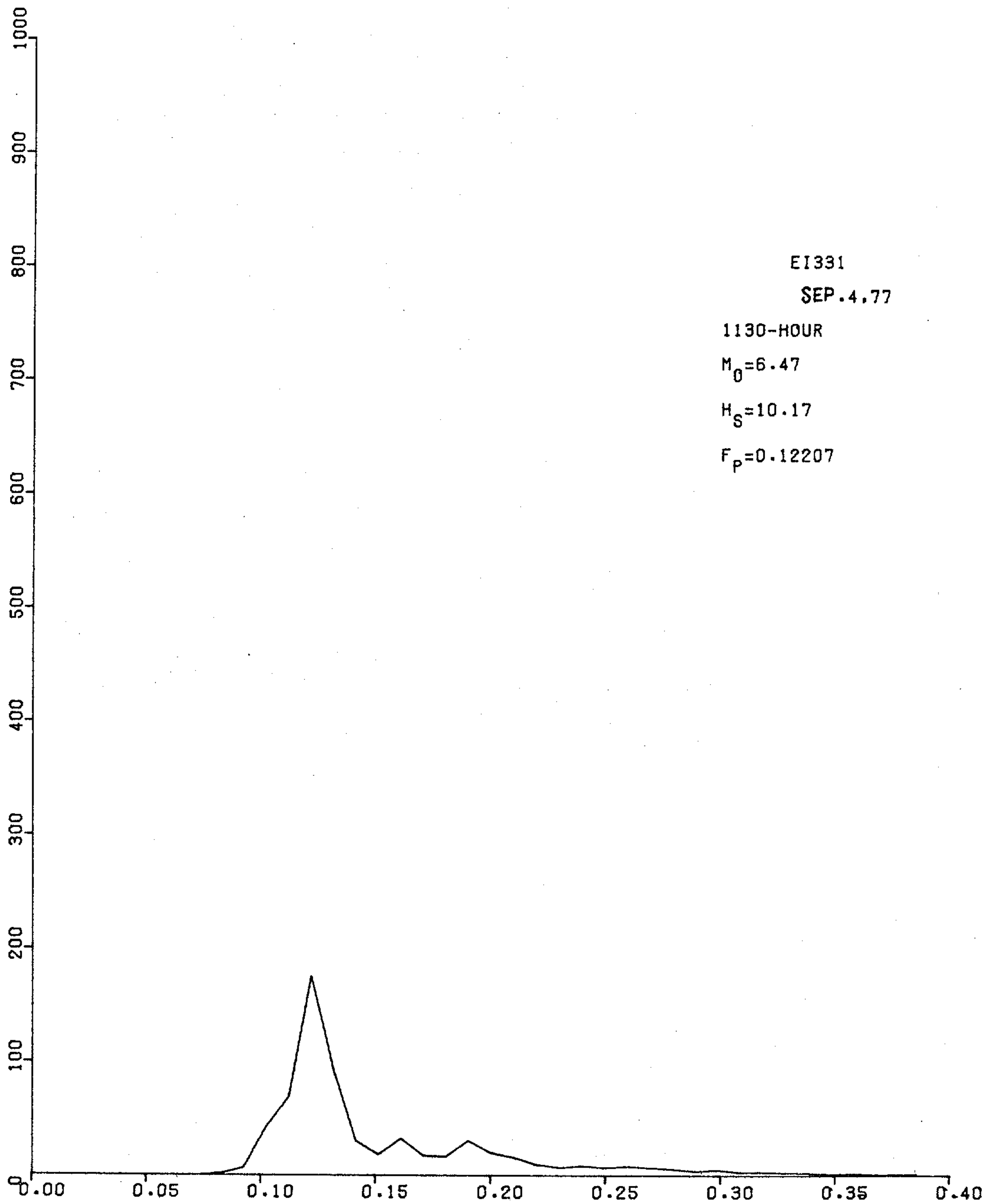

Fig. 57 - Wave spectrum from station 2, 1130 CDT, September 4, 1977.

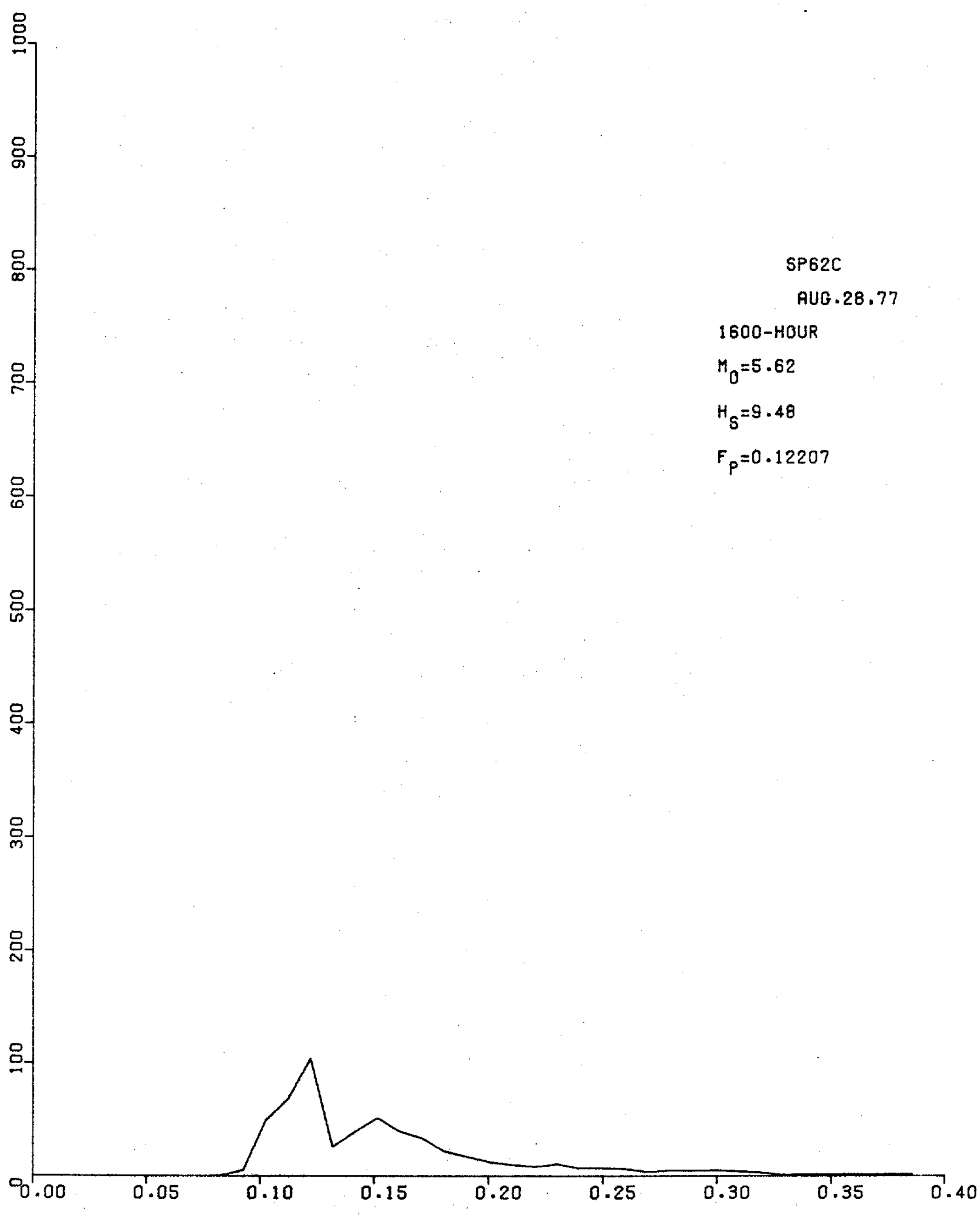

Fig. 58 - Wave spectrum from station 3, 1600 CDT, August 28, 1977.

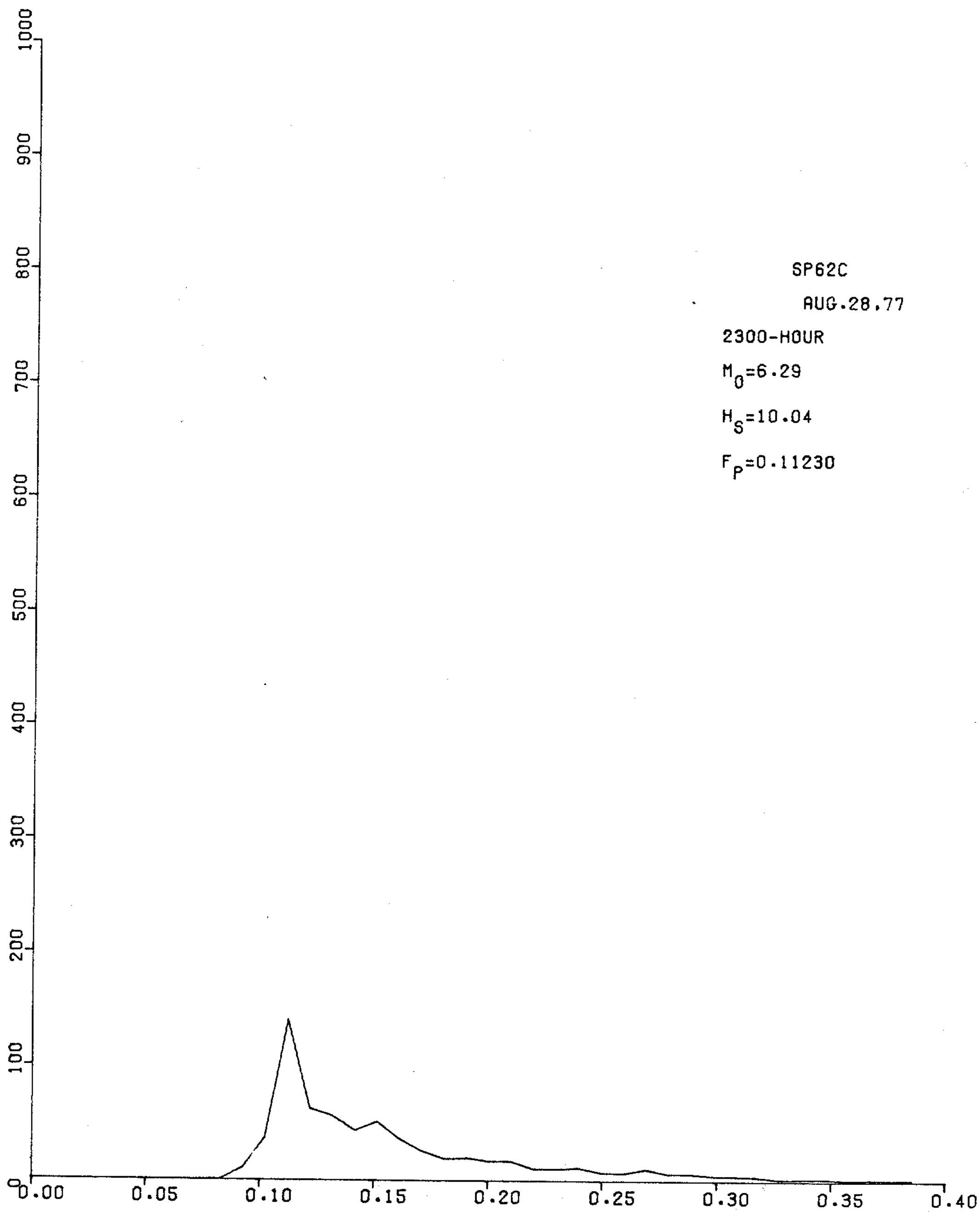

Fig. 59 - Wave spectrum from station 3, 2300 CDT, August 28, 1977.

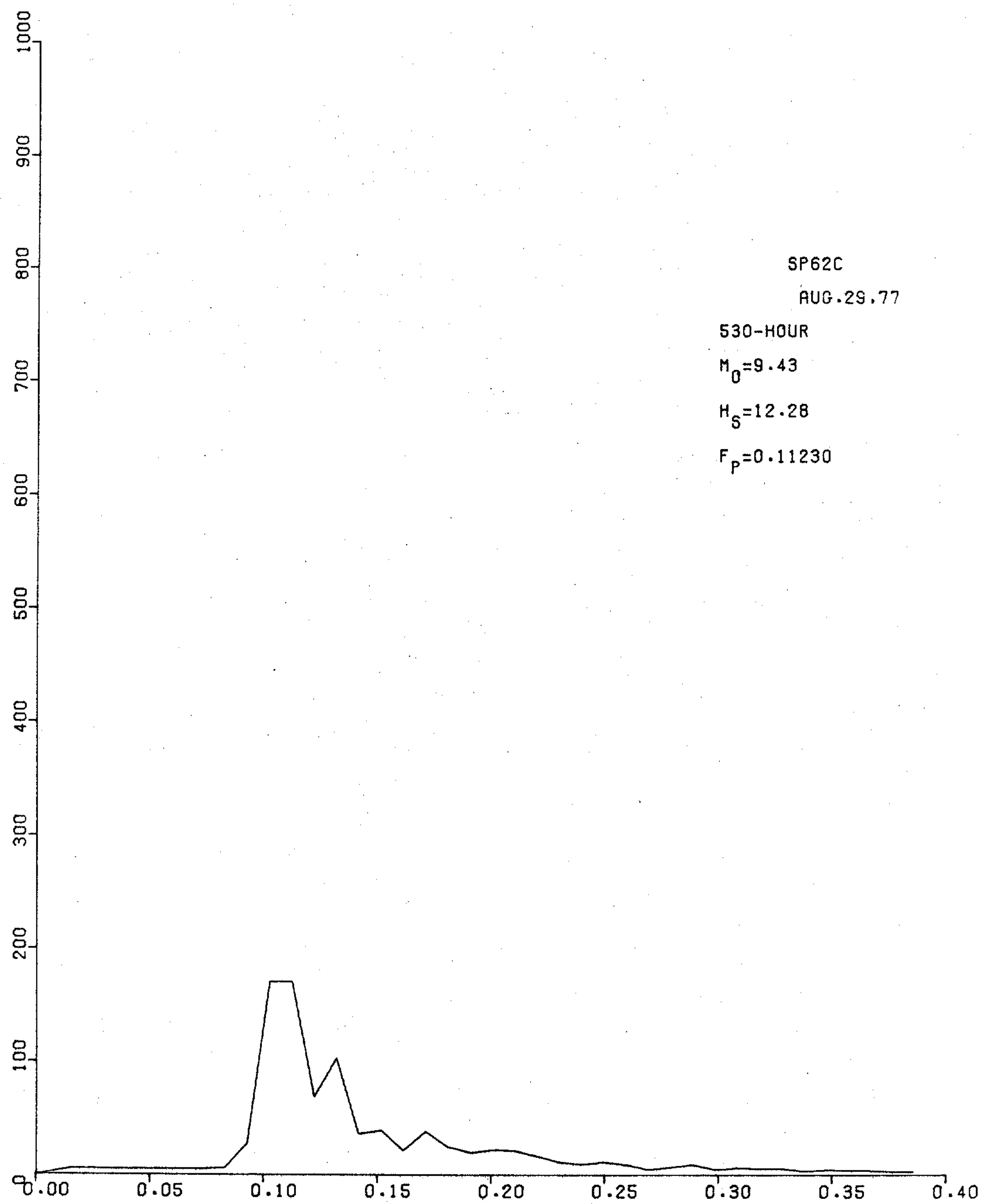

Fig. 60 - Wave spectrum from station 3, 0530 CDT, August 29, 1977.

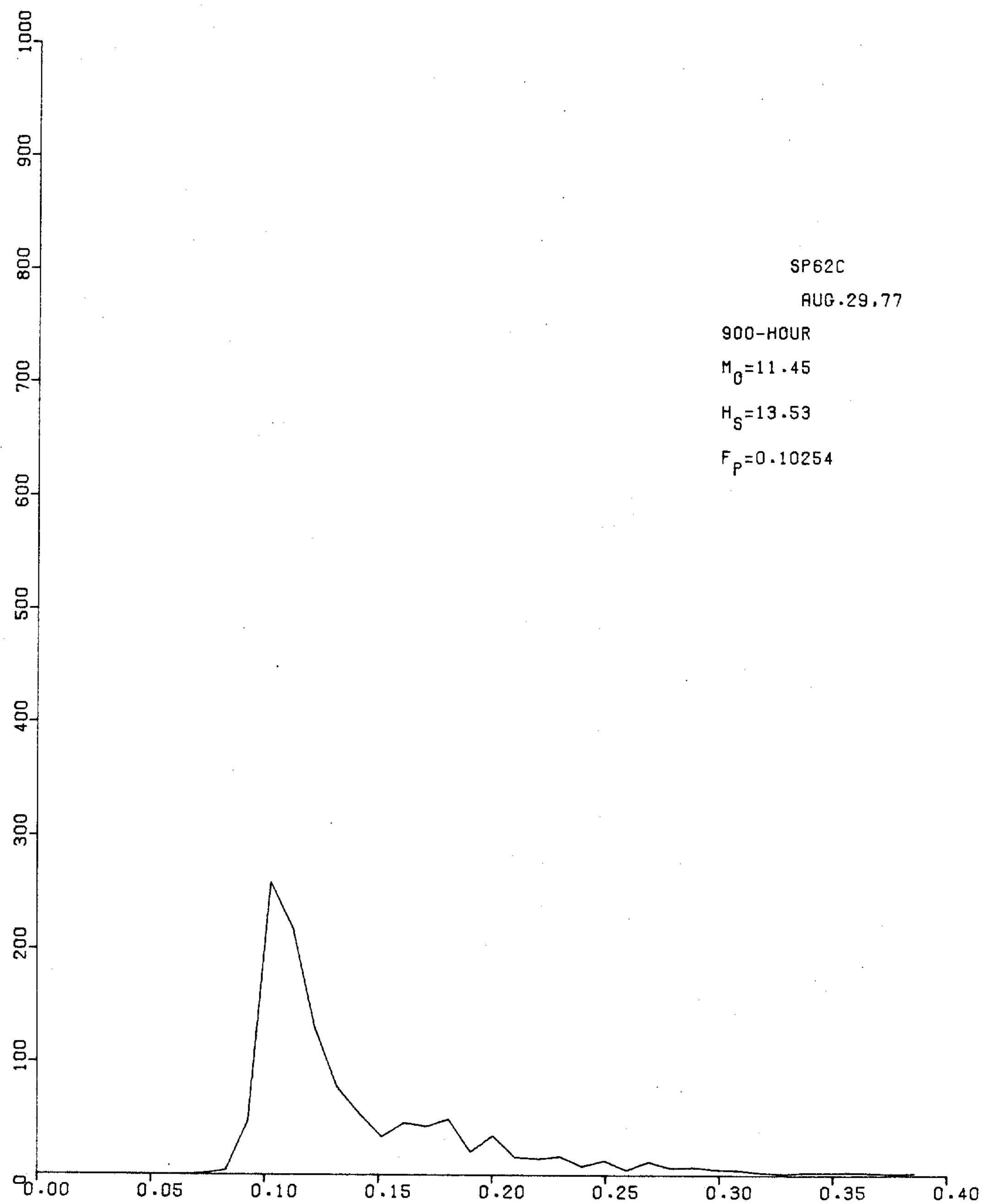

Fig. 61 - Wave spectrum from station 3, 0900 CDT, August 29, 1977.

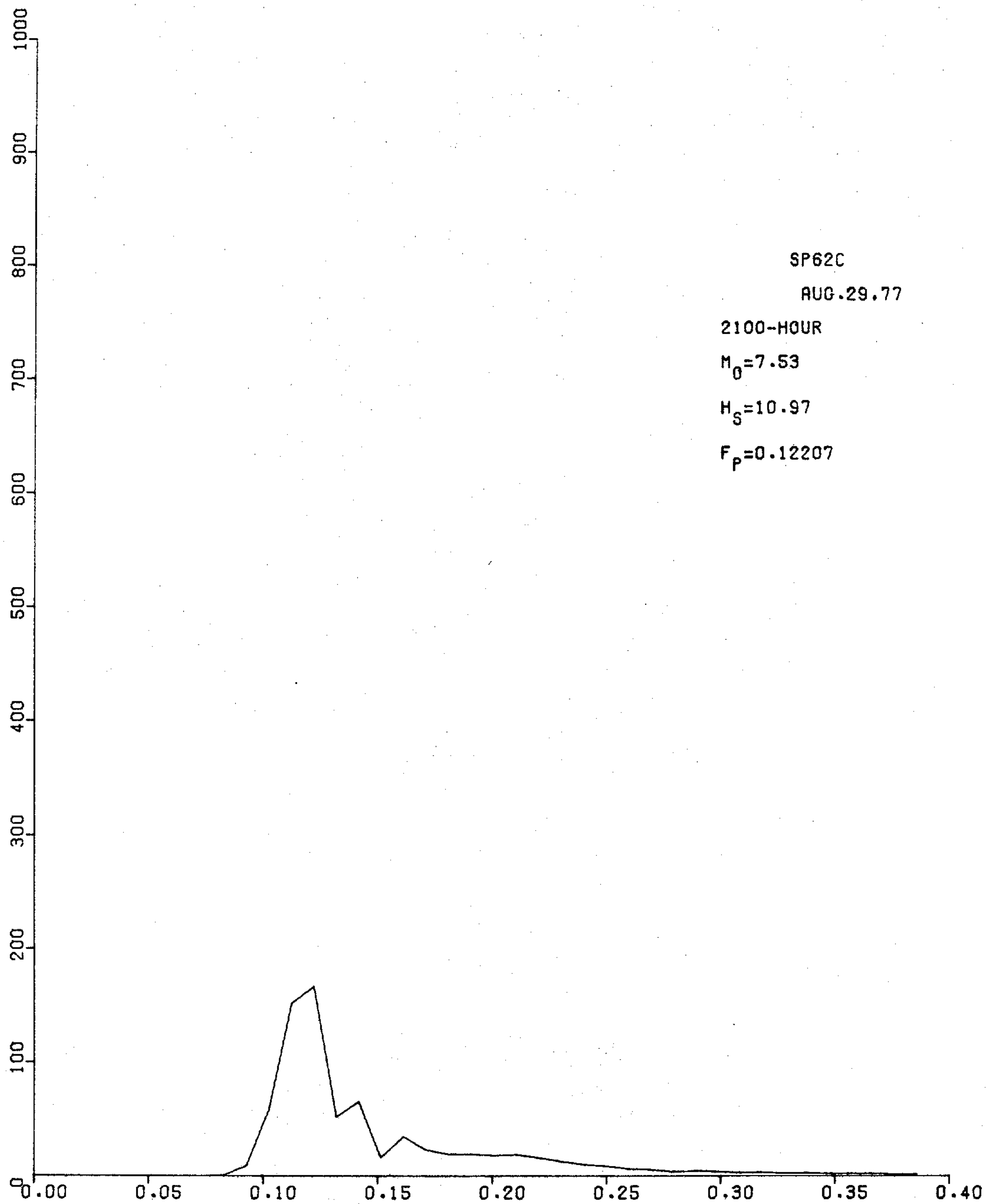

Fig. 62 - Wave spectrum from station 3, 2100 CDT, August 29, 1977.

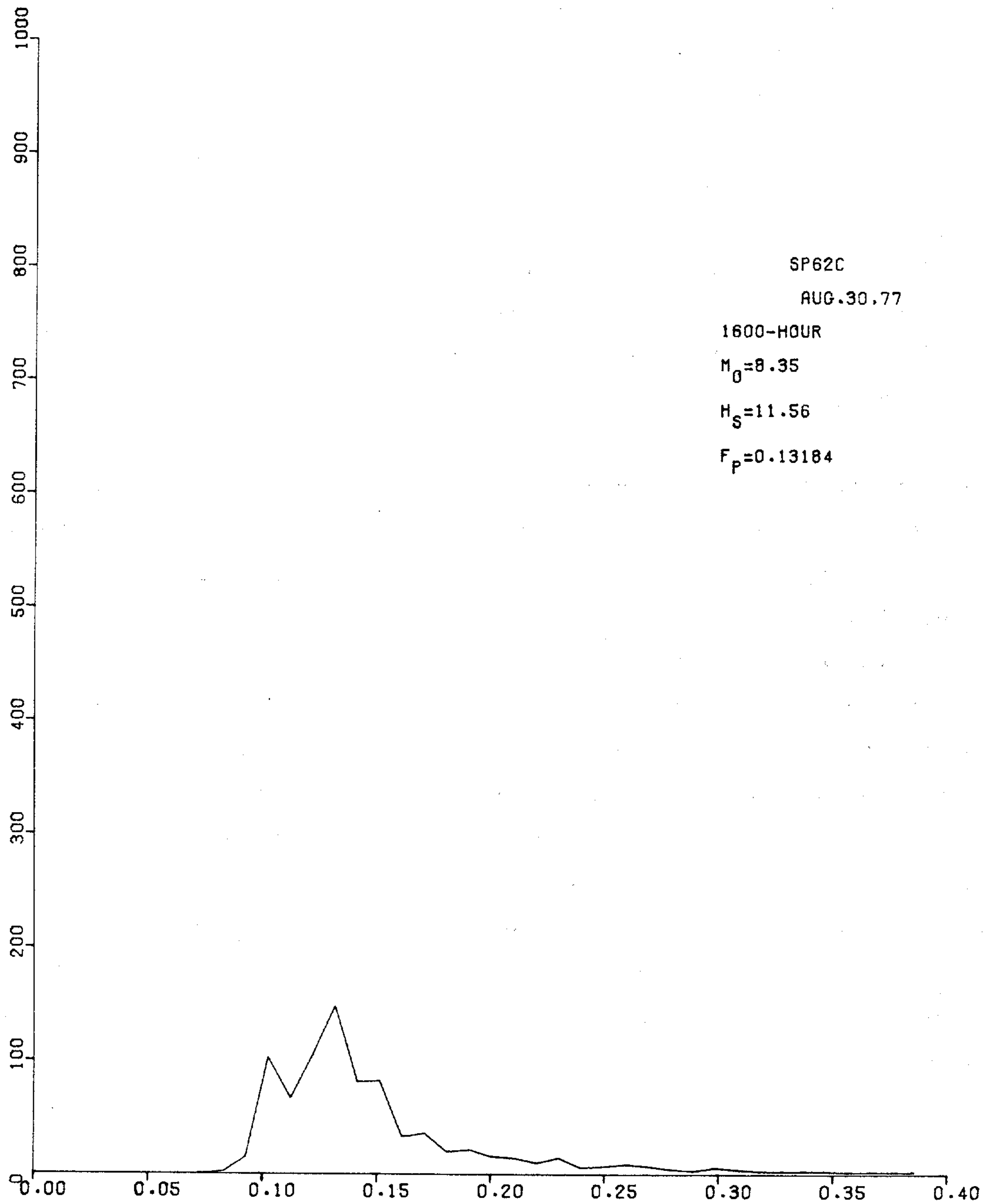

Fig. 63 - Wave spectrum from station 3, 1600 CDT, August 30, 1977.

this incompatible with good resolution on linear plots. Thus, attention should be paid to the energy density scale.

Each graph is labeled with the station name and date. The hour is the time at the start of the 30-minute record. The total variance of the spectra, M_o, is given in ft^2. The significant wave height, H_s, is defined in equation (4). Finally, F_p equals the frequency of the highest spectral peak. The frequencies plotted are the center frequencies of the smooth bands.

The spectra from Station 1 generally show a low frequency peak near the ten-second period superimposed on a high frequency tail with rather low energy. The spectrum with maximum energy occurred at 0630 CDT on September 1 and is shown in Figure 43.

Most of the spectra from Station 2 during Anita are unimodal and appear well developed, particularly the spectrum of maximum energy which occurred at 1200 CDT on August 31 and is plotted in Figure 49. As the storm center moved away from the station, the energy at all frequencies decayed, leaving the spectrum dominated by the low frequency peak shown in Figure 52.

The spectra generated by Babe at Station 2 were never very energetic, but they do show an interesting development. Early in the storm, the spectra in Figures 53 and 54 are very broad. As mentioned earlier, the passage of the east-west convective band produced a local energy maximum at 0100 CDT on September 4. The spectrum for this time, shown in Figure 55, does not have the steep forward face associated with a fully developed spectrum and the period of maximum energy is only 6.6 seconds. The waves then fell before rising again as the center of the storm approached the station from the south. The recorded spectrum of maximum energy is shown in Figure 57. Note the change in scale from the previous four figures. A reasonably steep peak as developed at a period of 8.2 seconds, but the forward face is still not very steep.

The spectra at Station 3 during Anita grew slowly with the peak shifting to slightly lower frequencies until the spectrum of maximum energy shown in Figure 61 developed. The spectra then declined slowly, leaving the broad spectrum in Figure 63 from 1600 on August 30, indicative of confused seas.

Filtered Wave Height

The wave-filtered trace in Figures 32-34 is the calibrated wave staff record, now digitally filtered with a two-minute cutoff. Note that the scale has been greatly expanded compared to the unfiltered record. The filtered wave trace is a history of the mean water level at the station, a tide record. The wave staffs used in the project are not perfectly suited for use as tide gauges and some problems can be noted in the records, but there is also some useful information.

The times when Station 2 and 3 are on platform power can be recognized by the presence of regular noise with 0.10-foot double amplitude and a period of about 30 minutes on the signal. There were shifts in the recorded tide level at Stations 2 and 3 when the stations first shifted to battery power and an additional unexplained shift at Station 3 at 1600 on August 31. During Anita, the record from Station 2 also includes numerous short shifts to lower levels.

In general, the tide records show the periodicities expected of astronomical tides and in fact follow the tide table predictions for coastal stations rather closely. The record for Station 1 should be compared to the predictions for Galveston and the records for Stations 2 and 3 should be compared with the predictions for Pensacola. However, the records from both Stations 1 and 2 show a general lowering of the sea level as Anita moved away from the stations in a westerly direction.

Wind Speed and Direction

Wind speed and direction are given as two-minute filtered signals on Figures 33 and 34. The anemometer at Station 1 was not operating during the storm. Note that in contrast to the other signals, a measure of turbulence remains in these records at this level of filtering. The wind speed is in miles per hour and the wind direction is the direction from which the wind is blowing, in degrees from true north. Thus, a wind direction of 90° means the wind is blowing from the east.

The passage of Anita far to the south of the stations created a long period of gale force winds, but no dramatic maxima. The two-minute wind at Station 2 was continually above 35 miles per hour on August 30 through most of September 1. However, the maximum two-minute wind was barely 50 mph. The recorded wind direction at Station 2 was near 135° for most of the storm. This value seems too southerly to match the known meteorology of Anita and there are indications in Figure 33 that the recorded value could have shifted about 30-40° too high early on the morning of August 31. The cause and details of this possible shift are not known.

Anita also produced a long period of gale force winds at Station 3 with the gusty two-minute wind often above 35 mph from August 28 through August 31. The peak two-minute wind was again barely 50 mph. The wind direction was near 90° for most of the storm.

Babe produced two recorded wind speed maxima at Station 2 which match the recorded wave height maxima. First, the east-west convective band produced 45 mph winds early on September 4. The wind speed then died down and its direction shifted rapidly to the south before the wind speed again increased with the approach of the center of Babe. The wind speed again reached 45 mph by about noon on September 4. By the time the power failed shortly after 1700, the wind speed had dropped to 20 mph, indicating the close passage of the center of Babe. Although there were probably stronger winds in the southeast quadrant of Babe, it seems unliekly that there were any sustained hurricane force winds in Babe.

Barometric Pressure

The barometric pressure recordings during Anita are not very interesting since the storm center was never close to the OCMP stations. The pressure record at Station 1 is somewhat noisy, but the minimum pressure of 29.80 in Hg seems to have been reached about the middle of the day on August 31. Thereafter, the pressure rose slightly. All pressures are in inches of mercury, corrected for temperature and latitude, but not for the average 60-foot height of the instruments. The pressure at Stations 2 and 3 remained below 29.80 inches most of the time Anita was in the Gulf. The minimum pressure at Station 2 was 29.65 inches on the morning of August 30 and the minimum pressure at Station 3 was 29.72 inches at about the same time.

The power failure and resulting noise as the center of Babe approached Station 2 makes the determination of the true minimum pressure from the strip chart rather difficult. However, careful examination of the original data indicates that the minimum recorded pressure was 29.52 inches at 1600 on September 4. It is possible that the pressure dropped somewhat more after the recorder stopped.

Currents

The currents recorded at the three stations are displayed in Figures 32, 35, and 36. Two vector components for the currents recorded at each meter are shown with the direction of the components and the nominal depth of the meter marked on the charts. Some problems with the instrumentation are also marked on the charts. All the currents are plotted in ft/sec and the direction is that toward which the current is flowing.

The special instrument locations at Station 1 were not designed to provide much information on steady currents. Naturally, the low pass filtered "current" from the meter at elevation +7 feet is meaningless. Preliminary indications are, however, that this meter recorded good data when immersed in the crests of the larger waves. Unfortunately, the lower meter was very noisy due to seawater leakage and suffered a large level shift about noon on September 1. The recorded current of three ft/sec to the west-southwest after the level shift would be in agreement with the measurements made[9] at a site further down the coast, but little faith should be placed in data from this noisy meter.

Much current data was lost at Station 2 due to the failure of the drive motor in the current recorder. However, the recorded did run for two short periods during Anita. Since the bottom current meter was recorded on the weather recorder, the data from it are available except when the recorder stopped due to low battery voltage. The signal at the lowest current meter has a dominant tidal periodicity, but the amplitude of the current increases during the storm. The maximum current at this level was 1.2 ft/sec to the west, recorded about noon on August 30. Shortly before this time, one of the short segments recorded from the upper meters showed that the current magnitude surprisingly decreased toward the surface. The direction of the current also reversed between the 47-foot and 103-foot depths. Just before the power failed on September 1, the other short data segment shows a rather constant current of about 1.0 ft/sec to the ENE above the 103-foot depth. The direction reversal was then between the 103-foot and 177-foot depths, where the current was 0.8 ft/sec to the WNW.

No data was recorded from the top three current meters during Babe. The strongest current recorded at the bottom meter was 1.8 ft/sec to the west on the afternoon of September 2 when the wind was not particularly strong. The bottom current then decayed before building to another maximum of 1.4 ft/sec to the west as the center of Babe approached on the afternoon of September 4.

The current meters and recording system worked very well at Station 3, but the currents were rather weak. Tidal periodicities are again evident. The strongest currents recorded came in a short burst on August 30 when the top current meter registered 1.6 ft/sec to the southwest. The event was very clear and of similar magnitude at all depths. The maximum current on August 31 was 1.0 ft/sec, again to the southwest. Just before the battery power failed on September 1, a surface current of 1.2 ft/sec to the southwest was recorded.

Salinity and Temperature

The salinity and temperature measurements made before and after the storms are shown in Figures 64-67. The density was calculated from the temperature and salinity measurements by using empirical tables[13] of the density anomaly, which is defined as:

$$\sigma_T = 1000\ (\rho - 1) \quad . \tag{7}$$

Figure 64 shows the measurements made at Station 2 at 1000 CDT on August 16. As is typical of this site in the summer, the density structure is dominated by increasing salinity through the top 100 feet and decreasing temperature below. The result is a reasonably steady increase in density with depth. The water is well stratified at all depths. The measurements made after the storm at 1100 CDT, September 9 and shown in Figure 65 indicate that a drastic change has taken place. The storm has mixed the upper 100 feet so that the salinity and thus density are roughly constant. Below that depth, the water remains well stratified. This observation is consistent with the current shears measured during the storm.

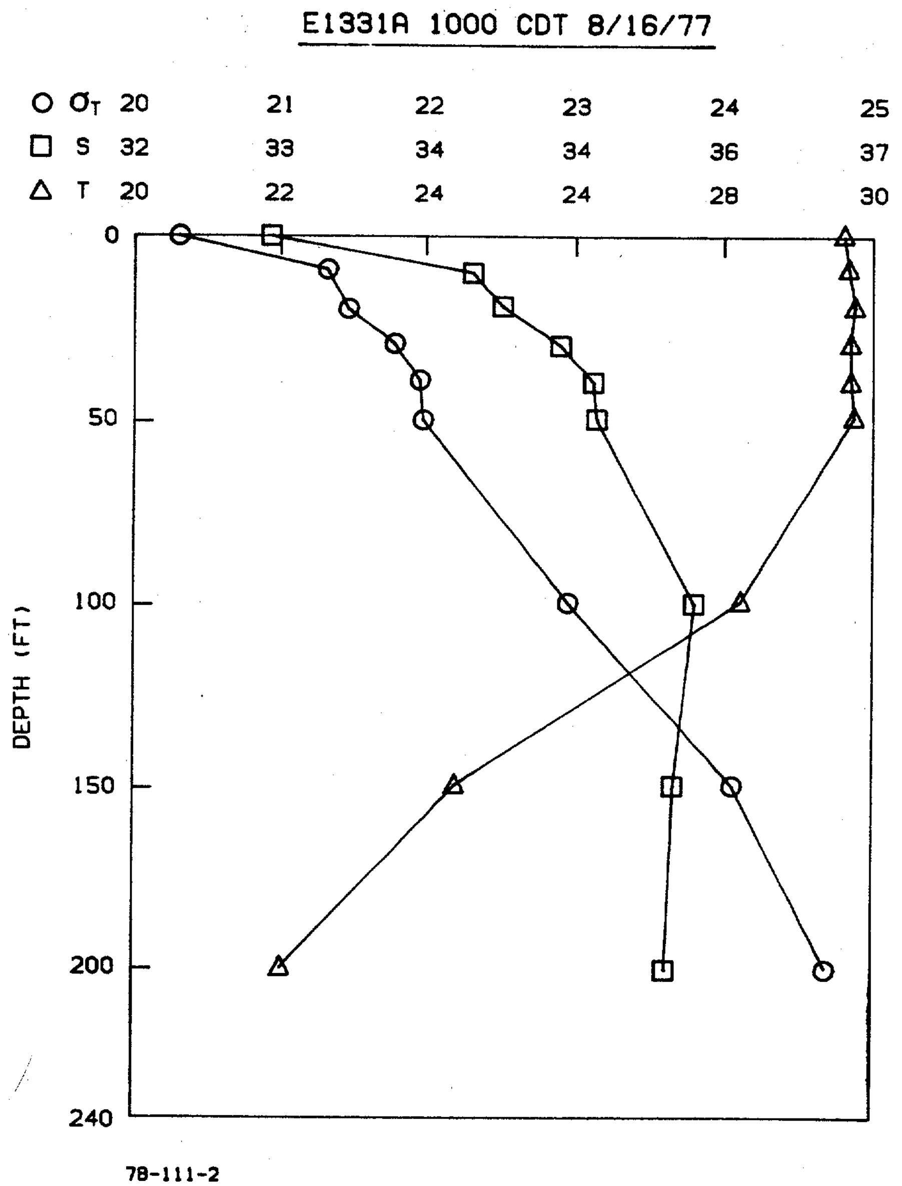

Fig. 64 - Stratification at station 2, August 16, 1977.

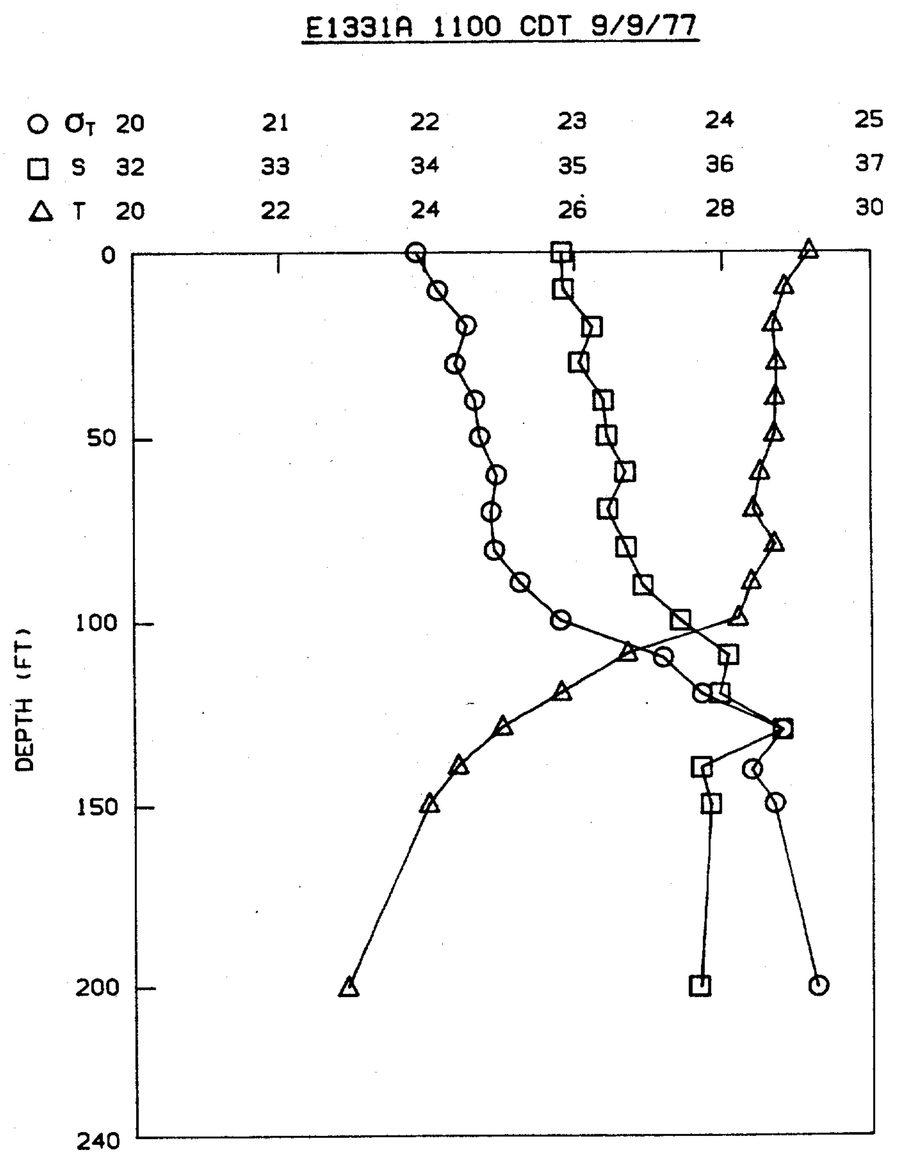

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Fig. 65 - Stratification at station 2, September 9, 1977.

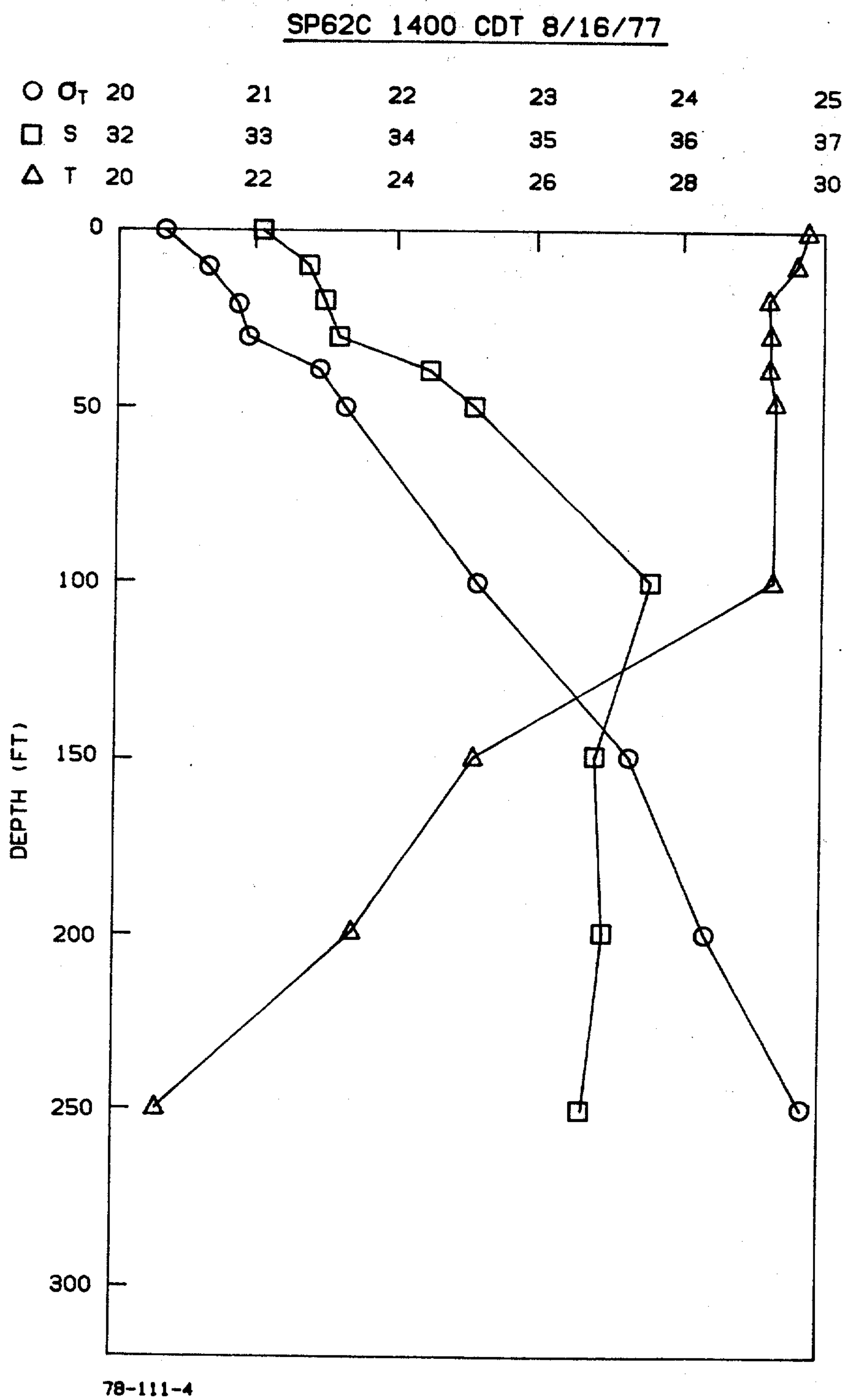
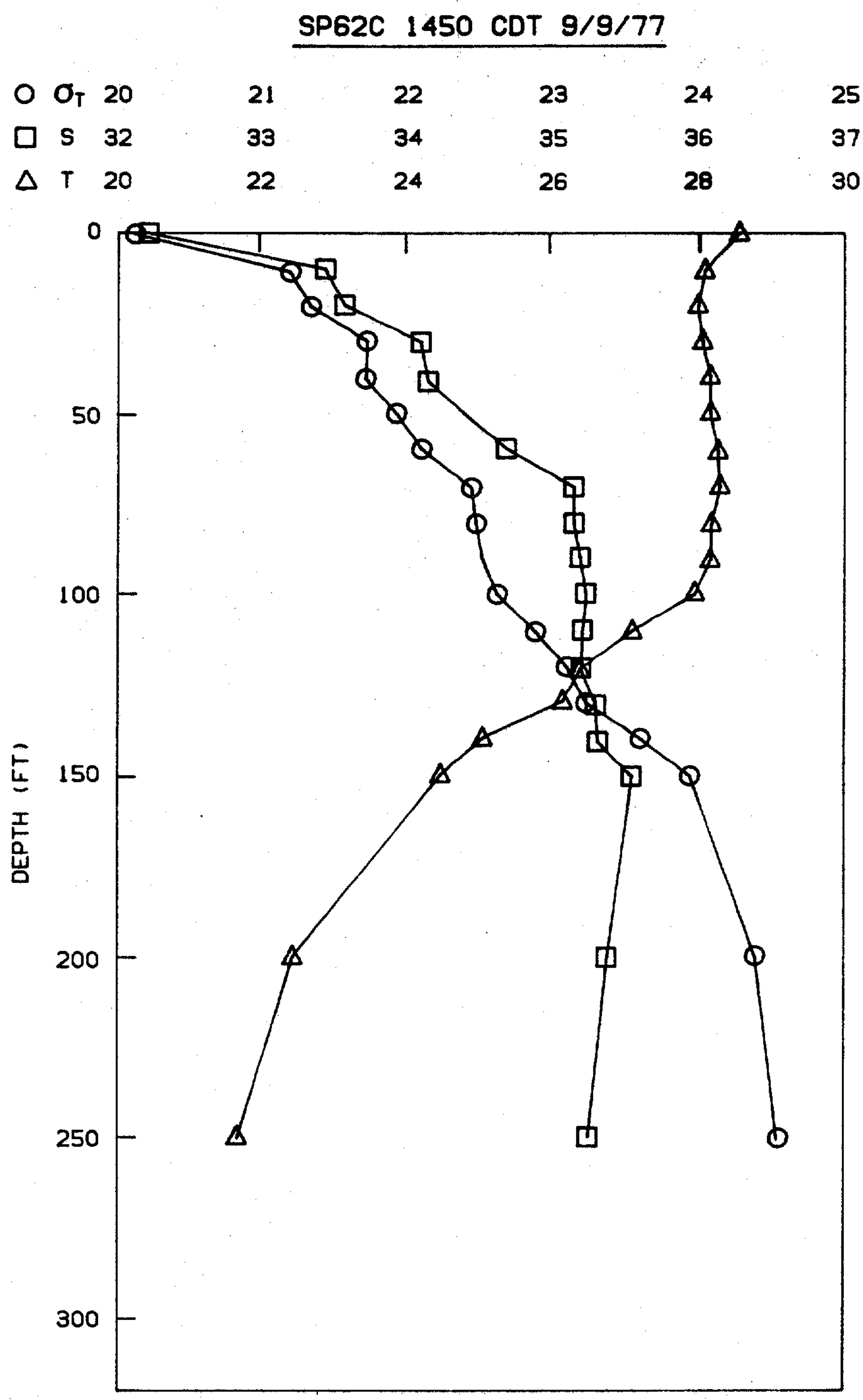


Fig. 66 - Stratification at station 3, August 16, 1977.



78-111-5

Fig. 67 - Stratification at station 3, September 9, 1977.

The situation at Station 3 before the storm (Figure 66) at 1400 CDT on August 16 was qualitatively similar to that at Station 2. After the storm (Figure 67) at 1450 on September 9, the water still appears at first glance to be well stratified. However, there is some evidence of a mixed layer remaining between 70 feet and 100 feet. The water may have been mixed to this depth during the storms and then the surface stratification re-established by the fresh water outflow from the Mississippi River in the days between the storms and the measurements.

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