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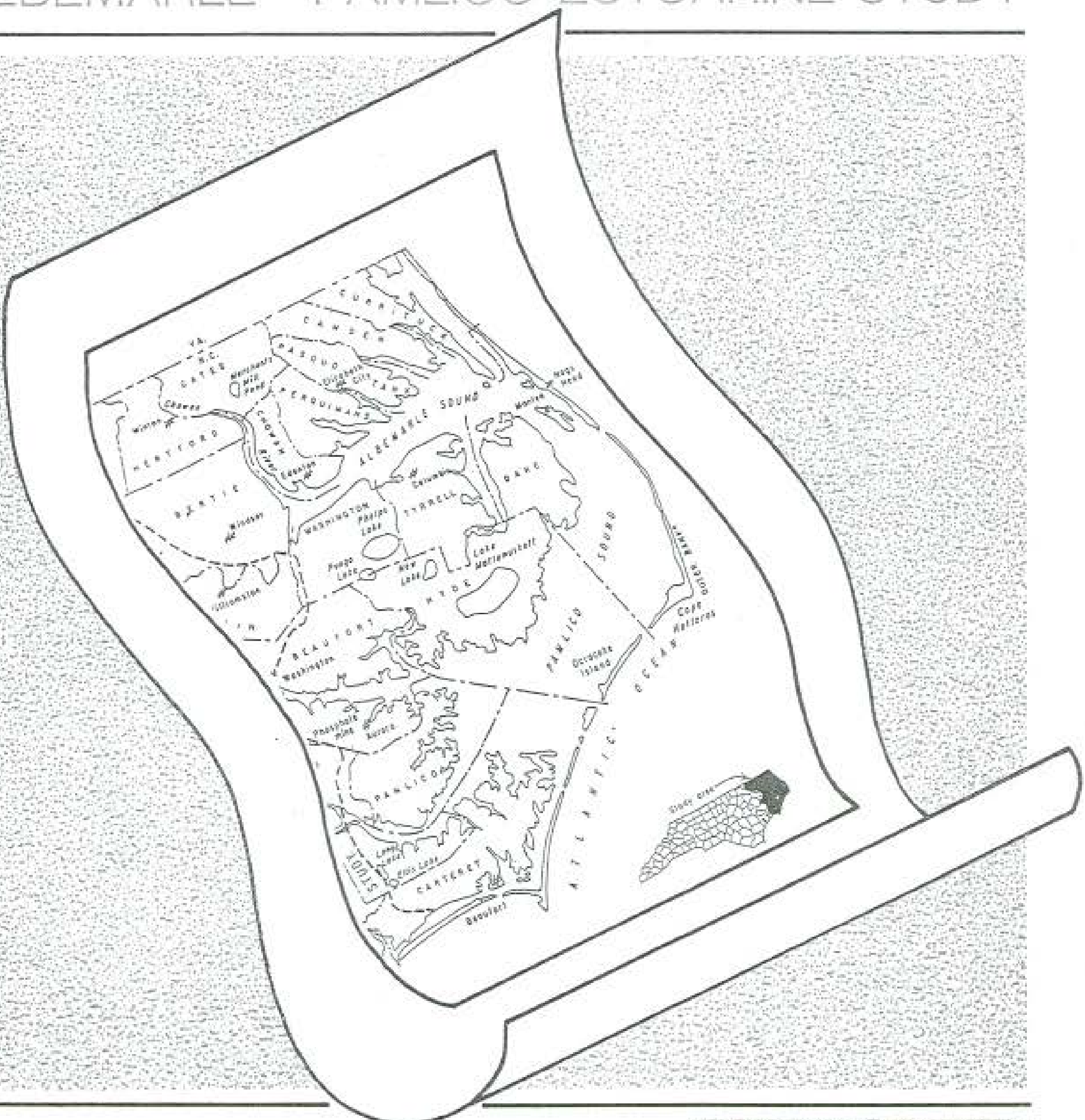
PROJECT NO. 90-13

The Albemarle-Pamlico Coupling Study

ALBEMARLE - PAMLICO ESTUARINE STUDY



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FINAL REPORT

ON

THE ALBEMARLE PAMLICO COUPLING STUDY

May, 1991

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1. EXECUTIVE SUMMARY

This project was undertaken with the objective of obtaining an understanding of the hydrodynamic coupling of Albemarle and Pamlico Sounds via Croatan Sound in order to determine whether this coupling can account for the scarcity of ocean spawning finfish in Albemarle Sound. An eighteen month field project was mounted to achieve this objective. A total of eleven data collection stations was maintained during the course of the experiment. At ten of these moored stations, water level data was obtained. At four of these ten moorings water temperature, conductivity, and velocity data were also collected. Meteorological data was obtained from four land based stations. Data was collected continuously during each of six deployments; each deployment lasted about two months and during each deployment data was collected at seven to nine of the stations. Each instrument-stored data internally on cassettes which were removed following each deployment. The cassettes were brought from the field to North Carolina State University where the tapes were first transcribed onto computer tapes, then converted to binary data and then, following an editing process to raw data. The raw data were then subjected to a three hour filtering to separate the signal from the noise and then forty hour low passed to separate the high and low frequency parts of the signal. Statistical analyses of the data were performed including auto and cross-covariances. It was found that in Croatan Sound the currents near the surface and bottom were virtually always in the same direction and that these currents are primarily wind-driven. Under southward winds the water flows southward from Albemarle Sound through Croatan Sound and into Pamlico Sound and under northward winds the water flows northward from the Pamlico to the Albemarle via Croatan. The observed coherence of water motion with the wind has implications for the recruitment of ocean spawned finfish larvae and juveniles into Albemarle Sound as follows. Under southward winds, sea level rises on the ocean side of Oregon Inlet while this same wind causes a drop in water level at the northern end of Pamlico Sound, on the sound side of Oregon Inlet. This wind induced tilt in water level enhances inflow on the tidal flood and decreases outflow on the ebb. Hence southward winds enhance recruitment of fish larvae into the sound system through Oregon Inlet. However, on these same southward winds, the wind induced flow in Croatan Sound is to the south bringing Albemarle Sound water to Pamlico Sound and preventing fish larvae and juveniles from entering Albemarle Sound. Hence the nature of the hydrodynamical coupling between Albemarle and Pamlico Sounds works against the recruitment of ocean spawned finfish larvae and juveniles into Albemarle Sound.

Predictive capabilities for the flow of water through Croatan Sound are then created using two different approaches. First, a data based, emperical model which utilizes the measured winds to predict currents is provided. Then three-dimensional time-dependent model results of water level throughout the entire APES system and currents in Croatan Sound are presented. Both the empirical and the numerical model results are in good agreement with observations.

2. INTRODUCTION

Miller, Reed and Pietrafesa (1984) discussed the migratory routes of five species of estuarine dependent finfish larvae and juveniles along the North Carolina (NC) continental shelf. These five species, Atlantic menhaden (*Brevoortia tyrannus),* Spot (*Leiostomus xanthurus*), Atlantic Croaker (*Micropogonias undulatus*), Southern Flounder (*Paralichthys lethostigma*) and Summer Flounder (*P. dentatus*), constitute only 10% of the fish species found in NC estuarine and coastal waters. However, these five finfish comprise upwards of 90% of the annual commercial catch in NC coastal waters. All five species spawn during the winter months near the shelf break along the western wall of the Gulf Stream. Their larvae and juveniles then migrate some 100 kilometers to major inlets in the barrier island chain (as shown in Figure 1) and then another 25-100 km to nursery areas across Pamlico Sound. Abiotic mechanisms to transport these larvae and juveniles across the shelf have been proposed by Pietrafesa and Miller (1986), through the inlets by Pietrafesa and Janowitz (1988) and across the Pamlico Sound by Pietrafesa, et al. (1987).

However, while these ocean spawned finfish use Pamlico Sound as a nursery, they are not found in any significant numbers in Albemarle Sound (Epperly and Ross, 1985). In fact their presence in the Albemarle is only occasional while they are found throughout the Pamlico. Hence the purpose of this study.

The Albemarle - Croatan - Pamlico Sounds Estuarine system (Figure 2) is the largest coastal lagoonal system in the United States. Pamlico Sound is approximately 140 km long in the northeast-southwest direction and 25-55 km in the northwest-southeast direction. The Albemarle is approximately 85 km aligned east-northeast to west-southwest and is as wide as 20 km in the eastern and narrowing to some 8 km at the western end. The two sound basins, Pamlico and Albemarle, are connected to each other by Croatan and Roanoke Sounds, separated from each other by Roanoke Island. Roanoke Sound is very shallow and is not hydrodynamically important. However Croatan Sound, which is about 25 km long and 7-10 km wide, and is aligned north-northwest to south-southeast, is the important connection between the two basins (cf. Figure 3). While Pamlico Sound has direct connections to the coastal ocean through Oregon, Ocracoke and Hatteras Inlets, the Albemarle has no natural connection to the adjacent coastal ocean. A more complete description of the morphology of the entire system can be found in Copeland and Gray (1989).

The objective of this study was to obtain an understanding of the hydrodynamic coupling of Albemarle and Pamlico Sounds via water motions in Croatan Sound to determine whether these motions could have a deleterious effect on the process of fish larvae recruitment into Albemarle Sound. In effect, the question asked is: "Are abiotic factors due to the hydrodynamic coupling of Albemarle and Pamlico Sounds responsible for the lack of a significant ocean spawned finfish population in the Albemarle?" The objective was to be achieved through a two year program consisting of a field measurement component and a data reduction and interpretation phase. The official period of this project was October 1, 1988 through September 30, 1990; however, actual funding was made available in November, 1988. Subsequently, instruments were refurbished, calibrated and prepped during the November and December 1988. During January and February 1989, reconnaissance surveys of potential instrument locations were conducted prior to instrument deployment. Measurements were made in the period March 1989 - August 1990. Preliminary data analysis was performed throughout the period following the first data retrieval and a draft report was submitted to the Albemarle-Pamlico Estuarine Study (APES) Program Executive Committee in December, 1990. Following receipt of APES review comments, the final draft report was completed in May 1991 and amended in August, 1991.

One of the principal investigators Leonard J. Pietrafesa (LJP) of this project was a co-principal investigator (along with J. Miller of North Carolina State University) of a concurrent National Oceanographic and Atmospheric Administration - University of North Carolina Sea Grant College Program grant (NOAA/Sea Grant) funded project entitled "Abiotic Factors Affecting Inlet Migration". The results of the Sea Grant project showed the following:

1. Under the action of northeasterly to northwesterly (southwestward to southeastward winds, sea level rises on the ocean side of Oregon Inlet while dropping on the Pamlico Sound side; this rise in sea level outside coupled with the drop inside the inlet creates a hydraulic head which enhances inflow on the flood stage of the tide and weakens or negates outflow on the ebb.
2. Southerly (northward) quadrant winds have the opposite effect.
3. Winds which blow from the quadrant lying between northwest to northeast directions (the Northerly quadrant) enhance recruitment of juvenile finfish into Pamlico Sound.

The primary hypothesis to be tested by this EPA/APES project is as follows: During periods of enhanced recruitment (northerly or southward quadrant winds), water flow within Croatan Sound would be to the south at all depths and there would be no flow into Albemarle Sound from the Pamlico. This "southerly flow at all depths" hypothesis follows from the conjecture that the upwind force due to water surface slope would be weakened in Croatan due to the obstacle to north-south flow posed by the presence of Roanoke Island. This hypothesized southerly flow would prevent fish larvae from entering Albemarle Sound and thus enhance the productivity of Pamlico Sound at the expense of Albemarle Sound.

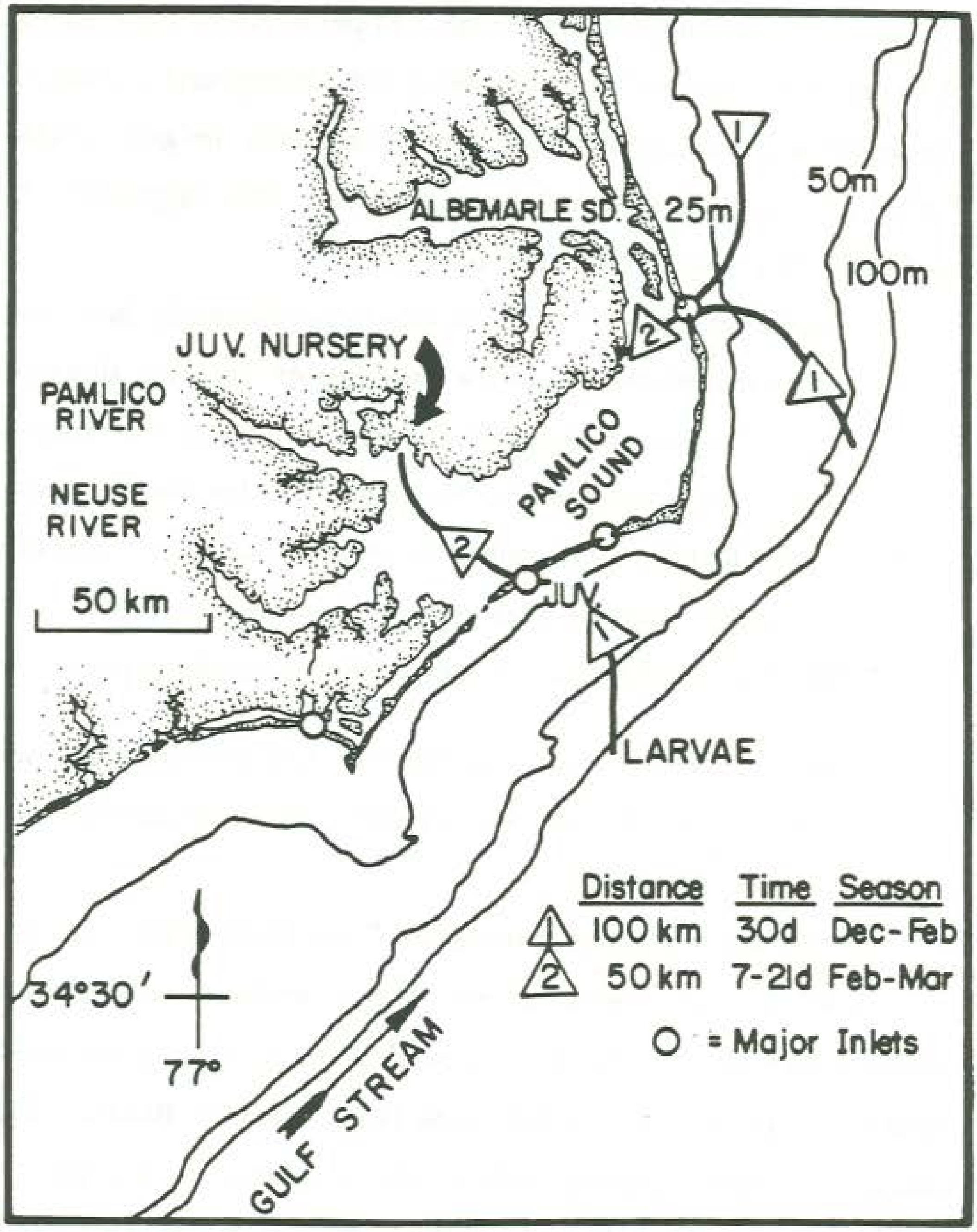

Figure 1. Age and distribution of larval spot and croaker off North Carolina. Juvenile nurseries exist along the western periphery of Pamlico Sound. (adapted from Miller, Reed and Pietrafesa, 1984)

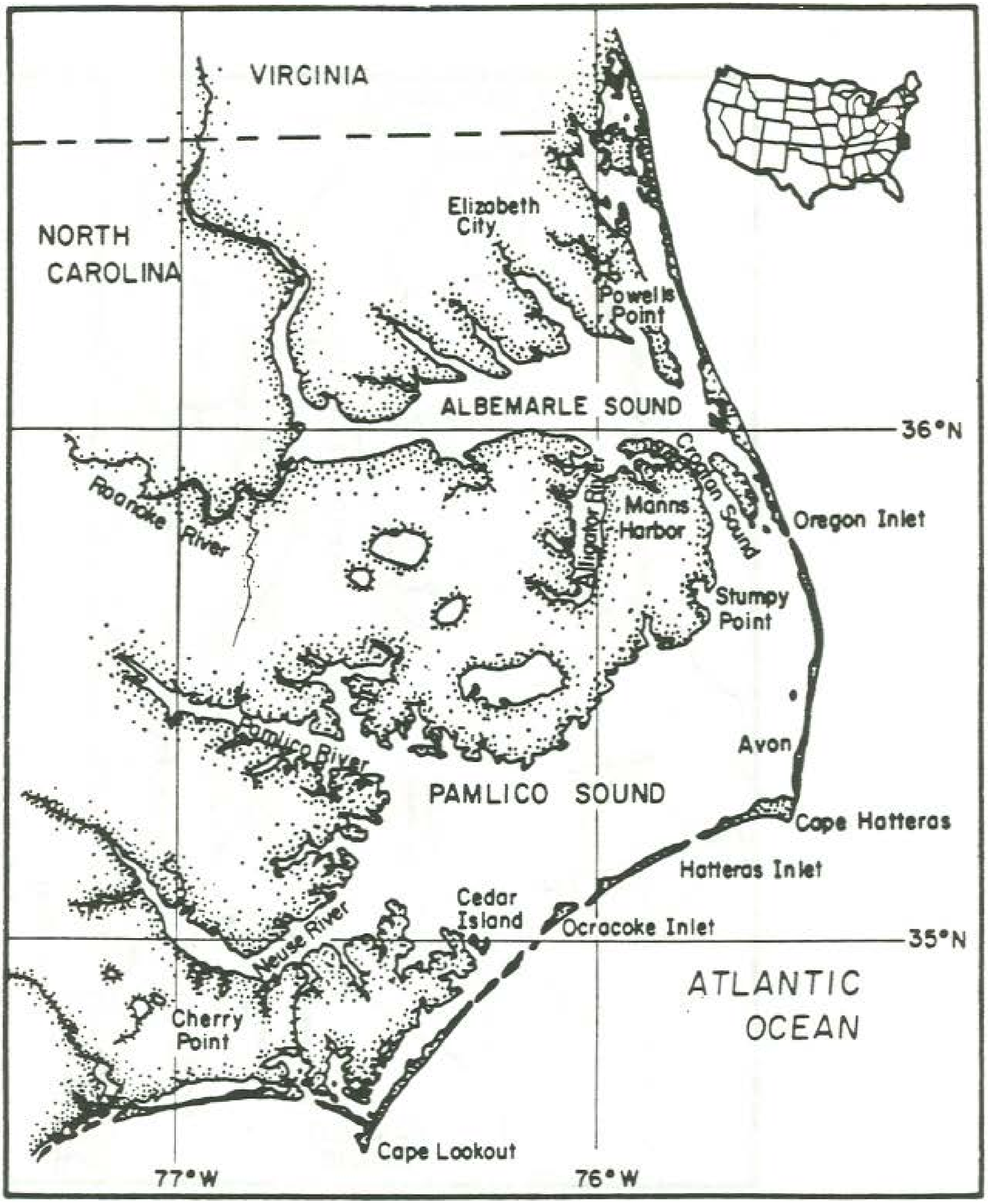

Figure 2. Albemarle-Croatan-Pamlico Sounds Estuarine System.

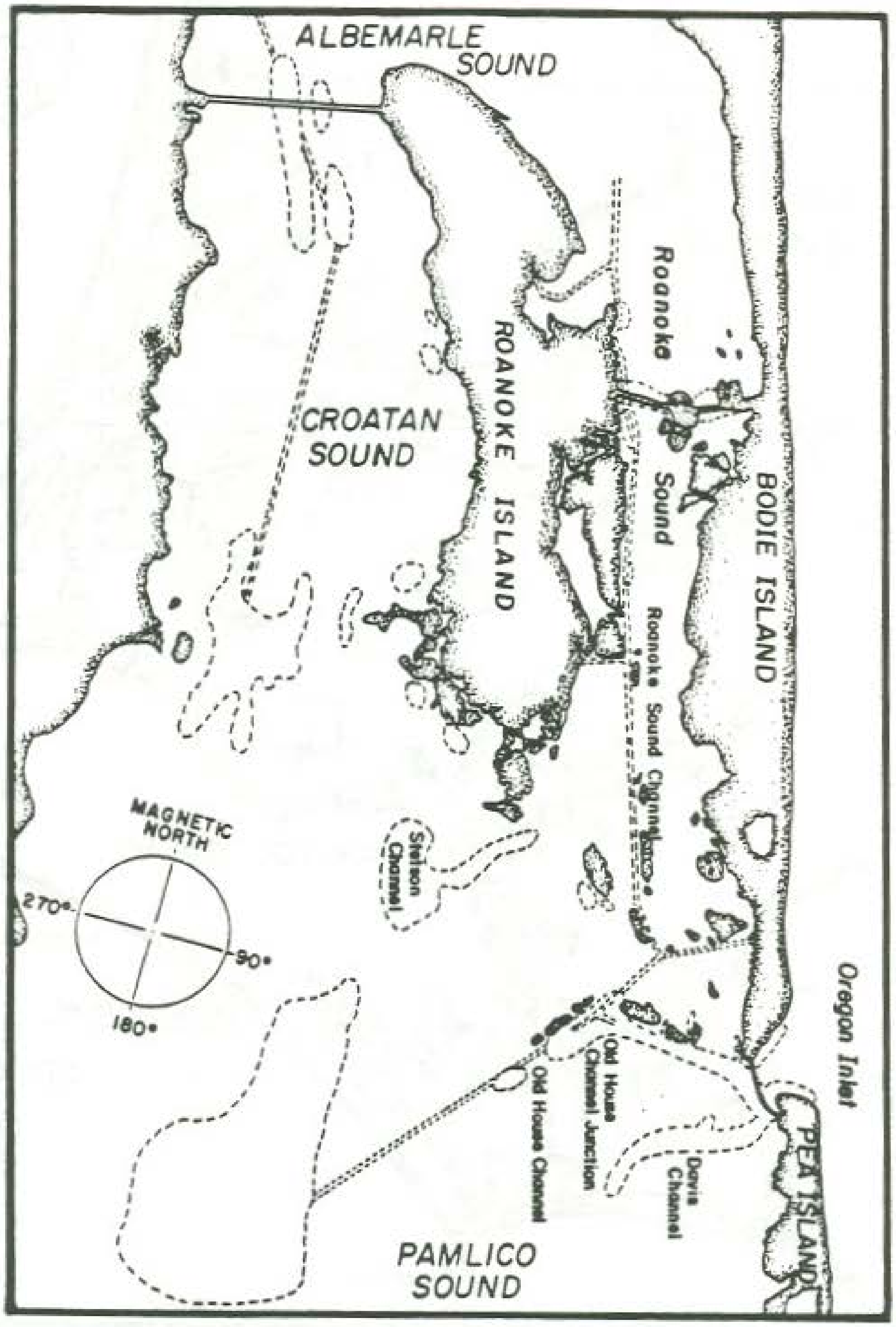

Figure 3. Croatan and Roanoke Sounds. Pamlico Sound is to south (↓) Albemarle Sound is to north (↑).

3. DATA

The project hypothesis was tested during the study period by measurements of water level, wind speed and direction, and water velocity, temperature, salinity and bottom pressure at a number of locations within the Albemarle-Pamlico system. The locations of the measurement sites are presented in Table 1 and shown in Figure 4. Sites 1, 3 and 7 are maintained by the National Weather Service while all other sites were installed as part of this project. The actual instrumentation present at each site during each deployment is given in Table 2. Sketches of the moorings at Site 10, actually the Intracoastal Waterway (ICWW) Marker 8 and Site 6, actually the Route US 64 Bridge, are given in Figures 5 and 6, as representative examples. All instruments utilized in this study recorded data internally on cassettes which were removed and replaced every eight weeks. The process included six separate complete instrument turnaround deployments. After each data retrieval, the tapes that were retrieved were returned to North Carolina State University (NCSU) for processing. The first round of processing produced binary data which was then converted to digital data. These data series were then subjected to a three hour low pass (hrlp) filtering process (Pietrafesa, et al., 1977) which removed high frequency noise which might be present in the raw data. Finally the data series were subjected to a forty hour low pass filtering process (Pietrafesa et al., 1977). This filtering technique allows us to distinguish between high and low frequency forced motions. Since for every individual deployment each data tape contains from one (at water level recorders) to six (at current meters) data time series and each time series may exist in three forms (raw, 3hrlp, 40hrlp) and there were a total of six deployments, a large quantity of data and data products exist. Fifty-five instruments were deployed, 54 were returned (1 was lost) and 11 were returned with no or bad data for an 80% success rate of good data versus instruments recovered. These data were analyzed using time series analysis techniques and conclusions were subsequently drawn.

Empirically derived conceptual relations between the flow in Croatan Sound and the wind field and water level fluctuations were obtained. Before proceeding to a discussion of the times series and analyses of the data, the forcing functions of the flow field and the theoretical basis for the analyses are discussed. Subsequently, conceptual and statistics based interpretations of the data are presented.

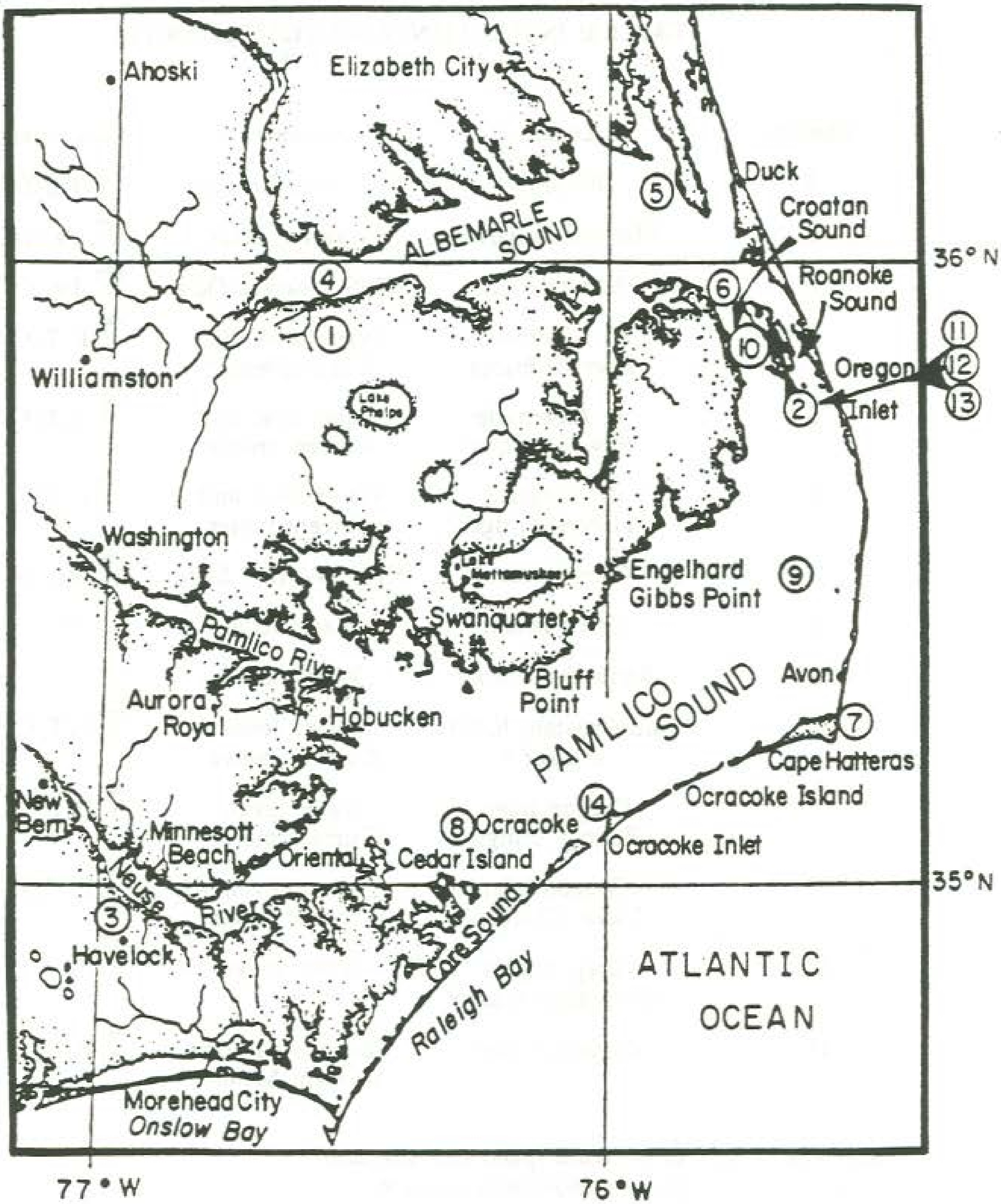

Figure 4. Location of field sites occupied by North Carolina State University during the Albemarle-Pamlico Coupling Study. (cf. Tables 1 and 2 for details).

TABLE 1: INSTRUMENTATION OF FIELD SITES

Station	Location	Instruments	Parameters
1	Plymouth	NWS Weather Data	$\vec{W}$, Pa, Ta
2	Manteo Aquarium	Weather Data	$\vec{W}$, Pa, Ta
3	Cherry Point	NWS Weather Data	$\vec{W}$, Pa, Ta
4	W. Albemarle, Hwy. 37 Bridge	Water level and Current meter	$\vec{V}$, P, T, C
5	E. Albemarle Powell's Point	Water level and Current meter	$\vec{V}$, P, T, C
6	N. Croatan, Hwy 64 Bridge	Water level and Current meter	$\vec{V}$, P, T, C
7	Cape Hatteras	NWS Weather Data	$\vec{W}$, Pa, Ta
8	Cedar Island	Water level	P
9	Rodanthe Harbor	Water level	P
10	Mid-Croatan, ICWW Marker 8	Water level Current meter	$\vec{V}$, P, T, C
11	Oregon Inlet, Bonner Bridge	Water level, Current meter	$\vec{V}$, P, T, C
12	Oregon Inlet Davis Channel	Water level, Current meter	$\vec{V}$, P, T, C
13	Oregon Inlet Inner range marker	Water level	P
14	Ocracoke Inlet	Water level and Current Meter	$\vec{V}$, P, T, C

Parameter Key:
- $\vec{W}$ = wind speed and direction
- Pa = atmospheric pressure
- Ta = atmospheric temperature
- P = water pressure
- V = water speed and direction
- T = water temperature
- C = water conductivity

TABLE 2 AP Coupling Study measurement periods, mooring sites, instrument type and recovery and data collection.

STATION	MAR-JUN 89	JUN-AUG 89	AUG-OCT 89	JAN-MAR 90	MAR-MAY 90	MAY-JULY 90
37 BRIDGE	NO INSTRUMENT	WLR-709	WLR-709	WLR-709(ND)	WLR-709(ND)	S4 #766
POWELLS PT.	WLR-912	WLR-912	WLR-912	WLR-912	WLR-912	WLR-912
64 BRIDGE N. CROATAN	S4 #241 (TOP) WLR-564 (BOT)	S4 #241 (TOP) WLR-564 (BOT)	S4 #241 (TOP) WLR-564 (BOT)	S4 #766 WLR-564(ND)	S4 #766	NO INSTRUMENT
ICCW MARKER 8 MID CROATAN	S4 #766(TOP) S4 #242(BOT)	S4 #766(TOP) S4 #242(BOT)	S4 #766(TOP)	MARKER 8 MISSING	S4 #242	S4 #242 WLR-709(ND)
BONNER BRIDGE	S4 #769(TOP) S4 #765(BOT)	S4 #765(BOT)	S4 #765(BOT)	S4 #765(BOT)	S4 #765(BOT) (BURIED)	NO INSTRUMENT
INNER RANGE MARKER OREGON INLET	WLR-751	WLR-751	WLR-751	WLR-751	WLR-751 (ND)	NO INSTRUMENT
MANTEO AQUARIUM	DL-1000	DL-1000	DL-1000	DL-1000 (ND)	DL-1000	DL-1000
RODANTHE HARBOR	NO INSTRUMENT	WLR-369	NO INSTRUMENT	NO INSTRUMENT	NO INSTRUMENT	NO INSTRUMENT
DAVIS CHANNEL OREGON INLET	S4 #791	S4 #791	NO INSTRUMENT	NO INSTRUMENT	NO INSTRUMENT	NO. INSTRUMENT
OCRACOKE MARKER 12	NO INSTRUMENT	NO INSTRUMENT	NO INSTRUMENT	S4 #241 WLR-369 (ND)	S4 #241(ND) WLR-564(ND)	S4 #241 WLR-564
CEDAR ISLAND	NO INSTRUMENT	NO INSTRUMENT	NO INSTRUMENT	NO INSTRUMENT	NO INSTRUMENT	WLR-751(ND)
PLYMOUTH CHERRY PT CAPE HATTERAS	NWS STATION	NWS STATION	NWS STATION	NWS STATION	NWS STATION	NWS STATION

*(ND) NO DATA

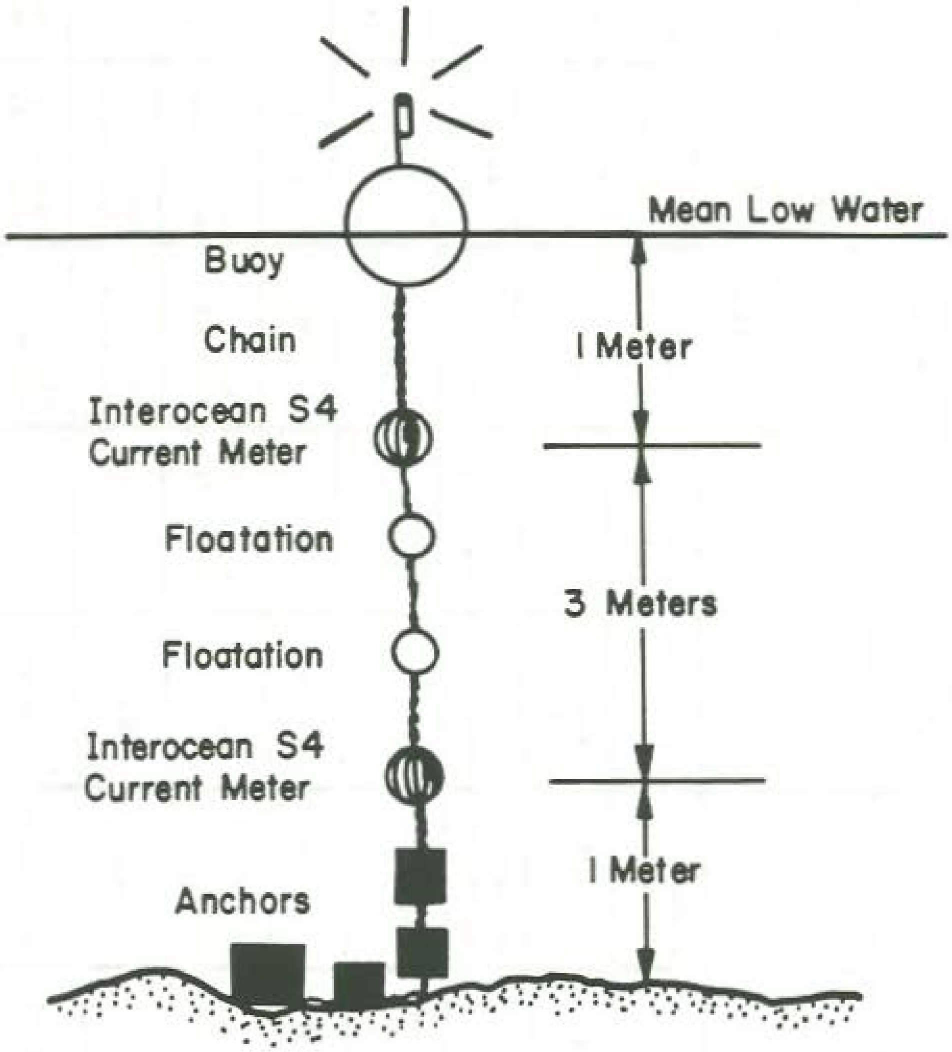

Figure 5. Sketch of mooring 10 at ICWW (Channel Marker) #8.

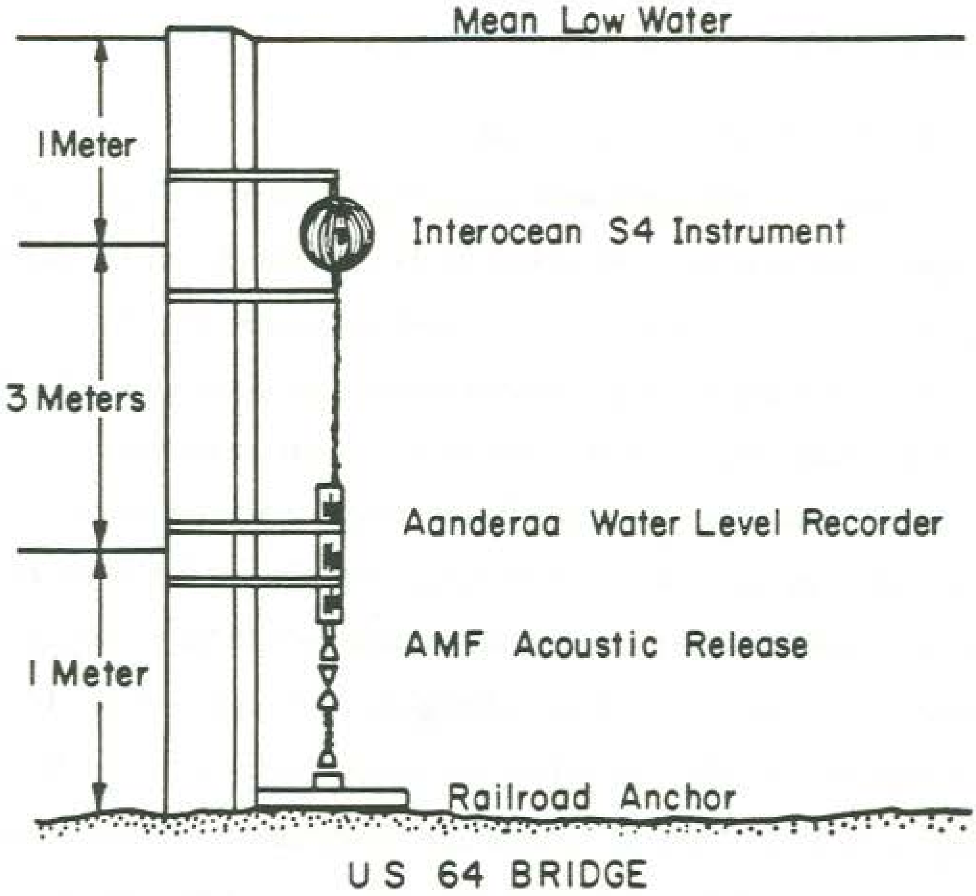

Figure 6. Sketch of mooring #6 at U.S. 64 Bridge across north Croatan Sound.

4. DRIVING FUNCTIONS FOR THE FLOW FIELD

The principal forcing functions for fluid motions in the system are the astronomical tides, riverine and fresh water inflow, and the wind field. We discuss the importance of each of these factors in turn.

(A) Tidal Forcing, Seabreeze Forcing

To examine the significance of tidal influence in our study, we first consider representative data collected as part of the aforementioned Sea Grant project. In Figure 7 we present the edited water level time series at Site 13 in Oregon Inlet during the first deployment. We can see that the mean tidal range (high to low water in a tidal cycle) is approximately 80 cm with an extremal range of 120 cm. The tidal signal is the high frequency (nearly twice a day) oscillation in this figure. The mean water level over a tidal cycle varies with time and is rarely zero; this reflects the time varying influence of the atmospheric windfield on sea level. The energy spectrum of water level at Bonner Bridge is given in Figure 8a. We note the dominant peak at 12.42 hours (the semi-diurnal tide) with a peak value of the energy density of 10 DB**2/CPH; where DB stands for decibars (or equivalently meters) and CPH stands for cycles per hour. While tidal fluctuations are dominant at the inlets, the tidal influence drops off away from these regions. In Figure 8b the energy spectrum at Site 10, located at Channel Marker 8, in mid-Croatan Sound is shown to have a peak value at 12.42 hours of only 0.1 DB**2/CPH, a hundred-fold drop off from the inlet value which implies that a ten-fold drop in tidal amplitude has occurred from the inlet to mid-Croatan Sound.

The water level at Site 6, the US 64 bridge across northern Croatan Sound, during the August - October deployment, (Figure 9a) shows a tidal range of from 5 to 8 cm, a ten-fold drop off in amplitude which is consistent with the hundred-fold drop off in energy. The tidal range of 8cm is clearly seen between days 285 and 290. Water level at Powell's Point, Site 5, in eastern Albemarle Sound during this deployment (Figure 9b) shows an even smaller tidal range of from 2 to 6 cm. However, the tidal range at Site 4, the Highway 37 bridge in western Albemarle Sound (Figure 9c) shows a tidal range of from 5 to 7 cm. The increase in the range of the tide at the western end of Albemarle Sound (Site 4) over the values at the eastern end of the Albemarle (Site 5) reflects the narrowing of the sound in the west. To assess the repeatability of this finding, we compare the fluctuating kinetic energy of water level fluctuations at Site 4 (Western Albemarle) to that at Site 5 (Eastern Albemarle) during the period May - July, 1990 (Figures 10 a,b) and find that 12.42 hour lunar tidal energy is greater at the Bridge 37 site.

We also note that while there is an essential absence of energy at the 24-25 hour period at the west end of the sound, while it is clearly present at the east end of the sound. A strong diurnal 24 hour period signal is present at Site 11, Bonner Bridge (Figure 8a) and to a much lesser extent at Site 10 in Croatan Sound (Figure 8b) as well as at Site 5, Powell's Point, (Figure 10b) but is absent at Site 4, the west end of the Sound. This response is similar to that of the 12.42 hour astronomical tidal signal signature at Oregon Inlet and Croatan Sound but reverses its relative signature in the Albemarle. Hence we conclude that the 24 hour signal consists of responses to both the astronomical, solar tide and the seabreeze phenomenon at Oregon Inlet and to a lesser degree in the Croatan but within the Albemarle, the response to the astronomical diurnal tide is essentially absent. Moreover, the atmospheric response to the land versus water daily differential heating and cooling process is the cause of the 24 hour signal at the east end of the Albemarle, but its' effect dies out to the west.

It should also be noted here that the term "Wind tides", so prevalent in the culture of Eastern N.C. must be used with appropriate qualification. We also note that there is a peak in the spectra shown in Figure 8 at about 6 hours which could be a manifestation of an axial basin seiching mode or a harmonic of the M2 tide.

Velocities in the water column, as well as sea level, show a strong decrease away from the inlets at the semi-diurnal tidal frequency. While at the inlets (Site 11) tidal currents can exceed 100 cm/sec. (cf. Figure 11) the velocities at tidal frequency in mid-Croatan Sound are approximately 5 cm/sec. (cf. Figure 12); a clear tidal signal is evident at day 81 in this figure. For future reference, we note that changes in current speeds of 70 cm/sec can occur over a several day period. We conclude that in our study area, which is away from the inlets, tidal effects are relatively unimportant.

(B) Riverine and Freshwater Inflow

Under normal conditions approximately 510 cubic meters/sec flow from the Albemarle Sound to Pamlico Sound (Giese, Wilder and Parker, 1985) via Croatan Sound. As the cross-sectional area of Croatan Sound at Site 10, the ICWW Marker 8 location, is 1.5x10**4m**2, the mean southwards flow at this cross-section is only 3 cm/sec, comparable to the tidal signal and far less than the total signal shown in Figure 12. In the less constricted cross-sections which occur in Albemarle Sound the mean velocity due to freshwater runoff and riverine discharge would be even smaller. Thus, neither the semi-diurnal nor diurnal tides nor response to the seabreeze nor riverine influence can account for the large observed currents; hence, the main discussion in what follows will be centered on wind driven water level and current variations. We do note that while the cross-channel component of flow appears to average to zero (upper panel, Figure 12), the net flow is from the Albemarle to the Pamlico (lower panel, Figure 12).

(C) Wind Driven Flow

From Section B above, it is clear that neither the tide (± 5 cm/sec) nor riverine effects (+ 3 cm/sec) can account for fluctuating currents which typically vary from +20 to -50 cm/sec. We next assess the data to determine if wind forcing could account for flows of these magnitudes. As an example of the windfield present along the NC coast, raw winds from the National Weather Service station are presented in Figure 13. The wind vector time series from 19 April - 07 August, 1988 is shown in 13a while the time series of wind stress is shown in 13b. The wind blows from a point on the horizontal axis at some time toward the head of the stick originating on the axis at that time. The stress was obtained from the wind speed and direction through the standard bulk aerodynamic formula with a drag coefficient of 1.6×10^{-3}.

In Figure 14, hourly or raw winds from Cape Hatteras are shown every six hours for clarity while in Figure 15, these same winds which have now been low pass filtered using a Lanczas cosine tapir filter with a half power point of 40 hours are shown for the period 26 March - 28 May, 1989. Note that unlike the schematic of the "raw" winds, the filtered winds look much less busy and choppy (Figures 13 or 14 vs 15). The upper panels in Figures 14, 15 show the entire wind vector while the middle panel depicts the east-west component (+ to east, - to west) and the bottom panel defines the north-south (+ to north, - to south) component.

We now consider water level fluctuations during the same period of time, March - June, 1989, at Site 10 (Marker 8), Site 12 (Oregon Inlet), Site 6 (Highway 64) and Site 5 (Powell's Point) as shown in Figures 16 a-d, in raw from, respectively, and in Figures 17 a-d, in 40hrlp filtered form. Figures 18 a-c and 19 a-c are the time series of the differences in water surface elevations between stations; depicting water level slopes.

We note first (Figure 16) that the amplitudes of the fluctuations in water level are largest at Oregon Inlet (Site 12) where the twice daily lunar (M2) tide is present. Next note that the water level fluctuations at Site 10 tend to track the north-south component of the wind (compare Figure 15c to Figure 17b) in that when the wind blows towards the south, the water at Site 10, in the northern end of Pamlico Sound drops and when the wind blows towards the north, water level at Site 10 rises. First impressions (Figures 16, 17) are that this rising or falling occurs at all sites, in concert, with northward or southward winds (Figures 14, 15) respectively, but a closer look shows that this is not the case.

Comparing water level fluctuations at Sites 6 and 4 (Figures 16c,d or 17c,d) show that at these locations, both of which are in the east end of Albemarle Sound, water level also rises with a wind blowing towards the east and drops with a wind blowing towards the west. This scenario appears to be visually true at Site 10 also, but to a much, much lesser degree than that at either of Sites 5 or 6.

In Figures 18 a-c, 19a-c, three series of sets of water level elevation differences are presented. In the upper panels of both figures we see that winds blowing towards the north create a downwards tilt from Site 10 to Site 12, that is, from Croatan Sound to Oregon Inlet. Winds blowing towards the south create the opposite effect, that is that the water level at Oregon Inlet (Site 12) is higher than that in Croatan Sound (Site 10). However, the water level response between the east end of the Albemarle on the north end of Croatan can complicate matters because of the alligence of water level fluctuations in the Albemarle to the east-west wind.

Comparing Figure 14b or 15b to 18b,c or 19b,c we see that a wind blowing towards the south is accompanied by a downwards tilt in water level from both Oregon Inlet to Croatan Sound (Site 12 minus Site 10) as well as from east Albemarle to Croatan (Site 5 minus Site 10). A northward wind will cause the opposite scenario to occur. Now, if the wind is blowing slightly towards the east also then there is a differential effect on the water slope from the east Albemarle to Croatan. In essence a wind blowing towards the southeast would make the downward tilt from the east end of Albemarle at Powell's Point to the middle of the Croatan at Marker 8 (Station 5 minus Station 10) even steeper while a south westward blowing wind would flatten this tilt and could even reverse it.

In Figures 20 a-c, the time series of velocity, temperature, salinity and water level at Oregon Inlet (Site 12) are shown for the period March - June, 1989. In Figures 21 a,b the flow field in Croatan Sound as measured at Site 10 is shown. Comparing the time series shown in Figures 20 and 21 to the wind field given in Figures 14 or 15 suggests the following sequence of events:

> When the wind blows towards the north, the water level at Oregon Inlet falls, but rises in the Croatan, this is accompanied by a drop in salinity at Oregon Inlet. At this time water is being exported from Pamlico Sound to the coastal ocean through Oregon Inlet. However, at this same time water is also flowing from the north end of Pamlico Sound into Croatan Sound and subsequently into Albemarle Sound. However, when the wind blows towards the south, then the water level at Site 12 (Oregon Inlet rises), the water becomes more saline as offshore coastal water enters the north end of Pamlico Sound. But concurrent with these events, the water is transported from the Albemarle into the Croatan and into the Pamlico. This is shown clearly by the series of events A, through T denoted variously in Figures 14, 20 and 21.

Pietrafesa and Janowitz (1988) showed that when winds blow towards the south, salty coastal waters, which are likely larvae laden enter Pamlico Sound through Oregon Inlet. From the data presented in this study we have found that under the action of southwards winds (which enhance recruitment into Pamlico Sound) the flow in Croatan Sound would be to the south at all depths; this would prevent fish larvae from penetrating into Albemarle Sound. Away from inlets and river mouths, the currents associated with tidal and riverine flows are fairly weak compared to wind-driven flows. In shallow basins such as the Albemarle-Pamlico system, currents appear to be due principally to the mechanical forcing of the wind and to horizontal pressure forces set up by the tilt of the water surface; this tilt itself is set up by the wind. The direct response to the wind appears as a downwind water flow at all depths. This downwind flow raises water level at the downwind shore and lowers water level at the upwind shore. This variation in water level at the periphery of the basin could then be communicated to the rest of the basin via a long gravity wave originating at the shore. Since we find that the water level tilts upwards in the downwind direction, an upwind pressure force could result which would tend to drive fluid upwind. If the wind field persists for a sufficiently long period, a strong pressure gradient can be set up which would cause upwind water flow near the bottom with direct downwind flow near the surface.

We now examine, in Figure 21, current meter data at Site 10, in mid-Croatan Sound (ICWW Marker 8) where we had deployed two InterOcean S4 current meters, one near the top and the other near the bottom. In Figure 16d we present water level data at Site 5, Powell's Point in eastern Albemarle Sound (top panel) approximately thirty kilometers north of Site 10 (ICWW Marker 8). Water level at Marker 8 is given in Figure 16b. The difference between water level at Powell's Point and that at Marker 8 is given in the bottom panel of Figure 18. Negative values in the lower panel imply a northwards pressure gradient force. We note that from 112 to 120 a fairly persistent northward force exists. Thereafter the pressure force is somewhat smaller in magnitude and not nearly as persistent as during the early period. We can trace the behavior of the tilt of the water surface to the wind given in Figure 14. From day 109 to day 115 the wind is significant and to the south. This would set up the tilt observed in the water surface from day 112 to 120. Thereafter the wind changes direction every one to two days and so no significant tilt can be set up. We now return to Figure 21, the velocity plots. These are stick plots with flow direction from the horizontal axis to the head of the stick. From day 120 through day 157 the currents at the top and bottom are in the same direction and go with the wind (the current flows downwind). From day 112 to 119 the bottom currents are to the north while the surface currents are to the south. The deep currents go in the direction of the strong pressure gradient while surface currents go with the wind.

Now, to explain these results we consider that in a shallow basin of uniform depth and in the absence of lateral boundaries, a wind stress applied at the surface should accelerate the water column until the speed near the bottom is sufficiently large so that the bottom stress can balance the applied stress; the momentum supplied by the wind at the surface is rapidly transferred downwards by turbulent mixing. If the bottom stress, taken as $2.5x10^{-3}\rho_w U_b{}^{-2}$, is set equal to the wind stress, T_w bottom currents would be 20 $(T_w/\rho_w)^{1/2}$ where U_b is the bottom water speed, ρ_w is the water density. For a 1 dyne/cm^2 windstress a 20 cm/sec bottom speed would occur. In the presence of boundaries, the downwind flow of water should result in the accumulation (piling up) of water at the downwind shore and a drop in water level at the upwind shore. This in turn would produce an upwards tilt in the sea surface in the downwind direction. Should the wind blow steadily for a sufficient time, the pressure force associated with the tilt in sea surface, ρ_w g h/L, would partially balance the wind stress force, T_w/H. This leads to an estimate of the amplitude of water level fluctuations of $T_w L/gH\rho_w$, where L is the downwind wind-driven fetch of the wind, g is the acceleration due to gravity, H is a mean depth and h the water level elevation. For a 100 kilometer fetch, a mean depth of 5 meters and a 1 dyne/cm**2 wind stress, the water level changes could reach 20 cm. As mentioned above, the tilt in water level would result in an upwind pressure force and could produce an upwind current, most prominent near the bottom, in contrast to the downwind flow directly forced by the wind. If the wind blows steadily for several days a steady state flow field could ultimately be reached in which the direct wind-driven downwind flow near the surface is balanced by pressure driven upwind flow near the bottom. We note that to produce upwind flow near the bottom, the surface tilt must apparently achieve nearly ninety percent of its ultimate steady state value, i.e., the wind must persist in the same direction for several days.

In Figures 22 - 25, the time series of conductivity, used as a surrogate for salinity, is plotted against the time history of the windstress vector for the period 12 April - 25 October, 1989 in Croatan Sound. What is clearly shown is effectively a one to one correlation between winds blowing towards the north and the appearance of high salinity water and winds blowing towards the south with fresh water. What is made clear is that higher salinity Pamlico Sound water only enters Croatan Sound on its way towards Albemarle Sound when winds are blowing from the south towards the north; winds which are not favorable for recruitment of ocean spawned finfish into Pamlico Sound. When winds are favorable for recruitment into the Pamlico, low salinity, i.e. fresh water is flowing from the Albemarle to the Pamlico as shown by events G-S in Figure 22, Events U-EE in Figure 23 and Events FF-XX in Figure 24.

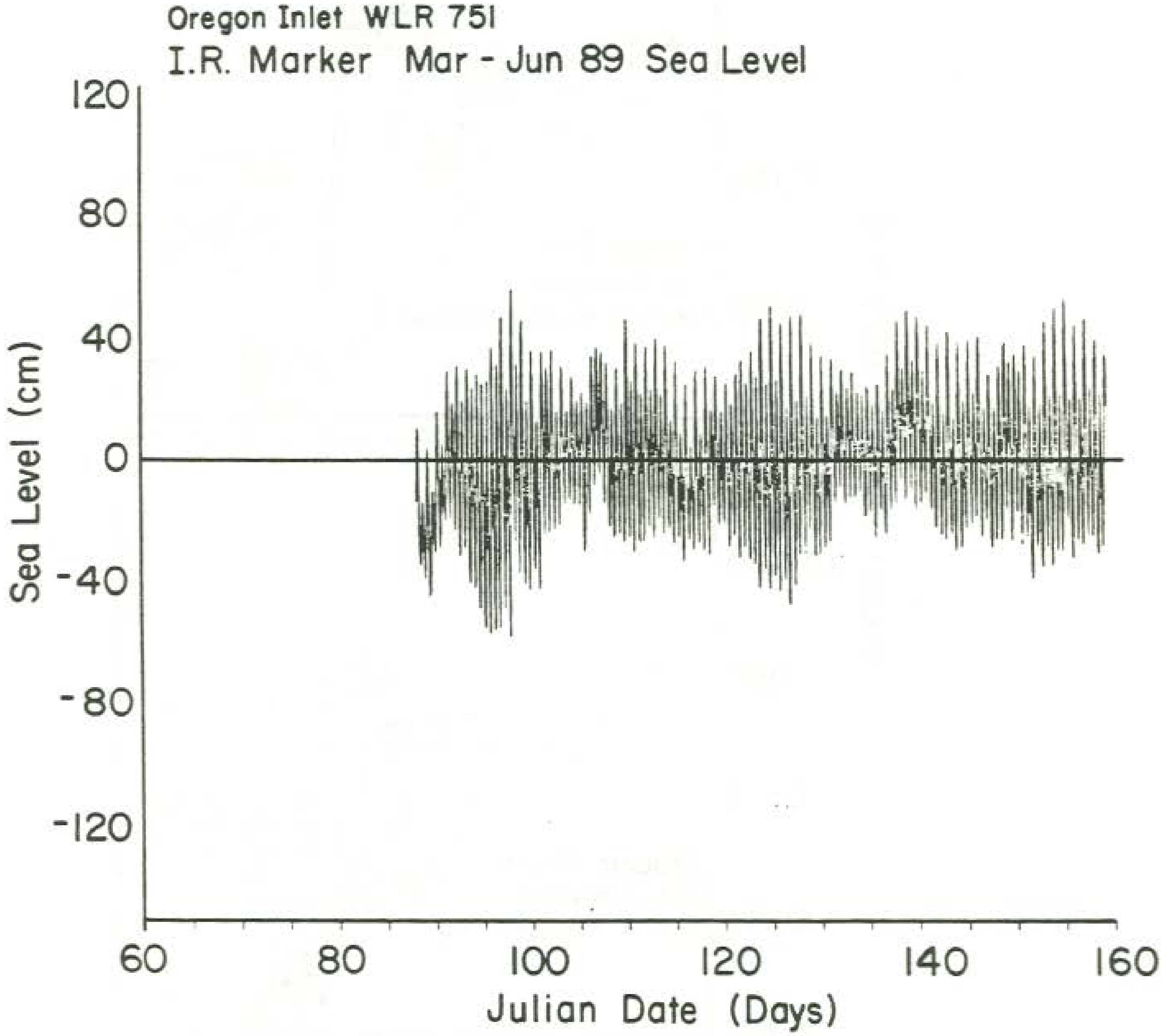

Figure 7. Water level at Oregon Inlet, Inner Range Marker, March - June, 1989.

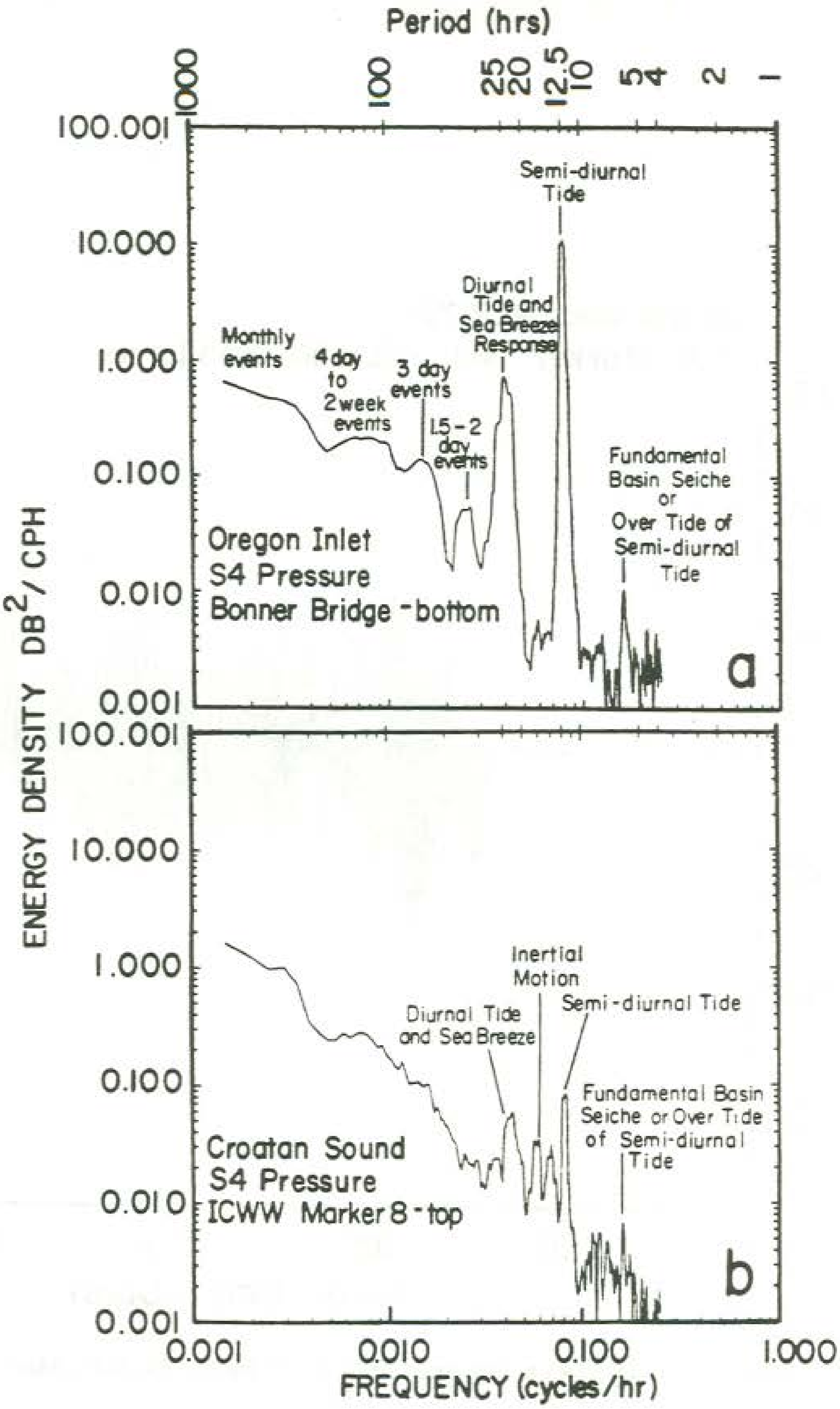

Figure 8 (a) Water level energy spectrum at Site 11, Bonner Bridge, Mar.-Jun., 1989. (b) Water level energy spectrum at Site 10, Croatan Sound, Mar.-Jun., 1989.

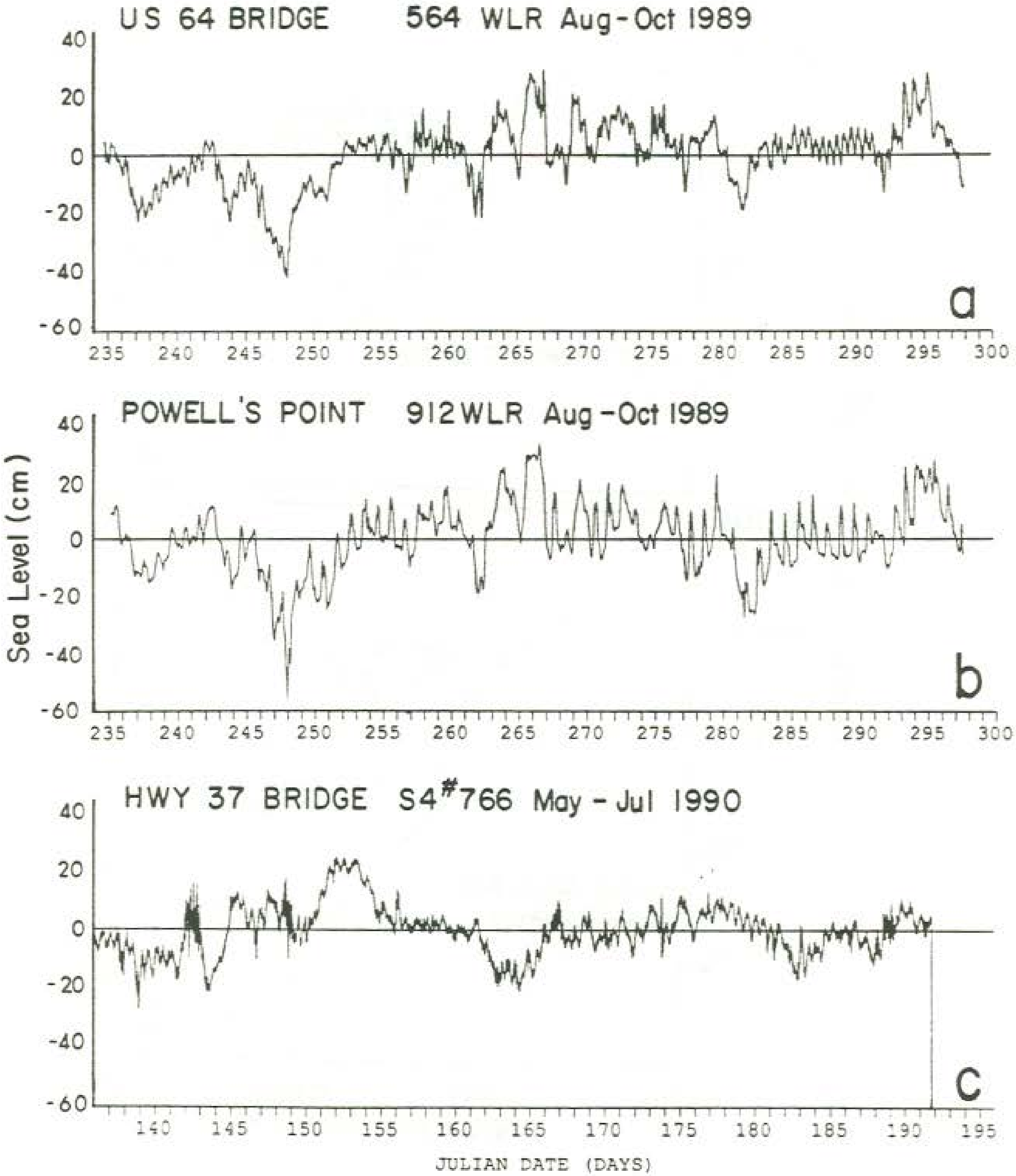

Figure 9. (a) Water level at Site 6, U.S. 64 Bridge, Aug.-Oct., 1989.
(b) Water level at Site 5, Powell's Point, Aug.-Oct., 1989.
(c) Water level in western Albemarle Sound, at Site 4, Highway 37 Bridge, May-July, 1990.

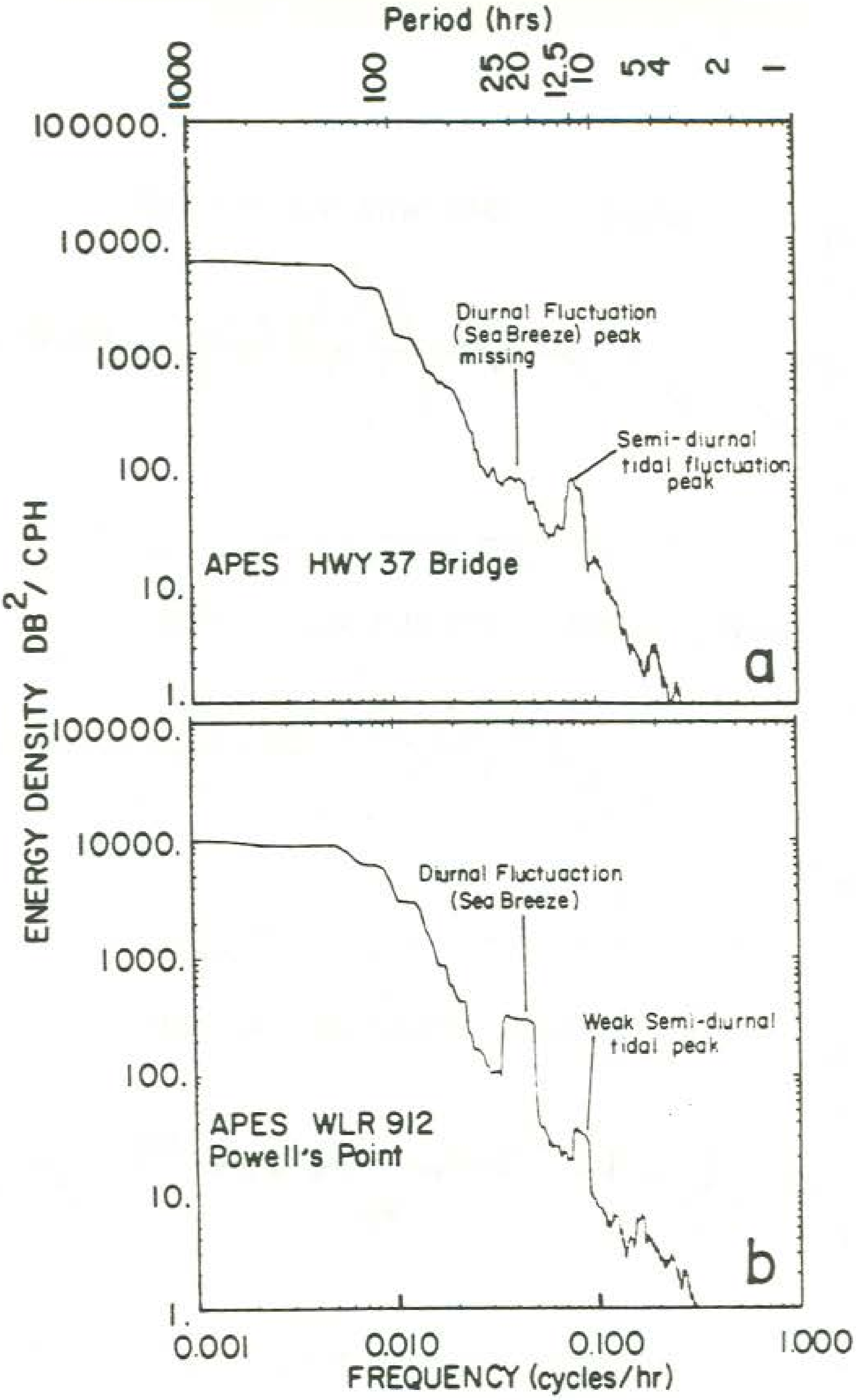

Figure 10. Energy density of water level fluctuations as a function of period/frequency at (a) Site 4 and (b) Site 5 for May-July, 1990.

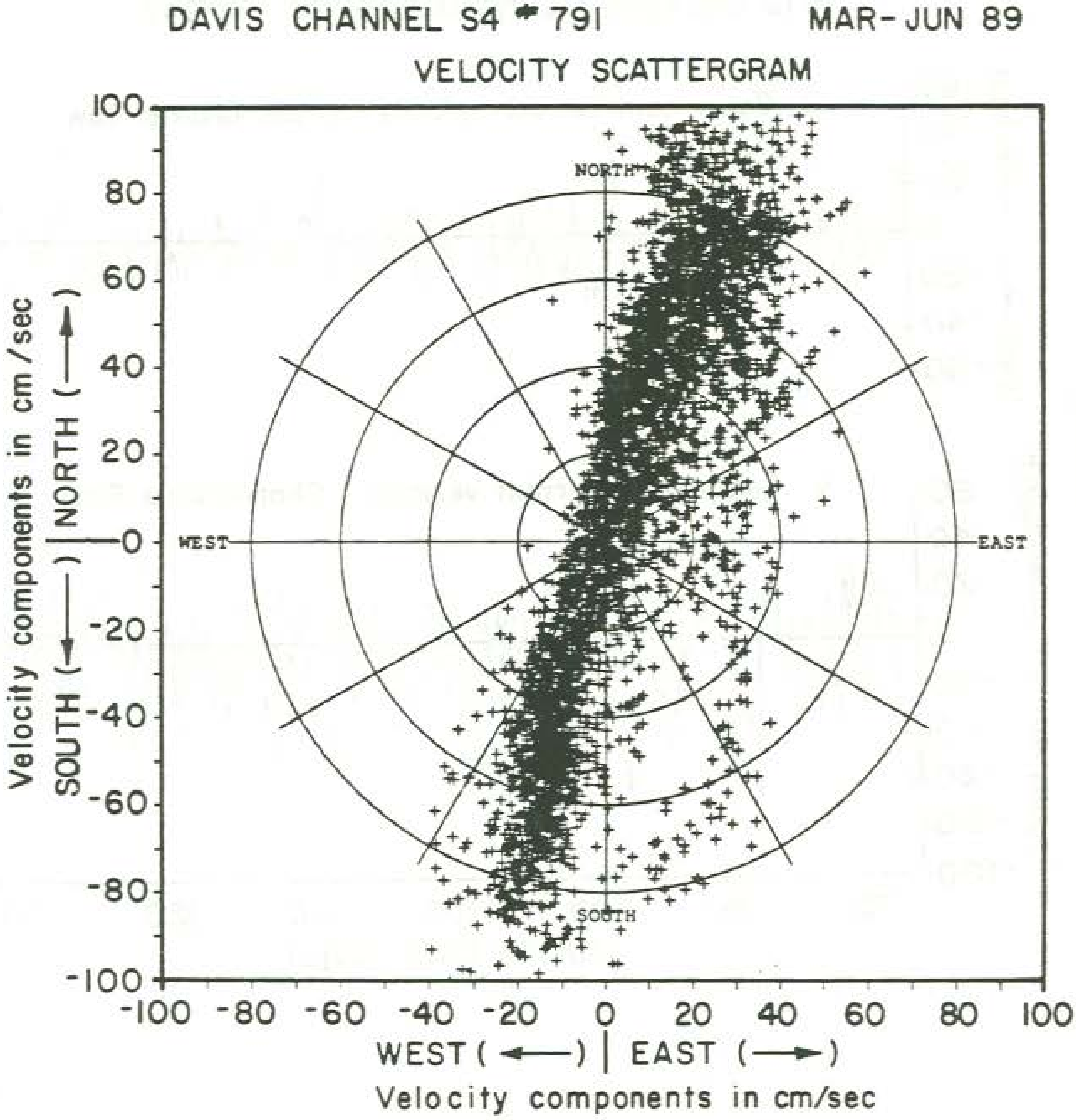

Figure 11. Scatter plot of currents at Oregon Inlet Top Site.

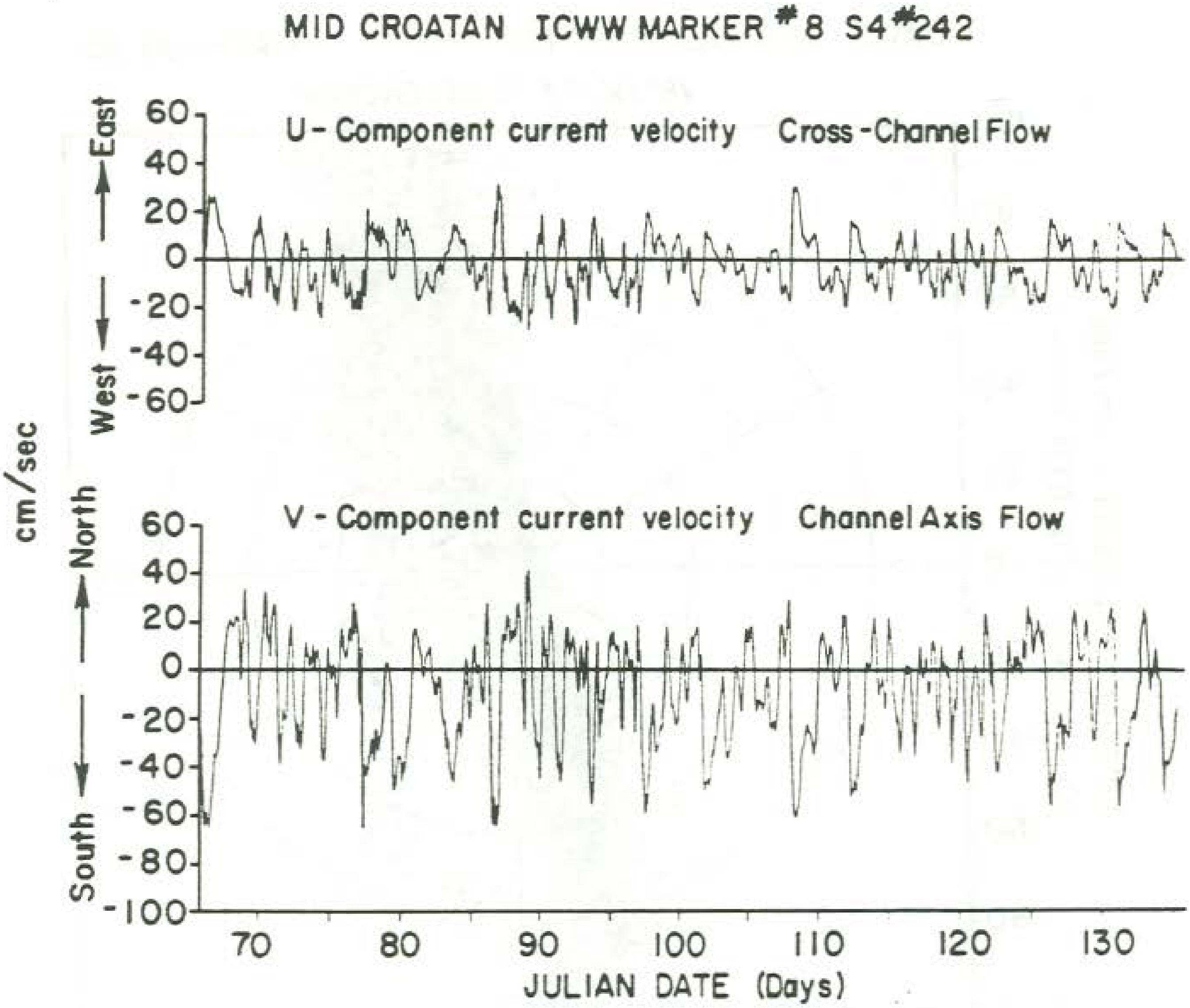

Figure 12. Velocity at Site 10, (ICWW Marker #8), March-May, 1990.

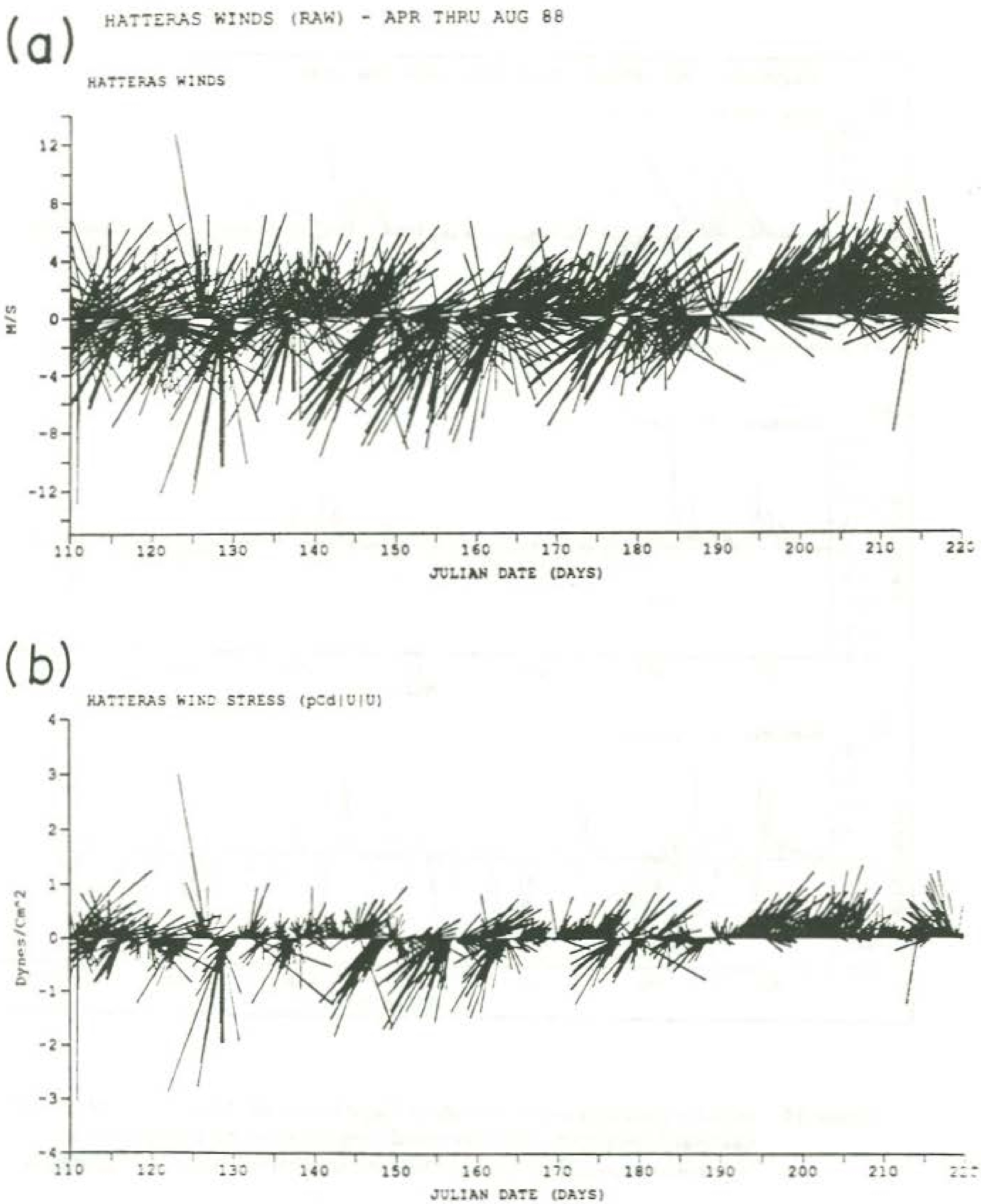

Figure 13. (a) Raw hourly wind vectors and (b) raw hourly wind stresses at Cape Hatteras, NWS Station; April-August, 1988.

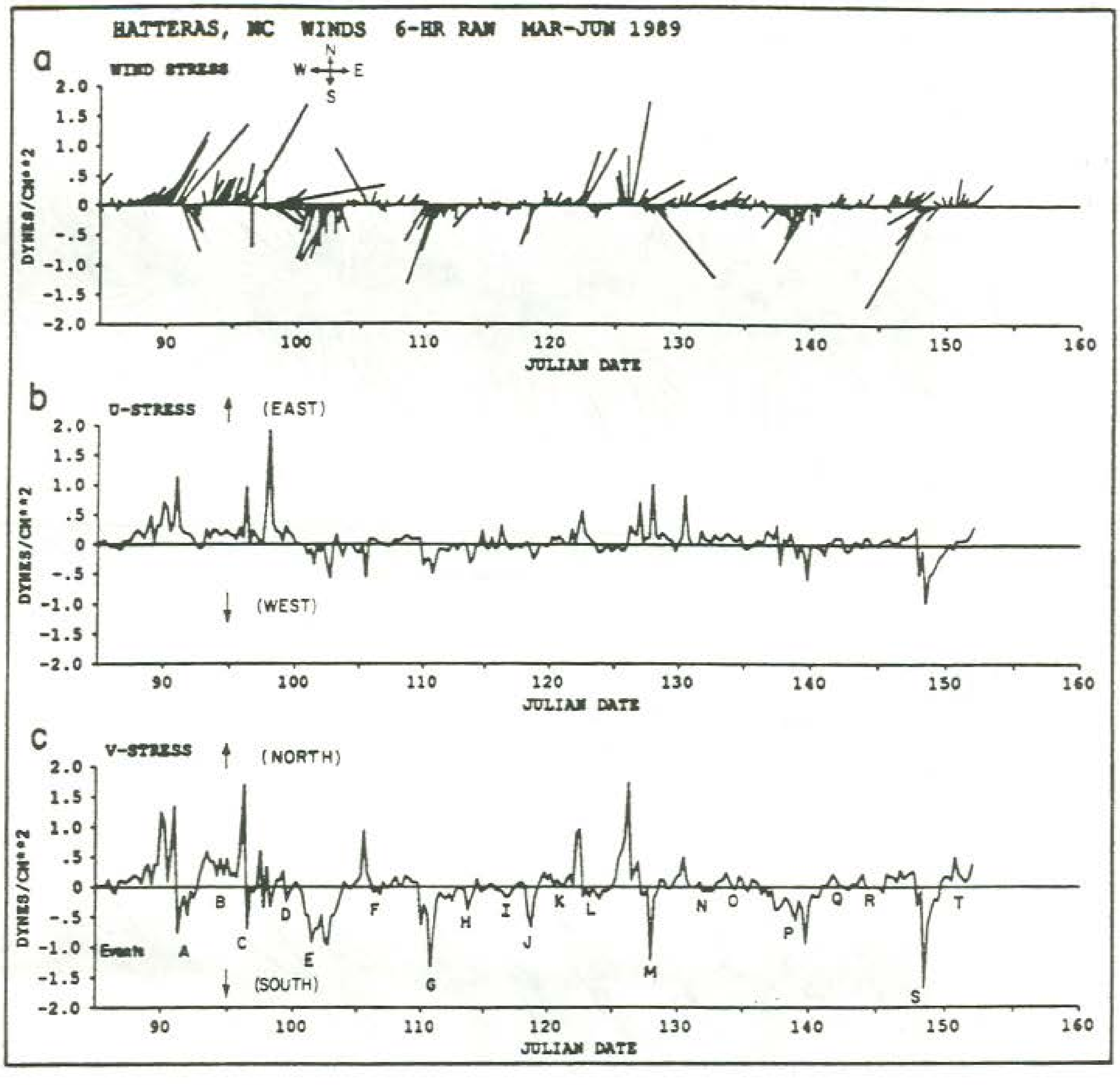

Figure 14. (a) Raw 3-hourly wind vectors at Cape Hatteras, Mar.-June, 1989. (b) Eastward (positive) and westward (negative) wind components. (c) Northward (positive) and southward (negative) wind components.

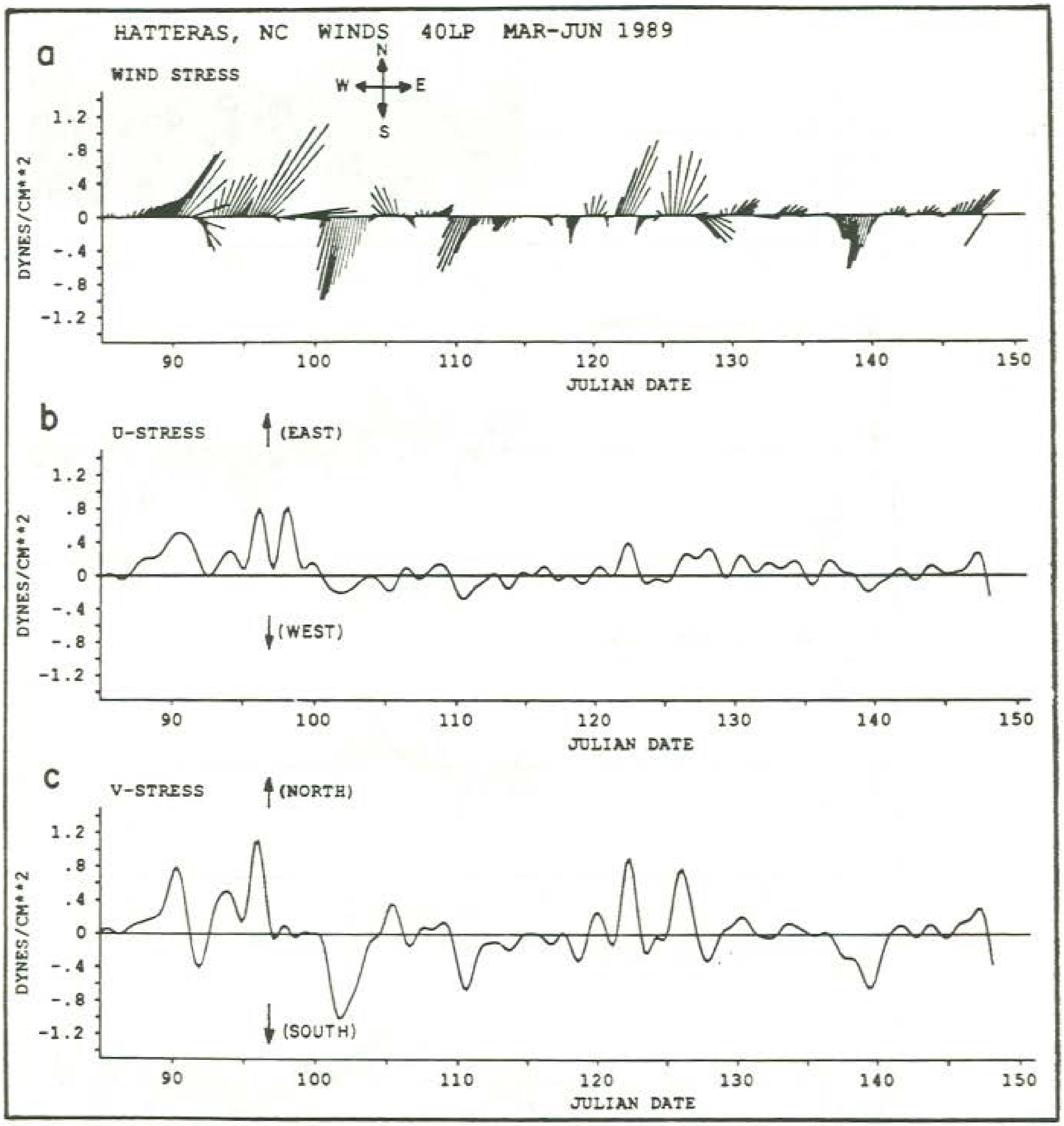

Figure 15. (a) 40-hrlp filtered wind vectors at Cape Hatteras, Mar.-Jun., 1989.
(b) 40-hrlp filtered eastward (positive) and westward (negative) wind components.
(c) 40-hrlp filtered northward (positive) and westward (negative) wind components.

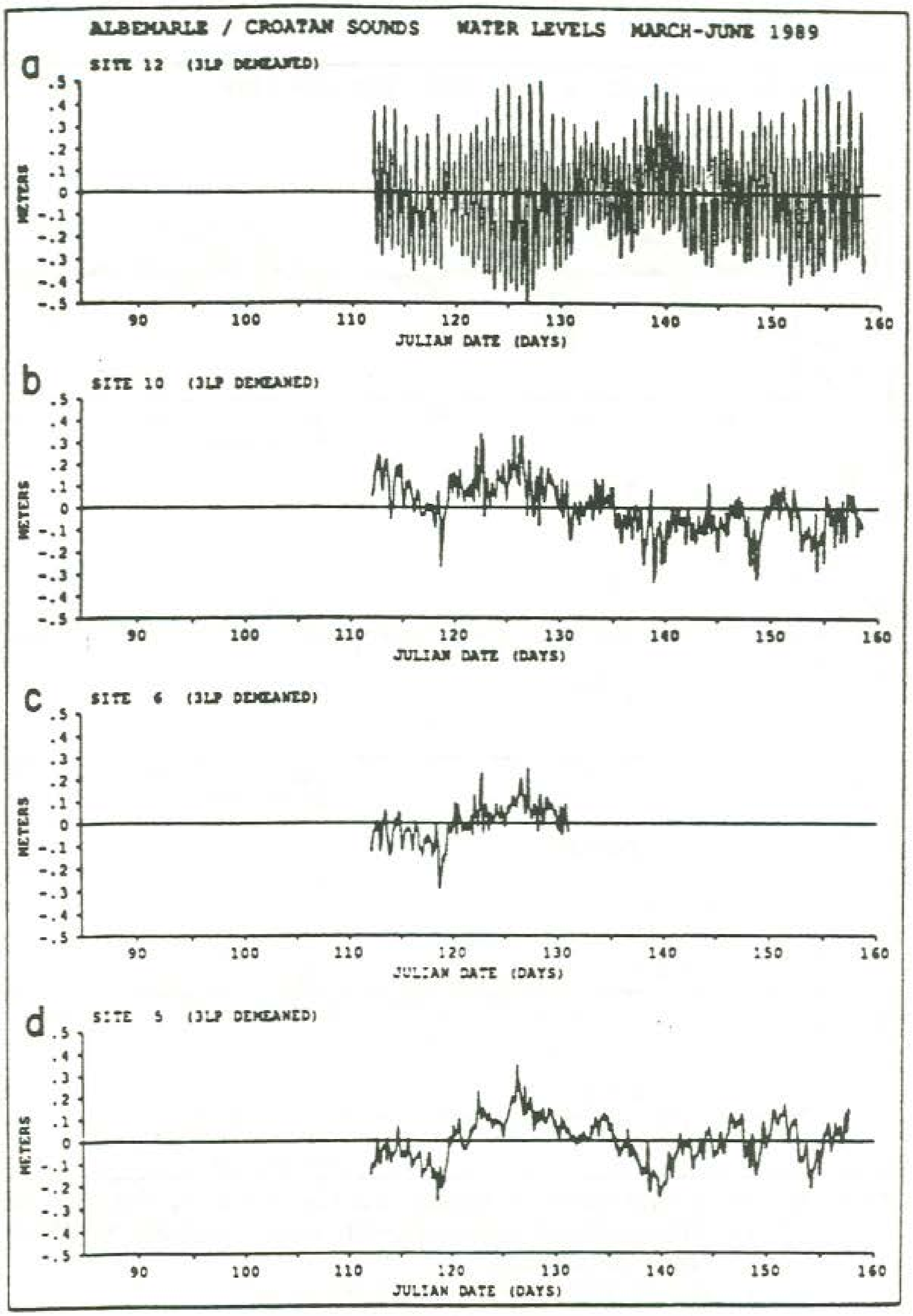

Figure 16. Water level fluctuation time series, sampled every 10 minutes during March-June, 1989 at sites shown in Figure 4.

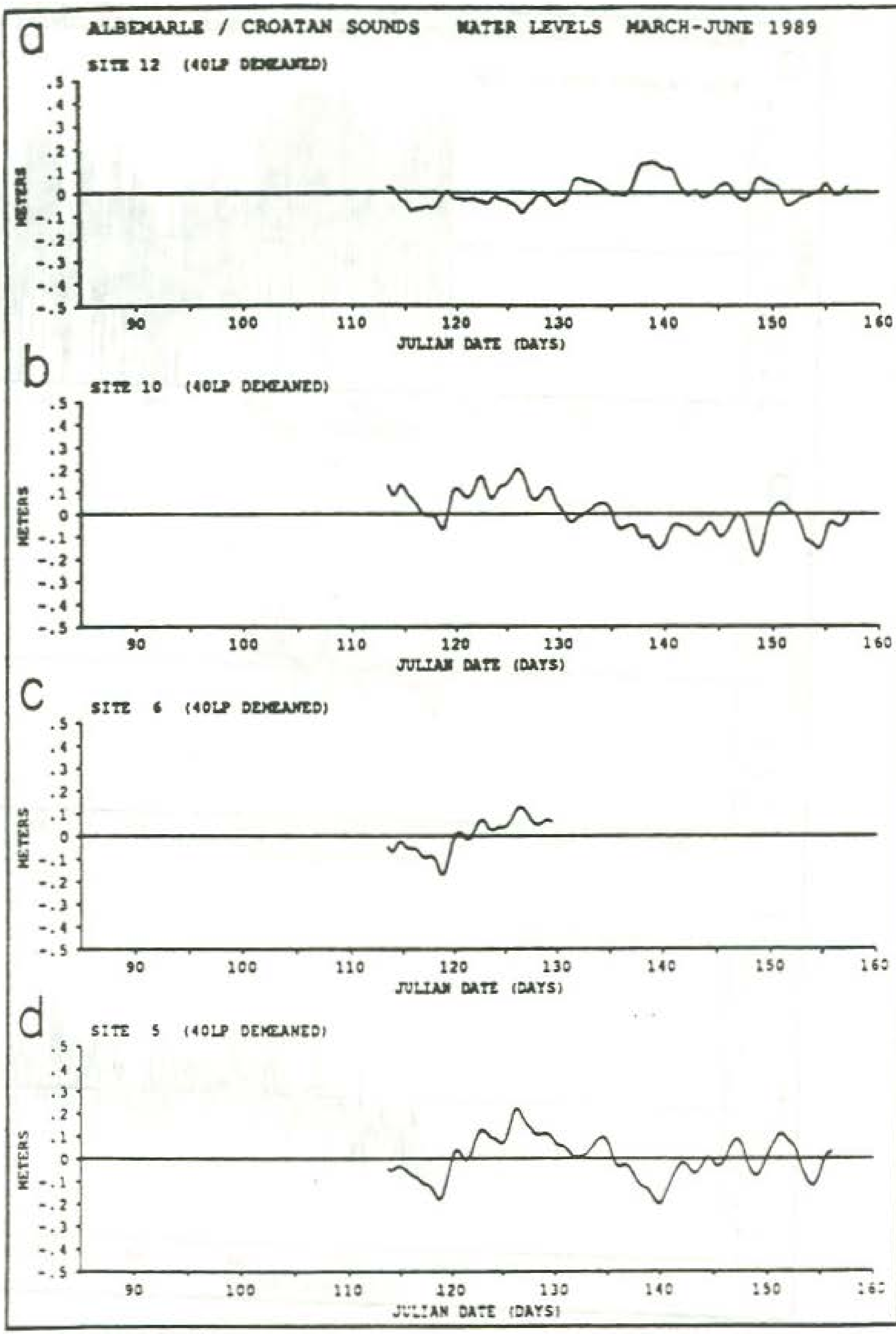

Figure 17. 40-hrlp filtered water level fluctuation time series, sampled every 10 minutes during March-June, 1989 at sites shown in Figure 4: (a) Highway 37 Bridge (West Albemarle) (b) ICWW Marker 8 (Mid Croatan (c) Highway 64 Bridge (North Croatan) (d) Powell's Point (East Albemarle).

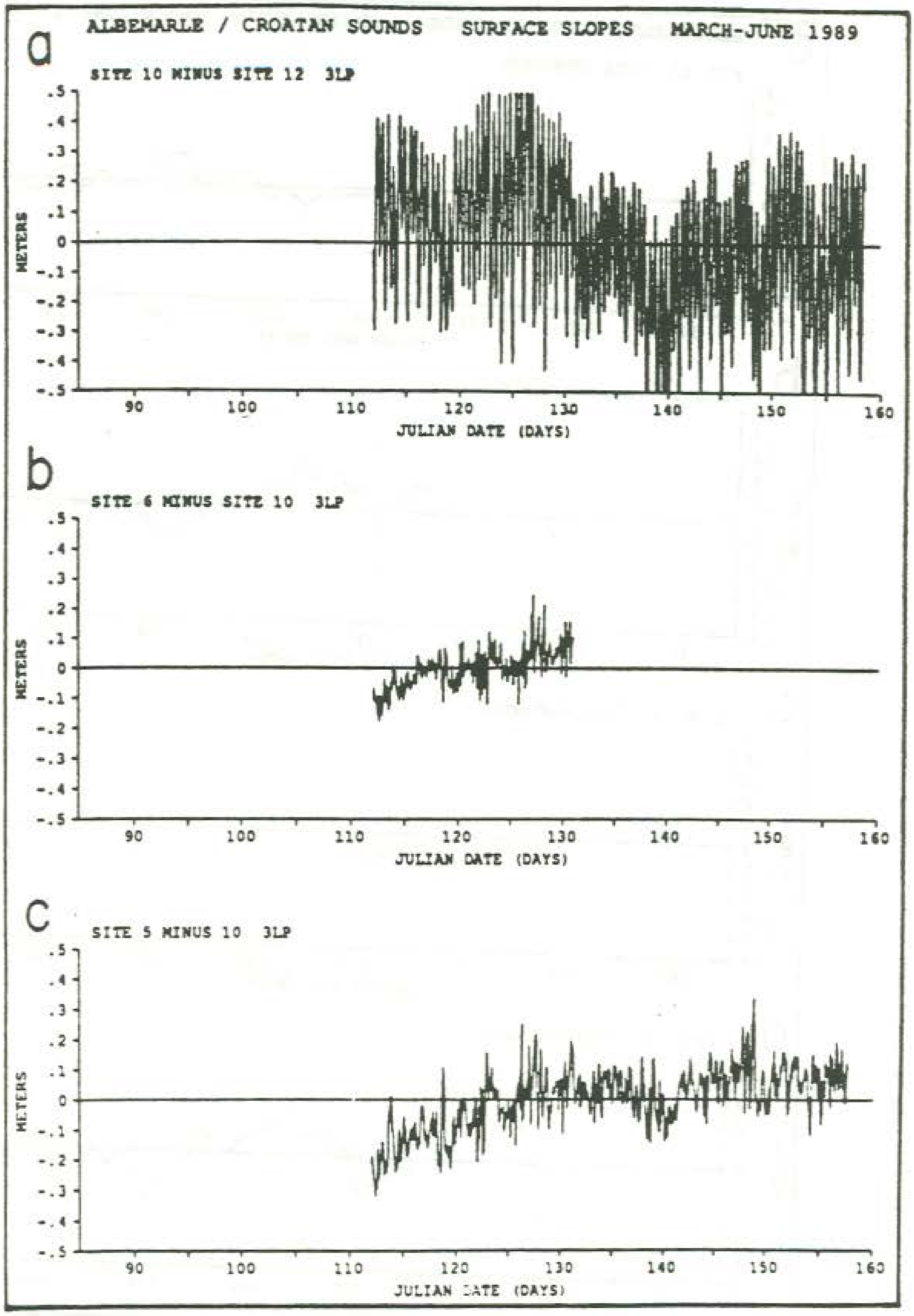

Figure 18. Time series of water level slope computed by differencing (raw) data between stations, as shown in Figure 4, for period March-June, 1989. See Figure 17 for individual time series. (a) Mid Croatan minus W. Albemarle (b) N. Croatan minus Mid Croatan (c) E. Croatan minus Mid Croatan.

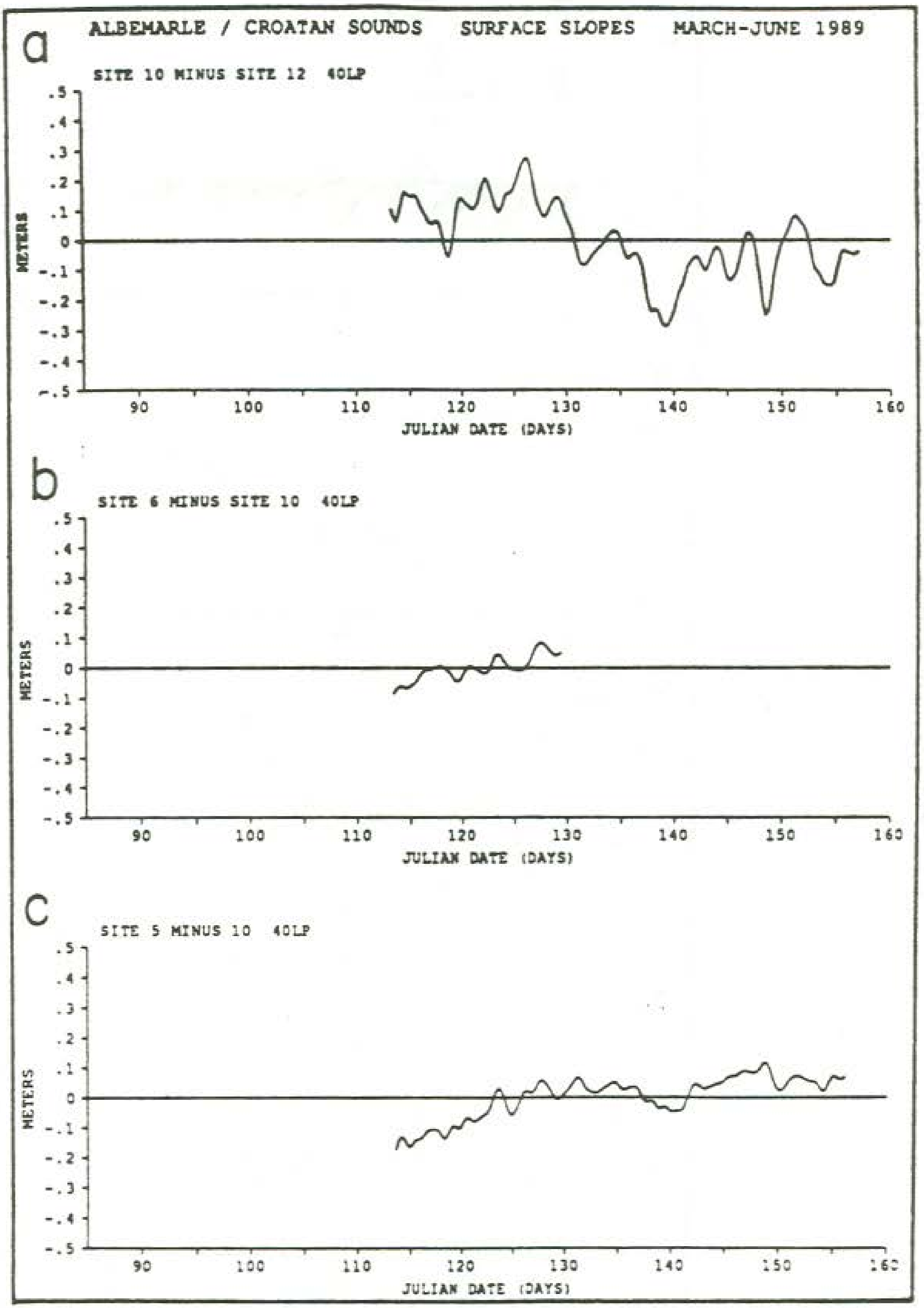

Figure 19. 40-hrlp filtered time series of water level slope computed by differencing data between stations, as shown in Figure 4, for period March-June, 1989. See Figure 17 for individual time series. (a) Mid Croatan minus W. Albemarle (b) N. Croatan minus Mid Croatan (c) E. Croatan minus Mid Croatan.

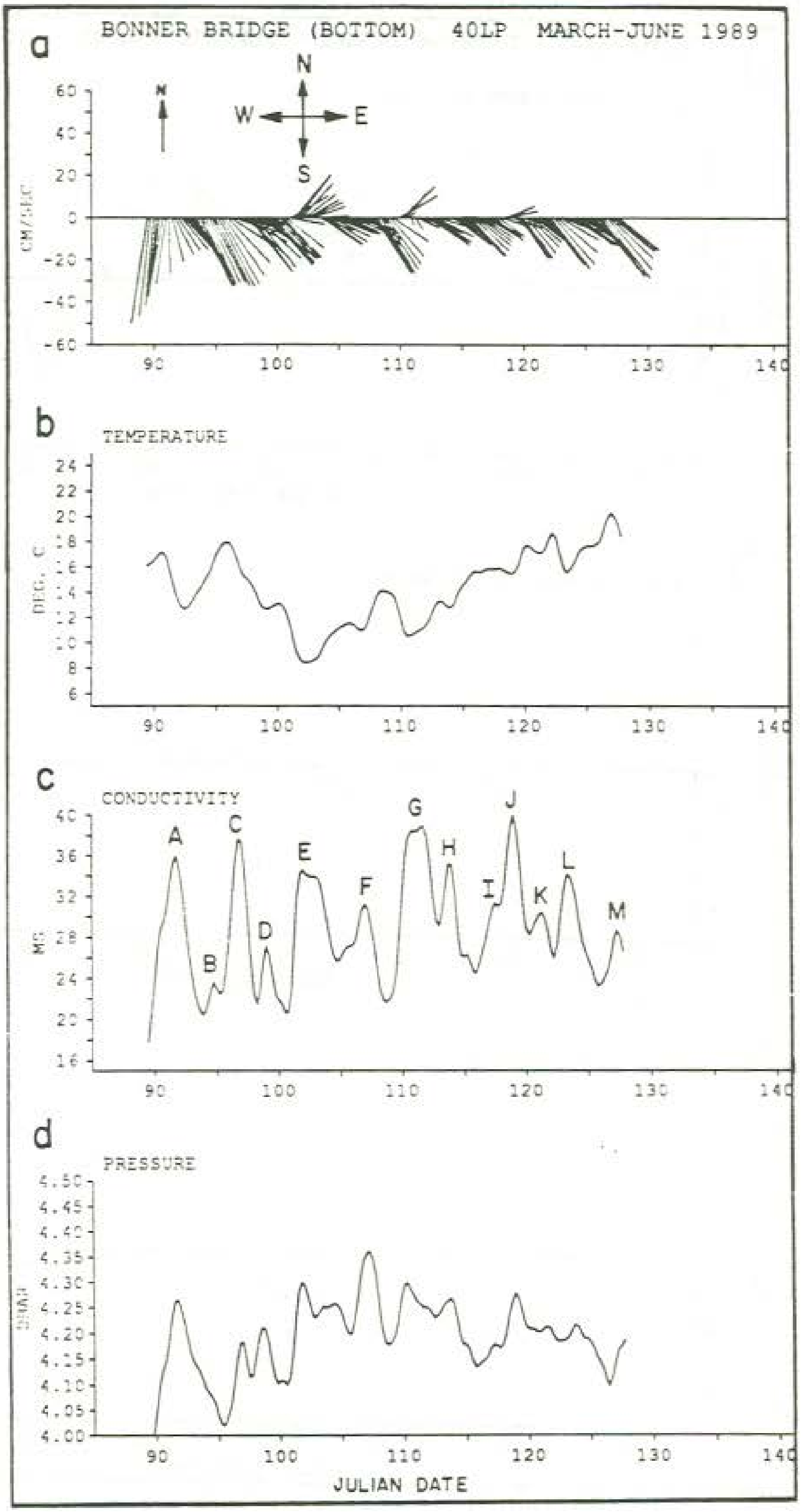

Figure 20. 40-hrlp filtered time series of (a) current vectors (b) temperature, (c) conductivity and (d) water level at Site 12 during March-June,1989.

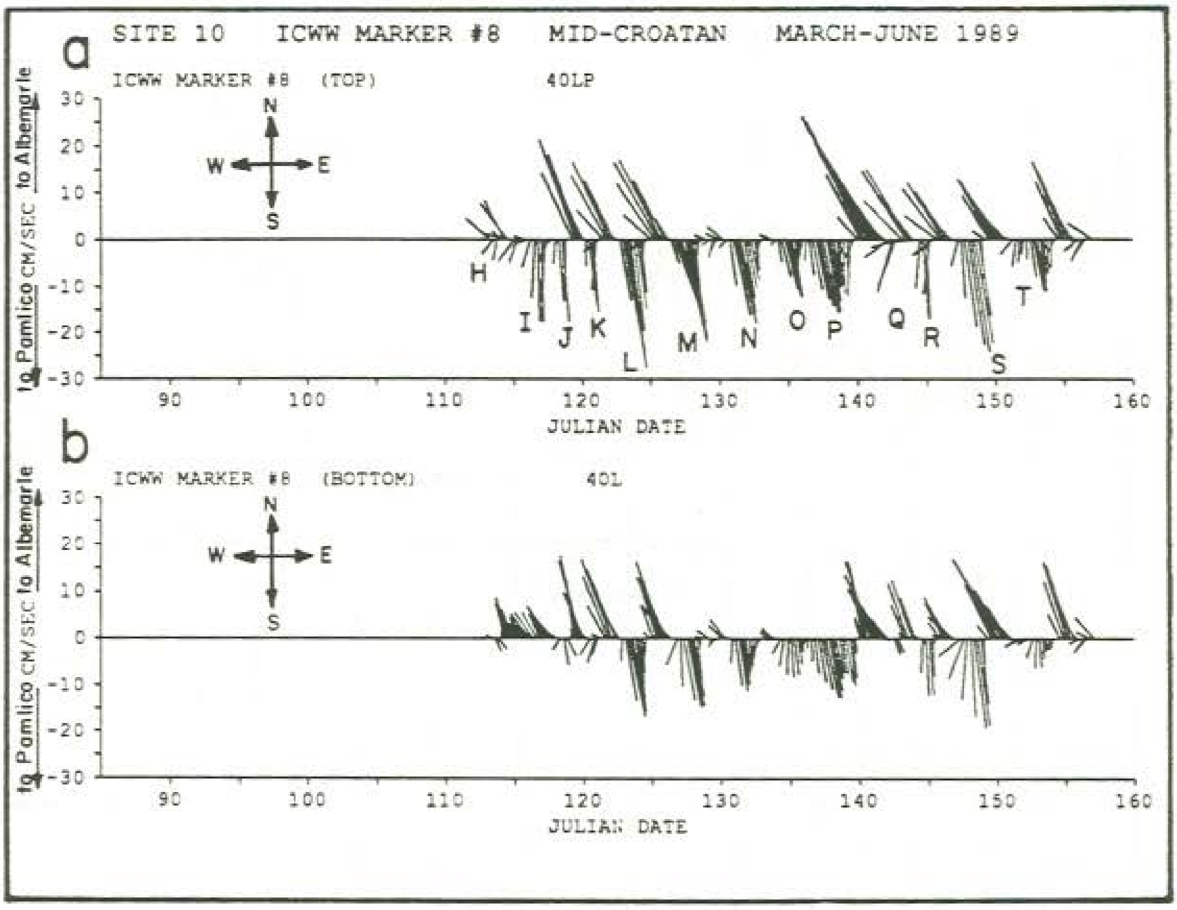

Figure 21. **40-hrlp filtered time series of current vectors at Station 10, in Croatan Sound. (cf. Figures 4 and 5 for station location).**
(a) 1 meter below the surface
(b) 1 meter above the bottom, during March-June, 1989.

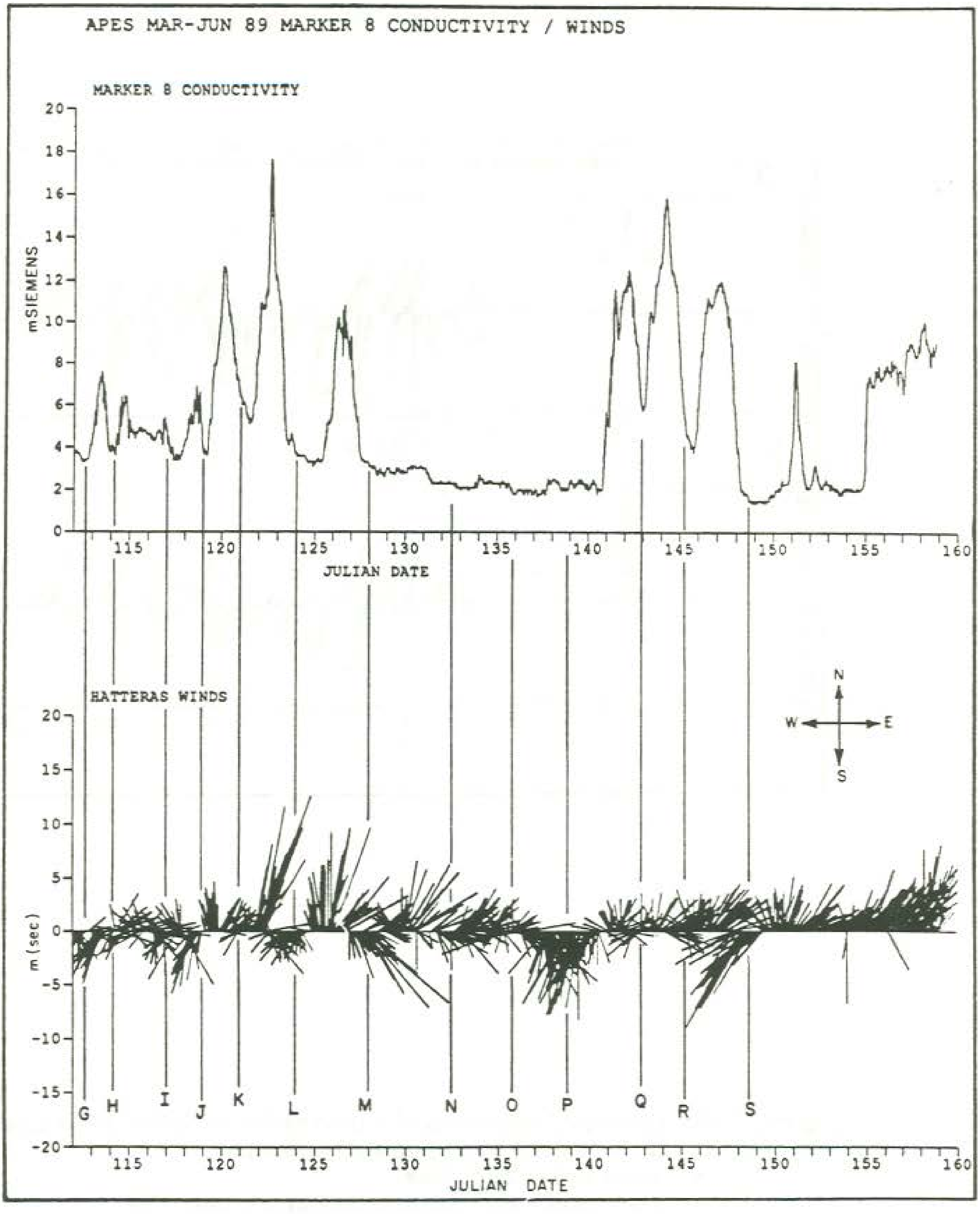

Figure 22. Events showing relation of appearance of low salinity water at Station 10 in Croatan Sound during southward wind events, period Mar-Jun, 1989. (cf. Figures 4 and 5 for station location).

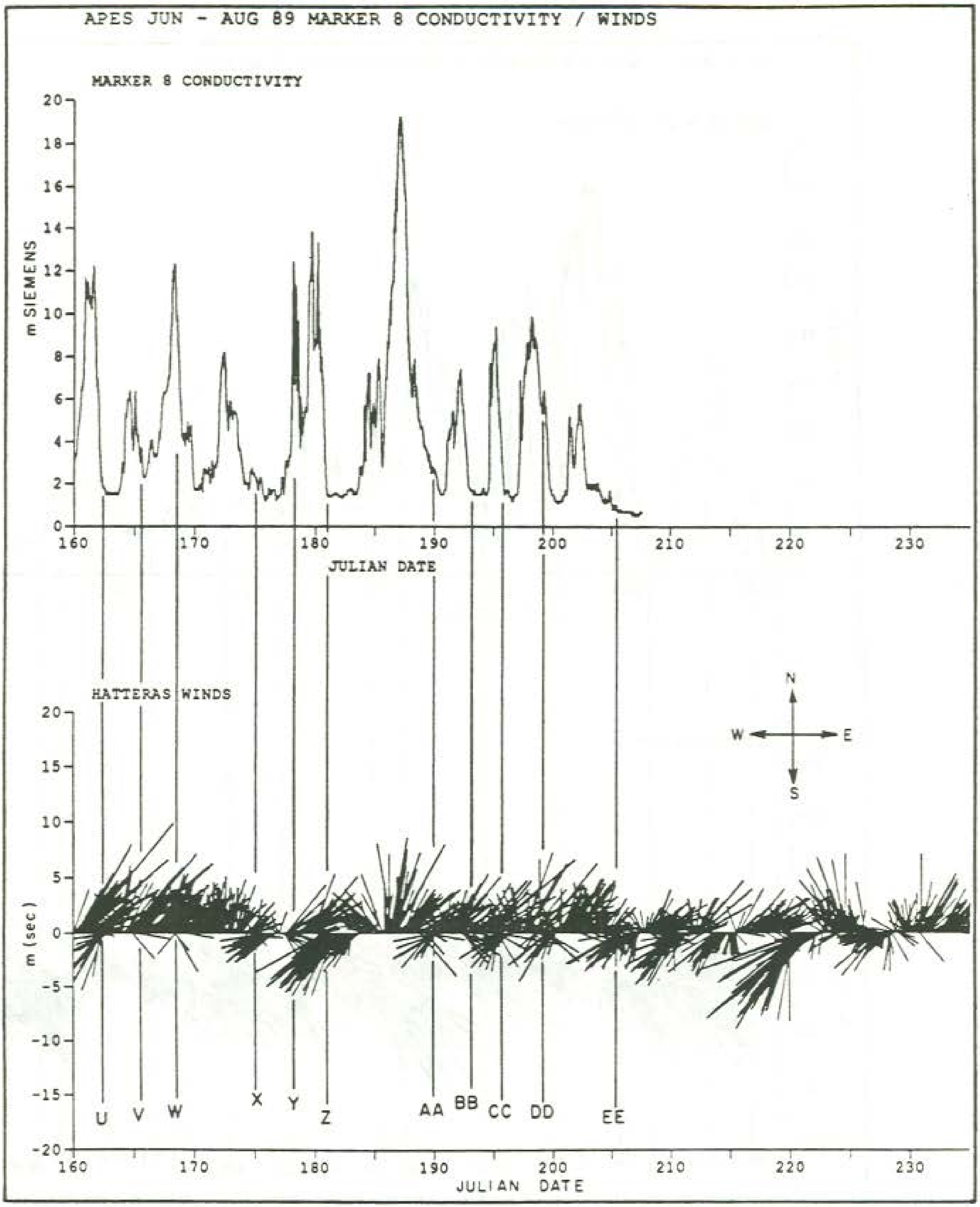

Figure 23. Events showing relation of appearance of low salinity water at Station 10 in Croatan Sound during southward wind events, period Jun-Aug., 1989. (cf. Figures 4 and 5 for station location).

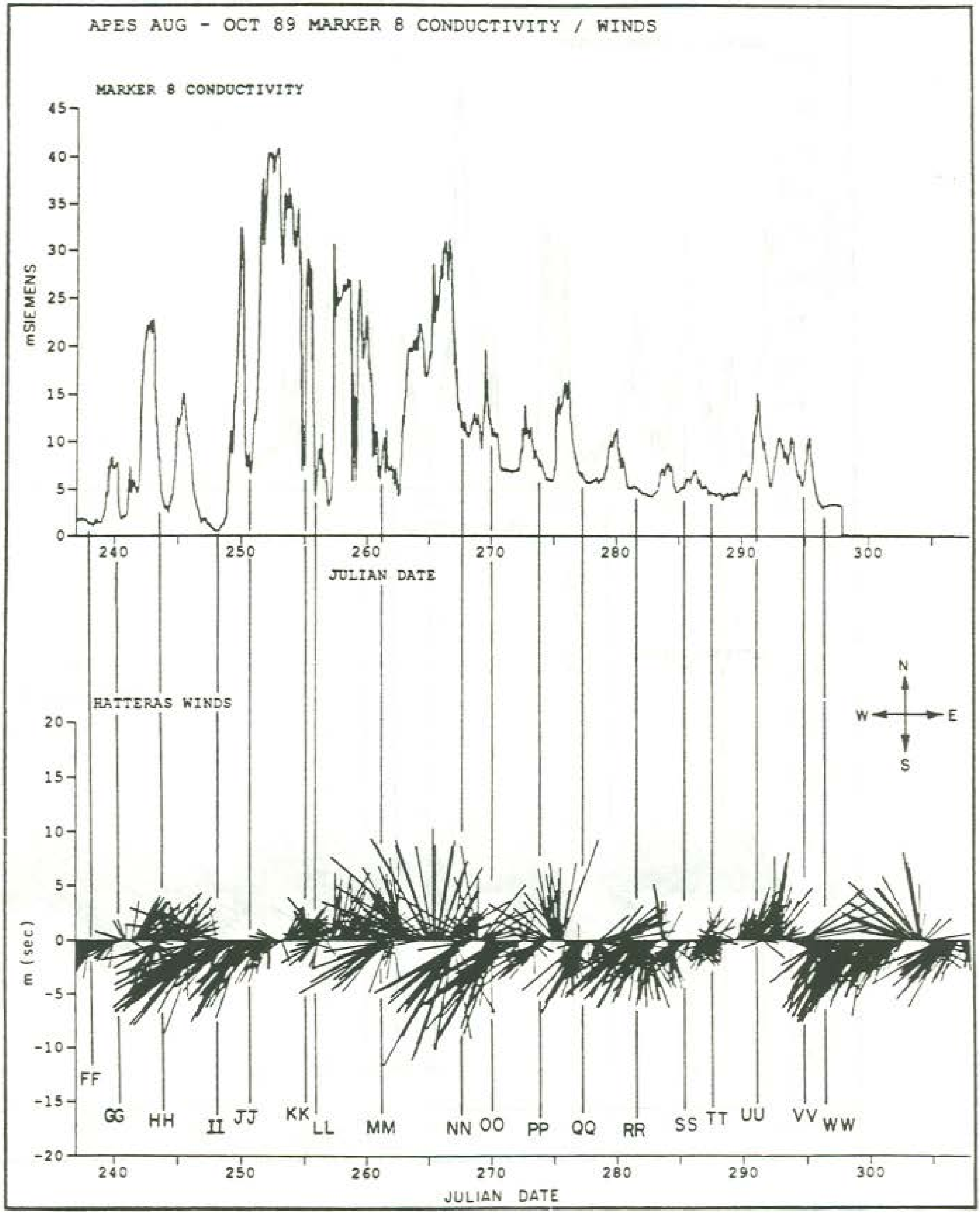

Figure 24. Events showing relation of appearance of low salinity water at Station 10 Croatan Sound during southward wind events, period Aug-Oct, 1989. (cf. Figures 4 and 5 for Station location).

5. STATISTICAL DATA ANALYSIS

To further elucidate and quantify the data analysis, cospectra were obtained using the standard techniques outlined in Bendant and Piersol (1971). We first consider the coherence of the north-south component of the currents in Croatan Sound with the north-south component of the Hatteras wind. Figure 25a and b give the cospectra for the US 64 bridge site during two deployments and 25c and 25d show the cospectra for ICWW Marker 8. As expected the coherence is quite high for periods exceeding one day at both sites for all periods and the phase shift is small. The transfer amplitude at subinertial or low frequencies suggests that about 3 cm/sec current is produced for each 1 m/sec of wind speed. In contrast the coherence of the velocity with the eastwards wind component (not shown) is less than 0.25.

The pressure gradient in Croatan Sound is quite coherent with the wind and currents as is shown in Figure 26. The difference in water level between Powell's Point and Marker 8 vs the north-sound wind component is given in Figure 26a and vs the north-south current in Croatan is provided in Figure 26b. Water level difference between the US 64 bridge and Marker 8 vs the north-south component of the wind is given in 26c and vs the east-west component of the wind in Figure 26d. The water slope leads the wind by 90° at low frequencies. We note from transfer function amplitudes that the north-south component of the wind is twice as effective as the east-west component in setting up the water slope in Croatan Sound. Figure 27 indicates that at lower frequencies the water levels at various locations are highly coherent with each other during all deployments. Figure 28 gives the cospectra of the east-west slope in water level in Albemarle Sound versus the east-west wind component (Figure 28a) and north-south wind component (Figure 28b). As the axis of Albemarle Sound runs east-west the east west slope in water level is considerably more coherent with the east west wind than with the north-south wind.

The above results indicate that fluctuations in water level, water level slopes and currents are consistent with our initial expectations that the system is wind-driven and that southwards winds produce southwards currents in Croatan Sound. Examples of these frequency domain results are presented in the time domain plots shown in Figures 29 and 30.

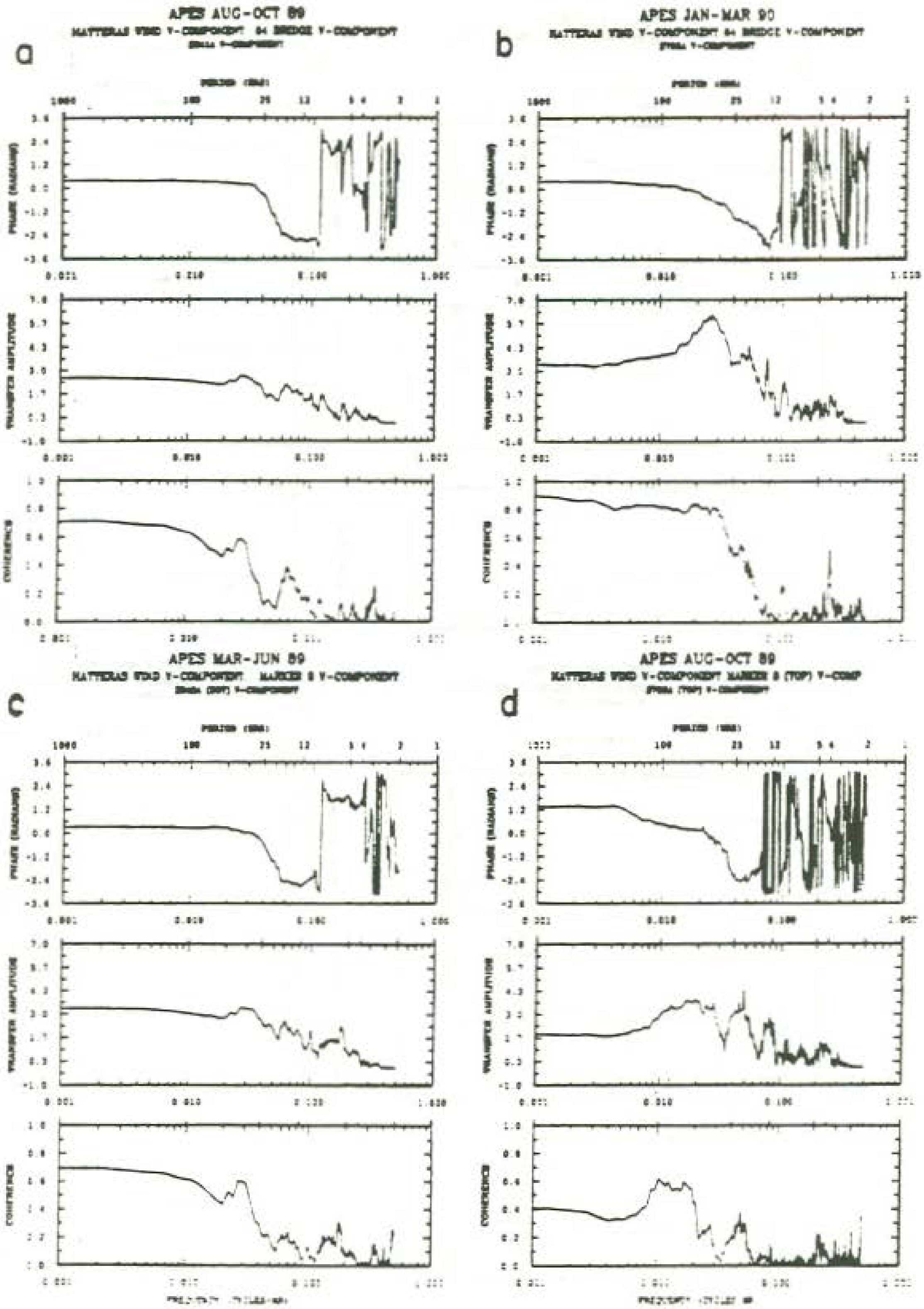

Figure 25. (a) Cross-spectra of north/south currents in upper Croatan Sound with the north/south wind component, during Aug-Oct, 1989. (b) Cross-spectra of north/south currents in upper Croatan Sound with the north/south wind component, during Jan-Mar, 1990. (c) Cross-spectra of north/south currents in Mid Croatan Sound with the north/south wind component during Mar-Jun, 1989. (d) Cross-spectra of north/south currents in Mid Croatan Sound with the north/south wind component during Aug-Oct, 1989.

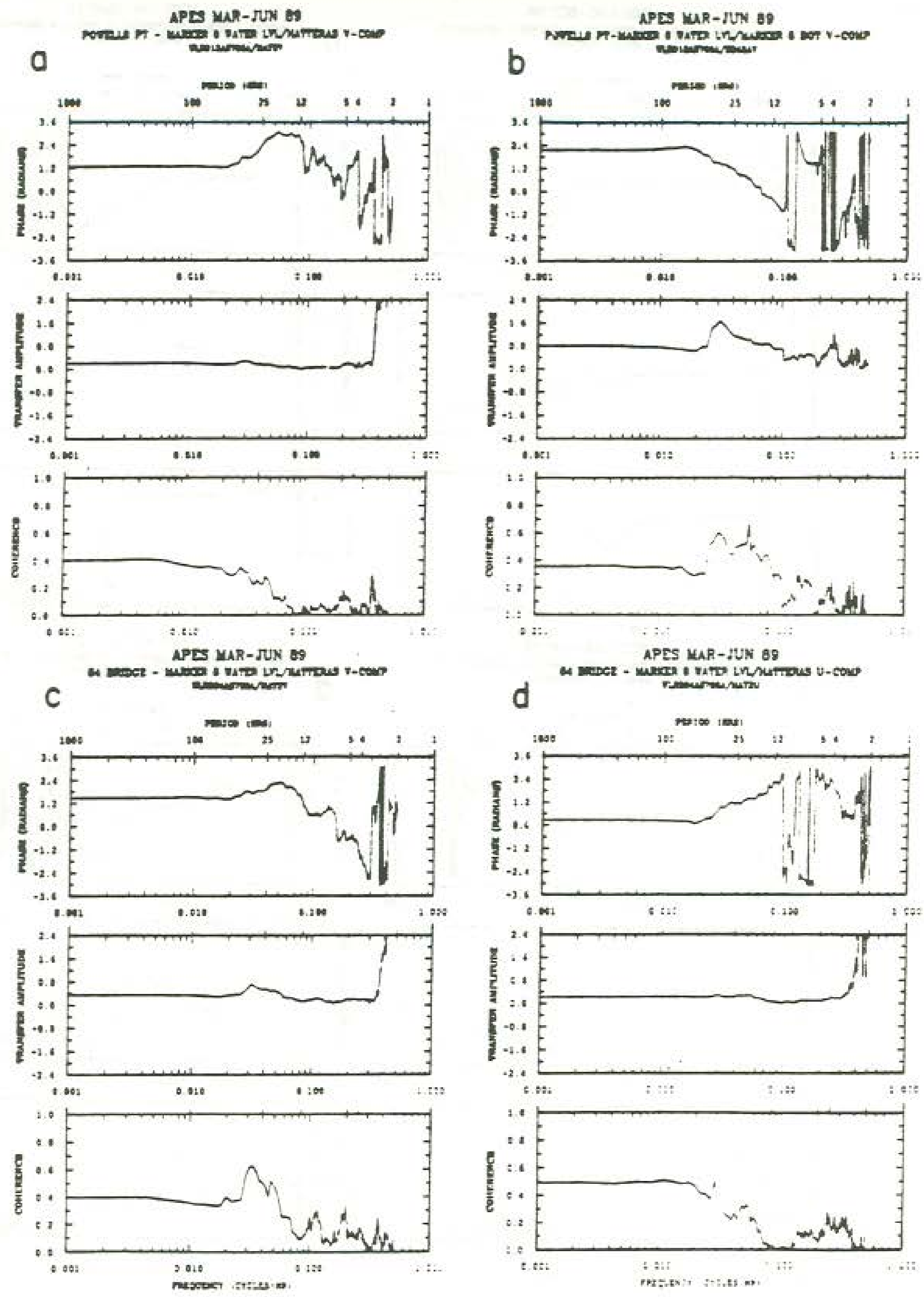

Figure 26. Cross-spectra of north/south water level slope versus winds (a,c,d) and current (b) in Mid Croatan Sound. (a) North Albemarle minus south Croatan vs north/south wind, Mar-Jun, 1989. (b) North Albemarle minus South Croatan vs north/south currents during Mar-Jun, 1989. (c) North Croatan minus South Croatan vs north/south winds during Mar-Jun, 1989. (d) North Croatan minus South Croatan vs east/west winds during Mar-Jun, 1989.

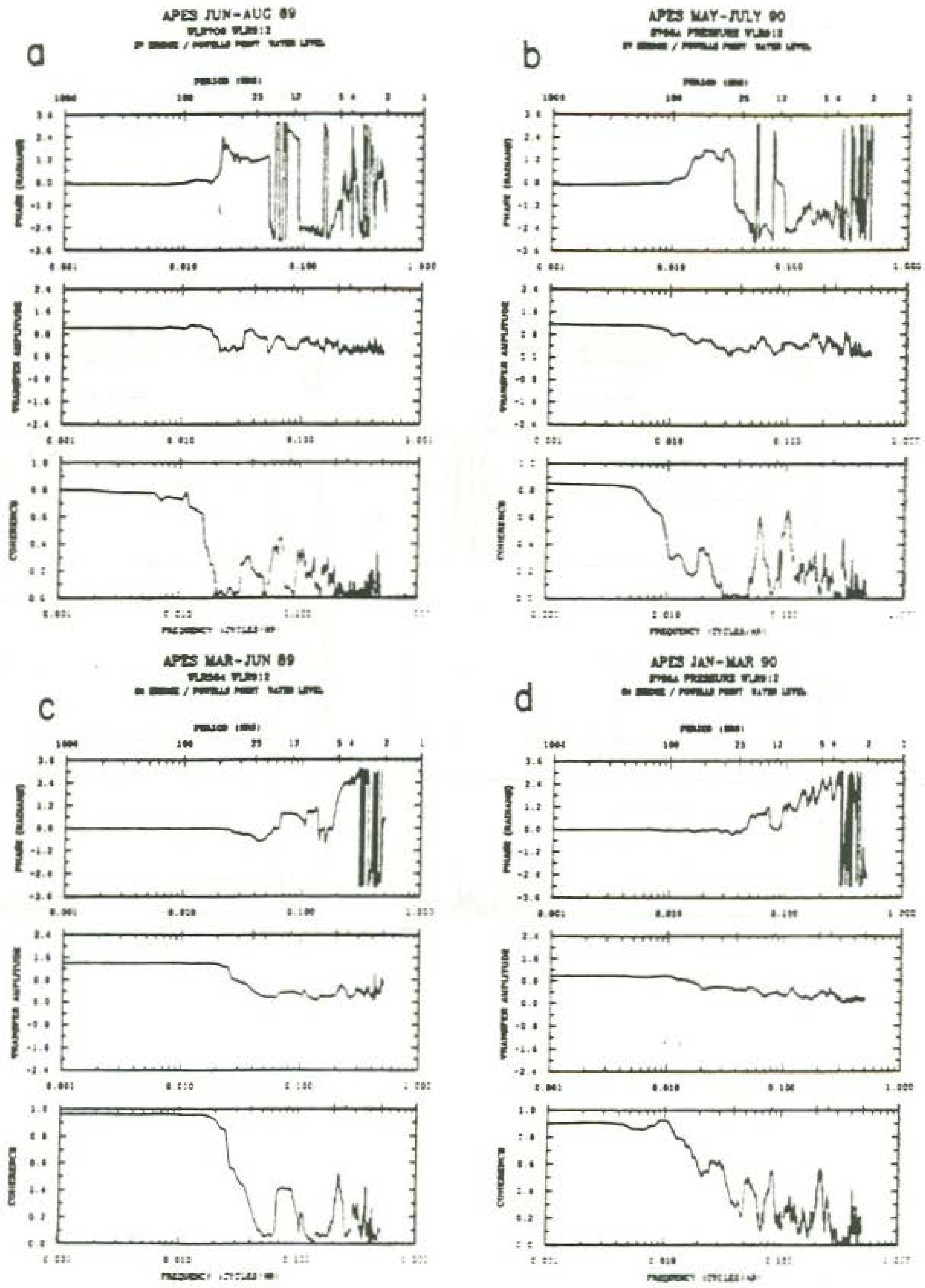

Figure 27. (a) Cross-spectra of west vs east water levels in Albemarle Sound during Jun-Aug, 1989. (b) Cross-spectra of west vs east water levels in Albemarle Sound during May-Jul, 1990. (c) Cross-spectra of South Albemarle vs Powell's Point water level during Mar-Jun, 1989. (d) Cross-spectra of south Albemarle vs Powell's Point water level during Jan-Mar, 1990.

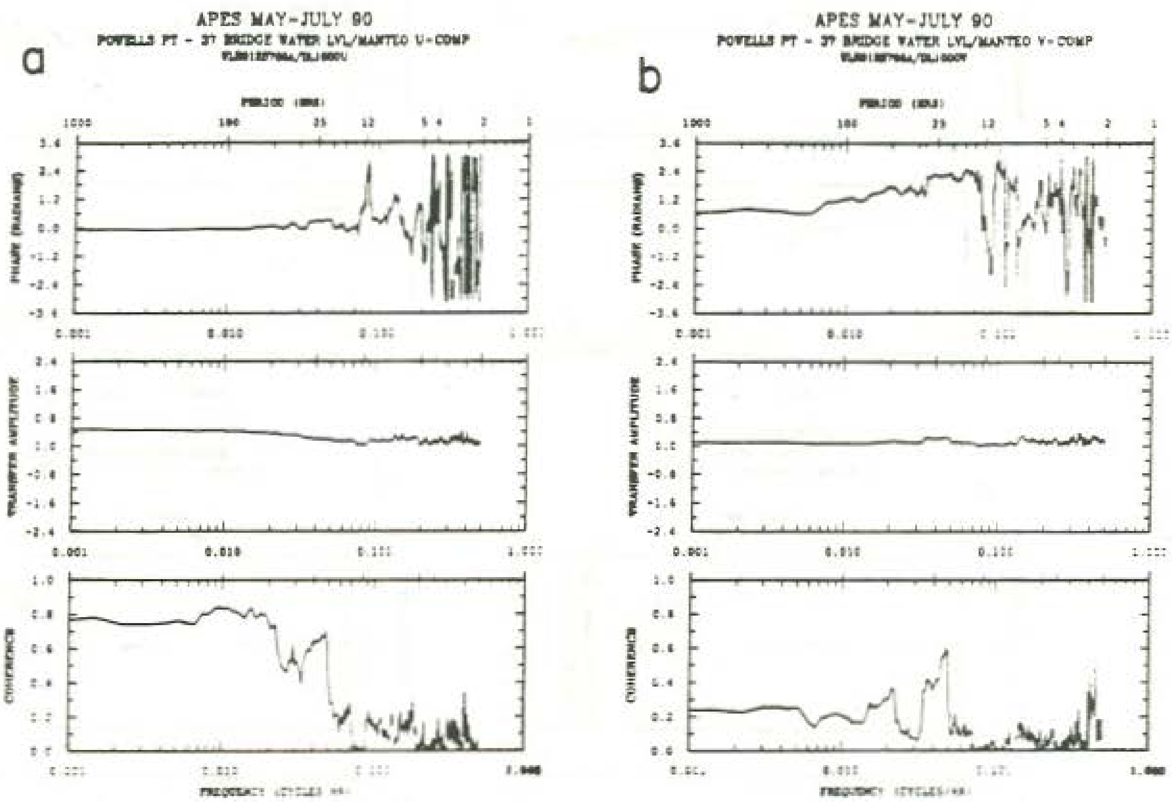

Figure 28. (a) Cross-spectra of east/west water level slopes in Albemarle Sound versus the east/west wind at Manteo. (b) Cross-spectra of north/south water level slopes in Albemarle Sound versus the north/south wind at Manteo, May - July, 1990.

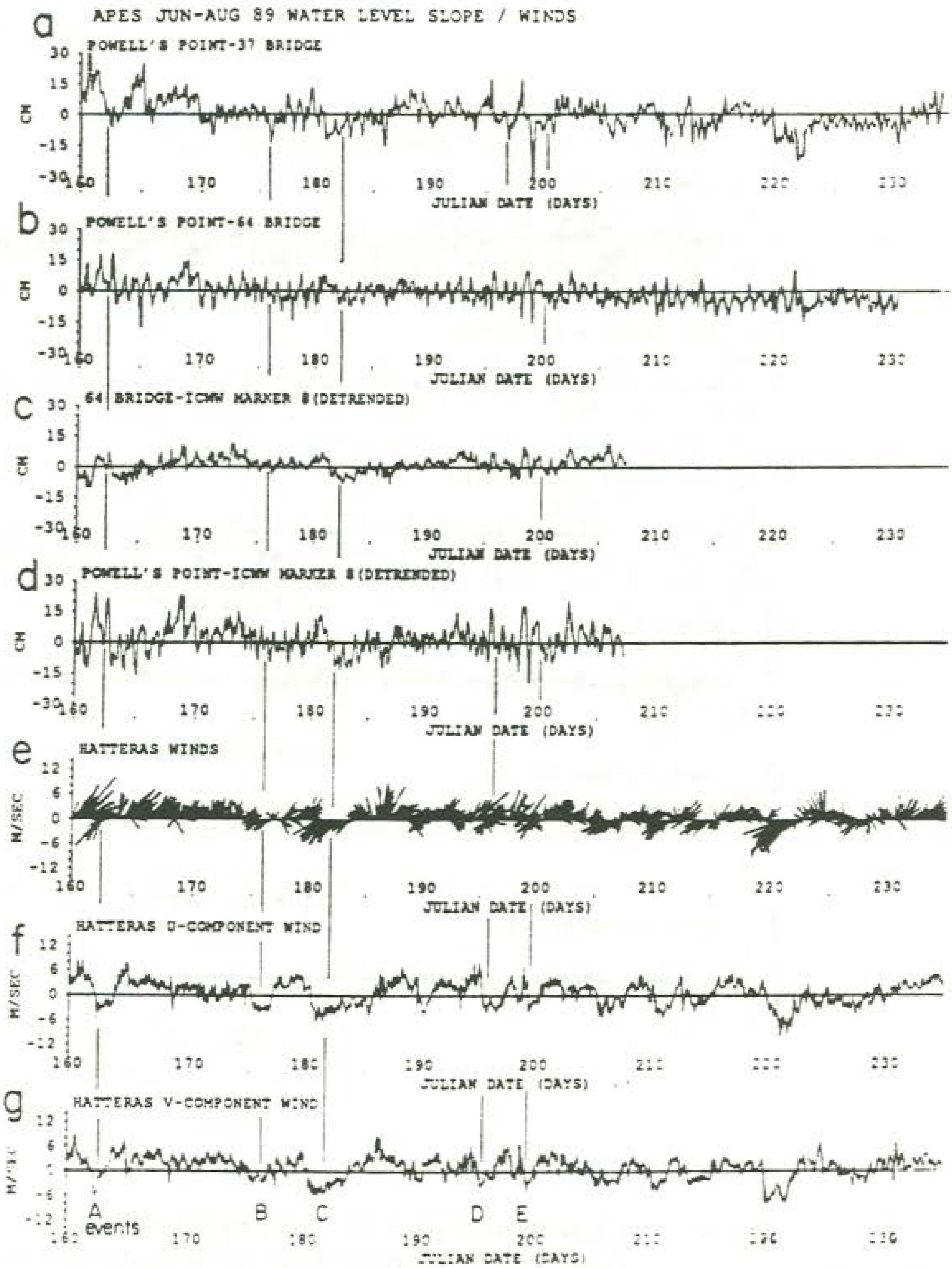

Figure 29. Time domain plots of: (a) water level at Powell's Pt. minus water level at Hwy 37 Bridge (E. Albemarle minus W. Albemarle) (b) Water level at Powell's Pt. minus water level at Hwy 64 Bridge (N. Albemarle minus S. Albemarle). (c) Water level at Hwy 64 Bridge minus water level at Marker 8 (N. Croatan minus S. Croatan). (d) Water level at Powell's Pt. minus water level at Marker 8 (N.Albemarle minus S. Croatan). (e) Wind vectors at C. Hatteras: stick up is wind towards north, stick down is wind towards south, etc. Stick towards right is. wind towards east, stick towards left is wind towards west. (f) East (up) west (down) wind components. (g) North (up), south (down) wind components.

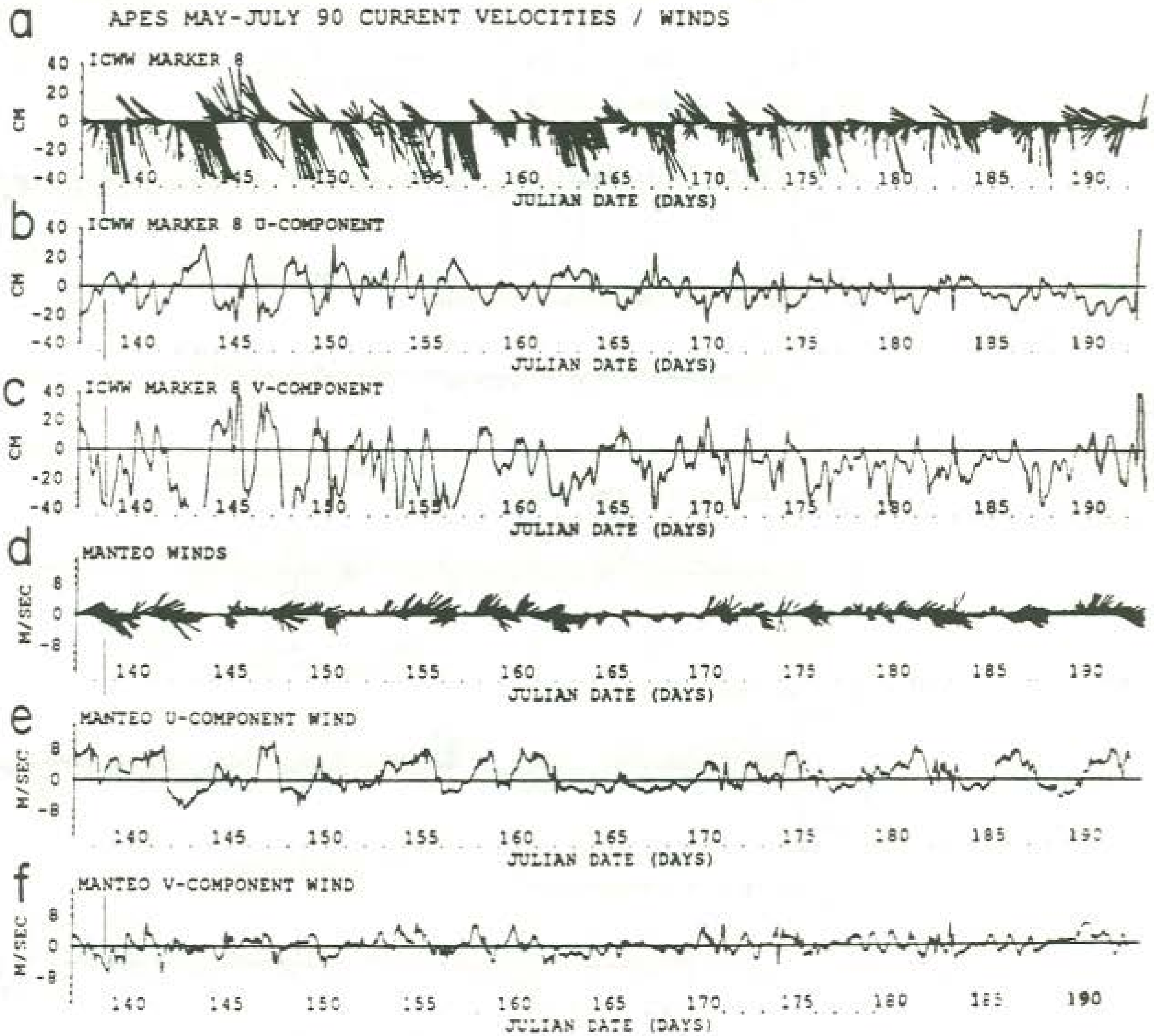

Figure 30. Currents at Marker 8 in Croatan Sound and the wind field at the Manteo Aquarium. (a) Current sticks pointing up indicate flow from Pamlico to Albemarle via Croatan and current sticks pointing down indicate flow from Albemarle to Pamlico via Croatan. (b) East (up)/West (down) current components in Croatan Sound. (c) North (up)/South (down) current components in Croatan Sound. (d) Wind vectors at Manteo: stick up is wind towards north, stick down is wind towards south, stick towards right is wind towards east,, stick towards left is wind towards west (e) East (up), west (down) wind components and (f) North (up), south (down) wind components.

6. A PREDICTIVE CAPABILITY: AN EMPIRICAL MODEL APPROACH

Based on our data analysis, it would appear that the variation in currents in Croatan Sound are wind driven and reflect the time history of the wind. That is the north-south component of the current at some time is determined by the history of the wind field over a few day period preceding the time in question. We state this empirical relation as

$$V_p(t) = \sum_{i=1}^{N} A_i \overline{X}_i(t) + \sum_{i=1}^{N} B_i \overline{Y}_i(t) \tag{1}$$

where Vp is the predicted current and the Ai, Bi are constants. Here the $\overline{X}_i(t)$ and $\overline{Y}_i(t)$ represents the previous history of the east-west and north-south wind speeds respectively. Each $\overline{X}_i/\overline{Y}_i$ represents the mean speed over a period τ preceding the present time by an amount that varies with i. In particular

$$(\overline{X}_i, \overline{Y}_i) = \frac{1}{\tau}\int_{t-(i-2)\tau}^{t=(i-1)\tau} (X(s), Y(s))\, ds. \tag{2}$$

Hence if τ is six hours, $\overline{X}_1$ is the mean X wind over the 6 hours preceding time t, $\overline{X}_2$ is the mean X wind over the period from 6 to 12 hours preceding the present time, etc. The memory of the system is then $N\tau$. The constants are determined by a least squares estimate which minimizes the difference between the observed currents and the predicted currents over the entire duration of the deployment. It was found that the coefficients, A_i, B_i, depended on the memory of the system N although the RMS error decreased only slightly beyond one day of memory. This occurred since the $\overline{X}_i$ and $\overline{Y}_i$ for large i were correlated with those for smaller values of i. To achieve an approach which was independent of memory the forcing functions were orthogonalized as follows. We defined $G_1(t)$ as equals to $\overline{X}_1(t)$. The function $G_2(t)$ is that part of $\overline{Y}_1(t)$ that is not correlated with $\overline{X}_1(t)$. $G_3(t)$ is that part of $\overline{X}_2(t)$ which is not correlated with either G_1 or G_2 etc., and we replace (1) with an equivalent statement that

$$V_p(t) = \sum_{i=1}^{2N} C_i G_i(t)$$

As the G_i (t) are orthogonal $C_i = \overline{V_o G_i} / \overline{G_o^2}$ where V_o (t) is the observed velocity and the overbar indicated the average over the data set. Forty-hour low passed current data at marker 8 and wind data from Cape Hatteras were utilized and one day memory with 6-hour averaging was also used. The coefficients, C_i, for the March 88 deployment were found to be (0.12, 3.60, -11.20, -6.00, -9.00, -10.23, -6.71, -9.72). For the June deployment these predictions were found to be (0.9, 3.34, -6.79, -4.36, -11.80, -11.67, -7.55 -11.3). The predictors for the $\overline{Y}$ components (even C_i) are fairly similar from one deployment to the next while the $\overline{X}$ components shared some variation. Observed and predicted currents are shown for the March deployment is shown in Figure (31). To check on effect of the variation of predictors (C_i) from one deployment to the next, we used predictions from one period to predict the currents in the other period. Figure (32) shows the use of the March predictions to predict the June currents and Figure (33) shows the use of the June predictors for the March currents. Fairly good agreement occurs in all three cases indicating the utility of this approach.

This approach can be used between any set of variables, for eg. salinity is current, salinity vs water level tilt, water level tilt vs currents, water level tilt vs winds, water level rise or fall vs winds or currents, etc.

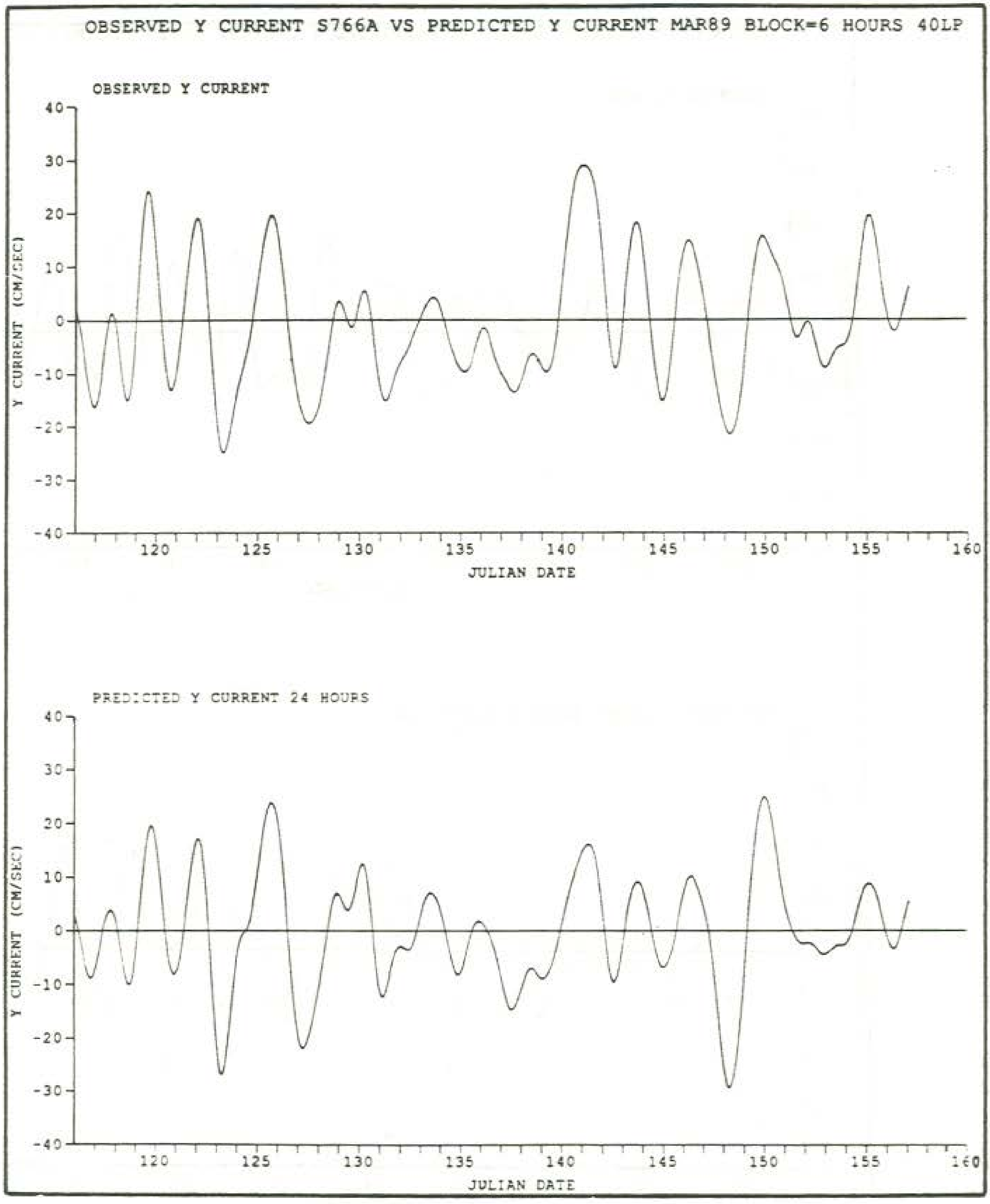

Figure 31. Prediction of currents mid April through May, 1989.

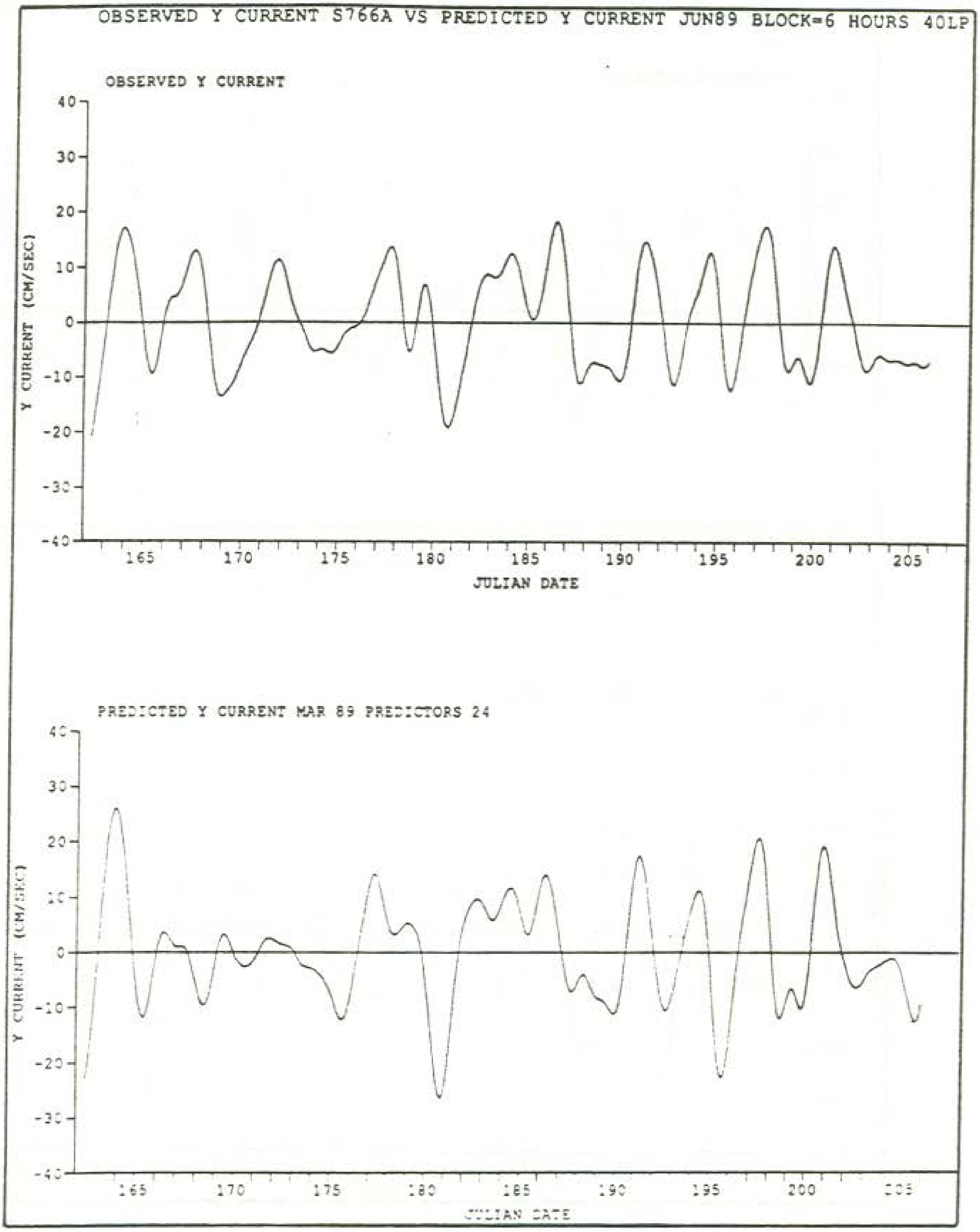

Figure 32. Prediction of June and July currents using April-May predictions.

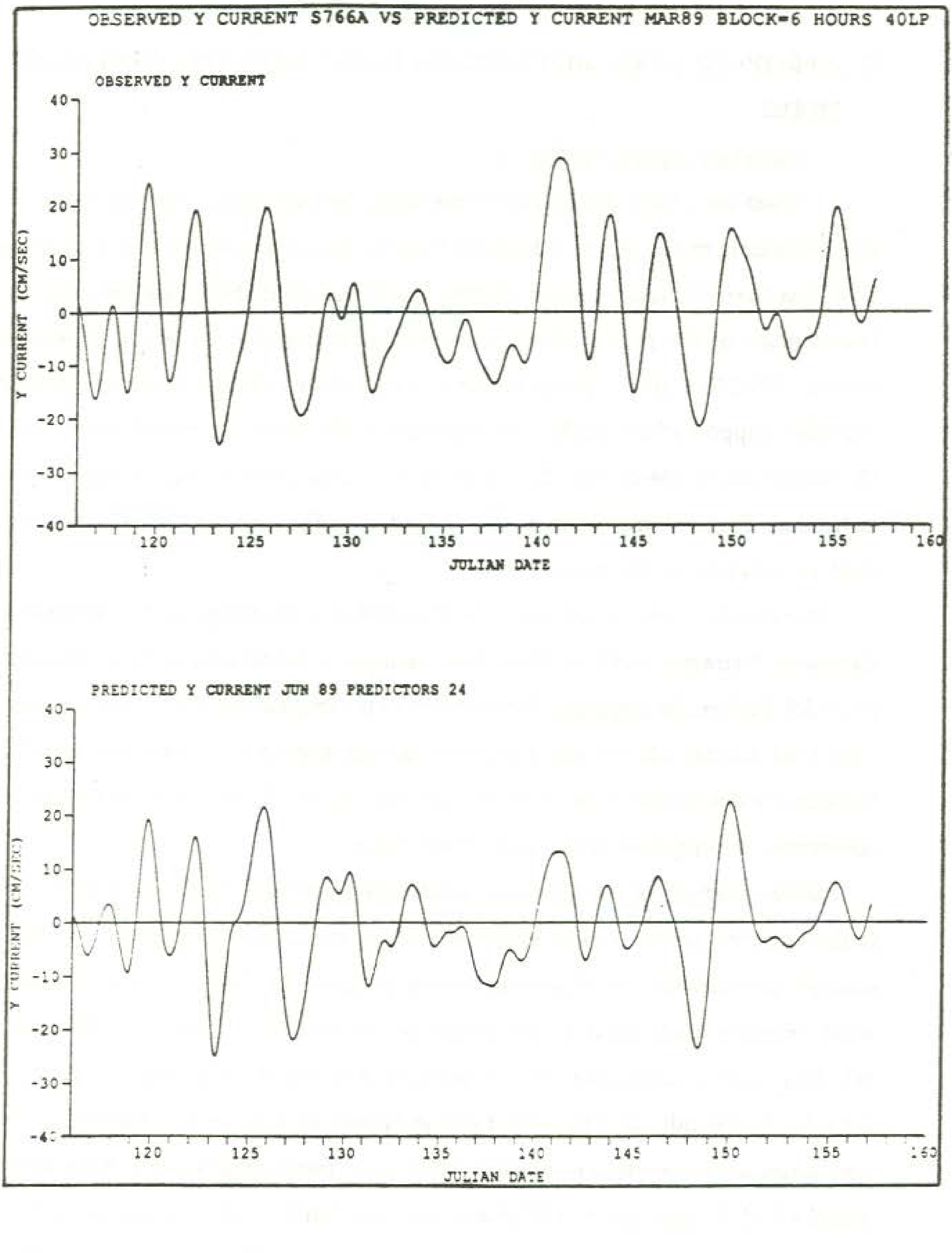

Figure 33. Prediction of April-May currents using June-July predictions.

7. A PREDICTIVE CAPABILITY: THE SEA GRANT-NCSU APES NUMERICAL MODEL

Numerical Model Prediction

Based on a three dimensional time-dependent stretched coordinate hydrodynamic model of the Albemarle-Pamlico Sound developed under previous UNC Sea Grant College Program funding (Pietrafesa, et al., 1987), the principal investigators of this project developed a numerical model of the entire three-sound system. UNC Sea Grant College funding, to one of the Principal Investigators (LJP), provided support of the further development of the numerical model, now called the NCSU Albemarle-Pamlico Estuarine Model. Data from this APES project as well as from an Oregon-Ocracoke Inlets study funded by Sea Grant to LJP provided the field verification for the model.

The details of this model are to be provided in a Sea Grant Technical Report (Janowitz, Pietrafesa and Lin, 1991). One example of model output consider Figure 34 which depicts the response of the system to the imposition of a 30.5 centimeter (2 foot) semi-diurnal tide at each of the three barrier island inlets. Note that in the Croatan the amplitude of the tide has been reduced to ± 1 centimeter and in the Albemarle, the response is less than 5 millimeters.

Other products of the numerical model are water level fluctuations anywhere in the estuarine system as well as currents at any depth and volumetric flux. For example consider the model stations shown in Figure 35. We then impose real winds, riverine discharge and tides for the period 1 January - 05 March, 1988, and calculate water level fluctuations and currents throughout the system. In Figure 36, the measured windfield is presented and in Figures 37 a-d, the resultant water level time series for the western end of the Albemarle (panel #37a) eastern Albemarle (Panel #37b), Croatan Sound (#37c) and northern Pamlico (#37d) are presented. Also shown is the volumetric adjustment of the entire Albemarle basin, relative to its annual mean (#37e) and the volumetric flux of water through Croatan Sound (#37f).

Next we compute time series of water level along the major axis of Pamlico Sound, the center axis of Croatan Sound and along a line from the Highway 64 Bridge to Powell's Point. This line set is shown in the inset shown in the upper right of each of the figures to follow. The computation is plotted in distance from the center of Croatan Sound (horizontal axis), such that Cedar Island is -140 km, the center of the Croatan is 0 km and Powell's Point is +40 km.

In Figure 38 we compute water level time series along the axial cut (shown in the insert in the upper right corner) for a 24 hour period in a response to a northward wind. Note that the system sets up within a 9 hour period and stabilizes thereafter. In Figure 39, the separate water level response cases of 1 dyne/cm^2 winds blowing for 24 hours for:

case A – Northward winds

B – Eastward winds

C – Southward winds

D – Westward winds

are shown. In Figure 40 water level adjustment to a 20 year flood lasting 4 days is shown. Finally in Figure 41 model predicted currents vs measured currents in Croatan Sound are shown.

The model clearly has great applicability. For example, one application of the model could be to artificially open an inlet at the eastern end of Albemarle Sound providing a direct connection to the coastal ocean. What would result? Would the Albemarle entrain Virginia coastal waters during finfish recruitment season?

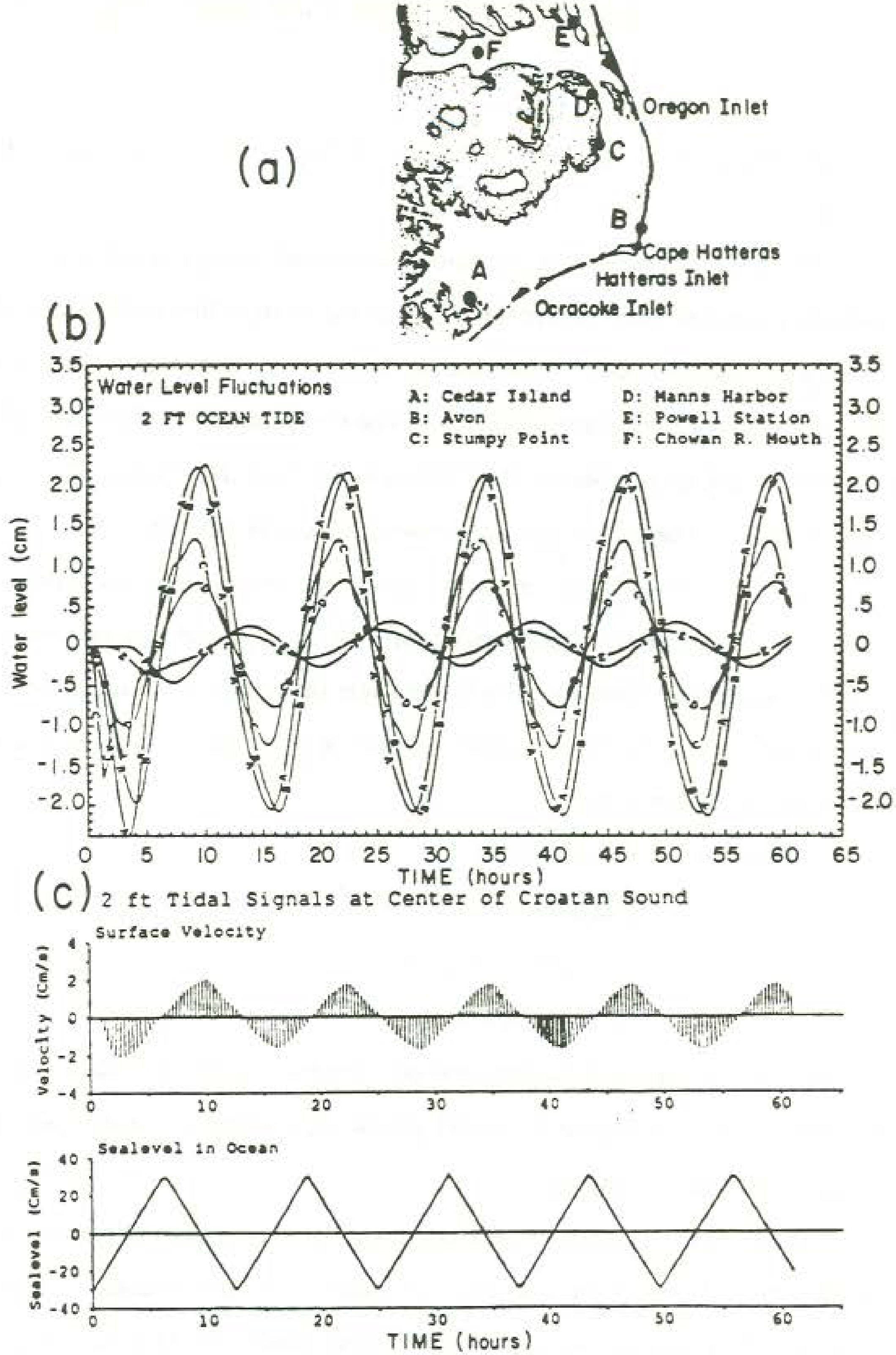

Figure 34. Numerical model output of water level response at (a) stations A, B, C, D, E, and F to (b) a 2 foot (30.5 cm) semi-diurnal tide imposed at the three barrier island inlets. (c) The surface velocity plot is calculated for the middle of the Croatan.

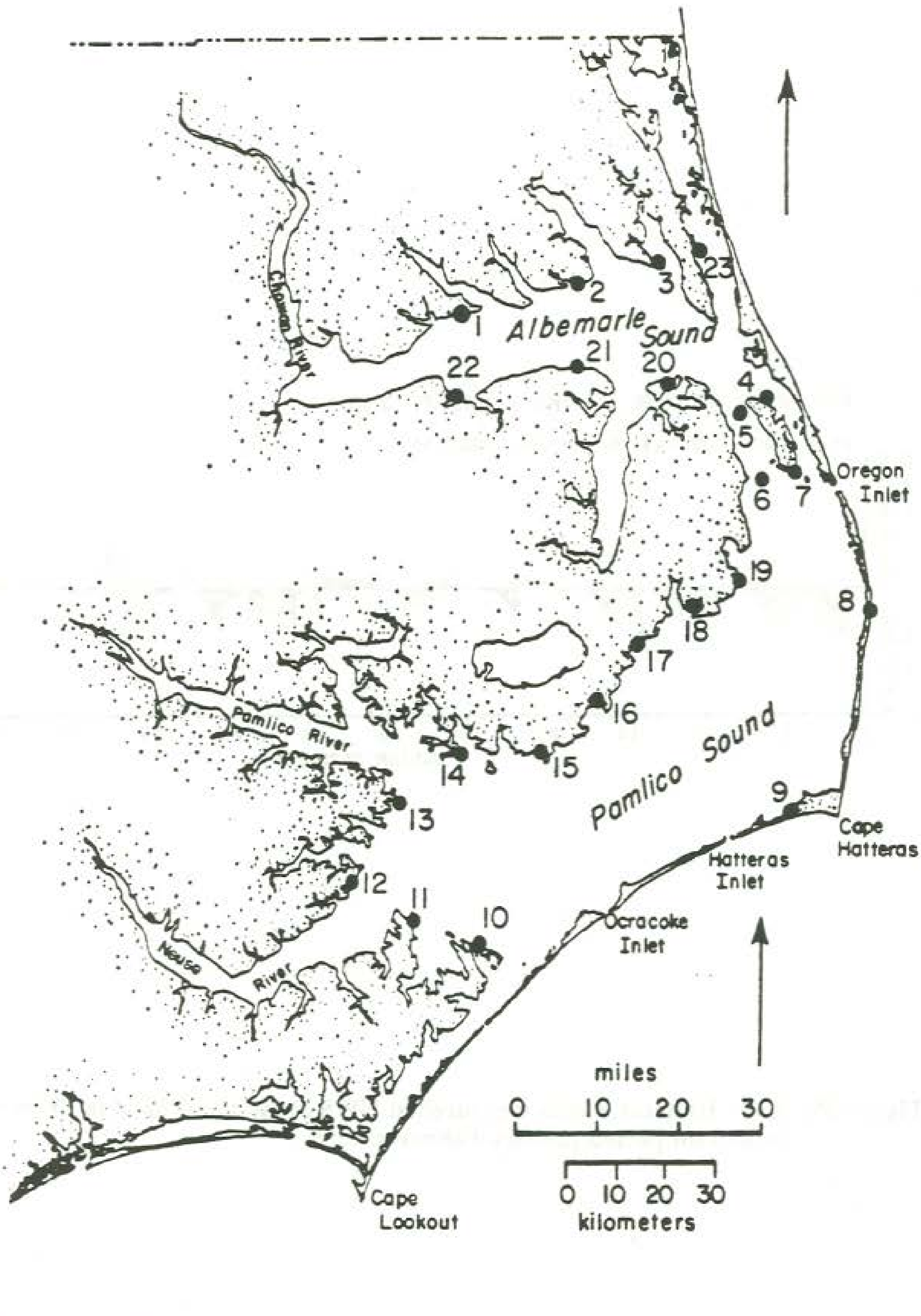

Figure 35. Numerical model stations for water level calculations around the periphery of the sound (shown in Figure 37).

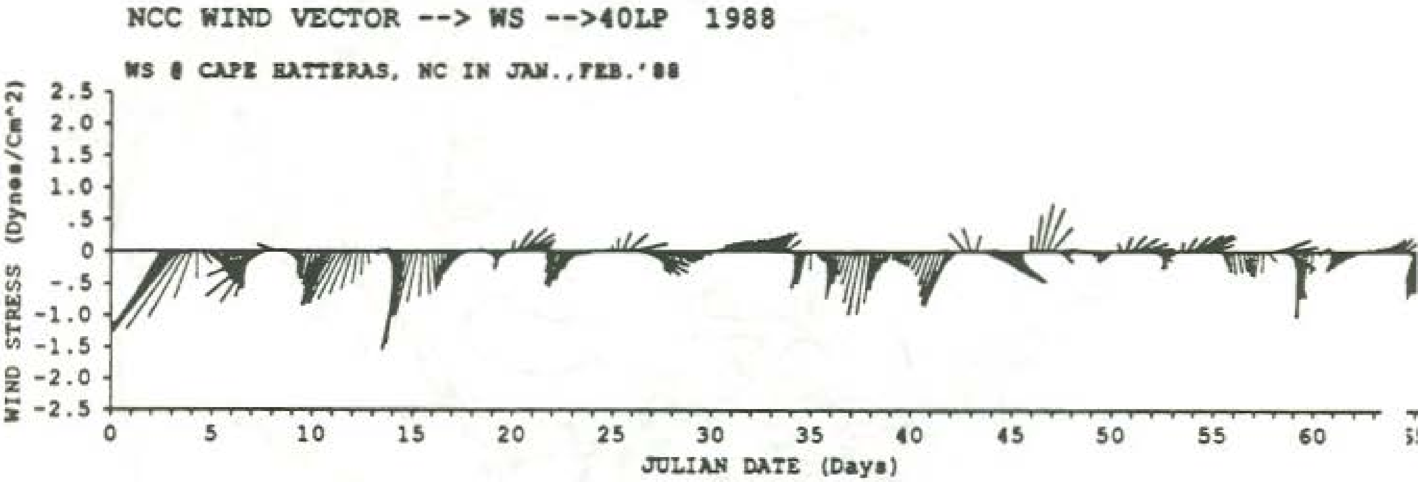

Figure 36. Cape Hatteras winds measured at NWS station and used to drive numerical model for period January-February, 1988.

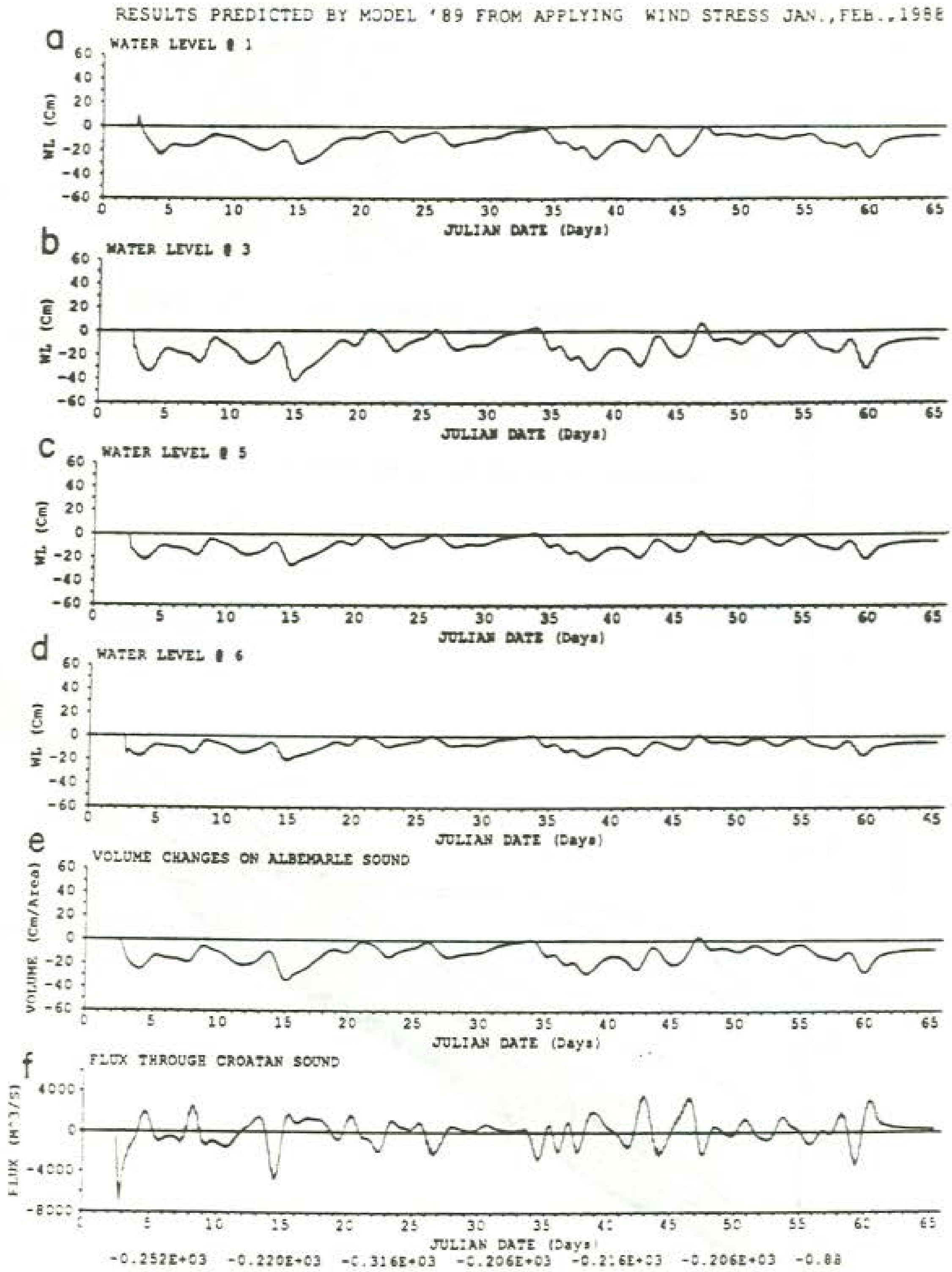

Figure 37. Model derived water level fluctuation time series at selected stations around the periphery of the A-C-P Sound system (cf. Figure 35) during the period January-February, 1988.

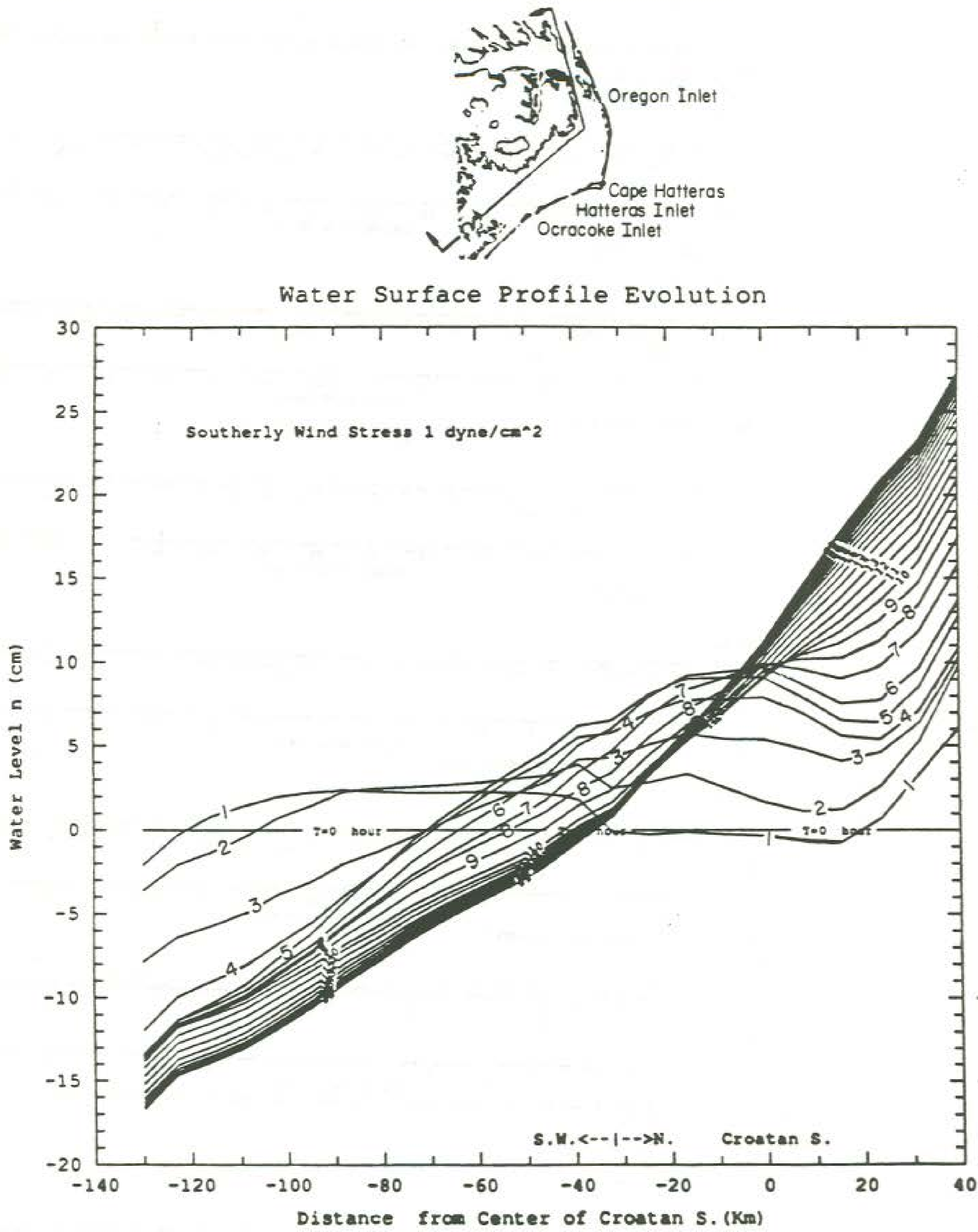

Figure 38. Model derived time sequence of water level adjustment along center line of A-C-P Sound system, to a persistent northward wind.

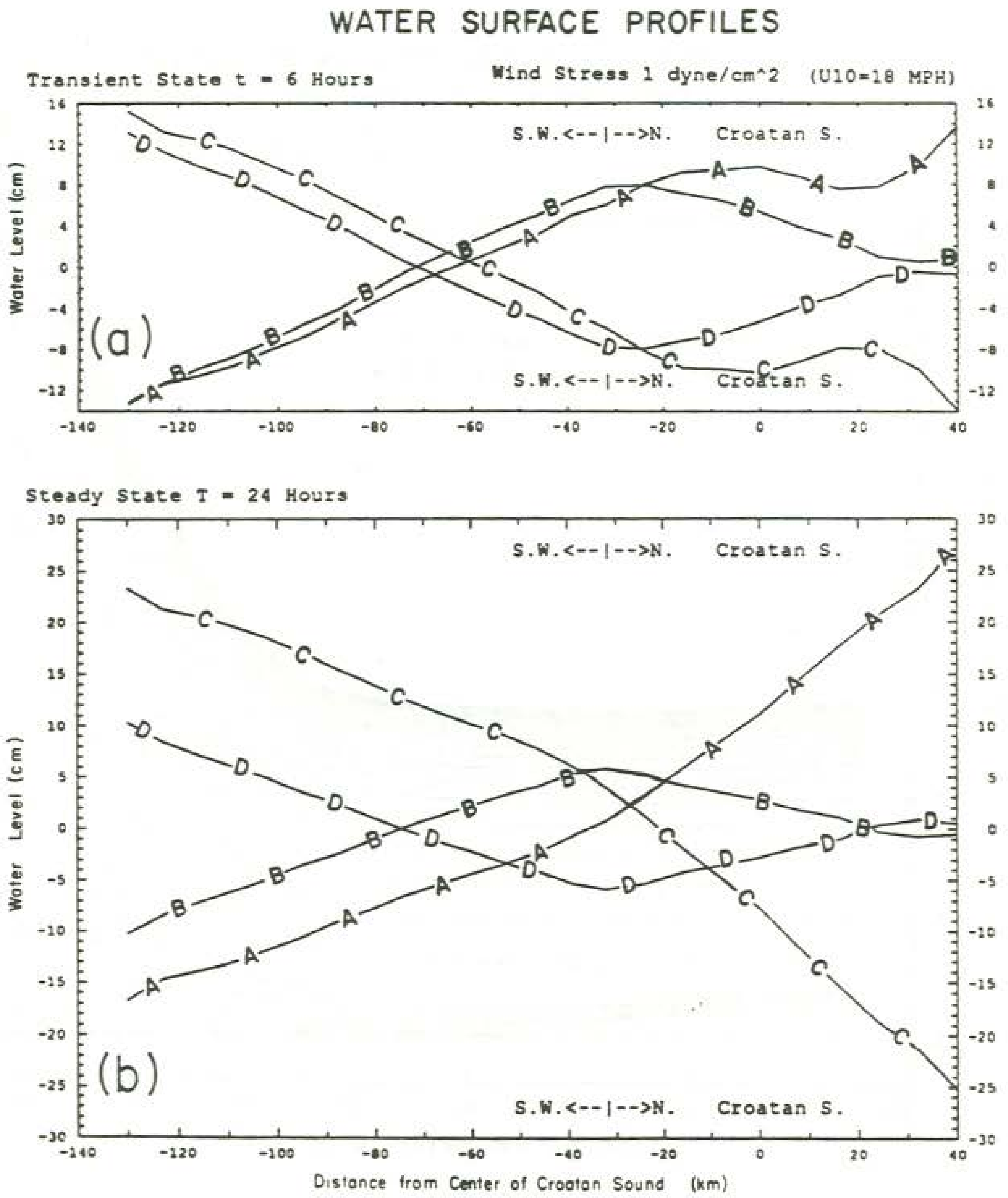

Figure 39. Model derived water levels along A-C-P Sound system center line shown in Figure 38 at (a) 6 hours after the onset and (b) 24 hours after the onset of:
A: northward winds B: eastward winds
C: southward winds D: westward winds

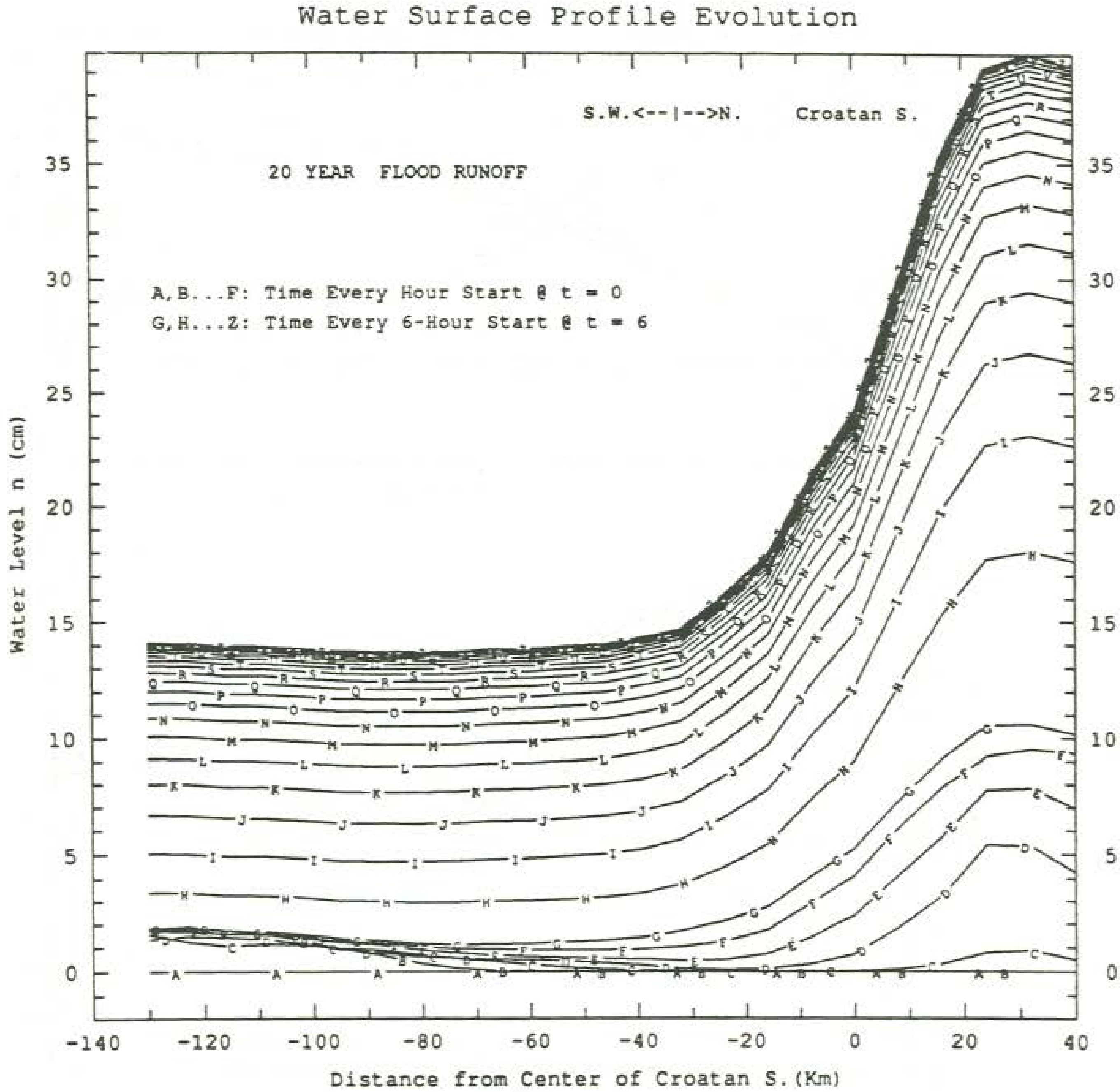

Figure 40. Model derived water levels along A-C-P Sound system center line shown in Figure 38 every 6 hours for 4 days during a 20 year flood.

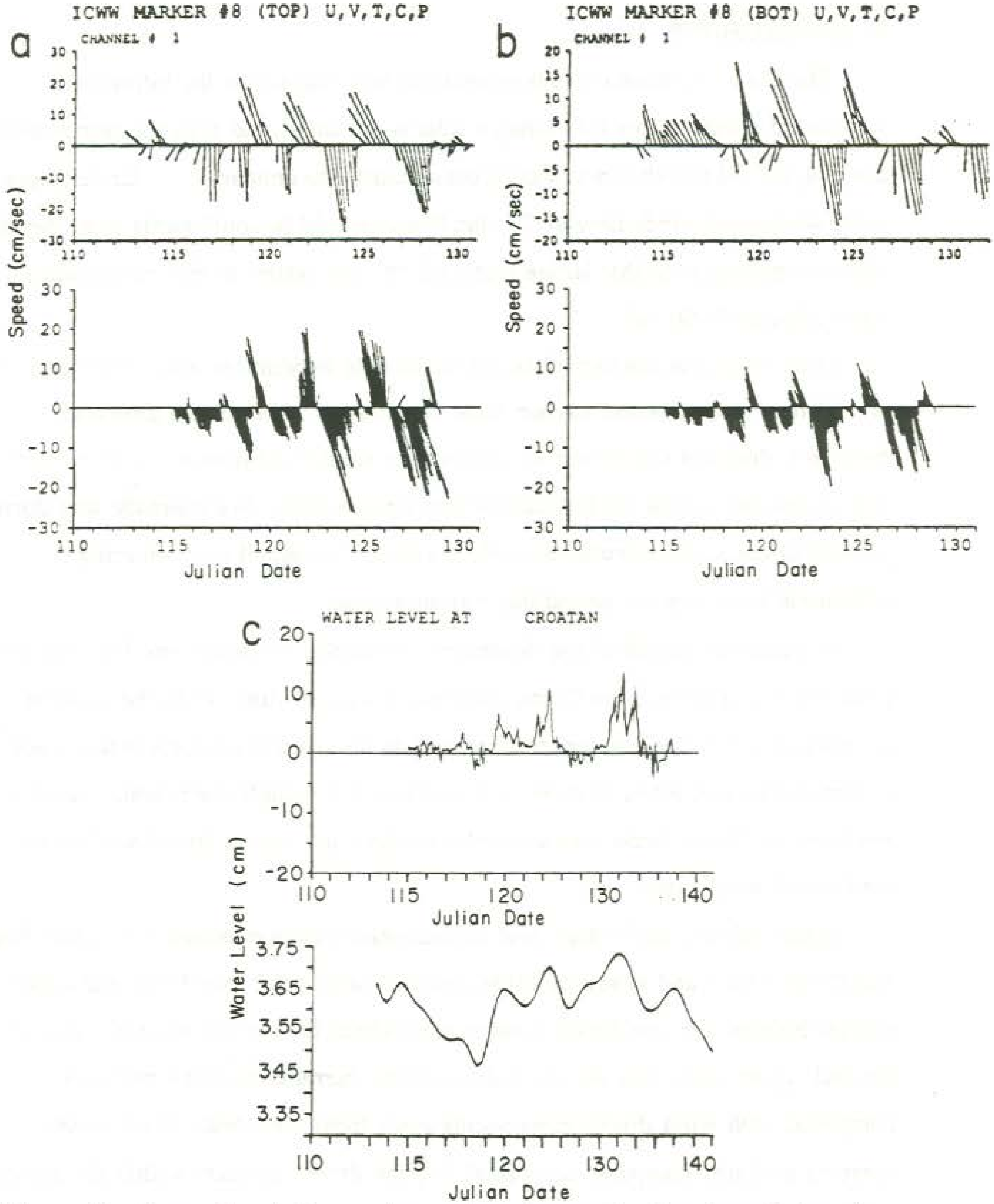

Figure 41. Comparison between observations (top sections) and predictions (bottom sections). (a) currents at Marker 8, top meter, (b) currents at Marker 8, bottom meter and (c) water level at Marker 8.

8. CONCLUSIONS

The basic hypothesis of this experiment was that under the influence of southward winds inflow into Oregon Inlet is enhanced,and thus the recruitment of ocean spawned finfish larvae would consequently be enhanced. Under these same southward winds,flow in Croatan Sound would be southwards at all depths, with the consequence that larvae recruited into the system at this time could not enter Albemarle Sound.

Our analysis of the data obtained in the field experiment which extended over an eighteen month period sustain these conclusions. Both in the time and frequency domains southward winds produce southward flow in Croatan Sound and southward winds enhance inflow into Oregon Inlet. We conclude that during periods of enhanced recruitment, fish larvae are prevented from entering Albemarle Sound by the prevailing current system.

A numerical model of the dependent circulation in the system developed with partial study of NOAA Sea Grant, confirms this conclusion. With the onset of southward winds, the pressure force as well as the wind stress force is to the south in Croatan Sound, while in Albemarle and Pamlico Sounds the pressure force is northwards. These forces lead to southward flow in Croatan Sound well into a southward wind invert.

Water velocity and water level measurements were obtained in Croatan Sound and Oregon Inlet and at several other locations within the sounds but the water surface heights and circulation patterns throughout the system must be inferred, in general. From these data we conclude that tidal currents are not significant compared with wind driven components away from the inlets. Wind driven currents are large compared to normal riverine driven currents within the system; the latter are too weak to measure directly away from river mouths but can be estimated by volume flux considerations. Thus we conclude that wind driven currents predominate in the system.

Outside of Croatan Sound, the water slopes upward in the downwind direction. This would tend to drive near bottom currents in the upwind direction if the wind direction is unchanged for a period of a few days. The surface currents tend to be in the downwind direction.

The constriction in the connection between the two major sounds caused by the presence of Roanoke Island tends to enhance southwards flow in Croatan Sound under southward winds due to the lag in time of the pressure force. The NCSU/Sea Grant model also shows that during periods of the year characterized by winds blowing predominantly from the north, typically September through February, there will be a net flushing of portions of the Albemarle. Now, since the release of Albemarle to the Pamlico is about 510 cubic meters per second on the average so that it takes approximately 11 months to completely replace all of the water in the Albemarle. However, there are periods of the year when atmospheric winds tend to blow from the south; May to August. This time of the year is not favorable for flushing the Albemarle. Since 2 day to 2 week atmospheric wind events are characterized by winds blowing from all directions, over the course of the event, each event contributes to a flushing of Albemarle. Nontheless, the amount of water flushed during any event is strictly a function of the intensity and persistence of the wind event. Moreover, the flushing of a particular portion of the Albemarle is extremely site specific. The NCSU/Sea Grant model can greatly aid in the hindcasting or forecasting of flushing throughout the Albemarle. While the NCSU/Sea Grant numerical model results presented yield good agreement for water level patterns and circulation point measurements, a further refinement of this model incorporating finer scaled horizontal boundaries is necessary to more accurately predict particle trajectories.

Finally, it would appear that the only real possibility of recruiting ocean spawned estuarine dependent finfish into Albemarle Sound is via the opening of an inlet at the eastern end of the sound. If an inlet were to be created the salinity of the Albemarle would certainly increase.

9. ACKNOWLEDGEMENTS

This report was word processed by Brenda Batts. The figures were rendered by LuAnn Salzillo. Both B. Batts and L. Salzillo assisted in editing. Charles Gabriel and Paul Blankenship deployed and retrieved the moorings. C. Gabriel transcribed and processed the data products, assisted by Jeff Alexander. G.Q. Lin produced the numerical model results.

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