

**Analysis of Water Level, Weather and Acoustic
Doppler Profiler Data from Biscayne Bay,
Card Sound and Barnes Sound**

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FINAL REPORT

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INTRODUCTION

In early June 1997, the Army Corps of Engineers Waterways Experiment Station (WES) initiated a field study of Biscayne Bay and adjacent waters, including Card Sound, Barnes Sound and Manatee Bay. The field study included the collection of water level data from 12 stations (see Figure 1), acoustic doppler profiler (ADP) data from five stations and weather data from Convoy Point, along the western shore of Biscayne Bay. Recording instrumentation was in place for an approximately one-year period. Station coordinates, starting and ending times are listed in Table 1. The objective of the field study was to collect data that could be used to verify a hydrodynamic model of the Biscayne Bay system.

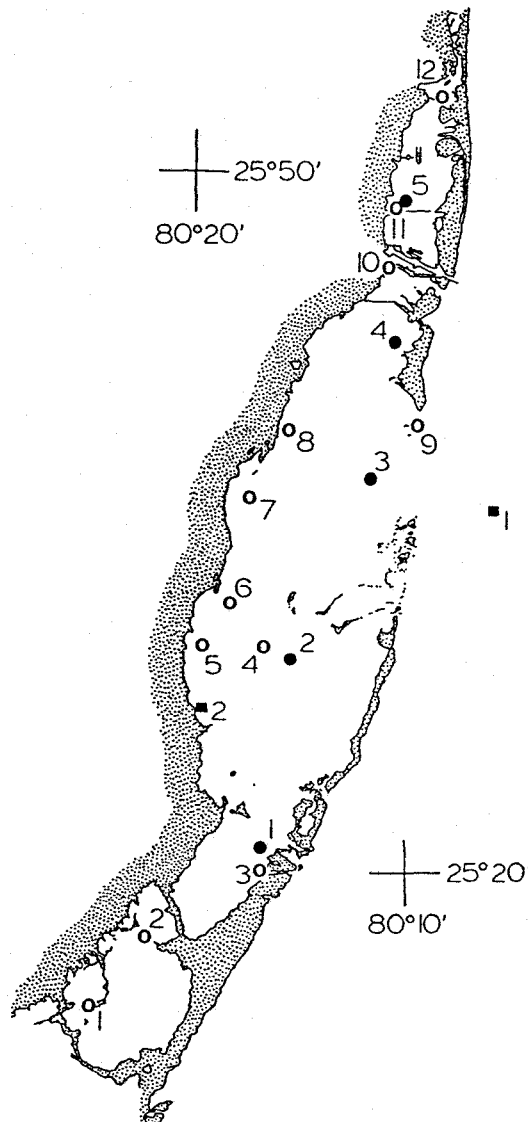


Figure 1. Map of the study area, including Biscayne Bay, Card Sound, Little Card Sound, Barnes Sound and Manatee Bay. Solid squares show locations of the weather stations at (1) Fowey Rocks and (2) Convoy Point; open circles show locations of water level stations 1-12; solid circles show locations of ADP stations 1-5.

In a June 7, 1999 letter to the National Park Service, Harbor Branch offered to analyze the water level, ADP and weather data within the restricted context of model verification. Following a period of negotiation, Harbor Branch offered a Scope of Work that included screening, editing, analyzing and plotting the data. Specifically, data would be inspected for outliers and gaps. Gaps longer than 12 hours would be considered breaks in the record, and data collected before and after a break would be treated as separate time series. Data would be plotted as time series and presented with expanded captions to aid in the interpretation. Data would be subjected to time series analyses to characterize tidal conditions, and to establish statistically significant associations between wind stress and both water levels and ADP transport. Two reports would be provided. The first would be a Quality Assurance Report that would address the suitability of the data for model verification purposes. The second would be a Final Report to summarize findings directly related to validating model simulations.

The Quality Assurance (QA) Report was submitted on September 9, 1999 and again in amended form on February 3, 2000. The QA Report included plots of north-south and east-west wind stress components from the C-MAN Station at Fowey Rocks and from the WES weather station at Convoy Point, plots of the water level data in analog form from each of the twelve stations, plots of the north-south and east-west components of ADP current speed from each of the five stations, a table of the harmonic constants (amplitudes and local phase angles) of the principal tidal constituents, and co-amplitude and co-phase charts of the M_2 and N_2 tidal constituents. Except for the table of harmonic constants and the co-amplitude and co-phase charts, the emphasis was on analog plots. While analog plots are useful for model validation, the QA Report did little more than repeat what had appeared earlier in the Biscayne Bay Field Data Report (Pratt 1999). The analog plots of current component speed and water level that appear in the Field Data Report provide information that can be compared with model results simulated for the same location and under the same environmental conditions. Such comparisons are qualitative, however, and the acceptance or rejection of the model's ability to reproduce variations in water level and circulation is subjective.

In this Final Report, we include analog plots, but we carry the analysis an important step further by presenting results that can be used for a digital approach to model validation. The Final Report focuses on results of harmonic analyses and spectral analyses. Amplitudes and local phase angles resulting from a harmonic analysis of field data can be compared with amplitudes and local phase angles obtained using simulated data from the corresponding part of the model domain. This quantifies the model's ability to reproduce tidal conditions in Biscayne Bay, and it permits comparisons of individual tidal constituents. Similarly, the gain resulting from spectral analyses of field data can be compared with the gain calculated from model input and output. For example, a spectral analysis of observations of winds and water levels will quantify the response to low-frequency variations in east-west wind stress. If the model is then forced specifically with east-west wind stress varying at the same periodicity, results can be compared directly. One sees immediately if the model is under- or over-estimating wind-forced variations in water level. The primary contribution that this report makes to the Biscayne Bay Field Study is the opportunity to take model verification beyond a subjective comparison of analog plots.

Data

a. Weather Data

Weather data are available from the WES study site at Convoy Point and from the Coastal-Meteorological Automated Network (C-MAN) station on the Fowey Rocks tower (Figure 1). The Convoy Point record covers the time period from July 17, 1997 to July 8, 1998 and data were collected quarter-hourly. The Fowey Rocks record covers the time period from June 6, 1997 to June 29, 1998 and data were collected hourly. Six gaps of as long as one day were found in the Fowey Rocks record. Because of the better exposure of the Fowey Rocks study site, however, and because the C-MAN station is a permanent weather station that can provide historical data, as well as data for future studies, the Fowey Rocks weather record was used for comparison with the water level and ADP records.

b. Water Level Data

Water level data were collected at twelve locations in Biscayne Bay, Card Sound and Barnes Sound (see Table 1, Figure 1). Most records start in June 1997, and continue through late June 1998. Water level was recorded at 15-minute intervals, but for comparison with wind records the data were sub-sampled at hourly intervals.

Gaps were expected, and major gaps were found in nine of the twelve records. Data from Station TG-10 did not start until December 15, 1997, but the remainder of the record was continuous. Minor gaps occurred when water level recorders were being downloaded. Gaps of twelve hours or less were filled by linear interpolation.

Timing errors of two kinds were found in the water level records. All records starting before approximately mid July are apparently annotated in Eastern Daylight Time; those records starting after mid July are apparently annotated in Eastern Standard Time. The one-hour time shift that occurs when EDT is being used becomes apparent when local phase angles are calculated for the principal tidal constituents and compared with phase angles from nearby NOS study sites. The second kind of timing error in the water level records resulted from missing observations. Several records included a missing observation in early to mid July 1997 that was not indicated by the time stamps. Again, harmonic analyses for tidal amplitudes and phase angles suggested approximately where data were missing, and analog plots were used to determine the missing hour.

c. Acoustic Doppler Profiler Data

Acoustic Doppler Profiler data were collected at five locations (see Table 1). Records began in late June 1997 at four of the five locations and on December 21 at Station ADP-1. End times vary from March 21 to July 31, 1998. Four of the five ADP records are fragmented with one or more gaps. Station ADP-3 contains five gaps, but two of the partial records are sufficiently long for characterizing wind forcing. Station ADP-4 has only two gaps, but the available partial records are short and suspect in appearance. Neither transport nor vertically averaged current speed could be calculated for Station ADP-4 because of a malfunction of the pressure sensor used to determine water depth. ADP data were recorded at 15- or 20-minute intervals, but all records have been sub-sampled and time-shifted when necessary to provide top-of-the-hour readings for comparison with wind records.

Table 1. Locations, start and end times (MM/DD/YY) of time series from WES study sites in Biscayne Bay, Card Sound, Barnes Sound and Manatee Bay. Also included is the NOAA C-MAN station at Fowey Rocks. The analog plot of instrument vs. time that follows the table shows when gaps appeared in the time series.

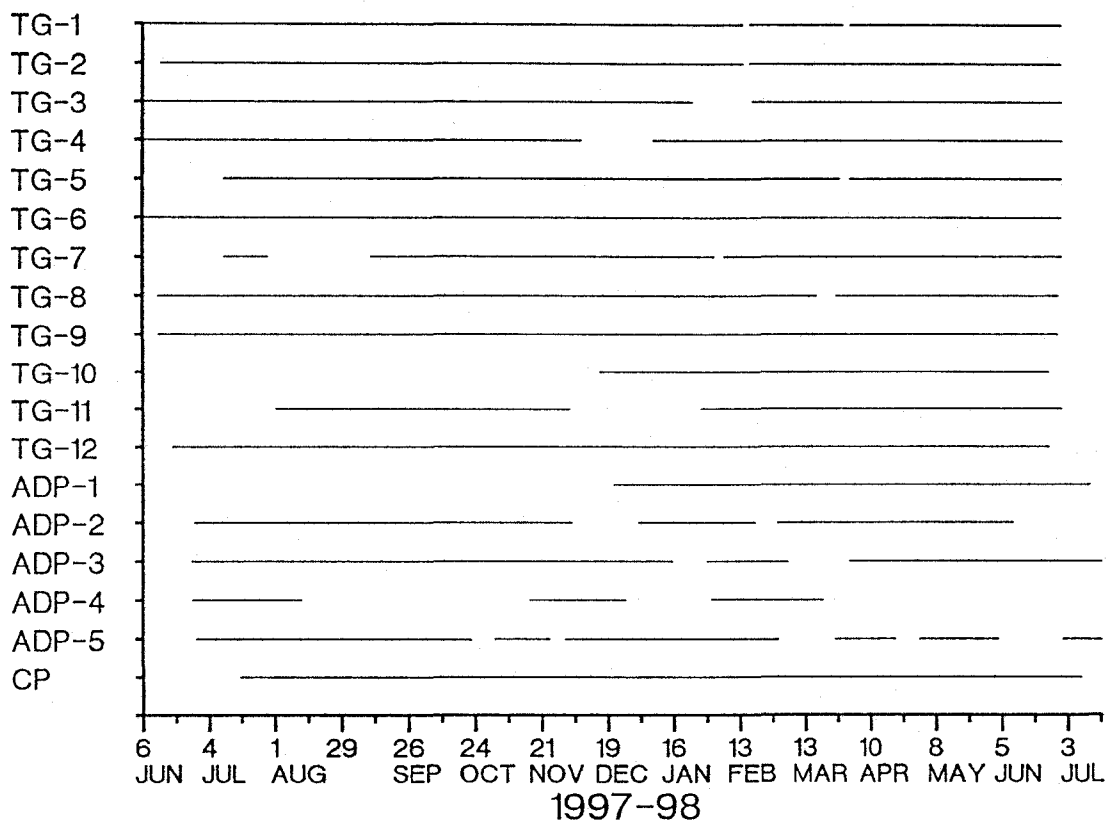
	Lat. (N)	Lon. (W)	Start	End
A. Water Level Data				
TG-1, Manatee Bay	25° 14.208'	80° 24.671'	06/06/97	02/14/98
			02/17/98	03/29/98
			04/01/98	06/30/98
TG-2, Card Sound Bridge	25° 17.304'	80° 22.122'	06/13/97	01/14/98
			01/17/98	06/30/98
TG-3, Angelfish Creek	25° 20.164'	80° 16.817'	06/06/97	01/24/98
			02/18/98	06/30/98
TG-4, Military Canal, East	25° 29.681'	80° 16.698'	06/06/97	12/08/97
			01/07/98	06/30/98
TG-5, Military Canal, West	25° 29.788'	80° 19.526'	07/10/97	03/28/98
			04/04/98	06/30/98
TG-6, Black Point, Marker 8	25° 31.638'	80° 18.244'	06/06/97	06/30/98
TG-7, Snapper Creek	25° 36.244'	80° 17.359'	07/10/97	07/29/97
			09/10/97	02/02/98
			02/06/98	06/30/98
TG-8, Gables by the Sea	25° 39.076'	80° 15.570'	06/12/97	03/18/98
			03/26/98	06/29/98
TG-9, Biscayne Channel	25° 39.269'	80° 09.567'	06/12/97	06/29/98
TG-10, Miami River	25° 46.224'	80° 10.902'	12/15/97	06/25/98
TG-11, Julia Tuttle Causeway	25° 48.823'	80° 10.489'	08/01/97	12/03/97
			01/27/98	06/30/98
TG-12, Broad Causeway	25° 53.413	80° 08.384'	06/18/97	06/25/98
B. Acoustic Doppler Profiler Data				
ADP-1, Angelfish Creek	25° 20.167'	80° 16.816'	12/21/97	07/12/98
ADP-2, Srn Biscayne Bay	25° 29.091'	80° 15.424'	06/27/97	12/03/97
			01/01/98	02/19/98
			03/01/98	06/10/98
ADP-3, Ern Biscayne Bay	25° 37.013'	80° 11.550'	06/26/97	01/15/98
			01/30/98	03/05/98
			04/01/98	07/31/98
ADP-4, Nrn Biscayne Bay	25° 42.886'	80° 10.630'	06/26/97	08/12/97
			11/15/97	12/26/97
			02/01/98	03/21/98

Table 1 (continued)...

ADP-5, Julia Tuttle Causeway	25° 48.828'	80° 10.492'	06/28/97	10/22/97
			11/01/97	11/24/97
			12/01/97	03/01/98
			03/25/98	04/21/98
			05/01/98	06/04/98
			07/01/98	07/31/98

C. Weather Data

Convoy Point	25° 27.894'	80° 20.048'	07/17/97	07/08/98
Fowey Rocks C-MAN	25° 35.417'	80° 05.800'	06/05/97	06/29/98



Methodology

a. Weather Data

Weather data from Fowey Rocks and Convoy Point were used to translate wind speed and direction into the magnitude and direction of the corresponding wind stress. The direction of the wind stress force is in the oceanographic convention, rotated 180° from the wind direction, and the magnitude of the wind stress is proportional to the square of the wind speed. We use the algorithm suggested by Wu (1980) for calculating wind stress, τ :

$$\tau = \rho c_d V^2,$$

where ρ is the density of the air, V is the wind speed, in m s^{-1} , measured 10 m above the water surface, and c_d is the drag coefficient, given by:

$$c_d = (0.8 + 0.065 V) \times 10^{-3}.$$

Air density, in turn, is a function of air temperature, surface pressure and atmospheric moisture (List 1963).

Hourly wind stress vectors can be plotted head-to-tail as progressive vector diagrams (Scientific Programming Enterprises 1985). This approach is well suited for characterizing the general nature of wind stress over the longest time scales covered by the study, but it is inappropriate for identifying wind forcing at a particular time or over the shorter time scales. To emphasize high-frequency variability, wind stress vectors were decomposed into north-south and east-west components and plotted as a function of time.

The similarity of wind stress calculated from the Fowey Rocks and Convoy Point weather records is quantified by calculating the vector correlation coefficient and the mean deflection of the wind stress vector (Kundu 1976). A high degree of similarity would indicate that wind observations from a single location are spatially representative of the entire Biscayne Bay, Card Sound and Barnes Sound system of coastal lagoons.

Wind stress records are used in spectral analyses (Little and Shure 1988) to examine the wind-forced rise and fall in water level or the wind-forced transport of water past any of the five ADP study sites. At any given location, the response to wind forcing will be a function of the time scale over which the forcing occurs, and it may be highly dependent upon the direction of the wind. Thus, for each study site, we consider several wind directions. Wind vectors are decomposed into components at intervals of 30°, and spectra are computed for each of the six components. Coherences are listed for all periodicities in excess of one day. If the coherence is significant at or above the 95% confidence level, the gain accompanies the coherence in parentheses. The gain, alternately known as the magnitude of the transfer function, is the change in water level that occurs with a unit change in wind stress (in dyne cm^{-2}). If the coherence is significant at or above the 99% confidence level, the coherence and gain values are italicized.

b. Water Level Data

Water level records were analyzed in three ways to (1) obtain an overview of the full time series, (2) characterize the principal tidal constituents, and (3) quantify the response to wind forcing.

To obtain an overview of the full time series, hourly readings have been low-pass filtered to remove the high-frequency variations, including the rise and fall of the tide and the response to the diurnal seabreeze. The numerical filter used for this is the 40-hour low-pass filter described by Bloomfield (1976). With this filter, 63 observations are lost

from each end of the record, and the cut-off between what is lost in the filtering process and what is passed occurs at a periodicity of about 1.5 days. Ten, 50 and 90% of the input variance is passed at periodicities of 30, 37 and 48 hours, respectively.

To identify and characterize the harmonic constants of the principal tidal constituents, the least squares harmonic analysis program developed by the National Ocean Service was used (Schureman 1958). This computer program requires time series at least 180 days in length, and it provides harmonic constants of 37 tidal constituents. In our analyses, we define a tidal constituent to be a "principal" tidal constituent if its amplitude is 1 cm or greater. To provide greater station density, we have incorporated harmonic constants from previous National Ocean Service studies in the same area. When only shorter water level records were available, a 29-day harmonic analysis program was used (Dennis and Long 1971). This same computer program can be used in the model validation exercises. Twenty-nine day model simulations can provide water level records suitable for analysis with the same harmonic analysis programs. Comparison of harmonic constants from model-derived water levels and harmonic constants from observations will indicate how well the model is reproducing amplitudes and phase angles for individual tidal constituents.

To summarize the large collection of harmonic constants for a given tidal constituent, we have constructed co-amplitude and co-phase charts. Co-amplitude charts are constructed by entering the amplitudes for a given tidal constituent on a map of the study area, then contouring. The resulting plot shows regions of high and low amplitudes, and thus how the tidal wave is damped as it enters and moves through these coastal lagoons. Co-phase charts are constructed by entering and contouring local phase angles from each of the study sites. Isopleths are at 30° intervals for semidiurnal constituents, and at 15° intervals for diurnal constituents. For semidiurnal constituents, a 30° phase lead or lag corresponds very closely to a one-hour time lead or lag. Thus, neighboring isopleths on a co-phase chart can be used to infer the speed and direction of movement of tidal waves through the study area. Similarly, a 15° phase difference for diurnal constituents corresponds very closely to a one-hour time difference, and isopleths can be used to describe the movement of the principal diurnal tidal constituents through the study area.

Harmonic constants are also used to calculate the total amount of water forced into and drawn out of this bay system with the flood and ebb of the tide. Each study site represents a fraction of the bay. As the water level in segment i changes, the product of the increase or decrease in height relative to mean sea level, $\Delta\eta_i$, and the surface area it represents, A_i , provides a volume. The hour-by hour change in volume of the entire bay system is given by:

$$\Delta V = \sum (\Delta\eta_i A_i).$$

Given the harmonic constants for each segment, hourly water levels can be predicted (Schureman 1958), and a time series of bay volume relative to mean sea level can be constructed. The result gives the tidal component of the total exchange of water between the bay system and the inner continental shelf. This information is important for estimating flushing rates for the bay system, and thus it can be an important component of the model validation exercises.

To quantify the response to wind forcing, we employ spectral analysis, using the MatLab software (Little and Shure 1988). Energy density spectra provide information on

the magnitude of the rise and fall in water level at a given periodicity. Thus, an increase in the energy density level (similar to the variance) is expected at periodicities corresponding to the diurnal and semidiurnal tides. Also, one can use energy density spectra to determine the relative importance of, for example, semidiurnal tides, diurnal tides and low-frequency nontidal variations in water level. Spectral analysis also provides coherence spectra. In this study, spectral analyses of wind stress and water level records will indicate the time scales at which the bay system responds most clearly to wind forcing. For model validation purposes, it is important to know the wind conditions to which the bay is most responsive, because the model bay should respond in a similar fashion. Finally, as noted above, spectral analyses provides information on the gain. The gain indicates the magnitude of the rise and fall in water level that occurs in response to a given change in wind stress forcing. This can be useful in model testing and validation exercises when wind conditions are specified so the response can be compared to observations in a quantitative way.

c. Acoustic Doppler Profiler Data

The ADP records consist of near-surface to near-bottom profiles of current speed and direction. The ADP profile begins above a "blanking zone" with an observation that is 69 cm above the top of the instrument. Given the height of the ADP above the bottom, it is estimated that the midpoint of the lowest current observation is 84 cm above the bottom. Current speeds and directions are given for layers having a thickness of 29 cm. The number of layers depends on the mean depth at the study site, and on the tidal and nontidal rise and fall of water level. A pressure reading, representing water depth, is included with each current profile. When a partial layer is indicated above the last full layer, the current speed and direction from the top full layer is extended into the partial layer. This is important for transport calculations.

ADP records are used to generate two-dimensional transport, which is the vertically-summed products of the currents and the layers they represent. The cumulative net transport diagrams are similar to the progressive vector diagrams calculated with wind stress vectors, but transport incorporates the time-varying water depth, and thus it is not just a measure of the current speed at the study site.

ADP data are used in conjunction with wind stress records in spectral analyses to determine the wind conditions most influential in moving water around within these three bays. This is important for model validation, because the model bay should show a similar response to the same wind forcing.

Results

a. Weather Data

A fundamental question at the start of the analysis involves the similarity of the two wind records, and thus the suitability of either wind stress time series to represent conditions at the other location. An 8,333-hour time interval was identified as an overlap period. Data from both locations were available from July 17, 1997 to June 29, 1998, and the two time series were analyzed to determine the similarity of wind conditions. Similarity was quantified by the vector correlation coefficient, and by the mean deflection of the wind stress vector at one location relative to that at the other location.

The vector correlation coefficient was +0.868, and the wind stress vector at Convoy Point was 4.3° to the left of the wind stress vector at Fowey Rocks on average. The mean deflection is within the combined accuracies of the wind directions recorded at the two weather stations. The high correlation coefficient and the similar wind stress headings justifies the decision not to assemble and integrate wind data from several other weather stations in the immediate vicinity of Biscayne Bay, Card Sound and Barnes Sound.

Scalar average wind speeds were calculated from the hourly wind speeds recorded at each location. Both records were adjusted to a common altitude of 10 m above the surface. The mean wind speed at the Fowey Rocks weather station was 6.8 m s^{-1} , while the mean wind speed at the Convoy Point weather station was 4.7 m s^{-1} . Part of the difference may be a result of the nearshore location of the Convoy Point weather station. When winds were out of the northwest and southwest quadrants, there may have been some "wind shadow" effect produced by nearby vegetation and buildings. To examine the possibility of wind shadow effects, scalar averages were calculated a second time, but using only winds out of the northeasterly and southeasterly quadrants. For this subset of the total, the scalar averages for Fowey Rocks and Convoy Point were 6.9 and 5.2 m s^{-1} , respectively. Thus, for all wind speeds, the Convoy Point average is 68% of the Fowey Rocks average, while for onshore winds the Convoy Point average is 75% of the Fowey Rocks average. This suggests that the wind shadow effect plays a small part in the difference between the two means. An alternate possibility, involving the calibration of either or both of the anemometers, could not be tested.

Figure 2. Progressive vector diagram calculated from hourly Fowey Rocks wind stress vectors, June 5, 1997 to June 29, 1998. Monthly annotations appear on the first day of each month.

During this 389-day time period, the resultant wind stress vector had a magnitude of $0.326 \text{ dynes cm}^{-2}$ and a heading of 287.7° . The June through mid September part of the plot shows relatively steady wind out of the southeast (wind stress toward the northwest). The abrupt counterclockwise deflection that occurs on the first day of October is a common feature of wind stress plots from South Florida and the Keys. Clockwise loops in the plot are formed by winds out of the southerly quadrant, preceding frontal passages, followed by winds out of the westerly and northerly quadrants following the frontal passage. Although wind directions are highly variable over time periods on the order of days, over time scales of months to seasons, wind directions are nearly consistently shoreward.

The scalar average wind speed at this location was 6.8 m s^{-1} . Statistical analysis of Fowey Rocks wind stress and wind stress measured simultaneously at Convoy Point, 15 nautical miles (28 km) southwest of Fowey Rocks, indicate that the correlation coefficient of the wind stress vectors was $+0.868$ and that the average deflection of the Convoy Point wind stress vector was 4° to the left of the Fowey Rocks wind stress vector.

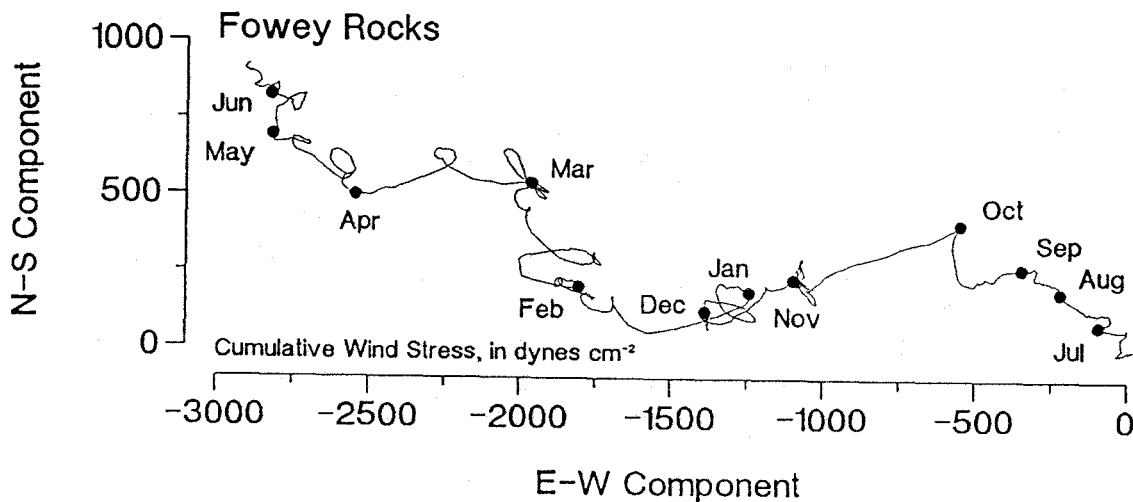


Figure 3. Wind stress data, calculated from weather observations made at Fowey Rocks from June 5, 1997 to June 29, 1998. Shown here are the north-south components (top) and the east-west components (bottom). Data gaps during this time period were short, and with interpolations a continuous record is available for comparison with overlapping segments of water level and ADP data from throughout Biscayne Bay, Card Sound and Barnes Sound.

Wind events, producing "spikes" in the wind stress record, appear through the year in both wind stress components. In general, however, high-frequency fluctuations are greatest during winter months, when cold fronts move through the study area. Wind forcing is noticeably suppressed during summer months.

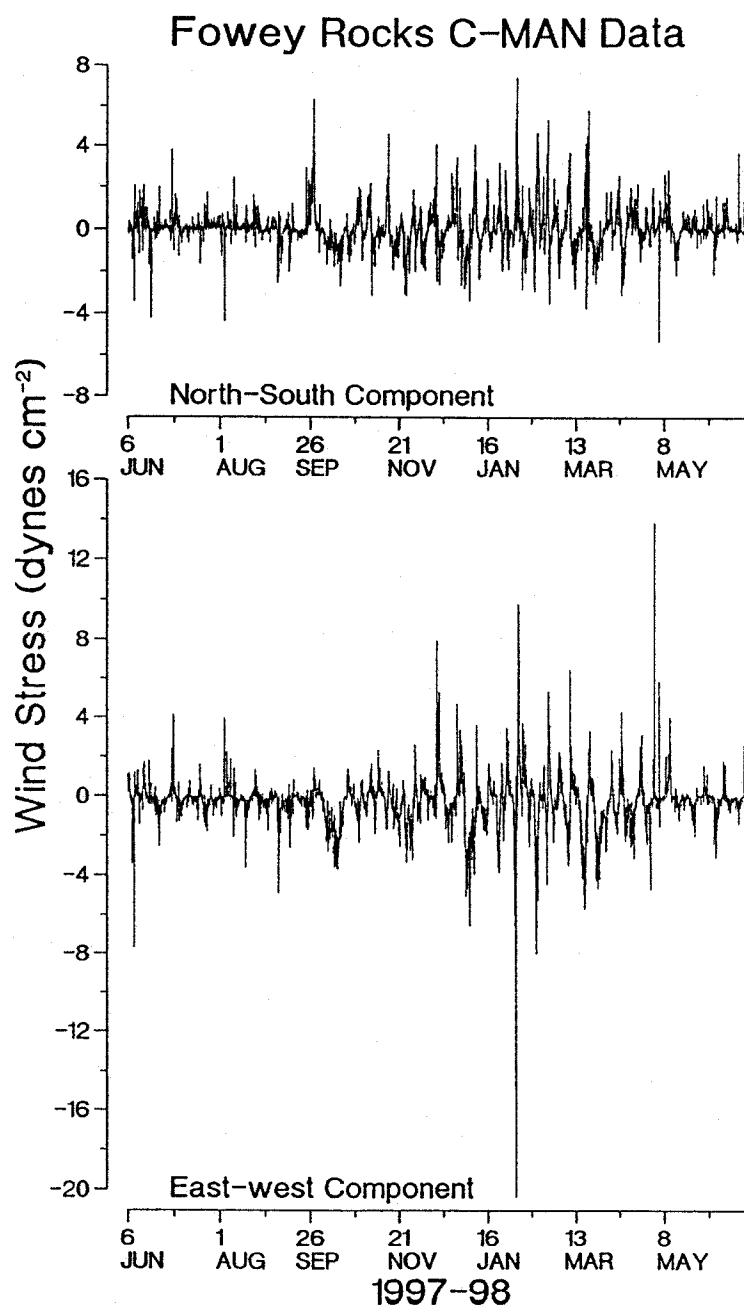


Figure 4. Progressive vector diagram calculated from hourly Convoy Point wind stress vectors, July 17, 1997 to July 8, 1998. Monthly annotations appear on the first day of each month.

During this 356-day time period, the resultant wind stress vector had a magnitude of $0.204 \text{ dynes cm}^{-2}$ and a heading of 283.6° . The scalar average wind speed at this location was 5.1 m s^{-1} . Clockwise loops in the plot are formed by winds out of the southerly quadrant, preceding frontal passages, followed by winds out of the westerly and northerly quadrants following the frontal passage. Many features of the Convoy Point wind stress record are similar to features seen in the Fowey Rocks data.

Statistical analysis of Convoy point wind stress and wind stress measured simultaneously at Fowey Rocks, 15 nautical miles (28 km) northeast of Convoy Point, indicate that the correlation coefficient of the wind stress vectors was $+0.868$, and that the average deflection of the Fowey Rocks wind stress vector was 4° to the right of the Convoy Point wind stress vector.

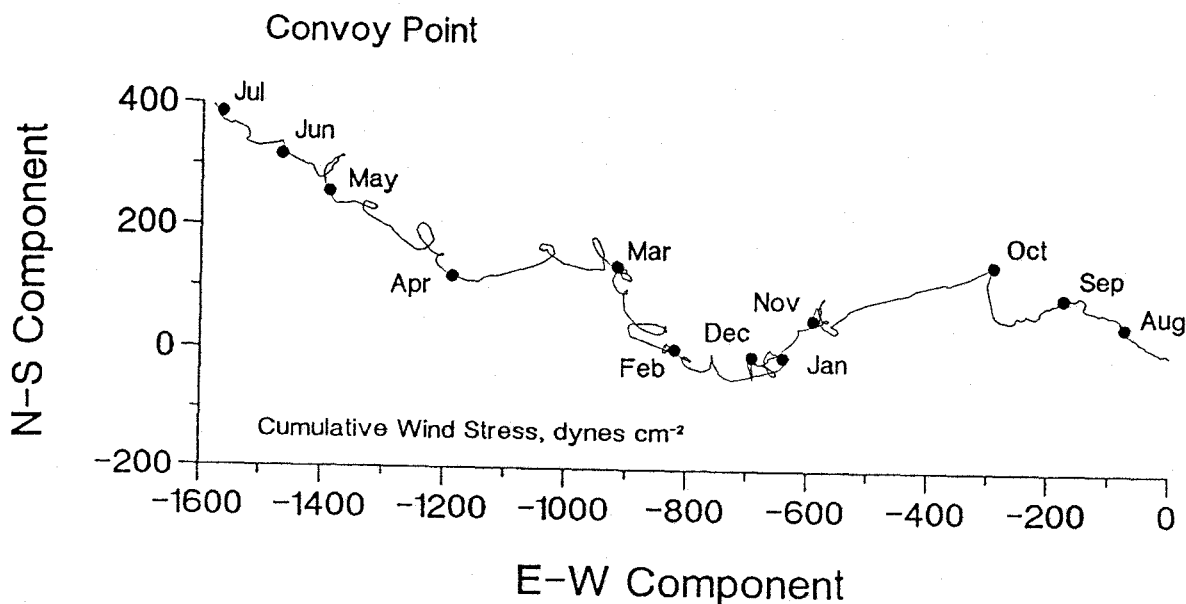
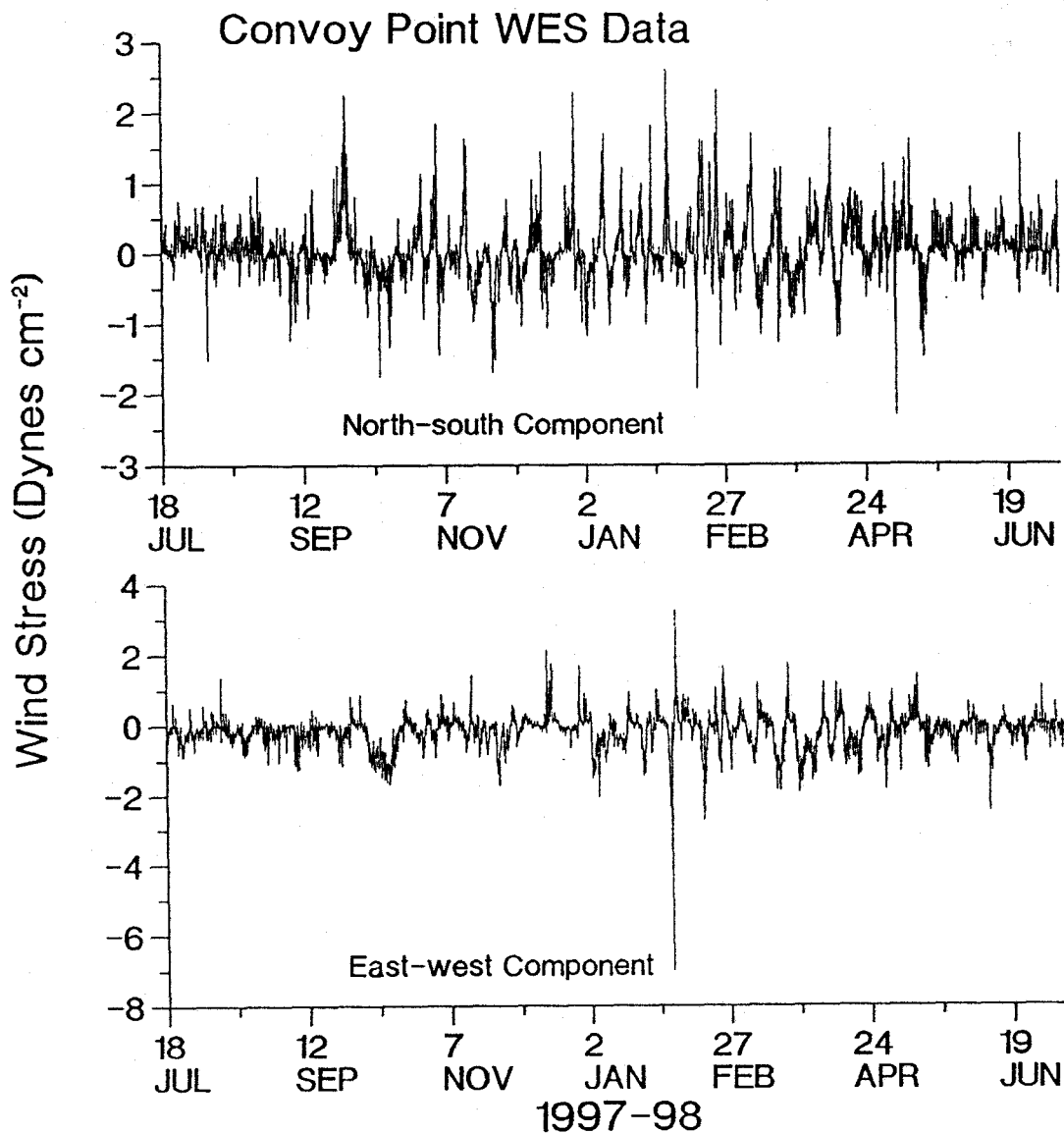


Figure 5. Wind stress data, calculated from weather observations made at Convoy Point from July 17, 1997 to July 8, 1998. Shown here are north-south (top) and east-west (bottom) components. A single continuous record is available for comparison with overlapping segments of ADP data from throughout Card Sound and Biscayne Bay.

Because of the strong westward wind stress in early February, the vertical scales are not the same for the two plots. In general, during summer months both wind stress components show less high-frequency variability. During winter months, variability increases as a result of changes in wind speed and direction associated with frontal passages.



b. Water Level Data

Results of the analysis of the water level data are presented in several ways. First, we provide low-pass filtered plots of the water level records. Each plot is accompanied by a caption that describes the length of the time series, and when and where the data were collected. The analog plots show an increase in the rise and fall in water level during winter months. This is a logical result of cold fronts moving through the study area and producing significant changes in wind speed and direction over time periods on the order of several days. Generally speaking, the plots show that low-frequency fluctuations in water level characteristically occur over time scales on the order of 1-2 weeks.

Second, and accompanying each analog plot, a table summarizes the results of the spectral analysis of the water level record with the Fowey Rocks wind stress data. The table includes the coherence and gain calculated for wind stress components and water level over time scales greater than one day. For example, for the $000-180^\circ$ (north-south) component, with northward wind stress defined positive, a gain of -0.014 at a periodicity of four days indicates that a wind stress of $\pm 1 \text{ dyne cm}^{-2}$ (produced by a wind speed of approximately 8 m s^{-1}) will produce a 0.014 m (1.4 cm) variation in water level. A negative gain indicates that this will be an inverse relationship. Northward (positive) wind stress will set down water levels. For this same four-day periodicity, a southward wind stress would set up water levels by the same amount. The algebraic sign of the gain is a function of periodicity as much as it is a function of the wind stress component. For example, over relatively short time scales, variations in the north-south wind stress component will set-up and set-down water levels at opposite ends of Biscayne Bay. Over longer time scales, however, the north-south wind stress component will produce an Ekman transport away from or toward the coast, and water level will rise or fall similarly everywhere in the bays.

A third way in which we present results of the analysis of water level data is with co-amplitude and co-phase charts for the five principal tidal constituents: M_2 , S_2 , N_2 , K_1 and O_1 . The semidiurnal (with subscript "2") M_2 constituent occurs as the earth rotates through the high water created by gravitational (near side, directly under the moon) and centrifugal (opposite side) forces that arise as the earth and moon rotate around a common center of mass. The S_2 constituent is created to interact with the M_2 constituent in such a way as to explain the fortnightly fluctuation in tidal range arising from the additive or subtractive effects of the sun's gravitational force—additive at times of new and full moon; subtractive at times of first and third quarter). The N_2 constituent is created to interact with the M_2 constituent in such a way as to explain the monthly fluctuation in tidal range as the moon passes through apogee, then perigee in its elliptical orbit around the earth. The diurnal (with subscript "1") K_1 and O_1 constituents are created to explain the fortnightly increase and decrease in tidal range associated with the moon's declination (the high tides induced by gravitational and centrifugal forces will be in opposite hemispheres).

The fourth way in which we present results of our analysis of the water level data base is in the form of histograms of flood and ebb tide volumes. Results should be of use in flushing studies, where flood and ebb intertidal volumes must be compared with the total volumes of the bay.

Figure 6. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-1 (**Manatee Bay**), June 6, 1997 to June 30, 1998. Due to breaks in the record, the plot is in three parts: June 6, 1997 to February 14, 1998 (6080 observations); February 17 to March 29, 1998 (960 observations) and April 1 to June 30, 1998 (2172 observations). Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

Note that the high water level recorded in late January and early February 1998 corresponds to the strong westward wind stress recorded at both weather stations (see Figs. 3 and 5).

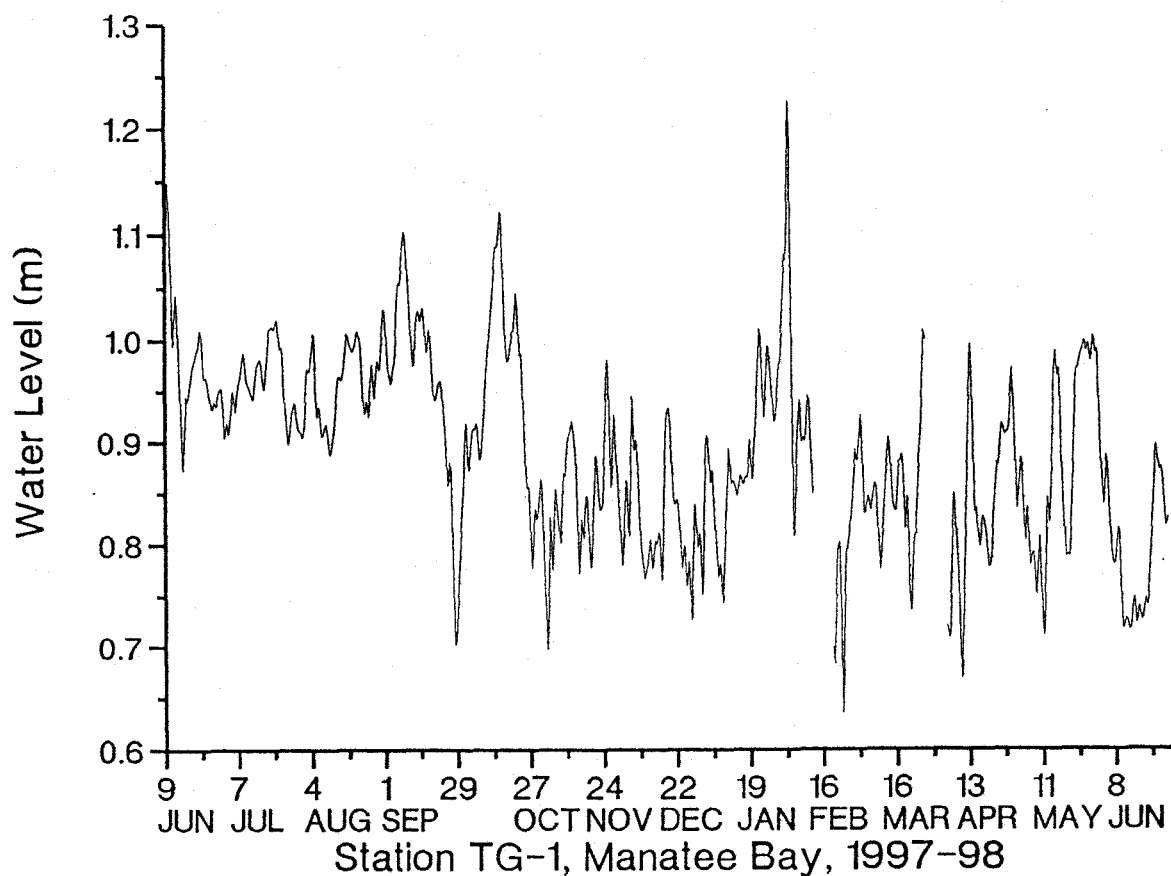


Table 2. Coherence of water levels at Station TG-1 and wind stress, calculated from data recorded June 6, 1997 to February 14, 1998. Bold numbers indicate coherence significant at the 95% confidence limit ($\beta_{05} = 0.307$); bold italicized numbers indicate coherence significant at the 99% limit ($\beta_{01} = 0.376$). The magnitude of the transfer function ("gain") is shown in parentheses beside coherence values when coherence is statistically significant. Each wind stress column is labeled with two compass headings that are 180° apart. The algebraic sign of the gain corresponds to the first compass heading. For example, a gain of -0.041 indicates that a northward wind stress reaching a magnitude of 1 dyne cm⁻² would produce a set down of water level reaching -0.041 m, or -4.1 cm.

Relatively few coherences are highly significant at this southernmost study site. The mostly negative gains indicate that northward wind stress will set down water levels in Manatee Bay.

Period (d)	000-180°	030-210°	060-240°	090-270°	120-300°	150-330°
16	.273	.291	.198	.154	.159	.199
8	.281	.323(-.041)	.203	.048	.059	.168
5.8	.256	.422(-.037)	.397(-.043)	.135	.054	.119
4	.359(-.014)	.621(-.040)	.668(-.044)	.507(-.034)	.342(-.022)	.261
3.2	.238	.429(-.034)	.458(-.033)	.376(-.028)	.258	.162
2.7	.162	.338(-.024)	.387(-.027)	.391(-.027)	.178	.064
2.3	.264	.470(-.023)	.443(-.025)	.280	.100	.051
2	.354(-.014)	.484(-.022)	.464(-.030)	.233	.047	.172
1.8	.550(-.023)	.622(-.041)	.530(-.048)	.369(-.038)	.322(-.018)	.410(.003)
1.6	.622(-.014)	.642(-.029)	.417(-.035)	.222	.273	.451(.001)
1.5	.408(-.018)	.311(-.021)	.030	.060	.214	.339(.014)
1.3	.621(-.005)	.542(-.012)	.159	.005	.123	.338(.006)
1.2	.536(-.005)	.475(-.010)	.230	.066	.121	.346(-.001)
1.13	.171	.266	.207	.057	.014	.066
1.08	.033	.075	.071	.020	.002	.008
1.0	.055	.102	.077	.038	.025	.029

Figure 7. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-2 (**Card Sound Bridge**), June 13, 1997 to June 30, 1998. Due to a break in the record, the plot is in two parts: June 13, 1997 to February 14, 1998 (5913 observations) and February 17 to June 30, 1998 (3203 observations). Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

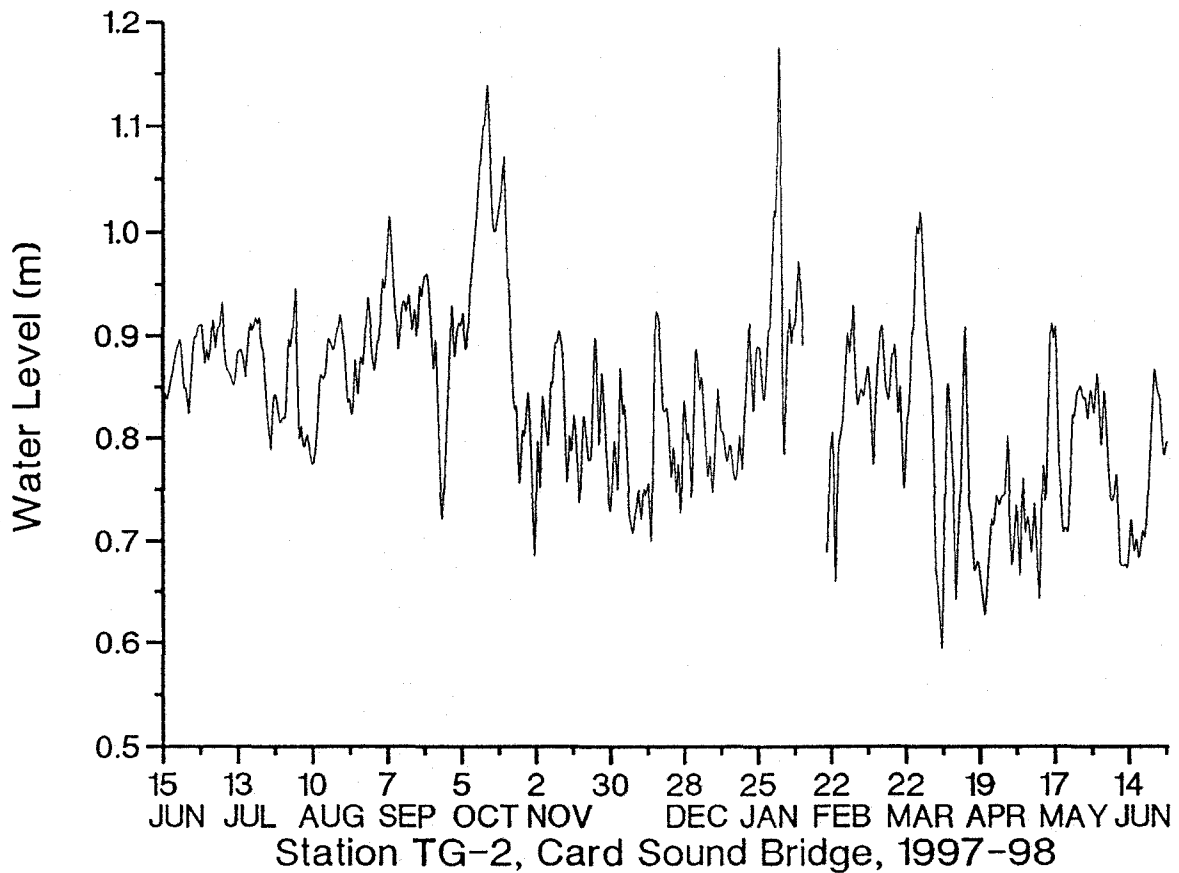


Table 3. Same as Table 1 except for Station TG-2 at Card Sound Bridge, between Little Card Sound and Barnes Sound. The spectral analysis covers the time period from June 13, 1997 to Feb. 14, 1998 ($\beta_{05}=0.312$, $\beta_{01}=0.381$).

Highest coherences occur for winds out of the northeasterly quadrant and over time scales on the order 2-8 days. This indicates a response to both a direct downwind transport, and to a shoreward Ekman transport across the shelf forced by southward wind stress.

<u>Period (d)</u>	<u>000-180°</u>	<u>030-210°</u>	<u>060-240°</u>	<u>090-270°</u>	<u>120-300°</u>	<u>150-330°</u>
16	.307	.353(-.044)	.305	.259	.231	.234
8	.527(-.012)	.620(-.044)	.512(-.040)	.420(-.032)	.372(-.026)	.383(-.018)
5.8	.374(.004)	.572(-.028)	.527(-.031)	.426(-.026)	.342(-.024)	.291
4	.407(.002)	.643(-.027)	.601(-.026)	.519(-.024)	.424(-.025)	.316(-.027)
3.2	.194	.556(-.022)	.578(-.022)	.468(-.019)	.348(-.018)	.217
2.7	.097	.446(-.016)	.540(-.017)	.465(-.017)	.317(-.016)	.102
2.3	.397(.004)	.597(-.017)	.605(-.205)	.496(-.026)	.369(-.025)	.292
2	.352(.0004)	.690(-.018)	.532(-.027)	.319(-.023)	.197	.196
1.8	.330(-.004)	.563(-.013)	.456(-.016)	.207	.057	.088
1.6	.336(.001)	.452(-.006)	.310	.178	.070	.042
1.5	.339(-.018)	.334(-.014)	.150	.038	.016	.115
1.3	.342(-.010)	.653(-.010)	.575(-.008)	.428(-.007)	.232	.001
1.2	.355(-.022)	.593(-.013)	.521(-.002)	.386(-.003)	.266	.198
1.13	.229	.284	.239	.125	.011	.073
1.08	.084	.078	.045	.017	.007	.038
1.0	.361(.027)	.194	.060	.093	.218	.345(-.033)

Figure 8. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-3 (**Angelfish Creek**), June 6, 1997 to June 30, 1998. Due to a break in the record, the plot is in two parts: June 6, 1997 to January 24, 1998 (5564 observations) and February 18 to June 30, 1998 (3178 observations). Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

The seasonal variation in sea level is a more prominent feature of this plot, with high water levels in late fall and low water levels in winter months. The several week period of high water level in March, and the several week period of low water level in late April and early May are significant departures from the normal annual cycle in sea level.

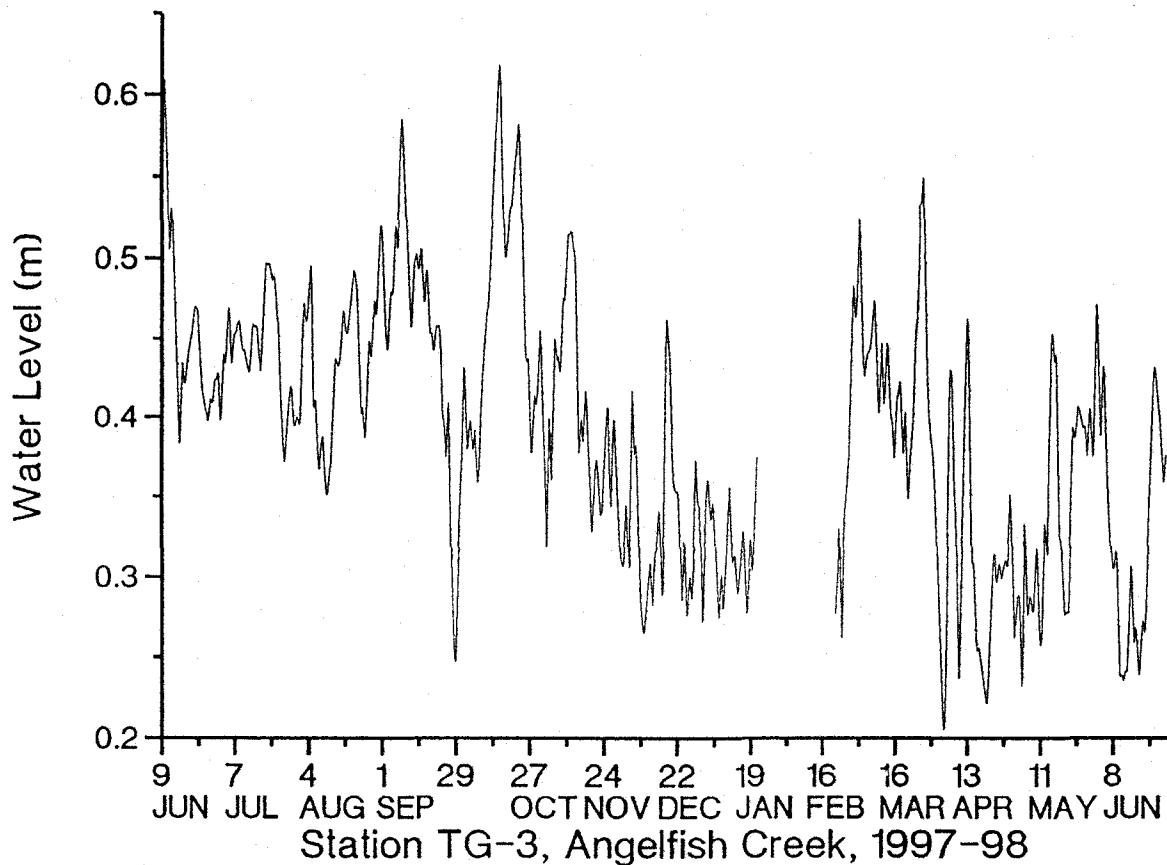


Table 4. Same as Table 1 except for Station TG-3, at the mouth of Angelfish Creek in northern Card Sound. Study period spans June 6, 1997 to Jan. 24, 1998 ($\beta_{05} = 0.321$, $\beta_{01} = 0.393$).

A notable feature of this table is the absence of significant coherence at periodicities in excess of about three days for all wind stress components. This study site is near the western end of Angelfish Creek. Thus, it is likely that water level variations are a response to both local forcing within the Biscayne Bay system and to more regional scale forcing acting on shelf waters and forcing water through Angelfish Creek.

<u>Period (d)</u>	<u>000-180°</u>	<u>030-210°</u>	<u>060-240°</u>	<u>090-270°</u>	<u>120-300°</u>	<u>150-330°</u>
16	.153	.091	.093	.139	.174	.184
8	.158	.127	.053	.022	.088	.144
5.8	.104	.107	.050	.001	.027	.071
4	.107	.247	.276	.164	.055	.027
3.2	.011	.113	.190	.171	.101	.024
2.7	.075	.183	.357(-.016)	.409(-.020)	.323(-.021)	.164
2.3	.129	.371(-.015)	.465(-.019)	.367(-.019)	.166	.022
2	.244	.394(-.025)	.449(-.032)	.281	.027	.073
1.8	.465(-.029)	.486(-.039)	.348(-.038)	.193	.211	.341(.015)
1.6	.443(.014)	.431(-.023)	.253	.114	.183	.331(.005)
1.5	.320	.242	.042	.027	.160	.272
1.3	.613(-.020)	.588(-.018)	.351(-.012)	.062	.090	.405(.019)
1.2	.445(-.006)	.453(-.005)	.304	.074	.029	.263
1.13	.053	.165	.212	.117	.029	.006
1.08	.023	.049	.115	.114	.078	.043
1.0	.109	.139	.052	.002	.011	.049

Figure 9. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-4 (**Military Canal - East**), June 6, 1997 to June 30, 1998. Due to a break in the record, the plot is in two parts: June 6 to December 8, 1997 (4437 observations) and January 7 to June 30, 1998 (4189 observations). Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

The seasonal rise and fall in sea level is well defined at this location, with highest water levels in fall months and lowest water levels in late winter and early spring. Highest water level was recorded in early February in response to strong shoreward wind stress (see Figs. 3 and 5).

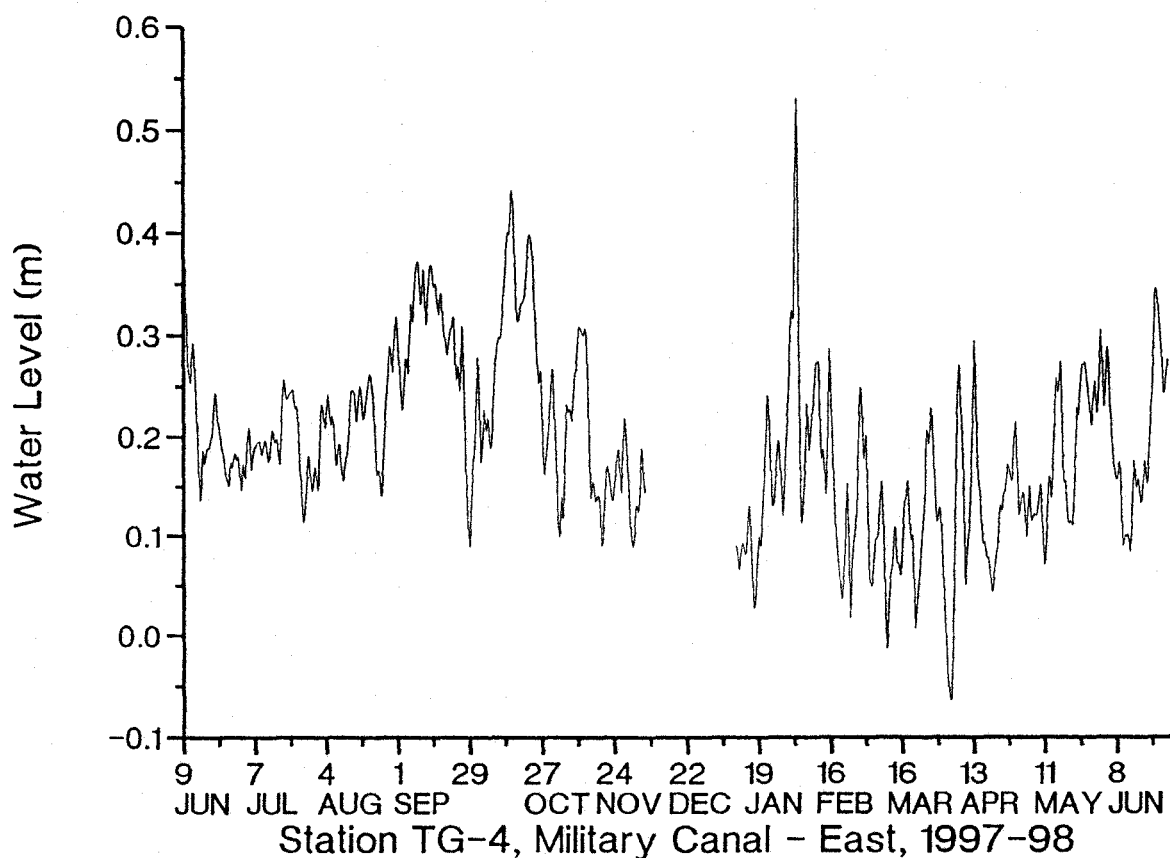


Table 5. Same as Table 1 except for Station TG-4, in south-central Biscayne Bay. This analysis included data from June 6 to Dec. 8, 1997 ($\beta_{05} = 0.360$, $\beta_{01} = 0.438$).

High coherence occurs infrequently, and primarily at periodicities on the order of 1-2 days. Water levels seem most responsive to winds out of the northeast and southwest quadrants.

<u>Period (d)</u>	<u>000-180°</u>	<u>030-210°</u>	<u>060-240°</u>	<u>090-270°</u>	<u>120-300°</u>	<u>150-330°</u>
16	.189	.072	.012	.041	.113	.190
8	.198	.147	.077	.019	.034	.156
5.8	.376(.009)	.286	.271	.309	.406(.044)	.486(-.041)
4	.084	.216	.319	.356	.309	.147
3.2	.004	.094	.174	.211	.196	.086
2.7	.163	.228	.321	.433(-.057)	.393(-.066)	.178
2.3	.249	.301	.300	.232	.088	.129
2	.162	.206	.215	.149	.041	.088
1.8	.408(-.035)	.448(-.038)	.396(-.035)	.297	.200	.252
1.6	.477(-.018)	.459(-.035)	.334(-.037)	.247	.256	.359
1.5	.222	.213	.080	.010	.066	.153
1.3	.414(-.029)	.607(-.027)	.655(-.027)	.561(-.029)	.209	.057
1.2	.481(-.012)	.605(-.014)	.649(-.017)	.580(-.025)	.181	.210
1.13	.037	.066	.101	.112	.082	.042
1.08	.081	.059	.089	.139	.154	.126
1.0	.244	.249	.147	.069	.083	.161

Figure 10. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-5 (**Military Canal - West**), July 10, 1997 to June 30, 1998. Due to a break in the record, the plot is in two parts: July 10, 1997 to March 28, 1998 (6260 observations) and April 1 to June 30, 1998 (2170 observations). Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

Prominent features in this plot are the seasonal cycle, with autumn high and mid-winter low water levels, and the transient high water event in early February, in response to strong shoreward winds.

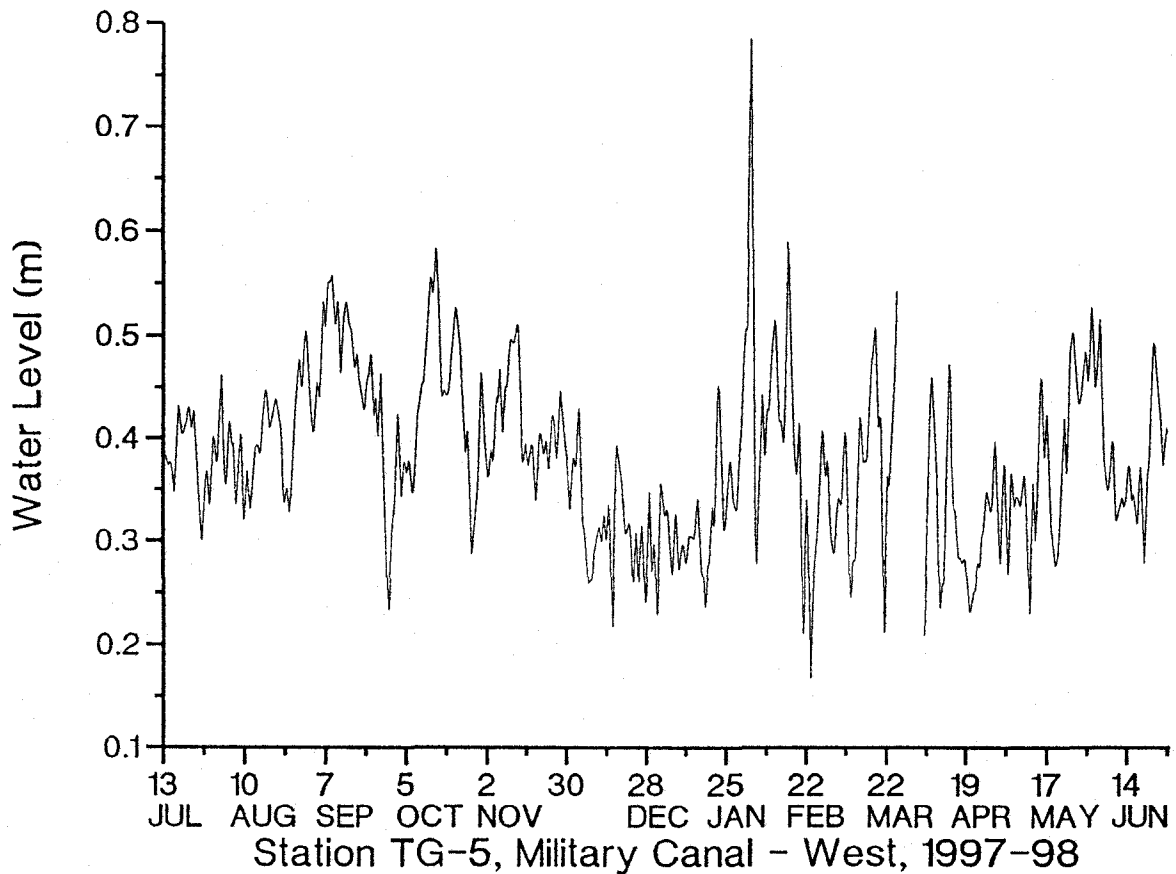


Table 6. Same as Table 1 except for Station TG-5, in west-central Biscayne Bay. Study period spans July 10, 1997 to Mar. 28, 1998 ($\beta_{05} = 0.303$, $\beta_{01} = 0.371$).

Highest coherences are confined largely to periodicities of approximately 2-6 days. The dominance of negative gains for most wind stress components indicate that bay water levels rise in direct response to westward winds, or southward winds producing a shoreward Ekman transport.

Period (d)	000-180°	030-210°	060-240°	090-270°	120-300°	150-330°
16	.094	.155	.306(-.038)	.312(-.029)	.264	.188
8	.055	.063	.231	.273	.242	.168
5.8	.312(.016)	.321(-.005)	.437(-.027)	.532(-.027)	.491(-.030)	.402(-.025)
4	.346(.007)	.367(-.011)	.396(-.023)	.403(-.018)	.388(-.026)	.361(-.021)
3.2	.245	.342(-.018)	.317(-.021)	.229	.157	.152
2.7	.427(-.001)	.477(-.019)	.516(-.037)	.488(-.040)	.432(-.028)	.409(-.014)
2.3	.574(.013)	.663(-.014)	.684(-.033)	.626(-.037)	.565(-.034)	.537(-.028)
2	.310(-.0003)	.367(-.016)	.435(-.031)	.422(-.033)	.352(-.024)	.305(-.012)
1.8	.113	.219	.407(-.041)	.378(-.033)	.272	.129
1.6	.127	.215	.203	.090	.024	.045
1.5	.023	.164	.293	.197	.099	.035
1.3	.125	.204	.317(-.026)	.307(-.025)	.236	.160
1.2	.070	.223	.382(-.024)	.424(-.029)	.314(-.028)	.119
1.13	.088	.077	.115	.180	.179	.130
1.08	.132	.097	.058	.088	.116	.132
1.0	.097	.135	.055	.012	.007	.031

Figure 11. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-6 (**Marker 8 - Black Point**) June 6, 1997 to June 30, 1998. There are no breaks in this record, and the 9346 observations are continuous. Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

The prominent feature in this water level record is the period of sustained high water through most of the month of October. This raises the normal seasonal high water in autumn months by about 0.2 m. The mid-to-late winter low water is shortened by an increase in water level in late January.

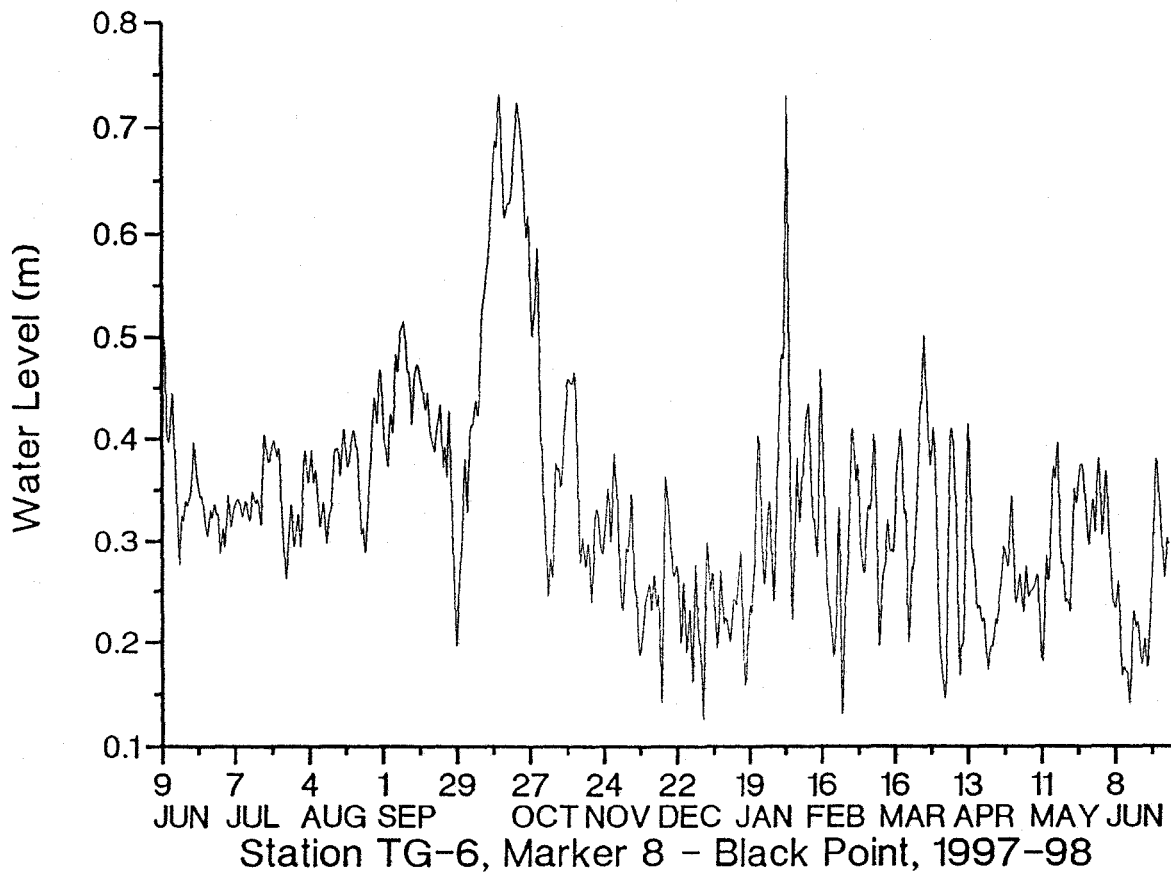


Table 7. Same as Table 1 except for Station TG-6 in west-central Biscayne Bay. The analysis covers the time period from June 6, 1997 to June 29, 1998 ($\beta_{05} = 0.248$, $\beta_{01} = 0.305$).

Highest coherences are broadly distributed, and highly significant relationships occur at nearly all periodicities. The core of highest coherence is found for periodicities on the order of 2-6 days and for winds out of the northeasterly and easterly quadrants. This indicates a response to the direct shoreward transport of water, and a shoreward Ekman transport.

Period (d)	000-180°	030-210°	060-240°	090-270°	120-300°	150-330°
16	.193	.257(-.042)	.351(-.049)	.337(-.035)	.293(-.026)	.239
8	.129	.197	.263(-.041)	.224	.163	.127
5.8	.229	.264(-.011)	.431(-.034)	.498(-.039)	.441(-.035)	.329(-.028)
4	.379(.019)	.417(-.016)	.562(-.034)	.627(-.038)	.607(-.039)	.510(-.037)
3.2	.299(.010)	.338(-.014)	.402(-.025)	.418(-.027)	.395(-.026)	.345(-.023)
2.7	.293(.005)	.369(-.019)	.407(-.030)	.388(-.033)	.336(-.032)	.284(-.025)
2.3	.215	.381(-.016)	.466(-.029)	.421(-.031)	.320(-.031)	.214
2	.134	.243	.280(-.021)	.213	.122	.081
1.8	.210	.338(-.028)	.327(-.030)	.212	.114	.104
1.6	.156	.328(-.030)	.407(-.035)	.323(-.030)	.188	.104
1.5	.019	.277(-.033)	.443(-.037)	.358(-.028)	.209	.061
1.3	.259(-.002)	.575(-.021)	.694(-.030)	.523(-.028)	.295(-.022)	.161
1.2	.206	.476(-.019)	.716(-.032)	.659(-.033)	.393(-.027)	.179
1.13	.046	.108	.284(-.036)	.362(-.046)	.269(-.040)	.127
1.08	.049	.039	.160	.213	.183	.121
1.0	.073	.097	.051	.018	.016	.034

Figure 12. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-7 (**Snapper Creek**), July 10, 1997 to June 30, 1998. Due to breaks in the record, the plot is in three parts: July 10-29, 1997 (456 observations), September 10, 1997 to February 2, 1998 (3487 observations) and February 6 to June 30, 1998 (3469 observations). Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

The early February 1998 transient peak is missing because of the break in the record. The fall maximum is not much higher than the mid July water levels recorded in the first segment of the data. Midwinter low water levels are broadly distributed between early December and late January.

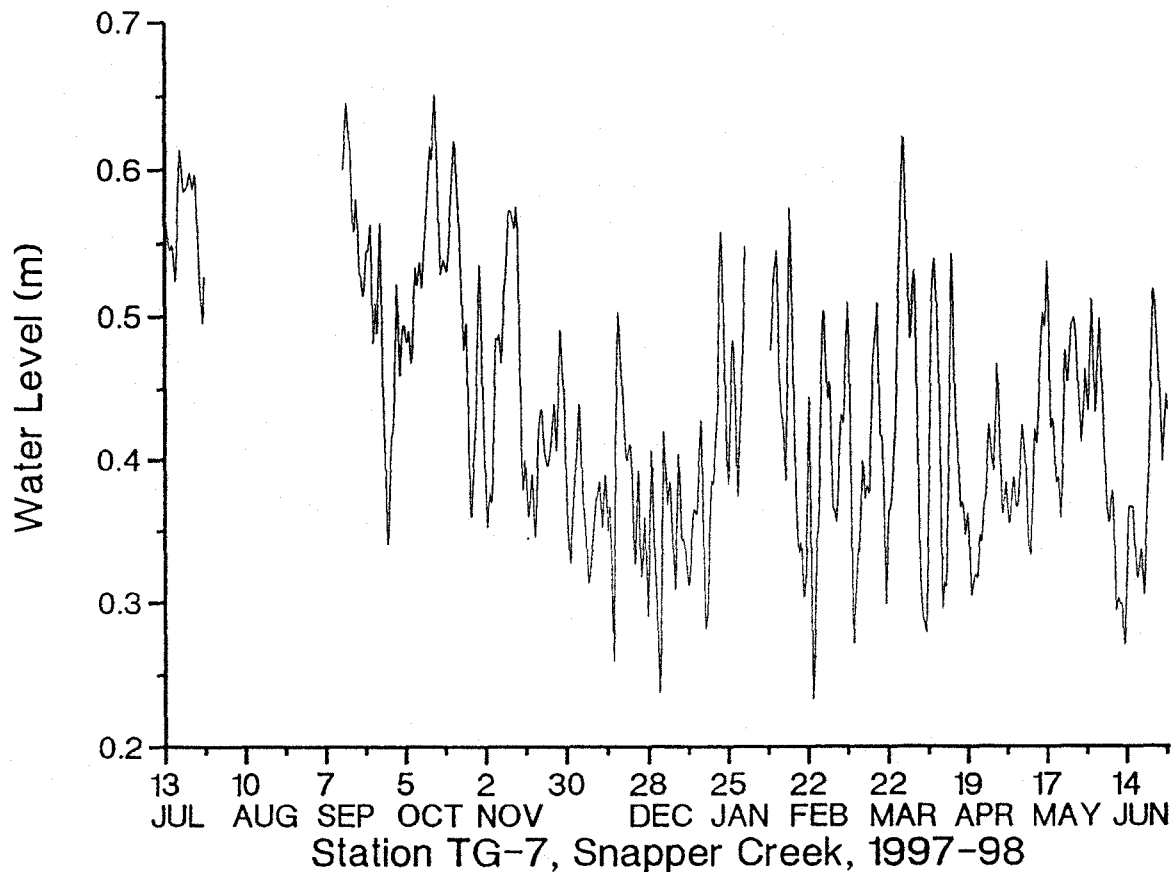


Table 8. Same as Table 1 except for Station TG-7, in west-central Biscayne Bay. The analysis covers the time period from September 1, 1997 to February 2, 1998 ($\beta_{05} = 0.406$, $\beta_{01} = 0.491$).

The table is noteworthy for the relatively small core of high coherences, covering periodicities of 2-6 days and for winds out of the easterly and westerly quadrants. A second region of high coherence is limited to periodicities of just over one day, but it includes some of the highest coherence levels found in data from this study site.

<u>Period (d)</u>	<u>000-180°</u>	<u>030-210°</u>	<u>060-240°</u>	<u>090-270°</u>	<u>120-300°</u>	<u>150-330°</u>
16	.100	.026	.215	.308	.304	.240
8	.083	.020	.017	.111	.156	.136
5.8	.295	.258	.435(-.018)	.589(-.040)	.505(-.034)	.391
4	.341	.377	.631(-.032)	.751(-.038)	.692(-.037)	.523(-.032)
3.2	.184	.263	.483(-.023)	.601(-.028)	.589(-.031)	.418(-.030)
2.7	.234	.171	.331	.504(-.030)	.594(-.036)	.502(-.037)
2.3	.272	.380	.536(-.035)	.585(-.041)	.529(-.043)	.386
2	.074	.134	.210	.247	.123	.049
1.8	.213	.276	.230	.073	.047	.123
1.6	.180	.176	.163	.160	.170	.177
1.5	.079	.011	.070	.161	.154	.125
1.3	.084	.209	.593(-.028)	.623(-.027)	.445(-.021)	.237
1.2	.164	.442(-.020)	.746(-.033)	.774(-.035)	.559(-.031)	.261
1.13	.037	.025	.181	.277	.229	.132
1.08	.230	.201	.105	.141	.187	.215
1.0	.038	.143	.219	.151	.087	.044

Figure 13. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-8 (**Gables by the Sea**), June 12, 1997 to June 29, 1998. Due to a break in the record, the plot is in two parts: June 12, 1997 to March 18, 1998 (6696 observations) and March 26 to June 29, 1998 (2281 observations). Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

The fall maximum water level stands out prominently from both midsummer and mid-winter levels. The highest water levels, occurring in October, are less clearly defined they were at Station TG-6 (Fig. 11), and the early February spike stands out as the highest point in the series of filtered water levels.

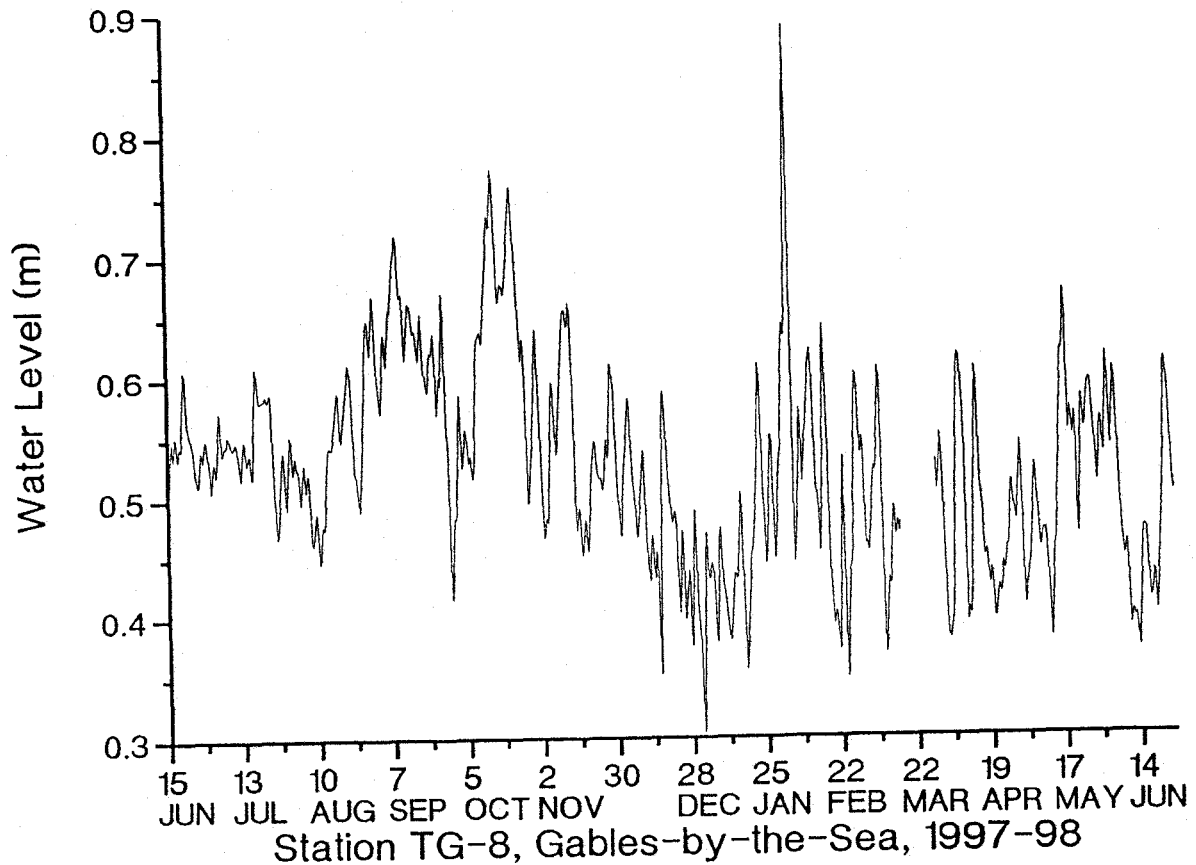


Table 9. Same as Table 1 except for Station TG-8, in north-central Biscayne Bay. The analysis covers the time period from June 12, 1997 to March 18, 1998 ($\beta_{05} = 0.293$, $\beta_{01} = 0.359$).

Highly significant coherences are found for virtually all wind stress components at periodicities of between 2 and 8 days. The negative gains indicate that northward and eastward wind stress will set down water levels along the west side of Biscayne Bay.

Period (d)	000-180°	030-210°	060-240°	090-270°	120-300°	150-330°
16	.365(.011)	.260	.223	.245	.285	.339(-.025)
8	.535(.028)	.518(-.016)	.437(-.034)	.419(-.033)	.432(-.032)	.468(-.034)
5.8	.579(.036)	.548(.003)	.501(-.033)	.510(-.035)	.532(-.034)	.557(-.036)
4	.389(.019)	.427(-.008)	.473(-.024)	.476(-.027)	.543(-.028)	.416(-.028)
3.2	.373(.022)	.413(-.004)	.581(-.026)	.623(-.029)	.577(-.029)	.482(-.028)
2.7	.260	.371(-.009)	.457(-.021)	.428(-.024)	.344(-.023)	.266
2.3	.576(.023)	.587(-.004)	.646(-.027)	.679(-.037)	.667(-.039)	.622(-.036)
2	.488(.027)	.458(-.004)	.623(-.032)	.739(-.042)	.734(-.042)	.635(-.040)
1.8	.240	.137	.338(-.035)	.533(-.044)	.557(-.043)	.444(-.039)
1.6	.279	.197	.283	.369(-.029)	.420(-.033)	.410(-.036)
1.5	.085	.106	.427(-.029)	.500(-.026)	.440(-.024)	.301(-.023)
1.3	.155	.270	.546(-.028)	.657(-.029)	.622(-.032)	.354(-.032)
1.2	.082	.240	.58.4(-.030)	.711(-.028)	.638(-.025)	.381(-.019)
1.13	.006	.040	.086	.115	.091	.024
1.08	.009	.023	.044	.054	.049	.027
1.0	.159	.094	.014	.008	.056	.124

Figure 14. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-9 (Biscayne Channel - Marker 10), June 12, 1997 to June 29, 1998. There are no breaks in this record, and the 9167 observations are continuous. Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

This record from the northern and more isolated part of Biscayne Bay shows the same seasonal cycle in sea level, but the pattern is significantly offset in the direction of higher water levels. The indicated mean water level at Station TG-9 is nearly 1.5 m higher than the means indicated at stations along the west side of Biscayne Bay. This calls into question the leveling and the datum used for the readings, but it does not affect the calculations of tidal amplitudes, nor the spectral analyses with wind data.

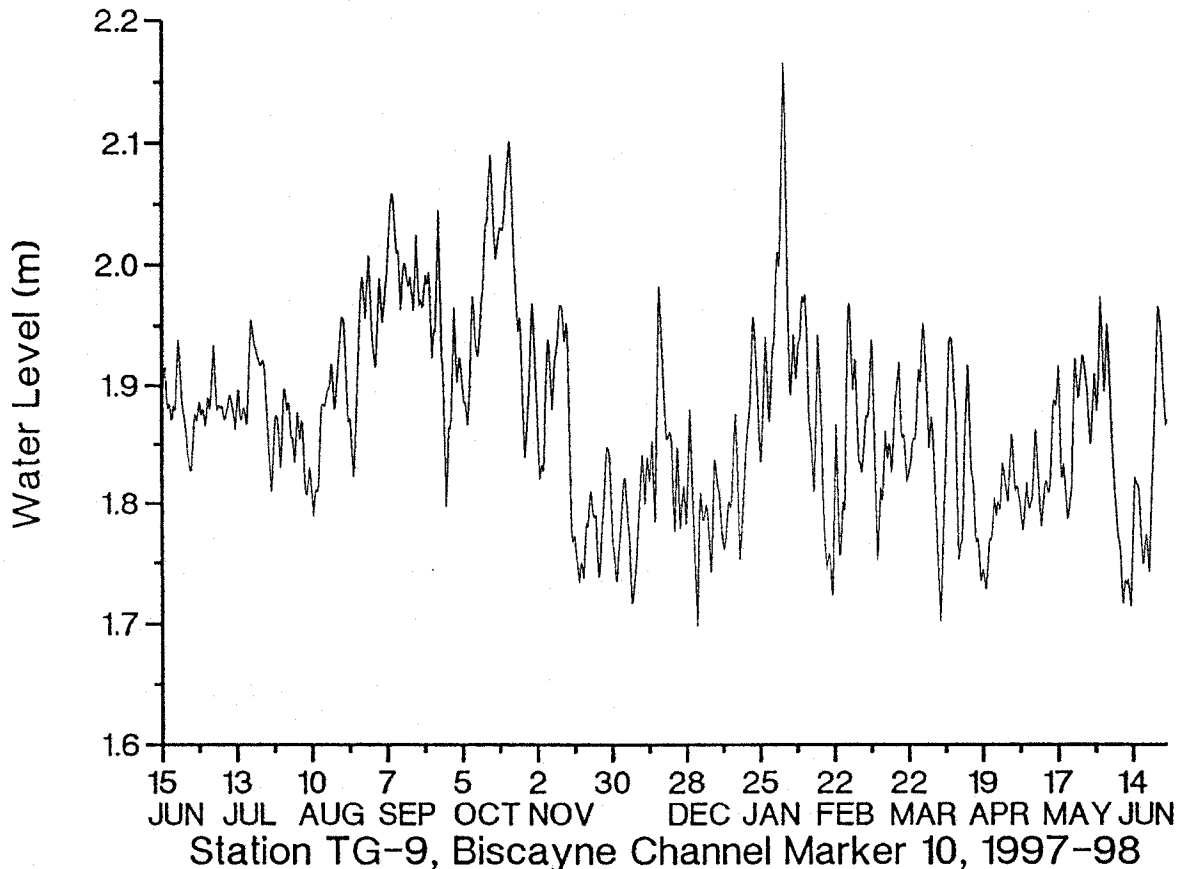


Table 10. Same as Table 1 except for Station TG-9, at the northern end of the Safety Valve and at the entrance to Biscayne Bay. The analysis covers the time period from June 12, 1997 to June 29, 1998 ($\beta_{05} = 0.250$, $\beta_{01} = 0.308$).

Significant coherence levels are relatively infrequent at this location. A band of highly significant coherences occurs at periodicities at and just over two days, and for all wind stress components. Few occurrence of significant coherence are found at the longest periodicities.

<u>Period (d)</u>	<u>000-180°</u>	<u>030-210°</u>	<u>060-240°</u>	<u>090-270°</u>	<u>120-300°</u>	<u>150-330°</u>
16	.121	.061	.056	.078	.103	.126
8	.284(.019)	.228	.161	.159	.178	.219
5.8	.323(.024)	.273(-.001)	.214	.224	.253(-.021)	.288(-.024)
4	.246	.269(.002)	.239	.210	.199	.210
3.2	.202	.165	.185	.217	.233	.231
2.7	.166	.188	.167	.133	.119	.133
2.3	.317(.017)	.342(.003)	.402(-.012)	.420(-.020)	.393(-.022)	.349(-.022)
2	.300(.016)	.294(-.002)	.434(-.021)	.517(-.028)	.489(-.027)	.400(-.024)
1.8	.166	.132	.224	.309(-.026)	.312(-.023)	.254(-.018)
1.6	.190	.140	.126	.151	.184	.206
1.5	.100	.026	.195	.298(-.015)	.311(-.015)	.251(-.016)
1.3	.017	.059	.183	.259(-.010)	.281(-.011)	.202
1.2	.032	.034	.171	.255(-.011)	.251(-.010)	.163
1.13	.067	.059	.054	.059	.070	.074
1.08	.071	.053	.089	.124	.132	.112
1.0	.067	.085	.055	.029	.024	.037

Figure 15. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-10 (Miami River), December 15, 1997 to June 25, 1998. This is an abbreviated record, but there are no breaks and the 4605 observations are continuous. Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

This approximately six-month time period misses the autumn high water level, but it includes the midwinter low water. The rise in water level starting in mid April is interrupted in early June, and water levels drop back temporarily to midwinter levels.

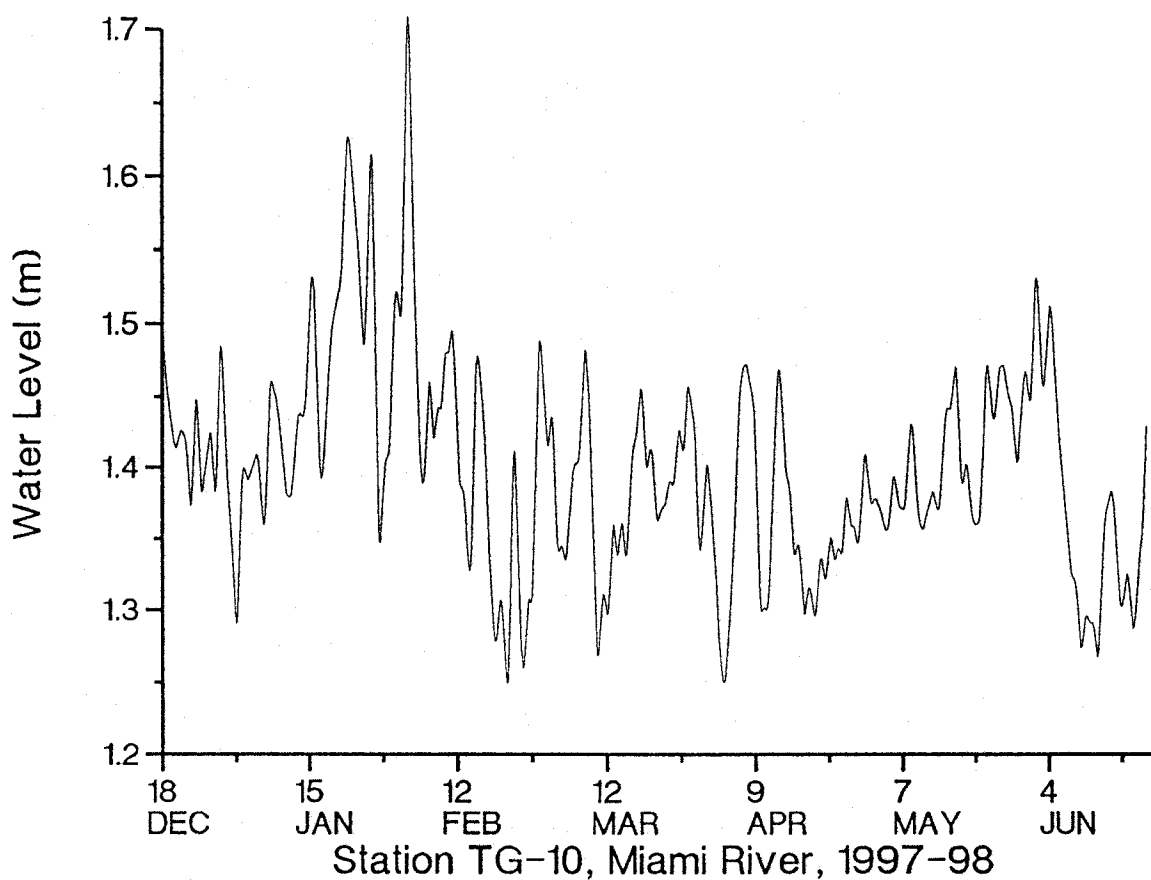


Table 11. Same as Table 1 except for Station TG-10 in northern Biscayne Bay. The analysis covers the time period from December 15, 1997 to June 25, 1998 ($\beta_{05} = 0.353$, $\beta_{01} = 0.430$).

Significant coherences are scattered irregularly through the table, though most occur in the 2-6 day band and for winds out of the easterly quadrant. A second region of high coherence occurs over periodicities on the order of 1-1.5 days, but for the same wind components.

<u>Period (d)</u>	<u>000-180°</u>	<u>030-210°</u>	<u>060-240°</u>	<u>090-270°</u>	<u>120-300°</u>	<u>150-330°</u>
16	.157	.138	.341	.389(-.027)	.360(-.023)	.286
8	.191	.236	.348	.337	.278	.234
5.8	.325	.311	.366(-.015)	.403(-.026)	.396(-.028)	.366(-.028)
4	.550(.040)	.474(.014)	.506(-.012)	.563(-.023)	.602(-.030)	.609(-.038)
3.2	.399(.026)	.436(.018)	.420(.002)	.390(-.007)	.370(-.014)	.369(-.021)
2.7	.283	.246	.152	.117	.138	.205
2.3	.433(.042)	.418(.018)	.374(-.009)	.364(0.019)	.373(-.026)	.398(-.035)
2	.109	.295	.278	.193	.129	.117
1.8	.008	.031	.037	.024	.010	.001
1.6	.136	.086	.018	.009	.043	.099
1.5	.088	.171	.329	.343	.305	.222
1.3	.193	.244	.441(-.014)	.490(-.017)	.435(-.018)	.322
1.2	.368(.017)	.170	.230	.408(-.016)	.510(-.018)	.500(-.019)
1.13	.226	.060	.122	.402(-.062)	.531(-.066)	.430(-.056)
1.08	.183	.031	.152	.316	.357(-.076)	.313
1.0	.093	.137	.094	.050	.036	.048

Figure 16. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-11 (**Julia Tuttle Causeway - Marker 35**) August 1, 1997 to June 30, 1998. Due to breaks in the record, the plot is in two parts: August 1 to December 3, 1997 (2974 observations) and January 27 to June 30, 1998 (3707 observations). Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

The midwinter low water levels are missing from this plot, due to the gap during December and January, but an irregular fall maximum is apparent. The record begins again shortly before the transient high water in early February, then water level remains variable but low through the end of the record.

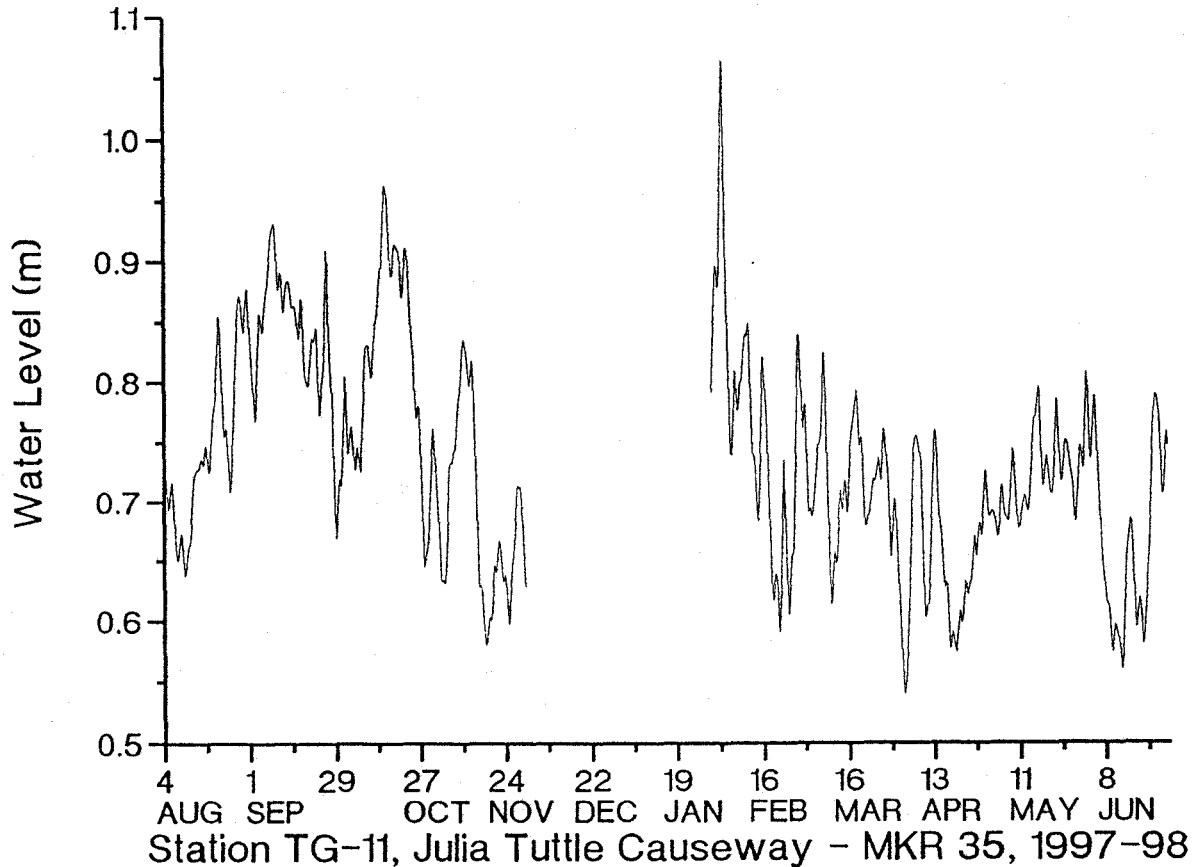


Table 12. Same as Table 1 except for Station TG-11 in northern Biscayne Bay. The spectral analysis covers the abbreviated time period from January 27 to June 29, 1998 ($\beta_{05} = 0.395$, $\beta_{01} = 0.479$).

Statistically significant coherences are clustered relatively tightly at periodicities of just over one day, then again at periodicities greater than about three days. In both cases, however, there is little indication of a preference for a specific range of wind components. In most cases, the gain is negative, indicating that northward and eastward wind stress will set down water levels in the bay. The positive gains found for the 000-180° components, however, indicate that northward wind stress will have the local effect of forcing water into the northern part of the bay and raising water levels.

Period (d)	000-180°	030-210°	060-240°	090-270°	120-300°	150-330°
16	.353	.167	.280	.395(-.027)	.459(-.029)	.471(-.033)
8	.689(.039)	.475(-.009)	.533(-.031)	.638(-.033)	.719(-.036)	.767(-.042)
5.8	.589(.030)	.726(-.012)	.742(-.027)	.699(-.027)	.650(-.028)	.599(-.033)
4	.731(.046)	.606(-.003)	.582(-.011)	.589(-.013)	.607(-.017)	.648(-.028)
3.2	.571(.027)	.422(.005)	.491(-.007)	.573(-.011)	.637(-.015)	.673(-.022)
2.7	.371	.135	.220	.344	.439(-.013)	.492(-.017)
2.3	.301	.220	.134	.146	.199	.263
2	.054	.237	.291	.195	.086	.016
1.8	.206	.168	.117	.070	.021	.046
1.6	.062	.012	.058	.120	.185	.205
1.5	.125	.529(-.020)	.618(-.015)	.613(-.014)	.546(-.015)	.306
1.3	.145	.515(-.019)	.635(-.014)	.675(-.013)	.670(-.014)	.510(-.015)
1.2	.011	.354	.564(-.009)	.639(-.010)	.618(-.011)	.374
1.13	.017	.100	.231	.299	.265	.119
1.08	.010	.004	.001	.003	.010	.130
1.0	.121	.045	.015	.080	.130	.146

Figure 17. Analog plot of low-pass filtered water levels (in meters, relative to NVGD29) from Station TG-12 (**Broad Causeway - Marker 13**), June 18, 1997 to June 25, 1998. There were no breaks in the record, and the 8926 observations are continuous. Quarter-hourly water levels were sub-sampled to obtain a time series of hourly values, and hourly values were low-pass filtered to remove the rise and fall of the tide. As a result of the filtering process 63 hours are lost from both ends of each segment.

This northernmost study site produced an annual cycle in sea level that was unlike that found elsewhere during this field study. The fall maximum is subtle, and the winter minimum is short-lived, with late-winter water levels as high as those found in September and October. A very unusual feature of the plot is the sharp rise in water level during the final month of the study, with the highest water levels recorded at the end of the record.

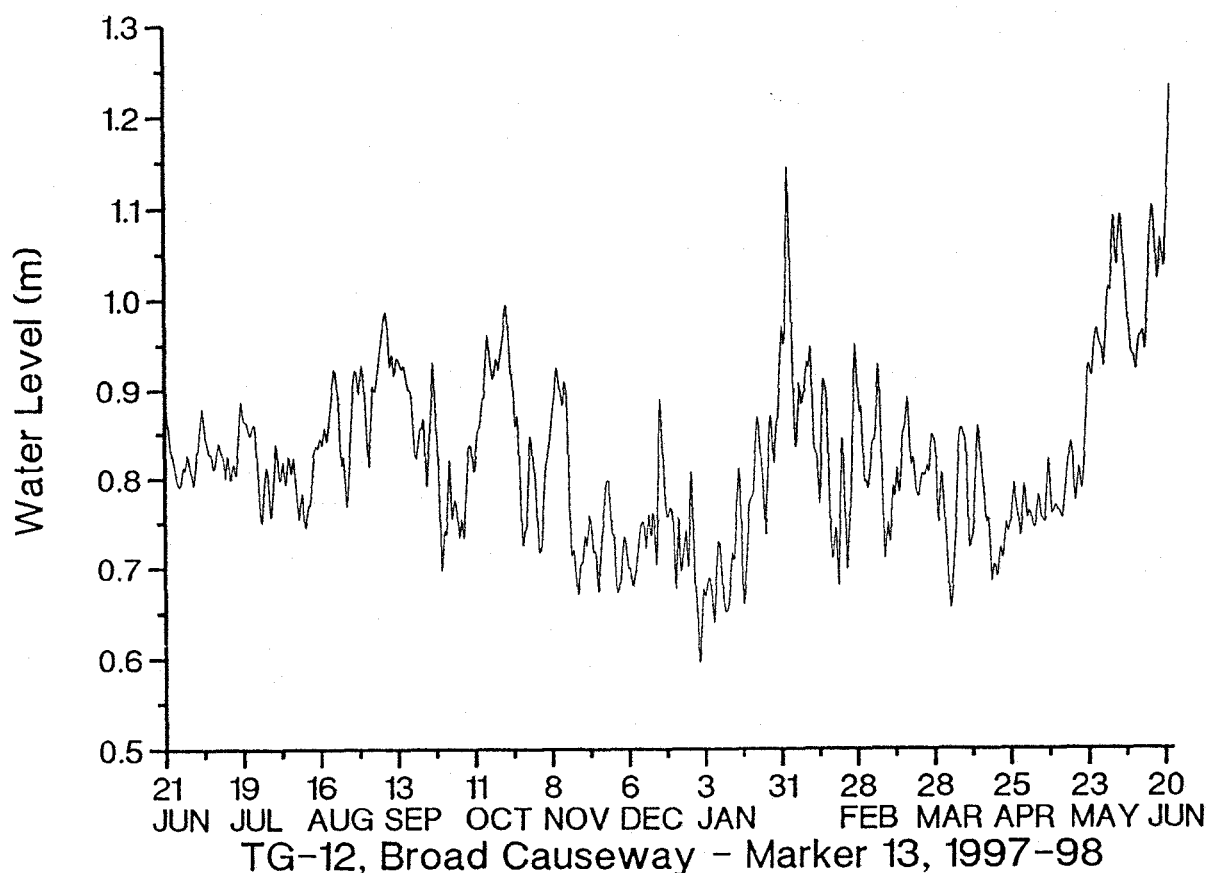


Table 13. Same as Table 1 except for Station TG-12 in northern Biscayne Bay. Study period spans June 18, 1997 to June 25, 1998 ($\beta_{05} = 0.254$, $\beta_{01} = 0.312$).

The pattern of highest coherences is relatively easily summarized, occurring over periodicities of between about 2 and 8 days and for all wind stress components. A second region of high coherence was found for southeasterly winds at periodicities of just over one day.

<u>Period (d)</u>	<u>000-180°</u>	<u>030-210°</u>	<u>060-240°</u>	<u>090-270°</u>	<u>120-300°</u>	<u>150-330°</u>
16	.176	.100	.095	.125	.163	.197
8	.489(.030)	.279(.004)	.223	.310(-.026)	.438(-.032)	.541(-.037)
5.8	.511(.038)	.575(.013)	.502(-.013)	.440(-.021)	.415(-.027)	.429(-.034)
4	.483(.042)	.422(.013)	.382(-.005)	.380(-.010)	.394(-.016)	.428(-.027)
3.2	.497(.035)	.327(.017)	.321(.0001)	.380(-.007)	.450(-.013)	.520(-.024)
2.7	.524(.028)	.301(.014)	.257(-.001)	.322(-.007)	.413(-.012)	.517(-.020)
2.3	.450(.033)	.345(.015)	.251	.257(-.013)	.306(-.019)	.385(-.027)
2	.163	.171	.133	.098	.098	.126
1.8	.044	.024	.019	.026	.046	.062
1.6	.043	.030	.018	.013	.020	.038
1.5	.013	.069	.151	.194	.207	.149
1.3	.033	.177	.320(-.004)	.393(-.006)	.412(-.008)	.291(-.012)
1.2	.161	.119	.172	.224	.269(-.007)	.280(-.013)
1.13	.130	.043	.093	.190	.263(-.029)	.255(-.038)
1.08	.021	.010	.016	.033	.043	.038
1.0	.202	.118	.009	.025	.097	.171

Table 14. Harmonic constants (amplitudes / local phase angles) of the principal tidal constituents at each of the twelve water level stations. Amplitudes are in meters; local phase angles are in degrees.

Station	Tidal Constituent				
	M ₂	S ₂	N ₂	K ₁	O ₁
TG-1	0.061 / 019	0.009 / 029	0.010 / 360	0.011 / 287	0.009 / 315
TG-2	0.083 / 330	0.016 / 353	0.015 / 311	0.013 / 257	0.010 / 276
TG-3	0.101 / 308	0.016 / 342	0.018 / 291	0.016 / 246	0.013 / 260
TG-4	0.217 / 287	0.035 / 335	0.041 / 270	0.028 / 229	0.021 / 239
TG-5	0.193 / 293	0.034 / 324	0.039 / 275	0.021 / 217	0.015 / 234
TG-6	0.220 / 284	0.035 / 321	0.041 / 266	0.024 / 216	0.021 / 233
TG-7	0.260 / 260	0.041 / 295	0.050 / 239	0.029 / 195	0.026 / 218
TG-8	0.274 / 251	0.048 / 283	0.055 / 232	0.029 / 192	0.025 / 210
TG-9	0.297 / 232	0.053 / 260	0.063 / 210	0.032 / 175	0.028 / 195
TG-10	0.311 / 236	0.049 / 264	0.065 / 216	0.034 / 180	0.031 / 198
TG-11	0.308 / 249	0.049 / 283	0.063 / 230	0.035 / 185	0.031 / 208
TG-12	0.296 / 259	0.046 / 297	0.057 / 243	0.032 / 189	0.028 / 210

Figure 18. Map showing the locations of the 38 study sites from which water level records were available to characterize tidal conditions. Water level records that were between one synodic month (29 days) and one year in length were used to calculate amplitudes and local phase angles in degrees. The study sites include 24 NOS sites occupied in the early 1970s, one Harbor Branch site occupied in 1998, one South Florida Water Management District site occupied in 1996 and 12 WES study sites from the 1997-98 field study.

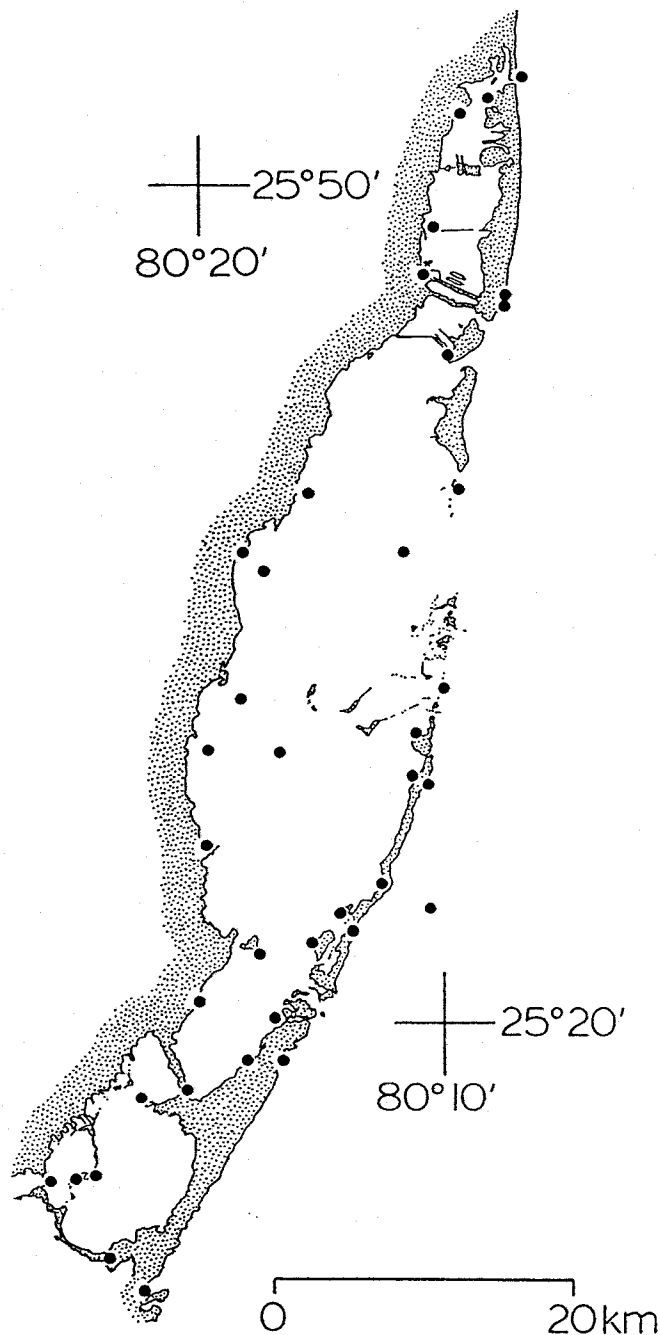


Figure 19. Co-amplitude chart for the M_2 tidal constituent. Amplitudes, in centimeters, are half of the tidal range. M_2 amplitudes are approximately 30 cm in shelf waters and in the northern part of Biscayne Bay. In central Biscayne Bay, amplitudes decrease only slightly, because of the relatively free exchange of water through the Safety Valve. Tidal amplitudes decrease rapidly from north to south in southern Biscayne Bay as tidal waves move over Cutter Bank into Card Sound. Tidal amplitudes in Card Sound and Barnes Sound are approximately 5 cm.

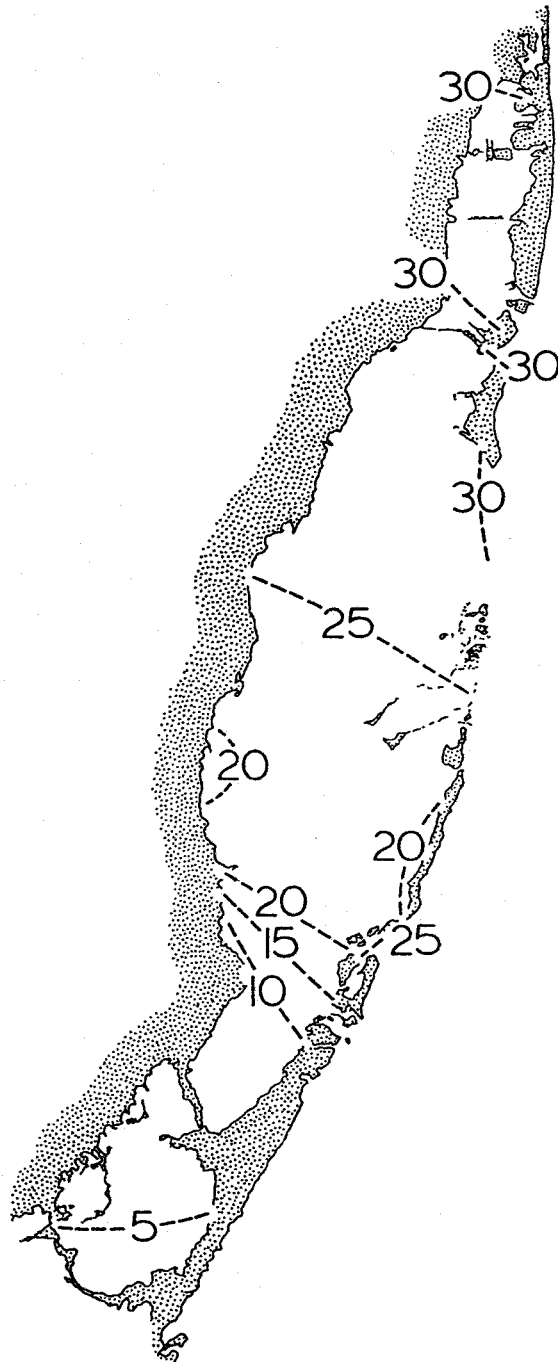


Figure 20. Co-phase chart for the M_2 tidal constituent. Phase angles, in degrees, have been contoured at intervals of 30° because a 30° difference in phase corresponds very closely to a one-hour difference in time. High water along the 260° co-phase line, for example, will have moved to the position of the 290° co-phase line one hour later. Phase differences of less than 30° show that M_2 tidal waves move from the inner shelf into the central and northern part of Biscayne Bay within one hour. The continued movement of the M_2 wave southward through Card Sound and into Barnes Sound is considerably slower as a result of the shallower water. The M_2 wave arrives at the southern end of Barnes Sound and enters Manatee Bay about six hours after entering through the Safety Valve or any of the smaller creeks that connect southern Biscayne Bay or Card Sound with inner shelf waters. The difference in phase angles between shelf waters and southern Barnes Sound is approximately 150° , indicating that high tide in shelf waters occurs within an hour of low tide in southern Barnes Sound, and *vice versa*.

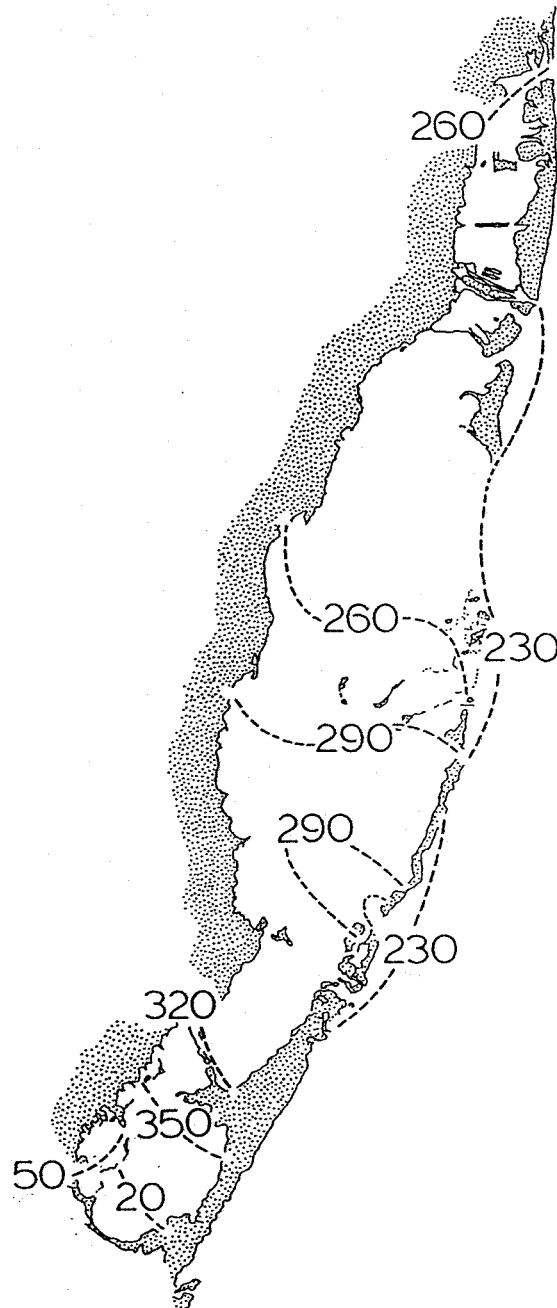


Figure 21. Co-amplitude chart for the S_2 tidal constituent. The interaction of the M_2 and S_2 constituents explains the fortnightly variation in the amplitude of the semidiurnal tide resulting from the relative positions of the sun and moon (i.e., the phase of the moon). Amplitudes of the S_2 constituent are spatially quite uniform at about 5 cm throughout the northern part of Biscayne Bay. Amplitudes decrease from north to south, especially as the tidal waves cross the shallow waters that separate Biscayne Bay and Card Sound. Amplitudes in the southernmost part of the bay system are on the order of 1 cm.

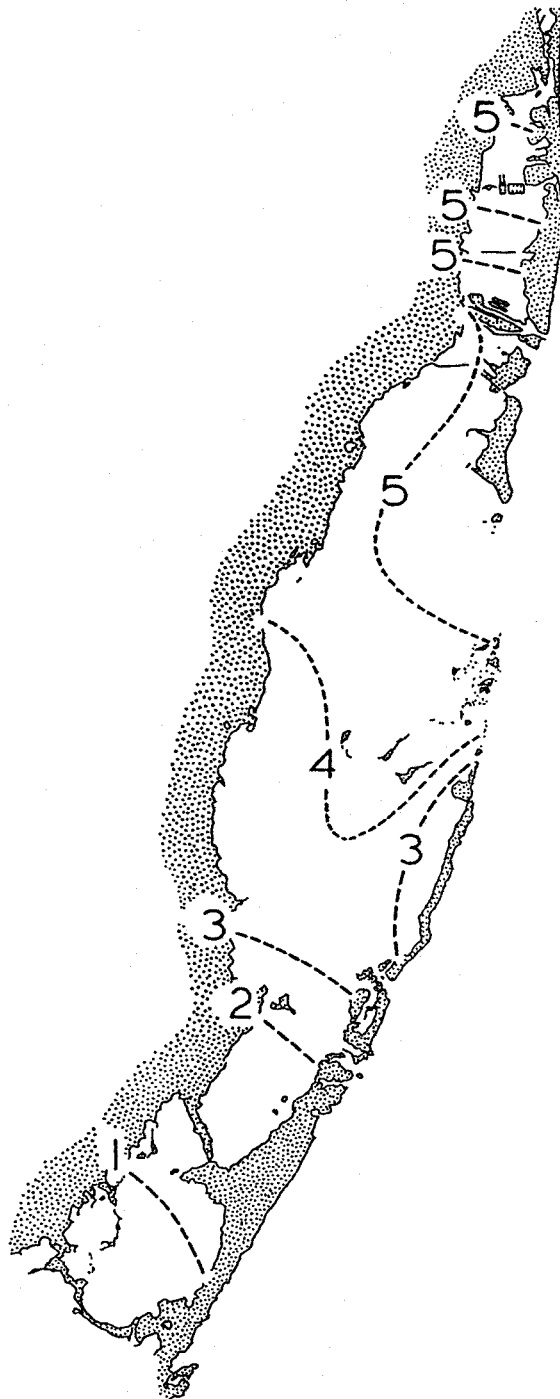


Figure 22. Co-phase chart for the S_2 tidal constituent. Phase differences are relatively small in the northern part of Biscayne Bay, indicating that the S_2 constituent reaches its high tide and low tide levels nearly simultaneously in this area. The 300 and 330° phase angles protruding into Card Sound are the effect of S_2 waves moving in through Angel-fish Creek, Broad Creek and Caesar Creek .

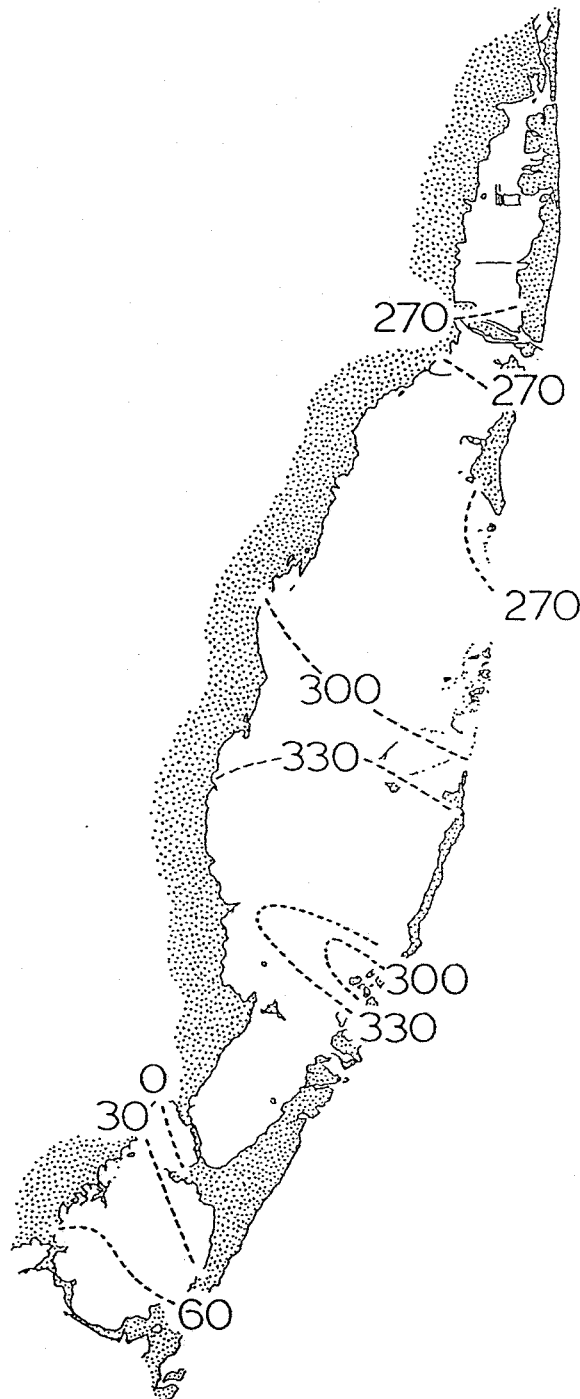


Figure 23. Co-amplitude chart for the N_2 tidal constituent. The combination of the M_2 and the N_2 constituents explains the monthly variation in the amplitude of the semi-diurnal tide resulting from changes in the distance from the earth to the moon (apogee and perigee). The N_2 constituent is the second most important in the Biscayne Bay lagoon system. N_2 amplitudes are approximately 8 cm in shelf waters, and amplitudes decrease only slightly to 7 cm in northern Biscayne Bay. Amplitudes are relatively uniform at 5-6 cm in central Biscayne Bay, then decrease quickly as the N_2 waves move southward over Cutter Bank into Card Sound. Amplitudes in Barnes Sound and Manatee Bay are approximately 1 cm.

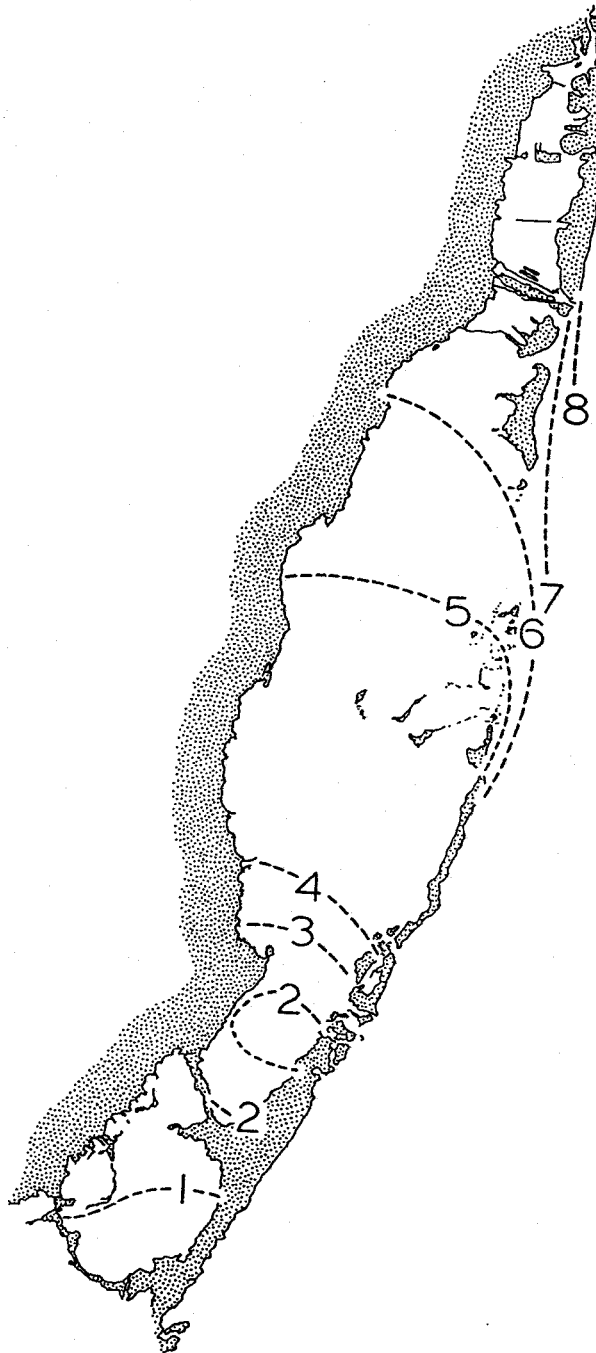


Figure 24. Co-phase chart for the N_2 tidal constituent. Phase angles are delayed by 30° or less throughout much of northern Biscayne Bay, indicating that the N_2 high and low tides occur within approximately one hour of each other throughout this part of the bay. Tidal waves enter Card Sound and southern Biscayne Bay also through Angelfish Creek, Broad Creek and Caesar Creek. The approximately 14 nautical mile separation of the 270° and 300° phase angles in southern Biscayne Bay and southern Card Sound, respectively, suggest that the N_2 wave moves southward at a speed of approximately 26 km h^{-1} (14 knots).

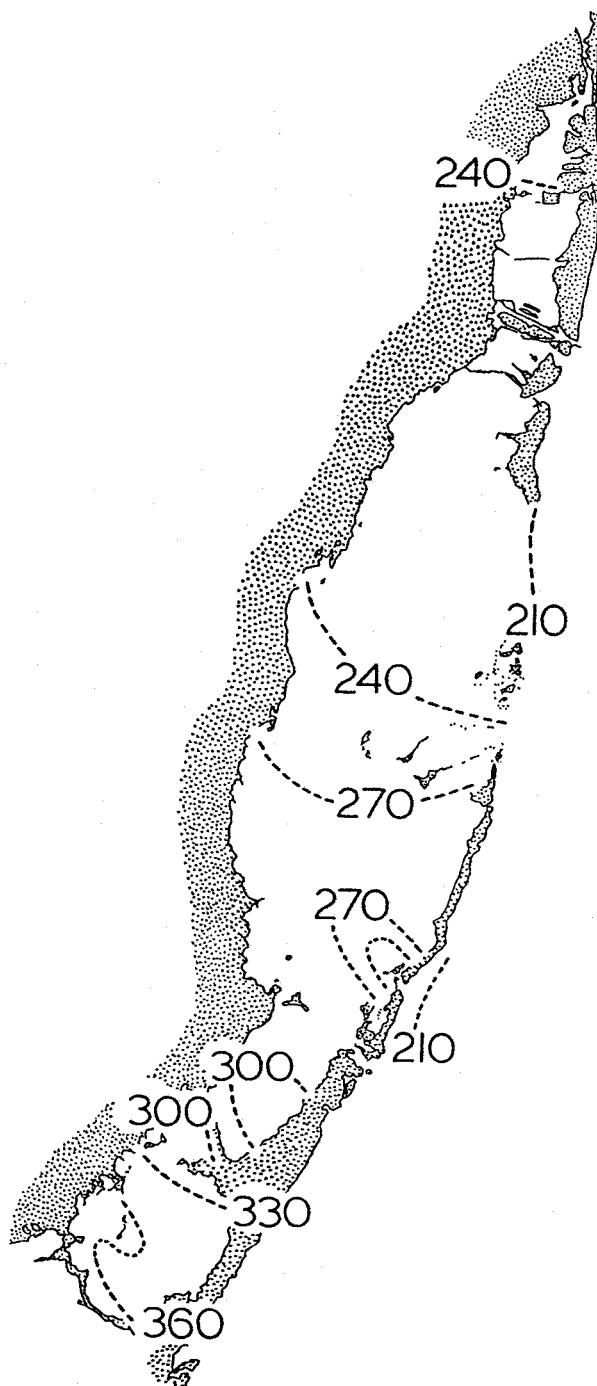


Figure 25. Co-amplitude chart for the K_1 tidal constituent. The pattern is a relatively simple one, because this tidal constituent is quite small everywhere throughout the Biscayne Bay system. K_1 amplitudes are at or just above 3 cm throughout northern Biscayne Bay, and at or just below 2 cm throughout central Biscayne Bay, Card Sound, Barnes Sound and Manatee Bay.

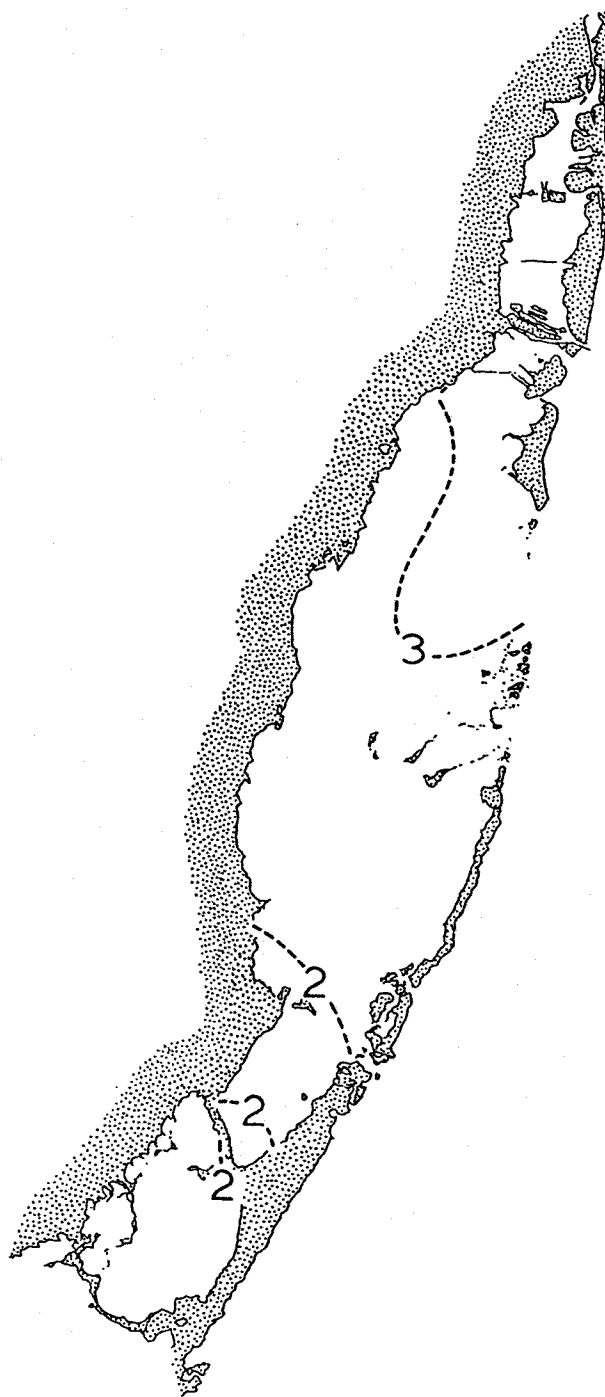


Figure 26. Co-phase chart for the K_1 tidal constituent. In contrast to the K_1 amplitudes, the co-phase chart is relatively complex because the tidal waves move slowly southward from one bay to the next. Phase angles are all in the vicinity of 180° in the northern part of Biscayne Bay, indicating that the N_2 waves reach their high and low tide conditions nearly simultaneously. Because of the slow movement of the tidal waves, especially in Barnes Sound, K_1 waves at the southern end of the bays are very nearly out of phase with those over the inner shelf.

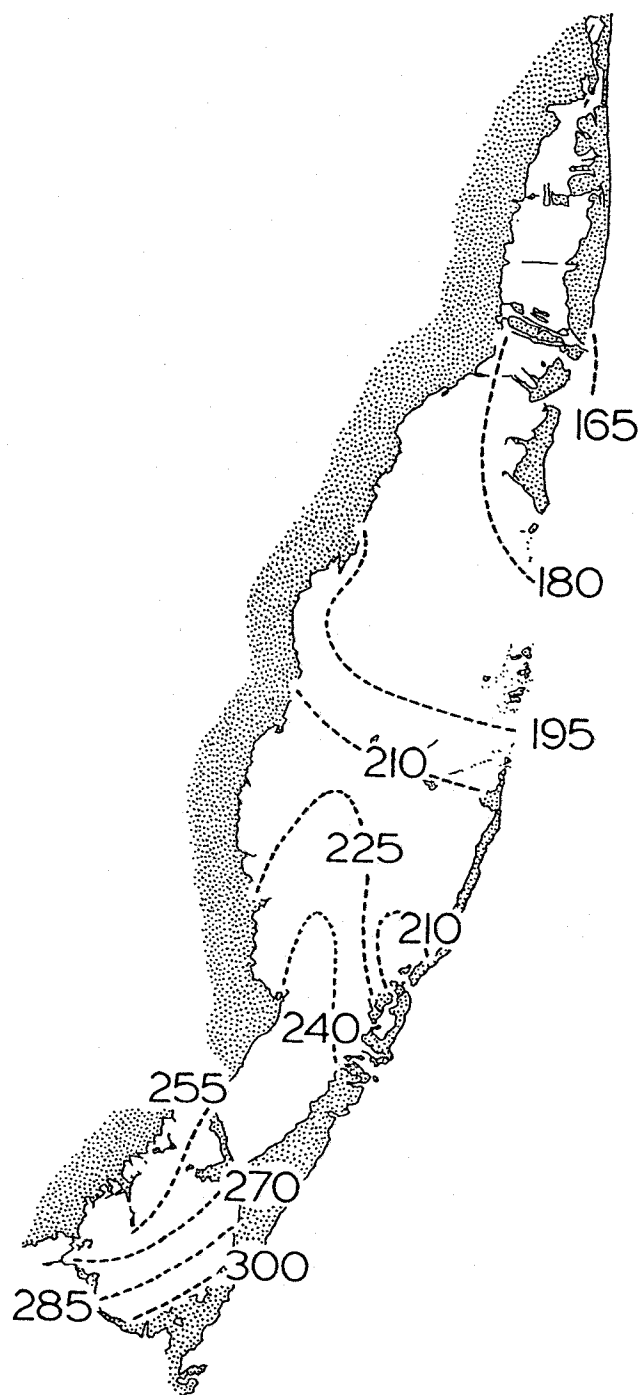


Figure 27. Co-amplitude chart for the O_1 tidal constituent. Amplitudes throughout the central part of Biscayne Bay are all between 2 and 3 cm. Values in the northern part are slightly higher, at or just above 3 cm. Because of the shallow water in Card Sound, Barnes Sound and Manatee Bay, O_1 waves decrease slightly to amplitudes of about 1 cm.

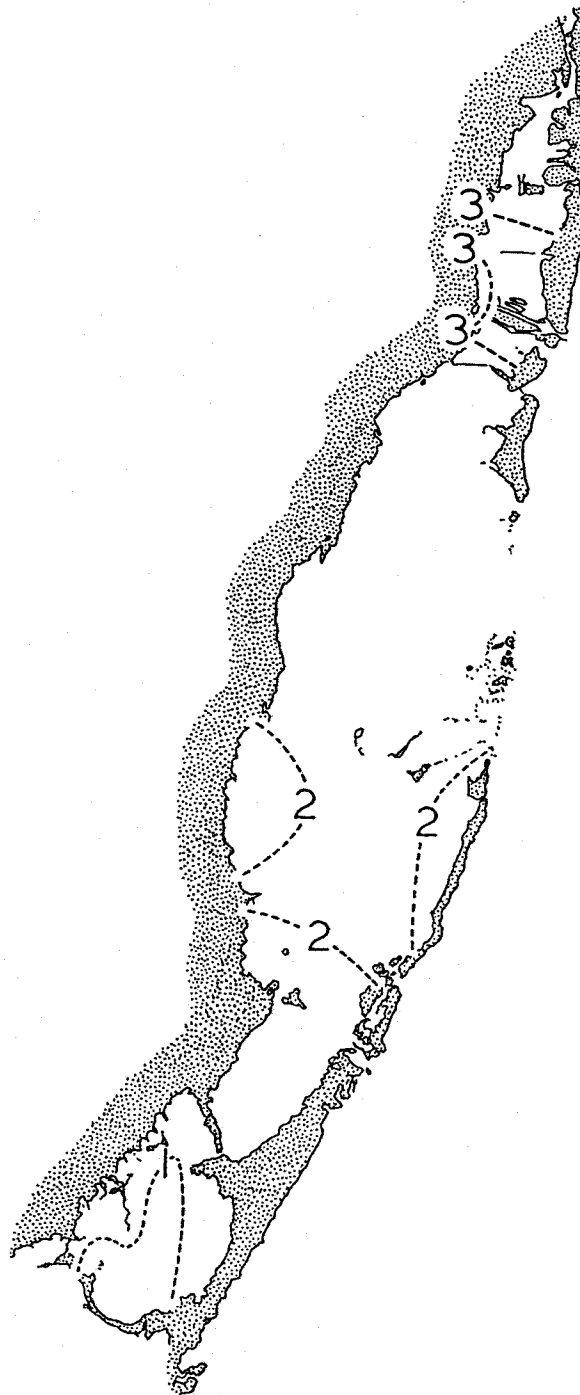


Figure 28. Co-phase chart for the O_1 tidal constituent. This is one of the most complex patterns found for the principal tidal constituents in the Biscayne Bay system. Again, however, phase angles differ only slightly in the northern part of Biscayne Bay, indicating that the O_1 constituent reaches its high and low tide condition nearly simultaneously throughout this area. Isopleths in the southern Biscayne Bay, Card Sound and especially Barnes Sound and Manatee Bay indicate a slowly southward moving O_1 wave that is interacting with the wave moving in through Angelfish Creek, Broad Creek and Caesar Creek.

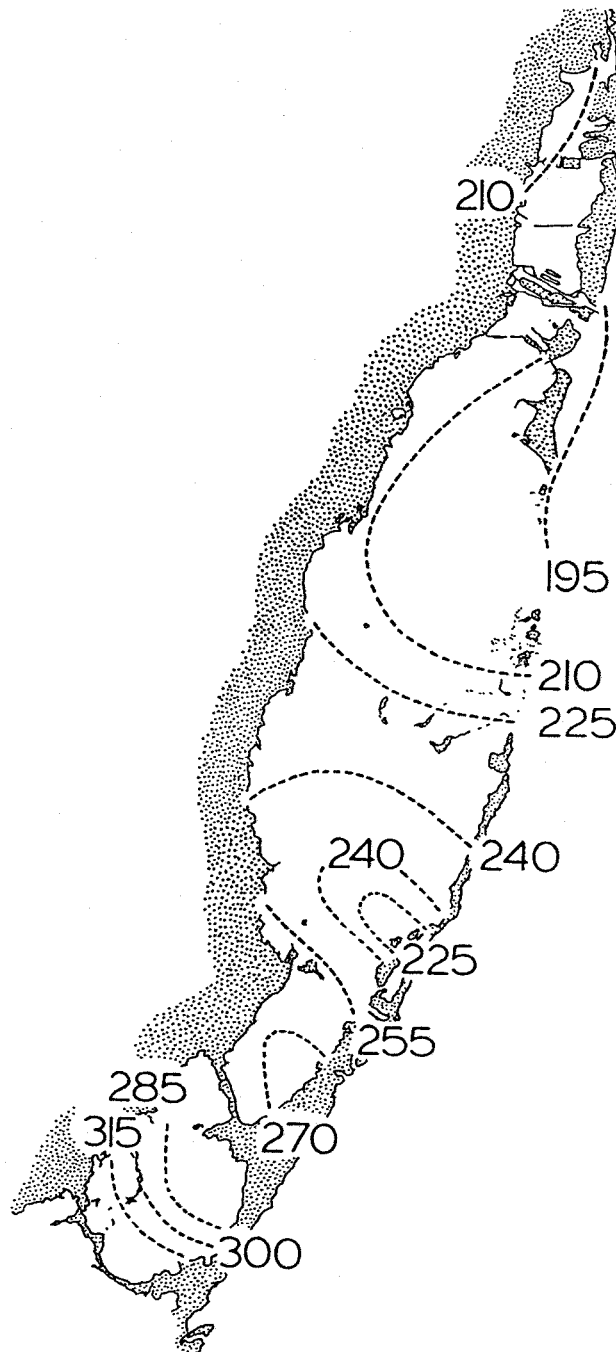
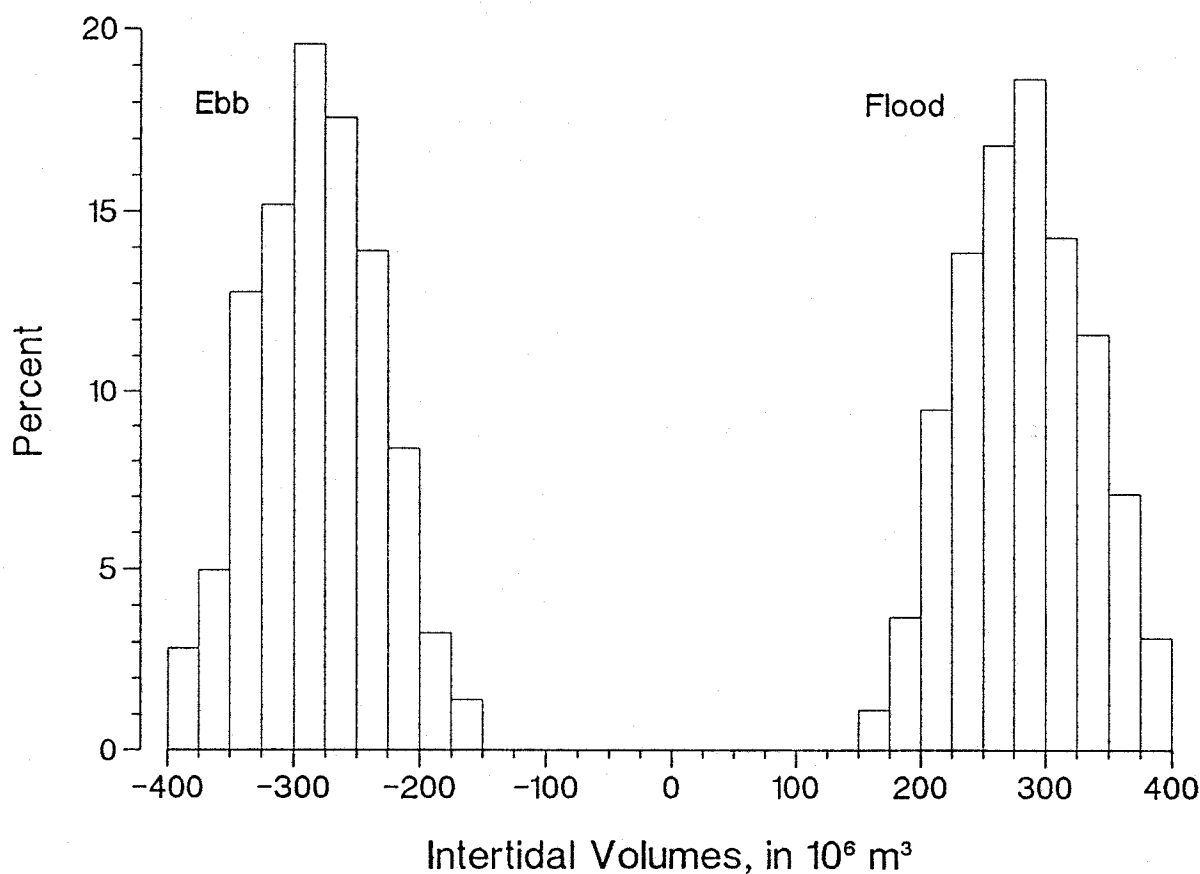


Figure 29. Histograms showing volumes of water, in millions of cubic meters, entering and leaving Biscayne Bay, Card Sound, Little Card Sound, Barnes Sound and Manatee Bay during the flood and ebb tide cycles. Histograms are based on tidal predictions over a one-year time period. Results are for diurnal and semidiurnal tidal exchanges only. Not included are the long-period tidal constituents, shallow-water (short-period) tidal constituents and effects of nontidal processes such as winds, rainfall, evaporation and freshwater runoff. Bin width is $25 \times 10^6 \text{ m}^3$.

Both histograms are characterized by well-defined peaks with frequencies of 18-19% for intertidal volumes between 275 and $300 \times 10^6 \text{ m}^3$. Intertidal volumes of between 200 and $350 \times 10^6 \text{ m}^3$ occur with 85% of the floods and 87% of the ebbs. Extremes, representing neap and spring tide conditions, are in the 150 - 175 and 375 - $400 \times 10^6 \text{ m}^3$ bins, respectively. Harmonic analysis of a one-year simulation of intertidal volumes indicates that the amplitude of the M_2 constituent is $134.2 \times 10^6 \text{ m}^3$. The mean flood and ebb intertidal volumes in the Biscayne Bay System of coastal lagoons are twice the M_2 amplitude, or $268.4 \times 10^6 \text{ m}^3$. The S_2 and N_2 constituents have amplitudes of 24.3 and $26.8 \times 10^6 \text{ m}^3$, and the K_1 and O_1 constituents have amplitudes of 12.8 and $13.8 \times 10^6 \text{ m}^3$, respectively. It is the interaction of these five tidal constituents that produces the neap and spring tide differences and determines the width of the histograms.



c. Acoustic Doppler Profiler Data

It is difficult to form generalizations regarding circulation patterns from the five ADP records. They are all influenced by local topographic features, and thus they are less spatially representative than are the water level records. Also, the ADP time series were the most fragmented. Station ADP-5, for example, was broken into six segments, the longest of which was only 116 days long. Station ADP-4 produced only three short records and the pressure sensor malfunctioned, degrading calculations of both transport and vertically-integrated current speed. Data from Stations ADP-1, 2 and 3 produced long records, but data from every location can be used in some form for model verification purposes, even if they cannot be used in every case to characterize local flow conditions.

Taken together, data suggest a complex net flow pattern for this system of coastal bays. Data from Station ADP-1, though probably influenced significantly by the local effects of exchanges through Angelfish Creek, suggest a south-to-north movement of water along the east side of Card Sound. Without additional information from elsewhere in Card Sound, however, it cannot be determined whether the observed northward flow represents a movement of water from Card Sound into southern Biscayne Bay or a more localized rotary flow that is contained within Card Sound.

Data from Stations ADP-2 and 3 cover a similar time period, and both study sites are from more open regions of Biscayne Bay. Many features of these two plots, notably the distinct change of direction in early October (see the Fowey Rocks wind stress plot), are very similar in form and timing. Both records indicate relatively little net transport during the few weeks before and after early November. From these two records, the general pattern suggests a transport of water into the northwestern part of Biscayne Bay. It is not clear how water is leaving the landward side of the bay.

Data from Station ADP-4 included only a small amount of information on water level. The pressure sensor drifted and produced little usable data. Thus, the displacement of water past the study site (i.e., the current speed) must be used to infer transport. Results can be used for model verification, but they are of marginal use for describing the general flow patterns of the bay.

Data from Station ADP-5 are limited to two segments of 3-4 months in length, but these two records are highly similar in appearance. Flow patterns are clearly constrained by local topographic features (shorelines or channels), but both patterns indicate a relatively steady flow toward the northeast—out of northern Biscayne Bay.

Figure 30. Acoustic doppler profiler data from Station ADP-1 in northern Card Sound near the mouth of Angelfish Creek. A single continuous record is available from December 21, 1997 to July 12, 1998. Shown here are vertically-averaged north-south (top) and east-west (bottom) current components. Results show maximum speeds for these two component of approximately $\pm 20 \text{ cm s}^{-1}$. Low-frequency fluctuations are more apparent in the north-south component, because tidal fluctuations are smaller. The larger fluctuations in the east-west component of the current are the direct results of exchanges through Angelfish Creek, just east of the study site.

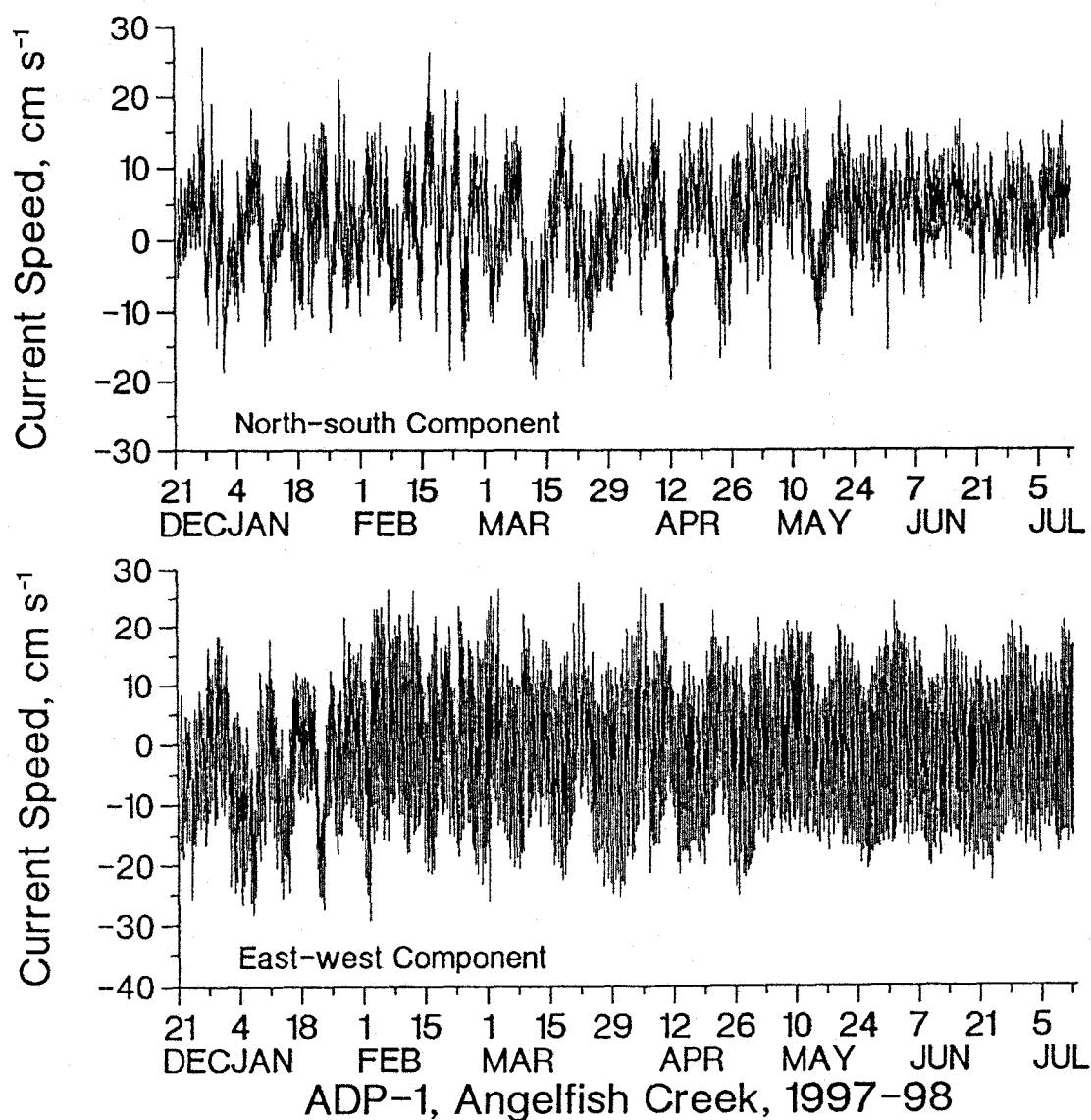


Figure 31. Cumulative net transport diagram constructed from data recorded at Station ADP-1, in northeastern Card Sound near the mouth of Angelfish Creek. Shown here are the data from December 21, 1997 to July 12, 1998. Dots have been entered at the beginning of the first day of each month.

The plot shows a two-part pattern. The first part is an approximately one-month period at the start of the record when the net transport is westward. This suggests a strong inflow through Angelfish Creek. Many tidal cycles are missing a well-defined ebb. The second part, starting in February, consists of a net northward transport that continues through the end of the record. Direct effects of exchanges through Angelfish Creek are apparent only in the form of the east-west flood and ebb of the tide. Wind stress data from Fowey Rocks (Figs. 2 and 3) do not indicate a clear seasonal change in wind direction coinciding with the transition from westward to northward transport at Station ADP-1.

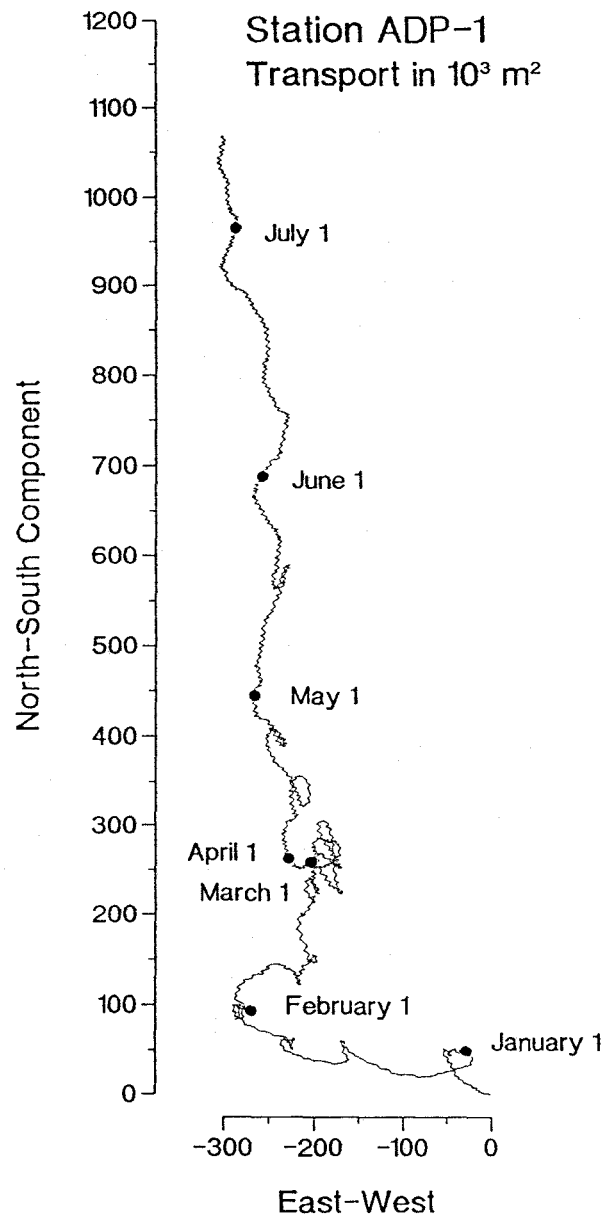


Figure 32. Acoustic doppler profiler data from Station ADP-2, in south-central Biscayne Bay. Data are available from three time periods during the June 27, 1997 to June 10, 1998 study. Shown here are vertically-averaged north-south (top) and east-west (bottom) current components. The middle and final data segments are too short for a spectral analysis, but the first segment was suitable for analysis of tidal conditions, and for a comparison with Fowey Rocks weather data to quantify the response to wind forcing.

An interesting feature of the north-south component currents is the enhancement of low-frequency variations in the latter part of the record. It is likely that this is because relatively steady shoreward winds during summer months are interrupted by cold-air outbreaks during winter months. The east-west component of the current suggests that low-frequency fluctuations are less seasonal, with variations in shoreward winds occurring throughout the year.

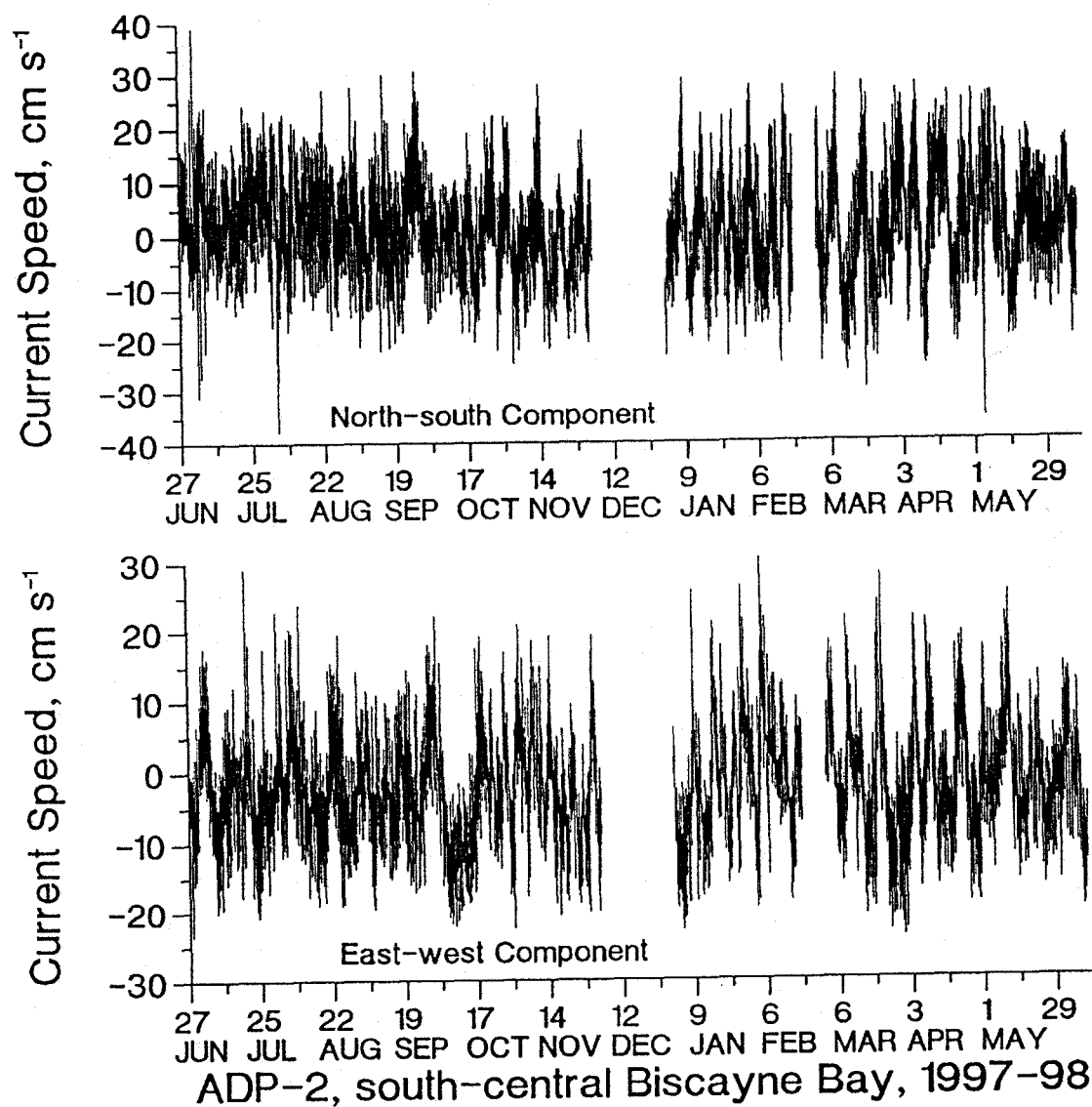


Figure 33. Cumulative net transport diagram constructed from data recorded at Station ADP-2, June 27 to December 3, 1997. Dots have been entered at the beginning of the first day of every month. The plot shows the movement of water past the study site in the south-central part of Biscayne Bay.

The plot begins with a generally northwestward movement of water that continues through early October. Superimposed onto the northwestward flow is a tidal oscillation that reverses the east-west component of the current, but not the north-south component. In early October, and coinciding with a seasonal shift in wind forcing (see Figs. 2-5), transport at the study site becomes westward and relatively steady. This pattern ends in late October and early November, and the net transport is minimal for the next few weeks. Wind forcing is not especially weak during this time (see Figs. 3 and 5), but winds are not consistent in direction (see Figs. 2 and 4). The net transport is southwestward for the final several weeks covered by this plot.

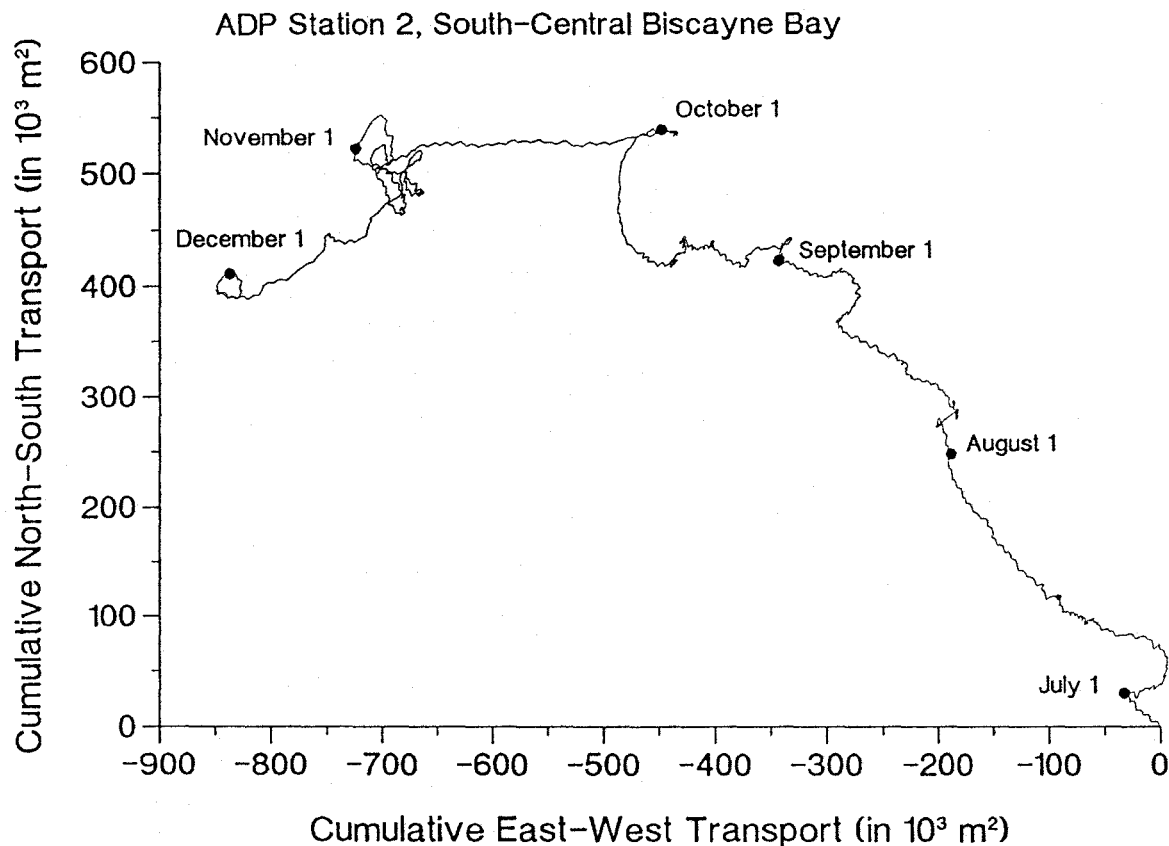


Figure 34. Acoustic doppler profiler data from Station ADP-3 in north-central Biscayne Bay, just west of the Safety Valve at Marker 1A. Data are available from three time periods during the June 26, 1997 to July 31, 1998 study. Shown here are the vertically-averaged north-south (top) and east-west (bottom) current components. The middle data segment is too short for a spectral analysis, but the first and third segments were suitable for an analysis of tidal conditions, and the first segment is suitable for a comparison with Fowey Rocks weather data to quantify the response to wind forcing.

Data from this location, plotted in this format, show little variation throughout the year. Current speeds are generally between $\pm 10 \text{ cm s}^{-1}$ for the north-south components and $\pm 20 \text{ cm s}^{-1}$ for the east-west components. The slightly more "ragged" appearance of the north-south component currents indicates that nontidal forcing has a greater influence on north-south flow than on east-west flow.

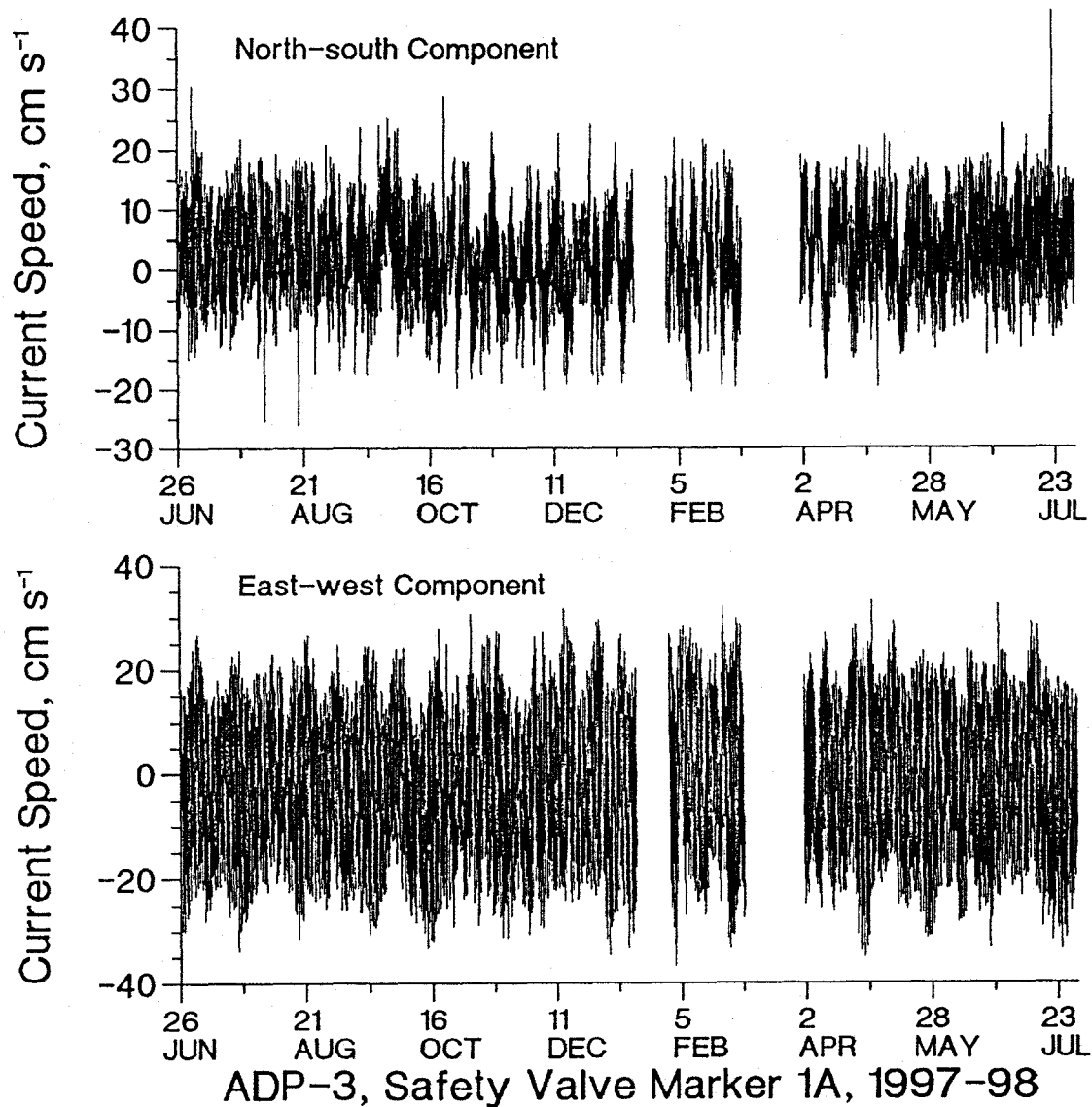


Figure 35. Cumulative net transport diagram constructed from data recorded at ADP Station 3, June 26, 1997 to January 15, 1998. Dots have been entered at the beginning of the first day of every month. The plot shows the movement of water past the study site in Biscayne Bay, directly west of the Safety Valve.

The plot consists of vigorous tidal exchanges superimposed onto a much more gradual inflow--first toward the northwest, then irregularly westward. The transition occurs in early October, shortly after a seasonal change in regional wind stress (see Figs. 2-5). Many features of this plot are similar to those appearing in the cumulative net transport plot constructed using data from Station ADP-2 in south-central Biscayne Bay (see Fig. 34).

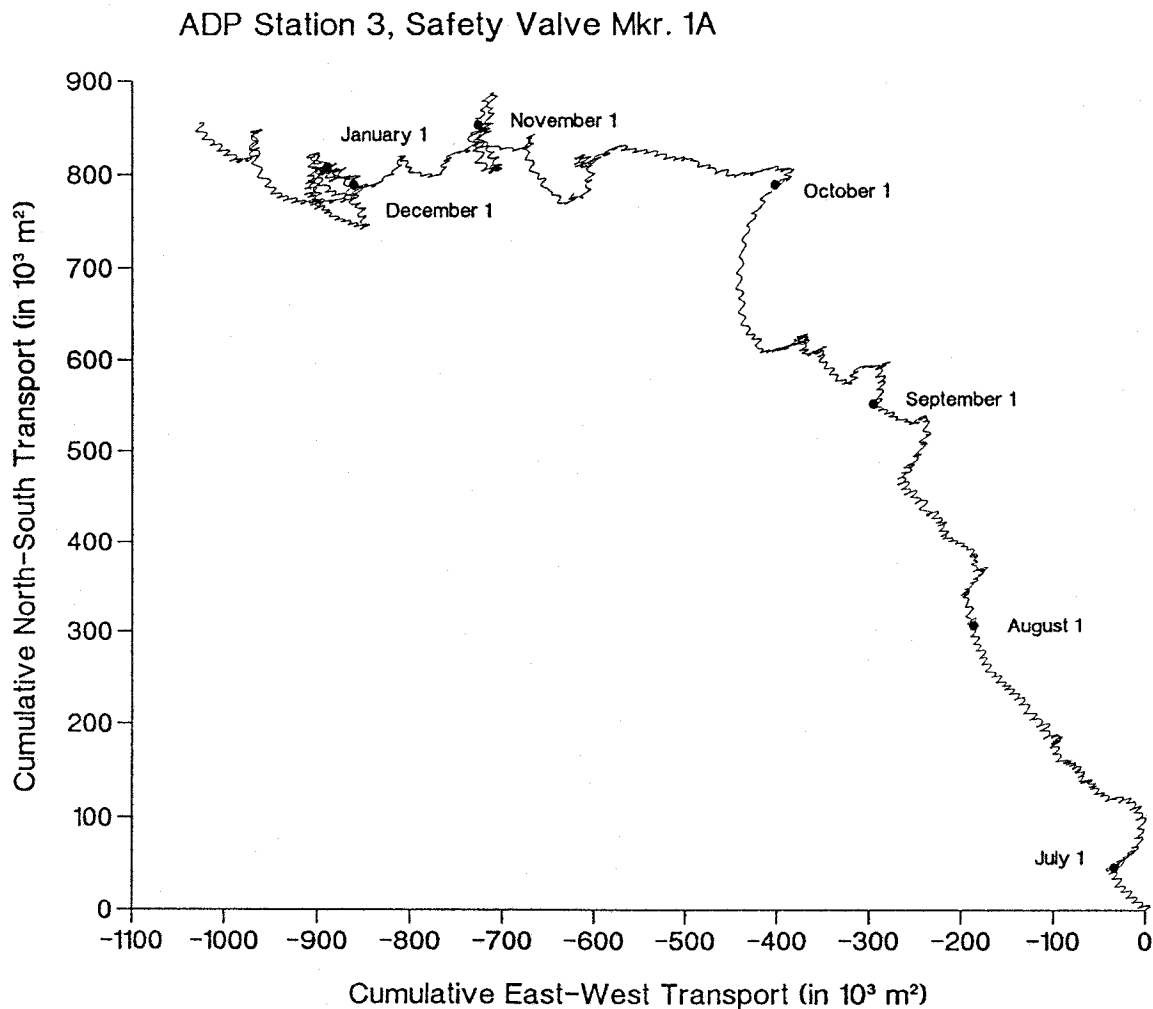


Figure 36. Acoustic doppler profiler data from Station ADP-4 in northern Biscayne Bay and just north of West Point at Bear Cut Marker 1. Data are available only from three short time periods during the June 26, 1997 and March 21, 1998 study (a fourth data segment, from May 1-6, was too short to plot). Shown here are the vertically-averaged north-south (top) and east-west (bottom) current components. The appearance of the north-south component current speeds changes significantly over the course of the study. Currents in the first segment are generally $\pm 10 \text{ cm s}^{-1}$, while north-south components in the second and third segments commonly reach $\pm 20 \text{ cm s}^{-1}$ as low-frequency fluctuations. Harmonic analyses to isolate tidal currents confirm that the north-south component of the ebb and flood changes unrealistically. It is probable that the second and third segments of north-south flow are contaminated, and they were not used for either harmonic analysis or spectral analysis. Only the first segment of the north-south component flow was used to characterize tides at that location. All three east-west components were used for harmonic analysis, though none was long enough for a meaningful spectral analyses.

Focusing on the first segment of both components, most of the total current is contained in the east-west component, where strongest floods and ebbs commonly reach 20 cm s^{-1} . The transition from neap to spring tide conditions is not well defined, and strongest current speeds rarely exceed 30 cm s^{-1} .

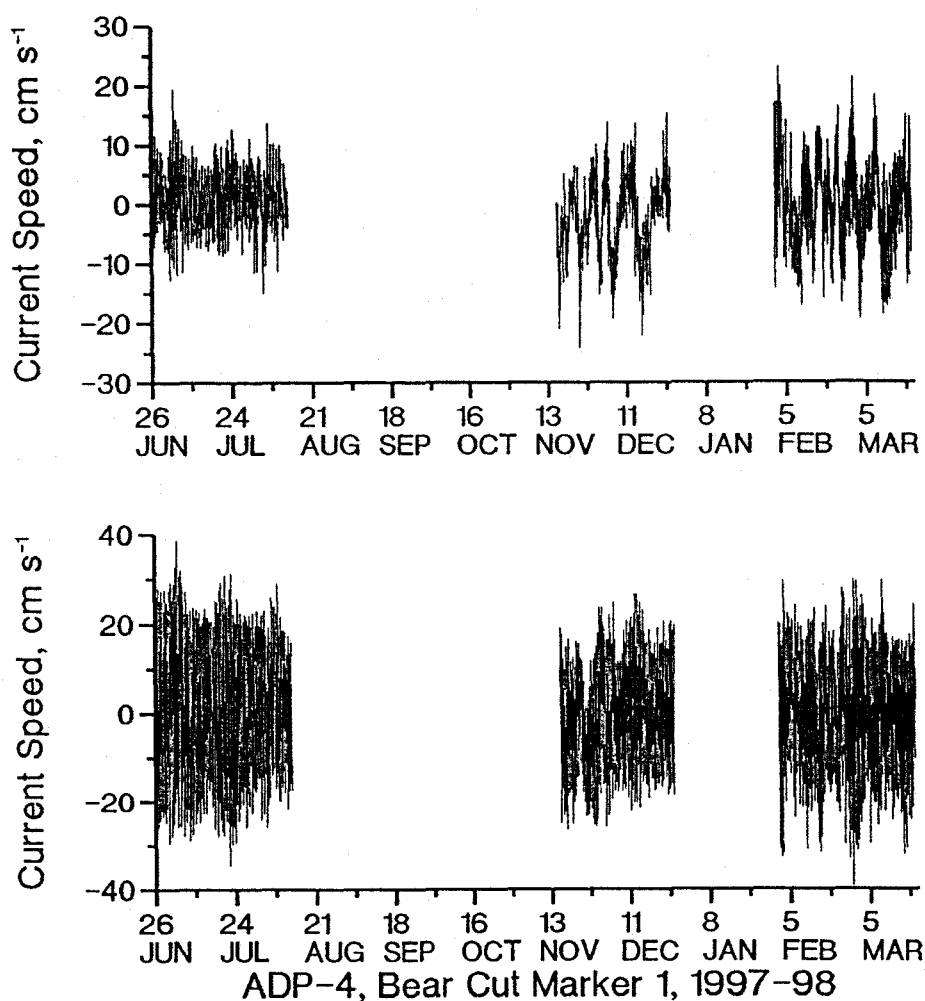


Figure 37. Cumulative net displacement diagrams constructed from data recorded at Station ADP-4, in northern Biscayne Bay, north of West Point on Biscayne Bay. Shown here are data from June 26 to August 12 (left) and from November 15 to December 26 (right), 1997. Dots have not been entered at the beginning of the first day of each month due to the short length of the records.

The two plots are quite different, and the differences should be useful in model verification. The June-August data indicate strong tidal oscillations superimposed onto a relatively weak net displacement toward the north-northeast. The November-December data show poorly defined tidal oscillations superimposed onto a relatively strong net displacement toward the south-southwest. Because of the strong inflow between Virginia Key and Key Biscayne, many tidal cycles have little or no ebb flow. Weather data from Fowey Rocks indicate a weak net northwestward wind stress during the June-August time period and stronger net southwestward wind stress during the November-December time period (see Fig. 2).

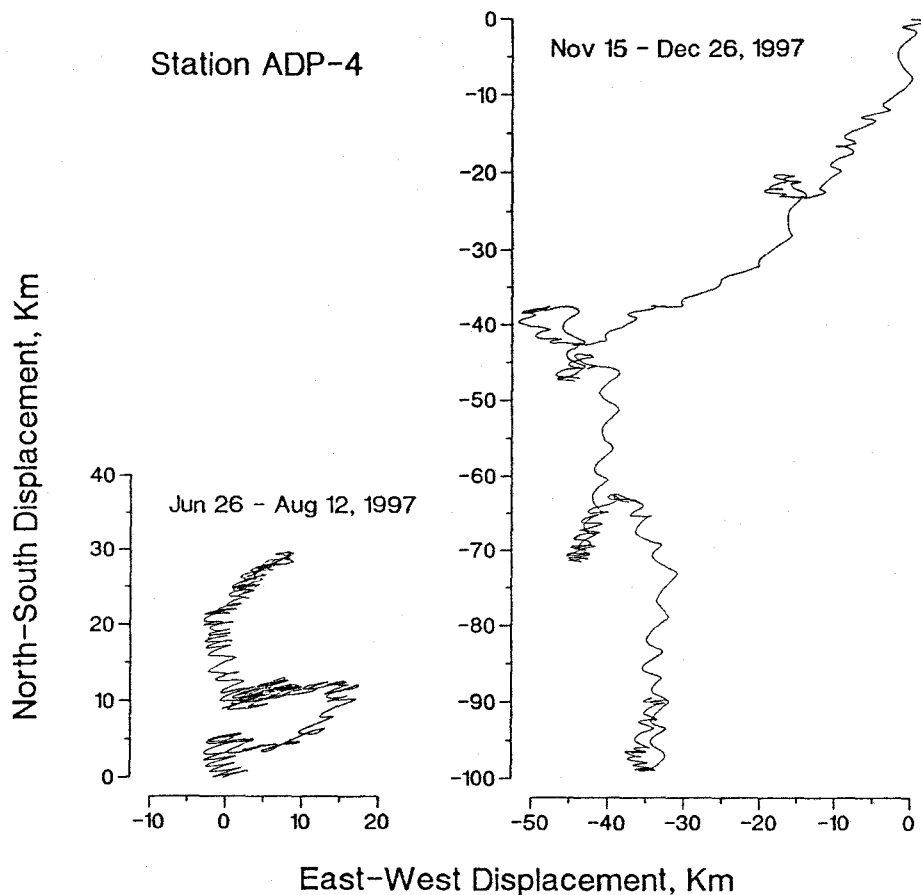


Figure 38. Acoustic doppler profiler data from Station ADP-5 in northern Biscayne Bay, at the Julie Tuttle Causeway Marker 35. Data are broken into six time periods during the June 28, 1997 to July 31, 1998 study. Shown here are the vertically-averaged north-south (top) and east-west (bottom) current components. None of the segments is suitable for spectral analyses, but only the second segment is too short for a tidal analysis.

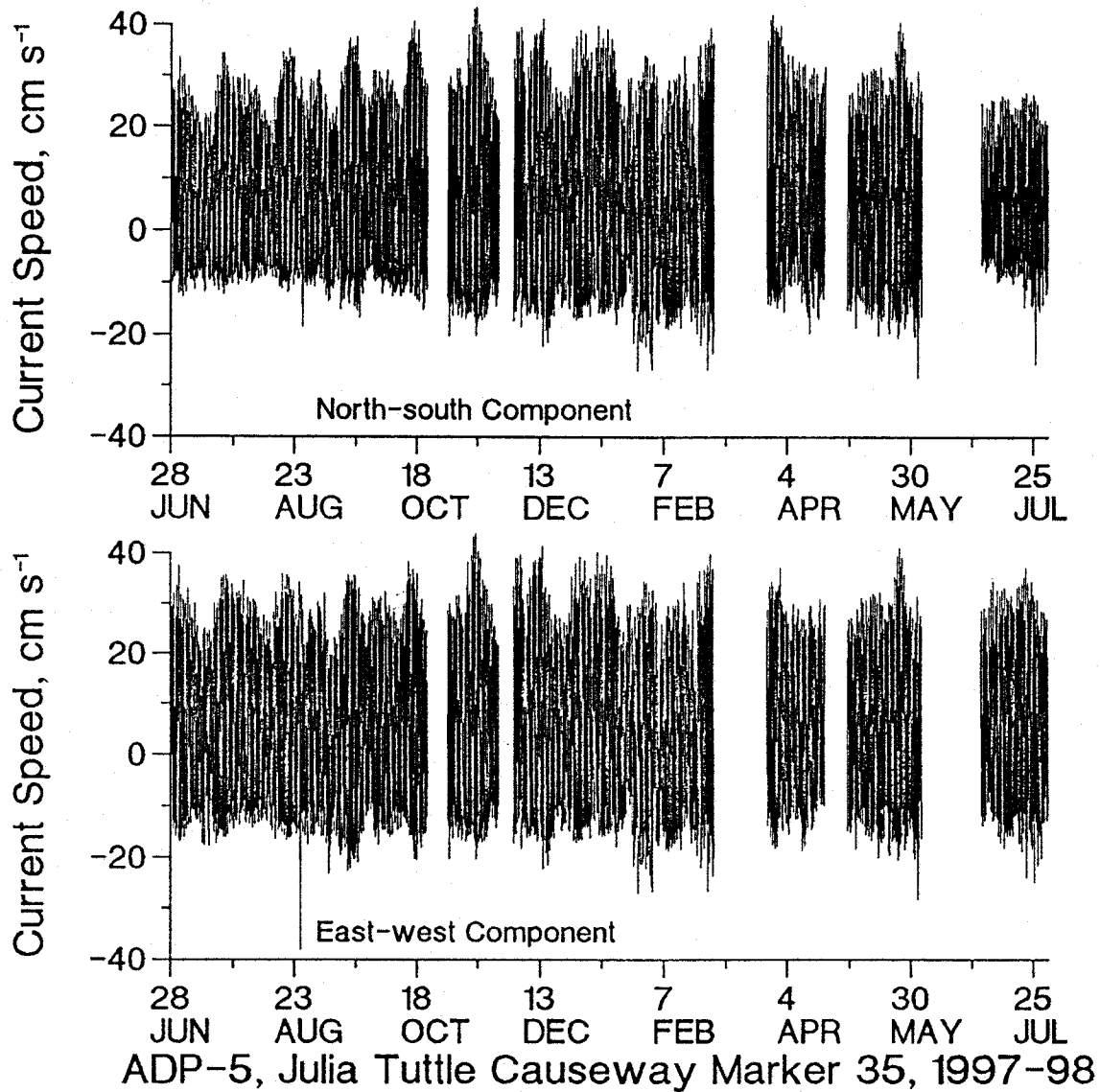


Figure 39. Cumulative net transport diagrams constructed from data recorded at Station ADP-5, in northern Biscayne Bay. Data are available from June 28 to October 22, 1997 (top) and December 1, 1997 to March 1, 1998 (bottom plot). Dots have been entered at the beginning of the first day of each month.

The plots show a remarkably consistent northeastward flow of water past the study site. The nearly constant direction of the flow is a result of the topographic steering produced by channels and nearby shorelines. Superimposed onto the nontidal northeastward flow is the back-and-forth ebb and flood of the tide. Tidal variations are difficult to detect because of the rectilinear nature of both the tidal and the nontidal flow.

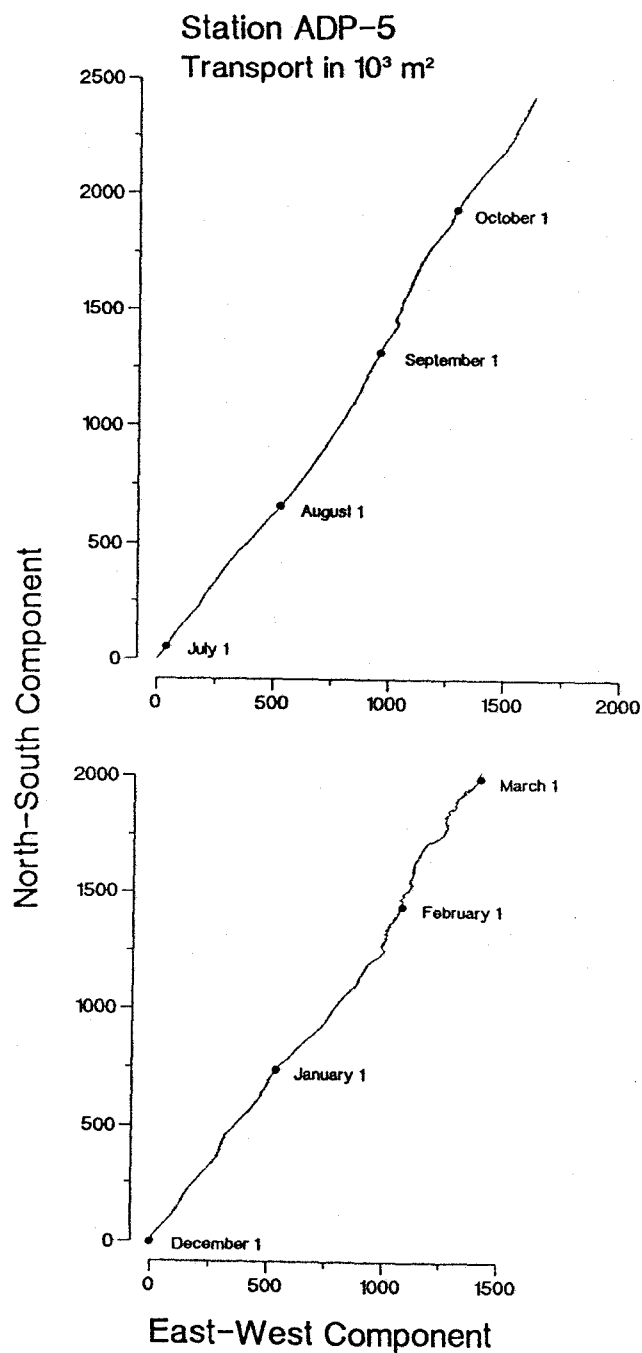


Table 15. Coherence of currents at ADP Station 1 and wind stress at Fowey Rocks, calculated from data recorded December 21, 1997 to July 12, 1998. Bold numbers indicate coherence significant at the 95% confidence level ($\beta_{05} = 0.280$); bold italicized numbers indicate coherence significant at the 99% level ($\beta_{01} = 0.344$). The magnitude of the transfer function (gain) is shown in parentheses beside coherence values when coherence is significant at or above the 95% confidence level. For the north-south components (N-S) northward flow is positive and for east-west components eastward flow is positive. Therefore, northward or eastward winds forcing currents to the north or east result in a positive transfer function. Similarly, southward or westward wind stress forcing currents toward the south or west will produce a positive gain. Alternately, northward or eastward wind stress forcing currents to the south or west result in a negative gain.

The units of gain are cm s^{-1} per dyne cm^{-2} . Thus, in the first example below, a gain of 5.68 indicates that wind stress reaching 1 dyne cm^{-2} with a periodicity of 10.6 days will result in a vertically averaged north-south current speed that reaches 5.68 cm s^{-1} . The positive gain indicates that northward wind stress produces a northward current.

Highest coherences are found for periodicities in excess of about two days. Highest gains occur for downwind flow. For example, north-south currents produced by north-south wind stress.

<u>Period (d)</u>	<u>N-S Winds</u> <u>N-S Currents</u>	<u>E-W Winds</u> <u>N-S Currents</u>	<u>N-S Winds</u> <u>E-W Currents</u>	<u>E-W Winds</u> <u>E-W Currents</u>
10.6	.856 (5.68)	.458 (-2.48)	.431 (-1.84)	.702 (2.88)
5.3	.768 (5.06)	.480 (-2.78)	.440 (-1.58)	.553 (2.78)
3.5	.707 (4.42)	.560 (-1.47)	.317 (-.838)	.374 (1.88)
2.7	.593 (4.15)	.349 (-.473)	.402 (-1.35)	.383 (2.08)
2.1	.482 (4.23)	.355 (-.093)	.305 (-.759)	.450 (2.87)
1.8	.604 (4.89)	.540 (.210)	.252	.465 (3.33)
1.5	.618 (5.32)	.185	.248	.514 (3.17)
1.3	.352 (4.72)	.135	.024	.436 (3.30)
1.2	.661 (5.20)	.299 (-.323)	.009	.312 (3.17)
1.1	.521 (5.89)	.201	.062	.133
1.0	.389 (5.52)	.148	.021	.026

Table 16. Same as Table 15 except for ADP Station 2. The analysis covered the time period from June 27 to December 3, 1998 ($\beta_{05} = 0.317$, $\beta_{01} = 0.387$).

The consistently highest coherences and the highest gains occur for downwind flow. For example, when northward wind stress produces northward currents. Occurrences of wind stress in any direction significantly related to currents 90° to the right or left are much less common, and gains are much less.

<u>Period (d)</u>	<u>N-S Winds</u> <u>N-S Currents</u>	<u>E-W Winds</u> <u>N-S Currents</u>	<u>N-S Winds</u> <u>E-W Currents</u>	<u>E-W Winds</u> <u>E-W Currents</u>
10.6	.810 (6.22)	.116	.249	.711 (7.96)
5.3	.702 (5.73)	.178	.263	.752 (8.13)
3.5	.560 (6.11)	.246	.176	.587 (6.83)
2.7	.352 (4.86)	.120	.488 (-.742)	.636 (5.85)
2.1	.265	.063	.261	.453 (6.01)
1.8	.295	.055	.329 (2.94)	.224
1.5	.372 (4.99)	.012	.219	.349 (4.95)
1.3	.266	.119	.171	.353 (5.34)
1.2	.346 (5.92)	.122	.214	.484 (6.31)
1.1	.402 (7.09)	.079	.081	.076
1.0	.624 (10.7)	.133	.250	.130

Table 17. Same as Table 15 except for ADP Station 3. The analysis covers the time period from June 26, 1997 to January 15, 1998 ($\beta_{05} = 0.280$, $\beta_{01} = 0.344$).

Results are similar to those summarized in Table 16 for Station ADP-2. Highest coherences and highest gains occur for current components parallel to wind stress components. This indicates a direct response to wind forcing in the form of a downwind flow.

<u>Period (d)</u>	<u>N-S Winds</u> <u>N-S Currents</u>	<u>E-W Winds</u> <u>N-S Currents</u>	<u>N-S Winds</u> <u>E-W Currents</u>	<u>E-W Winds</u> <u>E-W Currents</u>
10.6	.842 (5.50)	.222	.247	.759 (3.67)
5.3	.779 (5.72)	.252	.283	.674 (3.78)
3.5	.584 (5.58)	.412 (-.946)	.311 (1.40)	.609 (3.68)
2.7	.541 (5.17)	.259	.406 (1.03)	.570 (3.86)
2.1	.767 (6.25)	.628 (-1.81)	.288 (.313)	.506 (3.02)
1.8	.719 (5.67)	.245	.035	.173
1.5	.597 (5.46)	.155	.000	.306 (2.56)
1.3	.540 (3.73)	.282	.122	.344 (3.42)
1.2	.508 (4.85)	.263	.113	.356 (4.67)
1.1	.351 (6.67)	.171	.105	.039
1.0	.523 (7.95)	.237	.211	.060

Table 18. Harmonic constants (amplitudes / local phase angles) of the principal tidal constituents at each of the five ADP current meter stations. Amplitudes are in cm s^{-1} ; local phase angles are in degrees.

Station	Tidal Constituent				
	M_2	S_2	N_2	K_1	O_1
ADP-1 (N-S)	2.6 / 114	0.6 / 330	0.6 / 131	0.5 / 007	0.5 / 236
ADP-1 (E-W)	12.5 / 044	2.4 / 088	2.2 / 015	0.9 / 366	1.1 / 018
ADP-2 (N-S)	6.8 / 051	2.0 / 062	1.4 / 028	1.2 / 284	0.6 / 313
ADP-2 (E-W)	4.0 / 016	1.1 / 115	1.1 / 001	1.1 / 339	0.1 / 034
ADP-3 (N-S)	7.2 / 046	1.8 / 088	1.3 / 036	1.6 / 279	0.3 / 285
ADP-3 (E-W)	17.5 / 010	2.7 / 040	4.0 / 354	1.7 / 306	0.9 / 306
ADP-4 (N-S)	4.5 / 001	1.2 / 025	0.6 / 001	0.8 / 323	0.6 / 217
ADP-4 (E-W)	20.4 / 017	3.2 / 039	4.2 / 009	2.0 / 296	1.7 / 289
ADP-5 (N-S)	17.7 / 182	2.6 / 219	3.5 / 163	0.9 / 096	1.1 / 117
ADP-5 (E-W)	20.2 / 180	2.7 / 213	3.8 / 161	1.1 / 099	1.0 / 121

Discussion and Summary

The assemblage of weather, water level and ADP data from the Biscayne Bay series of coastal bays, is a database well suited for model verification. Individually, the twelve water level stations and five ADP stations provide data that can be compared with output from the corresponding part of the model domain. Taken together, the water level data, though not the ADP data, characterize tidal conditions throughout the bay. Wind data are adequate for verifying the model's ability to reproduce the effects of wind stress on water level and circulation. Coherence identifies the broad range of wind directions to which water levels are most responsive, and the transfer function (gain) quantifies the magnitude of the set-up or set down of water level in response to wind forcing. Comparisons of the five ADP transport records make it clear that five study sites are insufficient for describing bay-wide circulation patterns. However, data from the five locations can be used to verify how well the model is reproducing flow patterns in the corresponding parts of the model domain.

Comparison of the two wind stress records supports the idea that wind data from several locations surrounding the bays were not needed. The high correlation in the long term, and the minimal mean difference in wind direction, suggests that one anemometer with an unobstructed exposure is adequate for recording both landward and seaward directed winds.

Integration of water level data from several sources provides a much better picture of the tidal conditions of the Biscayne Bay system. The co-amplitude and co-phase charts provide a significantly better understanding of tidal conditions than was possible from earlier databases consisting of a smaller number of stations. Although not a part of this study, the WES database makes possible a follow-up investigation of shallow-water and fortnightly tidal constituents.

The progressive vector diagrams of wind stress (Figs. 2 and 4) are helpful for understanding the distinct change in transport direction that appears at Stations ADP-2 and 3 in early October. This seasonal change in wind direction has been noted in wind data from several Florida Keys weather stations, and in many cases it has been found to trigger a dramatic change in transport. Similarly, the plots of north-south and east-west wind stress (Figs. 3 and 5) are useful for explaining the transient spike in water level in early February.

The analyses of tidal conditions and wind forcing reported here make possible model verification exercises that focus specifically on tides and wind stress. For example, the tables of gain values, presented both with the analyses of water level records and the analyses of ADP records, show a specific response to equally specific wind forcing. If model simulations are forced only by east-west wind stress reaching a magnitude of 1 dyne cm^{-2} , then Tables 2-13 can be used to test the simulated rise and fall in water level throughout the bay, and Tables 15-17 can be used to test the simulated current speeds at three of the ADP study sites. Similarly, if the model is forced by a single tidal constituent in shelf waters, then the five co-amplitude and co-phase charts (Figs. 19-28) can be used to test the simulated rise and fall in water level, or the movement of high or low tide at any point within the bay specific to that tidal constituent. Forcing the model with observed winds, whether from Fowey Rocks or Convoy Point, introduces a degree of complexity by combining a wide range of periodicities, speeds and directions. Similarly, a combination

of tidal and nontidal water level variations in shelf waters may be a more realistic form of forcing, but it makes an interpretation of the response correspondingly more difficult.

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