Tidal and Sub-inertial Fluctuations in the Florida Current[1]

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ABSTRACT

A 50-day time series was obtained from a current meter mooring in the Florida Current off Miami. The results agree with earlier observations regarding the significance of several-day oscillations in the Gulf Stream. The energy spectrum of the V component shows a pronounced peak at periods of 5–6 days with an amplitude of about 20 cm sec^{-1}. Quantitatively the results are reminiscent of barotropic shelf waves, although definite conclusions about the occurrence of such waves require additional observations.

Analysis of tidal fluctuations shows that 25% of the variance in the V component and 6% of the variance in the U component can be accounted for by the four major constituents, M_2, S_2, K_1 and O_1. The largest constituent in the V component is the O_1 tide, whereas the K_1 tide dominates in the U component. The results are in good agreement with earlier observations from the sea surface, indicating that the vertical structure of the tides is predominantly barotropic.

1. Introduction

Recent observations from the Florida Current show considerable variability in the period range from 1 to 10 days. In extreme cases, the fluctuations on a several-day time scale can be nearly as large as the seasonal fluctuations (Niiler and Richardson, 1973). Although one cannot always discern changes in transport from cross-stream axis shifts, observations repeatedly show energy peaks in the period range from 4 to 10 days. DeFerrari (1970) analyzed a 180-day time series of cable transport and the phase of acoustic signals transmitted across the Straits of Florida. The spectra of both time series have peaks at a mean period of 5.8 days. Webster (1961) found that 4- and 7-day periods are dominating the meandering of the Gulf Stream farther north. Lee (1972) showed that similar periodicities occur on the western inshore edge of the Florida Current. Some of these observations, as well as additional ones from other boundary current regions [e.g., by Hamon (1962) off Australia or by Mooers and Smith (1968) off Oregon], have stimulated theoretical discussions in terms of continental shelf waves. Studies by Robinson (1964), Mysak (1967a,b), Adams and Buchwald (1969), and Niiler and Mysak (1971) have shown that low-frequency oscillations with several-day periods can occur as free or forced modes along coastal boundaries (continental shelves). In the presence of a mean current with a horizontal shear, the dispersion relations exhibit a complex behavior, showing that stable and unstable waves are possible and that they can travel either northward or southward along a meridional coastline. Additional observations are required to improve our understanding of such shelf waves and to clarify whether these modes of oscillation are a possible explanation of the initiation of Gulf Stream meanders along the continental rise as hypothesized by Niiler and Mysak (1971). Alternatively, the observed fluctuations might be interpreted as baroclinic instabilities of the Gulf Stream frontal system as discussed by Orlanski and Cox (1973).

The Division of Physical Oceanography at the University of Miami has carried out extensive fieldwork in the Florida Current. The main thrust of this work focuses on variations on a time scale of several days, such as those mentioned above. Our interest in these phenomena was partially stimulated by the finding of intermittent deep southward flow under the northward flowing water masses of the Florida Current (Düing and Johnson, 1972). Based on an intensive 16-day current meter profiling experiment with four anchored ships, Düing (1973a, b) found that westward meandering of the Florida Current is accompanied by deep southward flow and a reduction of the volume transport. The meandering motion was interpreted as a predominantly barotropic wave with a time scale of several days. Particular attention must be paid to oscillations on tidal time scales since they possibly interact with longer period fluctuations. This fact has been taken into account in the data-analytical part of this paper.

Experiments with anchored ships provide high resolution in the vertical; but, due to ship time limitations, they do not yield time series of sufficient length for the analysis of low-frequency oscillations. We have thus deployed recording current meters at a location determined to be representative of the occurrence of several-

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day oscillations and deep southward flow by previous observations from anchored ships. A 50-day time series of current observations was sampled at a depth of 200 m (water depth 320 m) in the cyclonic region of the Florida Current during spring 1972. The analysis of the time series is divided into two parts: one dealing with fluctuations in the several-day range and one with tidal fluctuations. The results of a comparison with atmospheric data and sea level data are briefly discussed.

2. Background

An intensive experiment (Project SYNOPS 71) was carried out in the Florida Straits between Miami and Bimini from 3 to 19 June 1971. Four anchored ships obtained high-resolution current profiles simultaneously every 3 hr. Detailed results of this study are presented in a report by Düing (1973a). Figs. 1 and 2 depict typical situations observed during Project SYNOPS. They are briefly discussed in order to provide a framework for the analysis of the current meter time series. Fig. 1 presents a time-depth diagram of the north–south component of the flow observed near the mean location of the axis of the surface flow, approximately 36 km east of the Miami sea buoy. The contour plot is based on 107 high-resolution vertical current profiles with nearly 200 data points per profile. Two outstanding features are diurnal tidal oscillations throughout the water column and the "pulse-like" occurrence of southward flow in the lower part of the water column. Three major events of deep southward flow can be distinguished during the experiment. Each event lasts approximately 2 days with maximum southward velocity up to 80 cm sec^{-1} during 17 and 18 June. Intermittent deep northward flow occurs from 9 to 11

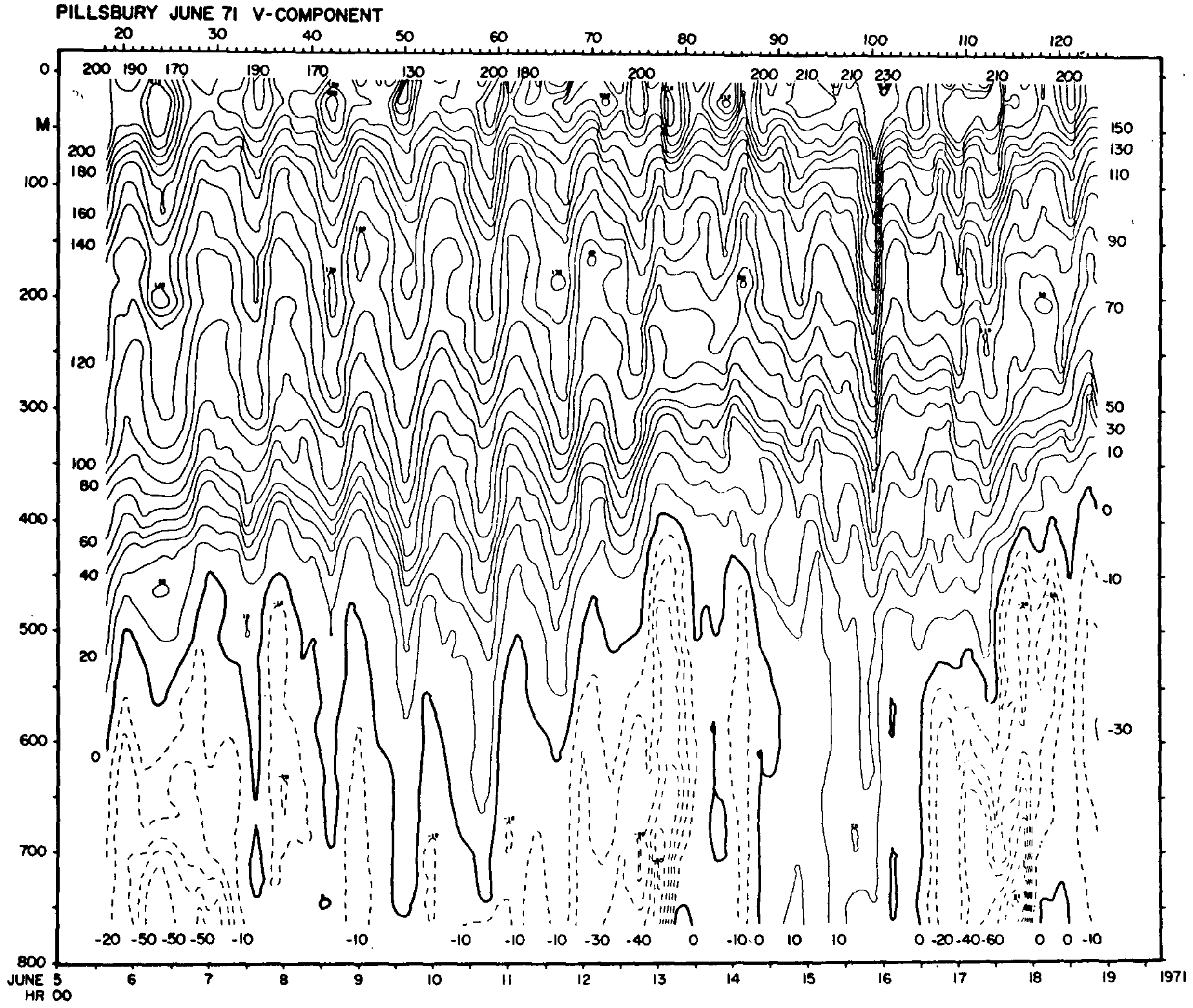

FIG. 1. Isotach contours of north–south component (cm sec^{-1}) from Project SYNOPS 71. Solid lines denote northward flow, dashed lines southward flow. Top scale shows profile numbers.

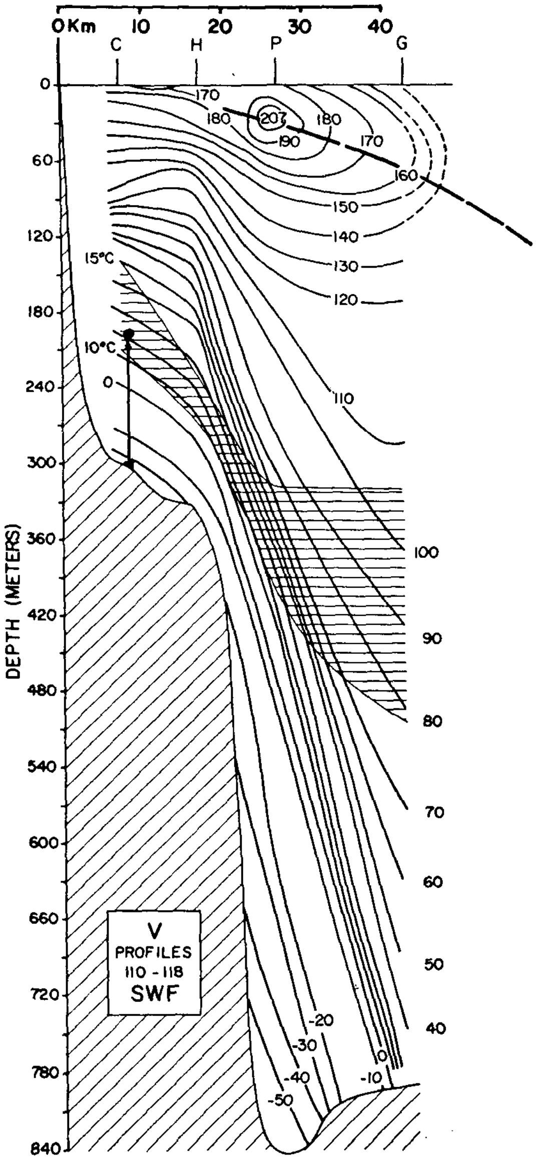

Fig. 2. Location of current meter mooring with cross section of north–south component for a special situation (17–18 June 1971 in Fig. 1).

June and more pronounced from 14 to 16 June. The deep northward flow does not exceed 20 cm sec^{-1}.

Fig. 2 shows a typical cross section for the *V* component, composed of observations made at the indicated locations, C, H, P and G. This cross section is based on mean profiles from the four positions. Each mean profile was obtained by averaging over nine consecutive profiles (110 to 118, top scale in Fig. 1), or 27 hr, in order to reduce tidal influence. In this case, southward flow occurred on the western side of the Florida Straits, including the deep region off the Miami Terrace. Normally the southward flow over the shallow region is less intense than in the deep trench to the east. The largest values for vertical and horizontal shears are found near location H; that is, near the shelf break. The hatched area depicts the thermal frontal structure as represented by the 10 and 15C isotherms.

It appears that the dynamically most active region, and hence the most interesting location for observations with moored current meters, would be halfway between positions H and P, extending from the bottom to at least a depth of 150 m. Technical problems prevented this arrangement. Current meters were located slightly east of the position C, as indicated in Fig. 2.

3. Observations

A first test mooring was maintained for 12 days at the location 25°44′N, 79°50′W in a water depth of 310 m. It was successfully retrieved on 25 March 1972 and replaced on 28 March 1972 at the same location and depth and remained at this position until 4 May 1972. A taut-wire mooring of 110 m length was used. A line tension of ~250 kg was used to keep the mooring as vertical as possible in the expected strong currents. Pressure recordings showed that little line tilt occurred at the top of the mooring, with tilt angles not exceeding 8°. The mooring was released by triggering an acoustical release device. No surface marker buoys or ground lines were used in order to simplify operations in the strong flow. Standard Aanderaa current meters were located at depths of 200 and 220 m. Since the records from both meters were practically identical, only that from the shallow meter was used for analysis.

The original time series (Fig. 3) shows that the dominant fluctuations consist of short-period fluctuations in the diurnal tidal range and of long-period fluctuations in the 4–7 day range. The southward flow event during 15 and 16 March shows an unusually high value of 80 cm sec^{-1}. G. Weatherly from Nova University (personal communication) found southward flow on the same date in a bottom current meter record at a location about 10 km west of Bimini. In general terms, the time series from spring 1972 shows many features similar to the SYNOPS observations from summer 1971.

4. Several-day fluctuations of the current

The analysis of the observation series reveals that there existed persistent fluctuations of the north–south component with a period of about 5–6 days. Fig. 4 shows a low-pass version of the data in Fig. 3. The amplitude response of the numerical filter is essentially unity for periods > 70 hr, the half-amplitude point being at 40 hr. The amplitude responses for diurnal and semidiurnal tidal fluctuations are about 0.05 and 0.0003, respectively. Therefore, the low-pass versions of the original series represent an undistorted picture of all fluctuations with periods >3 days. The main features of the low-passed *V* component are fluctuations with a period of about 5–6 days and an average amplitude of about 15 cm sec^{-1}. The *U* component does not exhibit such regular 5–6 day periods, and its amplitudes are con-

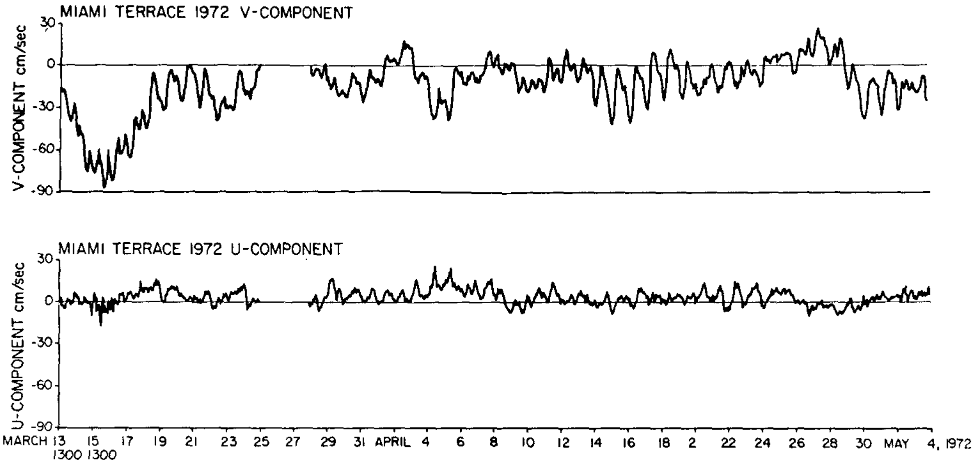

FIG. 3. North–south and east–west components at 200 m depth.

siderably smaller. Energy spectra were computed for the low-frequency fluctuations (Fig. 5) and for the tidal fluctuations (Fig. 7). Fig. 5 shows a low-frequency spectrum [bandwidth 0.084 cycle per day (cpd)] of both velocity components for the range from 0 to 0.7 cpd. Significant energy is found in the spectrum for the V component between 0.1 and 0.25 cpd (10 to 4 days). It should be noted that this spectrum was computed from 3-hr averages of the original series without any filter applied. The mean was removed and the data were detrended (Bendat and Piersol, 1966) before computing the spectrum. Computations without detrending show almost the same drop-off in energy density below 0.1 cpd for the V component. Fig. 5 also shows that the energy level for the spectrum of the U component is generally much lower ($\sim\frac{1}{6}$) than that of the V component. In particular, there is no significant energy concentration in the range 0.1-0.25 cpd, nor is there a drop-off in energy below 0.1 cpd.

To obtain statistical reliability for the energy peak in the V spectrum, the spectral bandwidth chosen was relatively large (0.084 cpd, Hamming window). This has the disadvantage of smoothing the spectrum over a broad frequency range, and the frequency of the energy peak cannot be determined precisely. Use of narrower bandwidths, however, always resulted in energy peaks at periods between 5 and 6 days. For a period of 5 to 6 days, the rms amplitude over the bandwidth of 0.084 cpd is about 20 cm sec^{-1}, which is slightly higher than the amplitude estimated from the low-passed version of the V component (Fig. 4).

Cross-spectral analysis between the U and V components for the several-day range may not be significant since the signal-to-noise ratio for U is almost zero. However, reasonable coherence estimates are obtained for the range from 0.1 to 0.2 cpd and from 0.4 to 0.6 cpd. The coherence squared is nearly 1 for 0.1667 cpd. The phase for the 5–6 day oscillation between U and V is such that V is leading U by about 90°, i.e., about a quarter period, indicating anticyclonic rotation along an elliptical path elongated in the north–south direction.

Our findings in this spectral range are in agreement

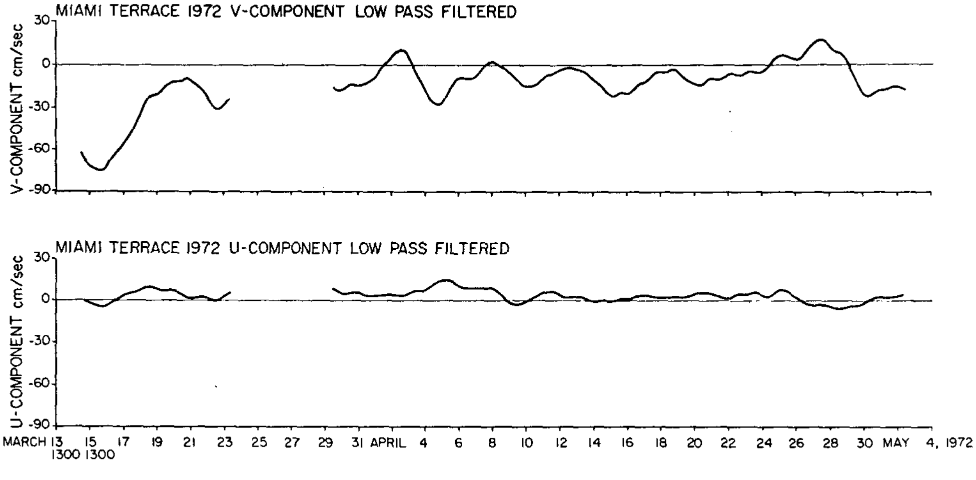

FIG. 4. Low-passed filtered components at 200 m depth.

with Mooers and Brooks (1973). They have studied four months of 1970 summer temperature data taken from five-element vertical thermistor arrays located on either side of the Florida Straits. The Miami array was located at 220 m depth at 25°37′N, 80°03′W, or about 7 n mi SSW of location C in Fig. 2. Mooers and Brooks (1973) found fluctuations in the Miami temperature field that were vertically coherent and essentially in phase over a depth range from 50 to 210 m in a period range of 4–5 days. One interpretation given is that these low-frequency temperature fluctuations are manifestations of lateral, primarily barotropic, meandering motions of the Florida Current in a fashion consistent with that discussed by Düing (1973b).

Further attempts were made to relate the current observations to a sea level record from a tide gauge located nearby. Cross-spectral analysis between the tide gauge record from Miami Beach and the *V* component of the current did not show statistically significant coherency between surface elevation and the *V* component in the 0.1–0.7 cpd range. However, a very broad-banded energy distribution with very low statistical significance was found in the sea level data in the range between 5 and 10 days. A rough estimate of the sea level fluctuation amplitude in this range yields about 8 cm.

Comparison with Atmospheric Parameters

Some of the theoretical studies mentioned in the Introduction show that temporal and spatial fluctuations associated with atmospheric storm systems near the coast of a continent can excite low-frequency fluctuations similar to those described here. We conducted a search for possible existing correlations between the current observations and atmospheric data, partly encouraged by the results of Webster (1961) who found a high degree of correlation between the meandering motion off Onslow Bay and the geostrophic offshore wind component. To this end, cross-spectrum analyses between the current measurements and meteorological data from Miami, Jacksonville, and Cape Hatteras were performed. We correlated each of the *U* and *V* series with each of the *U*, *V*, wind, pressure, and pressure gradient series. Although the spectrum of the *U* component of the wind shows considerable energy concentration around 5–10 days, no significant coherence was found between the time series of the local wind at the three locations and our current time series. No significant coherence was found between current and sea level pressure at the three stations at 5–7 day periods. The pressure spectra at all locations show a strong peak with about a 10-day period rather than a 5–7 day period. There is fair coherence (0.8–0.9) at the 10-day range between current and barometric pressure.

The highest coherence values were obtained with cross-spectrum analyses of the Jacksonville-to-Miami pressure gradient and the *V* component of the current.

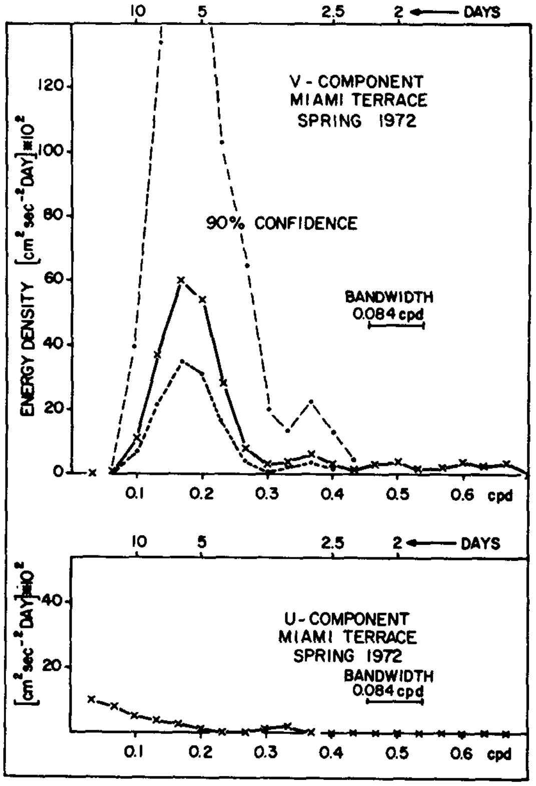

FIG. 5. Low-frequency spectra of north–south and east–west components.

The pressure gradient between Cape Hatteras and Miami does not show any significant coherence with the current. Fig. 6 shows spectra of the pressure gradients between Jacksonville and Miami. The spectrum in Fig. 6b was computed from the pressure gradient series that had the same length and the same starting time as the current series. The spectrum in Fig. 6a was computed from the same pressure gradient series of the same length but the start time was one week earlier. The comparison shows a high degree of nonstationarity for the pressure gradients. There is an energy peak in Fig. 6a at the 5–6 day period contrasting an energy gap in Fig. 6b for the same period range. The cross-spectrum between the current and the pressure gradient shows peaks in both cases around 5–6 days. The coherence estimates for the cases in Figs. 6a and 6b are as variable as the autospectra of the pressure gradients; however, coherence is almost 1 in case (a) for the 5–6 day period but very low for case (b). The computed phase for case (a) is nearly 0°, indicating a delay between pressure gradient and current of about one week. The fact that the pressure gradient series are highly nonstationary was also apparent in the low-pass filtered versions of these series (not shown here). Thus, the given confidence limits are somewhat unreliable, and the difference in the spectra seems to reflect only the variance in a narrow frequency band. We also computed spectra with lower resolution but higher statistical reliability. The spectra of series (a) and (b) look very similar then.

In case of a considerable delay between input and output signal, a cross-correlation function alignment is recommended by Jenkins and Watts (1968) to improve cross-spectral estimates between the two processes. The cross-correlation function between series (b) and the current series were thus aligned. Iterative alignments, however, did not lead to improvements. This may be due to the observed nonstationarity of the pressure gradient series. Only the one-week alignment of the pressure gradient series itself [case (a)] led to satisfactory results where a cross-correlation alignment was not necessary. The magnitude of the pressure gradient fluctuations in the 5–6 day period range is about 0.005-0.01 mb km^{-1} as computed from Fig. 6a. The distance between Miami and Jacksonville is about 500 km, resulting in a pressure difference of 2.5–5 mb over this distance. Like Webster (1961), we found some correlation between the current measurements and atmospheric fluctuations. However, as in his case, the observational series is too short to decide whether these findings are accidental or whether they point to a causal relationship. The results may well indicate that mesoscale atmospheric fluctuations are of certain influence, whereas local- or large-scale atmospheric fluctuations may be of lesser importance.

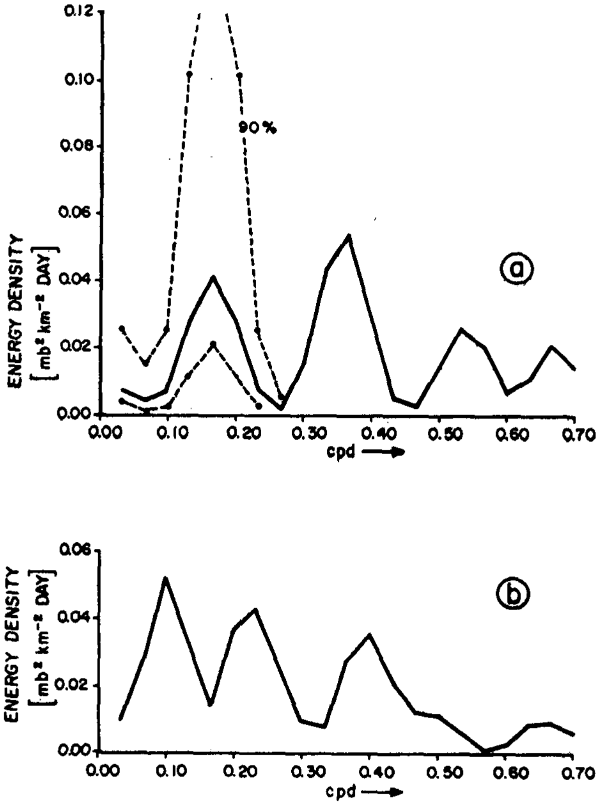

FIG. 6. Low-frequency spectra of atmospheric pressure gradient series, Miami–Jacksonville. In (a) the Δp series starts one week earlier than current observations; in (b) the Δp series starts parallel with current observations.

5. Tidal fluctuations

Little is known about the tidal oscillations of the current in the Florida Straits, especially in the deeper layers of the current. According to Zetler and Hansen (1970), the longest current series known from offshore waters in the Florida Straits are a 15-day record [off Hollywood (Smith *et al.*, 1969)] and a 7-day record [off Fowey Rocks (Pillsbury, 1891)], both observed at the surface. Smith *et al.* and Zetler and Hansen support the hypothesis of a standing wave for the barotropic K_1 and O_1 tides with the possible existence of a wave node close to the Miami latitude. Based on transport data gained by using the free-fall instrument technique, Schmitz and Richardson (1968) indicate that fluctuations of tidal periods account for the major modulation of the Florida Current transport. Schmitz and Richardson found that the transport variation of the O_1 and K_1 tides are comparable to the M_2 tide. Smith *et al.*, (1969) found larger amplitudes for the O_1 and K_1 tide than for the M_2 tide. The results from Project SYNOPS 71 show tidal oscillations predominantly of the diurnal type throughout the water column for the Miami–Bimini cross section.

Fig. 3 confirms the predominance of diurnal or inertial constituents at 200 m depth in the V component. Fig. 7 shows high-frequency energy spectra of the V and U components on a logarithmic energy scale. The V component energy spectrum shows energy peaks near the O_1 and M_2 frequencies. The U spectrum shows a much lower signal-to-noise ratio for the diurnal and semidiurnal tidal bands and a broad energy peak in the diurnal band, with a peak near the K_1 frequency. Cross-spectral analysis reveals high coherence at diurnal frequency, highest at K_1; however, there is low coherence at the semidiurnal frequency.

Spectrum analysis is not an appropriate means to compute amplitude and phase of quasi-deterministic signals such as tides. In order to obtain the harmonic constants of the major tidal constituents, a least-squares analysis of the current series was performed. Tables 1 and 2 give the results of this analysis. No attempt has been made to account for minor constituents; thus, K_1 probably contains some energy of the P_1 constituent as well as of other constituents. A more rigorous analysis will be performed on a year long time series resulting from a long-term monitoring program which was started in the fall of 1972. For each amplitude and phase value, least-square error bounds have been computed. The amplitudes are given in cm sec^{-1}; the phases are Greenwich epochs. There are three computations each for O_1, K_1, M_2, S_2. The first is for the entire series (37 days, 28 March to 4 May), the second for the first half of the series, and the third for the second half of the series. Table 1 shows that about

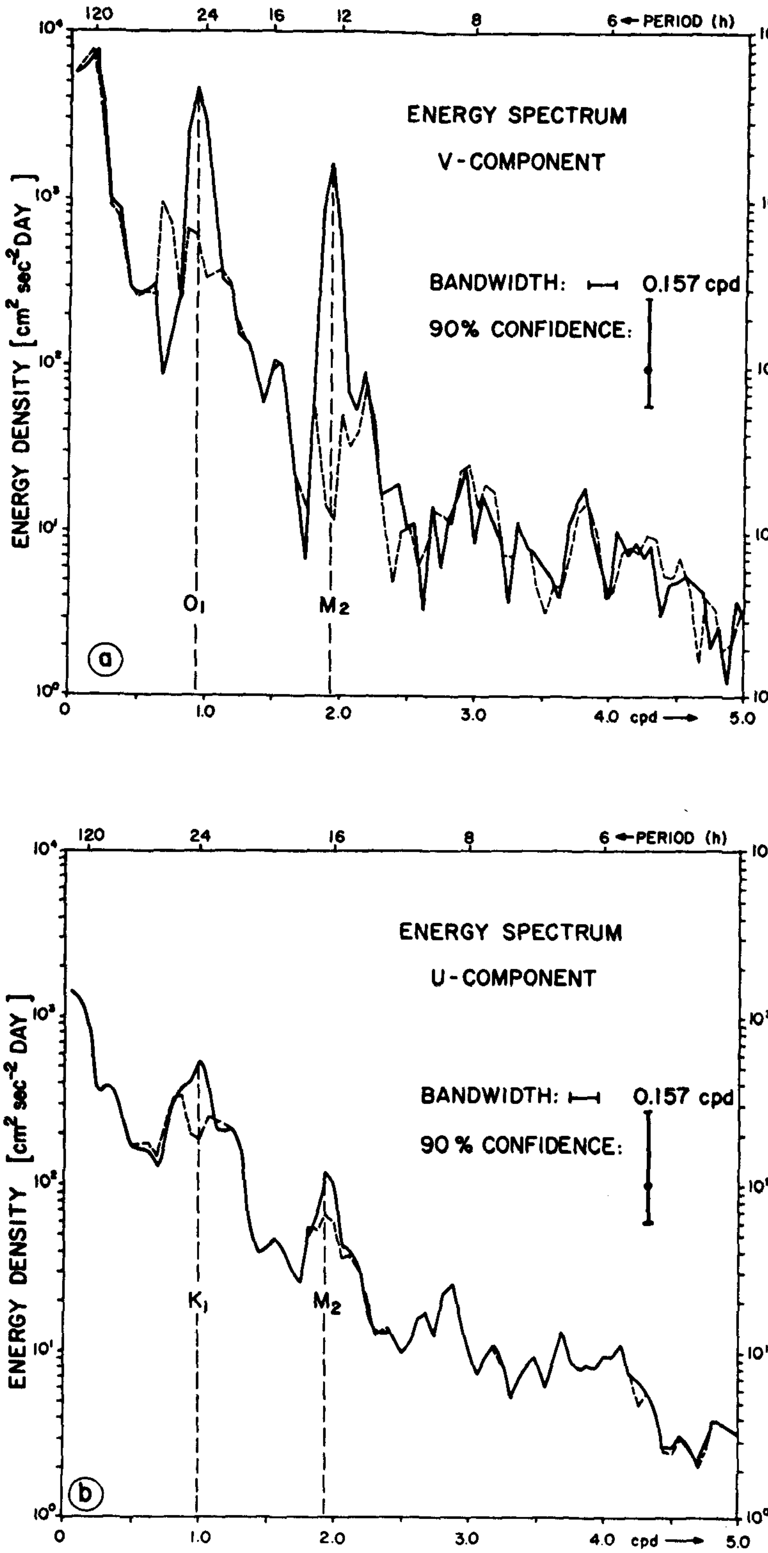

FIG. 7. High-frequency spectra of north–south and east–west components (solid lines) and spectra of residuals after removal of tidal oscillations K_1, O_1, M_2, S_2 (dashed lines).

TABLE 1. Variance due to dominant astronomical tides.

Component	Mean (cm)	Total variance ($cm^2\ sec^{-2}$)	Percentage of total variance due to O_1, K_1, M_2, S_2
V	−7.6	151.0	25.3%
U	3.6	30.6	6.4%

25% of the total variance in V, but only about 6% of the total variance in U, can be explained by astronomical tides. Table 2 shows that the major part of the V variance is due to the O_1 tide, whereas the major part of the U variance is due to the K_1 tide. The tidal amplitudes in the V component are about six times higher than those of the U component. The uncertainty in amplitude and phase estimates of the U component are, in some cases, very high. For example, the amplitudes and phases of S_2 have very high error bounds for both V and U components. The dominance of the K_1 tide in the U component agrees very well with the good coherence found between V and U at the K_1 frequency by cross-spectral analysis. The analysis of shorter parts of the time series (Table 2) shows that amplitude estimates can differ considerably; e.g., almost 1.7 cm sec^{-1} difference for K_1 between the amplitude of the first and second half of the V component. The same is true for the phases; e.g., for K_1 the difference is 30°. This could be due to several reasons: either the small signal-to-noise ratio inhibits separation of tidal constituents, or the tidal amplitudes are modulated by other physical forces. It is also possible that the variations are due to internal tides, i.e., to the baroclinic part of the tides ("baroclinic noise"). This may be seen from the spectra of the residual series shown in Fig. 7. The analysis reveals that there is considerable energy left in the diurnal-inertial and the semidiurnal ranges. Since the effective inertial frequency at the Miami Terrace location is close to the diurnal frequency of the astronomical tides, inertial oscillations may account for the remaining energy in this range.

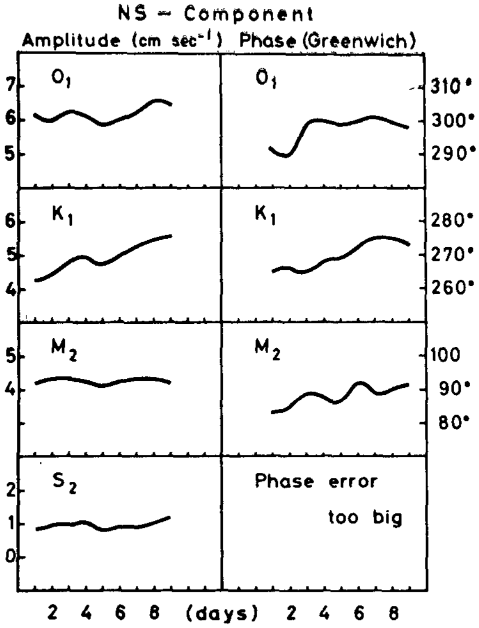

FIG. 8. Tidal amplitude and phase variation of north–south component from 29-day series advancing one day at a time.

In order to establish some reliability criteria for the estimated harmonic constants in Table 2, the following computation was carried out as well. As the length of the series is 37 days, least-square tidal analysis was performed on 9 subseries of 29 days length, separated by 1 day. Fig. 8 shows the amplitude and phase variations of the V component during these 9 days. It can be seen that the K_1 amplitude and the O_1 phase, for example, show rather high variations. The same

TABLE 2. Harmonic constants and associated error bounds* for O_1, K_1, M_2, S_2.

Tides	Series length	$A(V)$ (cm sec^{-1})	Error $A(V)$	$G(V)$ (deg)	Error $G(V)$	Var (V) (%)	$A(U)$ (cm sec^{-1})	Error $A(U)$	$G(U)$ (deg)	Error $G(U)$	Var (U) (%)
O_1	37 days	5.8	±0.4	298	±11	11.1	0.9	±0.2	81	± 36	1.3
	1st half	5.0	±0.5	287	±17	8.3	0.3	±0.3	127	±133	0.1
	2nd half	6.2	±0.5	307	±16	12.7	1.7	±0.3	75	± 24	4.7
K_1	37 days	5.0	±0.4	270	±13	8.3	1.6	±0.2	224	± 20	4.2
	1st half	4.3	±0.5	252	±19	6.1	1.8	±0.3	215	± 27	5.3
	2nd half	6.0	±0.5	283	±16	11.9	1.4	±0.3	239	± 27	3.7
M_2	37 days	4.0	±0.4	86	±16	5.3	0.7	±0.2	326	± 46	0.8
	1st half	3.9	±0.5	80	±21	5.0	1.1	±0.3	319	± 43	2.0
	2nd half	3.9	±0.5	94	±25	5.0	0.3	±0.3	339	±112	0.1
S_2	37 days	1.2	±0.4	327	±53	0.5	0.3	±0.2	352	±103	0.1
	1st half	1.8	±0.5	295	±45	1.1	0.6	±0.3	317	± 82	0.6
	2nd half	1.3	±0.5	15	±72	0.6	0.4	±0.3	301	±108	0.3

* $A(V)$, $A(U)$: Amplitude (cm sec^{-1}) of V, U.
$G(V)$, $G(U)$: Greenwich epoch (deg) for V, U.
Var(V), Var(U): Percentage of total variance due to constituent for V, U.

Table 3. Comparison of harmonic constants from Smith *et al.* (1969) with the present estimates.

	Observations off Hollywood* Surface current speed		Miami Terrace V-component at 200 m	
Tides	Amplitude (cm $\sec^{-1}$)	Phase	Amplitude (cm $\sec^{-1}$)	Phase
O_1	5.5	272°	5.8±0.4	298°±11°
K_1	5.7	284°	5.0±0.4	270°±13°
M_2	3.4	95°	4.0±0.4	86°±16°
S_2	2.5	309°	1.2±0.4	327°±53°

* From Smith *et al.* 1969.

analysis, not shown here, was performed for the U component. In general, the variations in the U component, especially of the phases, are larger than in the V component. Qualitatively these results agree with those in Table 2, thus underlining the time-dependent variation of the harmonic constants. However, some of this variation may be reduced by a more rigorous analysis of future longer time series.

Table 3 shows a comparison of the harmonic constants from the surface current observations off Hollywood by Smith *et al.* (1969) with those estimated here. The agreement is surprisingly good considering that (i) Smith *et al.* analyzed the absolute current speed rather than the components; (ii) our estimates are gained from observations at 200 m depth, theirs from observations at the surface; and (iii) the observational points were located 17 mi apart in a north–south direction. From our current observations, we cannot conclude anything about the vertical structure of the observed tides. However, since the phases of the tidal constituents from the surface observations agree well with those from the near-bottom observations (Table 3), it seems likely that both, i.e., Smith *et al.* (1969) and our analysis, estimated mainly the barotropic part of the tides. This is confirmed by results from Project SYNOPS 71 (Düing, 1973a) which show a predominantly barotropic structure of the tides.

Table 4 shows the harmonic constants of the tidal current ellipses as computed from the 37-day analysis (Table 2). The orientation of the major axis of the current ellipses is approximately north–south for all four estimated constituents. The ratio of minor to major axis is about $\frac{1}{10}$ for the O_1, M_2, S_2 tides, i.e., the tidal current is almost oscillating in a north–south direction. The rotational sense of the current vector is not very significant for O_1, M_2, S_2, as can be seen from the high relative error in the estimation of the minor axes. The ratio of the K_1 axes is about $\frac{1}{5}$; the current vector is rotating in a cyclonic sense.

6. Summary and conclusions

A current meter record from 200 m depth in the Florida Current off Miami shows persistent fluctuations at periods of about 5–6 days. The mean values of the flow during the observational period from 28 March to 4 May 1972 were 7.6 cm $\sec^{-1}$ to the south and 3.6 cm $\sec^{-1}$ to the east. In general terms, the observations are consistent with results by Düing (1973a) from summer 1971. The energy spectrum of the V component shows a pronounced peak at periods of 5–6 days, whereas no significant peak occurs for the U component. The amplitude of the V component in this range is about 20 cm $\sec^{-1}$, or roughly six times that of the U component. The V component leads the U component by about a quarter period, indicating anticyclonic rotation. Were this type of information available from several observation points in the cross-stream and downstream directions, one could draw conclusions on the type of wave and on its propagation direction. With observations from a single point such conclusions would at best be speculative. Correlation attempts with wind and sea level pressure from Miami, Jacksonville and Cape Hatteras were not very conclusive. The best results were found by correlating the V component of the current with the pressure gradient between Miami and Jacksonville, a distance of about 500 km. Correlation with local atmospheric data from any of the three

Table 4. Parameters for ellipses of tidal currents.*

Constituent	O_1	K_1	M_2	S_2
Length of major axis (cm $\sec^{-1}$)	5.8±0.4	5.1±0.4	4.0±0.4	1.2±0.4
Length of minor axis (cm $\sec^{-1}$)	0.5±0.4	1.1±0.4	0.6±0.4	0.1±0.4
Orientation of major axis against north (deg)	173°±2°	13°±3°	175°±3°	13°±10°
Time (hr) of maximum current in direction of major axis	8.4±0.9	17.8±1.1	9.2±0.7	10.9±2.1
Rotation of current vector	anticyclonic	cyclonic	cyclonic	anticyclonic

* All constants are based on the component amplitudes and phases of the 37-day analysis given in Table 2. The times of maximum current are chosen such that the maximum current vector points to the given orientation of the major axis. To get the time for opposite direction of the maximum current vector, add or subtract half a tidal period.

stations was low as well as correlation with pressure gradients between Miami and Cape Hatteras (distance of about 1200 km). This may indicate that mesoscale forcing is of some importance, whereas local- or large-scale effects are not. This result, however, must be considered as preliminary and should be checked when longer time series (at least of one-year duration) become available.

The described features further establish the importance of several-day oscillations in the Florida Current. They are reminiscent of barotropic shelf waves as, for example, discussed by Niiler and Mysak (1971). Quantitatively, amplitude values of the same magnitude result from simple model calculations by Cutchin and Smith (1973). However, a definite conclusion about the existence of shelf waves cannot be drawn at this time since there is no information on the wavelength, phase speed, and propagation direction of these waves.

Analysis of the tidal fluctuations in the record shows that 25% of the variance in the V component and only 6% of the variance in the U component can be accounted for by the four major constituents, M_2, S_2, K_1, O_1. The largest constituent in the V component is the O_1 tide, whereas the K_1 tide dominates in the U component. The direction of the major axis of the current ellipses is approximately north–south for all four estimated constituents. The results are generally in good agreement with those by Smith *et al.* (1969) obtained from a record at the sea surface in the Florida Current off Hollywood. The similarity of the harmonic constants, especially the phases from 200 m depth and from the surface, suggest that the vertical structure is predominantly barotropic, although "baroclinic noise" seems to play a fairly important role in our record. Thus, the variability of the V component of the four major constituents is typically about 20% for the amplitudes and about 10° to 25° for the phases. For the U component, the variability is even higher; e.g., 50% for the amplitude of O_1 and 100% for the amplitude of S_2. The phase variability is correspondingly high.

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