Simultaneous pressure, velocity and temperature measurements in the Florida Straits

by Carl Wunsch[1] and Mark Wimbush[2]

ABSTRACT

We present a descriptive picture of the variability in the Florida Current as measured by a large number of current meters, temperature sensors, and bottom mounted pressure sensors in the period March-August, 1974. Because of the very high velocities, only measurements made in the near-bottom region were possible. The tidal regime is found to be somewhat more complex than postulated from earlier measurements. The great bulk of nontidal variability in the Current is confined to the periods between 4 and 14 days, with the motion being most organized and energetic near 5 and 14 days. This variability is in horizontal wavelengths of about 50 km and appears (with some ambiguity) as northward propagating waves. Space and time scales are roughly consistent with extant stability theories, but the motion appears coupled to meteorological forcing in a way unaccounted for by any model. The motion appears to be finite amplitude waves which have reached a possible equilibrium representing a balance of energy extraction from the mean flow and meteorological forcing, and dissipational processes of unknown form. The Current is very stable at periods between 2 weeks and a year. Transport fluctuations are not simply related to bottom pressure variations.

1. Introduction

The purpose of this paper is to report some results of simultaneous measurements of bottom pressure, near bottom velocity, and temperature across and along the Florida Current in the Miami-Bimini region. These measurements were carried out for the most part in the period March-August, 1974, and were a portion of a larger cooperative experiment between the University of Miami and Nova University for the study of the dynamics of the Florida Current. The individuals responsible for the experimental design were I. Brooks, T. Lee, P. Niiler, and W. S. Richardson.

The history of studies of the Florida Current is now a long one, beginning with Pillsbury (1891), Wüst (1924) and continuing to this day. But the modern period of intensive study may fairly be said to have begun in the early 1960's with the

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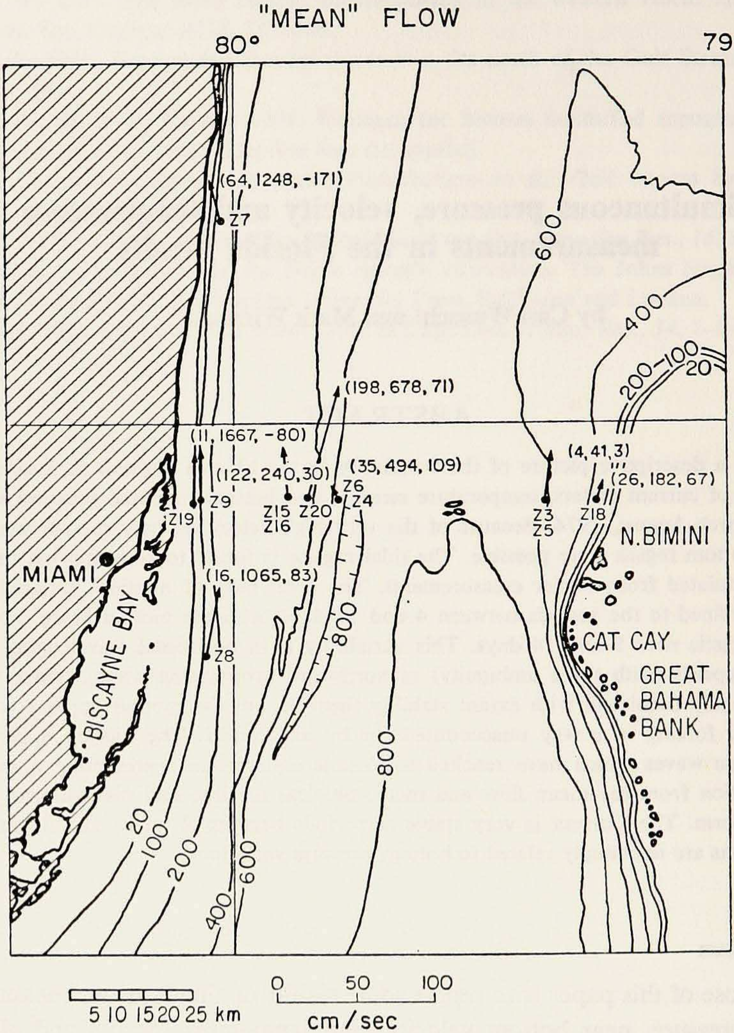


Figure 1. Map showing mooring positions. Moorings are designated by numbers preceded by Z. Depth contours are in meters. Also shown are the mean flow vectors during second portion of experiment for upper current meter on mooring. Numbers are $\overline{u'^2}$, $\overline{v'^2}$, $\overline{u'v'}$, in (cm/sec)^2 where u', v' are defined about record mean and contain the variance at 28 hour periods and longer. Where no numbers are shown the mooring did not have an upper level current meter.

work of W. S. Richardson and his colleagues (e.g. Richardson and Schmitz, 1965; Richardson *et al.*, 1969). This region is a highly complex one, in which a strong highly baroclinic current is confined to flow over a rapidly changing 3-dimensional topography. Superimposed upon the mean Florida Current are a great variety of

Table 1. Bookkeeping information for experiment. Numbers preceded by *Z* are instrument designations. *P* denotes a strain-gauge pressure sensor, *PV* a Vibrotron pressure sensor, *C* a current meter. Most instruments measure temperature as well. Also tabulated are record mean velocities (*u*-east, *v*-north) and temperatures, as well as mean square deviations of velocity.

Mooring & Instr.	Lat.	Long.	$\overline{p}$ = water depth (decibars)	Start time 1974	End time 1974	Distance to bottom	$\bar{u}$	$\bar{v}$	$\bar{T}$	$\overline{u'^2}$	$\overline{v'^2}$	$\overline{u'v'}$
z 33 P	25°50.9′	79°22.0′	640	18 March	17 May	0	—	—	10.04	—	—	—
z 43 P	25°51.2′	79°47.4′	622	18 March	17 May	0	—	—	6.24	—	—	—
z 151 C	25°51.2′	79°53.6′		21 March	18 May	50	−3.5	30.2	9.13	76.7	286	1.4
152 C				21 March	9 Apr	10	−4.6	7.5	8.56	19.5	67.8	−20
153 PV			308	21 March	16 May	0	—	—	8.26	—	—	—
z 192 C	25°50.7′	80°05.1′	30 meters	21 March	12 July	16	−2.3	29.5	25.18	11.4	847	−84
z 51 C	25°50.9′	79°22.0′		4 June	13 Aug	101	1.6	26.8	11.67	3.8	41.1	3.3
52 C				4 June	13 Aug	11	—	—	10.02	—	—	—
53 P			637	4 June	15 Aug	0	—	—	9.95	—	—	—
z 61 C	25°51.2′	79°47.4′		3 June	14 Aug	101	−2.1	3.8	6.73	35.0	494	109
62 C				3 June	14 Aug	11	1.3	−7.8	6.21	5.8	272	8.9
63 P			621	4 June	31 July	0	—	—	6.20	—	—	—
z 71 C	26°22.4′	80°01.5′		29 May	12 Aug	51	−6.7	26.4	20.53	64.0	1248	−171
72 C				29 May	12 Aug	10	0.2	6.5	14.84	4.0	341	31.9
73 P			113	30 May	12 Aug	0	—	—	13.58	—	—	—
z 81 C	25°34.7′	80°04.0′		28 May	13 Aug	51	3.8	41.7	20.01	15.8	1065	82.9
82 C				28 May	13 Aug	10	0.4	5.8	14.15	4.5	188	24.8
83 P			114	28 May	13 Aug	0	—	—	13.07	—	—	—
z 91 C	25°51.0′	80°04.3′		21 March	14 Aug	50	−3.2	30.5	20.28	10.7	1667	−80
92 C				21 March	14 Aug	10	−.06	5.2	13.96	4.6	268	1.4
93 P			117	30 May	13 Aug	0	—	—	12.44	—	—	—
z 161 C	25°51.3′	79°53.6′		23 May	12 Aug	51	−4.4	26.4	9.20	122	240	29.7
162 C				23 May	12 Aug	10	−8.8	9.0	8.00	75.4	93.2	12.6
163 PV			300	27 May	8 Aug	0	—	—	8.03	—	—	—
z 181 C	25°51.2′	79°17.2′	300 meters	4 June	15 Aug	51	3.2	9.5	18.76	25.8	182	66.6
z 202 C	25°51.1′	79°51.1′	304 meters	21 March	23 Nov	98	8.6	71.2	14.29	198	678	71.4

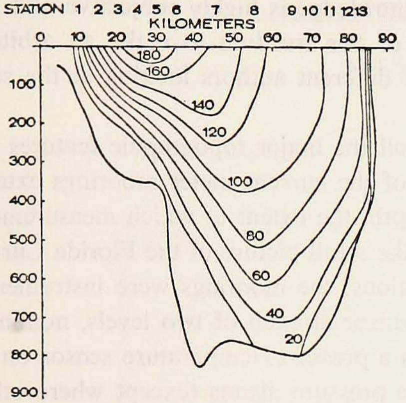
motions spanning a large range of time and space scales, possessing both spatial inhomogeneities related to the topography and mean current structure, and temporal inhomogeneities evidently related to the local meteorological conditions.

Given the complexity of the region, technical limitations in observation techniques, and the absence of anything resembling a complete theoretical context into which to place the observations, it will be some time before a complete analysis of the available data can be undertaken. It is the purpose of this paper to sketch the general structure of the motion within the Florida Straits during the period of the experiment, and to relate the motions to the existing ideas insofar as they are available. But the result is unfortunately more descriptive and less analytical than we would like; a complete and detailed analysis is necessarily postponed.

This experiment was unique in having produced six simultaneous pressure records in addition to those of velocity and temperature (see Fig. 1 and Table 1). Pressure sensors are a comparatively new oceanographic tool, and have rarely been used in array fashion. Therefore, one of our purposes here is to discuss specifically the significance of these measurements and to assess the utility of the instruments. (The original motivation for this paper was to make some sense of the pressure measurements alone. We were led ever deeper into *all* of the data in a never ending quest for simple explanations. The indulgence of the group actually responsible for the experiment is appreciated). One can easily think of simpler regions in which to test the efficacy of pressure measurements but there is an inherent interest in the results of pressure measurements across a strong, confined current system. For example, some discussion has occurred in the past of "monitoring" the transport of strong western boundary and other currents by use of bottom pressure gauges. We will try to shed some light on this possibility. Such fluctuations, if they exist, might be related to global climate changes.

Current meters were of both the Savonious rotor and the Aanderaa types. Moorings did not extend more than 100m from the bottom and the observed velocities were sufficiently low that we believe mooring motion to be negligible, and hence that there should be no systematic differences between velocity measurements of different type.

The pressure measuring instruments consisted of one deep-sea pressure capsule (Wimbush, 1977) and six temperature/pressure (T/P) recorders of the strain gauge type described by Wunsch and Dahlen (1974). The Wimbush instrument employed a 750 psi Vibrotron pressure sensor and its use here to detect residual nontidal pressure fluctuations of a few centimeters is within its design specifications. However, the strain gauge instruments were designed to measure mooring motion, where pressure changes of meters of water are significant. The use of these instruments as on-the-bottom pressure gauges with a required resolution of centimeters of water is thus something for which they were never intended. Therefore, one of the questions we must address here is the consistency and utility of these pressure measur-



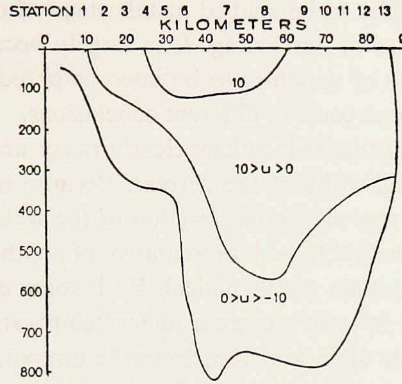


Figure 2. Summer mean Florida Current as measured by Niiler and Richardson (1973). a) north component, b) east component.

ing systems. The experiment designers did not have the assessment of the instruments in mind as a major goal—thus evaluation must proceed by indirection.

The moored instrumentation was deployed in two groups: in an experiment that took place from March-April, 1974, and a second, and fuller, deployment in May-August, 1974. A few records overlap or span the full period. Bookkeeping information is given in Table 1. From the two experiments, we have used here 17 current meter records, 26 temperature records, and 9 pressure records. With minor exceptions, the data have been treated in two groups corresponding to the two experimental periods. We have also tended to concentrate attention upon the second and fuller set of data.

The major topographic feature of this region is the Miami Terrace (continental shelf) at the western side of the Florida Straits with water depths to about 350m (Fig. 1). To the east of the Terrace, there is a rapid drop-off into much deeper water. At the eastern edge of the Strait, the depth decreases abruptly at the Grand Bahama Bank and associated islands.

An estimate of the summer mean Florida Current at 25°44′ N latitude taken from Niiler and Richardson (1973) is shown in Fig. 2. The Florida Current as it crosses the Miami Terrace at an angle is also in the process of adjusting from the 90° turn to the north in the transition from the Florida Keys region. The structure of the current is very complex, even in the mean (see Stommel, 1965) and one can by no means regard the overall baroclinic structure as uniform. This combination of varying topography and changing current makes it impossible to regard the instruments as a homogeneous array. In such a situation, the relationship between any given pair of time series in principle contains new information; the number of such possible pairs resulting from this experiment is immense (2628) and each is, of course, frequency dependent. Any choice of appropriate combinations of physical variables to be studied at this stage of our knowledge is highly subjective and perhaps even misleading. It is largely because of this freedom to make an arbitrary choice of variables to be intercompared that different authors looking at the same data can come to different conclusions.

Instrument locations clearly range across all the major topographic features and the full width of the current. Because none of the current meter moorings extends over any substantial fraction of the water depth, the extent to which measurements can be said to be representative of anything like a full picture of the Florida Current will remain problematical. With some exceptions, the moorings were instrumented so as to have a current meter/temperature sensor at each of two levels, nominally 100 or 50m, and 10m from the bottom, plus a pressure/temperature sensor on the bottom. The water depths in Table 1 are the pressure means (except where otherwise stated) and do not always agree with charted depth.

A large and complicated literature exists on the motions within the Florida Current (see for example, Düing, 1973, Mooers and Brooks, 1974, Lee, 1975, among many others) including several papers in this issue of the Journal of Marine Research. An exhaustive attempt to cross-reference has not been made and in any case it is often difficult to trace the origin of an idea. Particular attention is called to the paper of Düing *et al.*, in this issue which treats much of the same data and comes to slightly different conclusions in a number of instances.

2. Overall description

The record mean flow vectors are displayed in Fig. 1, along with a tabulation of $\overline{u'^2}$, $\overline{v'^2}$, $\overline{u'v'}$, where u', v' are deviations from the record mean (energy with periods shorter than 28 hours was first removed from the data). One sees a general northward mean flow at all mooring positions, with the greatest value at the edge of the Miami Terrace where the surface maximum lies. Table 1 shows that, with one exception, the flow at the level nearer bottom is reduced, but is still northward. The one exception is current meter 62 in the deep water at the terrace edge where the net flow is to the south.[3]

It should be emphasized that these means are taken over the record lengths of the second setting and no conclusion concerning their long-term stability is implied at this stage. For the most part, the record means are less than or comparable to the record standard deviation and are not obviously significant.

Some representative spectra of the velocity and temperature records are shown in Figs. 3, 4, 5. Typically the northerly components of velocity show strong diurnal and semidiurnal peaks superimposed upon a reddish background. The inertial period at 26°N is 26.5 hours and is not a prominent signal when identifiable at all. That is, the diurnal peak is quite clearly tidal in origin. The internal wave band

3. The full instrument designation would be Z62—the second instrument on mooring 6, but we will generally drop the Z prefix.

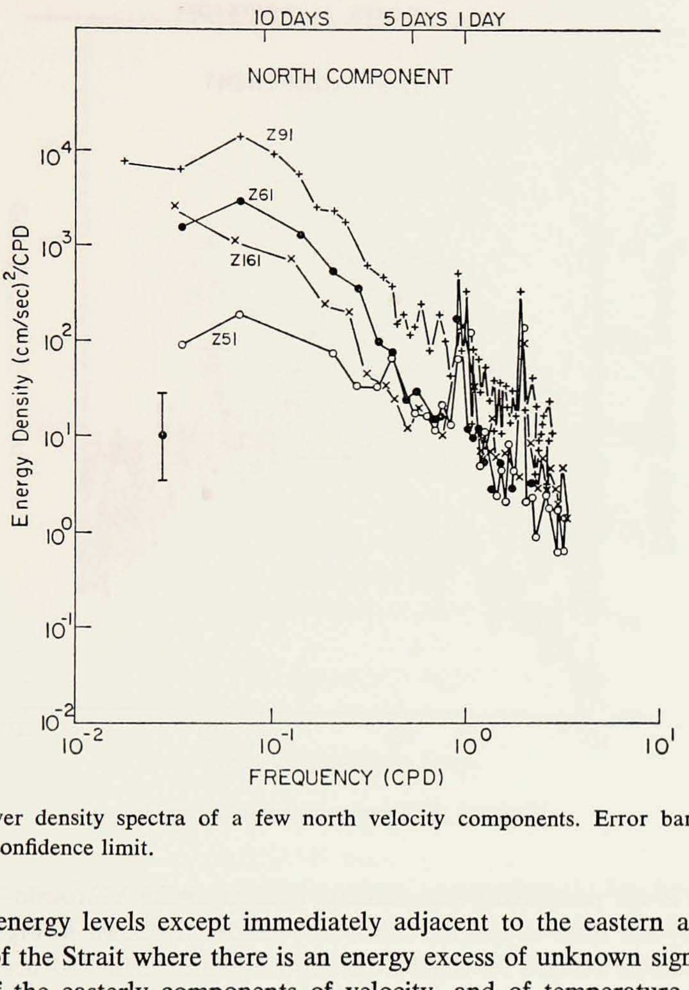


Figure 3. Power density spectra of a few north velocity components. Error bar is approximate 95% confidence limit.

has normal energy levels except immediately adjacent to the eastern and western boundaries of the Strait where there is an energy excess of unknown significance.

Spectra of the easterly components of velocity, and of temperature, are somewhat more variable. Figs. 4 and 5 show strong suppression at certain locations of the semidiurnal tidal peaks in both easterly component and temperature. The northerly component of velocity is more energetic than the easterly at the low frequency end of the spectrum, with greater equality at periods shorter than about 10 days. Easterly velocity energy is generally suppressed adjacent to the north-south trending topography. Most of the energy in the velocity records is found near 10-14 days. Unless this experimental year was exceptional, the record means are thus representative of the true mean values for this particular season. Notice (Table 1, Fig. 1) the sign changes occurring in the correlation $\overline{u'v'}$ on the western, shallow side—a further indication of the spatial inhomogeneity, and of the need for great care in generalizations made from point measurements.

Pressure records are dominated by the tides in all cases and so a display of the

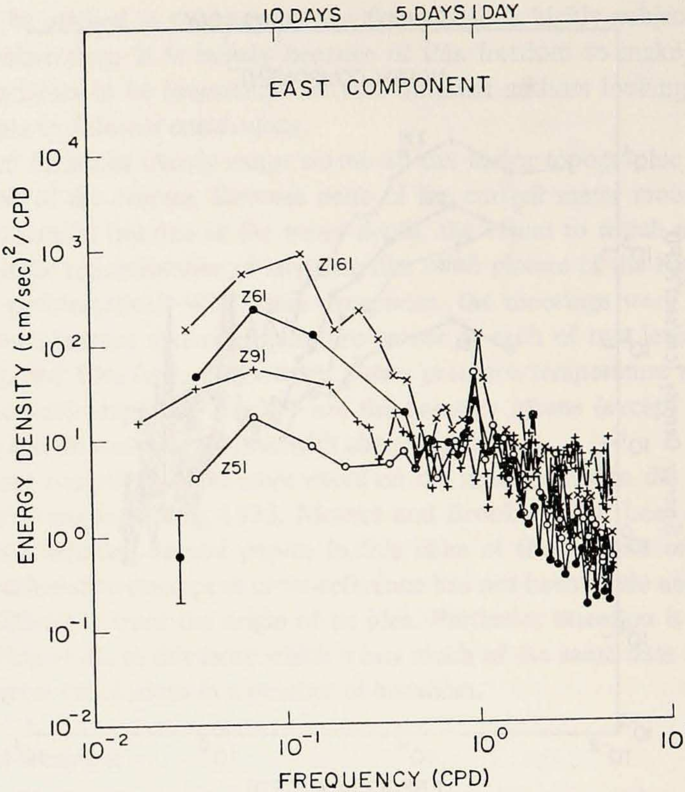


Figure 4. East component velocity spectra.

raw curves is not particularly illuminating. Spectra of the Vibrotron gauge record (record 163) and three of the T/P recorder records are shown in Fig. 6. The T/P recorder pressure records obtained from depths greater than 150 decibars showed a strong drift 0(100) centimeters throughout the experiment. This drift is believed to be due to creep in the bonding of the strain gauge sensing element and is normally negligible when the instruments are used to monitor mooring motion. But here we wish to use signals on the order of centimeters and the drift must be removed. The nature of the drift is not fully understood and was not predicted. However, experimentation with the instruments used here, and those used elsewhere, supports the notion that the drift is accurately described by a curve of form

$$p = A ln(t/t_o) \tag{1}$$

where p is pressure, t is time, and A and t_o are constants. We do not reproduce here the details of the experimentation with drift laws, but suffice it to say that for given instruments, the constants A, t_o remain reasonably constant from one deployment to the next, suggesting that they are characteristic of an individual instrument.

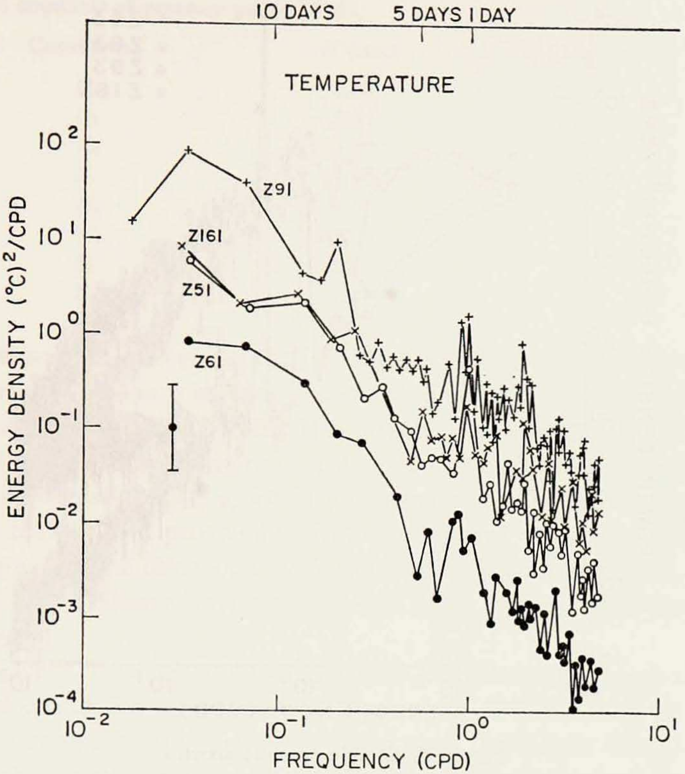


Figure 5. Sample temperature spectra.

For all purposes of this paper a drift law given in equation (1) has been removed from records 33, 43, 53, 63, 93. The drift was 0(100 cm) in 33, 43, 53, 0(50 cm) in 63, and 0(10 cm) in 93. This removal of an empirical drift law is obviously not a rigorous nor wholly satisfactory procedure.

The record 93 spectrum is typical of the three instruments along the 100 m contour on the west of the Strait and shows a generally red structure with strong superimposed diurnal and semidiurnal tidal peaks, a weak M_3 component, and tidal overtones near 6 hours. Total energy falls rapidly out to the Nyquist period of 15 minutes. The spectrum of record 163 at 300 m near the edge of the Miami Terrace is essentially the same except that it levels off just short of 10 cycles/day. Perhaps, owing to the greater depth, the instrument noise level is reached at this frequency.

It is the two deeper pressure records, 53, and 63, that produce somewhat puzzling spectra. The most obvious feature of Fig. 6 is that in the period range of about 10 days to 1 hour, there is nearly 3 orders of magnitude more energy in the deep records than in the others. That this additional energy is *not* due to instrument

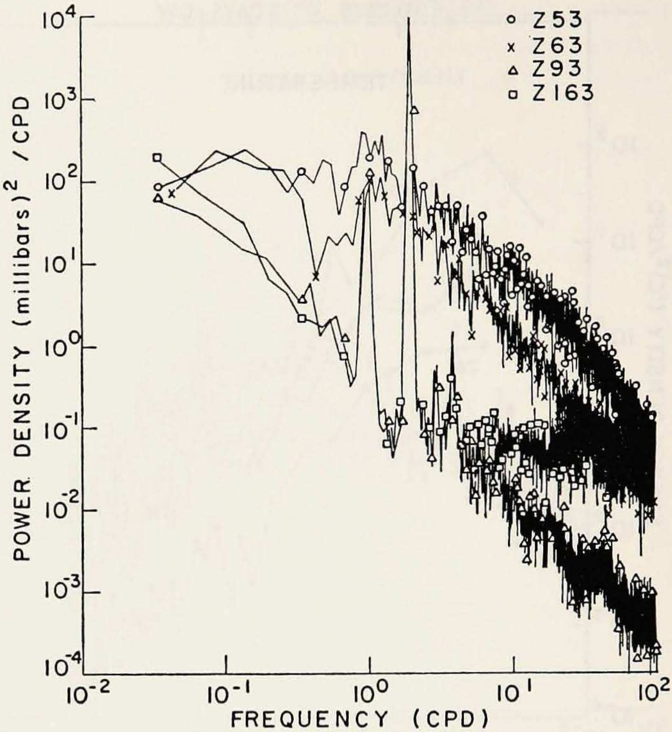


Figure 6. Sample pressure spectra.

noise is suggested by the rapid drop-off to near the least count level at the very highest frequencies, and the convergence to the energy level of the shallower instruments at the lowest frequencies where one would ordinarily expect to have the greatest difficulty with instrument noise (though we have of course removed considerable energy at the lowest frequencies through the de-trending process). The range of periods, diurnal to the cut-off, is normally that of internal waves. One would expect the pressure spectrum in the internal wave band to scale with the local buoyancy frequency, and hence to be *reduced* in the deep water. Obviously, we will have to return later to the question of whether any of the results of the deeper pressure measurements are to be believed.

3. Tidal regime

We begin with a discussion of the tidal regime, as it represents a strong signal and one in which there is a considerable independent context. Zetler and Hansen (1970) describe the barotropic tides of this region and Niiler (1968) the internal tides. The Florida Straits are a transition region where the barotropic tide goes from the predominantly semidiurnal type characteristic of the North Atlantic to the

Table 2. Tidal constants of pressure gauge Z0163.

Constituent	H (cm.)	G (degrees)
Q_1	0.82	265
O_1	3.01	261
K_1	3.20	237
P_1	1.04	238
N_2	8.51	358
M_2	36.86	18.8
S_2	7.56	53.3
F_2	1.77	56.6

dominantly diurnal regime of the Gulf of Mexico. Zetler and Hansen (1970) conclude that the diurnal tide is essentially a standing wave of the Gulf, with an elevation node near the latitude of Miami. They suggest that there ought to be a velocity maximum of the barotropic tide near that node (a simple model is used). On the other hand, the semidiurnal tide, which is dominated by the M_2 component, is believed to be essentially a progressive wave propagating into the Straits and Gulf from the north. C.f. the discussion by Schmitz and Richardson (1968). In Table 2 are given the tidal constants from the Vibrotron gauge record 163 at the edge of the Miami Terrace.

a. M_2 Tide. In Fig. 7, we display the amplitude and Greenwich phase G of the M_2 tide in the region of our measurements. These were obtained from an analysis of the Vibrotron record by the method of Munk and Cartwright (1966). The other pressure records were then analyzed by using the Vibrotron record as a reference station. We also show the Miami Beach, North Bimini, and Cat Cay constants obtained from National Ocean Survey records.

We have used the tidal constants from record 33 of the first setting rather than 53 of the second setting because the noise level at tidal frequencies was uniformly higher in the second setting for unknown reasons (the instruments were the same). Generally speaking, the tidal amplitudes are highest on the western side of the Strait and the phase propagation is clearly from the north.

This is a region of strong baroclinic tides (Niiler, 1968) and it is not clear to what extent bottom pressure is affected by the baroclinic tides. The classical picture deduced from the Miami, Cat Cay and Bimini sea level records is of constant phase lines across the Strait. A sketch of the phase line $G = 19°$ in Fig. 7 suggests a deviation from cross-strait uniformity. The phase line has, however, been dashed, since it depends mostly upon the delay deduced from a single record, 63, in the deep water. Such a phase delay corresponds to 10 minutes, and it is difficult to be absolutely certain of the reliability of the measurement. The record from the first setting at this point, record 43, also indicates a delay but of only 4-5 minutes. For this reason, we regard the result as tentative. Occam's razor suggests the simpler picture, and the spectra, Fig. 6, show a noise level at M_2 frequency 20

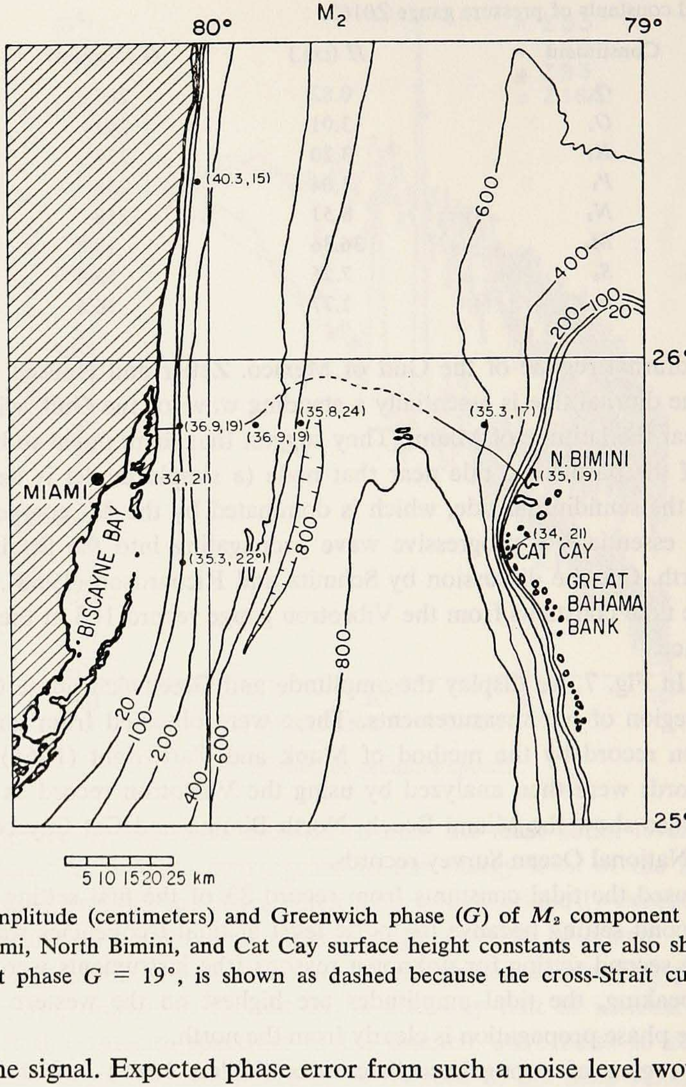


Figure 7. Amplitude (centimeters) and Greenwich phase (G) of M_2 component of pressure in Strait. Miami, North Bimini, and Cat Cay surface height constants are also shown. The line of constant phase $G = 19°$, is shown as dashed because the cross-Strait curvature is uncertain.

db below the signal. Expected phase error from such a noise level would be about $\pm 3°$ and so constant phase across the strait is highly probable.

A real delay in time of high pressure at 63 could be due to a small baroclinic component. But somewhat surprisingly, despite the large topographic feature, the temperature records obtained on this mooring show virtually no semidiurnal tide, certainly not enough to generate a pressure signal sufficient to shift the time of high pressure by 10 minutes. If the effect is real, it is possibly due to the strong adverse current and the three-dimensional topography at this position. Slight changes in the position of the maximum current might account for the change in phase seen between the two settings.

The tidal ellipses for the M_2 tide are shown in Fig. 8. The motion is nearly

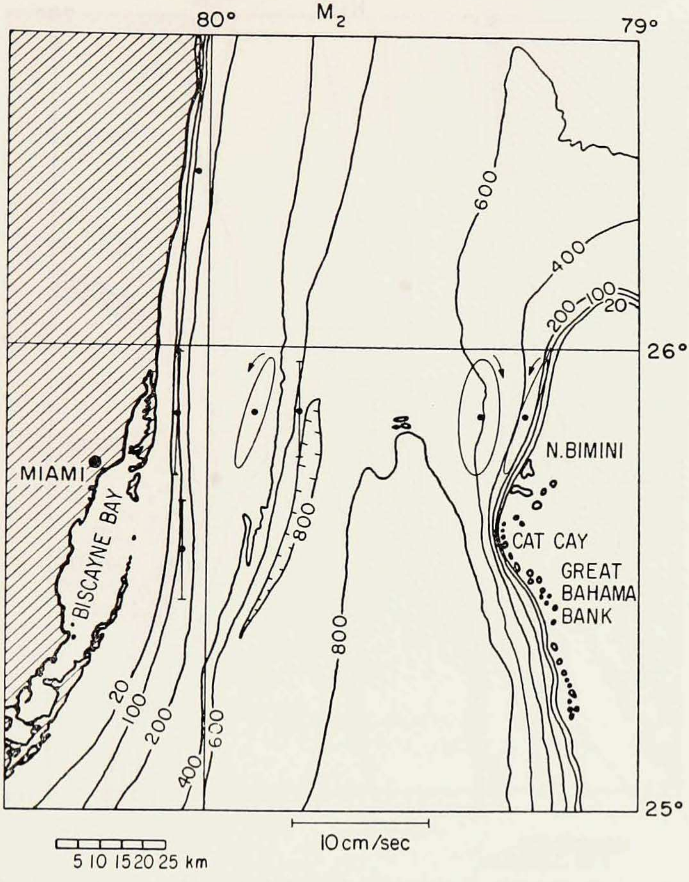


Figure 8. M_2 component tidal ellipses at upper current meters. There was no measurable tidal signal at the northernmost current meter.

linearly polarized adjacent to either steep topographic features or the channel boundaries. On the basis of the available velocity measurements, which do not penetrate very far into the water column, one cannot distinguish the baroclinic from the barotropic tidal velocities. At the position on the edge of the terrace (mooring 16), the ellipse shrinks between the upper and lower current meters, but this is more likely to be a boundary layer effect than a baroclinic one. Some direct generation of internal tides undoubtedly occurs over the topographic gradients but there is little one can say about it with the available data. Thus, it is suggested that the interpretation of these tidal ellipses is simply as the tidal coherent velocity, encompassing both the barotropic tide and whatever part of the baroclinic tide is coherent. Typical *u-v* coherence is 0.8. For unknown reasons current meter 71 yielded no significant semidiurnal tidal peak.

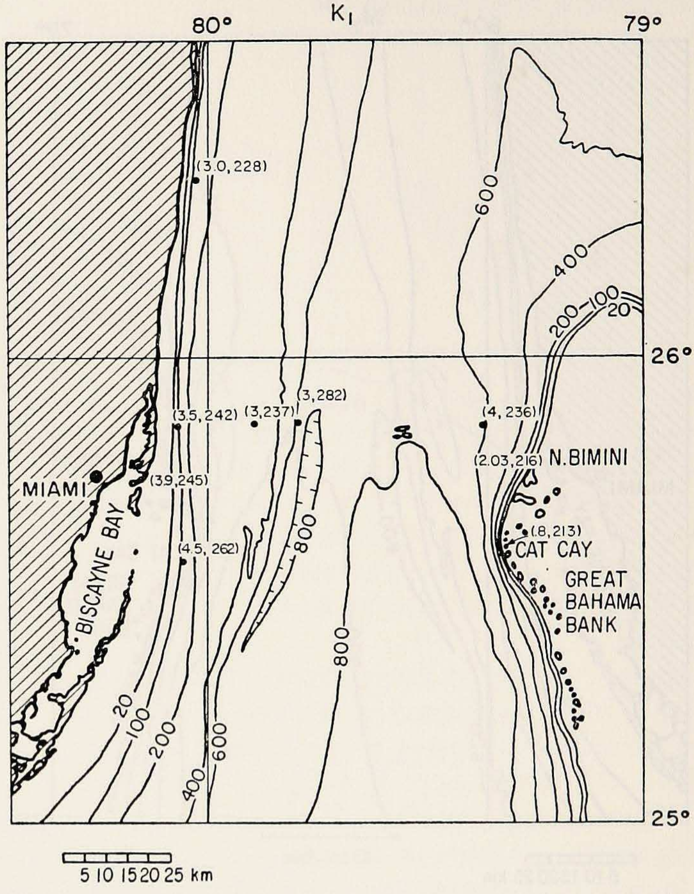


Figure 9. Amplitude and phase of K_1 constituent in Strait.

b. K_1 Tide. The diurnal tides are very weak in elevation in this region, growing progressively stronger as the Gulf of Mexico is penetrated to the south (Zetler and Hansen, 1970). In addition, the background noise is greater at diurnal periods, as is evident from Fig. 6, especially in the deeper parts of the Strait. This combination of circumstances renders the diurnal tidal constants much less reliable than the semidiurnal. For example, the typical coherence between pressure sensors 63 and 53 is .99 at the M_2 period, but only .8 at K_1, suggesting that roughly 1% of the energy at M_2 frequencies is noise, but that about 35% is noise at K_1. In addition, the noise levels change considerably between the first and second periods especially on the eastern side of the Strait. Using the records from both periods, the best estimate of the elevations and phases is shown in Fig. 9. Owing to the high noise levels we have refrained from contouring the figure. Typical deep water phase uncertainty is about $\pm 11°$ and 1-2 cm in amplitude. The picture that emerges is not

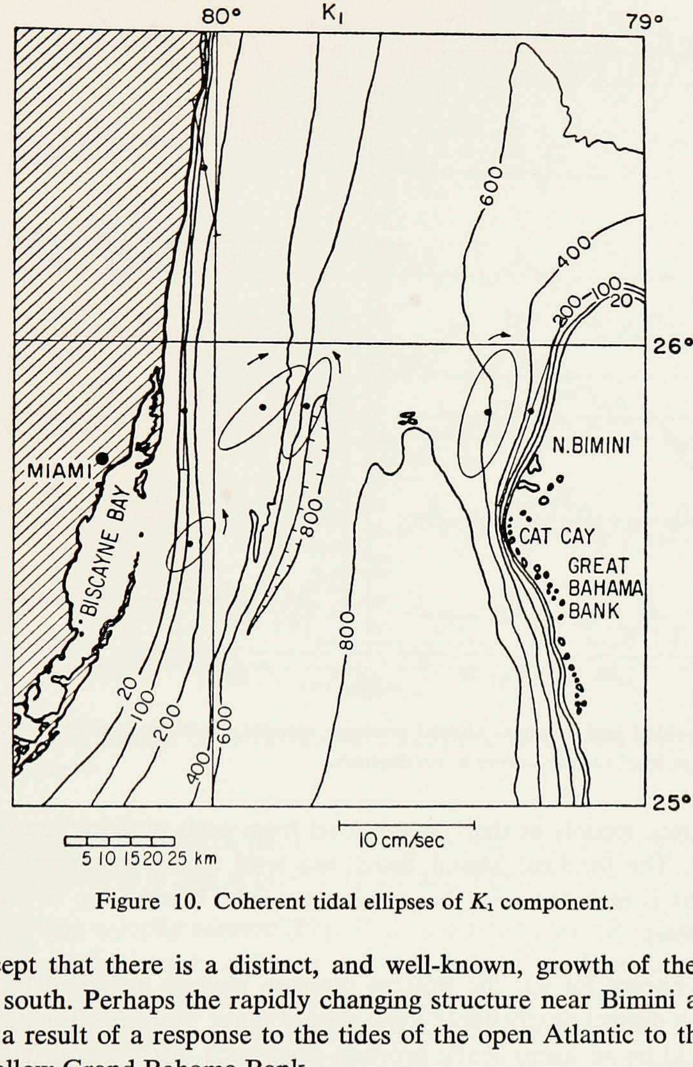


Figure 10. Coherent tidal ellipses of K_1 component.

simple, except that there is a distinct, and well-known, growth of the constituent toward the south. Perhaps the rapidly changing structure near Bimini and Cat Cay is partially a result of a response to the tides of the open Atlantic to the east, over the very shallow Grand Bahama Bank.

The K_1 velocity ellipses are displayed in Fig. 10. As for M_2, these represent the coherent part of the velocity field, barotropic plus baroclinic. Typical u-v coherence is .6-.7. One hesitates to draw any conclusion except that the behavior of the tide is complex.

4. Sub-tidal continuum

The pressure records generated by removing the tides, and then filtering to a 28 hour average are reproduced in Fig. 11. Notice that the scales are variable in order to make obvious the fluctuations in each record. Corresponding velocity component

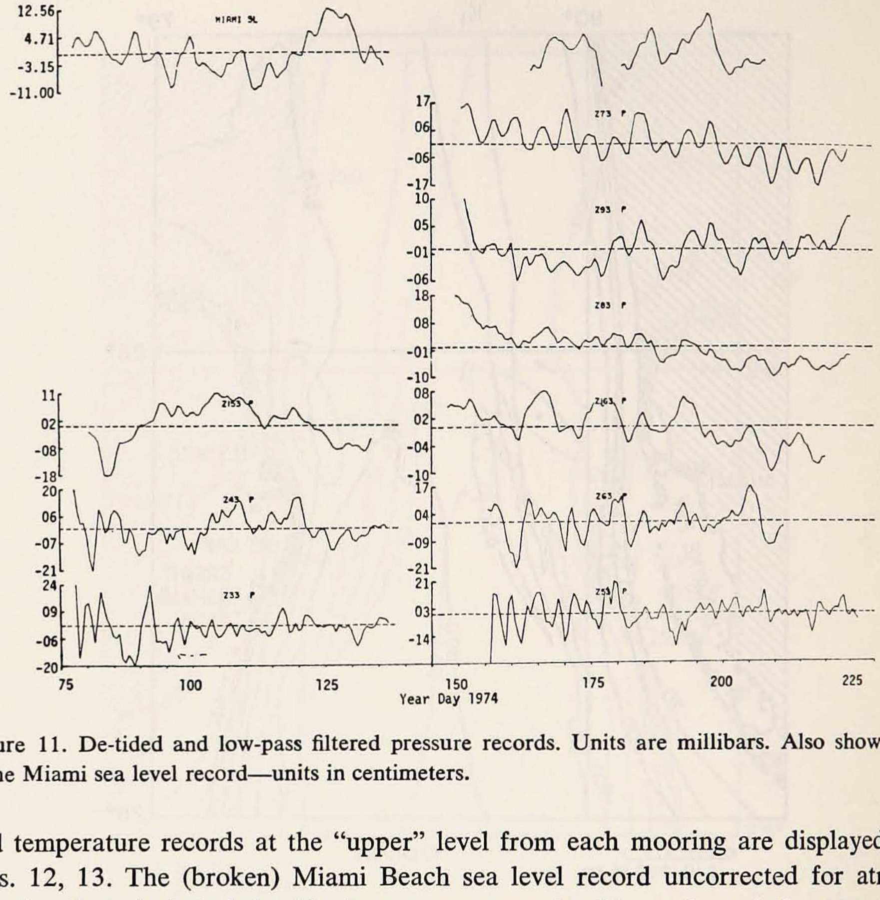


Figure 11. De-tided and low-pass filtered pressure records. Units are millibars. Also shown is the Miami sea level record—units in centimeters.

and temperature records at the "upper" level from each mooring are displayed in Figs. 12, 13. The (broken) Miami Beach sea level record uncorrected for atmospheric effects is included with the pressure records. (Correction of the record is discussed below).

a. Pressure. Except for 93, the western pressure records including the Vibrotron gauge, show a distinct nearly linear trend toward *lower* pressure. It is difficult to see how this could be an instrumental problem since such instruments, if they drift at all, normally tend toward higher pressure. The result could derive from a large scale, long-term change in elevation and possibly transport. The absence of the trend in 93 is probably due to the slight instrumental drift which this instrument apparently underwent and which was not completely removed. Any long-term trend to lower pressures of similar magnitude in the deep instruments 53 and 63 would be lost in their drift.

Otherwise, the records are clearly dominated by oscillations of nominal 5-7 and 10-14 day periods. Superficially at least, the 5-7 day oscillation is best developed at the western side, especially in record 73. Record 163 near the edge of the terrace is dominated by the 10-14 day oscillation instead. The two deeper records 53, 63

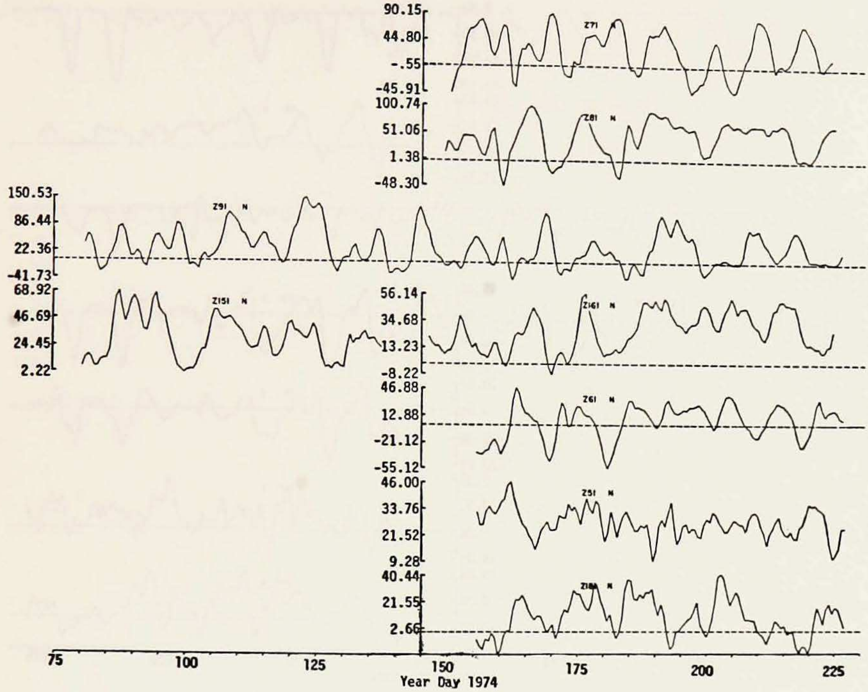


Figure 12a. 28 hour average north component velocities at upper current meters. Units are centimeters/second.

in the deep water in the eastern parts of the Straits have a much noisier appearance, but with some visual structure at periods of 2.5 and 5 days.

b. Velocities. The velocity records (Fig. 12a), one must remember, are taken from very different depths in very different regions of the mean Florida Current. Care must be taken in comparing such spatially inhomogeneous records.

With the exception of 51 in the eastern region, all locations show oscillations of northerly components of velocity sufficiently strong actually to reverse the sense of the current. On the Terrace, one often finds nearly 1 knot to the south. Visually, the periods of these oscillations are either 5-7 or 10-14 days, the exception again being record 51 on the deep eastern side which looks much like the corresponding pressure record with higher frequencies more prominent. Record 181 in the very shallow water on the eastern side again tends to show a more organized 10-14 day motion.

Little or no lower frequency energy is visible in these velocity records. The spectra of a representative sampling of the northerly components (Fig. 3) show a distinct flattening or even drop for periods longer than about 14 days. Evidently, at these depths at least, there is little variability between about 14 days and the

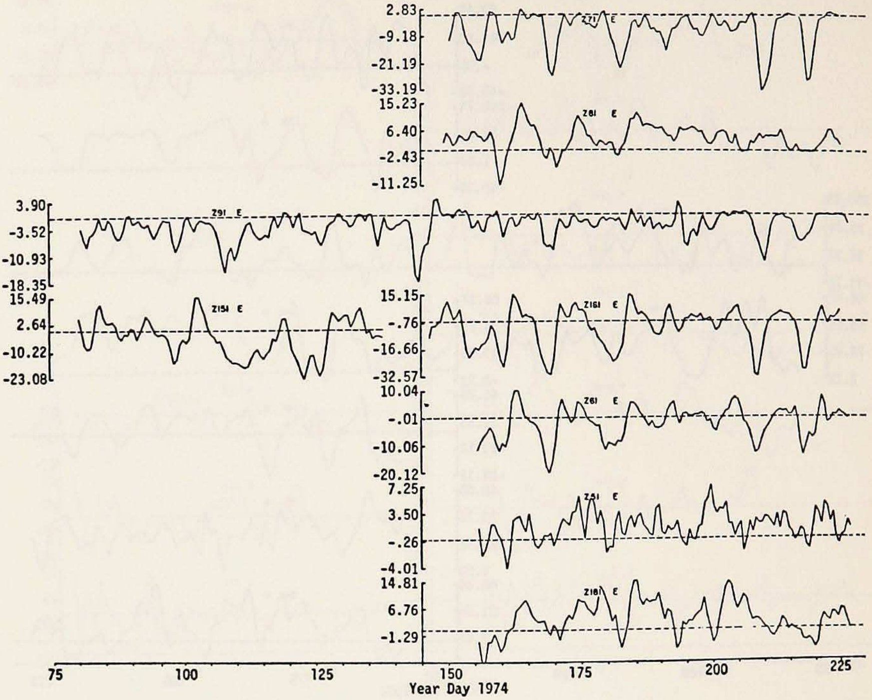


Figure 12b. 28 hour average east component velocities at upper current meters.

record duration (order five months). This is in marked contrast to open ocean velocity records.

The easterly components of velocity are shown in Fig. 12b. Generally speaking, these fluctuations mimic the northerly components, but are weaker.

c. Temperature. The low frequency temperature variability at the upper level is displayed in Fig. 13 and is similar to that in the velocities. Again, the records are remarkable for the absence of any obvious energy content at periods exceeding about 10-14 days.

d. Kinematics and dynamics of the variability. These observations of very energetic variability at periods between 5 and 14 days are by no means the first. See Kielmann and Düing (1974), Mooers and Brooks (1974), among many others. Using restricted data sets, these authors have speculated upon the nature of the dynamics governing these phenomena. Unfortunately, most of our ideas derive from studies of linear wave motion and their applicability in this region of a strong mean baroclinic current over three-dimensional topography is far from clear. For example, as has been pointed out before, even the meaning of a barotropic mode becomes obscured in the data. Because of the substantial isotherm slope associated

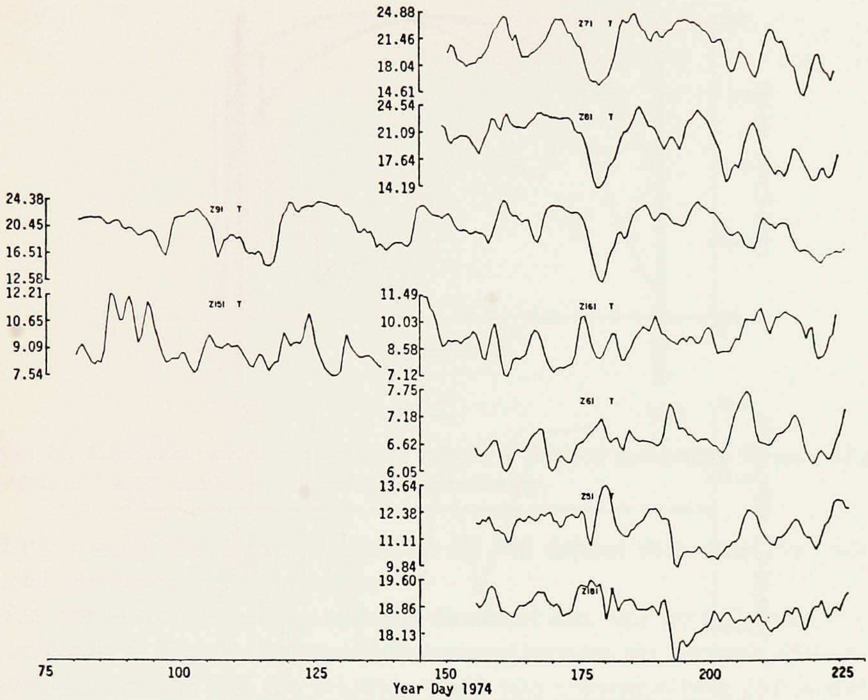


Figure 13. 28 hour average temperature traces at upper current meters.

with the mean Florida Current, motions that are quasi-depth independent will generate substantial temperature signals. It is also difficult to distinguish motion of the mean current axis from a linearly superposed wave motion. For this reason a complete understanding of the motions we observe is going to take a considerable time. Most of what we can set out here is in the nature of a preliminary description.

(i) Geostrophy

The presence of the pressure gauges does permit us to make some simple direct tests of the geostrophic relationship that normally cannot otherwise be performed. The Florida Straits was, of course, the site of Wüst's (1924) classic demonstration of the validity of the dynamic method.

Strictly speaking, bottom pressure gradients are related to the bottom velocity and would bear a simple relationship to velocities higher in the water column only in the event that the motion were barotropic. The coherences between pressures and velocities measured on the same mooring are generally quite weak, no matter which of the two current meters is used. What coherence there is tends to have a phase indistinguishable from 90°. This small amplitude and phase tendency confounds an effort to deduce any nonzero energy fluxes through the correlations of p' and v'.

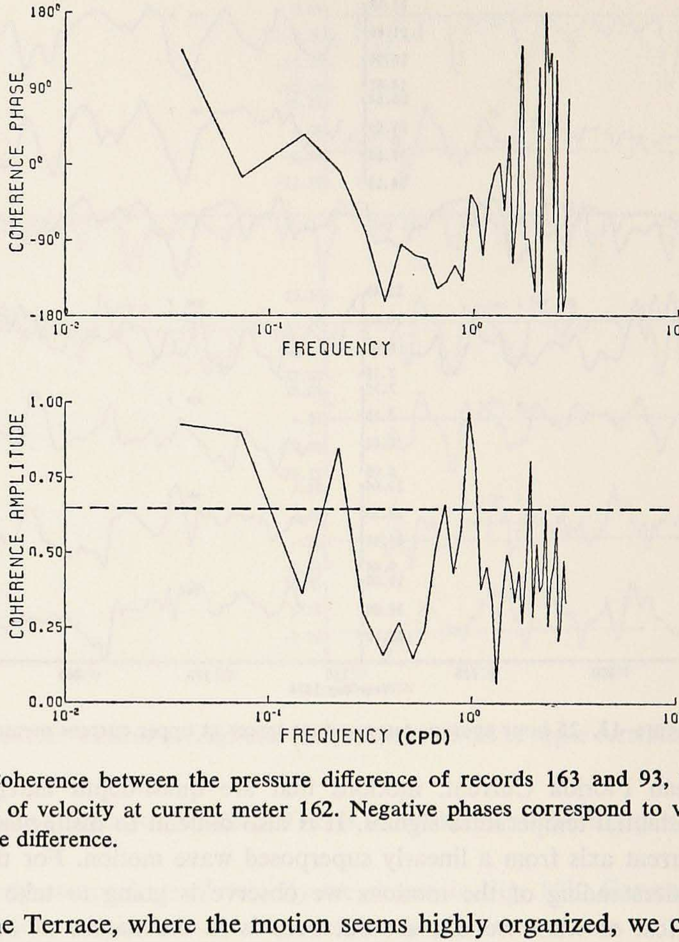


Figure 14. Coherence between the pressure difference of records 163 and 93, with the north component of velocity at current meter 162. Negative phases correspond to velocity leading the pressure difference.

Up on the Terrace, where the motion seems highly organized, we can, however, compute nonzero coherences between velocities and pressure *gradients*. But the interpretation is not altogether straightforward.

The geostrophic relationship

$$fv = 1/\rho \frac{\partial p}{\partial x} \qquad (1)$$

may be translated into finite difference form as

$$fv_i = 1/\rho \{p_{i+1} - p_{i-1}\}/\Delta x \qquad (2)$$

where the transport

$$v_i \Delta x$$

ought to be computed by way of an average velocity between the two pressure sensors at positions $i+1$, $i-1$. But our velocities are measured at the end-points of the two-point pressure array; the success of a comparison between these velocities,

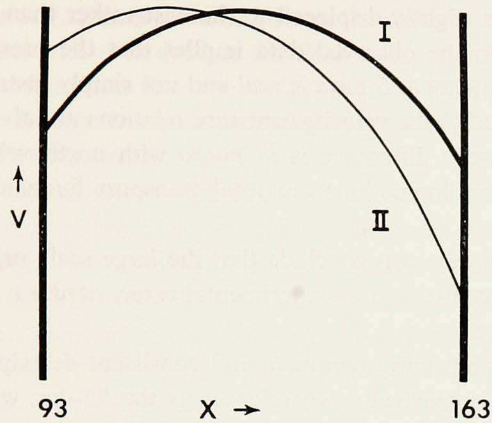


Figure 15. Schematic picture of northward velocity v between instruments 93 and 163 at two phases of 5-day meandering process. All units arbitrary.

and the velocity that figures in equation (2) will depend then upon the scale over which pressure and velocity change.

The northward component, v, is the dominant one, and we will make the comparison with it. Fig. 14 displays the coherence between the pressure differences of sensors 163 and 93 and the velocity at 162 (the coherence with 161 is distinctly reduced, probably from baroclinicity). There are two distinct sub-tidal coherence peaks, at a nominal 5 days and at 14 days and longer. Phase at 5 days is close to 0°. Equation (2) implies that we should measure over this line a velocity fluctuation of 8.8 cm/sec/millibar of pressure change. The observed relationship for current meter 162 is 8.1cm/sec/millibar at 5 days, (this is the coherent part), which may be deemed good agreement. But for the current meter 92 at the other end of the pressure line, the observed phase between the pressure difference and the current meter is indistinguishable from 180° phase, which would imply an inverse relationship. Taken together, the two results suggest that the 5-day fluctuations may be due to a meandering of the Florida current whose core flows between moorings 9 and 16. If the northward velocity v between instruments 93 and 163 has a maximum in the western half of the interval, then, as shown in Fig. 15, a current meander can produce the observed phase relationships: as a result of a change of velocity profile from curve I to curve II in Fig. 15, the bottom pressure difference 163-93 (proportional to the area under the curve, for geostrophy) decreases along with v at 16, while v at 9 increases. Indeed, observed velocities at 92 and 162 are 180° out of phase at 5 days.

In the deep water at 5 days, the pressure difference 53-63 is very coherent (.8) with the north velocity from current meter 62, but again at essentially 180 degree phase, implying a similar velocity maximum between these pressure sensors. Figure 2a does show a pronounced velocity maximum (60 cm/sec) at the 630 m level of these gauges, but it is slightly displaced to the east rather than the west. However, this high coherence in the observed data implies that the pressure variation measured by these instruments at 5 days is *real* and not simply instrumental noise.

At 14 days (nominally) the velocity/pressure relations are about the same, except that the 163-93 pressure difference is *in phase* with north velocities at both 162 and 92. Perhaps these fluctuations are total transport fluctuations of the Florida Current.

Generally speaking, one can conclude that the large scale organized motions are geostrophically balanced to within experimental error, hardly a startling conclusion.

(ii) The 5-day wave

It is possible to give a fairly complete and consistent description of the 4-7 day variability which for convenience we refer to as the "5-day wave." It does, however, represent a broad-band and there is some weak evidence that it might represent two distinct motions close to 4 and 7 days, respectively.

The pressure coherences in the north-south line of instruments 73-93-83 range from about .6 to .8 in the 5-day band. The phase relationship between them is best represented as a *northward* propagating wave with wavelength between 46 and 60 km. Taken at face value, the phase relationships suggest that the motion may grow in wavelength from the southern pair to the northern pair in a way perhaps related to the changing width of the Miami Terrace or the structural change in the Florida Current.

The velocity field, or at least the energetic north component, is somewhat more coherent (at about 0.88) along the north-south line. The most probable wavelength is about 60 km with an uncertainty of roughly ±5 km, consistent with the pressures. Again the sense of propagation is to the north.

The temperature field measurements add little to this picture: they are best described as northward motion with a wavelength slightly less than 60 km.

The 180° phase between current meters 92 and 162, and their relationship to the pressure differences at those points, means the wave is geostrophically balanced with a meridional velocity (v') node somewhere between these two moorings on the Terrace (Fig. 15). It is tempting to conclude that the motion is confined to the Terrace, as perhaps a form of continental shelf wave interacting with the mean current (cf. Niiler and Mysak, 1971). But this might not be the case. Pressure gauge 33 at the eastern edge of the Strait is highly coherent (about .7) at 5 days with gauge 153 on the Terrace, though gauges 53 and 163 in the same positions during the second setting are not very coherent. This difference may be related to the extra noise, referred to previously, that was present in 53. Furthermore, the velocity field in the deep water shows a considerable energy at 5 days, though, because of the difference in water depth, it is very difficult to know whether it represents more or less energy than is seen up on the Terrace. The pressure difference 53-63 is coherent also with the north velocity 62, suggesting geostrophic balance at 5 days in the deep water as well. Current record 181 on the extreme eastern side in shallow water is also coherent with record 62 in the deep water at the edge of the Terrace. Thus, there is a presumption that the 5-day motion extends entirely across the Straits, and may only appear more prominently on the Terrace because of the shallow water. (But see discussion below.)

The presence of the strong Florida Current suggests that this motion might be the result of baroclinic or barotropic instability, though all models of such processes are much simpler than the actual configuration in the Florida Straits. If there is active baroclinic instability in this region, one might hope to find a significant relationship between the temperature field fluctuations and the velocity field, as part of the release of potential energy of the current into eddy energy. In the 5-day band however, the correlations required between velocity and temperature are not clearly those required for energy conversion. At current meter 81 for example, the coherence between temperature and both components of velocity is nonzero, but the phase is indistinguishable from 90° which makes the contribution to $\overline{u'T'}$, or $\overline{v'T'}$ in that frequency band vanish. On the other hand, for current meter 161, u', T' are again 90° out of phase; but there is significant coherence at 0° between v' and T', suggesting northward flow is associated with warmer temperatures. The associated source term would be $\overline{v'T'}\,\frac{\partial T_o}{\partial y}$ and might represent a release of potential energy from the mean flow. In contrast again, record 61 in the deep water is dominated by coherences at 90° between v' and T', and u' and T'. Thus there is a bare hint of baroclinic instability, but the evidence is hardly conclusive, and indeed we will later suggest a different energy source for the motion. The question of whether instability does occur here must remain open for now. Measurements higher up in the water column might give very different results.

(iii) Ten-fourteen day motion

These longer period motions are more difficult to characterize unambiguously than is the 5-day band, because the motion is inherently more inhomogeneous at the longer periods. Any notion that the observed variability is related to tidal nonlinearities (the M_2-S_2 difference interaction occurs at 14 days) can be dismissed. In the two-year long Miami and Cat Cay Sea level records 1938-39 (examined by Wunsch *et al.*, 1969) the dominant energy is clearly at periods longer than that of the tidal interaction period; the amplitude of the motion is at least an order of magnitude more energetic than the M_2-S_2 sum interaction at 6 hours; and the broadband nature of the motion seems incompatible with any plausible notion of how the tides work. Some small fraction of the energy is, however, undoubtedly tidal in origin.

Working from the phases of the north velocity components, and the temperatures, the motion can be described as a northward propagating wave of nominal wavelength 50-70 km, but with a large change from about 26 km between the southern pair, to about 60 km between the northern pair. The result is generally compatible with the pressure measurements. However owing to the station spacing, the data is also describable as waves of similar wavelength travelling to the south. Based upon phase information alone, we cannot choose the sense of propagation. Schott and Düing (1976) believe the propagation is to the south with a wavelength of 170 km.

The question of whether the motion tends to be confined to the Terrace or whether it spans the Strait is, as with the 5-day motion, made difficult by the very different water and instrument depths. There is considerable coherence between current meter 181 on the shallow eastern side and current meters on the west at these periods, so that the eastern deep region is responding at least to some extent to the 14-day motion.

e. Interaction with weather. A number of authors, e.g. Mooers and Brooks (1974), Düing, *et al.* (1977) point out that many of the physical variables in the Florida Straits are correlated, sometimes in complex ways, with the local meteorological variables. The necessity of including direct local forcing in the discussion of the observed motions greatly complicates any attempt at interpretation. Here we will try to sketch the relationship between the National Weather Service daily mean pressure and wind velocities, and *some* of the observed parameters.

(i) Weather and velocity field

The pattern of coherences between the three meteorological variables and velocity and bottom pressure is an intricate one. Overall, it does appear that the 5-14 day motions are definitely related to meteorological forcing. For example, the north component at current meter 91 is highly coherent (.7-.8) at 5 days with both east and north components of wind. Coherence with east wind is slightly higher than with north wind at a phase near 90°. At 10-14 days in this record, the east wind coherence is also clearly greater (.7-.8) at zero phase than it is with north wind. At the very longest periods resolved, 30 days and longer, there is a very strong coherence with east wind, implying that what little energy there is in the water is wind-driven.

Near the edge of the Terrace, record 161 north component tends to be incoherent with all meteorological variables except with the north wind at the short period of 2-3 days. If the 5-14 day motion is indeed wind induced, it appears to be driven primarily in the shallow water, unless the excess water depth at 161 masks the relationship higher in the water column. But to confuse the picture, record 61 north component *is* coherent with north wind at 10-14 days. In the deeper water to the east, record 51 is coherent with north wind at 5 days, but not at other periods.

These relationships between weather variables and the current meter records imply that the coherence noted previously between current meters on the opposite sides of the straits may in fact simply be due to a mutual coherence with a large-

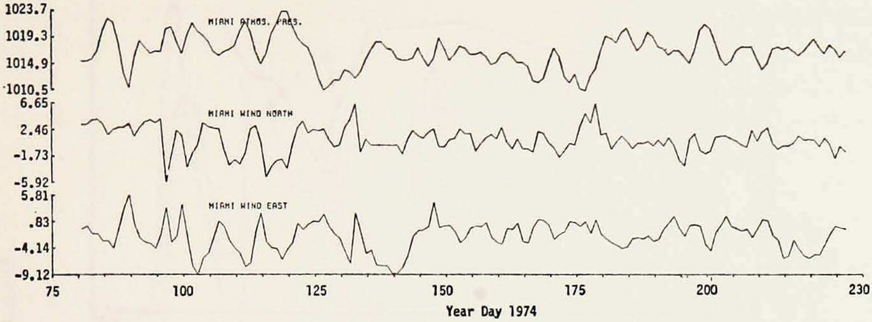


Figure 16. 28 hour average meteorological variables at Miami during course of experiment. Pressure is in millibars, wind in meters/second.

scale wind field. The organized motion in the Strait then begins to appear to be one that is primarily wind forced. A substantial fraction of the response appears to be due to the *local* wind, with the response appearing in comparatively limited frequency bands. Presumably there is some form of resonance, but even this conclusion is made slightly shaky owing to the fact that the wind field appears to have a considerable banded structure of its own in this frequency range (see Fig. 16), but with less intensely developed energy peaks.

(ii) Weather and bottom pressure

Wunsch *et al.* (1969) pointed out that at Key West there was a weak inverted barometer effect in sea level at periods longer than about 10 days. But, at shorter periods, the effect tended to be direct, i.e. increasing pressure tended to appear as a rise in sea level, ascribable either to dynamical modes in the Strait, or to an interaction dominated by wind, which is in turn correlated with pressure. During the period when the Miami Beach tide gauge was operating in this experiment a similar relationship was true: about 50% of the low frequency energy at periods longer than 2 days in the tide gauge record is inverted barometer, but the presence of nonstatic response has led us to refrain from statically correcting the sea level record in Fig. 11.

The study here of the interaction of the weather variables with bottom pressure was confined to gauges 153 and 163 on the Terrace. If atmospheric pressure and sea level are in static equilibrium, then there should be no coherence between bottom pressure and atmospheric pressure fluctuations. This is the simplest interpretation of the relationship between atmospheric pressure and the 153 record; there is only weak, and probably not significant, coherence. Indeed, none of the 3 weather variables, wind, or atmospheric pressure, show any coherence with bottom pressure greatly exceeding 0.5 at any frequency, the exception being at about 3 days where there is a significant relationship between the observed pressure and the east wind component (velocity here was coherent with north wind). But there is not much energy involved.

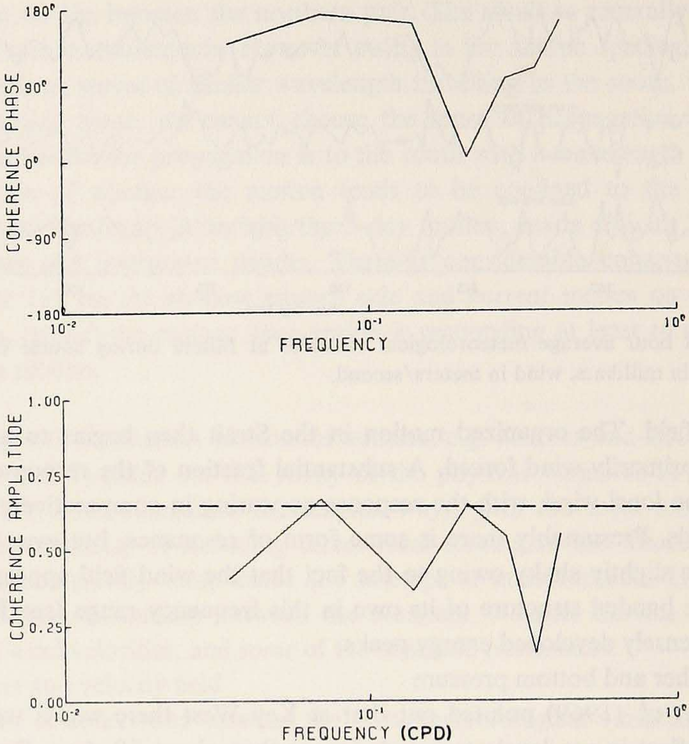


Figure 17. Coherence between pressure record 163 and local atmospheric pressure. Dashed line is approximate level of no significance.

For the second experimental period, the relationship is different. The coherence between the pressure record 163 and the atmospheric pressure is shown in Fig. 17. There are coherence peaks in the 10-14 day and 4-5 day bands. The 10-14 day band has a phase of 180°, the 4-5 day band a phase close to 0°. Unfortunately, owing to the gaps in the sea level record, we cannot say what the relationship to sea level was at this time. If the result at 14 days is real, there is an over-compensation of sea level to atmospheric pressure, i.e. when pressure increases, sea level drops, but too far. Zero-phase observed at 5 days is consistent with a direct response, described as the normal condition at this period by Wunsch *et al.* (1969).

It is, however, probably coincidental that we see these relationships. The bottom pressure field is probably responding indirectly to winds through the relationship to the water velocity field. There is a finite coherence between atmospheric pressure and wind which shows up as an essentially spurious relationship between bottom pressure and atmospheric pressure.

We have no simple explanation of why there is increased coherence in the second experimental period. Weather forcing is greater in the first period (Fig. 16) and

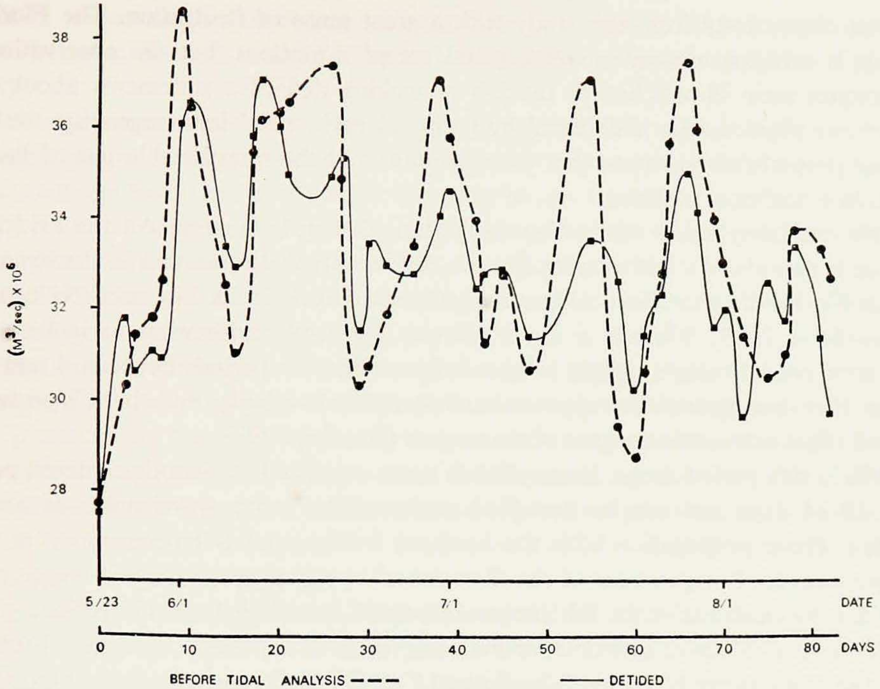


Figure 18. Transport fluctuations of the Florida Current during experiment (from Brooks, 1977). Note presence of strong 5-14 day oscillations.

would normally tend to drive a more coherent motion (higher signal-to-noise ratio), but the spatial structure of the wind could be more complex at the more energetic time.

5. Discussion

Most of the variability of the net transport of the Florida Current as a whole seems bound up in the oscillatory motion seen at 5-14 days. In Fig. 18 we show the transport of the current during the period of the moored observations measured by Brooks (1977) using the dropsonde method of Richardson and Schmitz (1965). The transport changes are clearly dominated by similar time scales. This resemblance suggests that we are not seeing a simple meandering of the current axis, but rather a motion which changes the total flux of water through the Strait.

There is not an obvious low frequency content to Fig. 18, leaving us with the question of the meaning of the trend seen in the pressure records. Assuming the absence of such a trend in the deep water off the Terrace, the observed trend corresponds to a bottom velocity increase of about 15% which cannot be ruled out and which may be part of the annual signal. (The total cross-stream head is believed to be about 66cm).

One comes away from this study with a great sense of frustration. The Florida Straits is a region of very interesting and complex motions, but the observational techniques seem ill-matched to the job of making definitive statements about the governing physics. One is defeated by temporal and spatial inhomogeneity, the inability properly to penetrate the water-column, and the questionable use of linear ideas in a nonlinear regime.

One can fairly easily summarize the picture that does emerge. All the evidence is that at periods of a few months, there is remarkably little variation in the strength of the Florida Current. The existence of an annual cycle is not in doubt (Niiler and Richardson, 1973; Wunsch *et al.*, 1969; etc.), but otherwise what variability we can see from this single sample is essentially confined to periods between 4 and 14 days. This strong variability appears in all dynamical variables and there is an integrated effect in the net transport of the current (Brooks, 1977).

Within this period range, the motion is most organized at periods centered on 5 and 10-14 days and can be described as "wavelike" with wavelengths of about 50 km. Phase propagation is to the north at 5 days, and is indeterminate at the longer periods. But questions of the direction of energy propagation are made complex by the existence of the inhomogeneous mean baroclinicity of the region.

There is a seductive resemblance between the time dependent motions observed and the motions predicted by Orlanski and Cox (1973) in a study of the baroclinic instability of the Gulf Stream. Their work suggests the appearance of baroclinic modes with periods of order 10 days and wavelengths of order 100 km, much as observed, with the motion largely confined to the shelf region. The growth times to maximum amplitude are of order 8 days. But there are some difficulties. We have not been able to demonstrate any strong direct average release of mean potential energy to either eddy potential or kinetic energy. Such release may be occurring, and our data may be in the wrong regions to observe it. By selecting any particular instrument on any particular mooring it is possible to deduce in any given frequency band an apparently significant Reynolds stress term of one sort or another. This can lead one to conclude that energy conversions are occurring. But no overall significant average patterns seem to emerge, and whatever conversions do occur are not robust and may be ephemeral. This generally agrees with the conclusions of Brooks and Niiler (1977) who, using the naturally integrating dropsonde system, suggest that the variability field is in equilibrium with the mean flow; the localized conversions average to zero across the section. Because the time dependent motions are coherent with meteorological forcing and one can demonstrate work being done by the atmosphere on the water, there is a major missing element in the existing models of this region.

It is possible that the waves we see were selected by a baroclinic instability mechanism, grew to finite amplitude (and they are very large waves), and are being maintained against dissipational mechanisms (frictional and losses to the mean current) by meteorological variables and possibly by a small extraction of energy from the mean flow. A model of the finite amplitude end state would be of great utility.

Reference was made at the beginning of this paper to the unique presence of the pressure gauges in the experiment. We have not seen any especially enlightening results emerge from their use, though that may be our shortcoming rather than that of the data or instruments. Bottom pressure is another dynamical variable related in complex ways to velocity, temperature, etc. We were able to present a demonstration of geostrophy in limited regions of space and frequency, but the geostrophic relationship was never in serious doubt anyway.

Pressure fluctuations are certainly related to the transport fluctuations, and, in principle, the pressure gauges could be used as a monitor of transport. But to convert pressures to transport obviously requires a complete understanding of the dynamics through the water column or, at the very least, an elaborate "calibration" procedure. Bottom velocity, which is measured by bottom pressure, could be simply related to the transport, but we have not yet been able to understand how or why that might be true in this region.

For longer periods, e.g. annual, Wunsch *et al.* (1969) did show that tide gauges on the sides of the Strait did seem to give transport changes consistent with measurements by other means (e.g. Niiler and Richardson, 1973). Thus there is still some possibility that annual and longer period, quasi-climatic fluctuations may be monitored by sea level or pressure in narrow strait regions. But we really can conclude only that it is still "not proven."

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This paper is dedicated to the memory of Dr. W. S. Richardson.

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