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Synoptic studies of transients in the Florida Current

by Walter Düing[1]

ABSTRACT

The SYNOPS experiment was designed to study the changing vertical structure of the Florida Current, covering tidal and subinertial fluctuations. The emphasis in this paper is placed on the discussion of highly energetic quasi-barotropic waves with a time scale of several days. These waves are superimposed on the mean baroclinic profile of the Florida Current; thus, in the simplest case, the mean profile is just shifted parallel to itself. Since the mean downstream flow is close to zero in the lower layer, temporary deep southward flow results. The typical amplitude of the barotropic component is 10 cm/sec, corresponding to a transport amplitude across the experimental cross-section of $2 \times 10^6 \, m^3/sec$. The fluctuation of the cross-stream component affects the temperature field by shifting it advectively in the east-west direction. Case studies show that the upper 500 m on the western side of the Straits are affected and that the typical amplitude of the temperature anomaly in this region is 2.5°C. The wavelike character of these motions is emphasized by the fact that the cross-stream component is leading the temperature change by 90° or a little over one day. The alternating cross-stream component of the several-day wave is identical to an east-west shift of the Florida Current. This "meandering" is most pronounced in the western region of the Florida Straits where the bottom topography has a maximum slope between the Miami Terrace and the deepest part of the Straits. Event studies show that two extreme cases occur during SYNOPS. During SWF (deep southward flow), the current is shifting to the western side of the Straits with parallel occurrence of deep southward flow, reduced volume transport, and positive temperature anomalies. During NWF (deep northward flow), the current shifts eastward and the flow is northward in the entire cross-section with increased volume transport and negative temperature anomalies. Simultaneous measurements of the electrical potential on a submarine cable 120 km north of the SYNOPS site show that the observed wavelike disturbances propagate northward with a mean phase speed of 47 cm/sec, possessing a wavelength of about 200 km.

Several-day waves occur in an intermittent fashion similar to inertial waves. Evidence is provided by short profiling time series, as well as by long time series from moored current meters. Observations during all seasons show that the occurrence of deep southward flow (as an indicator for such waves) is quite frequent. There is evidence that atmospheric forcing may play a role in the generation of these waves. Some of the observed features are reminiscent of barotropic shelf waves; however, occurrence of baroclinic instabilities also seems possible. The dominant generating mechanism is unknown at present.

1. Introduction

Studies of time-dependent motions in the Florida Current have been carried out for almost a century. Stommel (1965) gives an account of the results achieved until

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[1] Division of Physical Oceanography, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida 33149, U.S.A.

the mid-sixties. Since then, the use of new tools and techniques has added to the general body of information. A number of theoretical studies reported during the last few years have expanded our understanding of the dynamics of this important branch of the Atlantic circulation. Despite these new insights, we are still not able to adequately explain time-dependent fluctuations of this western boundary current.

One particularly intriguing problem concerns motions in the period range from 4 to 20 days. A variety of phenomena, such as meandering, transport variations, fluctuations of the temperature and acoustic parameters, and deep flow reversals, consistently show periodicities in the several-day range. As Niiler and Richardson (1973) have demonstrated, the variability on that time scale can be larger than the seasonal variability.

Webster (1961) found that 4- and 7-day periods are dominating the meandering of the Gulf Stream further north. Fluctuations on this time scale not only affect the deep water portions of the Florida Current but they also occur in nearshore regions. Lee (1972) has shown that coastal eddies on these time scales have a profound influence on the estuarine and shallow water circulation along the east coast of Florida. DeFerrari (1970) analyzed a 180-day-long 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. Steinberg, *et al.*, (1972) observed for several years a number of acoustic and oceanographic parameters in the Straits between Miami and Bimini. Their results implied that there must exist interrelations between acoustic propagation (i.e., the temperature field), horizontal meandering, mass transport fluctuations, etc. Preliminary results by Düing and Johnson (1972) also pointed in this direction. Exploratory measurements indicated that the deep southward flow was of transient character; i.e., reversals from northward to southward flow in the lower part of the water column would typically occur over two or three days. Furthermore, flow reversals in the north-south direction were accompanied by a directional shift of the cross-stream component and by apparent vertical displacements of the temperature field.

This paper describes time-dependent variations of the vertical structure of the Florida Current based on observations from Project SYNOPS 71 (*Syn*optic *O*bservations of *P*rofiles in the *S*traits). A brief discussion of experimental aspects is followed by a detailed description of the time-depth distribution of the flow components. The emphasis is placed on the discussion of quasi-barotropic waves with a time scale of several days. An attempt is made to clarify how these waves affect transport fluctuations, horizontal shifting of the current, deep southward flow, and changes in the thermal structure.

2. Experimental aspects

a. Experimental design and scales of motion. The observational requirements dealing with the aforementioned phenomena occurring in the intense mean flow of the Florida

Current are difficult to satisfy with our present oceanographic tools. The intermittent occurrence of several-day oscillations requires long observation series; meandering requires sufficient resolution in cross-stream and downstream direction; and the changing vertical current profiles require high resolution in the vertical domain. The compromise sought was to carry out a relatively short but intensive study by using high resolution current profiling devices deployed from anchored ships. The objective was to attempt to develop a meaningful long-term monitoring experiment by placing a few sensors only at "critical" locations.

The profiling current meter (PCM) method has been successfully used in the Florida Current for several years (Düing and Johnson, 1972). It suffices to say here that the strong surface flow in the Florida Current exerts a stabilizing influence on the motion of the anchored vessel, thus helping to reduce errors. A detailed discussion of various error sources and estimates of their magnitude is given by Düing and Johnson (1972) and by Düing (1973a). Considering all facts, we concluded that a reasonably good estimate of the relative error of the current components is 5% in the upper half of the water column, approaching 10% in the lower half.

Vertical scales. Previous results from the PCM method were helpful in determining an adequate vertical resolution. We observed a subsurface current maximum four miles west of Bimini and the occurrence of deep current reversals on the western side of the Straits. Observations in the cyclonic zone of the current revealed a 180° change of the direction of the flow over vertical distances of less than 10 m. To identify significant vertical structure, a resolution of 5 to 10 m seems to be sufficient. The resolution of the PCM method is given by the sampling interval times the sinking rate. The usual sampling interval of 26 seconds with a mean sinking speed of 10 cm/sec yields a vertical resolution of 2.6 m. Due to large wire angles in the surface layer, a downward lift occurs, causing the instrument to sink faster than in the lower layers where wire angles are almost zero. The vertical resolution is therefore typically 6 m in the top layer and 2 m in the lower layer.

Horizontal scales. Previous experimental work (Pillsbury, 1891; Schmitz and Richardson, 1966) has shown the systematic difference in the vertical structure of the flow between the anticyclonic and cyclonic regions of the Florida Current. These investigations also revealed that the absolute values of horizontal shear are considerably larger in the cyclonic than in the anticyclonic region. Therefore, a closer spacing of the observational platforms seemed desirable for the cyclonic region of the stream. Since only four ships were available, they were anchored along an east-west baseline for redundancy (Fig. 1), and the north-south dimension had to be ignored. The horizontal spacing was a compromise: For the investigation of several day waves, even two vessels in the east-west direction would have been sufficient; for the study of kinetic energy redistribution, much closer spacing would have been desirable.

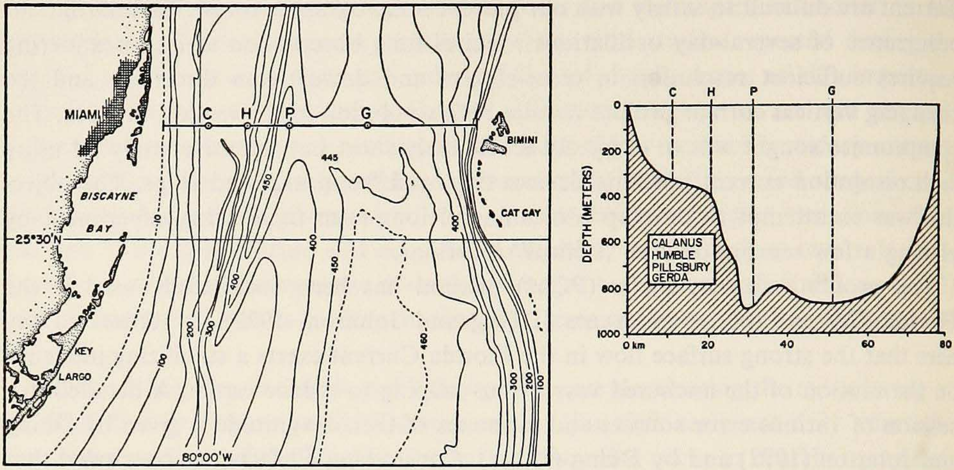

Figure 1. Anchor positions during SYNOPS 71 and corresponding bottom profile.

Time scales. Series of vertical profiles from three locations between Miami and Bimini had shown that the overall features of subsequent profiles taken every two hours did not change significantly. Even smaller features on a vertical scale of decameters were found to persist for half a day or longer. Examples of such profile series are given by Düing and Johnson (1972) in Figs. 5, 7, and 9. On the other hand, it is known that tidal effects are of importance as shown by Wunsch, *et al.*, (1969). Considering operational constraints, it was decided to make simultaneous profiles from all anchored ships every three hours. The field experiment lasted from 3 to 19 June 1971.

b. Field operations. Preceding the main experiment in June 1971, a two-week long test experiment ("PRESYNOPS") was conducted on board R/V PILLSBURY at the same location as during SYNOPS 71. This experiment yielded a set of current profiles with features similar to those found during the main experiment. The locations of the four anchored vessels used in SYNOPS 71 and a cross-section along 25°45.0′N latitude are shown in Fig. 1. Table 1 provides further relevant information. The given locations are mean positions. At times, deviations up to several hundred meters to the east or to the west were observed. Simultaneous profiles were scheduled

Table I. Locations of anchored vessels during SYNOPS 71; positions from west to east.

Date	Ship	Latitude	Longitude	Depth (m)
21 April–3 May 1971	R/V PILLSBURY	25°45.0′N	79°47.0′W	≈ 840
3 June–19 June 1971	R/V CALANUS ("C")	25°45.0′N	79°59.0′W	≈ 310
	R/V HUMBLE ("H")	25°45.0′N	79°52.5′W	≈ 335
	R/V PILLSBURY ("P")	25°45.0′N	79°47.0′W	≈ 840
	R/V GERDA ("G")	25°45.0′N	79°36.0′W	≈ 790

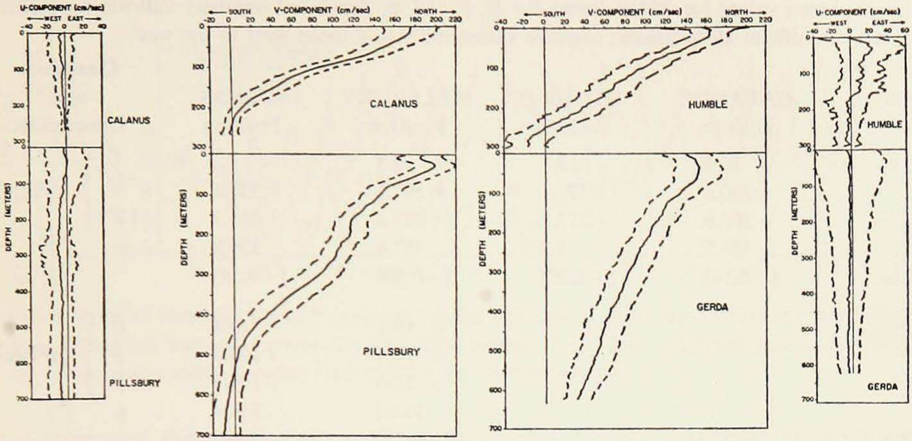

Figure 2. Mean profiles of *U*- and *V*-components and their standard deviations at four locations.

from each vessel every three hours at 0000h, 0300h, 0600h, etc., local Miami time. A fifth mobile vessel, the 10-m long ORCA II, conducted rapid vertical temperature profiling along latitude 25°45.0′N; that is, along the line of anchored vessels. Seven XBT sections with drops one mile apart were made between 4 and 18 June. On the return leg, ORCA II stopped at each vessel and picked up the previous two days' PCM data tapes. Through immediate processing of these, instrument failures were quickly detected, resulting in a data recovery of about 85%. Details on the processing of the PCM data are outlined in a technical report by Düing (1973a).

3. Observations

The following subsections describe some of the more characteristic features of the time-dependent vertical structure of the Florida Current. The description of the mean state and overall variability statistics is followed by a brief discussion of tidal fluctuations and aperiodic transients. The main part of the discussion deals with deep flow reversals and low frequency oscillations (section 3.d).

a. The mean state and overall variability statistics. The term "mean state" strictly refers to data from SYNOPS 71; that is, the various computed quantities given below are derived from the observations made during 3 to 19 June 1971. The mean profiles for the *U*- and *V*-components, and their respective standard deviations at the four locations, show the following features (Fig. 2). The largest mean vertical shear of the *V*-component, $\bar{V}_z \approx 9.5 \times 10^{-3}$ sec^{-1}, is found at the CALANUS position, well within the cyclonic region of the current. The shear then decreases proceeding to the other three positions from west to east. The respective values are HUMBLE 6.5×10^{-3} sec^{-1}, PILLSBURY 3.5×10^{-3} sec^{-1}, GERDA 1.8×10^{-3} sec^{-1}. The standard deviations for both *U*- and *V*-components are largest in the upper layer, ranging

Table II. Mean values for 300-m layers for $\hat{U}$, $\hat{V}$, $\lvert\hat{V}\rvert$, φ. Bracketed numbers indicate normalized east-west shifts at all locations; negative values indicate a mean shift to the west.

Depth	CALANUS Position	HUMBLE Position	PILLSBURY Position	GERDA Position	Quantities and Dimensions	
0 m	− 10.1	+ 15.8	− 16.5	− 7.7	$\hat{U}$	[m^2/sec]
	+ 200.6	+ 276.7	+ 397.1	+ 355.6	$\hat{V}$	
to	+ 200.9	+ 277.2	+ 397.4	+ 355.7	$\lvert\hat{V}\rvert$	
	356.9	3.3	357.6	358.8	φ	[°]
300 m	[− 0.34]	[+ 1.00]	[− 0.50]	[− 0.54]		
300 m			− 19.6	− 13.8	$\hat{U}$	[m^2/sec]
			+ 70.4	+ 173.2	$\hat{V}$	
to			+ 73.0	+ 173.7	$\lvert\hat{V}\rvert$	
			344.4	355.4	φ	[°]
600 m			[− 0.73]	[− 0.50]		

from ± 10 cm/sec at the CALANUS position to ± 30 cm/sec at the GERDA location. The V-components at the CALANUS, HUMBLE, and PILLSBURY positions indicate that weak mean deep southward flow occurred during the observational period. The U-component is directed to the west at three locations, whereas it is directed eastward in the upper half of the water column at the HUMBLE position. This mean distribution at the HUMBLE position is caused by eastward cross-stream flow throughout the period from 4 to 15 June, indicating converging flow between the HUMBLE and PILLSBURY locations. Mean values integrated over 300-m layers are given in Table II. They indicate that the cross-stream component, $\hat{U}$, of the volume transport per unit width is typically 5% of the downstream component, $\hat{V}$. The mean deviation from north is typically ± 3° in the upper 300 m and slightly more in the 300- to 600-m layer. Constructing progressive vector diagrams, one can determine the relative magnitude of the east-west shift. The normalized values (bracketed numbers in Table II) show that the largest east-west excursions occur at the HUMBLE location, near the steep drop-off region off the Miami Terrace. The relative east-west shifts at the neighboring locations are considerably smaller than at the HUMBLE position: one-third over the Miami Terrace and about one-half in the deeper region.

The dashed curve in Fig. 3 shows the fluctuations of the volume transport in the section covered by the four ships. The relationship between the SYNOPS transport and the potential difference (also shown in Fig. 3) along a submarine cable will be discussed later. The volume transport was obtained by vertical integration of the V-component at the four anchor positions and by subsequent horizontal integration between them. This determination of the transport is fairly crude because of the wide station spacing and only takes into account a little more than half the cross-section between Miami and Bimini. The mean value and its r.m.s. fluctuation were found to be $17.1 \pm 1.9 \times 10^6\,\mathrm{m^3/sec}$. Deep southward flow is of dynamical importance, but it does not play a very important role in the net transport through the Straits.

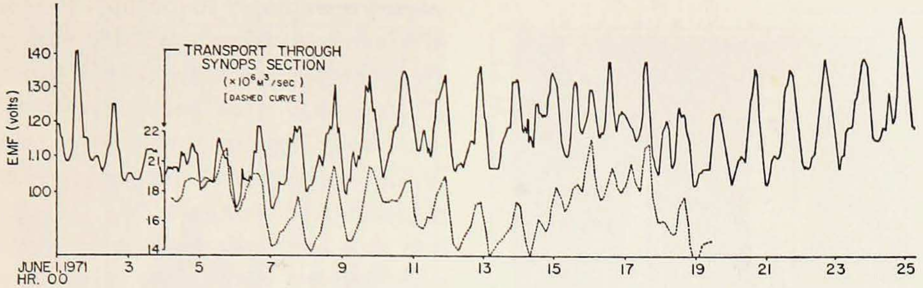

Figure 3. Parallel observations of "transport" at the latitudes of Miami and of Jupiter Inlet. Dashed line: Integrated transport across the SYNOPS section. Solid line: Electrical potential difference on a submarine cable between Jupiter Inlet and Settlement Point.

It is estimated that peak values of net southward volume transport hardly exceed $1 \times 10^6 m^3/sec$, or about 3% of the mean steady-state value given by Schmitz and Richardson (1968).

b. Tidal fluctuations. Although tidal fluctuations are very significant in the Florida Current, only two aspects will be discussed. The contour plots of the *V*-components (Figs. 4 to 6) emphasize the dominance of diurnal tidal fluctuations at the latitude of Miami. Zetler and Hansen (1970) postulate the existence of a standing wave node close to the latitude of Miami, which explains the very large diurnal tidal components in the current observations. The oscillations induced by the diurnal tidal component are in phase at all four ship locations. This can be verified by superimposing selected isotachs (e.g., the 100 cm/sec line) in the contour plots of the *V*-component at the various positions. For example, the isotachs at the CALANUS and PILLSBURY

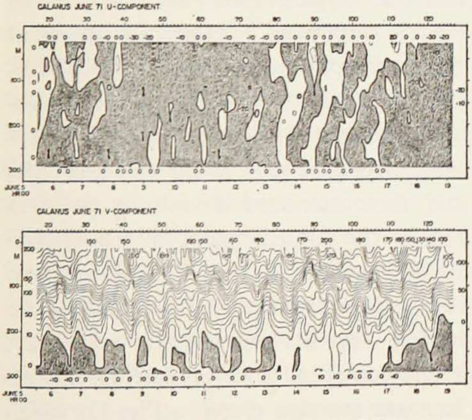

Figure 4. Time-depth contour plots of flow components at the CALANUS position. Shaded areas denote westward, respectively southward, flow. Top scale shows profile numbers.

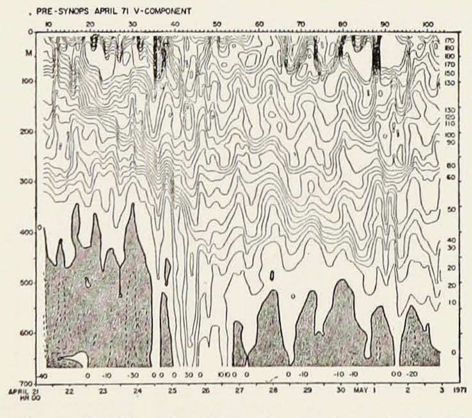

Figure 5. Time-depth contour plot of the *V*-component during PRESYNOPS at the PILLSBURY location.

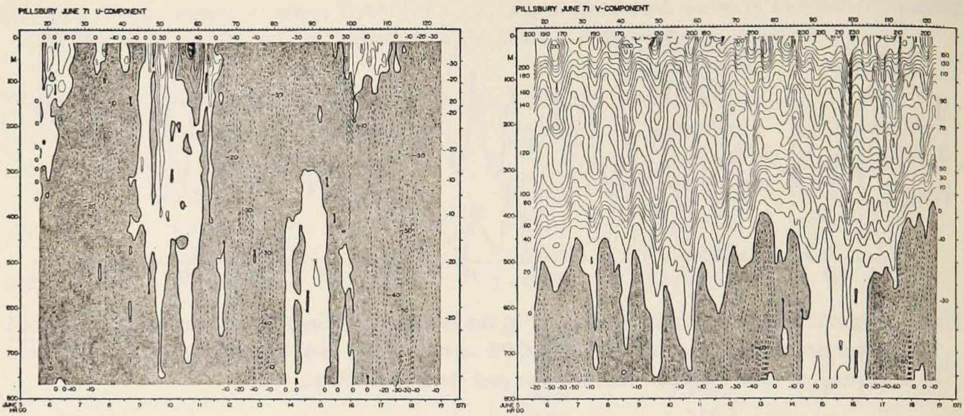

Figure 6. Time-depth contour plot of flow components at the PILLSBURY position.

positions are well in phase during the entire SYNOPS period, indicating that the phase lines of the diurnal tide across the Straits are perpendicular to the channel axis.

Figure 7 shows an example of the high pass filtered residuals for the *V*-component at the PILLSBURY location. The typical amplitude of the diurnal tidal fluctuation is 15 cm/sec. The vertical pattern of the contour lines suggests that there exists a strong barotropic component in the deep region of the Straits. Concerning amplitude and vertical structure, the SYNOPS observations are in qualitative agreement with results from a more detailed tidal analysis performed by Kielmann and Düing (1974), based on longer time series from moored current meters.

c. Aperiodic transients. A conspicuous feature of many current profiles is the occurrence of an intermediate velocity maximum at about 50-m depth. It occurs at irregular but frequent intervals in profiles of the *V*-component. It is more frequent at the offshore positions, HUMBLE, PILLSBURY, and GERDA, and practically absent at the CALANUS location, as can be seen in the mean profiles and their standard deviations given in Fig. 2. The contour plots for the PILLSBURY position (Figs. 5 and 6) show strong accelerations in the upper 100 m, lasting several hours up to one day. Examples of such longer lasting subsurface jets are also given in Fig. 11, which will be discussed in a different context later. To demonstrate the time-dependent development of such a feature, we pre-

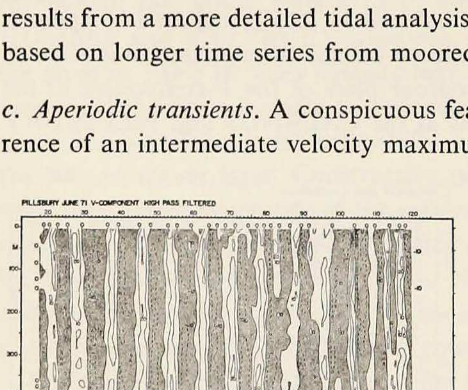

Figure 7. Example of high pass filtered residuals of the *V*-component demonstrating the predominantly barotropic structure of tidal oscillations.

sent one sequence of *V*-component cross-sections based on the simultaneous profiles 88 to 94 from all four ships (Fig. 8). The cross-sections were contoured by using a standard meteorological contouring program developed at NCAR, Boulder. This program minimizes the second-order derivatives and can lead to artificial small scale features, such as the wavy pattern in the isotachs on the right-hand side of the cross-section where no observations were made. Also, for contouring purposes, it was assumed that the flow vanishes at the boundaries.

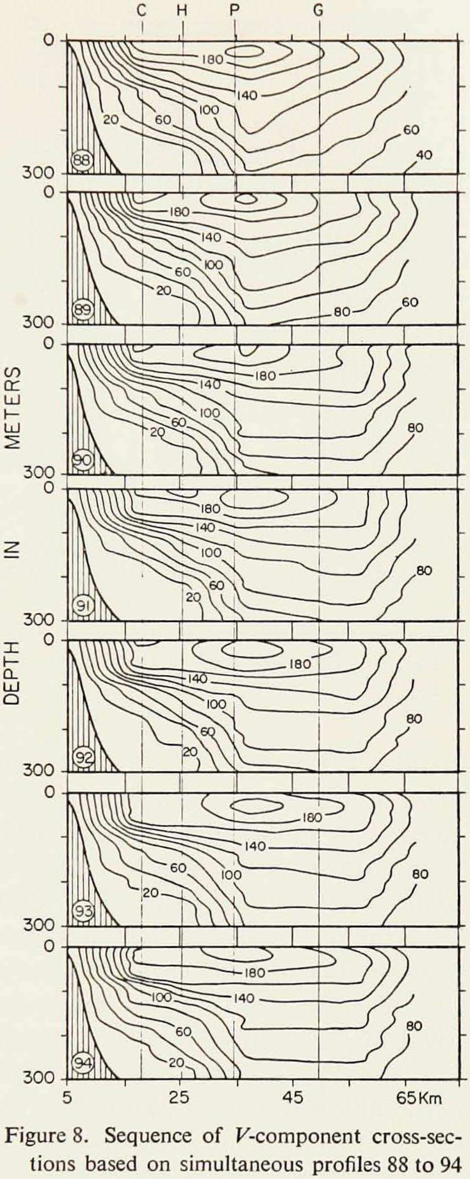

Figure 8. Sequence of *V*-component cross-sections based on simultaneous profiles 88 to 94 from four positions. Sampling interval between profiles is 3 hours.

The sequence is 18 hours long, and the cross-sections are 3 hours apart. The near surface jet is located near the PILLSBURY position, reaching a maximum value of 220 cm/sec. The temporary formation of a second jet can be noticed at the surface near the CALANUS location. The fluctuations reach fairly deep; i.e., even the 100 cm/sec isotach undergoes a deformation at a depth of almost 300 m. The formation and decay of the subsurface jet typically occur on a time scale between one-half day and one day. Attempts to correlate these fluctuations with changes in the local wind field have not been successful. One might speculate that this is a manifestation of the "shingle structure" as described by Fuglister (1951b) or by von Arx, *et al.*, (1955). It is also possible that eddies of several kilometers diameter were advected past the anchored ships, which were too widely spaced for proper observation. A direct consequence of these strong fluctuations in the upper layer is the finding by Hallock (1973) that the Reynolds stresses and the fluctuation of kinetic energy are largest in the upper 250 m and of no great significance below that depth.

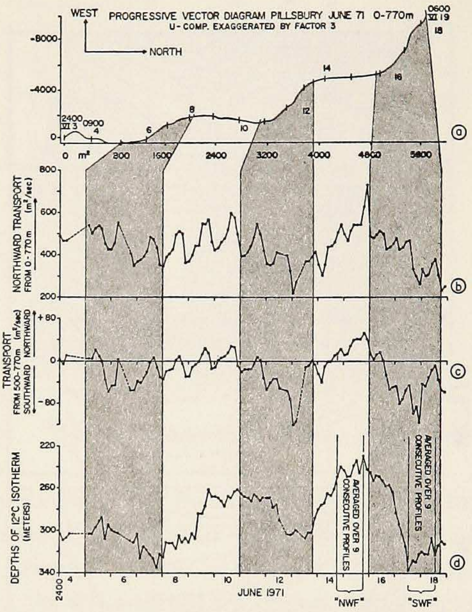

Figure 9. Composite picture of results from PILLSBURY position. For explanation, see text.

d. Low frequency oscillations. Besides diurnal tidal oscillations, fluctuations with periods from 4 to 6 days are the most prominent features found in the sequences of current profiles. The most characteristic display of such fluctuations is seen in the observations made at the PILLSBURY location in the sequences during PRESYNOPS in April 1971 (Fig. 5) and during SYNOPS in June 1971 (Fig. 6). Deep southward flow occurs at times in the entire lower half of the water column. It displays a pulselike behavior with southward-directed currents lasting three days, whereas the ensuing deep northward currents last only two days. A maximum value of 87 cm/sec for southward flow was observed at 750 m on 17 June 1971; maximum values for deep northward flow at 700 m on 25 April 1971 were around 30 cm/sec. The observations at the CALANUS and HUMBLE positions also show deep southward flow (Fig. 2), although not as pronounced as at the PILLSBURY location. The absence of southward-directed flow components at the GERDA location seems to indicate that the deep flow reversals are restricted to the western side of the Straits. It is characteristic that deep southward flow is accompanied by westward-directed cross-stream flow throughout the entire water column. Deep northward flow on the contrary is accompanied by eastward flow throughout the water column as can be seen by comparing the contour plots for the *U*- and *V*-components at the PILLSBURY location (Fig. 6). The SYNOPS observations confirm results from previous years which also showed that the deep southward flow displayed transient behavior; i.e., reversals from northward to southward flow in the lower part of the water column would typically occur over 4 or 5 days, accompanied by a 180° shift of the cross-stream component (see Düing and Johnson, 1972, Fig. 7).

A brief explanation of the interrelation between deep southward flow, meandering, and variation of mass transport was given by Düing (1973b) based on a preliminary perusal of the SYNOPS data. A review of these interrelations and new information on the current and thermal fields follows.

The current profiles made from the PILLSBURY location were vertically integrated over the water column from 0 to 770 m (Fig. 9b) and over a selected depth range where deep southward flow occurs most frequently; that is, from 500 to 770 m

(Fig. 9c). In both cases, only the north-south component is shown. Both transport curves show large amplitude fluctuations of the diurnal tidal flow superimposed on the several-day trend. It is only the latter which concerns us here. Figure 9a shows a progressive vector diagram based on the vertically integrated profiles from 0 to 770 m. A comparison of Fig. 9a and Fig. 9b shows that a westward trend in the progressive vector diagram is paralleled by decreasing transport towards the north. This happens during three time periods as indicated by the shaded areas. When the northward transport is large, the progressive vector diagram points more eastward. Observations by Schmitz and Richardson (1966) imply a similar relation between volume transport variation and east-west shift of the current; when the total transport through the Straits is low, the transport axis is shifted towards the west and vice versa. Thus, typically, the axis of the volume transport may shift from 45 km to 65 km offshore; the corresponding variation in transport may range from 28 to $36 \times 10^6 \text{m}^3/\text{sec}$ (see Fig. 3 in Düing, 1973b). Other features are the pulselike occurrence of southward flow (Fig. 9c) and the parallel trend between the curves for the transport for the entire column (0 to 770 m) and for the deep column (500 to 770 m). The three transport minima in the entire column coincide with the maxima of southward-directed flow in the lower part of the column. Thus, the meandering, as indicated in the progressive vector diagram, the fluctuation of transport of the entire water column, and the deep southward flow are parallel in time with major events occurring approximately every 4 to 6 days. Furthermore, the temperature observations (Fig. 9d) show the same long-period trend as those of the transport, indicating that the several-day oscillations are geostrophically balanced.

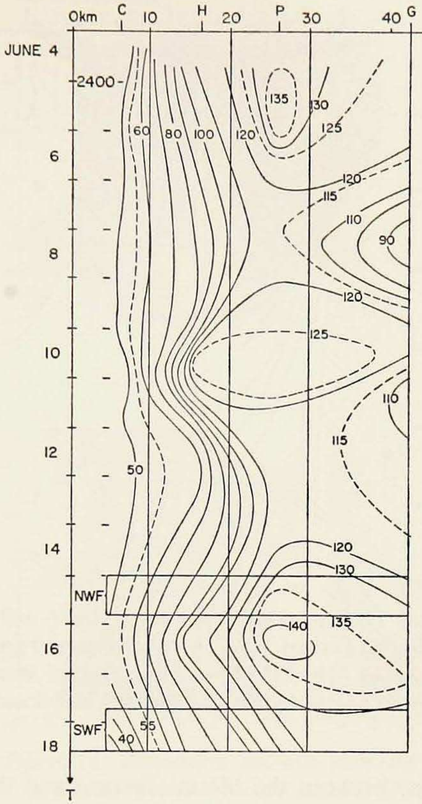

Figure 10. t, x distribution of the low pass filtered V-component (cm/sec) simultaneously observed at four anchor stations; average values for the layer from 100 m to 200 m are contoured; NWF, SWF refer to sections in Fig. 11.

Figure 10 gives a visual representation of the meandering as a function of time and longitude. Horizontal coherence is highest in the western region of the Straits. This region coincides with the location where the bottom topography has a maximum

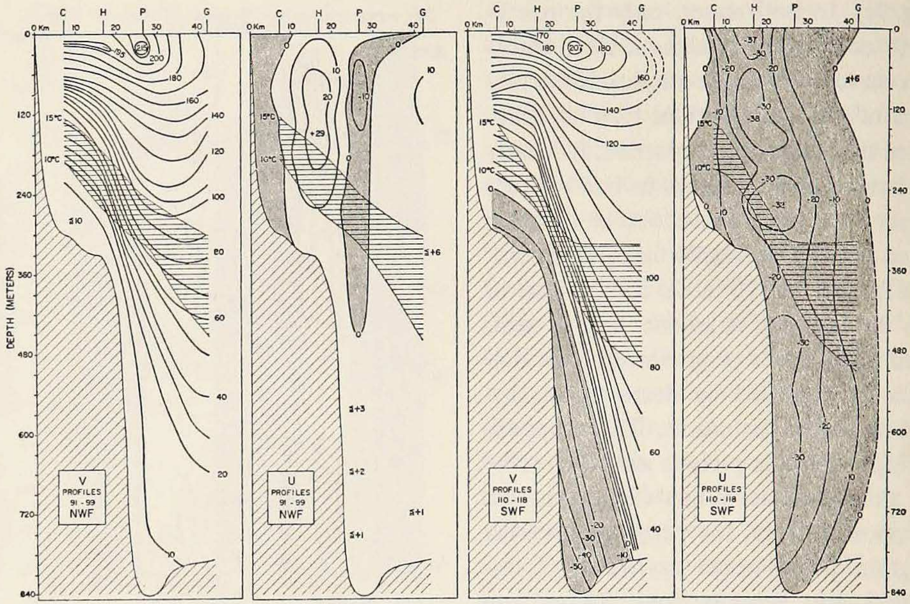

Figure 11. Typical cross-sections of the *U*- and *V*-components depicting two extreme states of the Florida Current: NWF, based on averaged profiles #91–99 (15 June); and SWF, based on averaged profiles #110–118 (17–18 June). Shaded areas indicate southward, respectively westward, flow. The horizontally hatched area indicates location of main thermal front.

slope between the Miami Terrace and the deep trench to the east of it. Subtraction of the time-averaged mean flow field from the pattern in Fig. 10 would yield a series of positive and negative cells which further below are interpreted in terms of a several-day wave. The distribution of isotachs on the right-hand side of the graph during 7–8 June and during 12–13 June may be indicative of the occurrence of a "pinch mode" in the Florida Current. The minima of the volume transport during these dates (see Fig. 3) support this view. In order to fully explore this phenomenon, longer time series across the entire width of the Straits are needed.

A case study will reveal further details of the changing vertical structure of the current. Two sets of profiles were chosen as being representative of the two extreme states which seem to occur in the Florida Current. For brevity, the first case will be referred to as NWF (profiles #91–99), indicating northward flow ocurring throughout the entire water column. The second case will be referred to as SWF (profiles # 110–118), indicating pronounced southward flow in the lower part of the water column. Four corresponding sets of nine profiles from each ship were averaged to remove tidal effects as much as possible. The mean profiles obtained were combined in cross-sections of the *U*- and *V*-components for NWF and SWF (Fig. 11). The same data were also horizontally integrated, yielding $18.4 \times 10^6 \mathrm{m}^3/\mathrm{sec}$ for NWF and $16.4 \times 10^6 \mathrm{m}^3/\mathrm{sec}$ for SWF. During SWF, deep southward flow occurs on the western

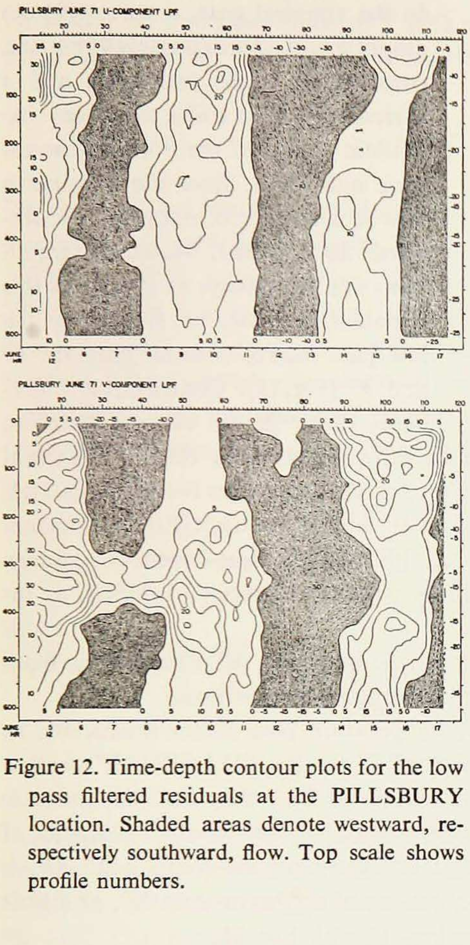

Figure 12. Time-depth contour plots for the low pass filtered residuals at the PILLSBURY location. Shaded areas denote westward, respectively southward, flow. Top scale shows profile numbers.

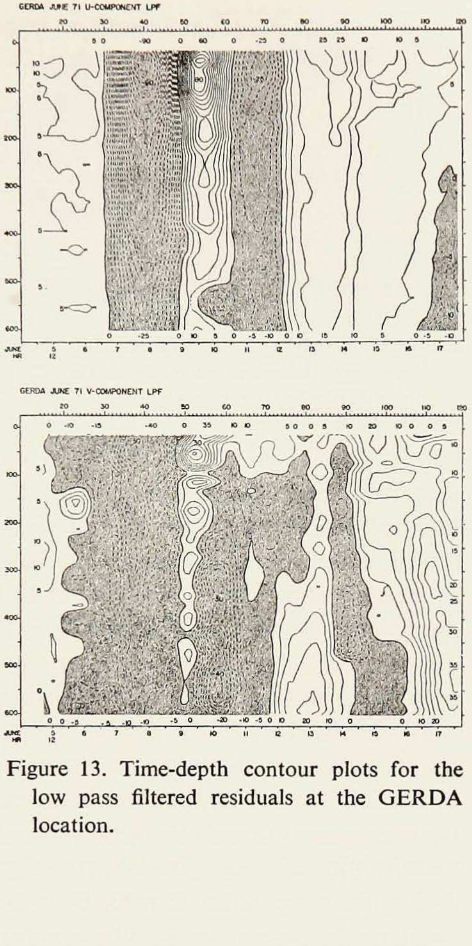

Figure 13. Time-depth contour plots for the low pass filtered residuals at the GERDA location.

side of the Straits. This, in connection with reduced surface velocities, accounts for smaller volume transport during SWF as compared to NWF. SWF is characterized by intense, westward-directed cross-stream components throughout the cross-section. NWF, on the contrary, shows well-developed eastward flow at the HUMBLE location and only weak westward flow inshore and offshore of it. The hatched area in all sections indicates the shape of the cross-stream temperature field during both cases. Only the 10° and 15°C isotherms are shown, since they mark the depth range where the largest horizontal temperature gradients occur.

How are meandering and deep southward flow related? A simplified explanation may be based on the vertical distributions of the *V*-components at the PILLSBURY location in Fig. 11. Subtracting the mean of the two cases, NWF and SWF, from each case itself yields the residuals representing two phases of a wave 180° apart. The vertical distribution of the residuals is nearly constant with depth (see also Düing, 1973b, Fig. 4b), thus indicating a predominantly barotropic modal structure.

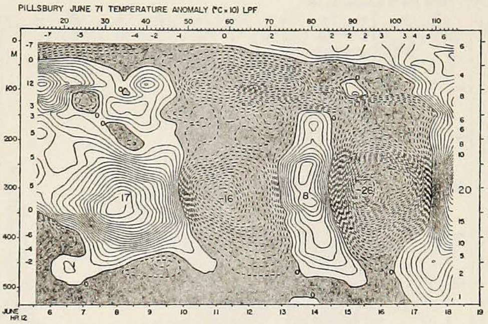

Figure 14. Time-depth contour plot for the low pass filtered temperature residuals (in °C×10) at the PILLSBURY location.

In the simplest case, a wave with an amplitude of approximately 15 cm/sec, constant in depth and time, and a period of 5 days shifts the mean baroclinic profile of the Florida Current back and forth. Since the deep mean flow is nearly zero, temporary southward flow results. However, conditions are not always as simple as this hypothetical case, as shown by the low pass filtered contour plots for U' and V' (Fig. 12). Considerable differences occur in the vertical structure for U' and V', with U' showing a more barotropic[1] behavior than V'. Typical amplitudes are 10 cm/sec for U' and 20 cm/sec for V'. Similar to the PILLSBURY observations, the low pass filtered versions of U' and V' at the GERDA location (Fig. 13) show dominant barotropic behavior, although the time-dependent pattern at this location is more reminiscent of solitary waves or a series of eddies, as indicated on the right-hand side of Fig. 10.

Despite these deviations from strictly barotropic behavior, all observations from deep water show that the barotropic mode is energetically dominant.

The fluctuations of U' and V' affect the temperature field rather drastically, as can be seen from the low pass filtered version of T' for the PILLSBURY location in Fig. 14. The anomalies have a typical amplitude of 2°C; they also demonstrate the occurrence of oscillations with periods of 4 to 6 days. The wavelike character of these motions is underlined by the fact that the cross-stream component, U', is leading the temperature change, T', with a phase lag of approximately 90°, or a little over one day, as can be seen by comparing Fig. 12 with Fig. 14.

Assuming that the changes in the temperature field are mainly caused by a horizontal east-west shift of the frontal structure and assuming that dissipative forces are absent, we have

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + w\frac{\partial T}{\partial z} = 0, \tag{1}$$

where u and w are the horizontal and vertical components of motion, with x to the east and z downwards. Assuming that the vertical term is small compared to the horizontal advective term so that $w\frac{\partial T}{dz}$ can be neglected, gives

$$u = -\frac{\partial T}{\partial t}\Big/\frac{\partial T}{\partial x}. \tag{2}$$

---

[1] "Barotropic" as used here means that the flow components are constant with depth; "baroclinic" means that they are depth-dependent.

Now let $\bar{T}$ be the mean value of T with respect to time: $T = \bar{T} + T'$, where T' is the perturbation of the temperature field. Hence, to the first order

$$u = -\frac{\partial T'}{\partial t} / \frac{\partial \bar{T}}{\partial x}. \tag{3}$$

To check if this relation provides a first-order description of the phenomenon, we inspect our observations. Figure 14 shows the temperature anomaly to vary from $-2°C$ to $+2°C$ within 2 days. The mean horizontal temperature gradient at the 300-m level is determined from XBT-sections. For the distance between HUMBLE and GERDA (~ 31 km), $\Delta\bar{T} \approx 8°C$. Inserting these values in (3) yields $u \approx 9$ cm/sec which is approximately the observed magnitude.

Asserting that the observed temperature fluctuations are caused by advective horizontal motion, we assume these to be of the form

$$T' = A \sin(\omega t + \varphi), \quad \text{or}$$

$$\frac{\partial T'}{\partial t} = A\omega \cos(\omega t + \varphi),$$

since

$$\frac{\partial \bar{T}}{\partial x} > 0 \quad \text{below the 100-m level, one obtains}$$

$$u \sim -\frac{\partial T'}{\partial t}$$

i.e., eastward cross-stream components cause negative temperature anomalies and westward components cause positive anomalies. Two cross-sections (Fig. 15) for the temperature anomalies observed parallel to NWF and SWF show that this is the case. The computation of the anomalies is based on seven XBT-sections taken in 2- or 3-day intervals during SYNOPS. Both cases show that the whole upper portion on the western side of the Florida Straits is affected by advective temperature shifts. The largest anomalies of nearly 3°C occur in a depth band approximated by the mean location of the 15°C and 10°C isotherms, where the largest horizontal temperature gradients are found. At the PILLSBURY location, this depth is about 300 m, thus explaining the maxima in the T' contour plot (Fig. 14). The same phenomenon occurs close inshore on the Miami Terrce according to 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 13 km SSW of the CALANUS location. Mooers and Brooks found fluctuations in the 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 to 5 days. The interpretation given is that these low frequency temperature fluctuations are mani-

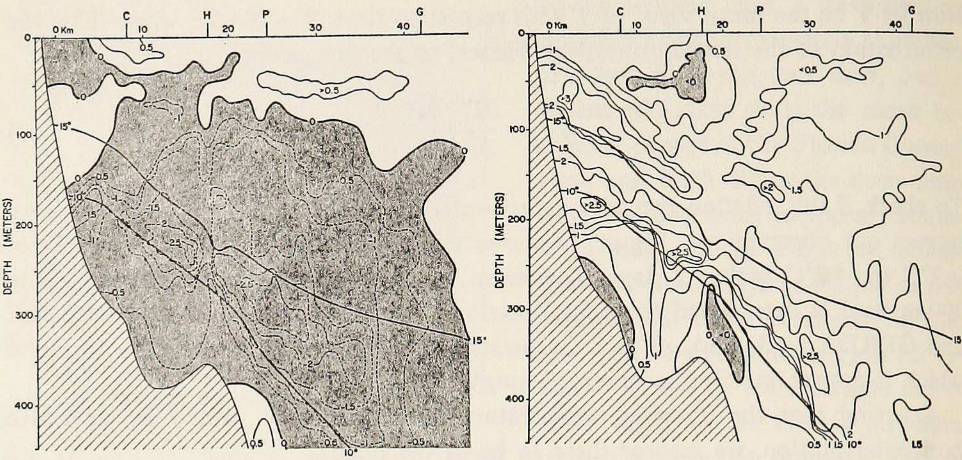

Figure 15. Cross-sections of temperature anomalies observed during SYNOPS 71. Left panel: During 16 June, shortly after the NWF situation depicted in Fig. 10. Right panel: During 18 June, parallel to the SWF situation depicted in Fig. 10. The thin solid lines depict the mean locations of the 10°C and 15°C isotherms during the entire period of observation.

festations of lateral, primarily barotropic, meandering motions of the Florida Current in a manner consistent with that discussed above.

4. Discussion of other data and relation to theory

It is difficult to assess the general significance of the SYNOPS results. Indications are that several-day waves display transient behavior, similar to inertial waves, and also that they occur frequently. Evidence is provided by short profiling time series showing that the occurrence of deep southward flow—as an indicator for such waves—is quite frequent. It was observed off Miami in November 1970, February 1971, April 1971, June 1971, April 1972, September 1972; off Fort Pierce September 1971; off Key West May 1972. These observations admittedly consist of short time series. A longer current meter record is available from the Miami Terrace at 300-m water depth (100 m above the bottom). This 50-day-long record shows persistent fluctuations with periods of about 5 to 6 days. The mean value during the observational period in spring 1972 was 7.6 cm/sec to the south (Kielmann and Düing, 1974). A series of free-fall instrument data also shows southward flow on the western side of the Straits during May–June 1969 (Stubbs, 1971). The strongest support for frequent deep southward flow is provided by geological observations. The sediments along the seaward slope of the Miami Terrace and in the adjacent trench indicate that southward flow is the rule rather than the exception (Neumann and Ball, 1970). The geologists found that southward-directed ripple marks are best developed (maximum heights 0.3 to 1 m) in the deep trench east of the Miami Terrace; i.e., where we observed the highest southward velocities. The permanent existence of southward-directed ripple marks can probably be explained by the strong southward flow which generates them, whereas the deep northward flow is too weak to completely erode them.

It is of interest that deep flow reversals were also found on the cyclonic side of the Kuroshio south of Cape Shionomisaki. The few published vertical current profiles from this region (Teramoto, 1972) are similar to those observed in the Florida Current. Shoji (1972) emphasizes the significance of 4- to 5-day oscillations in the speed of the Kuroshio south of Japan. Taft, *et al.*, (1973) recently obtained long bottom current meter records from various positions in the Kuroshio and found in some cases that the mean bottom flow was counter to the surface flow. Whether these similarities are accidental or whether they point to identical dynamical features in western boundary currents cannot be decided at present.

a. Propagation of several-day waves. Establishing propagation direction and phase speed is helpful in determining the type of wave being observed and may provide a first clue to the generating mechanism. These parameters may be determined by using electrical potential measurements that were made on a submarine cable running from Jupiter Inlet (Florida) to Settlement Point (Grand Bahama Island), 120 km north of the SYNOPS baseline, Miami-Bimini. Data overlapping the SYNOPS 71 period were made available to the author by Drs. Sanford and Schmitz from Woods Hole Oceanographic Institution. The method has been used repeatedly (e.g., Wertheim, 1954) and is thought to provide information on the volume transport through a channel. The potential difference across the cable, V, is related to transport, T, by

$$V = \frac{H_z T}{D},$$

where H_z is the vertical component of the geomagnetic field, and D is the parametric "average" water depth. As pointed out by Wertheim and emphasized by Schmitz and Richardson (1968), fluctuations in D can lead to fluctuations in V with constant T and H_z; that is, to apparent transport fluctuations. Variations of the parametric "average" water depth, D, may be caused by meandering of the current over a varying bottom profile. Since meandering occurs with periods of several days, a comparison of cable data and directly observed transport data in this low-frequency range must be approached with caution. An example will show that the effect of increasing depth can easily overwhelm the effect of increased transport and thus cause a *lowering* of the observed voltage. A 10 km eastward shift of the current axis at the latitude of Jupiter Inlet causes a change in water depth from $D_1 = 270$ m to $D_2 = 370$ m. During a SWF situation, the current was close to the western side of the Straits with a transport of $T_1 = 16.4 \times 10^6 \text{m}^3\text{sec}$. During a NWF situation, it moved farther east with a transport of $T_2 = 18.4 \times 10^6 \text{m}^3\text{sec}$. Hence,

$$\frac{V_1}{V_2} = \frac{T_1 \times D_2}{T_2 \times D_1} = \frac{16.4 \times 370}{18.4 \times 270} = 1.22,$$

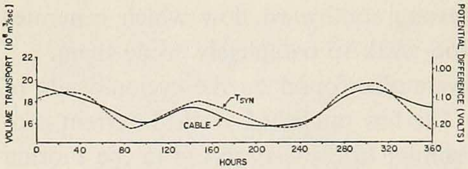

Figure 16. Low pass filtered versions of the time series shown in Fig. 3. The cable data have been inverted and lagged 70 hours behind the SYNOPS data.

that is, despite the increased volume transport, the voltage, V_2, has decreased by 22%. Assuming that the mechanism for meandering and transport fluctuation is identical at both locations off Miami and off Jupiter Inlet, the sign of the voltage fluctuation has to be inverted in order to allow a meaningful comparison between cable data and SYNOPS transport data in the low-frequency range. Figure 16 shows low pass filtered versions of both time series. The cable data have been inverted and shifted 70 hours so that the SYNOPS transport data from Miami lead the cable data from Jupiter Inlet. To what degree fluctuations of the cable data are to be attributed to meandering or to transport variation cannot be decided. However, this is unimportant for our purposes as long as meandering and transport variation are related as described earlier. The important point is to align identical events on the time axis. The 70-hour lag over 120 km thus leads to the result that the observed wavelike motions propagated *northward* with a mean phase speed of 47 cm/sec. Periods ranging from 4 to 6 days would thus correspond to wavelengths ranging from 160 km to 240 km.

Comparable observations in the southern part of the Florida Current are sparse. The few that exist give parameters of similar magnitude. Lee (1972) observed that spin-off eddies in the Florida coastal region propagate northward with phase speeds varying from 19 cm/sec to 46 cm/sec. O'Hare, *et al.*, (1954) report a characteristic wavelength of 220 km in the region over the Blake Plateau. Chew and Berberian (1970) tracked shallow parachute drogues in the region between Fort Pierce and Cape Kennedy. They traced a meander with 3 km amplitude and a wavelength of 150 km. In conclusion, the observed northward phase speed is considerably smaller than the value of the mean flow. This means that the intrinsic phase speed is directed southward, but since it is smaller than the mean flow, the wavelike disturbances are advected northward.

The observed wavelike motions are strongly reminiscent of barotropic shelf waves as discussed by Niiler and Mysak (1971). The range of parameters which they found for the fastest growing unstable mode in the presence of bottom topography over the Blake Plateau agrees reasonably well with the SYNOPS results. As in the observed case, the propagation is to the north, with phase speeds considerably smaller than the mean flow and wavelengths of about 200 km. It is not clear how their results would be modified by using a mean baroclinic jet rather than a barotropic jet as in the present model. Presumably, however, the barotropic mode would still be energetically predominant. There is one distinct difference between the Niiler-Mysak model (as well as other similar models) and the Florida Current; namely, different geometries. The models assume straight coastlines running in a north-south direction, whereas the Florida Current is bounded on the east by the Bahamas and bends 90° between Key West and Miami. Meteorological forcing, or some instability mechanism, is necessary to generate barotropic waves in the existing models. In the Florida Current, on the other hand, barotropic shelf waves can probably be generated as an inertial reaction to the flow "around the corner." Such topographically induced shelf waves would thus always be present although their characteristic parameters would vary over a wide range. Ignoring nonlinear interactions, the phase speed, c, of the barotropic mode in the presence of a mean flow, V_0, can be approximated by

$$c = V_0 - \frac{Lf}{1.44},$$

where L is a representative shelf width and f is the Coriolis parameter (see Mooers and Smith, 1968). $V_0 = 100$ cm/sec, and $L = 15$ km, yielding a phase speed of $c = 40$ cm/sec. Since values for $\frac{Lf}{1.44}$ are close to values for V_0, varying mean flow could lead to reversals of the propagation direction or even to standing waves. Slowly varying mean flow may also cause frequency shifts; e.g., on a seasonal time scale. According to Fuglister (1951a) and to Niiler and Richardson (1973), the mean flow has its annual maximum in June/July and its minimum in October/November. One may therefore expect to observe waves with a slightly different frequency (and wavenumber) during summer than during fall. Mysak and Hamon (1969), for example, have pointed out that there is some evidence of seasonal variation in the speed of continental shelf waves off North Carolina and that this variation may be associated with the seasonal variation in the surface speed of the Gulf Stream. Since mesoscale atmospheric phenomena on a several-day time scale undoubtedly also exert some influence, it becomes difficult to determine the dominating mechanism which generates these waves. A better understanding would be useful since the observed type of wave may grow into the large-scale meanders frequently occurring much farther downstream.

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Contribution from the Rosenstel School of Marine and Atmospheric Science, University of Miami, Miami, Florida 33149.