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TRANSPORT INVESTIGATIONS IN THE NORTHWEST PROVIDENCE CHANNEL

JAMES R. FINLEN

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Transport Investigations in the Northwest Providence Channel. (June 1966) Abstract of a Master's Thesis at the University of Miami. Thesis supervised by Associate Professor William S. Richardson.

This thesis describes a short investigation of the circulation pattern in, and volume transport through the Northwest Providence Channel. Measurements were made on the 20th, 21st and 22nd of March 1966 along a transect between Lucaya and Little Isaac, Bahama Islands. Such measurements included direct transport and surface current determinations using free-drop instruments and a highly accurate navigation system. A current meter and tide gage were also installed on both the north and south shores of the channel to provide additional information on the nature and influence of the tides.

Results of the investigation showed that two major flows existed in the channel. An easterly directed movement was taking place throughout the southern section and in the upper (above 275 meters) layer of the central section representing an off-shoot of the Florida Current. A westerly directed movement occurred throughout the northern section and in the lower (below 275 meters) layer of the central section. This latter flow was evidently the result of a westerly component in that portion of the North Atlantic Gyre east of the Bahama Islands. The tides in the channel were found to be semi-diurnal and acted to modulate both flows.

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THE UNIVERSITY OF MIAMI

TRANSPORT INVESTIGATIONS IN THE NORTHWEST

PROVIDENCE CHANNEL

BY

James R. ^{endell}Finlen
"

A THESIS

Submitted to the Faculty
of the University of Miami
in partial fulfillment of the requirements for
the degree of Master of Science

Coral Gables, Florida

June 1966

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Finlen, J.

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Subject

Transport Investigations in the Northwest
Providence Channel

James R. Finlen

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PREFACE

Much time and effort had gone into instrument design, the ship positioning system, field techniques and computer programming before the idea for this investigation was ever conceived. It is largely to the people responsible for this fundamental research and those contributing to the development of this work that this section of the thesis is devoted.

The financial support for this study was entirely provided by the Office of Naval Research under a recurrent grant for the investigation of the Gulf Stream System.

Dr. William S. Richardson, Associate Professor of Physical Oceanography was the principal instrument designer and instigator of the measurement techniques employed. In addition it was Dr. Richardson who suggested and supervised this investigation, so that primary thanks must go to him. Further acknowledgment to the other members of this group are due

William J. Schmitz, for his assistance in familiarizing the author with the basic techniques, establishing the computer programs and for his general assistance with the data reduction; Fred White for his assistance in performing the field work; and Fred Koch and Carla Cangiamila for their assistance in the data reduction.

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James R. Finlen

Coral Gables, Florida
June 1966

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INTRODUCTION AND HISTORY

In approaching the study of water movement within a hundred miles of the southeast coast of the United States one must necessarily consider the influence, either direct or indirect, of that portion of the Gulf Stream System which passes through the area. Such is the case with an investigation of water transport in the Northwest Providence Channel, and it is with a brief discussion of the Florida Current that this thesis should appropriately begin.

While transport values for the Florida Current taken from past works have varied over a wide range of values, most recent information obtained by direct measurement, Schmitz and Richardson (1966), indicates that a representative figure is between 30 and 35 million cubic meters per second. Transport values per se, and measurement techniques have been discussed to some length and included in this thesis as Appendix B. In addition to some mean transport

figure, an essential characteristic of the Florida Current is a rather substantial transport fluctuation which varies in a complex manner. There exists a wealth of literature; Pillsbury (1890), Parr (1937), Murray (1952), Wagner and Chew (1953), von Arx, et al. (1954, 1955), Werthein (1954a, 1954b), Stommel (1957, 1959, 1961, 1965), Broida (1962, 1963, 1966), von Arx (1962), and Schmitz and Richardson (1966) speculating upon the nature of the seasonal changes, tidal modulation and long period fluctuations. A detailed discussion of these theories would be out of context with the subject of this thesis but time-series plots of transport through the Florida Straits (Figs. 15-17 of Appendix B) have been included to provide a quick insight into the relative magnitudes and time intervals involved with these fluctuations.

Relevant to understanding the total transport of the Florida Current is the question of what possible contribution is made from an easterly direction, by water passing over the Bahamian Platform. Smith (1940) found that sluggish currents existed over the shallow

bank, and that the direction of these currents was controlled very largely by local wind conditions. A cursory inspection of an appropriate chart leads to the conclusion that, even in the summer with the predominating south-easterly winds, the total contribution of waters flowing over the Banks is insignificant in relation to the Florida Current. Since the Bahamian Platform is cut by only two major channels one need only consider these as possible routes for some significant transport contribution.

One of these possibilities, the Old Bahama Channel, has a very definite transport limitation imposed by its relatively small cross-sectional area. At one of the more restricted sections of the channel the profile is found to be some 15 kilometers wide and a maximum of 500 meters deep. Considering the relatively high dissolved oxygen values (4.0 to 4.5 ml/L) found in Old Bahama Channel, Smith (1940) and Wagner (1956) concluded that the water is supplied from the Sargasso Sea and that movement was taking place to the northwest. Wüst (1924), using data

collected by Pillsbury in 1889, calculated that the maximum possible transport through the Old Bahama Channel was about 2 million cubic meters per second. More recent results obtained by Chew and Wagner (1958), Hela, et al. (1954, 1955) and Wagner (1955b, 1956) indicate that only a portion of the surface waters can be found to be flowing to the northwest at any one time. This provides additional evidence that little contribution to the Florida Current is to be made through the Old Bahama Channel.

The Northeast and Northwest Providence Channels provide the second major easterly opening between the Atlantic and the Florida Straits. Here we find that the channels even at their narrowest points are at least 33 kilometers across. In the Northeast Providence Channel soundings range between 1400 and 4000 meters. The greater portion of the Northwest Providence Channel has depths in excess of 900 meters with a shoaling towards the sill at the western end. A deepening of this sill on the north side of the channel provides a connection with the Straits of

Florida as deep as 800 meters. Based upon cross-sectional area alone it seems that some significant transport might take place through the channel.

In a manner similar to that cited for the Old Bahama Channel, Smith (1940) and Wennekens (1959) used salinity-temperature, oxygen-density and inorganic phosphate-density relationships to identify the water mass below 300 meters in the Providence Channels as having originated in the western Sargasso Sea. Furthermore, hydrography on the eastern side of the Northern Straits of Florida indicates that this water mass is actually entering the main flow of the Florida Current. Stimson (1966) has substantiated these findings with identical results.

Surface currents in the Northeast Providence Channel, as depicted in the Sailing Directions for the West Indies are variable, but with an easterly set of 1 knot frequently experienced after a period of northerly winds. The set experienced in the center of the Northwest Providence Channel is usually slight while near the reefs, relatively strong tidal

currents are set directly on-to and off-of the banks. Schmitz (1962) provides data from a single 33-hour anchor station at the western edge of the channel. Ekman current meter readings taken at the surface, 10 meters, 50 meters, 100 meters, 200 meters, 300 meters and 400 meters all indicated a flow taking place out of the channel into the Straits with a mean surface current of approximately 30 centimeters per second. As reported by Schmitz, an inertial or diurnal periodicity could possibly be read into the results of the surface current direction. Considering the location of the anchor station (Lat. $26^{\circ}19'N$, Long. $79^{\circ}04'W$) it appears conceivable that these results could be contaminated by cross-stream components of the main flow passing through the Straits.

Broida (1966) reported the results of 12 three and four station hydrographic transects taken at one month intervals across the western end of the Northwest Providence Channel. Any deductions to be drawn from this data should be made in the light of the critique on dynamic calculations presented in

Appendix B. Broida's results seem to substantiate the idea of a slow (less than 1 knot) westerly flow below 200 or 300 meters. The core of this flow appears to be fairly centered in the middle of the channel and at depths between 200 and 400 meters. Each sectional transport value computed from a pair of hydrographic stations was quite evidently phase-biased by the tides. Total transports computed from these sections present a confused picture with the net values varying between a westward flow of 2.14 million cubic meters per second and an eastward flow of 3.27 million cubic meters per second. While Broida's work represents a long period of time an insufficient sampling rate precludes any appreciation for the influence that the moon's declination has upon the results.

In view of the scant conclusions to be drawn from this series of hydrographic transects, no discussion will be made of the 8 random but similar hydrographic transects made by the University of Miami's Marine Laboratory prior to 1962.

Hydrographic stations made from the privately owned vessel, Vicca across the Northwest Providence Channel in October of 1961 at $78^{\circ}18'W$ longitude while not being suitable for a transport determination, do indicate a strong westerly flow below 200 meters passing through the northern sector of the channel. Looking at the bottom topography of the Northwest Providence Channel such an asymmetric flow would appear quite logical.

Assuming that some significant westerly flow is taking place through the Northeast and Northwest Providence Channels, it is pertinent to consider the water circulation as it exists to the East of the Bahamas. Wagner and Chew (1953) after making a GEK survey in this area found no evidence of an organized surface current associated with the Antilles Current. Day (1954) using information available from deep-water hydrographic stations made in 1947 and the recorded recoveries of 94 drift bottles, concluded that surface waters in this region move in a generally southwesterly direction, and that the Antilles

Current appears at depth and varies in transport greatly from one time to another. Wertheim (1954a) suggests that the seasonal strengthening or destruction of the Bermuda-Azores High may act as the agent controlling transport of the Antilles Current.

Wertheim's suggested "switching process," while being an attractive hypothesis, implies a surface movement which is not in agreement with Day's conclusions.

OBJECT OF THE EXPERIMENT

Based on the foregoing information, some very general conclusions were drawn concerning water movement in the Northwest Providence Channel. First, one was led to believe that a predominantly westerly flow was taking place below 200 meters. While the diurnal tidal terms might be inferred as being dominating from Schmitz's current meter work in the channel, this is not in agreement with the clear semi-diurnal response exhibited at tide stations in the adjoining area of the Straits. Second, the flow picture for the upper 200 or 300 meters was confused, and was most likely the result of wind and tide induced currents having been superimposed on a slow westerly movement. It also appeared likely that large transport fluctuations in the Straits of Florida had some influence on the circulation and transport as had been monitored in the western part of the channel. Summarily, the conclusions to be drawn concerning the absolute volume

transport through the Northwest Providence Channel were very questionable, although intuitively one might expect this figure to be less than 5 million cubic meters per second.

With these conclusions in mind, a field experiment was designed to provide a clearer insight into the water flow in the Northwest Providence Channel. The main objective of the experiment, however, was to collect more definitive data concerning the absolute volume transport. In addition to this main objective, the experiment was programmed to collect tide and current data which when taken in conjunction with the transport information could provide information on the tidal response in this area.

DESIGN OF THE EXPERIMENT

Several considerations played a role in the selection of the transport sampling transect illustrated in Fig. 1. Hi-Fix signal strengths and desirable base line angles dictated an area of operation at the western end of the Providence Channels. From a logistics standpoint it was most desirable that one end of the transect terminate at some point convenient to replenishment facilities necessary in a small power-craft's cruising operations. Although not critical to the performance of the transport investigation itself, it was further desirable that both ends of the transect terminate as near as possible to some site suitable for installing a tide gage. Shorter transects lying to the west of that actually chosen, and meeting all of the above conditions, were disregarded in an effort to have the sampling stations as removed as possible from any misleading contaminations from the Florida Current.

Figure 1. Chart of the Northwest and Northeast Providence Channels showing the transport, tide and current measuring locations.

Lacking any conclusive evidence that the major portion of the flow in the channel was to be found concentrated within a limited area, it was decided that sampling stations along the transect would be equally spaced with an interval of 10 kilometers. Fig. 2 illustrates the horizontal and vertical distribution of the transport measurements. The employment of two free instruments in the upper 350 meters at the deep stations was based upon results of previous work in the Florida Current where approximately 75 per cent of the transport was found to take place in the upper half of the water column. The results of Broida's dynamic calculations for the Great Isaac to Settlement Point hydrographic stations also indicated that by far the greater portion of the transport occurs above 350 meters.

In addition to the direct transport measurements it was decided that the use of two current meter-tide gage combinations be included in the investigation. Such installations were to verify the nature of the tides and determine the tidal influence on the steady

Figure 2. Depth profile of the
Lucaya to Little Isaac transect
across the Northwest Providence
Channel.

state flow in each area. Due to pressure sensing limitations, the tide gages were restricted to water depths of less than two meters. For this reason and the need for a sheltered location, the south shore tide gage was installed on the southern side of Little Isaac in about 1.3 meters of water. The south shore current meter was bottom-moored in 100 to 150 fathoms of water in order to have it removed from an expected tidal set on-to and off-from the Great Bahama Bank. Not having to consider such an effect on the north shore, the current meter was moored in less than 25 fathoms of water, just a few hundred meters from transport station number 1. The site for the north shore tide gage was selected at the eastern side of the Lucayan harbor breakwater in about 1 meter of water.

EXPERIMENTAL TECHNIQUE AND INSTRUMENTATION

Free Instrument Technique

The free instrument technique is a method whereby one is able to compute the magnitude and direction for a surface current, an average current over the sampled depth and a volume transport per unit width of water column. Critical to these computations are a highly accurate navigational system and a time-temperature-depth recording instrument which can be made to sink to some preselected depth, release its ballast weights and return to the surface under its own positive buoyancy. The basic concept underlying the transport computation is presented in the following equation:

$$\vec{T} = \int_0^D \vec{v} \, dz = \vec{R}D/t$$

where $\vec{T}$ is the volume transport per unit width and to the sampled depth D , $\vec{R}$ is the horizontal separation between the drop and surfacing points and t is the

total time of the run. From this, one may note that the accurate ship positioning system is necessary to determine $\vec{R}$, while the function of the free instrument is to record the quantities D and t . While the navigation system and the free instrument are discussed in the succeeding sections, the technique will not be dealt with any further as it is identical to that described by Richardson and Schmitz (1965).

Navigational System

Perhaps the essence of the transport measuring technique is the Decca Hi-Fix (Survey) System which provides an exceptionally high degree of positioning accuracy. In this respect the Hi-Fix System has demonstrated a standard deviation of 0.015 lanes or approximately 1.1 meters in distance.

The system consists of a mobile master station shown in Fig. 3, located aboard the Institute's 43 foot research vessel Austausch (also shown in Fig. 3) and two slave stations located respectively at Boca Raton, Florida and the Institute of Marine

Figure 3. The research vessel
AUSTAUSCH and shipboard Decca Hi-
Fix positioning equipment (receiver
and transmitter).

Science on Virginia Key. In operation, the Austausch periodically (repetition rate of 1 second) interrogates the two shore-based stations. Interrogation consists of a continuous wave, 1.7 megacycle signal which is time shared between the master and each of the two slave stations. As in all CW electronic positioning systems signal phase comparison between the master and slave stations is required for range determination. The phase comparison provides a precise measure of the fractional part of a lane (one-half wave length) between the master station and each shore station. A record of the total number of lanes existing to each slave station is continuously displayed on the master receiver at all times.

Time-Temperature-Depth Recorder

The time-temperature-depth recorder or "free instrument" shown in Fig. 4 was used in conjunction with the Hi-Fix System to obtain all transport measurements and surface currents. Briefly, the

Figure 4. The time-temperature-depth recording instrument and associated mid-depth and bottom release mechanisms.

instrument consists of a 16-mm camera that takes time lapse pictures of a bourdon tube pressure gage, an electric wrist watch and mercury thermometer all housed in a 150 cm long aluminum pressure case. The instrument and the associated release mechanisms have also been described by Richardson and Schmitz (1965), and it is to that paper that the interested reader is referred for additional information.

Current Meter

The current meter used during the investigation along with the associated mooring gear is illustrated in Fig. 5. General design criteria and mooring techniques have been described by Richardson, Stimson and Wilkins (1963). Modifications to the basic design include the relocation of the Savonius rotor to the upper end of the instrument and the replacing of the encoded film recording with time lapse pictures of an electric wrist watch, a mercury thermometer, a magnetic compass dial, a vane relative bearing dial and a rotor counter. A 16-mm camera installation

Figure 5. The current meter and mooring employed in the Northwest Providence Channel.

identical to that used in the free instrument makes up the recording section. The film was advanced by a 1/10 RPM, 6-volt d.c. motor which provided a sampling every minute and 25 seconds.

Tide Gage

The tide gage and the method of anchoring are illustrated in Fig. 6. The sampling section of the tide gage consists of a bourdon tube with its dial calibrated in inches of water and an electric wrist watch. The camera installation is also identical to that used in the current meter providing time lapse photographs every 1 minute and 25 seconds. The resultant 16-mm film records from either the tide gage or current meter are then read at desired sampling intervals for composing some form of graphic results. Other than end-caps the pressure cases for all three instruments just described are interchangeable as evidenced by the similarities of Figs. 4-6.

Figure 6. The tide gage and anchoring gear employed in the Northwest Providence Channel.

RESULTS

Four separate transport transects across the Northwest Providence Channel were carried out during the period 20-23 March, 1966. The first measurements took place on the 20th of March and included a full 7 station transect and the installation of the tide gage and current meter on the south shore of the channel. Following the tide gage and current meter installations at the north shore on the morning of the 21st, a transect with transport measurements taken at every other station was accomplished in a southerly direction. The third transect took place during the afternoon of the 21st and again included the full 7 stations across the channel this time from south to north. The final transect which included only the first 4 stations took place on the 22nd of March but was discontinued when only half way through due to rough sea conditions.

Tabulated transport and current results for

individual instrument drops have been grouped by depth category and transect date and included as part of Appendix A. Results from the shallow-drop (175 meters) instruments are presented in Tables II-V. Mid-depth (350 meters) instrument results are presented in Tables VI-IX and the bottom-drop instrument results make up Tables X-XIII. No results were obtained from the shallow drop at station 2 on the 22nd of March due to improper servicing of the instrument. Three transport graphs Figs. 8-10 represent the westerly (295°T) component of transport for the three different vertical layers; the shallow layer 0 to 175 meters, an intermediate layer 0 to 350 meters and that for the entire water column. A summary of the net total transport representing all four transects is given in Table I.

Westerly (295°T) components of surface current versus distance across Northwest Providence Channel are shown in Fig. 7. Current meter records for the north shore installation are presented in Fig. 13 in Appendix A. The current meter moored in deep water

Figure 7. The westerly (295°T) component of surface current vs. distance across the Northwest Providence Channel.

Figure 8. The westerly (295°T) component of transport vs. distance across the Northwest Providence Channel for the entire water column.

Figure 9. The westerly (295°T) component of transport vs. distance across the Northwest Providence Channel for the upper 350 meters.

Figure 10. The westerly (295°T) component of transport vs. distance across the Northwest Providence Channel for the upper 175 meters.

Figure 11. The westerly (295°T) component of transport vs. depth at stations 1 through 7 across the Northwest Providence Channel.

Table 1. Summary of the net total
transport for the Northwest Providence
Channel.

TRANSECT	DATE	LOCAL TIME (EST)	WESTERLY FLOW (295°T) (10 ⁶ m ³ /SEC)	EASTERLY FLOW (115°T) (10 ⁶ m ³ /SEC)	NET WESTERLY FLOW (295°T) (10 ⁶ m ³ /SEC)
LUCAYA TO LITTLE ISAAC	20 MARCH	0745-1543	4.62	2.10	2.52
LUCAYA TO LITTLE ISAAC	21 MARCH	0914-1236	4.55	2.59	1.96
LITTLE ISAAC TO LUCAYA	21 MARCH	1236-1734	3.82	2.40	1.42
LUCAYA TO LITTLE ISAAC	22 MARCH	0917-1130	2.39	--	--

on the south shore while offering a complete direction record illustrated in Fig. 12 did not produce information on the current's speed. Satisfactory functioning of the instrument's components before and after the mooring leads one to conclude that the malfunction of the Savonius rotor must have been due to blocking by some form of debris while the instrument was operating at depth. Such an obstruction might very likely have been due to some drifting seaweed or even part of the mooring tackle used in the rig itself.

A smoothed time plot of the tide data for the south shore is presented as Fig. 15 in Appendix A. Here the installation site proved to be satisfactory as the noise level proved less than ± 3 inches. Due to a malfunction of the wrist watch in the north shore tide gage, a resultant time plot of tide data from that instrument was not developed; although information on the tidal amplitude was recovered.

DISCUSSION OF RESULTS

The results show that the transport in the northern section of the channel was essentially all in a westerly direction. The middle section of the channel demonstrated an easterly flow at the surface with a westerly flow below 275 meters. An easterly flow at all depths was found at stations in the southern section of the channel. This is easily recognized in the plots of transport versus depth for the various stations given in sequence (Fig. 11). While there appears to be a tidal modulation of the transport at all stations, data collected from the two current meters precludes a periodic flow-reversal in both the north and south sections. Furthermore the transport results showed a net westerly transport out of the Northwest Providence Channel making a significant contribution to the Florida Current. Comparing the westerly components of transport in the entire water column, Fig. 8, with that for the upper

350 meters, Fig. 9, one finds by far the greater portion of the total transport takes place above 350 meters. The two measurements made at station 5 on the 20th of March have been disregarded in plotting the transport curves Figs. 7-9 since their results seem almost unquestionably to be in error. An analysis of the data collected during these measurements indicates that the Hi-Fix positioning equipment had likely slipped one or several lanes during the course of that particular station.

Both current meters show what are essentially steady flows, each in a single general direction. The word "essentially" is used because the current meter record for the north shore indicates one complete directional reversal occurring during a period of approximately 2 hours. No corresponding alteration is noted in the record for the south shore, and while no explanation is offered for this occurrence in the north it is clearly of a non-tidal nature. Surface currents show maximum values within 20 kilometers of either shore and reversal of direction

roughly half-way across the channel. On the south shore of the channel the flow is predominantly in a direction of 130 degrees and an indication of a semi-diurnal periodicity might be read into the first half of the current meter record (Fig. 12). The north shore instrument exhibits a predominant flow in a direction of 240 degrees, with no readily discernable periodicity evident in any part of the record (Fig. 17). It is interesting to note that both predominant flow directions are within 10 degrees of the trends of the north and south shore 100 fathom curves.

Tidal signatures show that the semi-diurnal terms are the dominating constituents. The tides at Little Isaac are in-phase (± 10 minutes) with those predicted for the Miami Harbor Entrance. While the clock malfunction in the north shore tide gage prevents an accurate determination of the phase relationship between the north and south shores of the channel, a phase difference of less than 10 minutes can be deduced from the installation time and frame rates of the instrument. The tidal amplitude for both

shores is 18 inches for the period investigated.

CONCLUSIONS

It is recognized that the results of this investigation represent only a three day-period. As such they can not be considered as depicting the steady state condition. On the other hand, the author would not expect to find a drastic seasonal change in the induced overall circulation pattern or a change in the net transport by an order of magnitude.

From the transport, current and tide measurements made during this investigation, an inference may be made concerning the overall circulation in the channel. Results show this general circulation to be a product of bottom topography, a westerly component of flow from the area east of the Providence Channels, the Florida Current, a tidal modulation and prevailing wind conditions in the immediate locality. More specifically, one can suggest a basic westerly flow through the channel being directed along the northern half of the channel and greatly

influenced by the channel's bottom topography (note the 500 fathom curve in Fig. 1). The Florida Current, on the other hand, entering a divergent section of the Florida Straits develops a strong easterly component which is able to predominate in the much shallower southern section of the channel. This easterly directed flow would not be expected to continue on through to the eastern entrance to the Northwest Providence Channel. Rather it would eddy counter-clockwise in the area northwest of the Berry Islands and become assimilated by the basic westerly flow. This particular aspect of the circulation would be greatly influenced by the bottom topography, since the 500 fathom curves encompass nearly the entire width of the transect between the Berry Islands and the southwestern tip of Great Abaco Island. In the central section of the channel, the westerly flow probably dominates in the deeper waters (> 275 meters) while the surface waters are influenced by the south shore branch of the Florida Current. Both the easterly and westerly directed

portions of the channel's circulation gave indication of what appears to be a tidal modulation. The relatively small number of absolute measurements made is not conducive to further speculation along these lines.

APPENDICES

APPENDIX A

TRANSPORT, CURRENT AND TIDE DATA
COLLECTED IN THE NORTHWEST PROV-
IDENCE CHANNEL.

Table II. 175 meter-instrument
transport and surface current
results for the Lucaya to Little
Isaac transect of 20 March 1966.

TRANSECT: LUCAYA TO LITTLE ISAAC			DATE: 20 MARCH 1966		
STATION NUMBER	2	3	4	5	6
LOCAL TIME (EST)	0850	0940	1032	1130	1227
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)	51.25	41.16	32.15	32.38	12.54
INSTRUMENT'S DROP DEPTH (METERS)	174.5	175.7	168.3	178.8	168.8
MAGNITUDE OF SURFACE CURRENT (CM/SEC)	55.6	65.0	61.6	42.6	83.5
DIRECTION OF SURFACE CURRENT (DEG. TRUE)	237.7	212.3	201.7	188.5	118.8
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)	83.9	102.5	108.8	64.4	56.9
DIRECTION OF THE TRANSPORT (DEG. TRUE)	236.4	227.3	194.0	161.3	115.9
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)	30.0	8.2	-3.5	-12.1	-83.3
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)	-46.8	-64.4	-61.5	-40.9	-5.6
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)	43.6	38.9	-20.8	-44.5	-56.9
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)	-71.6	-94.9	-106.8	-46.5	-0.9

Table III. 175 meter-instrument
transport and surface current
results for the Lucaya to Little
Isaac transect of 21 March 1966.

TRANSECT: LUCAYA TO LITTLE ISAAC		DATE: 21 MARCH 1966	
STATION NUMBER		3	5
LOCAL TIME (EST)		1042	1146
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)		41.48	22.06
INSTRUMENT'S DROP DEPTH (METERS)		171.8	167.5
MAGNITUDE OF SURFACE CURRENT (CM/SEC)		47.6	82.1
DIRECTION OF SURFACE CURRENT (DEG. TRUE)		242.1	163.8
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)		73.5	102.6
DIRECTION OF THE TRANSPORT (DEG. TRUE)		244.4	146.0
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)		28.7	-54.1
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)		-38.0	-61.7
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)		46.6	-87.9
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)		-56.8	-52.9

Table IV. 175 meter-instrument transport and surface current results for the Little Isaac to Lucaya transect of 21 March 1966.

TRANSECT: LITTLE ISAAC TO LUCAYA							DATE: 21 MARCH 1966		
STATION NUMBER	6	5	4	3	2				
LOCAL TIME (EST)	1319	1405	1503	1558	1648				
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)	12.51	22.97	32.57	41.97	52.15				
INSTRUMENT'S DROP DEPTH (METERS)	164.4	170.6	164.0	164.8	168.7				
MAGNITUDE OF SURFACE CURRENT (CM/SEC)	61.1	74.9	53.0	59.9	90.4				
DIRECTION OF SURFACE CURRENT (DEG. TRUE)	186.4	162.7	205.9	246.4	255.8				
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)	55.9	85.1	71.6	101.1	82.4				
DIRECTION OF THE TRANSPORT (DEG. TRUE)	140.9	155.7	204.5	237.9	262.9				
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)	-19.5	-50.4	0.8	39.6	70.1				
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)	-57.9	-55.3	-53.0	-44.9	-57.0				
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)	-50.3	-64.5	-0.6	55.0	69.8				
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)	-24.4	-55.5	-71.6	-84.9	-43.7				

Table V. 175 meter-instrument transport and surface current results for the Lucaya to Little Isaac transect of 22 March 1966.

TRANSECT: LUCAYA TO LITTLE ISAAC		DATE: 22 MARCH 1966		
STATION NUMBER		2	3	4
LOCAL TIME (EST)		1055	1049	1131
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM).		--	41.33	32.29
INSTRUMENT'S DROP DEPTH (METERS)		--	171.0	172.5
MAGNITUDE OF SURFACE CURRENT (CM/SEC)		--	34.4	47.4
DIRECTION OF SURFACE CURRENT (DEG. TRUE)		--	259.0	227.1
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)		--	95.3	87.4
DIRECTION OF THE TRANSPORT (DEG. TRUE)		--	215.5	192.4
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG TRUE (CM/SEC)		--	27.8	17.9
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)		--	-20.2	-43.9
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)		--	17.3	19.0
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)		--	-93.7	-85.3

Table VI. 350 meter-instrument transport and surface current results for the Lucaya to Little Isaac transect of 20 March 1966.

TRANSECT: LUCAYA TO LITTLE ISAAC		DATE: 20 MARCH 1966	
STATION NUMBER	2	3	4
LOCAL TIME (EST)	0841	0937	1030
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)	51.38	41.32	32.20
INSTRUMENT'S DROP DEPTH (METERS)	328.1	330.1	354.4
MAGNITUDE OF SURFACE CURRENT (CM/SEC)	54.4	67.0	62.1
DIRECTION OF SURFACE CURRENT (DEG. TRUE)	236.0	214.7	202.6
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)	148.1	126.3	97.2
DIRECTION OF THE TRANSPORT (DEG. TRUE)	258.0	245.0	235.4
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)	28.0	11.3	-2.5
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)	-46.7	-66.0	-62.0
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)	118.4	81.2	49.2
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)	-89.1	-96.8	-83.9

Table VII. 350 meter-instrument transport and surface current results for the Lucaya to Little Isaac transect of 21 March 1966.

TRANSECT: LUCAYA TO LITTLE ISAAC		DATE: 21 MARCH 1966
STATION NUMBER	3	
LOCAL TIME (EST)	1042	
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)	41.47	
INSTRUMENT'S DROP DEPTH (METERS)	344.7	
MAGNITUDE OF SURFACE CURRENT (CM/SEC)	50.4	
DIRECTION OF SURFACE CURRENT (DEG. TRUE)	242.9	
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)	145.0	
DIRECTION OF THE TRANSPORT (DEG. TRUE)	246.2	
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)	31.0	
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)	- 39.7	
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)	95.6	
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)	-109.0	

Table VIII. 350 meter-instrument transport and surface current results for the Little Isaac to Lucaya transect of 21 March 1966.

TRANSECT: LITTLE ISAAC TO LUCAYA		DATE: 21 MARCH 1966	
STATION NUMBER	4	3	2
LOCAL TIME (EST)	1502	1558	1647
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)	32.58	41.97	52.17
INSTRUMENT'S DROP DEPTH (METERS)	346.9	323.1	328.3
MAGNITUDE OF SURFACE CURRENT (CM/SEC)	51.1	60.9	86.4
DIRECTION OF SURFACE CURRENT (DEG. TRUE)	209.7	250.2	254.4
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)	123.5	141.9	143.6
DIRECTION OF THE TRANSPORT (DEG. TRUE)	209.6	250.9	264.6
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)	4.2	43.2	65.6
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)	-51.0	-42.9	-56.2
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)	9.8	101.9	123.9
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)	-123.1	-98.8	-72.7

Table IX. 350 meter-instrument transport and surface current results for the Lucaya to Little Isaac transect of 22 March 1966.

TRANSECT: LUCAYA TO LITTLE ISAAC		DATE: 22 MARCH 1966		
STATION NUMBER		2	3	4
LOCAL TIME (EST)		0955	1044	1130
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)		51.34	41.45	32.28
INSTRUMENT'S DROP DEPTH (METERS)		339.5	320.7	340.3
MAGNITUDE OF SURFACE CURRENT (CM/SEC)		45.3	56.4	50.3
DIRECTION OF SURFACE CURRENT (DEG. TRUE)		225.8	217.6	218.4
MAGNITUDE OF THE TRANSPORT (SQ. METERS /SEC)		100.1	129.6	145.7
DIRECTION OF THE TRANSPORT (DEG. TRUE)		243.8	227.8	210.9
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)		16.1	12.3	11.6
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)		-42.4	-55.1	-48.9
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)		62.7	50.3	15.1
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)		-78.0	-119.5	-144.9

Table X. Bottom-instrument transport and surface current results for the Lucaya to Little Isaac transect of 20 March 1966.

TRANSECT: LUCAYA TO LITTLE ISAAC DATE: 20 MARCH 1966							
STATION NUMBER	1	2	3	4	5	6	7
LOCAL TIME (EST)	0745	0839	0936	1030	1129	1226	1543
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)	59.86	51.44	41.35	32.24	22.43	12.54	7.03
WATER DEPTH (METERS)	261.9	784.5	700.1	531.0	457.8	354.4	201.9
MAGNITUDE OF SURFACE CURRENT (CM/SEC)	56.4	57.7	65.9	62.1	42.3	84.3	43.2
DIRECTION OF SURFACE CURRENT (DEG. TRUE)	256.4	235.5	214.3	206.1	191.7	118.3	135.8
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)	129.2	252.8	211.9	80.1	76.0	142.4	40.7
DIRECTION OF THE TRANSPORT (DEG. TRUE)	248.4	262.2	256.8	241.8	319.6	132.7	137.0
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)	44.1	29.3	10.6	1.2	- 9.7	-84.2	-40.4
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)	-35.9	-49.7	-65.0	-62.1	-41.1	-4.9	-15.3
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)	88.7	212.4	166.6	48.0	69.1	-135.7	-37.7
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)	-94.0	-137.1	-130.9	-64.2	31.6	-43.2	-15.2

Table XI. Bottom-instrument transport and surface current results for the Lucaya to Little Isaac transect of 21 March 1966.

TRANSECT: LUCAYA TO LITTLE ISAAC		DATE: 21 MARCH 1966				
STATION NUMBER	1	3	5	7		
LOCAL TIME (EST)	0914	1041	1145	1236		
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)	59.57	41.48	22.06	6.00		
WATER DEPTH (METERS)	437.5	709.5	453.5	239.3		
MAGNITUDE OF SURFACE CURRENT (CM/SEC)	76.2	52.7	77.3	41.2		
DIRECTION OF SURFACE CURRENT (DEG. TRUE)	245.3	243.9	166.7	127.0		
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)	203.5	218.4	161.4	28.6		
DIRECTION OF THE TRANSPORT (DEG. TRUE)	250.8	253.1	153.8	124.2		
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)	49.4	33.1	-48.0	-40.3		
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)	-58.1	-41.0	-60.7	- 8.6		
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)	145.9	162.6	-125.8	-28.3		
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)	-141.9	-145.8	-101.2	-4.6		

Table XII. Bottom-instrument transport and surface current results for the Little Isaac to Lucaya transect of 21 March 1966.

TRANSECT: LITTLE ISAAC TO LUCAYA DATE: 21 MARCH 1966									
STATION NUMBER	7	6	5	4	3	2	1		
LOCAL TIME (EST)	1236	1319	1405	1506	1558	1646	1734		
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)	6.00	12.51	22.97	32.59	41.99	52.03	59.47		
WATER DEPTH (METERS)	239.3	352.0	456.1	525.3	714.0	768.2	479.4		
MAGNITUDE OF SURFACE CURRENT (CM/SEC)	41.2	59.9	68.5	50.4	61.5	83.5	67.2		
DIRECTION OF SURFACE CURRENT (DEG. TRUE)	127.0	185.7	163.2	210.2	251.6	253.0	247.2		
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)	28.6	138.1	156.8	163.2	208.4	212.9	176.5		
DIRECTION OF THE TRANSPORT (DEG. TRUE)	124.2	143.1	158.5	207.1	252.1	259.5	251.1		
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)	-40.3	-19.8	-45.6	4.6	44.7	62.0	45.1		
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)	-8.6	-56.5	-51.1	-50.2	-42.2	-55.8	-49.8		
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)	-28.3	-121.9	-113.8	5.9	152.6	173.2	127.3		
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)	-4.6	-65.0	-107.9	-163.1	-141.9	-123.8	-122.3		

Table XIII. Bottom-instrument transport and surface current results for the Lucaya to Little Isaac transect of 22 March 1966.

TRANSECT: LUCAYA TO LITTLE ISAAC		DATE: 22 MARCH 1966		
STATION NUMBER	1	2	3	4
LOCAL TIME (EST)	0917	0954	1045	1130
STATION DISTANCE ALONG TRACK FROM LITTLE ISAAC (KM.)	58.92	51.32	41.42	32.27
WATER DEPTH (METERS)	489.9	783.2	692.0	528.3
MAGNITUDE OF SURFACE CURRENT (CM/SEC)	37.4	43.7	56.2	46.6
DIRECTION OF SURFACE CURRENT (DEG. TRUE)	261.0	225.3	218.1	221.8
MAGNITUDE OF THE TRANSPORT (SQ. METERS/SEC)	127.8	186.9	213.7	206.6
DIRECTION OF THE TRANSPORT (DEG. TRUE)	248.7	246.8	225.7	203.6
SURFACE CURRENT COMPONENT ACROSS TRACK 295 DEG. TRUE (CM/SEC)	31.0	15.2	12.7	13.4
SURFACE CURRENT COMPONENT ALONG TRACK 025 DEG. TRUE (CM/SEC)	-20.9	-41.0	-54.8	-44.6
TRANSPORT COMPONENT ACROSS TRACK 295 DEG. TRUE (SQ. METERS/SEC)	88.3	124.5	75.5	-5.2
TRANSPORT COMPONENT ALONG TRACK 025 DEG. TRUE (SQ. METERS/SEC)	-92.3	-139.4	-199.9	-206.5

Figure 12. Time-series plot of current direction from the south shore current meter installation Northwest Providence Channel.

Figure 13. Time-series plots of current direction, current magnitude, westerly (295°T) component of current magnitude, and southerly (205°T) component of current magnitude from the north shore current meter installation Northwest Providence Channel.

Figure 14. Tide curve from south shore tide gage installation at Little Isaac, Northwest Providence Channel.

APPENDIX B

WATER TRANSPORT IN THE STRAITS OF FLORIDA

- I. A review of transport data for the Straits of Florida.
- II. A critique of transport measurement techniques as applied to the Straits of Florida.
- III. Time-series plots of transport in the Straits of Florida.

I. A review of transport data for the Straits of Florida

Estimates of transport of the Florida Current presented in the literature during the past 50 years have understandably differed. Nevertheless this data presents a range of values which when taken in the light of measurement techniques (Part II of this Appendix) develops a general picture. A summary of this transport data, presented in Table XIV indicates that the volume transport through the Straits of Florida ranges from approximately 16×10^6 to 41×10^6 cubic meters per second. What relative percentage of this transport range may be attributed to observational errors, investigational techniques or actual volume fluctuations remains a moot question. From this, one may conclude that besides the rough general picture most benefit is to be derived from the relative fluctuations in the time-series data. For further consideration of this last point, three time-series have been included as part III of this Appendix.

Table XIV. Summary of transport
measurements in the Florida Straits.

TRANSPORT ($10^6 \text{ M}^3/\text{SEC}$)	DESCRIPTION OF TRANSPORT VALUE	CHRONOLOGY	MEASUREMENT SITE	MEASUREMENT TECHNIQUE	LITERATURE CITED
24.2	7 CURRENT METER STATIONS (FILLSBURY DATA)	FEB-MAY 1887	REBECCA SHOAL-HAVANA	CURRENT & DEPTH CALCULATION	WÜST (1924)
25.6	SINGLE HYDRO SECTION (BACHE DATA)	MAR. 1914	POWEY ROCKS-GUN CAY	DYNAMIC CALCULATION	WÜST (1924)
GREATER THAN 30	24 HOUR AVERAGE FROM TWO HYDRO STATIONS AND EXTRA- POLATION TO SHORE	APR. 1937	POWEY ROCKS-GUN CAY	DYNAMIC CALCULATION	FARR (1937)
27.8	MEAN VALUE OF 4 DIFFERENT HYDRO SECTIONS (5-7 STATIONS) WITH EXTRAPOLATION TO SHORE	MAR. 1934- MAR. 1938	REBECCA SHORE-HAVANA	DYNAMIC CALCULATION	MONTGOMERY (1941)
23.0	ANNUAL AVERAGE OF 36 DAILY AVERAGES	1952	KEY WEST - HAVANA	CABLE POTENTIAL	WERTHEIM (1953)
40.5	SINGLE GEK TRANSECTS	DEC. 1952	MIAMI - BIMINI	GEK METHOD	HELA, et.al. (1954)
35.0	ANNUAL AVERAGE OF 99 DAILY AVERAGES	1953	KEY WEST - HAVANA	CABLE POTENTIAL	WERTHEIM (1954)
25.7	ANNUAL AVERAGE OF 12 GEK TRANSECTS	1953	MIAMI - BIMINI	GEK METHOD	HELA, et.al. (1954)
24.9	ANNUAL AVERAGE OF 52 DAILY AVERAGES	1954	KEY WEST - HAVANA	CABLE POTENTIAL	STOMMEL (1957)
23.2	SINGLE HYDRO SECTION OF 8 STATIONS	FEB. 1954	PAIM BEACH - SETTLEMENT POINT	DYNAMIC CALCULATION	WAGNER (1955a)
25.4	ANNUAL AVERAGE OF 38 DAILY AVERAGES	1955	KEY WEST - HAVANA	CABLE POTENTIAL	STOMMEL (1957)
19.8	ANNUAL AVERAGE OF 9 HYDRO SECTIONS	1955	VARIOUS SECTIONS	DYNAMIC CALCULATION	CHEW, et.al. (1957) WAGNER (1955a) WAGNER (1957a) WAGNER (1957b)
24.8	ANNUAL AVERAGE OF 82 DAILY AVERAGES	1956	KEY WEST - HAVANA	CABLE POTENTIAL	STOMMEL (1957) STOMMEL (1959)
25.1	ANNUAL AVERAGE OF 6 HYDRO SECTIONS	1956	VARIOUS SECTIONS	DYNAMIC CALCULATION	CHEW, et.al. (1957)
25.8	ANNUAL AVERAGE OF 52 DAILY AVERAGES	1957	KEY WEST - HAVANA	CABLE POTENTIAL	STOMMEL (1959)
36.0	SINGLE HYDRO SECTION	APR. 1957	KEY WEST - HAVANA	DYNAMIC CALCULATION	CHEW, et.al. (1957)
39.9	ANNUAL AVERAGE OF 49 DAILY AVERAGES	1958	KEY WEST - HAVANA	CABLE POTENTIAL	STOMMEL (1959) STOMMEL (1961)
32.3	ANNUAL AVERAGE OF 5 DAILY AVERAGES	1959	KEY WEST - HAVANA	CABLE POTENTIAL	STOMMEL (1961)
40.0	ANNUAL AVERAGE OF 48 DAILY AVERAGES	1960	KEY WEST - HAVANA	CABLE POTENTIAL	BROIDA (1962)
35.6	ANNUAL AVERAGE OF 32 DAILY AVERAGES	1961	KEY WEST - HAVANA	CABLE POTENTIAL	BROIDA (1962) BROIDA (1963)
17.9	ANNUAL AVERAGE OF 13 HYDRO SECTIONS	MAY 1962- MAY 1963	MIAMI - BIMINI	DYNAMIC CALCULATION	BROIDA (1966)
16.8	ANNUAL AVERAGE OF 12 HYDRO SECTIONS	MAY 1962- MAY 1963	PAIM BEACH - SETTLEMENT POINT	DYNAMIC CALCULATION	BROIDA (1966)
36.4	AVERAGE OF 2 TRANSECTS	AUG. 1964	MIAMI - BIMINI	FREE DROP INST.	SCHMITZ, et.al. (1966)
30.1	AVERAGE OF 2 TRANSECTS	OCT. 1964	MIAMI - BIMINI	FREE DROP INST.	SCHMITZ, et.al. (1966)
35.9	AVERAGE OF 2 TRANSECTS	APR. 1965	MIAMI - BIMINI	FREE DROP INST.	SCHMITZ, et.al. (1966)
32.4	MONTHLY AVERAGE OF 23 TRANSECTS	MAY-JUNE 1965	MIAMI - BIMINI	FREE DROP INST.	SCHMITZ, et.al. (1966)

II. A CRITIQUE OF TRANSPORT MEASUREMENT TECHNIQUES AS APPLIED TO THE STRAITS OF FLORIDA

Transport measurements of the Florida Current have been made employing one or a combination of several basic measurement techniques. Five of these are discussed briefly here, in order to provide a better appreciation for the absolute values of transport presented in part I of this Appendix.

DYNAMIC CALCULATIONS

Since this method has provided the bulk of the information on transport of the Florida Current, the inherent difficulties involved should be carefully considered. Noting the time necessary to transit the Florida Straits and carry out the hydrographic stations (sometimes as much as 16 hours) one can easily visualize a number of factors influencing the results. First, there is the question of tidal phase changes with the accompanying fluctuations of density structure and mass transport discussed by Parr (1937).

Secondly, there is the question of a more random oscillation of the density structure connected with the passage of internal waves and possibly periodic oscillation of a tide induced internal seiche. Stommel (1965) made the point that the dimensions of the channel at Miami and the existing density structure appear to favor a resonance in a cross-stream semidiurnal internal seiche.

The navigational technique must also be considered as inaccuracies in station positioning leads to erroneous computed currents. Even the time of positioning relative to the actual tripping of the sample bottles can result in a considerable error. Recent work with the Hi-Fix System in the Miami-Bimini transect indicates substantial drift of the ship during the course of executing a single station. Station spacing is also critical to the transport measurement and presents a problem which has not always been carefully considered. Early transport measurement associated with the Antilles Current and mentioned in connection with the Northwest Providence

Channel might have been influenced by this particular consideration.

Extrapolation of data from end stations to the sides of the Straits obviously must be accepted with a certain degree of doubt. Montgomery (1941) points out that few hydrographic stations taken prior to his report reached near the bottom so that considerable uncertainty was involved in extrapolating the surfaces of specific volume anomaly to the edges of the Straits.

To the author's knowledge all dynamic calculations with reference to the Florida Straits have been carried out under the assumption that there is no cross-stream horizontal pressure gradient existing at the bottom. While direct measurements by Richardson and Schmitz (1965) have revealed that only 10% of the northerly transport exists in the bottom 30% of the Straits, such an assumption may not always be valid.

The final point to be made concerning this measurement technique is that the geostrophic equilibrium which is fundamental to the technique might not strictly hold when applied to the Straits. Von Arx,

et al. (1954) pointed out that during a concurrent time period, while large transport fluctuations have been observed at the Key West-Havana section and at Onslow Bay, only small variations in the density field had been observed at an anchor station east of Miami. Here we might speculate that the equations of motion for the Florida Current must include an additional term or terms besides those included in the geostrophic equation.

G.E.K. CALCULATIONS

Briefly, this method equates the total transport to the mean current velocity times the cross sectional area of the current. The mean current in turn is determined by the set of the recording vessel minus the GEK's velocity, uncorrected for a K factor. This K factor is the ratio of the actual current to the current computed from the electrical signal measured with the GEK. This method by Malkus and Stern (1952) was discussed with specific application to the Florida Straits by Wagner and Chew (1953).

Inherent difficulties in the method as originally applied are: first, the actual ship's set across the current could not be accurately determined and secondly, the cross sectional area of the Florida Current not accurately determined. Besides these technical difficulties the reliability of these measurements is likely to remain low simply because they depend upon the evaluation of small differences between large quantities, and upon a subjective estimate of the proper limits of integration. Since a zero wind drift is rarely fulfilled in the Straits of Florida errors are induced into the integrals necessary for the transport determination. Since the time this method was first applied by the Marine Laboratory both technical difficulties have been cleared up.

ELECTROMAGNETIC CABLE MEASUREMENTS

Cable measurements employ the same basic principle as that used in the GEK. Briefly the motion of a conductor (salt water) in a magnetic field leads to an induced potential difference in the water at right

angles to its direction of motion. This technique of transport measurement assumes the bottom to be flat and non conducting and the horizontal variation of the earth's magnetic field to be negligible.

Wertheim (1954) discussed the ambiguities related to these assumptions. His calculated potential-to-transport conversion factor of 25.6 was selected by neglecting the effects of bottom conductivity and irregular bottom topography. If these assumptions are not negligible, erroneously low results are caused by the bottom conductivity and erroneously high results by irregular bottom topography.

TIDE GAGE CALCULATIONS

While absolute transport values have rarely, if ever been presented upon the evidence of tide gage reading alone, this method has often been applied in substantiating fluctuations indicated by other transport measuring techniques. As pointed out by Stommel (1954) the chief difficulties in utilizing tide gage data are twofold. First, with the information

usually available, it has been impossible to make proper allowance for that portion of the slope of the water surface produced by the direct stress of local wind over the continental shelf. Secondly, unless some definite information is available concerning the vertical distribution of velocity, the cross stream slope which is related only to surface velocity can only give an approximate value for total transport. Montgomery (1941) pointed out that, while the agreement between sea level differences and total transport appeared poor, a close correlation may be seen between transport of water having temperatures warmer than 23°C and the sea level difference. Taken in this context and with atmospheric pressure corrections applied, this technique may still prove important in supplying corroborating evidence for transport fluctuations.

FREE INSTRUMENT MEASUREMENTS

Other than directly measuring the current velocity and depth distribution from anchored stations

across the Straits, the free instrument technique exists as the only direct measurement for computing volume transport. This technique described by Richardson and Schmitz (1965) calculates volume transport per unit width of water column from measurements of run time, depth and horizontal deflections of a freely falling instrument. While accuracy and precision limitations discussed by Schmitz and Richardson (1966) are imposed by ship positioning, instrumental, observational and computational errors, the technique remains the best method of computing absolute transport values. Because of this and the inherent difficulties involved with the indirect techniques, the author feels that much greater weight should be placed upon the free instrument results for absolute values, while results from the indirect methods, particularly the continuous ones, be used to study fluctuations.

III. VARIATION OF TRANSPORT IN THE STRAITS OF FLORIDA

Three time-series are presented here to emphasize the wide ranges and rapidity of fluctuations of transport through the Straits of Florida. Figure 15 represents nearly 10 years of information collected with the electromagnetic method at the Key West and Havana cable stations. Each plotted value represents the average daily transport for the particular day indicated. Transport values used in developing this plot were taken from Stommel (1957, 1959, 1961) and Broida (1962, 1963). Figure 16 represents 13 months of information collected using dynamic calculations from the Miami to Bimini and Palm Beach to Settlement Point transects. Each plotted value represents the results of a single transect taken during the indicated month. Transport values used in developing this plot were taken from Broida (1966). Figure 17 represents 23 days of information collected using the free instrument technique at the Miami to Bimini or South Cat Cay to Sands Key transects. Each value

represents the results of a single transect taken
on the indicated day; values from Schmitz (1966).

Figure 15. Time-series plot of transport in the Florida Straits from the Key West to Havana cable data.

Figure 16. Time-series plot of transport in the Florida Straits from a 12 month series of dynamic calculations.

Figure 17. Time-series plot of transport in the Florida Straits from a one month series of direct measurements.

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