8. *U.S. Geol. Surv. Water Supply Pap. 1301* (1954), *1304* (1960), *1311* (1955), *1721* (1964), *1724* (1963), *1731* (1964), *1901* (1969), *1902* (1970), *1903* (1970), *1904* (1970), *1905* (1970), *1906* (1971), *1920* (1969); U.S. Geological Survey "Water Resources Data" reports for individual states for water years 1966–69; U.S. Geological Survey, unpublished data; Canada Department of Northern Affairs and National Resources, Water Resources Branch, *Water Resour. Pap. 130* (1961), *134* (1964); Canada Department of Mines and Technical Surveys, Water Resources Branch, *Water Resour. Pap. 144* (1966); Canada Department of Energy, Mines and Resources, Inland Waters Branch, "Surface Water Data—Atlantic Provinces," reports for water years 1965–67; Inland Waters Branch, Halifax, N.S., unpublished data.
9. In the coastal indentation between Cape Cod and Cape Hatteras, for example, we compared the total of the gauged discharges at 11 stations on the nine largest rivers with the total computed by Bue for his segments 3 to 6 for each of the 29 years from 1932 through 1960. Streamflow at the 11 stations accounted for a mean proportion of 0.551 of the total for segments 3 to 6. This proportion varied from year to year, but it was within 12 percent of the mean value (expressed as percent of the mean proportion of 0.551 rather than as percent of the total inflow to the coastal indentation) during all 29 years, and it was within 10 percent of the mean value in all years but one. To estimate the total inflow to the indentation during the years 1961–69, we totaled the discharges at the 11 selected stations for each year and divided each total by 0.551.
10. A. Wilson and K. T. Iseri, *U.S. Geol. Surv. Hydrol. Invest. Atlas 282* (1969).
11. We thank M. A. Rosenfeld, D. W. Spencer, and M. Hunt for their interest and aid in the statistical analyses, and we thank Rosenfeld, D. F. Bumpus, and J. E. Upson for their comments on the manuscript. Contribution 2600 of the Woods Hole Oceanographic Institution. Publication authorized by the director, U.S. Geological Survey.

2 April 1971; revised 1 June 1971 ■

Southward Flow under the Florida Current

Abstract. *High-resolution current profiles were obtained in the Florida Straits by means of a new technique. Large temporal variations in the current profiles were observed. At times extensive southward flow, with speeds up to 30 centimeters per second, was recorded in the lower half of the water column.*

The subject of deep-current reversals in the Florida Straits has fascinated oceanographers ever since Pillsbury carried out his classical current observations during the latter part of the last century. On the basis of his measurements in the narrowest part of the Florida Straits between Fowey Rock and Bimini, Pillsbury thought it likely "that at the bottom there is, at times, a current setting to the southward in all parts of the stream, except on the extreme eastern side" (*1*). The temporary existence of a southward bottom current was supported by occasional observations made near the bottom on the western side of the stream. Pillsbury's interpretation was further supported by Wüst (*2*) in an application of the dynamic method in which he used temperature and salinity observations that were made along the Fowey Rock-Bimini section. Forty years elapsed before qualitative evidence for the existence of a deep countercurrent was established by geological observations at the bottom of the straits. Deep-sea photographs by Hurley (*3*) exhibited well-defined current ripple marks on the sandy bottom. These ripples indicated bottom velocities of at least 10 to 30 cm/sec directed toward the south. Direct visual observations (*4*) made from the submersible *Aluminaut* confirmed the findings by Hurley. Bottom-current measurements made with an instrument attached to the submersible yielded southward velocities of approximately 5 cm/sec.

The uncertainty about the precise vertical structure of the Florida Current is due to the lack of adequate observational tools for the extremely difficult conditions in the Florida Straits. Absolute current measurements require the anchoring of a vessel or an unattended mooring, both of which are rather difficult to maintain for any length of time. Furthermore, because the strong flow in the upper layer produces very large angles between the surface and the wires used for mooring and for current meters, the commonly used Savonious rotors are not oriented perpendicular to the flow; this results in intolerable errors. Relative current measurements from a drifting array do not allow a sufficiently high resolution of current velocities in the lower layers, which are generally an order of magnitude smaller than the surface velocities.

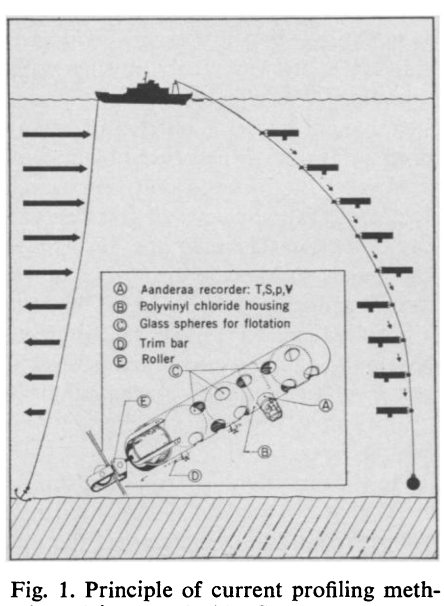

Fig. 1. Principle of current profiling method used in the Florida Current.

Considerable progress was made in the mid-1960's when Richardson and Schmitz (*5*) applied their free instrument technique, which allowed them to determine the vertically integrated net transport. A great number of carefully planned measurements have been made with this method during the last few years. Some results of these studies are described by Richardson *et al.* (*6*). On the subject of the deep southward flow the authors state, ". . . on the average the north component of velocity fills the whole channel. Thus there can be no significant counter-flow beneath the Florida Current in the Straits. . . . We have occasionally observed weak southerly flow in the same region. The origin of this flow is not clear, but our measurements indicate that there cannot be any significant southward transport associated with it."

This finding certainly does not agree with the observations quoted earlier, but it may be that the different results are not comparable. The earlier category of observations constitutes point measurements, whereas the free instrument technique integrates over a water layer with a thickness of several hundred meters. However, the apparent discrepancy points out the need for studies directed toward obtaining velocity profiles of high vertical resolution through the entire water column. A method for obtaining such profiles and initial results are described in the remainder of this report.

The principle of the profiling method is illustrated in Fig. 1. The instrumentation consists of a self-contained Aanderaa (Norway) current meter attached to a cylindrical hull whose density is slightly greater than that of the surrounding water. The Savonious rotor extends out from the bottom side of the cylindrical hull when it is in its horizontal working position. The entire package is attached by a roller to a taut wire suspended beneath an anchored ship; it is allowed to descend slowly through the entire water column.

During our experiment, a complete

profile was made to a depth of 500 meters every 2 hours in the Florida Straits, with the instrument sampling current speed and direction (**V**), pressure (p), temperature (T), conductivity (S), and battery reference as a function of time. The advantages of the method are (i) a single (inexpensive) instrument yields complete vertical profiles; (ii) owing to horizontal trimming of the hull, the Savonious rotor is always perpendicular to the flow of water; (iii) the 2-m-long profiler hull acts as a stable current vane; and (iv) the roller attachment decouples the instrument from vertical ship motions.

Since the instrument takes a "snapshot," so to speak, of the current direction at the end of each interval of current-speed averaging, it was felt that a high sampling rate was necessary to reduce aliasing in direction. Consequently, the six channels were sampled at 30-second intervals, which corresponds to a depth change of about 5 m in the upper layers and about 2 m in the lower layers. The high sampling rate introduced a "quantizing" error (digital resolution) of about 9 cm/sec, however, which was then reduced with a low-pass digital filter. The reduced error in precision is ± 2.2 cm/sec. The filtered resolution is then approximately 20 m in the upper layer and 8 m in the lower layers.

Large wire angles and large currents in the upper layer produce a horizontal motion of the profiler, which produces an error in accuracy. This error is eliminated by taking into account the wire angle and the descent rate of the instrument during each sampling interval.

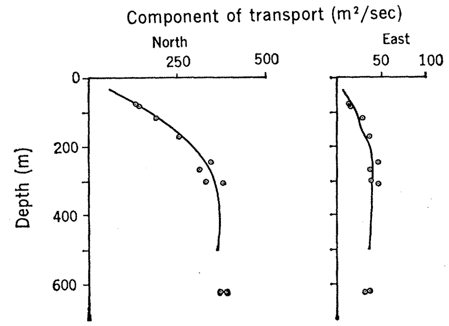

Fig. 2. Comparison between the free instrument technique by Richardson and the current profiling method based on simultaneous observations over a distance of a few hundred meters. Circles, Richardson technique; solid line, current profiler (corresponds to profile 5 in Fig. 3).

During this experiment a comparison of the profiler performance was made with direct transport measurements conducted at the same time and same location by Richardson with his free instrument technique. The results are compared in Fig. 2.

Three sets of vertical current profiles made at an anchor station near the main current axis are presented in Fig. 3. The time interval between each profile in a set is 2 hours. The first set was observed from 1400 to 1800 hours (7) on 9 November 1970; the second set from 0900 to 1300 hours on 11 November 1970; and the third set from 1900 to 2300 hours on 12 November 1970. A continuous series of profiles was not obtained owing to temporary malfunctioning of the Aanderaa recorder.

The selected three sets of north-south and east-west flow components demonstrate a remarkable evolution of the vertical profile during the 3½ days of observation. On 9 November the flow is directed toward the north and the east. Layers of high vertical shear alternate with layers of constant speed. On 11 November the profiles undergo a transition: the overall vertical shear in the north-south component increases, and the lower 100 m of the profile indicate southward flow of approximately 10 cm/sec. At the same time the cross-stream flow begins to change sign in the lower 250 m. On 12 November the northward flow in the upper 250 m is essentially unchanged as compared with the day before. In the lower layer, however, the flow is directed toward the south, and the cross-stream flow in the entire water column is now toward the west. Maximum southward velocities are 30 cm/sec, and maximum westward velocities are 70 cm/sec. Vertical integration of the north-south component (profiles 7 to 9) shows that up to 11 percent of the flow in the water column at this point in the straits is directed toward the south. It is probable that this figure would be higher had we extended our observations to the bottom (580 m).

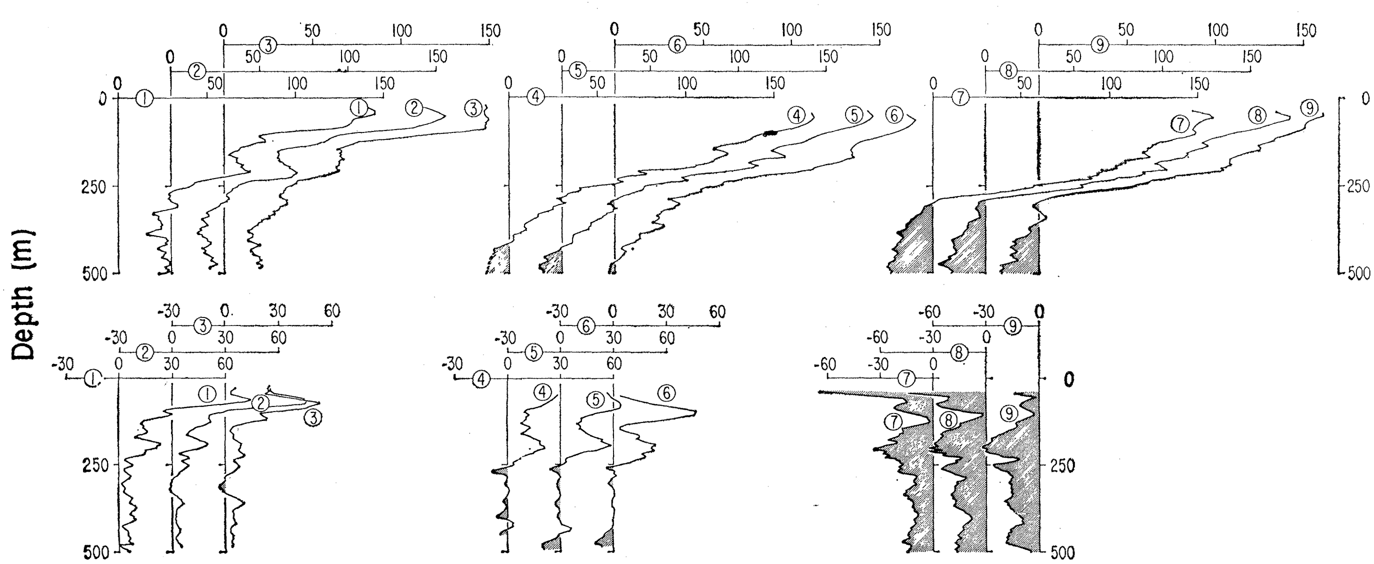

Fig. 3. Vertical current profiles observed at an anchor station in the Florida Current, 14 nautical miles (26 km) east of Fowey Rock (25°41.2′ N, 79°50.3′ W) at a water depth of 580 m. The horizontal scale is in centimeters per second. The top row of profiles shows the north-south component, with the hatched areas indicating the southward flow. The lower row of profiles shows the east-west component, with the hatched areas indicating the westward flow.

Additional current profiles were made on the eastern side of the straits 4 miles off Bimini from 27 to 29 October 1970, and on the western side 8 miles off Key Biscayne on 26 and 27 January 1971. On the western side, southward flow (up to 25 percent of the net flow) was observed at times. However, none of the profiles on the eastern side exhibited southward flow.

These results are part of an initial survey in the Florida Current. An interpretation of the sparse data available, whether of the earlier observations mentioned in the introduction or of our measurements reported here, is necessarily speculative. The data suggest, however, that there are two phenomena of importance to be considered: (i) a deep countercurrent and (ii) a horizontal meandering of the current axis of the Florida Current, which extends over the whole water column and, thus, includes the deep southward flow. Our results have contributed to the design of a large-scale investigation of the dynamics of the Florida Current to be conducted during the summer of 1971.

Note added in proof: Observations of the southward flowing undercurrent in June 1971 revealed a flow of 80 cm/sec at times in the deepest part of the Florida Straits off Miami.

WALTER DÜING
DONALD JOHNSON
Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida 33149

References and Notes

1. J. E. Pillsbury, *Report of the Superintendent of the U.S. Coast and Geodetic Survey* (1887), appendix 2.
2. G. Wüst, *Veroeff. Inst. Meereskd. Univ. Berlin, Ser. A* **12**, 1 (1924).
3. R. J. Hurley and L. K. Fink, *Science* **139**, 603 (1963).
4. A. C. Neumann and M. M. Ball, *Geol. Soc. Am. Bull.* **81**, 2861 (1970).
5. W. S. Richardson and W. J. Schmitz, Jr., *J. Mar. Res.* **23**, 2 (1965).
6. W. S. Richardson, W. J. Schmitz, Jr., P. P. Niiler, *Deep-Sea Res.* **16** (Suppl.), 225 (1969).
7. These times mark the start of the profiler downward. Normal descent time to 500 m was 70 minutes.
8. We thank Dr. W. S. Richardson for his cooperation during the fieldwork on the Florida Current and for putting his data at our disposal. This research was supported by the Office of Naval Research through contract N0014-67-A-0201-0013, under project NR 083-060/7-16-70 (481).

25 March 1971

Petroleum: Tar Quantities Floating in the Northwestern Atlantic Taken with a New Quantitative Neuston Net

Abstract. *The neuston net has been modified to obtain quantitative samples of surface zooplankton. Petroleum lumps are commonly taken with these nets, and quantities of tar up to almost 0.1 gram (wet weight) per cubic meter of filtered surface water have been taken in the northwestern Atlantic. This information is used to estimate the quantity of tar lumps present in the North Atlantic and to indicate the probable limits of the degree of existing oil pollution in this region. It is suggested that previous estimates of ocean oil pollution may be too low.*

The neuston net sled is intended for zooplankton sampling at the immediate ocean surface. The original design (*1*) is not quantitative, and later versions as used by some workers, for example Horn *et al.* (*2*), have been only semiquantitative at best. Modifications, described below, have been incorporated that make the unit more quantitative.

Improved neuston sleds have been used on three cruises to investigate the surface zooplankton of the northwestern Atlantic Ocean. Petroleum tar lumps were a component of each of the 20 tows made (see Fig. 1). The quantities observed, combined with the amounts reported by Horn *et al.* (*2*) for the Mediterranean Sea and adjacent eastern Atlantic Ocean, are used to examine the possible scale of oceanic oil pollution.

The sled itself is essentially the same as the one David (*1*) described. It consists of a pair of wooden skis, each with a keel along its inner border. The skis are joined by three cross members, one forward and two aft. The eye bolts for the towing bridle are mounted on the forward cross member, one above each ski. The two aft cross members hold the net frame.

The quantitative modification is wholly within the net arrangement (Fig. 2) attached to the net frame. It consists of a Dacron sleeve, a brass drum to hold the flowmeter, and the net itself. The brass drum is mounted at the rear of the sled in such a position that it is constantly submerged. The drum is stayed by four guy wires, two to each keel. A flowmeter is mounted within the brass drum. A Dacron sleeve runs backward and slightly downward from the mouth of the net frame to the brass drum. Water entering the net frame is funneled through the sleeve, through the drum, past the flowmeter, and into the plankton net. The sleeve is vented with grommets on its upper surface to allow air entering the mouth of the net frame to escape and not pass the flowmeter. The plankton net itself is attached to the rear perimeter of the drum.

Although both air and water enter the mouth of the net frame, only the water flows past the flowmeter and into the net. Although the rate of flow varies with the level of water entering the mouth of the frame, the total amount of water filtered by the plankton net is accurately given by the flowmeter reading. This design has worked well at towing speeds of about 2 knots (3.7 km/hr) in sea states to force 5.

Tar lumps were collected in neuston sampling with these nets during cruises of the C.S.S. *Hudson* (16 to 26 September 1969), the C.S.S. *Dawson* (17 June to 3 July 1970), both of the Bedford Institute, Dartmouth, Nova Scotia, and of the R.V. *Panulirus II* (28 July 1970) of the Bermuda Biological Station.

Figure 1 gives the wet weights of tar (in milligrams per cubic meter of filtered surface water) at 20 stations in the northwestern Atlantic. Every tow netted some quantity of these lumps, and the quantities ranged from 0.7 to 96.9 mg/m³. The wet weights of zoo-

Table 1. Calculated amounts of pelagic tar in the North Atlantic from 10°N to 55°N and in the Mediterranean Sea and adjacent eastern Atlantic.

Ocean	Area ($\times 10^6$ km²)	Area as percentage of world oceans	Tar concentration (mg/m²)	Total tar present (Q_x) ($\times 10^3$ tons)
North Atlantic	27	7	1.0	27
Mediterranean Sea*	2.5	1	20.0	50
Northern Atlantic and Mediterranean Sea	29.5	8		77

* Values adapted from Horn *et al.* (*2*).