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.

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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/m^3. 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 ($\times 10^6$ km^2)	Area as percentage of world oceans	Tar concentration (mg/m^2)	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*).

plankton in the same tows varied from 22 to 176 mg per cubic meter of filtered surface water, with an average value of 74.5. Tar lumps thus composed, on the average, slightly over 20 percent of the wet weight of the neuston samples. Considering that zooplankton are about 2 to 5 percent carbon, the quantity of carbon in the tar surpassed the quantity of living animal material in the neuston net. There was, however, no apparent correlation between the wet weight of tar and the quantity of zooplankton.

Horn *et al.* (*2*) recently estimated the quantities of tar lumps they encountered in the Mediterranean Sea and adjacent eastern Atlantic Ocean. Although they expressed their quantities differently, as the displacement volume (in milliliters) of tar lumps per surface area of ocean skimmed (in square meters), the data can be usefully compared if two conversions are made. Tar lumps of 1000 mg (wet weight) were determined to have a displacement volume of only slightly over 1.0 ml. By a somewhat less accurate conversion, the volume of water filtered (in cubic meters) can be expressed as surface area skimmed (in square meters). The mouth of the net frame skimmed to a depth of about 10 cm; thus the surface area skimmed would be about ten times the volume of water filtered. Expressed in these terms, Horn *et al.* found tar quantities between 1.0 and 540.0 mg (wet weight) per square meter of water surface; present northwestern Atlantic values range from about 0.1 to 9.7 mg/m^2.

In my attempt to estimate the total quantity of tar lumps present over the North Atlantic and in the Mediterranean Sea, it was immediately obvious that these tar lump quantities were overdispersed; that is, their wet weights per square meter of water surface did not follow a normal distribution but were skewed toward the lower values. However, the raw data were normalized by means of a logarithmic transformation (*3*). The graph at the lower right of Fig. 1 presents this transformed data for both regions. The upper scale is the actual quantity of tar on a logarithmic scale, and the lower scale is the logarithmic value of the quantity encountered at each station. The data are presented along the horizontal center line. The mean of each region is signified by the central vertical crossbar, the range of values by the extreme

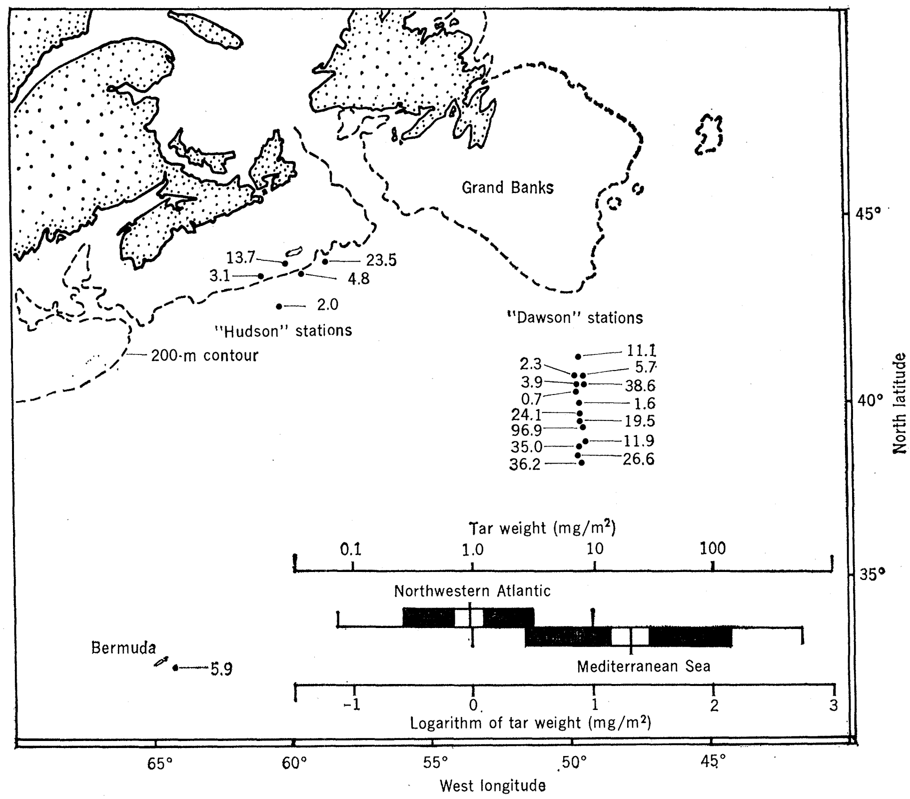

Fig 1 (top). Distribution of tar lump quantities (milligrams per cubic meter) at 20 stations in the northwest Atlantic. The graph at the lower right gives the quantitative distribution of tar in units of milligrams per square meter for the northwestern Atlantic as found in the present study (upper bar) and for the Mediterranean Sea and adjacent eastern Atlantic as reported by Horn *et al.* (*2*) (lower bar). The quantities have a log-normal distribution.

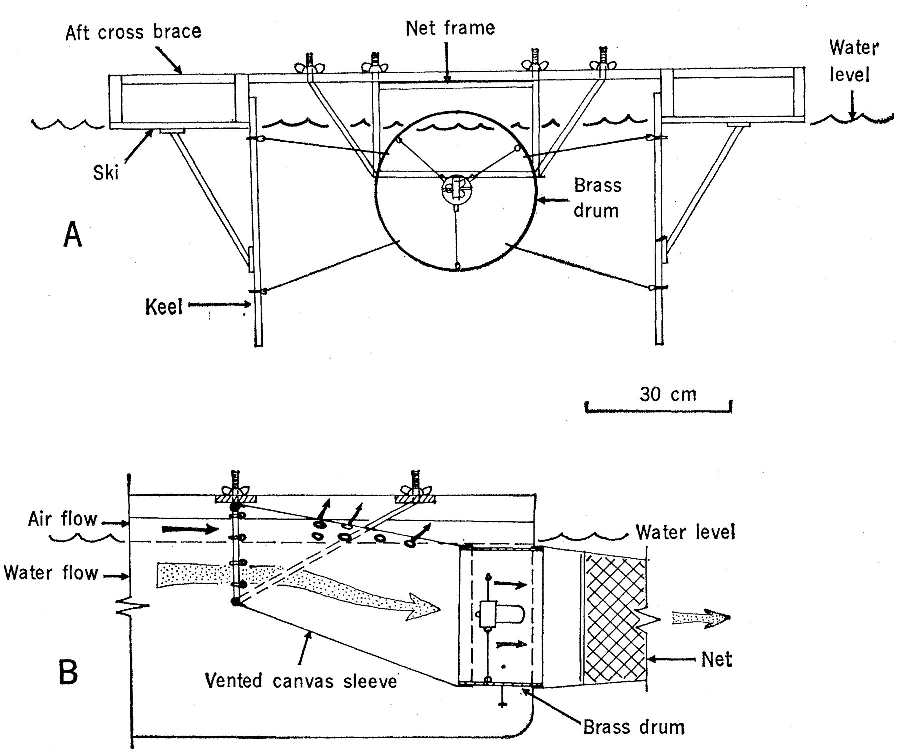

Fig. 2 (bottom). Diagrams of the modification made in the neuston net for the purpose of obtaining quantitative samples. (A) Rear view; (B) side view cross section (aft).

Table 2. Estimated amounts of total annual oil pollution on the North Atlantic and Mediterranean Sea based on the calculations of Q_x in Table 1. It is assumed that the rate of supply (R) is at equilibrium with the rate of decay. The values chosen for the half-lives of the tar and for the residual fraction of an oil discharge forming tar define the probable limits of the annual oil discharge in these areas.

Tar half-life ($t_{1/2}$) (yr)	Rate of supply of tar (R)* ($\times 10^3$ ton/yr)	Total oil discharge per year ($\times 10^5$ ton) if tar = x percent of the residue†		
		$x = 1$	$x = 10$	$x = 50$
		North Atlantic (10°N to 55°N)		
1.0	19	**19**	1.9	0.4
0.5	38	**38**	3.8	0.8
0.25	76	**76**	7.6	1.5
		Mediterranean Sea		
1.0	35	**35**	3.5	0.7
0.5	70	**70**	7.0	1.4
0.25	140	**140**	**14**	2.8
		Northern Atlantic and Mediterranean Sea		
1.0	53	**53**	5.3	1.1
0.5	106	**106**	**11**	2.2
0.25	212	**212**	**21**	4.4

* Calculated from a simple exponential decay formula at equilibrium with the rate of supply given as follows: if $dQ/dt = 0 = -\lambda Q + R$, where $\lambda = 0.693/t_{1/2}$, then $R = Q_x \times 0.693/t_{1/2}$. † Boldface values are those which exceed previous estimates for all oceans (see text).

vertical crossbars. In the bar portions of the graph, the unshaded central portion shows one standard error on each side of the mean, and the shaded portion shows one standard deviation. The mean quantity for the North Atlantic is 0.93 mg/m^2; for the Mediterranean Sea the mean quantity is 19.6 mg/m^2.

In Tables 1 and 2 the above mean quantities are used to estimate the total quantity of tar over each area and the possible rates of discharge of crude oil into these areas per year if the quantities of tar represent a specified residual fraction of the total discharge. The real situation has been simplified for the calculations. A simple exponential decay model at equilibrium is used to predict the rate of supply of tar per year.

This rate is based on the quantity of tar globules present and the decay rate of the tar. If the system is not at equilibrium and tar concentrations are increasing, then the rate of supply of tar and the total discharge of crude oil will be underestimated. Significant unknowns are the rate of decay of the lumps, the fractional amount of a discharge of crude oil that forms tar lumps, and the water content of the lumps. There is virtually no information available on these important factors. None, of course, will have a fixed value but will depend on the grade of crude oil and on environmental conditions (*4*). Combinations of possible values were chosen for the calculations (*5*).

The estimates in Tables 1 and 2 can be compared with previous estimates in the literature. Present world oil production is near 2×10^9 metric tons (*6*), of which about 0.7×10^9 to 1×10^9 tons is transported by ship (*6–8*). The amount of oil dumped into the oceans during transport has been estimated to be from 4.4×10^5 tons (*8*) to 1×10^6 tons (*7*), or from 1×10^6 tons (*6*) to 1×10^7 tons (*7*) from all sources. These estimates are for all oceans, whereas the estimates in Table 1 are for an area covering only 8 percent of the world's ocean surface.

The scientific observation to be derived from Tables 1 and 2, that is, the estimate of total oil spillage to the sea from measurement of tar lumps, is critically dependent upon the values for the percentage of oil x that becomes tar and upon the half-life $t_{1/2}$ of the lumps. These factors are vitally in need of quantitative investigation if a meaningful assessment of the amount of oil in the marine environment is to be made. However, if the values are taken as $x = 1$ to 10 percent and $t_{1/2} = 0.25$ year, respectively, then the estimated quantity of spillage per year for the North Atlantic or the Mediterranean exceeds the published figures for the world oceans. On the other hand, if the values of x and $t_{1/2}$ are taken as lying between 10 to 50 percent and 0.5 to 1.0 year, respectively, then a quantity of spillage in the range of 0.4×10^5 tons to 3.8×10^5 tons per year is indicated for the North Atlantic, which would not seem to be at odds with previous world estimates, considering what one might expect to be the share of global oil pollution contained in the North Atlantic. The half-lives suggested in Table 2 would also include loss from beaching, which Zachariasen (*6*) estimated for the Florida coastline would occur at a rate of 1 ton per mile per year.

The quantities of tar lumps in the Sargasso Sea can also be estimated and compared with the estimated quantities of *Sargassum* weed present. Parr (*9*) estimated that the Sargasso Sea contains 7×10^6 tons (wet weight) of *Sargassum* weed within its area of 7×10^6 km^2 (2×10^6 square nautical miles). At a wet weight of 1 mg per square meter of ocean surface, there would be 7×10^3 tons of pelagic tar in the Sargasso Sea, or a disturbing amount of 0.1 percent (by weight) of tar to *Sargassum* weed.

Monitoring of petroleum lumps is continuing in the Sargasso Sea off Bermuda. Bermuda is a strategically located ocean platform for monitoring levels of mid-ocean pollution of all types. The island is well removed from the sources of most pollutants and contributes little pollution of its own. Nevertheless, in recent months there have been a number of instances of oil pollution on Bermuda beaches. Although some larger oil slicks have been attributed to port and nearshore activities, most of the oil comes from chronic beaching of these tar lumps of pelagic origin. Continued monitoring will give further information on this background amount of pelagic oil pollution in the North Atlantic, and it is important to determine if these concentrations are increasing.

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References and Notes

1. P. M. David, *J. Mar. Biol. Assoc. U.K.* **45**, 313 (1965).
2. M. H. Horn, J. M. Teal, R. H. Backus, *Science* **168**, 245 (1970).
3. R. M. Cassie, *Zooplankton Sampling, U.N. Educ. Sci. Cult. Organ. Monogr. Oceanogr. Methodol.* (1968), pp. 105–122.
4. N. Pilpel, *Endeavour* **27**, 11 (1968).
5. The contribution of water to the tar weights was not included in the estimates in Table 1. The estimates may have to be adjusted when this information becomes available.
6. F. Zachariasen, *Inst. Def. Anal. (JASON) Res. Pap. P-432* (1968), pp. 1–27.
7. M. Blumer, *Oceanus* **15**, 2 (1969).
8. J. H. Kirby, *Int. Conf. Oil Pollut. Sea Prepr. Pap. No. 12* (Rome, 7–9 Oct. 1968), pp. 1–12.
9. A. E. Parr, *Bull. Bingham Oceanogr. Collect. Yale Univ.* **6**, 1 (1939).
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