Columbia University in the City of New York

LAMONT GEOLOGICAL OBSERVATORY

PALISADES, NEW YORK

A NOTE ON SOME OBSERVATIONS OF DYE IN COASTAL WATERS

Report prepared by: R. Gerard
and
B. Katz

Technical Report No. CU-3-63 to the Atomic Energy Commission
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In his recent text (1962) von Arx has written, (p. 114) "The Ekman spiral has been observed in the atmosphere and has been produced in the laboratory in rotating tanks and ocean models, but its occurrence in the wind-influenced layer of the ocean has not been demonstrated beyond the tendency for sea ice and some currents to move at some angle to the right of the wind." In a number of observations using dye tracers we have noticed certain features which seem to be explained best by the "Ekman Effect", though the circulation pattern in the area of these experiments is so intricate that it is doubtful whether an Ekman spiral in the ideal sense could be expected.

Since the summer of 1961 we have performed a number of experiments usin Rhodamine dye on the sea surface as a tracer to aid in the study of turbulent diffusion and local circulation. The methods used are those described by Pritchard and Carpenter (1960). We often supplement our measurements with aerial photographs, mainly to assist in determining the actual shape of the dye patch, which is often fairly complex.

Most of our observations have been made in the area of the New York Bight. Here the circulation in summer and fall is dominated by weak counter-clockwise eddies close to the New Jersey shore, which carry southward the low salinity effluent of the Hudson-Raritan estuaries. Outside this coastal band, about ten miles off shore in more saline water, there is a northward moving current. Superimposed on this pattern are weak tidal currents whose main vectors lie on a northwest - southeast axis, the excursion of the ebb to the southeast being of greatest magnitude. This circulation pattern is rapidly broken up in the presence of storms. The wave and swell pattern may be very complex due to reflection and refraction at the shores, and refraction over the Hudson submarine Canyon.

Our discussion concerns certain characteristics of surface dye patches in

this area, particularly during the early stages of their spreading. Figures 1, 3 and 5 are aerial photographs of dye patches on different dates; all exhibit features which appear to be common during the first few hours of surface dye introductions in the presence of steady, moderate winds and in the absence of strong currents and high seas. These characteristics can be listed as follows:

1. The patch will initially take on a striated pattern which is aligned with the swell waves.
2. The trailing (more tenuous) portion of the patch that most strongly exhibits the striated pattern lies at a level below the surface, while the concentrated leading portion lies at the surface. This can be clearly seen in Figure 1, where the research vessel (whose draft is nine feet) has stirred dye up to the surface when passing through the tail (center of photograph). On the upper right in this photograph, the ship's wake reveals that it has crossed the head of the dye and stirred clear water up to the surface.
3. Where moderate winds prevail, the dye patch takes a comet-like form with a curved tail. In all but one case the curvature was counter-clockwise, i.e. as though the leading portion (the high concentration head) was turning to the left.

The curvature has been observed in seven out of ten experiments, six of which were conducted in the New York Bight, two south of Jamaica in the Caribbean, and two on the Bahama Banks. Of the three experiments which did not produce a curved pattern, two were in the very shallow water on the Bahama Bank the other, south of Jamaica, consisted of a long line of dye introduced fifteen feet below the surface and running perpendicular to the direction of the wind, which

was mild (about 5-10 knots), until the very last stages when the dye had already become highly attenuated.

Since we have observed that in surface and near-surface experiments the dye responds quite readily to changes in the wind, we attempted at first to explain the curvature on this basis. However, in four cases where no significant change in wind direction was observed, the dye patch assumed a counter-clockwise curvature. Thus changes in wind direction are not of themselves adequate explanation for the observed curvature.

If local and/or transient gyrals are the cause of the curvature, we should reasonably expect that they would have random directions of rotation, and hence that we should see clockwise and counter-clockwise curvatures with about equal frequency. In fact, we have observed clockwise curvature only once in a dye introduction at fifteen feet depth and there is evidence for attributing this case to the effects of changing wind direction. (The wind had shifted from SSE to NW). The persistence of this counter-clockwise curvature in the presence of moderate winds which remain steady in direction makes it unlikely that it can be attributed to purely local or transient phenomena.

The shear between horizontal water layers evidenced in photographs, such as Figure 1, suggests that the pattern we see could be the result of rotary tidal currents or of wind-driven drift currents. In fairly shallow waters cum sole rotary tidal currents could produce patterns similar to the ones we have observed, but in inshore waters reflection from the coastline and the effects of bottom irregularities can combine with tidal forces to give alternating or contra solem rotary tidal currents. Added to this the effluent of large rivers can produce very distorted tidal current ellipses. Such is the case in the New York Bight, the extreme complexity of which is indicated in the tidal current diagram Fig. 2. It seems unlikely

FIGURE 1

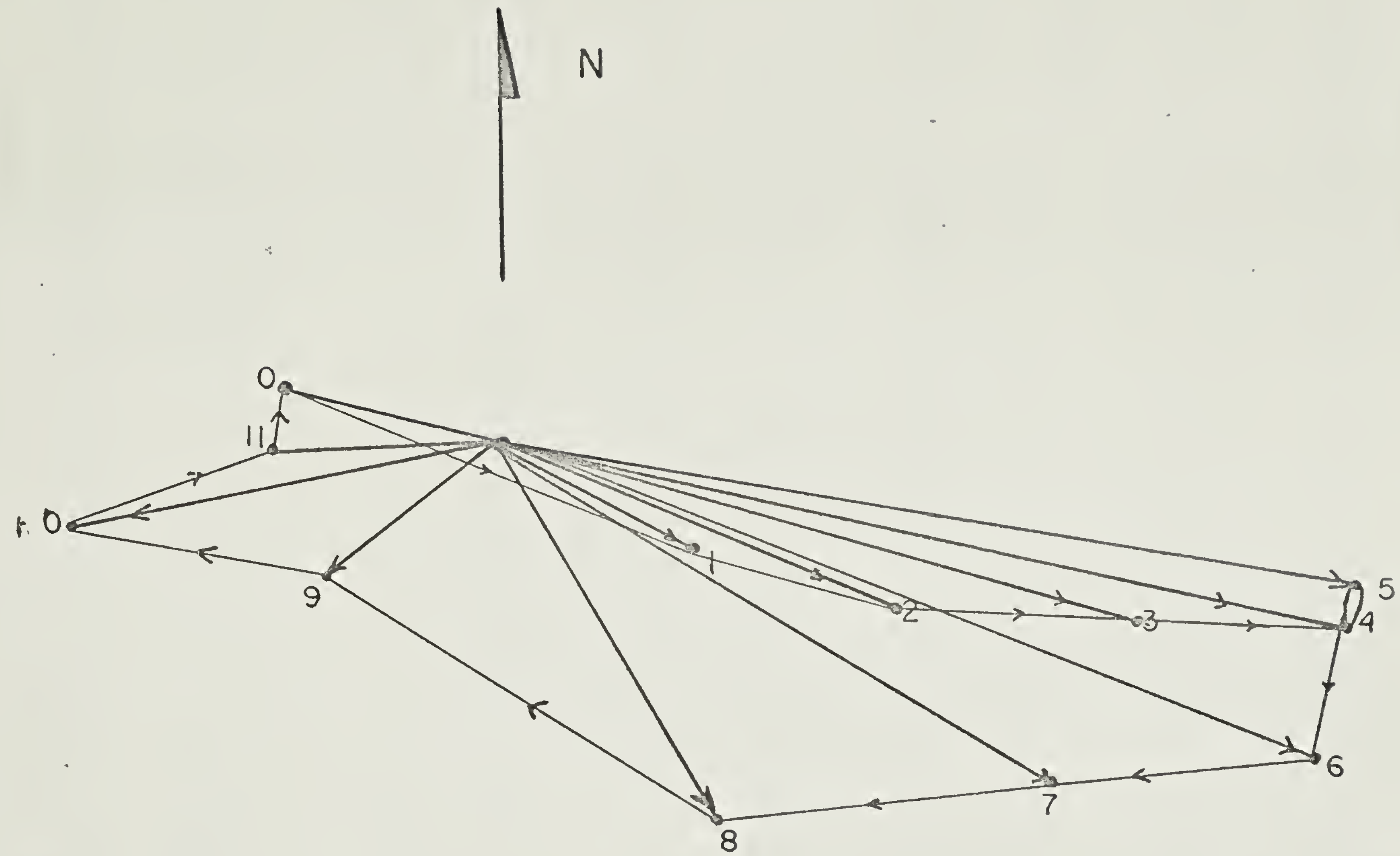

FIG 2

TIDAL CURRENTS IN

THE NEW YORK BIGHT

AMBROSE LIGHTSHIP

that such a current pattern could account for the observed shapes of our dye patches. Furthermore, if the dye pattern is due mainly to tidal currents, in an experiment conducted over two or more tidal cycles, a periodic change of shape is expectable. No such periodicity has been observed. There remains to be considered pure wind effects. The ready response of the dye to wind changes, the general resemblance of the patterns to the upper portions of an Ekman spiral, and the fact that fewer difficulties arise from attributing the curvature to the combination of wind stress and Coriolis force than any of the other possibilities considered make us favor this explanation.

Projected on a horizontal plane, a wind-driven current will show a decrease in velocity and change of direction at regular intervals of depth down to a depth D, the upper frictional depth. The classical relationship is: $D = 7.61\ w\ \sin\phi$ meters, where w = wind velocity and ϕ = latitude, but most investigators take it to be about 100 meters in mid-latitudes and for moderate winds (Ekman, 1928; Proudman, 1953). Figures 3 and 5 are photographs of experiments conducted in different areas within the New York Bight. The photographs were taken about one and one-half and two hours respectively after the dye was introduced.

At the time of these experiments the seasonal thermocline had disappeared, and temperatures were nearly uniform to the bottom. The depth in the areas of these experiments was considerably less than 100 meters, and the effects of the bottom friction have been taken into consideration in the manner of Defant (1961) in determining the configuration of the expected distribution. To obtain the expected configuration, we have assumed an established drift current having velocity at the surface given by Proudman (1952:

$$U_s = \frac{T_p k\ \gamma_a}{\sqrt{2D\gamma}}\quad U_a^2$$

where:

$$T_p = \frac{\pi}{w \sin 0}$$, the half pendulum day

$k = 2.5 \times 10^{-3}$

ρ_a = density of air, taken as 1.25×10^{-4} gm/cm^3

ρ = density of sea water, taken as 1.03 gm/cm^3

D = thickness of the upper frictional layer, taken as 100 meters

U_a = the wind speed.

Using this formula, we have plotted the position of a "disk" of dye on the surface two hours after dye injection. From a graphical description by Defant giving the vertical structure in drift current for water depths less than D, we have been able to plot the relative positions of several other "disks" at discrete levels down to forty feet, the limit of visibility. The size of these "disks" was estimated on the basis of a "most probable diffusion velocity" of 1 cm/sec, which is approximately the value yielded by our experiments. Distortion due to the fact that the dye does not instantly reach a depth of forty feet is believed to be minimal, since vertical diffusion was quite rapid due to the homogeneity of the water. In plotting the observed configuration, the drift due to tidal motions has been estimated from tide tables and tidal current charts, and this has been subtracted from the actual displacement of the dye from the position at which it was dumped. Shear between horizontal layers due to tidal movements, the river effluent, and the intricate pattern of the coastline could also be expected to contribute their effects. However, since we have insufficient data, these influences have not been taken into account.

The experiment on October 17 (Figures 3 and 4) was made about eight miles east of Sandy Hook in water of 27 meters depth. The wind was fairly steady for several hours at about 16 knots from the west. The observed displacement of the dye patch was to the left, rather than to the right of the wind. Since only tidal

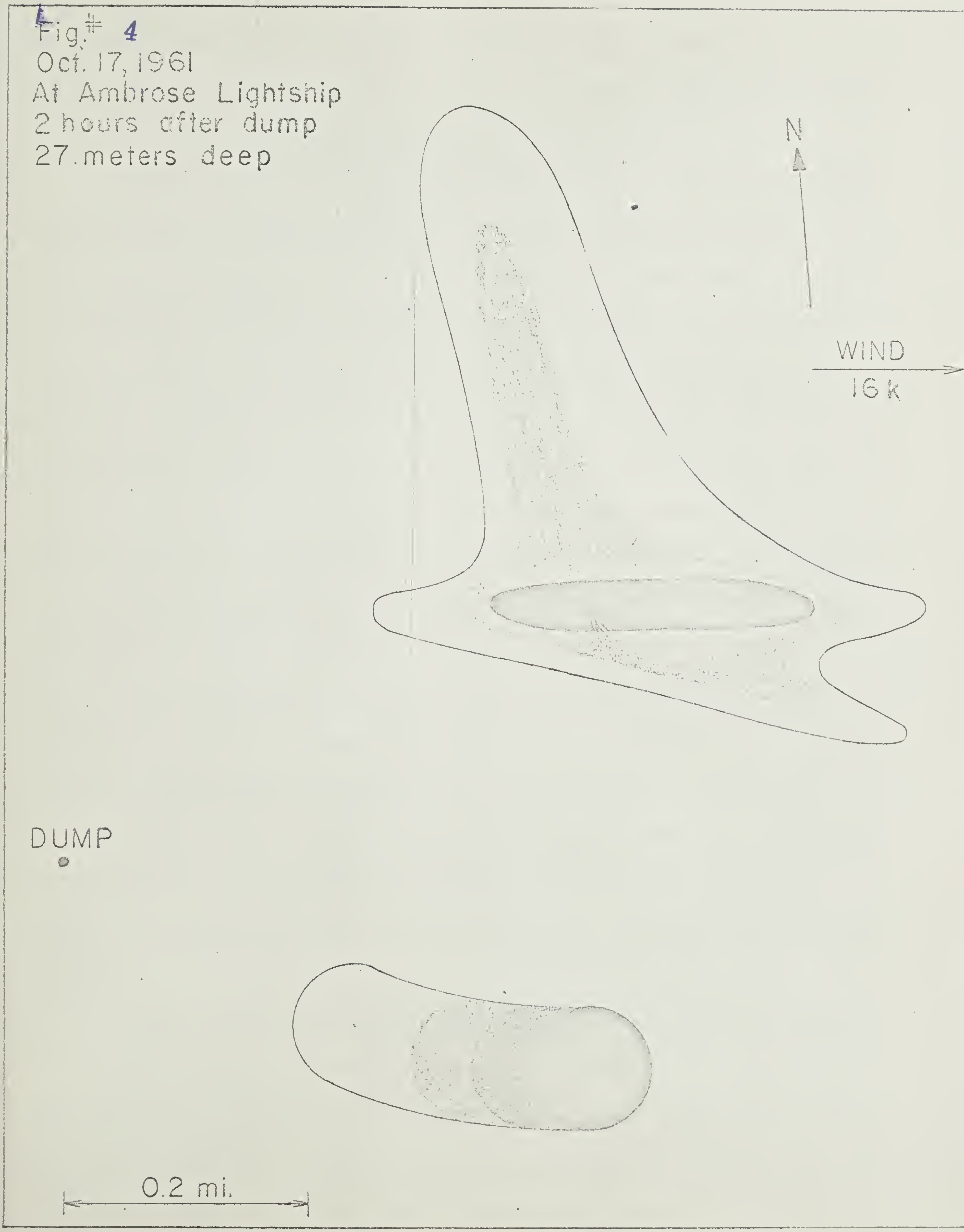
Fig.# 4
Oct. 17, 1961
At Ambrose Lightship
2 hours after dump
27 meters deep
N
WIND
16 K
DUMP
0.2 mi.

drift was taken into account in the figure, these seemingly contradictory results could readily be accounted for by a net north current of 0.2 knots. The counter-clockwise curvature is still present, but greatly distorted by other forces.

On October 31 at a location about nineteen miles southeast of Sandy Hook, two experiments were performed in water of 61 meters depth. In the first, a barrel of dye was introduced at 0300 hours, when the wind was 7 knots from the west-southwest. At 0900 hours the wind remained unchanged, and at 0800 hours the dye had roughly assumed the shape of a broad ellipse with many finger-like projections perpendicular to the long axis on both sides. This shape was maintained until about 10:30, at which time the second experiment was begun. The second dye patch immediately began to assume a comet-like shape with tenuous tails and counter-clockwise curvature. A wind reading taken at this time showed that the velocity had increased to 12 knots, still from the west. Figures 5 and 6 show the pattern of the second experiment about two hours after the introduction. At this time the plane returned to the site of the first dye patch to find that it, too, was beginning to assume a shape with an unmistakable counter-clockwise curvature. A number of photographs were taken showing this, but the dye had become so attenuated that good reproductions of the photographs cannot be made. The photographs show that, in both cases, the orientation of the curved dye patch with respect to the wind was the same and about what would be expected for a pure drift current.

In later stages of dye patches we have observed that, when the direction of the wind is steady, the curvature usually tends to disappear. We believe that this is due to the fact that as the dye becomes more attenuated, the depth to which it can be seen decreases. Thus, although the overall dimensions of the pattern increase with time, we observe an increasingly smaller portion of an increasingly

FIGURE

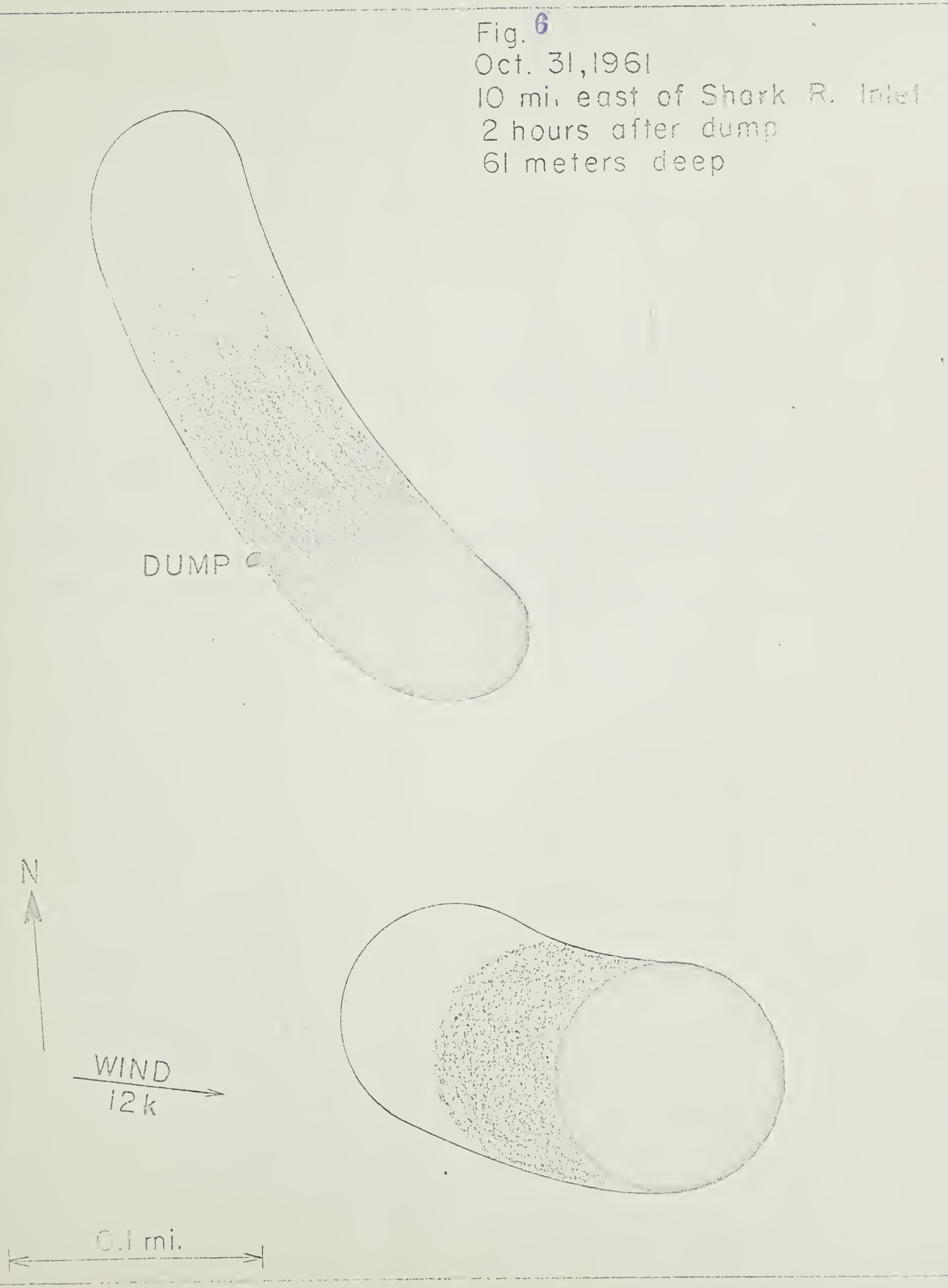
Fig. 6
Oct. 31, 1961
10 mi. east of Shark R. Inlet
2 hours after dump
61 meters deep
DUMP
N
WIND
12 k
0.1 mi.

larger spiral.

Probably the best evidence in support of the notion that the observed curvature is the result of the Ekman effect is its persistence in a wide variety of circumstances. It would, therefore, be interesting to see the results of a similar experiment conducted in the southern hemisphere, where the curvature should be clockwise.

It is also of interest to consider a dye experiment designed to test the wind current. For quantitative work, an area of simple circulation and greater depth would have to be chosen. A useful method might be the simultaneous ejection of filaments or pulses of dyd at regular depth intervals in a clear deep-water area. The resulting pattern could be photographed from the air under various wind conditions. Several such experiments are underway at the present time.

TABLE I

Experiment Date, Location Time of Dump	Tidal Cycle (time of) High	 Low	Wind Measurements Time	 Direction (from)	 Speed (knots)	Remarks	Results
October 16, 1961		05:47	09:15	150°	6	Dye injected at 15 feet	Patch maintained a crab-like shape with several large projections until 16:30 hrs.
New York Bight	12:21					Sea choppy from start of experiment	
12:55		19:00	19:30	320°	23		By 17:15 hrs. a sharp CW* curvature had appeared.
						Wind increased continuously	
						No photos between 16:30 and 17:15	
October 17, 1961	00:52		04:15	285°	22	Dye dunped on surface	Tail with CCW** curvature began after about half an hour and remained quite pronouned until 13:00 hrs.
New York Bight		07:11	06:15	250°	23		
(Ambrose Lightship)	13:25		07:30	260°	20	No photos between 13:00 and 15:00	
10:35		20:11	10:50	260°	20		By 15:30 hrs. the curvature had disappeared, and there was no longer any tail in the true sense. The dye patch was an irregular oblong with two centers of high concentration
			13:20	290°	15		
			16:45	270°	3		
			18:45	270°	9		

* CW - Clockwise
** CCW - Counter-clockwise

TABLE I (Cont'd) 2

Experiment: Date, Location, Time of Dump	Tidal Cycle (time of): High	Tidal Cycle (time of): Low	Wind Measurements: Time	Wind Measurements: Direction (from)	Wind Measurements: Speed (knots)	Remarks	Results
October 19, 1961	02:37		10:50	180°	10	Dye poured on surface	Extreme CCW curvature began immediately and persisted throughout the period of observation.
New York Bight		08:53	13:33	160°	8		
(12 mi. east of Asbury Park, New Jersey)	15:10		15:55	140°	5		
		21:26	17:37	140°	6		
11:57			20:05	70°	2		
October 30, 1961			09:45	250°	13	Dye injected at 15 ft.	Elliptical pattern with finger-like projections perpendicular to the long axis. (Very similar to early stage of Oct. 16)
New York Bight		05:17	16:00	285°	13		
(12 mi. east of Asbury Park, New Jersey)	11:43		17:00	210°	12	No photos between 12:57 and 14:15	
10:10		18:18	20:00	270°	3		By 14:15 hrs. tail CCW curvature had developed.
October 31, 1961			03:55	240°	8	Dye poured on surface	Elliptical pattern with finger-like projections perpendicular to the long axis until 11:21, at which time a broad tail with CCW curvature began to develop
	00:24		09:20	270°	8		
New York Bight (12 mi. east of Asbury Park,			10:45	270°	12	No photos until 07:53	
New Jersey)		06:20	11:30	280°	11		
03:05	12:33		12:30	290°	16		

TABLE I (Cont'd.) 3

Experiment: Date, Location, Time of Dump	Tidal Cycle (time of) High	Tidal Cycle (time of) Low	Wind Measurements: Time	Wind Measurements: Direction (from)	Wind Measurements: Speed (knots)	Remarks	Results
October 31, 1961			13:50	290°	16	Dye poured on surface in four discrete patches about 100 yds. apart.	Comet-like tails with CCW curvature began to form after about half an hour.
B	00:24		15:45	270°	14		
New York Bight (12 mi. east of Asbury Park, New Jersey)		06:20	16:20	270°	14		
	12:33		18:23	240°	14		
10:21		19:18	20:22	250°	17		
			23:17	270°	23		
June 10-11, 1962			6/10			Line of dye injected at depth of 15 ft. running in N-S direction.	Diffusion appeared to be isotropic until the morning of the second day, when wind effects became noticeable. Long streaks appeared parallel to the direction of the wind. No curvature noticed.
Caribbean			14:02	100°	12		
76 32'W 17 40'N			18:15	360°	5	Wind data taken at Palisados Airport	
South of Jamaica			6/11 06:15	130°			
15:40			12:23	135°	15		
			14:06	135°	25		
			15:00	105°	18		

TABLE I. (cont'd) 4

Experiment Date, Location Time of Dump	Tidal Cycle (time of) High	 Low	Wind Measurement Time	 Direction (from)	 Speed (knots)	Remarks	Results
June 23-25, 1962			6/21			Dye injected at depth of 25 ft.	Slight CCW curvature evident during first two hours. By 14:44 the shape had become very complex. The dye had, by this time, drifted from the deep water (500 fathoms) of the dump area to the 100-fathom line of the wide bank south of Jamaica.
Caribbean (27 mi. SSE of Port Kaiser, Jamaica)			08:30	90°	30	No photos between 12:56 and 14:44	
			12:40	90°	15		
11:10			6/23				
			16:41	110°	15		
			6/24				
			14:37	120°	20		

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