The angle of windrows in the ocean[1]

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ABSTRACT

Direct observations of the angle of windrows in the ocean with respect to the direction of the wind within a few feet of the surface show that there is a systematic deflection of the row orientation to the right of the wind direction. The average angle of the data is 13 degrees with a standard error of estimate of 2.0 degrees. Observations were obtained from small boats or by measurements from aerial photographs of the angle between the wind and windrows as indicated by smoke flares and material in the water.

This systematic angle and earlier measurements of row spacing as a function of wind speed are interpreted as evidence that the Langmuir circulations in the ocean are produced by shear-flow instability in the Ekman boundary layer.

Introduction

In laboratory experimental work it has been demonstrated that the initial instability of laminar Ekman boundary-layer flow takes place with the formation of horizontal roll vortices (FALLER, 1963). These occur at a significant angle with respect to the direction of the stress on the fluid at the boundary, and the horizontal spacing of these vortices is proportional to the depth of the boundary layer. These laboratory results have suggested an analogy between the experimental roll vortices and the Langmuir circulation cells which produce windrows in the ocean and in lakes (LANGMUIR, 1938). Accordingly, it has been postulated by the author that windrows in the ocean are primarily a result of shear-flow instability in the layer of surface wind drift.[2]

Two significant consequences of the proposed analogy are that: (1) the spacing of windrows should be dependent upon wind speed, and (2) there should be a systematic angle between the orientation of windrows and the direction of the wind stress on the water surface. In a recent paper Woodcock and I demonstrated that the spacing of windrows of *Sargassum* (L) is dependent upon wind speed (W) by the empirical relation $L = W \times 4.8\ \text{sec}^{-1}$, although more data of that type should be collected to further examine the dependence of row spacing upon wind speed and other parameters (FALLER & WOODCOCK, 1964). With respect to the question of a systematic angle, it has generally been taken for granted that windrows on the average are oriented exactly in the direction of the wind, but there are no records of detailed measurements to substantiate this belief. In this study, data which were collected to examine the relation between wind direction and row orientation are presented. It is assumed throughout the discussion that the mean stress on the water has the same direction as the mean wind within a few meters of the surface.

It is the intent to present here only observations of the angle between the wind and windrows, and to indicate the significance of these observations to various models which purport to explain the Langmuir circulations. The theoretical basis of the analogy which is referred to above and details of this analogy are defered to a future publication.

The Observational Data

The data of Table 1 were collected by W. H. Sutcliffe and E. R. Baylor of the Woods Hole Oceanographic Institution from small boats

[1] The research reported here was performed at the Woods Hole Oceanographic Institution under contract with the Office of Naval Research, and is Contribution No. 1517 from the Woods Hole Oceanographic Institution.

[2] This concept was first advanced by the author at the Washington, D.C. meeting of the American Geophysical Union, April 25, 1962.

TABLE 1. *A summary of wind directions and row orientations as observed from a small boat by W. H. Sutcliffe and E. R. Baylor of the Woods Hole Oceanographic Institution. Heights at which the wind speeds and directions were measured are indicated in parentheses. Positive angles indicate row orientation to the right of the wind direction.*

Date	Time (EST)	Wind speed ($m\ sec^{-1}$)	Wind Direction (degrees)	Row Direction (degrees)	Angle (degrees)	Remarks
Oct. 31 1961	1233	4.1 (2m)	248			
	1235	4.7 (2m)	240			
	1238	4.8 (2m)	240	235	−5	Determined from a slick
	1325	4.0 (1m)	232			
	1328	3.4 (1m)	236			Other row directions were obtained from lines of foam or from lines of paper dropped from a plane. Wind speed was estimated to be 7–8 knots. Rows of bubbles and associated slicks were quite well developed and were estimated to be 40–60 ft. apart
	1404		240	250	10	
	1408	2.6 (1m)	232			
	1410	2.8 (1m)	237			
	1414			260	23	
	1415		237			
	1417			256	16	
	1418		240			
	1423	3.2 (1m)	235			
	1445			255	17	These observations were obtained in water approximately 30 m deep off Martha's Vinyard, Mass.
	1446		238			
Mar. 3 1962	1040	1.5–4.0 (5m)	ENE		10 degrees to right	
Mar. 4	1330	9.0 (5m)	320	335	15	These observations were obtained in deep water of Bermuda
	1345		319	334	15	
Mar. 9	1005	5.4 (5m)				
			025			
			015	027	12	
			018	039	21	
	1015	6.4 (5m)				
Mar. 11		9–gusts to 14	ENE		17–20 degrees to right	
Mar. 12	1500	6.6 (5m)	155	170	15	
			Average angle		14.0 degrees,	Standard deviation, 6.8 degrees.

during their investigations of the effects of Langmuir circulations upon biological productivity (SUTCLIFFE, BAYLOR & MENZEL, 1963). Inasmuch as they at first were uninformed of the sense of the angular difference to be expected, the data for October 31, 1961 may be regarded as completely unbiased by prejudice of the observers. The boat was directed so that a pennant erected on a small mast at the bow was oriented along the axis of the boat, and a magnetic compass fixed in the boat was read. The boat was then directed along the windrows, which were visible because of foam, slicks, weed, or debris, and their magnetic orientation was determined.

The data for October 31 show little variation of wind direction with time over a period of 2 hours. Therefore, it is unlikely that the systematic angle of the rows to the right of the wind can be attributed to a changing wind. The first observation (−5 degrees) is questionable since it was determined from a slick of doubtful origin before routine methods of observation had been established. Including this doubtful value, the average angular difference in Table 1 is 14.0 degrees with a standard deviation of 6.8 degrees.

TABLE 2. *A summary of the analysis of aerial photographs of the angle between the surface wind and windrows. These observations were obtained in water ranging from 30–200 m deep off Provincetown, Mass. from the R4-D and the Helio-Courier of the Woods Hole Oceanographic Institution.*

Date	Angle (degrees)		Remarks
May 16, 1962		11.5	This angle is the average of two analyses of the same photograph, by the authors (8.5) degrees and by E. R. Baylor (14.5 degrees)
		8.0	This value was obtained from streaks of "Zonalite" insulation material which was dumped onto the water from a small boat. (See Fig. 2)
June 22, 1962		8.5 9.7	These values are uncertain because the camera was tilted from the vertical to avoid reflections of the sun and because of the paucity of papers near the smoke flares. (See Fig. 3)
July 11, 1962		8.5	Evalution by P. M. Saunders of W.H.O.I. from a 16 mm ciné film
Nov. 7, 1962	Pass		The interval between succesive passes was 4 min. Passes 3, 5, and 7 were with rapid sequence 35 mm photographs (see Fig. 1), and others were with 16 mm ciné photographs
	1	10.9	
	2	19.4	
	3	4.1	
	4	16.8	These observations were on a day with cold air advection over relatively warm water. The large variation of angle is due to changes of wind direction while the row orientation remained constant
	5	18.5	
	6	—	
	7	−0.8	
	8	19.2	
	9	22.5	

Average angle 12.1 degrees, Standard deviation 6.5 degrees

Positive angles indicate windrows to the right of the wind, in accord with the proposed analogy.

Angle data in Table 2 were obtained from aerial photographs. In most cases wind direction was indicated by plumes from smoke flares in the water, and row orientation was determined from bands formed by sheets of $8\frac{1}{2} \times 11$ inch paper which were scattered over the ocean from an airplane.[1] The technique of dropping both papers and smoke flares into the same area was to: (1) drop a single smoke flare as a reference marker, (2) fly upwind from the flare to drop the papers at an appropriate elevation and distance such that they would land close to the first flare, and (3) drop additional flares in the midst of the papers from a low level. Approximately 15,000 sheets of paper were used in each experiment. Their distribution over the ocean depended upon the degree of turbulence in the air, the altitude from which they were dropped, the orientation of the flight path with respect to the wind, and the method of release of the paper. To obtain a sufficient density of papers to clearly indicate rows, the papers were distributed from an elevation of 300 m or less, and they were cast through a hatch in the bottom of the plane in batches of 500 sheets by two or three people as rapidly as possible. Except for the last case, November 7, 1962, the flight path was across wind. Strong turbulence on that occasion required that the flight path be upwind at slow speeds (50 knots) for an adequately dense distribution of papers. Because of the slow fall rate of the paper sheets (approximately 1 m sec^{-1}) it was necessary to fly $1\frac{1}{2}$ km upwind of the original flare for a mean wind of only 5 m sec^{-1} in order that the papers would land close to the marker. Using such a technique the papers could be found readily without a time-consuming search, and a second batch of papers could be dropped close to the first by repeating the flight path. Although the papers were dropped in batches, there was no observable small-scale organization when they first landed on the water. Usually, they were

[1] This phase of the operation was known locally as "Project Litterbug".

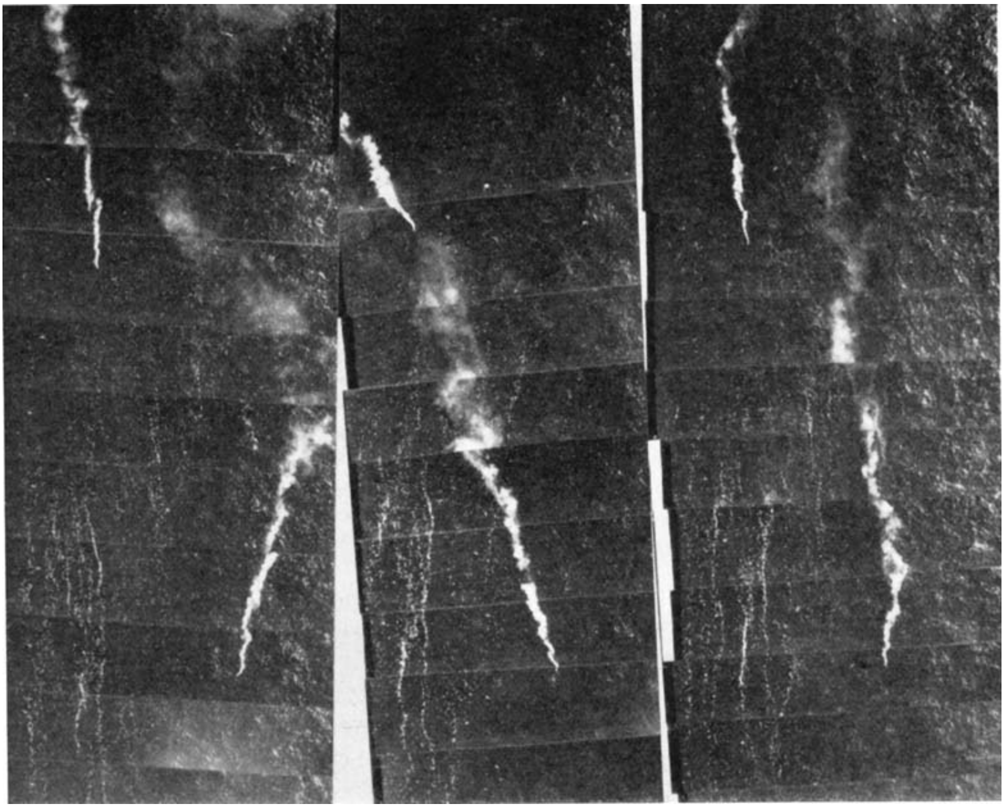

FIG. 1. The distributions of paper sheets on the ocean surface and plumes from smoke flares for the case of November 7, 1962. The three sequences, from right to left, correspond to runs 3, 5, and 7 (see Table 2) with an 8 minute interval between each of these sequences. The spacing between the two flares is approximately 230 m and the altitude of the airplane (Helio-Courier) was 270 m. The photographs are matched so that a line between the two flares maintains a constant orientation and so that the windrows of paper are parallel to the side of the figure. It is apparent that the windrows maintained constant orientation over this period of time despite large variations of wind direction.

observed to become organized into bands within 5 min after they landed.

All of the experiments listed in Table 2 were for steady, light winds, and statically stable atmospheric conditions, except the case of November 7, 1962 which took place during cold air advection over relatively warm water. To obtain the values of angle quoted in Table 2 for this last experiment, a mean wind direction was determined from the entire visible plumes of the two flares for each of 8 photographic passes. Angles measured from smoke at varying distances downwind were weighted by the distance from the flare, because the portion of a smoke plume further from its flare represents an average wind direction over a longer period of time. Assuming a wind of 5 m sec^{-1}, the mean angle for each pass of November 7 represents the mean wind for an interval of 30–60 sec before the photographs. Passes 3, 5, and 7, which are illustrated in Fig. 1, were recorded with rapid sequence 35 mm photographs, and the others were recorded on 16 mm ciné film. The average angle was 12.6 degrees with a standard deviation of 8.0 degrees for the 8 passes. It has been assumed that the two flares maintained a nearly fixed orientation, and it may be seen from Fig. 1 that the average angle of the windrows with respect to the line connecting the flares remained sensibly unchanged.

The data for November 7 suggest that there was a variation of the mean wind direction with a period of 15 min. This fluctuation may truly represent a periodic oscillation of the wind

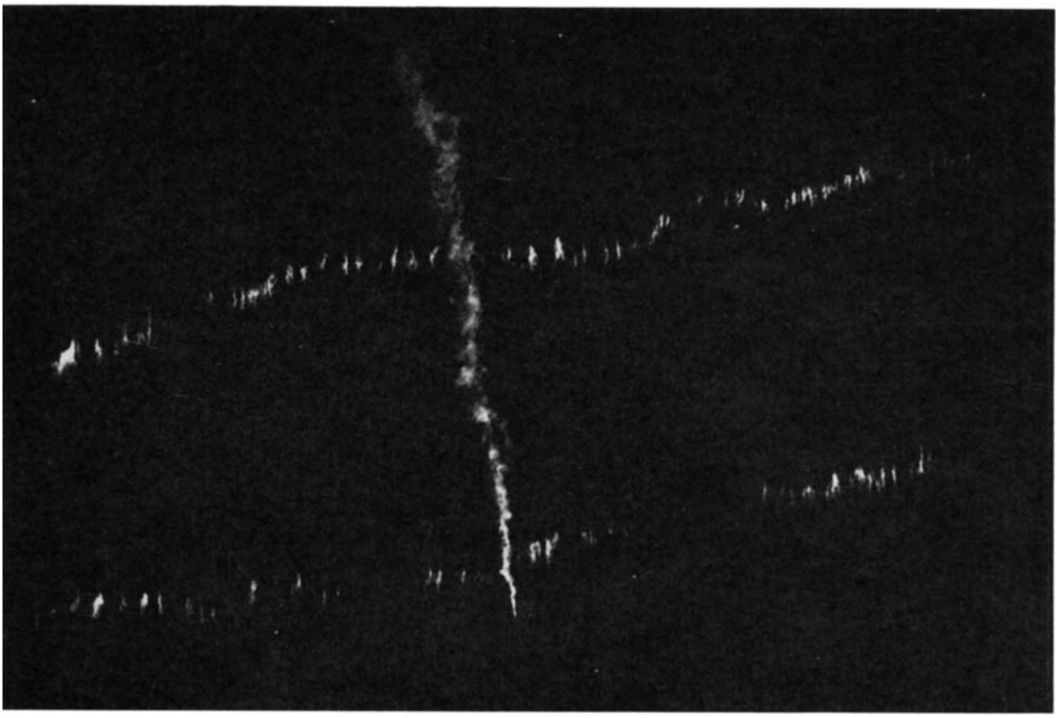

FIG. 2. Streaks formed from "Zonalite" expanded-mica insulation material which show an average angle with respect to the smoke plume of 8.0 degrees. (May 16, 1962).

because of large-scale convective motions in the atmosphere. But there were also significant shorter-period fluctuations which are seen, for example, from the irregularity of the smoke plume in the third sequence of Fig. 1. Taking only those portions of the smoke plumes within 75 m of the flares and treating each flare separately I obtained the average angle 10.7 degrees with a standard deviation of 12.8 degrees for 15 observations. This larger standard deviation indicates the greater apparent variability of the wind when shorter period averages are used. From the motions of individual features of the smoke plumes the wind speed was found to be 3.5 m sec^{-1} at a height of 2 m, where the height was determined by assuming that the vertical extent of a plume was the same as its width. This computed speed agrees with the value 8 knots at 6 ft above the water that was measured from a small boat in the vicinity.

Fig. 2 shows streaks formed from "Zonalite" expanded-mica insulation material which was dumped onto the water during the experiment of May 16, 1962. The average angle of these streaks with respect to the smoke plume was 8.0 degrees with a standard deviation of angle of 2.2 degrees for 112 measurements. The smoke plume on this occasion extended downwind in a straight line for a great distance, and it is asserted that the wind direction indicated by the single plume is representative. In another photograph which showed only a few streaks of Zonalite but also some sheets of paper, the streaks indicated no appreciable angle with respect to the two smoke flares which were present, but the papers showed an average angle of 11.5 degrees.[1] On this occasion the wind speed was less than 2 m sec^{-1} and rows were not observed until 20–25 min after the papers landed.

Fig. 3, taken at local noon on June 22, 1962, was at an oblique angle to avoid the glitter pattern of the sun. Again, the atmospheric stratification was stable and the wind direction was notably steady. Because of the poor density

[1] For this photograph see Oceanus, Vol. IX, No. 1, September, 1962.

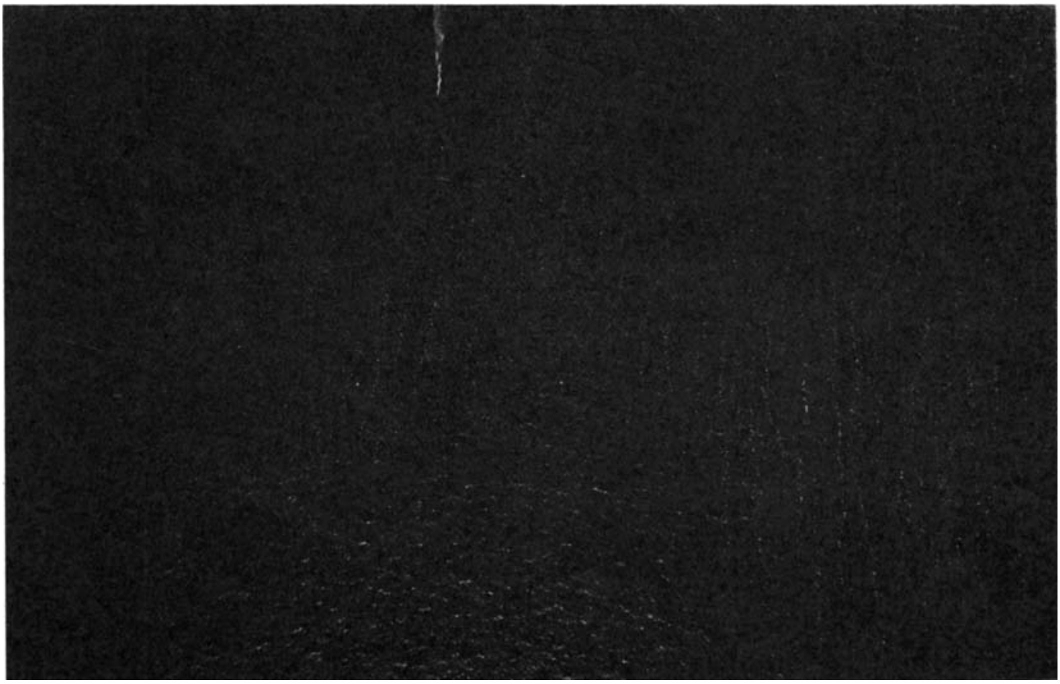

FIG. 3. Windrows of paper and a smoke flare on June 22, 1962. Because of the oblique angle, to avoid the glitter pattern of the sun, the orientation of the windrows appears to vary across the picture.

of papers near the flare, and because of the oblique angle of the photographs, the angles listed in Table 2 were determined in each case by plotting the apparent angle of the rows as a function of the cross-wind distance from the flare. The angle at the flare was then found by interpolation.

For the average angles of Tables 1 and 2 the several observations on October 31 and on November 7 have been treated as individual values so as to weight those days more heavily on which the data were more reliable or more representative. Taking all values from both tables, the average angle was 12.9 degrees with a standard deviation of 6.6 degrees. If we then take only the number of days on which data were obtained as the number of independent observations (11), the standard error of estimate is 2.0 degrees. Thus the observed average angle is very significantly different from zero by standard tests.

Fig. 4*a* is a photograph taken by the staff of the Chesapeake Bay Institute of the Johns Hopkins University (to whom the author is indebted) on August 5, 1962 during their investigations of the diffusion of Rhodamine B dye off Cape Canaveral, Florida. Fig. 4*a* is interpreted as evidence of an Ekman spiral flow, and the presumed patter of flow as a function of depth is indicated in Fig. 4*b*. This initial dump of dye took place at 0842 EST and formed a patch 10–30 m diameter. Fig. 4*a* was taken 2 hr 24 min later at 1106 EST, during which time the average wind as indicated by the Cape Canaveral Lighthouse was steady from the West at 8 knots. One wind observation from the ship at 1032 EST indicated 5 knots from 215 degrees. However, perhaps more suitable indicators of wind direction are the orientation of the locally-generated waves and the direction of shear of the main body of the dye patch. These both indicate a wind direction of 280 degrees. If the interpretation in Fig. 4 is correct, the mean drift of the surface water (relative to a possible mean drift of the water mass) was approximately 7.9 cm sec^{-1}, 21 degrees to the right of the surface wind direction.

Evidence of regular banded structure in Fig. 4*a* is meagre, but there are areas in the photograph where several bands may be detected,

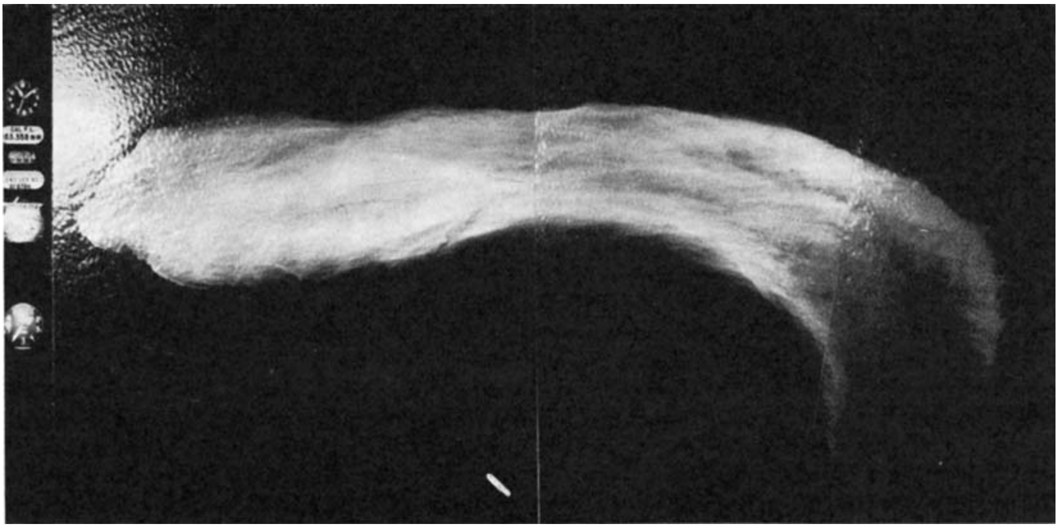

FIG. 4*a*. The pattern of Rhodamine *B* dye 2 hr 24 min after release off Cape Canaveral, Florida by staff members of the Chesapeake Bay Institute of the Johns Hopkins University on August 5, 1962. The ship, R. V. Gosnold from the Woods Hole Oceanographic Institution, is 30.5 m long.

notably, at the western edge of the dye patch. These bands, and others with the same orientation and spacing, are 12 degrees to the right of the wind direction and have an average spacing of 7 m. From the linear relation between spacing and wind speed given in the introduction, this spacing corresponds to a speed of 1.5 m sec^{-1}, a value which is not greatly different from the speed observed at the ship. Observations of temperature and salinity on this occasion showed very slightly stable density stratification to a depth of 10 m where an abrupt decrease of temperature was encountered. The total depth of water was approximately 20 m.

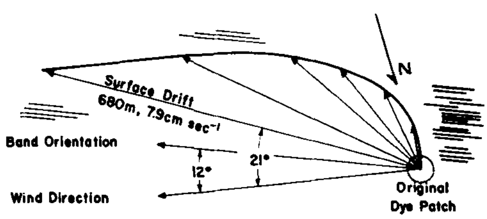

FIG. 4*b*. An interpretation of the pattern of dye as an Ekman spiral flow. Wind direction was determined from the glitter pattern of the waves and from the apparent direction of shear of the nose of the dye patch. Several bands of dye with an average angle of 12 degrees to the right of the wind and with an average spacing of 7 m are indicated.

Discussion and Conclusion

Additional evidence of banded structure has been reported recently by ICHIYE (1964) who has made dye experiments similar to those of the Chesapeake Bay Institute. Sketches of the striations of dye which he observed suggest a systematic angle of the bands to the right of the wind by approximately the average angle found here. Furthermore, the band spacings indicated in his sketches for September 12, 1963 are approximately $L = 50$ m for a wind speed of $W = 12$ m sec^{-1}, in good agreement with the empirical relation mentioned above.

The establishment of these two facts, the systematic angle and the dependence of spacing upon wind speed, from several independent sources, reveals a great deal about the nature of the Langmuir circulations and supports Langmuir's contention that these circulation cells have the wind as their source of energy. From the systematic angle it follows that the cellular motions which produce lines of material on the surface must extend to a significant depth into the Ekman boundary-layer flow. If this were not the case it is difficult to imagine how Coriolis forces could influence such cellular motions, and, indeed, Coriolis forces are the only apparent source of a systematic deviation from the wind. In addition, data of WOODCOCK (1950) and of SUTCLIFFE, BAYLOR & MENZEL (1963) are direct evidence that these cells produce strong vertical motions (greater than 5 cm sec^{-1}) which extend at least several meters in depth.

This evidence for strong cellular motions which extend to appreciable depths makes it rather doubtful that surface processes, such as the surface film mechanism suggested by WELANDER (1963) for smaller scale streaks and slicks, could be the source of these large-scale motions. A mechanism similar to that of Welander has been suggested by ICHIYE (1964). He assumes that variations in the surface stress occur due to variations in roughness of the sea surface. However, it has been my experience that the large cells are present even without visible variations in the character of the free surface. While models which depend upon surface processes deserve further investigation and may represent smaller-scale phenomena, it seems unlikely to this author that they are adequate to explain the Langmuir circulations.

As alternatives to direct surface processes there remain the possibilities of organized thermal convection and organized shear-flow instability. While it has commonly been assumed that the former of these was responsible for the Langmuir circulations, with the wind acting only to organize the cellular convection into bands, the dependence of cell spacing upon wind speed is a strong argument in favor of the hypothesis of shear-flow instability. It is undoubtedly true that in the absence of significant wind stress, thermal sources of energy will dominate convective motions in the oceanic boundary layer. Similarly, in the absence of thermal sources tending to produce either strong thermal stability of instability, it is not unreasonable to assume that convective processes are dominated by wind mixing. It is asserted here, in support of the original deductions by Langmuir, that relatively large-scale wind-driven cells are an important part of the wind-mixing process.

Determination of the relative importance of thermal convection and wind-induced convection is one of the central problems of the mixed layer. It has been my experience and that of others (W. H. SUTCLIFFE and E. R. BAYLOR, personal communication) that Langmuir circulations are nearly always present, although their detection may require the introduction of foreign tracer material. Thus, the common occurence of these cells under a wide variety of circumstances indicates that the effect of the wind stress may be of greater significance compared to thermal processes that has commonly been believed.

In a subsequent paper, a model of Langmuir circulations based upon an analogy with laboratory experimental results and numerical computations will be presented. This model indicates that the Langmuir circulations should normally extend to depths greater than that of the Ekman spiral. Consequently, erosion of a shallow seasonal or diurnal thermocline by wind mixing may be due more to the Langmuir circulations than to the small scale turbulent motions associated with the Ekman spiral itself. This model also serves to explain WOODCOCK's observations (1944) of the asymmetry of oppositely rotating cells, and gives detailed description of the Langmuir cells and their interaction with the Ekman boundary-layer flow.

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