STUDY OF THE NEAR SHORE SURFACE CHARACTERISTICS OF WINDROWS AND LANGMUIR CIRCULATION IN MONTEREY BAY

ALEXANDER MARATOS

United States Naval Postgraduate School

THESIS

STUDY OF THE NEAR SHORE SURFACE CHARACTERISTICS OF WINDROWS AND LANGMUIR CIRCULATION IN MONTEREY BAY

by

Alexander Maratos

Thesis Advisor: N. Boston

September 1971

Study of the Near Shore Surface Characteristics of Windrows and Langmuir Circulation in Monterey Bay

by

Alexander Maratos
Lieutenant, Greek Navy

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
September 1971

ABSTRACT

Observations of the spacing and angle of windrows with respect to the wind speed and direction were conducted in Monterey Bay, using aerial photographs taken of windrow accumulations on 13, 20, 27 April and 3, 11 May 1971.

The spacing of windrows was found to depend upon wind speed. These windrows are indicative of the presence of helical vortices in the surface waters, and the data support Langmuir's contention that the vortices are wind-driven. Deflection angles showed small variation to the left and right of the wind with 0° being the most common angle. No correlation was found between depth of the thermocline and row spacing.

The Langmuir circulation investigated in Monterey Bay showed a cellular pattern with vertical velocities of 2.2 cm/sec downward in the area of convergence and 0.8 cm/sec upward in the area of divergence, at a wind speed of 6.0 m/sec.

TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGEMENTS

I wish to first thank my advisor, Professor Noel E. Boston of the Department of Oceanography, for his interest and guidance during this study.

I would like to express my special appreciation for the help given me by Professor Jerry A. Galt of the Department of Oceanography.

The Navy boat crew, the Postgraduate School Photographic Laboratory, and the many pilots that flew the helicopter also deserve special thanks.

I. INTRODUCTION AND OBJECTIVE OF INVESTIGATION

A. INTRODUCTION

When sufficiently strong winds blow over bodies of water there frequently appears on the water surface a fairly regular pattern of streaks, aligned approximately in the direction of the wind. These streaks, commonly called "windrows," may appear as lines of foam from breaking waves, or as accumulations of other floating matter (leaves, seaweed, ice, etc.). Often however, they are visible when no floating objects are present, owing to a change in reflectivity of the water surface in the vicinity of the streak; this change is caused by the accumulation near the streak of a film, or "slick" of surface contaminant (usually oil or natural organic matter) which smooths the water surface by eliminating short capillary waves.

The first - and still the most comprehensive - experimental investigation of windrows was made by Langmuir (1938), who found them to be associated with an underlying cellular motion in the water. The streaks appear between converging surface currents and above a downward flowing current, which is produced by alternately rotating longitudinal vortices, often called "Langmuir vortices." This structure is represented diagrammatically in Figure 1, which depicts a vertical section of the flow in a plane perpendicular to the wind direction. The converging surface currents are

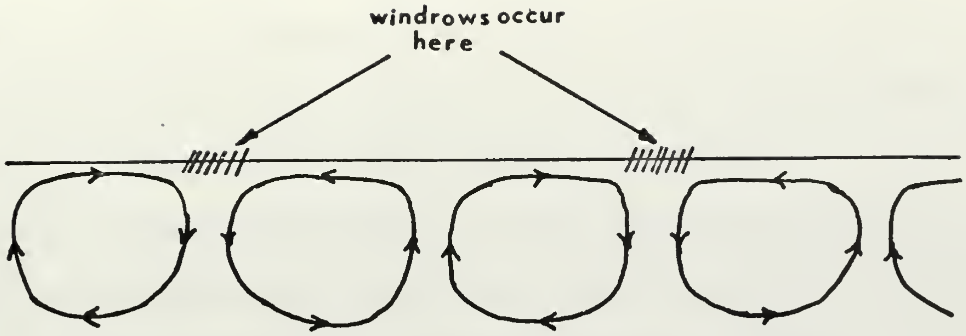

Figure 1. Diagrammatic Representation of Langmuir Vortices, Showing Location of Windrows.

clearly responsible for the accumulation of buoyant foreign matter or for the compression of a film of surface contaminant into the observed longitudinal streaks.

Since Langmuir's experiments, there has been no shortage of theories to explain the occurrence of streaks on water surfaces. In a brief but useful review, Stommel (1951) distinguishes between "single streaks" of various origins and "multiple streaks which usually appear in long parallel lines or with a vein-line pattern." Of these multiple streaks, not all can be classified as "windrows." For example, Ewing (1950) and Dietz and Lafond (1950) have reported parallel streaks with orientation bearing no relation to the wind direction; these are apparently caused by internal waves, and are quite commonly observed running parallel to coastlines.

A notable feature of windrows is their ability to realign themselves quickly in response to a change in wind direction.

While it is recognized that the wind plays a crucial role, there is no real agreement as to the cause of the Langmuir vortices which give rise to windrows.

An attractive suggestion is that they are driven by thermal or thermohaline convection due to surface cooling, and that the orientation of the convection "rolls" is determined by the shear flow induced by the wind stress. Support to this view is given by Owen (1966) who observed, at sea, rows of horizontal vortices about 1.5 m apart, when no significant wind was present. These were almost certainly thermohaline in origin. Further, it is known (Gallagher & Mercer 1965; Deardoff 1965) that longitudinal rolls are the preferred configuration of thermal convection in the presence of a shear flow. Experimental investigation by Csanady (1965) and Faller & Woodcock (1964) failed to find evidence of any correlation between the spacing of windrows and the heat flux from the water surface; on the other hand, this spacing is strongly dependent upon wind speed, the rows being wider apart at larger wind speeds. These facts suggest that the cellular structure may have a dynamic, rather than thermal origin. This view is supported by Stommel (1951), who concluded that, in his cinematographic studies of streaks on ponds, "thermal convection seemed also unlikely because the streaks occurred at times of intense heating of the ponds" and with a very stable epilimnion (0.1 cm).

Such a dynamic mechanism was proposed by Faller (1964), who suggested that Langmuir vortices are the direct result of hydrodynamic instability of the Ekman boundary layer in the water. He supports this view with experimental observations which appear to show that the orientation of windrows is systematically deflected by a small angle to the right of the wind direction.

Very little work has been done concerning the surface characteristics of windrows. Langmuir discovered that the row spacings in Lake George are approximately proportional to the depth of the thermocline and are 5-10 m for a shallow thermocline in May and June and 15-20 m for a deep thermocline in October and November. Faller and Woodcock found from the data of Sargassum in the North Atlantic that the spacings are proportional to wind speeds, varying from 20 m for wind of 4 m/sec to 50 m for 12 m/sec.

B. OBJECTIVE OF INVESTIGATION

Prior to this thesis investigations of the Langmuir circulation and near-shore surface characteristics of windrows have suffered from two important inadequacies:

1) Lack of experimental evidence showing the cellular motion of the Langmuir circulation.
2) The lack of sufficiently large numbers of observations to study the near-shore surface characteristics of windrows.

The intent of this thesis is to present an experimental investigation of the Langmuir circulation and the near-shore

surface characteristics of windrows in Monterey Bay. The windrow characteristics investigated include:

1) Dependency of windrow spacing on wind speed.

2) Angle of deflection of windrow orientation from the direction of the wind.

3) Response time of windrow orientation to a wind shift.

4) Relationship(s) between windrow spacing and the depth of the thermocline.

The Langmuir circulation investigated includes:

1) Shape of the Langmuir circulation.

2) Vertical velocity(ies) of the Langmuir circulation.

3) Dependency of the Langmuir circulation and vertical velocity(ies) on wind speed.

II. INVESTIGATIVE PROCEDURES

A. INVESTIGATIVE PROCEDURE OF NEAR-SHORE SURFACE CHARACTERISTICS OF WINDROWS

1. Equipment

The core of the data acquisition system was a K 20 - 4 x 5 Aerial Mapping Camera. This is the primary camera used by the U.S. Air Force, and U.S. Navy for accurate mapping. The camera was operated from a U.S. Navy helicopter attached to the Naval Auxiliary Landing Field, Monterey. Windrows were investigated just offshore of the Oceanography Beach Laboratory. This is an area impossible to be photographed by fixed wind aircraft due to the proximity of the Monterey County airport's traffic pattern. The camera is operated from the open right hand side door of the helicopter. An assistant of the camera operator has only to note the heading and altitude of the helicopter at the time the picture is taken. The responsibility of the pilot is to maintain a good course and altitude during the final phase of approach. After the photo runs, the camera's magazine is unloaded and the film is sent to the Photo Media Department for development.

Surface wind speeds were obtained with a Cassela cup amemometer. The amemometer uses the number of revolutions of the cup assembly per minute to give an accurate average wind speed over the previous minute. Each instrument is provided with its own calibration sheet of rpm versus wind speed.

Thermal structure was obtained by means of a standard U.S. Navy shallow water bathythermograph. Bucket thermometer readings were taken concurrently to obtain some estimate of the sea surface temperature. An electronic psychrometer was used in conjunction with a standard dry bulb thermometer.

Two buoys were used for extrapolating the spacing of the windrows. With the exception of the camera and the buoys, all instruments were mounted on the Naval Postgraduate School's 63 foot oceanographic research boat. The marking of windrows was accomplished by dropping $3\frac{1}{2}$ x $7\frac{3}{8}$ inch computer cards from the helicopter and from the boat. Approximately 3,000 cards were used during each sampling period. The idea of using Sulfur Dust for marking the windrows was abandoned when it was found that the dust was not easily visible especially with wave activity.

2. Sampling Technique and Dates

A complete sampling period consisted of twenty or more photographs of a given windrow accumulation. The time interval between photographs was roughly two minutes.

The boat would position itself in a likely area for windrow occurence off shore of the Oceanography Beach Laboratory and at a depth not exceeding 12 fathoms. Voice communications would be established with the helicopter. Prior to arrival of the helicopter two buoys were anchored in a pre-estimated position and at a fixed distance of 65 feet apart.

Upon arrival overhead, the helicopter would fly directly over the buoys on a heading upwind and release the load of computer cards from the right hand side door. The cards would immediately separate one from another and fall in a completely random pattern. Moving around the periphery of this pattern, the boat would plant a standard U.S. Navy MK. 6 smoke float slightly upwind of the computer card pattern. The boat would then stand off downwind of the pattern, commence taking wind speed measurements and make a BT cast. Upon sighting the smoke from the float, the helicopter would commence flying a race track pattern, so as to pass over the smoke float, the computer cards and the two buoys, roughly every two minutes. The photographs would be taken directly overhead and the helicopter's heading and exact altitude noted. All wind speed readings were obtained with the boat lying to with all protuberances of ship structure being downwind of the amemometer. Wind direction was obtained from the photographs of the smoke float and its plume. Upon completion of approximately twenty photo runs, a second bathythermograph reading was taken, and the day's investigation concluded.

Sampling runs were conducted in Monterey Bay on 13, 20, 28, of April and 3, 11, of May 1971.

B. INVESTIGATIVE PROCEDURE OF LANGMUIR CIRCULATION

1. Equipment

The investigation of Langmuir circulation in Monterey Bay was conducted through a study using fine sands

of 20 microns in diameter. The sand was provided by the Laboratory of Del Monte Sand Plant Co.

Nansen reversing water bottles operated from the 63 foot boat, were used for collecting the sand at different depths.

Computer cards, a Cassela cup amemometer and a shallow water bathythermograph (as described in Chapter I) were used for obtaining the pattern of the windrows, the surface wind speed and the thermal structure of the ocean.

2. Sampling Technique

Immediately upon arrival of the boat at the area of investigation off shore from the Beach Oceanography Laboratory, the boat started to cruise upwind releasing the load of computer cards from both sides. The cards would separate one from another and fall in a random pattern. The boat would then stand off downwind of the pattern waiting 5 - 8 minutes for the cards to form the surface pattern of windrows, taking wind speed measurements and BT cast. After the computer cards formed the pattern of the surface windrows the boat approached along side of the outer downwind windrow very slowly and carefully so as not to disturn the pattern. A hydrocast was made in this area. The reversing bottles were lowered at the pre-estimated depths. The sand was then introduced at the surface and commenced to sink. After five minutes the bottles were reversed and the water samples were collected. A second hydrocast was made in the

midway position between two windrows in the very same way as the first.

The area of the windrow itself and the area of midway position between the windrows were chosen for the hydrocasts, because they are representative areas of convergence and divergence in Langmuir circulation.

Sampling runs were conducted twice in Monterey Bay. The first on 11 of March 1971 and the second on 15 July 1971. In the first run the depths of 5, 10, 15 meters were used and in the second run the depths of 4, 8, 12, 15 meters were used.

The water samples were analyzed for the number of particles at each depth using a Coulter Counter.

III. PRESENTATION AND DISCUSSION OF DATA

A. PRESENTATION AND DISCUSSION OF DATA OF NEAR-SHORE SURFACE CHARACTERISTICS OF WINDROWS

Data derived from the five sampling runs is presented and discussed on the following pages. Initially each day's results are shown in an individual table. Following each table is a descriptive analysis of the prevailing meterological and bathythermometric conditions during the sampling process. Following the tables is a discussion of symbols used for the definitions of parameters. The first part concludes with graphs and discussions concerning the correlation of the various windrow characteristics. The actual photographic negatives are included with this report under separate enclosure. Final analysis and conclusions are presented in the next chapter.

13 April 1971

PHOTO NO.	TIME	ALTITUDE	WIND	NO.ROWS	SPACING	DEFL.	S/D
131	1327	400	3.4	-	-	-	-
137	1333	400	4.3	6	13.0	0°	1.08
138	1334	400	-	-	-	-	-
139	1336	400	4.5	5	13.3	3°L	1.14
1310	1338	300	4.7	5	15.0	1°R	1.28
1314	1341	300	4.5	6	13.3	4°R	1.14
1316	1343	300	4.8	5	16.7	2°L	1.42
1318	1345	300	4.5	7	15.0	0°	1.28
1320	1347	300	5.0	6	16.7	3°L	1.42
1322	1349	300	5.0	7	16.7	5°L	1.42
1323	1351	300	5.0	6	16.7	1°L	1.42
1324	1353	300	3.9	6	15.0	3°R	1.28
1326	1355	300	3.5	6	13.3	2°R	1.14
1327	1356	300	3.6	5	13.3	0°	1.14
1328	1357	300	3.3	-	-	-	-
1329	1358	300	3.2	5	11.7	3°R	1.00
1330	1359	300	3.2	-	-	-	-
1331	1401	300	3.0	5	11.7	2°R	1.00
1332	1403	300	3.1	5	11.7	1°R	1.00
1333	1405	300	3.3	-	-	-	-

Thermocline remained fixed at 35 feet during observational period. $T_s > T_w$ during entire period. Data taken in 66 feet of water; visibility unlimited; cloudy sky with light rain; 1 foot swell from southwest.

20 April 1971

PHOTO NO.	TIME	ALTITUDE	WIND	NO.ROWS	SPACING	DEFL.	S/D
201	1331	1000	6.8	4	20.0	1°R	1.66
202	1332	1000	6.2	-	-	-	-
203	1334	1000	6.0	-	-	-	-
204	1336	1000	6.0	3	16.7	2°R	1.38
206	1338	1000	6.2	3	16.7	0°	1.38
207	1340	1000	6.0	4	16.7	1°L	1.38
209	1343	1000	6.0	-	-	-	-
2010	1345	1000	6.0	4	16.7	1°L	1.38
2011	1347	1000	6.0	4	-	-	-
2012	1348	1000	6.3	3	16.7	0°	1.38
2013	1350	1000	6.2	2	16.7	0°	1.38
2014	1354	1000	6.0	-	-	-	-
2015	1356	1000	6.0	-	-	-	-
2016	1358	1000	6.0	3	16.7	2°R	1.38
2017	1359	1000	6.1	-	-	-	-
2018	1401	1000	6.1	3	16.7	0°	1.38

Thermocline remained fixed at 36 feet during observational period. Ts > Tw during entire period. Data taken in 60 feet of water; visibility unlimited; cloudy sky; 1 foot swell from southwest.

28 April 1971

PHOTO NO.	TIME	ALTITUDE	WIND	NO.ROWS	SPACING	DEFL.	S/D
281	1426	1200	3.2	5	-	-	-
282	1428	1200	3.0	4	8.4	2°L	.83
283	1430	1200	3.0	4	9.4	2°R	.93
284	1431	1200	3.0	3	6.7	0°	.66
285	1432	1100	3.0	3	8.4	2°R	.83
286	1434	1200	3.0	3	8.4	7°L	.83
287	1436	1100	3.1	-	-	2°R	-
288	1438	1175	3.4	-	-	2°R	-
289	1440	1150	3.0	4	8.4	2°L	.83
2810	1442	1200	3.1	4	6.7	2°L	.66
2811	1444	1200	3.3	-	-	5°L	-
2812	1446	1200	2.9	-	-	-	-
2813	1447	1200	2.8	-	-	-	-
2814	1449	1200	2.7	-	-	-	-
2815	1451	1200	2.6	-	-	-	-
2816	1453	1200	3.0	4	9.4	2°R	.93
2817	1454	1200	3.0	-	-	-	-
2818	1456	1200	2.9	4	8.4	2°L	.83
2819	1458	1200	3.1	-	-	0°	-

Thermocline remained fixed at 30 feet during observational period. $T_s > T_w$ during entire period. Data taken in 60 feet of water; visibility unlimited; cloudy sky; 1 foot swell from southwest.

3 May 1971

PHOTO NO.	TIME	ALTITUDE	WIND	NO.ROWS	SPACING	DEFL.	S/D
31	1408	900	-	-	-	-	-
32	1409	1000	2.9	-	-	-	-
33	1410	1000	3.0	5	-	-	-
34	1411	1000	3.0	5	8.4	0°	.83
35	1412	1000	3.1	6	10.0	0°	1.00
36	1413	1000	3.0	6	8.4	0°	.83
37	1414	1000	3.0	4	6.7	1°R	.66
38	1415	1000	3.0	6	9.4	2°L	.93
39	1416	1000	3.1	4	8.4	3°R	.83
311	1418	650	3.1	8	6.7	0°	.66
313	1420	1000	3.0	8	6.7	1°R	.66
315	1422	1000	3.0	7	8.4	1°R	.83
318	1424	600	3.0	6	9.4	0°	.93
320	1425	580	3.0	5	8.4	2°R	.83
322	1427	600	3.0	7	6.7	-	.66
324	1429	600	3.0	4	7.4	5°R	.73
325	1430	580	3.0	6	6.7	0°	.66
327	1434	600	3.2	7	8.4	o°	.83
330	1436	650	3.5	6	10.0	3°R	1.00
332	1438	620	3.5	7	9.4	3°R	.93
334	1440	600	3.3	8	8.4	0°	.83

Thermocline remained fixed at 30 feet during observational period. $T_s > T_w$ during entire period. Data taken in 66 feet of water; visibility good; cloudy sky with light rain; 1 foot swell from southwest.

11 May 1971

PHOTO NO.	TIME	ALTITUDE	WIND	NO.ROWS	SPACING	DEFL.	S/D
111	1400	600	3.9	7	10.0	3°L	1.00
112	1402	590	3.6	7	10.0	3°L	1.00
113	1404	600	3.5	6	9.4	3°L	.93
114	1407	600	3.5	7	10.0	2°L	1.00
115	1409	600	3.6	8	9.4	2°R	.93
116	1411	600	3.5	-	-	-	-
117	1413	600	3.5	8	8.4	0°	.83
118	1415	600	-	-	-	-	-
1193	1417	600	3.6	8	8.4	3°R	.83
1110	1419	600	3.5	-	-	-	-
1111	1421	600	3.7	7	7.4	0°	.73
1112	1423	600	-	-	-	-	-
1113	1425	800	3.9	7	9.4	0°	.93
1114	1427	800	-	-	-	-	-
1115	1429	800	-	-	-	-	-
1116	1431	800	3.6	6	8.4	0°	.83
1117	1433	800	3.5	-	-	-	-
1118	1434	800	3.5	-	-	-	-
1119	1436	750	3.5	6	10.0	2°R	1.00
1120	1438	800	3.3	-	-	-	-
1121	1439	800	3.5	-	-	-	-
1122	1441	800	3.6	-	-	-	-

Thermocline remained fixed at 30 feet during observational period. $T_s > T_w$ during entire period. Data taken in 60 feet of water; visibility good; cloudy sky; 1 foot swell from southwest.

Remarks on Symbols

PHOTO - Number refers to date and sequence. PHOTO 131 is first photograph taken on 13 of April. PHOTO 2017 is 17th photograph taken on 20 of April.

TIME - Local time on a 24 hour basis relative to midnight as time 00.00.

ALTITUDE - The altitude of the helicopter in feet at the time the photograph is taken.

WIND - Wind speed in meters/second during the two minutes immediately preceeding the photograph.

NO. ROWS - The number of windrows clearly distinguishable on the photograph.

SPACING - The predominant or average spacing in meters between windrows.

DEFL. - The angle between windrow orientation and the wind direction. Wind direction (relative) taken from plume of smoke float.

S/D - The ration of SPACING over depth of the thermocline. Thermocline depth used as depth where temperature 1° lower than surface temperature as taken by bucket thermometer.

Ts - Surface water temperature.

Tw - Wet bulb temperature.

Spacing measurements were determined by use of the two anchored buoys and through the standard optical equation:

$$\frac{\text{IMAGE}}{\text{FOCAL LENGTH}} = \frac{\text{GROUND COVERED}}{\text{ALTITUDE}}$$

As long as both the two buoys and the computer cards appeared in the photographs, the 65 foot known distance of the two buoys was used for obtaining the spacing of the windrows. At the end of the sampling run, where only the

computer cards appeared in the photographs due to wind-drifting away from the buoys, the standard optical equation was used for obtaining the spacing of the windrows. The image and focal length of the K20 camera are fixed at four and five inches respectively. With the altitude of the helicopter at the time of shutter-trip known, the ground covered in the photograph can be found, and converted to feet of horizontal distance per inch of photograph. Only those photographs were used for spacing analysis where the windrows appeared reasonably parallel and straight.

Where no deflection values appear in the tables, the smoke plume was not visible in the photograph. Often the windrows extended beyond the smoke plume, and the photograph was taken of that section of the windrows rather than being centered on the smoke float. Clearly S/D values can be presented only if a spacing measurement is available.

13 April 1971

Fifteen observations of windrow spacing yielded an average of 14.2 meters with an average wind speed of 4.0 m/sec. The average angle of windrow deflection was found to be 0.1 to the right of the wind. Actually during this sampling run we had a windrow deflection ranging from 5 L to 4 R of the wind. During the first 20 minutes of the observational period, the wind speed increased fairly steadily from 3.4 m/sec to 5.0 m/sec and remained constant at 5.0 m/sec for the next eight minutes. After this it started decreasing to 3.0 m/sec.

The photographs of this day's run, show very clearly the formation of the slicks into windrows. Slicks are smooth glassy patches on the rippled surface of the ocean and are commonly seen in coastal waters, bays and lakes. When the wind is a slight breeze the slicks are in patches. At wind speeds greater than about 4 m/sec, the slicks break up into windrows. Slicks are distinguished by the smooth oily appearance of wavelets and the lack of ripples.

<u>20 April 1971</u>

Only nine photographs were used for spacing analysis, with an average of 17.0 meters for an average wind speed of 6.1 m/sec. Mean windrow deflection was 0.6° to the right of the wind. Four of the nine observations showed no angle of deflection.

<u>28 April 1971</u>

Again nine measurements of spacing were used to obtain an average spacing of 8.2 meters with an average wind speed of 3.0 m/sec. Using 12 values the average deflection was found to be 0.9° to the left of the wind. During the last 12 minutes of observation, the runs became more irregularly spaced and seemed to converge upon one another, due to very low wind speed. No spacing measurements were taken during this segment in order to avoid biasing the statistics.

<u>3 May 1971</u>

Eighteen measurements of spacing were used to obtain an average spacing of 7.7 meters with an average wind speed of

3.0 m/sec. The average angle of windrow deflection was 2° to the right of the wind. Fully eight of the 18 measurements showed no angle of deflection.

11 May 1971

Eleven measurements of spacing were used to obtain an average spacing of 9.1 meters with an average wind speed of 3.5 m/sec. The average angle of windrow deflection was 0.6° to the left of the wind. Once again the mode was 0°, occurring in 4 of the 11 phctographs.

Summary of Statistics

	13 April	20 April	27 April	3 May	11 May
Average wind speed (m/sec)	4.0	6.1	3.0	3.0	3.5
Average spacing (meters)	14.2	17.0	8.2	7.7	9.1
Average deflection	9.1 R	0.6 R	0.9 L	2.0 R	0.6 L

Graphs and figures of statistical significance are presented on the following pages. The first three figures are best-fit curves for spacing versus wind speed. Next are histograms of deflection angles, spacing and S/D for each individual day's data. The last three figures are histograms of deflection, spacing and S/D using the total of all three days of data as an input.

A close examination of the data tables at the beginning of this chapter indicates the significance of correctly interpreting any statistic developed from the data therein.

Sixty per cent of the total number of observations have been used to generate the best-fit curves of spacing versus wind speed. Also 52% of the photographs were used for obtaining the deflection angles of the windrows. In several photographs, there can be seen extremely good correlation between the meanders of the smoke plume and the trace of adjacent windrows. This feature will be mentioned in the next section concerning significant individual photographs.

Individual photographs

All photographs presented in this study have been enlarged using the Simon-Omega Autofocus 4 x 5 Enlarger to show clearly some of the characteristics and difficulties involved in measuring both deflection and spacing of windrows.

Photograph 281 has been enlarged $3\frac{1}{2}$ times. It is an excellent photograph taken one minute after completion of card dumping, showing the randomness of the initial pattern and the two buoys anchored 65 feet apart.

In photograph 286 individual rows can be seen forming in large numbers and parallel to each other. This photograph shows also the difficulty involved in measuring both deflection and spacing. Although the majority of visible windrows show general parallelism, there can be seen significant crossings of rows. In the area of row crossing, spacing measurements were impossible. In such a situation deflection angles are at best difficult to define.

Photograph 2816 has been enlarged $2\frac{1}{2}$ times. This photograph is a good example of correlation between the smoke plume meanders and a neighboring windrows orientation.

Photograph 204 has been enlarged 3 times. This photograph shows the difficulty involved in correlating the windrows with the high wind speed. Photograph 204 was taken with a wind speed of 6.0 m/sec. A very interesting characteristic of this photograph is the small number of windrows forming at high wind speeds compared with the large number of windrow showing in the other photographs forming at lower wind speeds.

B. PRESENTATION AND DISCUSSION OF DATA FOR THE STUDY OF THE LANGMUIR CIRCULATION

The number of particles obtained analyzing the water samples using the Coulter Counter, as described in the second part of the previous chapter, were plotted against the size of the particles. Two plots for each day's run, corresponding to the areas of convergence and divergence of Langmuir circulation, are presented on the following pages. The significance of these plots will be discussed later in the next chapter. The x-axis of these plots corresponds to the channel number of the Coulter Counter. The y-axis corresponds to the number of particles. The graphs on these plots give the number of particles at each channel at each depth. The size of the particles corresponding to each channel is indicated below the channel number on the x-axis of the plots. The 02 channel number corresponds to the

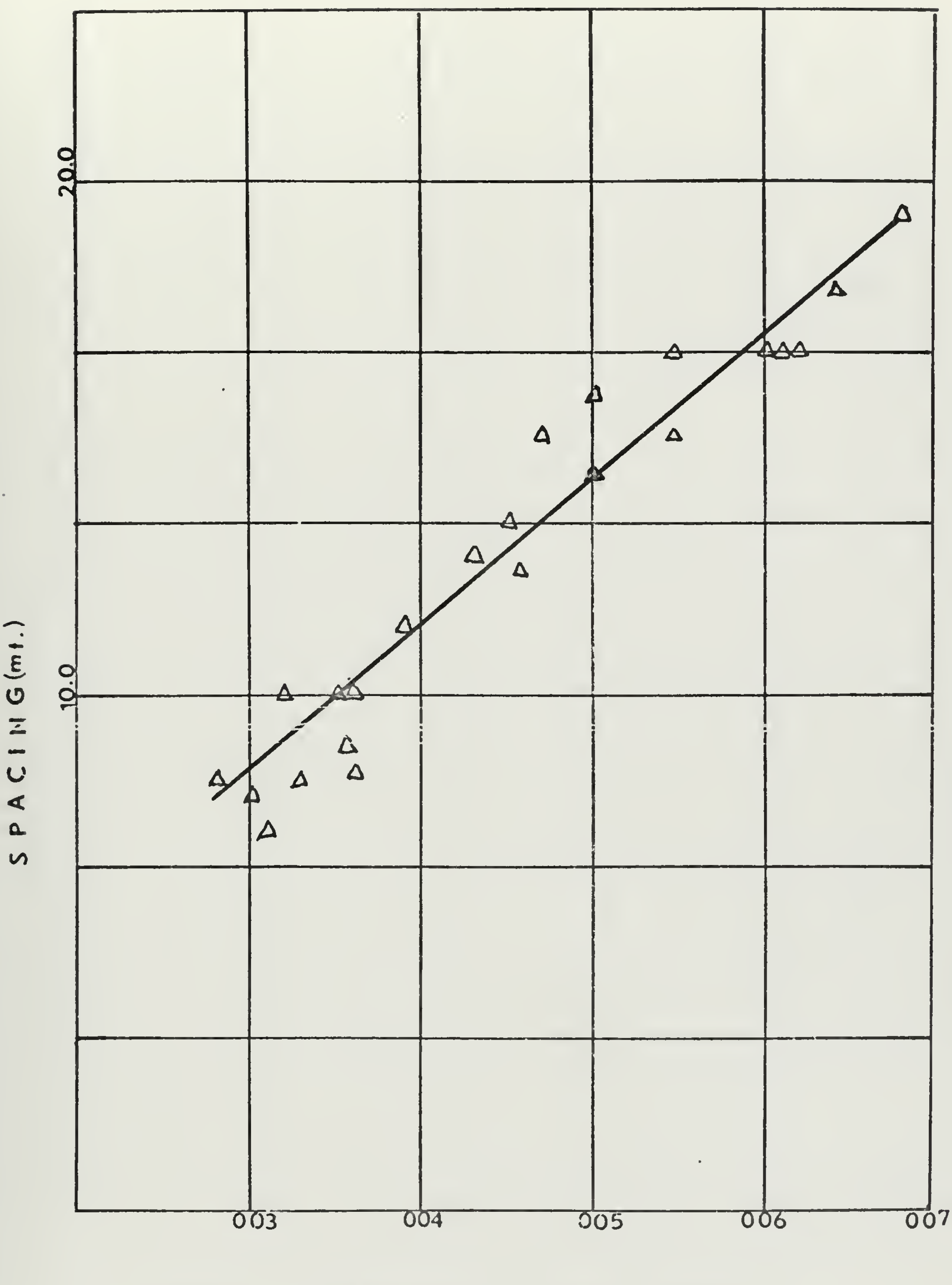

Figure 2. Least-Squares Fit, First Degree, for Spacing Versus Wind Speed.

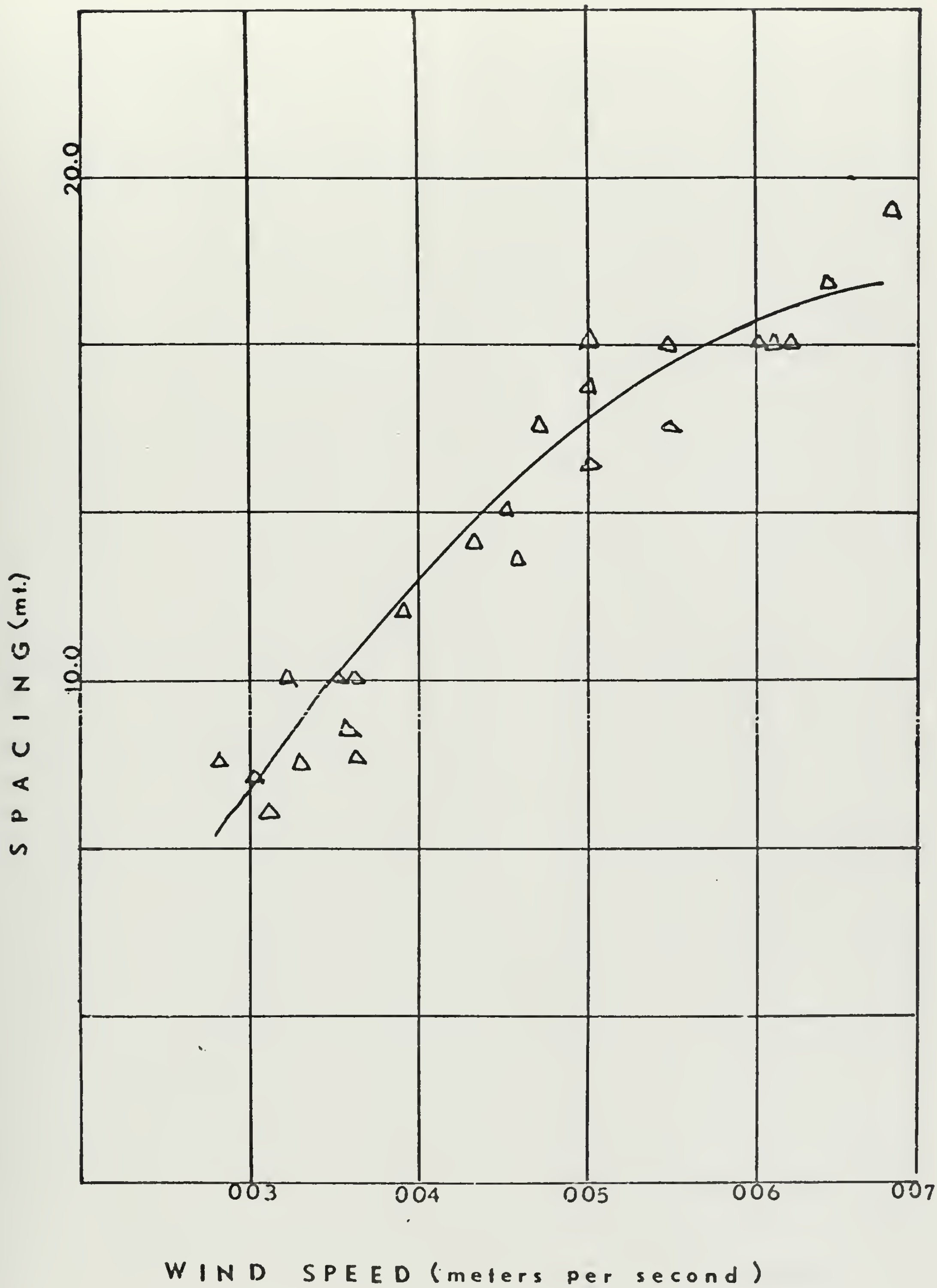

Figure 3. Least-Squares Fit, Second Degree, for Spacing Versus Wind Speed.

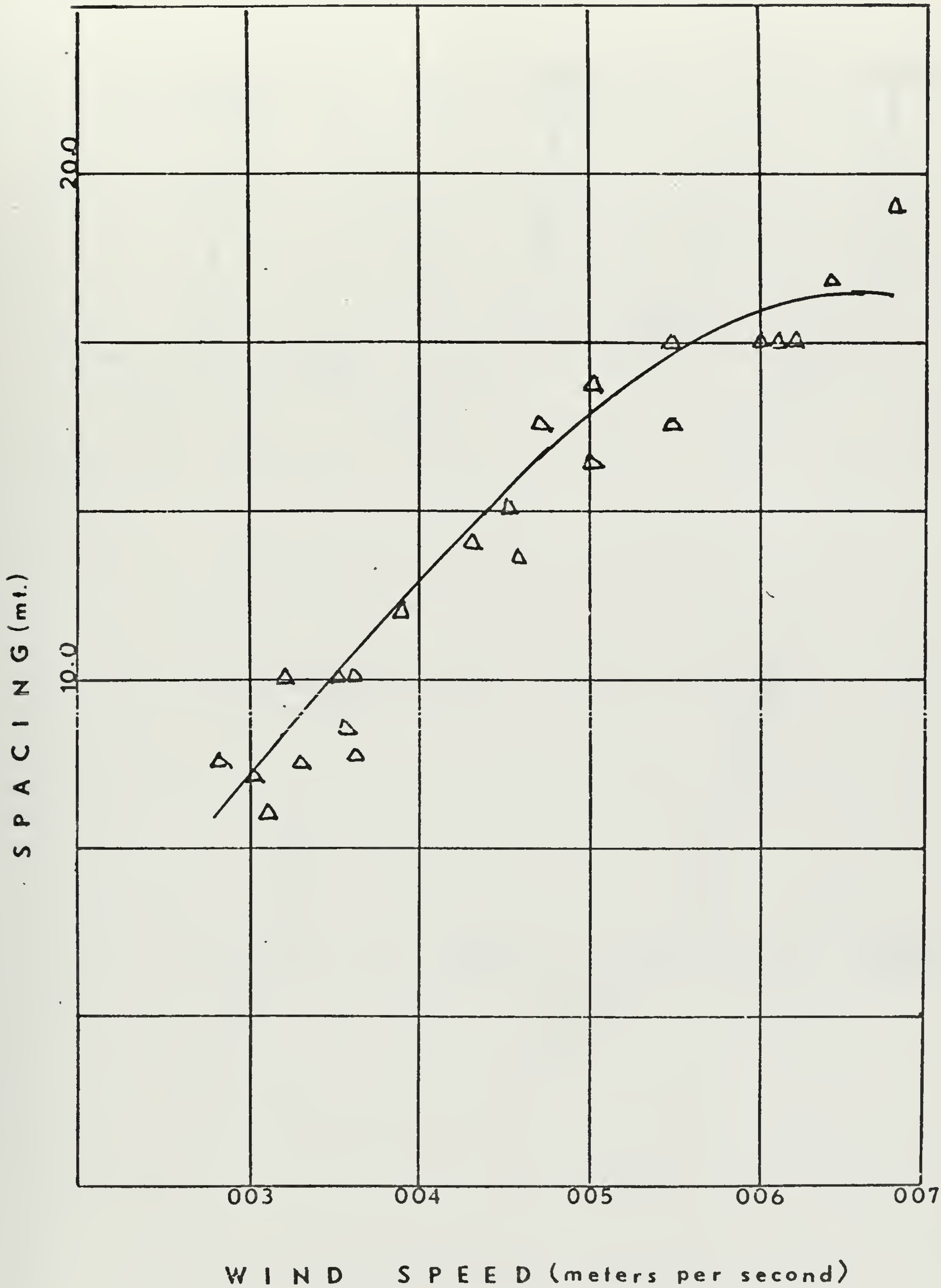

Figure 4. Least-Squares Fit, Third Degree, for Spacing Versus Wind Speed.

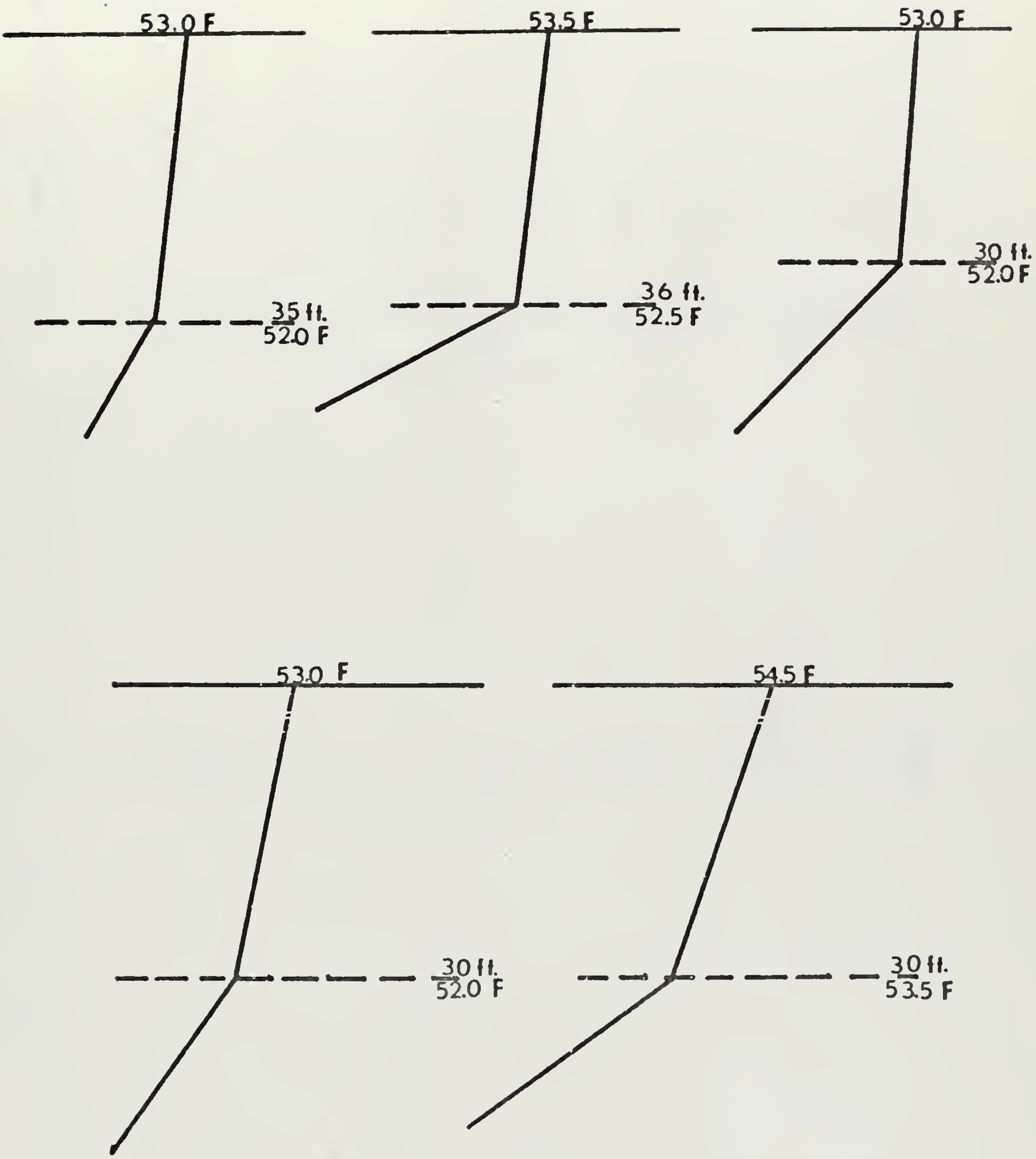

Figure 5. Bathythermograph Traces for 13, 20, 27 April and 3, 11, May.

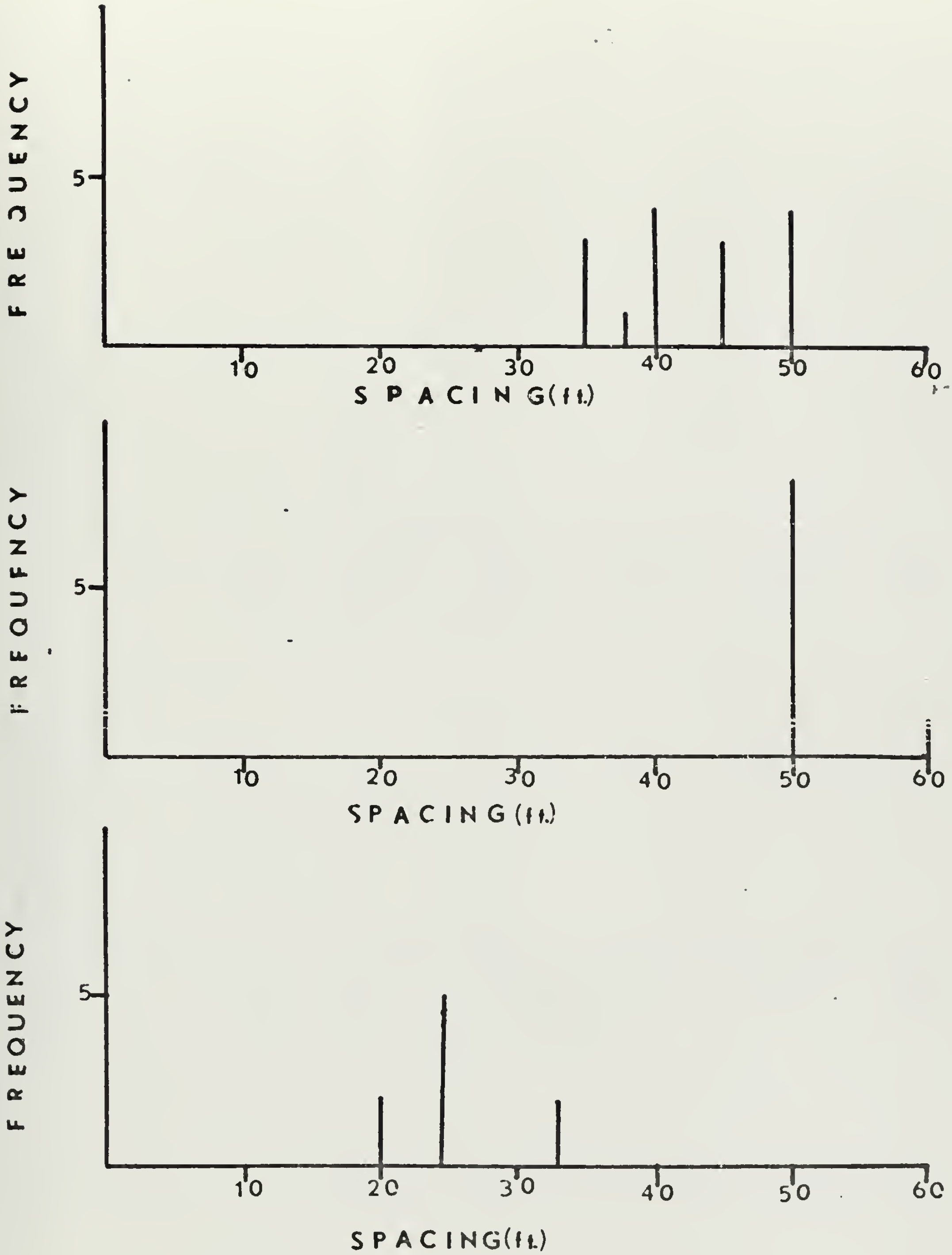

Figure 6. Spacing Histograms for 13, 20, 27 April.

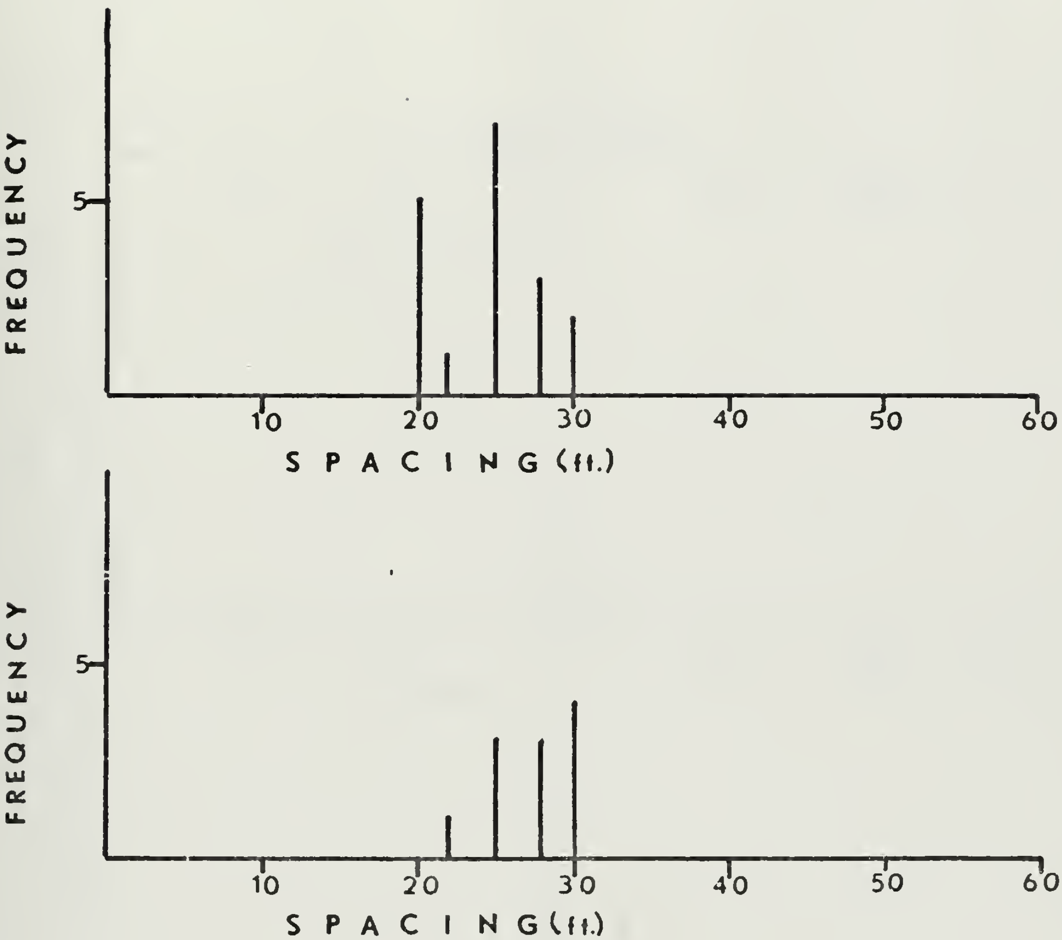

Figure 7. Spacing Histograms for 3, 11 May.

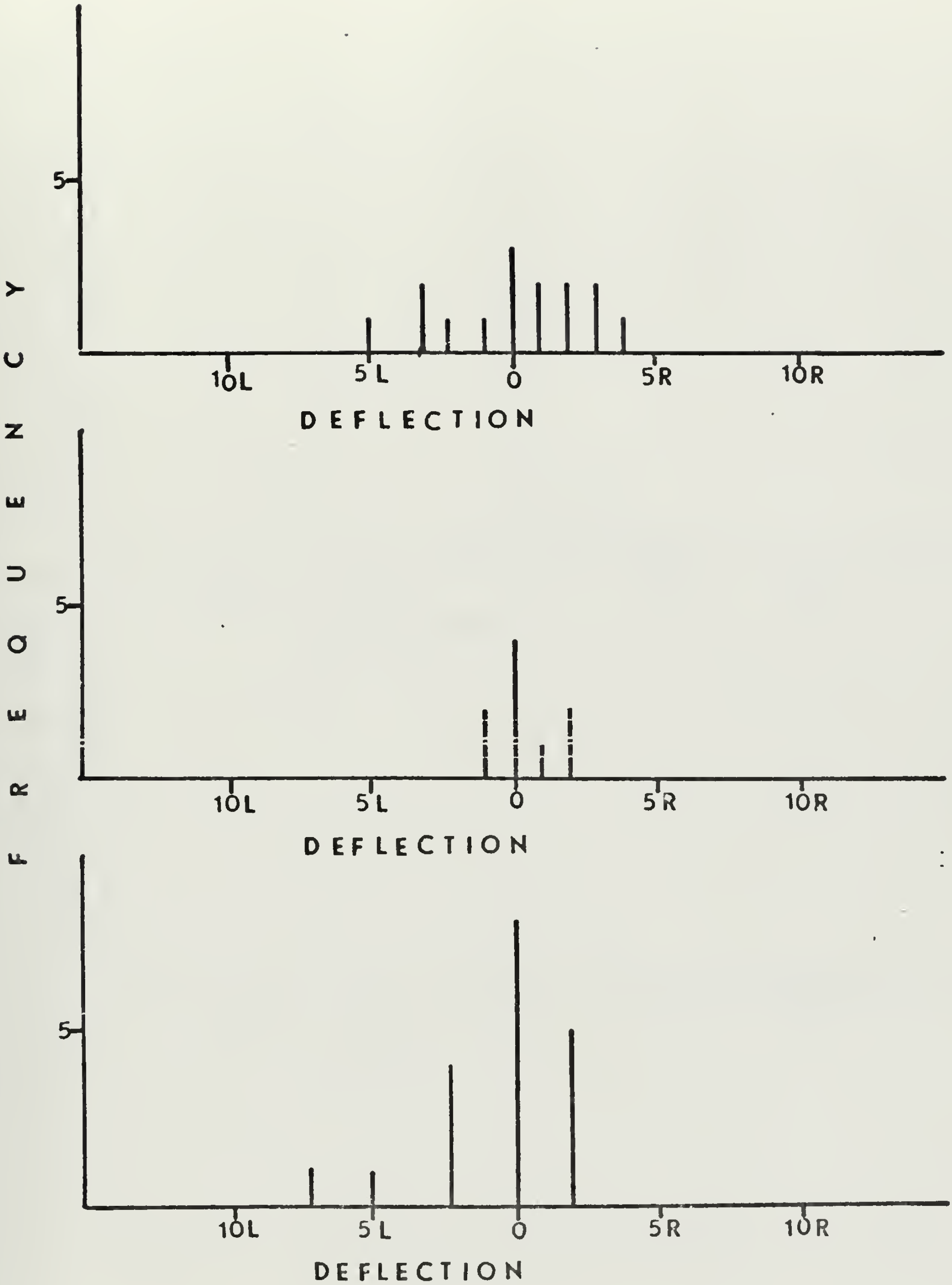

Figure 8. Deflection Histograms for 13, 20, 27 April.

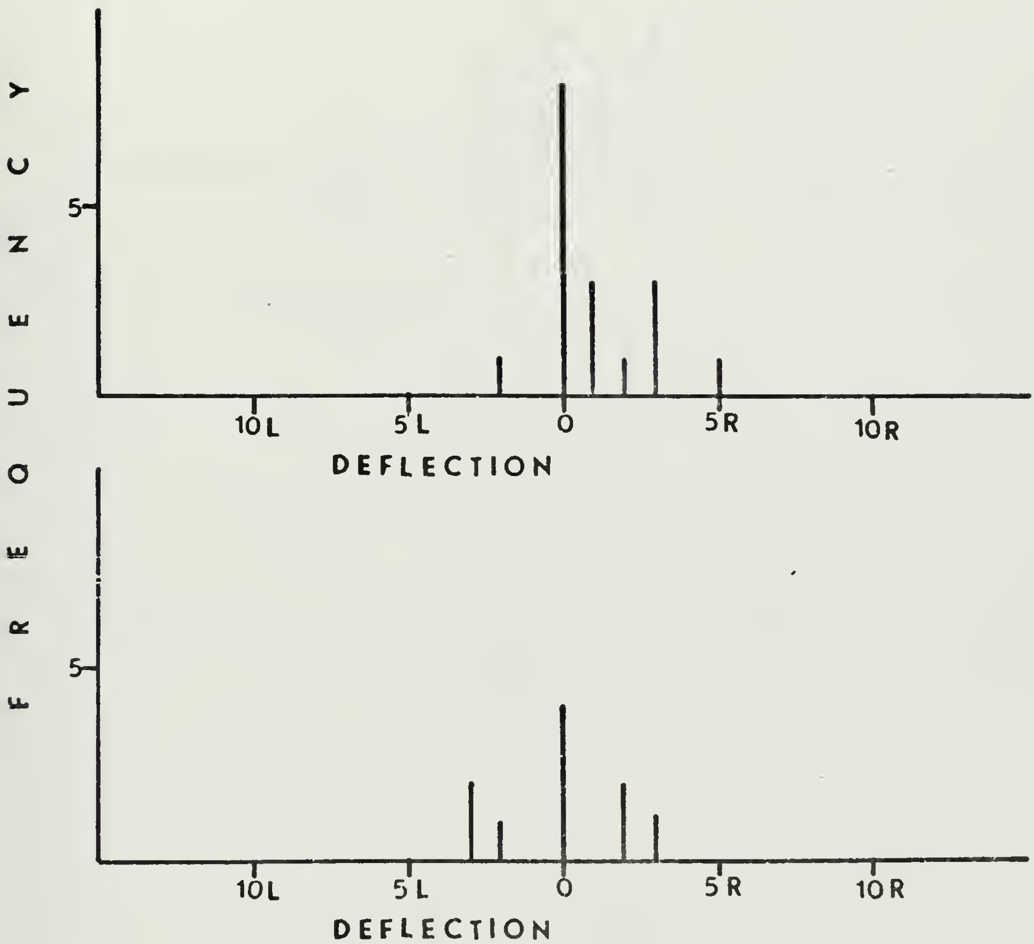

Figure 9. Deflection Histograms for 3, 11, May.

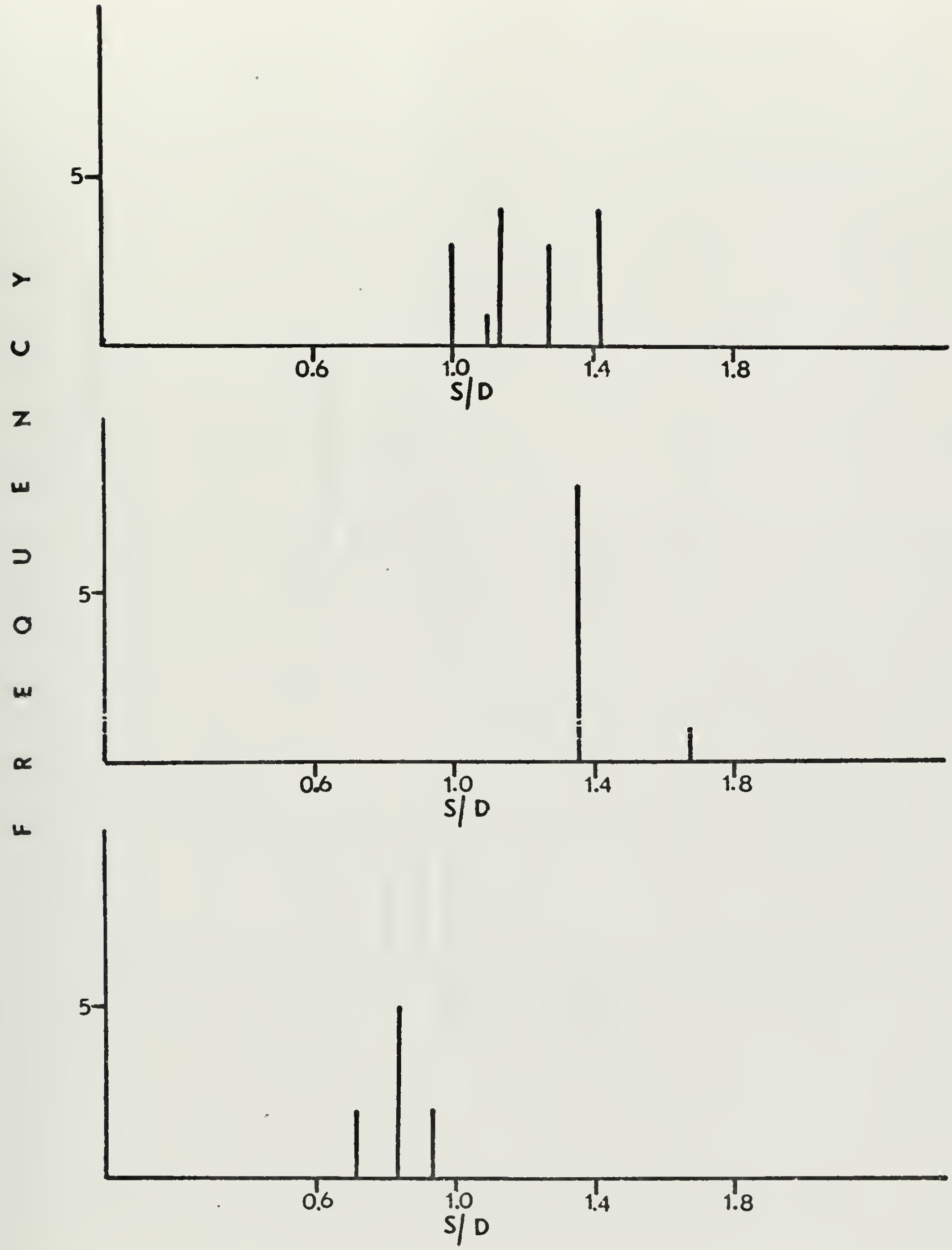

Figure 10. S/D Histograms for 13, 20, 27, April.

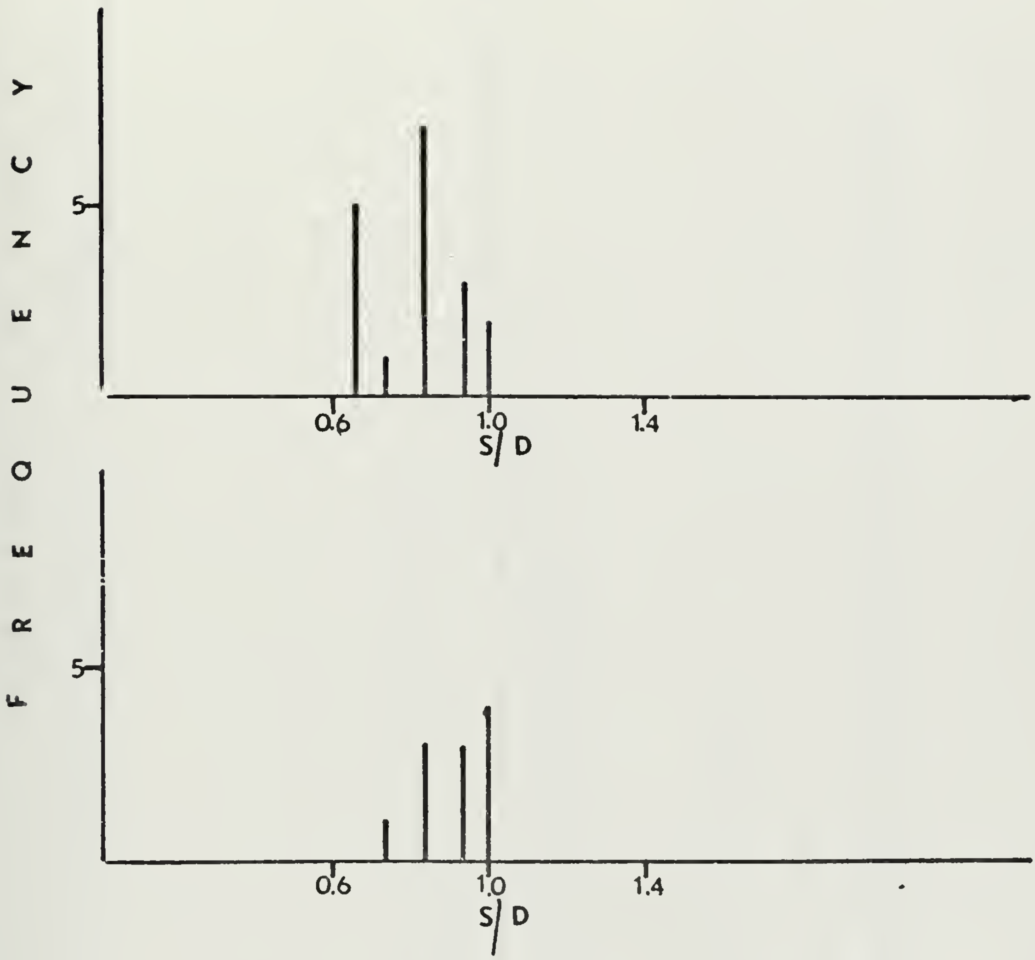

Figure 11. S/D Histograms for 3, 11 May.

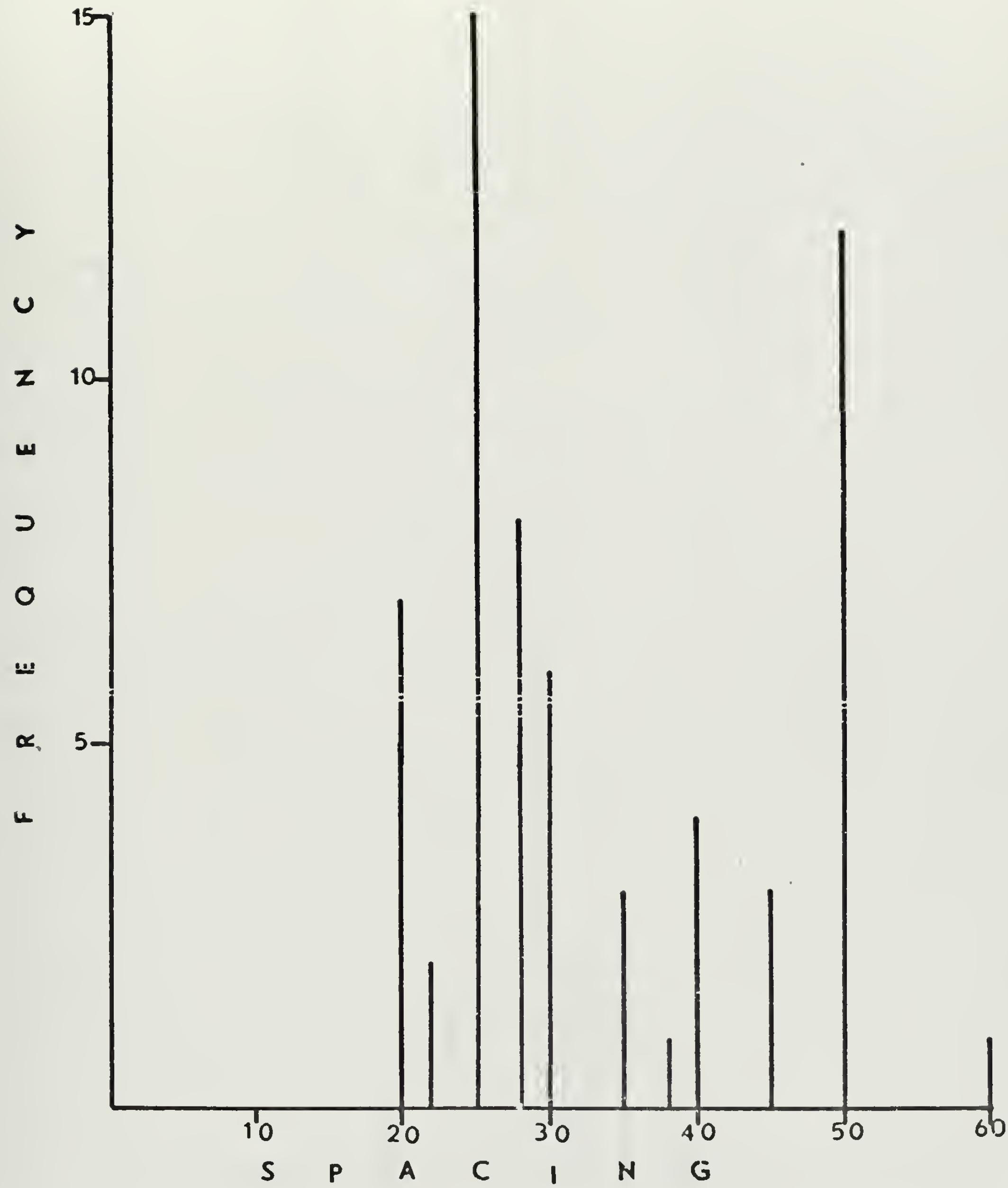

Figure 12. Histogram of Total Spacing Data.

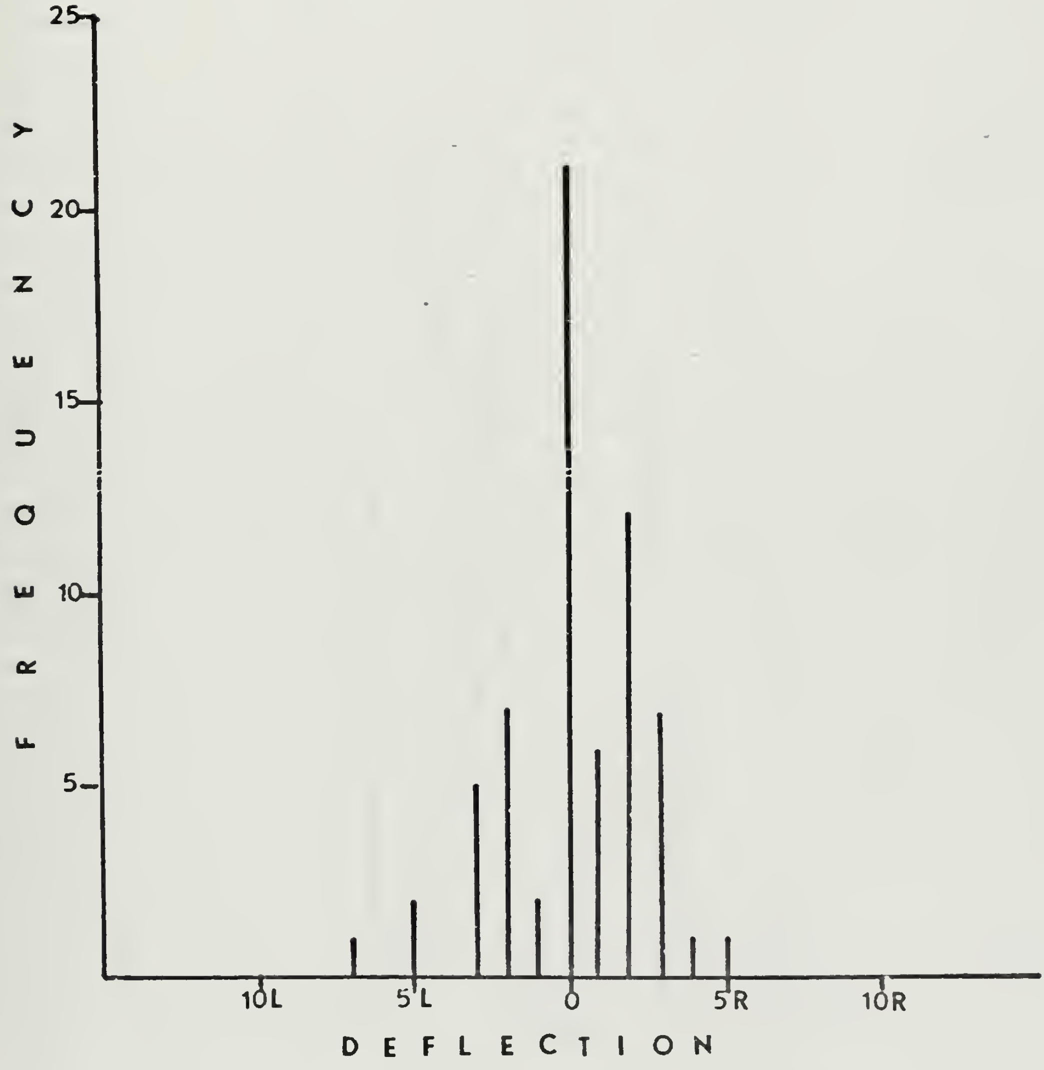

Figure 13. Histogram of Total Deflection Data.

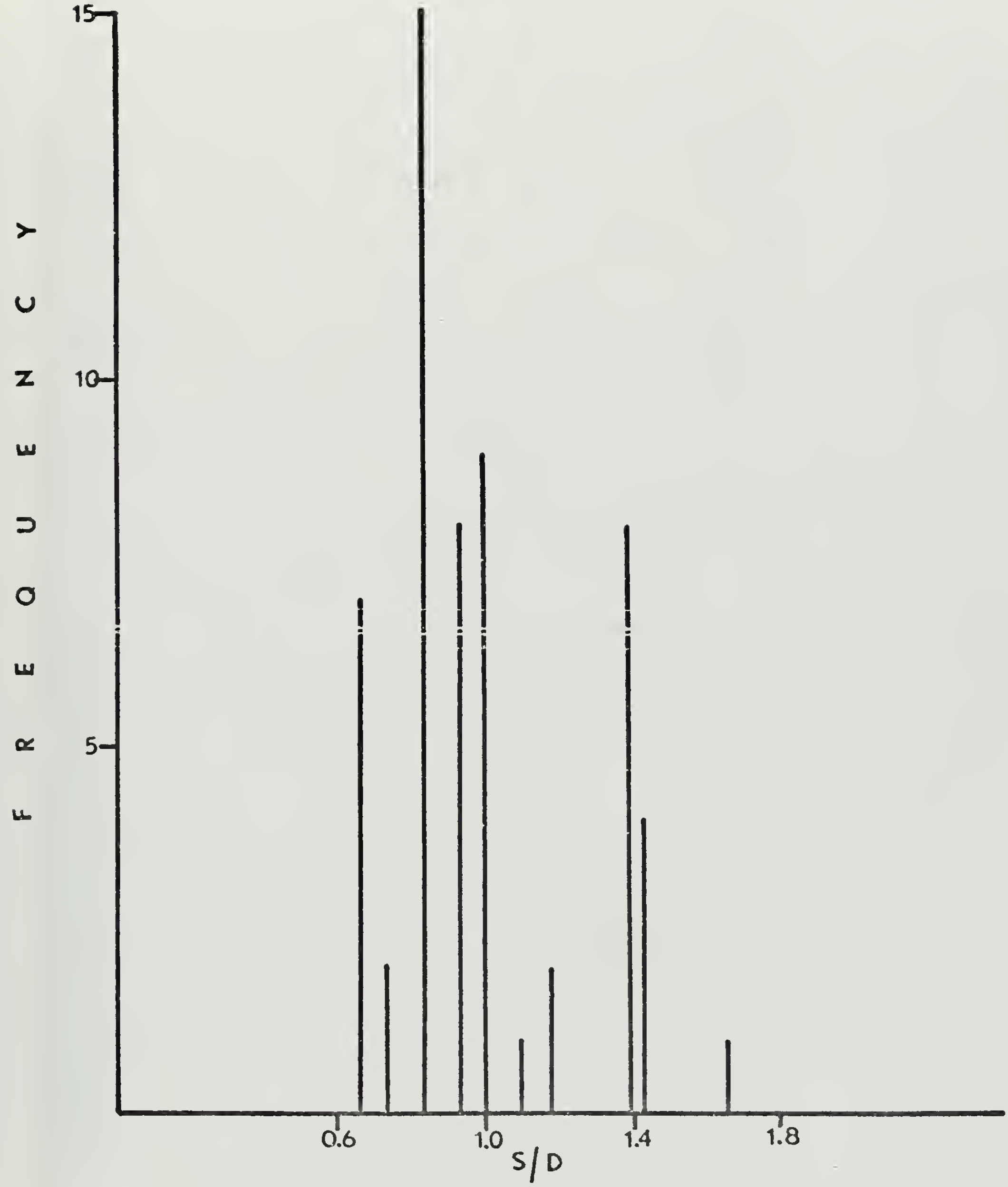

Figure 14. Histogram of Total S/D Data.

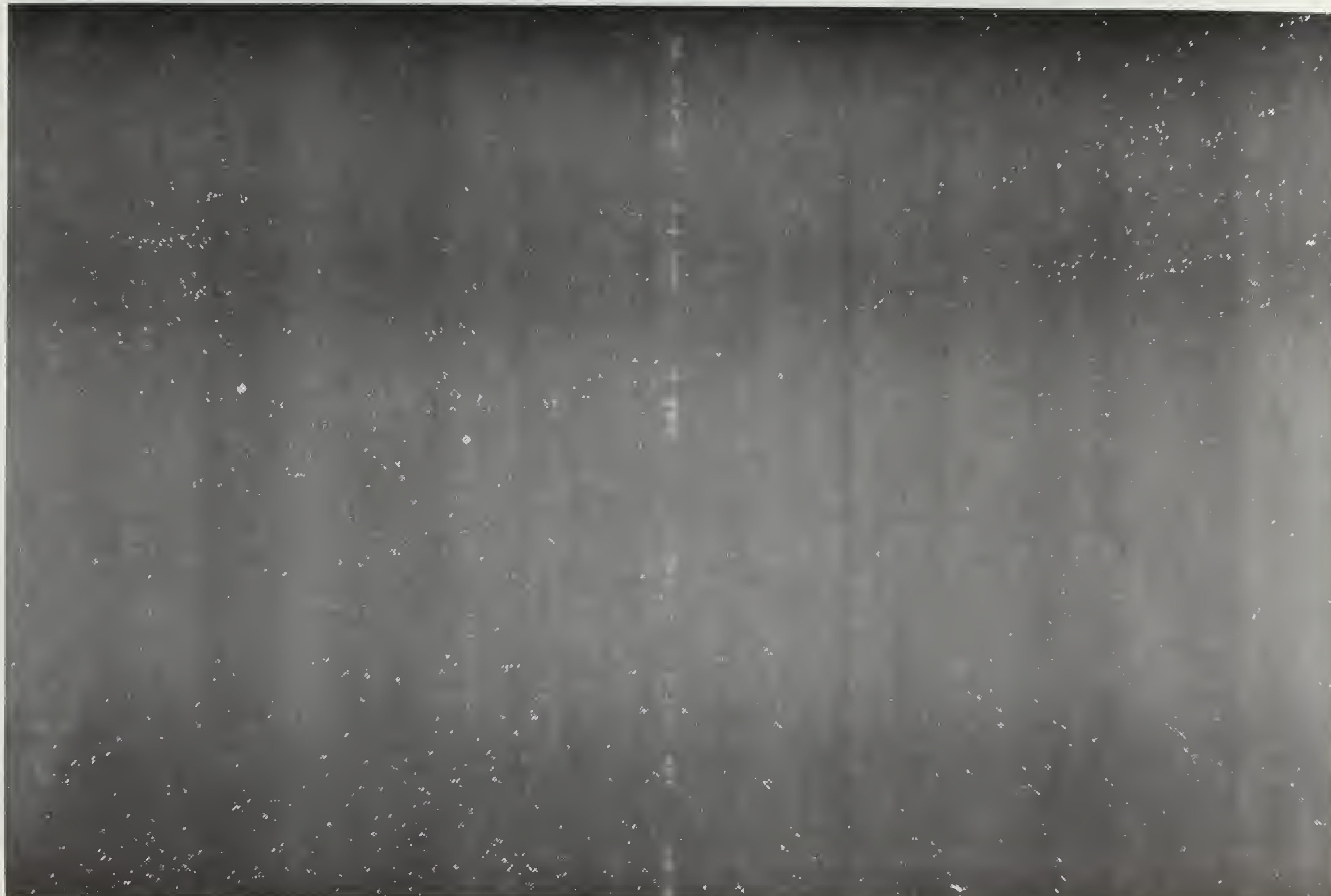

Figure 15. Photograph 281.

Figure 16. Photograph 286.

Figure 17. Photograph 2816.

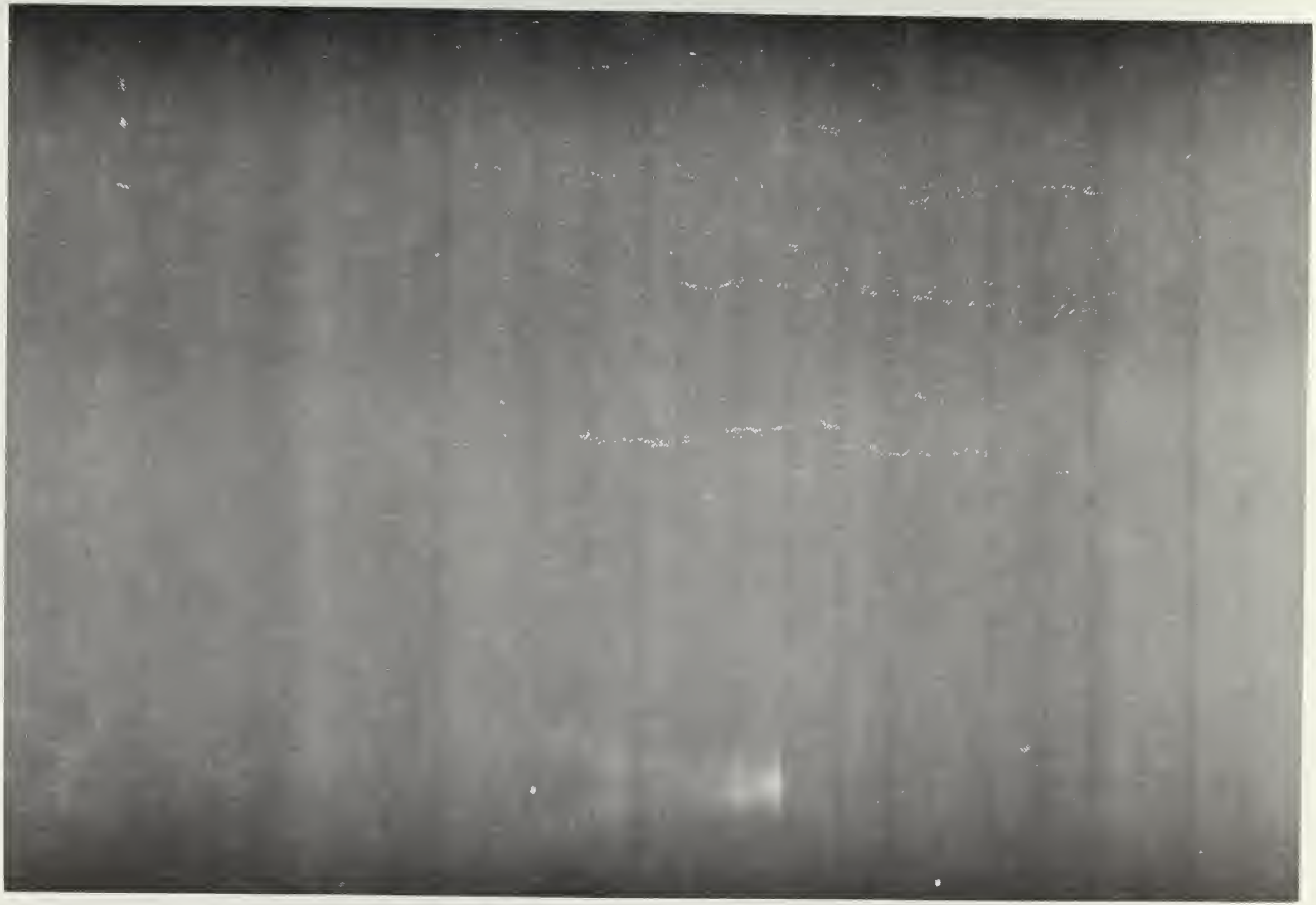

Figure 18. Photograph 204.

20 micron diameter sand that was used in this study. From the graphs it can be seen that the number of particles increases tremendously by increasing the channel number due to the existance of plankton in the water samples.

Some difficulties that were encountered while obtaining the data for the study of the Langmuir circulation are the following: (1) maintaining the boat in a good position so that the pattern of the windrows is not disturbed, (2) keeping the sand in the same water column during most of the 5 minutes time interval, (3) collecting the sand at different depths. The first difficulty was solved by keeping the boat along the outer downwind windrow so that any drifting of the boat due to wind would move the boat away from the windrow pattern. The second difficulty was solved by assuming that from the time the sand was introduced in the surface of the sea and above the Nansen bottles, it was trapped in the vertical current caused by the Langmuir circulation. The collection of the sand at different depths came out to be a very important factor in this study because it gives a representation of the diffusion of the sand which will be used in the calculations of the vertical velocities of the Langmuir circulation. This part will be discussed in more detail in the next chapter.

Also it has to be noted that the first day's data were taken with an average wind speed of 6.0 m/sec and the second day's data were taken with an average wind speed of 3.2 m/sec.

Five different underwater observations of vertical velocity were made just offshore from the Coast Guard pier in Monterey Bay, on 21 of August, in order to determine the average rate of sinking of the 20 microns sand. No wind and no wave activity were present at the time of observation. An average value of 2.8 cm/sec was determined, as representative of the rate of sinking of the sand in the upper 15 meters of the water column.

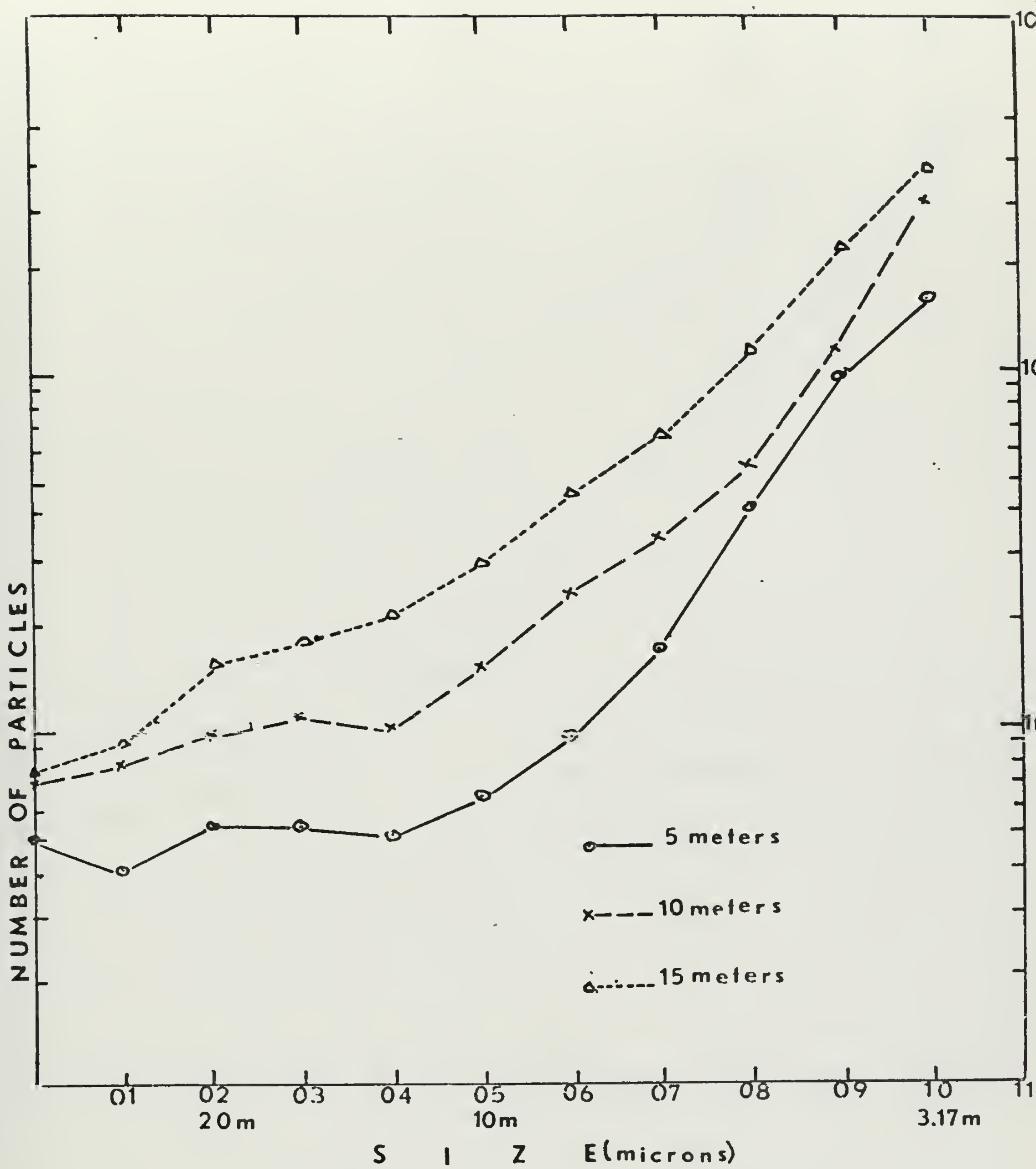

Figure 19. Distribution of Particles Versus Size in the Area of Convergence for 11 March.

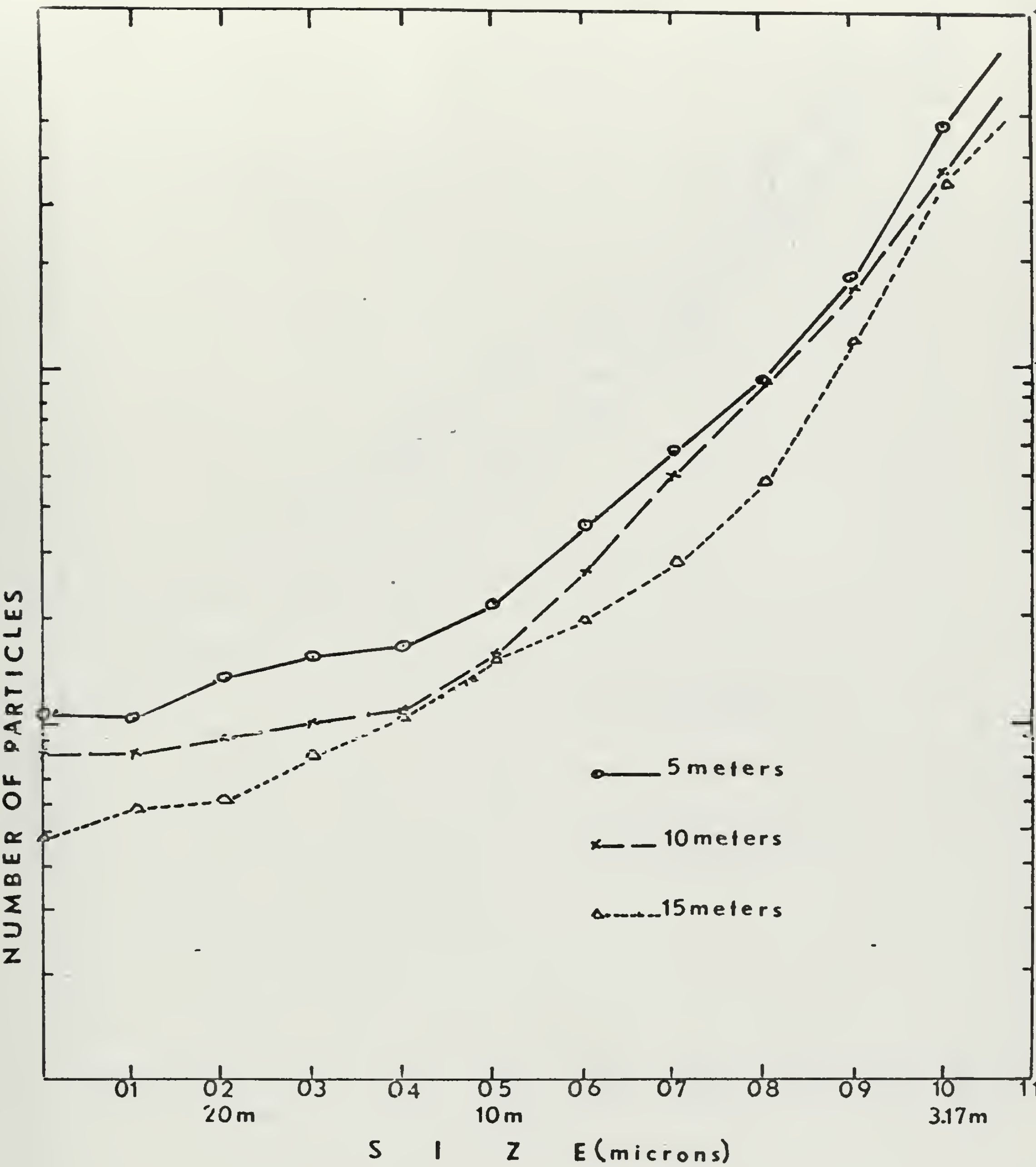

Figure 20. Distributuon of Particles versus Size in the Area of Divergence for 11 March.

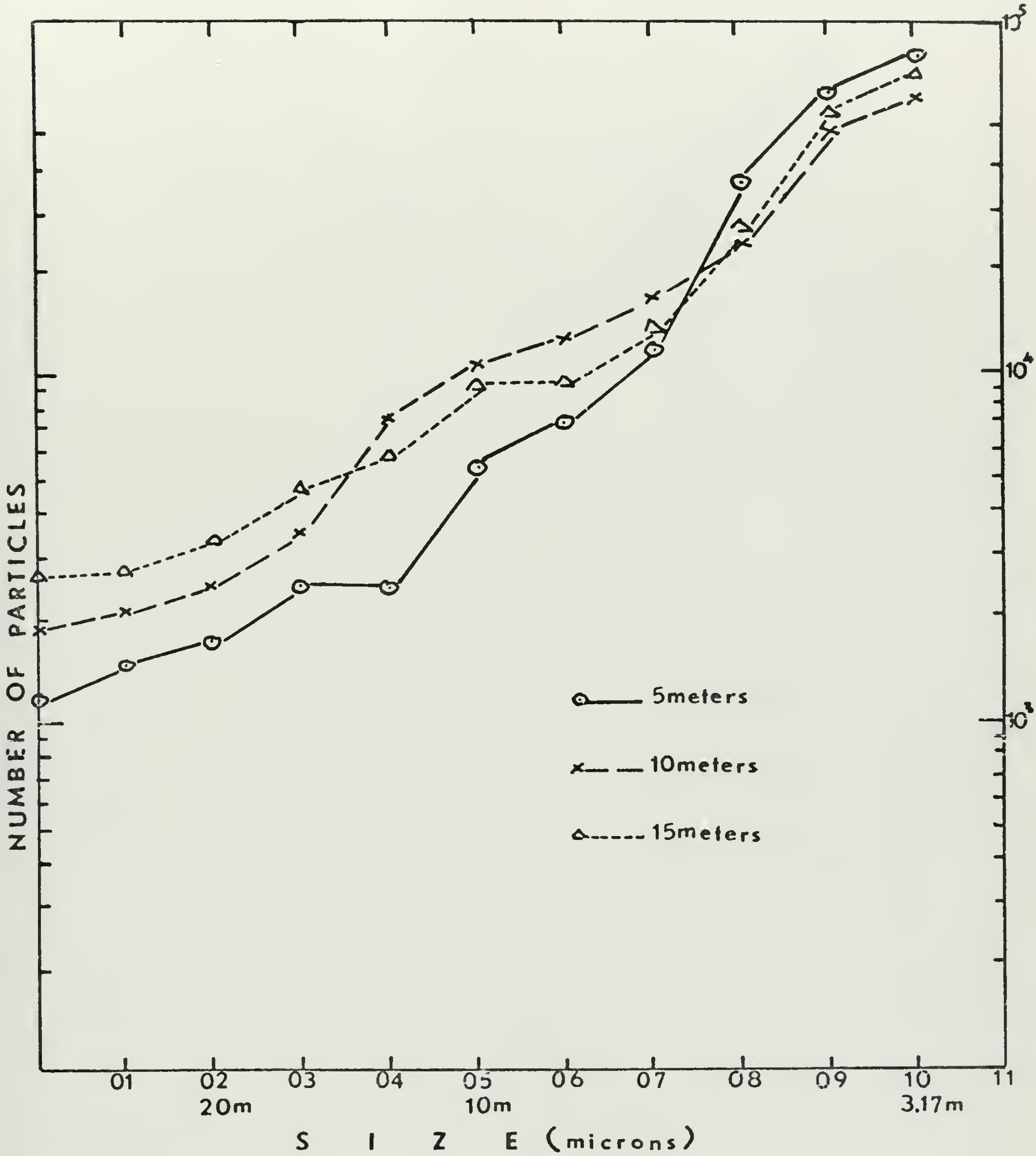

Figure 21. Distribution of Particles Versus Size in the Area of Convergence on 15 July.

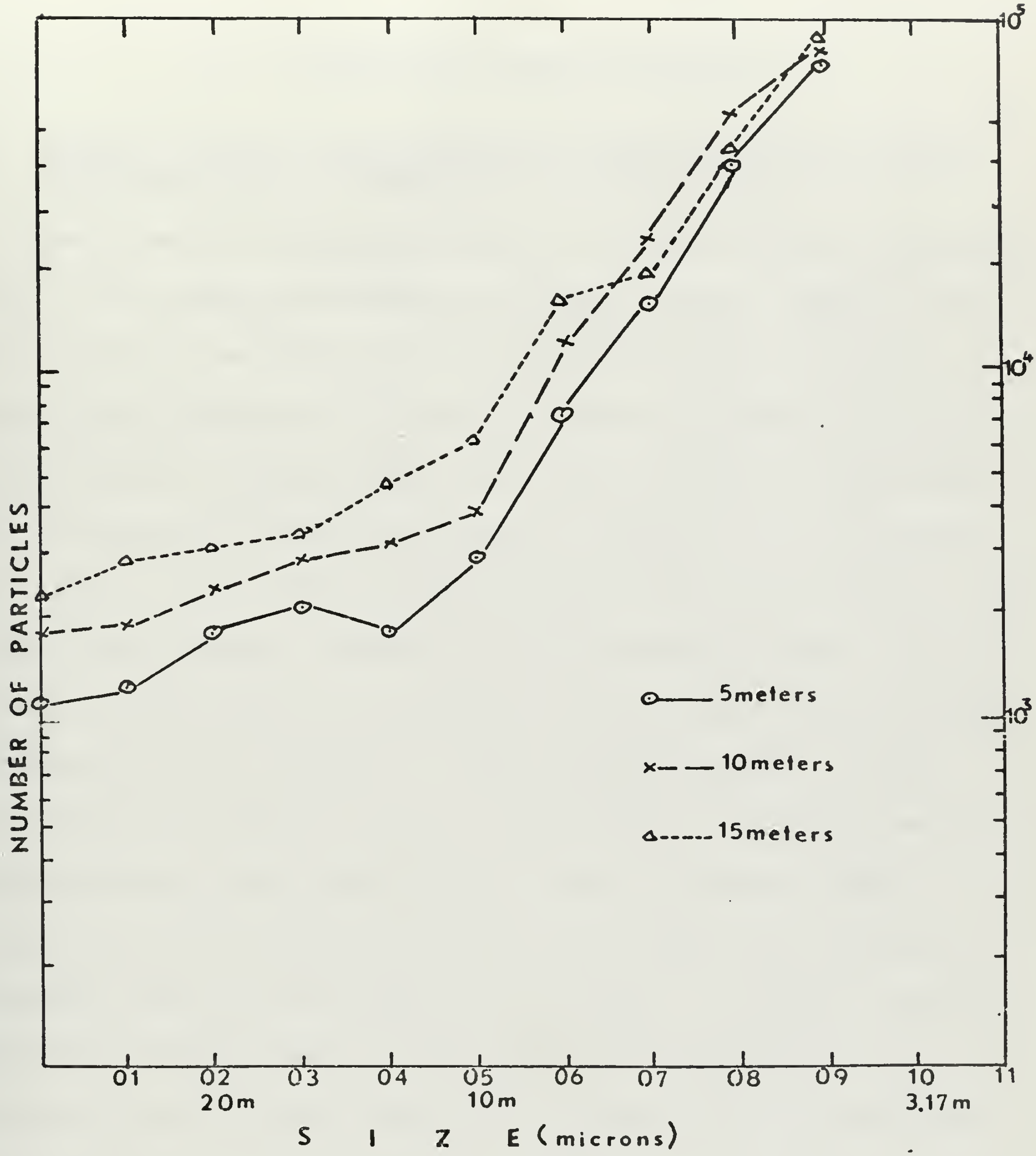

Figure 22. Distribution of Particles versus Size in the Area of Divergence on 15 July.

IV. RESULTS AND RECOMMENDATIONS

A. RESULTS OF THE INVESTIGATION OF THE NEAR SHORE SURFACE CHARACTERISTICS OF WINDROWS IN MONTEREY BAY

The primary conclusion derived from the data of the first part of the previous chapter, is that a great number of observations is required before any significant statistics concerning spacing and deflection can be derived. This in turn leads to the conclusion that any statistical relationship concerning deflection angle or spacing must be viewed in light of the number of observations taken and the physical conditions present. Based on the photographs taken for this report, near shore windrow spacing in Monterey Bay must be considered to be related to the wind speed alone. Also from the photographs it can be seen that no windrows were formed below a wind speed of 2.8 m/sec. Csanady (1965) reported on 246 observations that only once were windrows observed below a wind speed of 2.1 m/sec. Sullivan (1964) made 27 sampling runs on Lake Huron and he observed no windrows below a wind speed of 3.5 m/sec. Faller and Woodcock observed that for winds of Beaufort 2 or less ($W < 3.0$ m/sec) the Sargassum generally gathers into large patches rather than into rows. All these reports indicate that the lower value of wind speed needed for the formation of the windrows, varies from place to place, depending upon the season, local sea state conditions, etc. A close examination of the least-squares fit curves (Fig. 2, 3,

and 4) indicates that there exists a first degree relationship between teh windrow spacing and the wind speed given by the formula:

$$L = 0.10 + W \times 2.8 \text{ sec.}$$

where:

L = spacing of windrows in meters

W = wind speed in meters per second

Faller and Woodcock (1964) used a data base of only 14 samples taken during August to postulate the dependence of windrow spacing upon wind speed as: L(meters) = 4.8(sec.) x W(m/sec) assuming that the line of L versus W passes through the origin.

The crucial question suggested by Langmuir namely, to what extent do the helical vortices determine the mixed-layer depth, is not answered in this study. The ratio of average windrow spacing to mixed-layer depth for 13 of April, and 20 of April is $\overline{L}/\overline{D} = 1.3$ with an average wind speed of 5.1 m/sec, and for 28 of April, 3 of May and 11 of May, is $\overline{L}/\overline{D} = 0.85$ with an average wind speed of 3.1 m/sec. Using all the data together the ratio $\overline{L}/\overline{D} = 1.1$ is obtained, which would be a reasonable ratio of cell width to depth, but the data exhibit no significant correlation between L and D. As only one example of the complexity of the problem, it is noted that internal waves on the thermocline would cause horizontal divergence in the mixed-layer (Ewing 1950) and might tend to produce a negative correlation

between L and W. In the presence of a steady wind the magnitude of this effect would depend on various factors including the amplitude, direction, and frequency of the internal waves, the mixed-layer depth, the response of the distorted vortices to the wind, and the rate of erosion of the thermocline by the vortices.

Deflection angle measurements indicate that windrows generally orient themselves roughly parallel to the wind. Although angles between 7° left and 5° right of the wind were observed, the angle of zero deflection was most common as indicated by the histogram of Total Deflection Data (Fig. 13). A statement is needed here concerning the derivation of a given angle from a particular photograph. Faller (1964) used a photograph of mica strips and smoke floats to derive deflection angles. Faller used the angle each windrow made with the smoke plume as an individual sample. In this report, the photograph itself is considered to be a single sample, and the rows seen used to determine a predominant or average angle of deflection. This method would seem to take into account a given set of physical circumstances during a given sample period and represent filtered data to some extent.

Response of the windrow orientation to major wind shift appears to occur within minutes. The single observation of an abrupt wind shift indicated a response time for row orientation of between two and four minutes.

A summary of the conclusion of the first part is as follows:

1) Near shore windrow spacing in Monterey Bay appears to be related strongly to wind speed.

2) Deflection of windrows to the right or left of the wind's direction occurs, but these deflecitons are small and can be expected to be within 5° of the wind.

3) Langmuir's conclusion that "the helical vortices set up by the wind apparently constitute the essential mechanism by which the epilimnion is produced" deserves further consideration and detailed observational study.

4) Windrows respond in their orientation to a wind shift within a few minutes.

5) The path of a windrow is most likely a good indication of the wind field immediately above that windrow.

B. RESULTS OF THE INVESTIGATION OF THE LANGMUIR CIRCULATION IN MONTEREY BAY

A close examination of the curves in Figures 19 and 20 in the second part of the previous chapter show a very important feature. In comparison over the time interval of 5 minutes, the area of convergence of the Langmuir circulation showed the maximum concentration of the 20 microns sand to be at 15 meters as shown in Figure 19, while in the area of divergence of the Langmuir circulation

the maximum concentration was at 5 meters (Fig. 20). The only way that such a result can be obtained, is when a cellular circulation exists, causing an increase in the rate of sinking of the sand in the area of convergence due to a downward current and a decrease in the rate of sinking of the sand in the area of divergence due to an upward current. Figures 19, 20 and the above observation show clearly the cellular form of the Langmuir circulation.

A model is used, in order to get the vertical velocities, in the areas of convergence and divergence, taking into consideration the diffusion of the sand with depth after the 5 minutes time interval. This model is represented with the Fickian equation of diffusion which is,

$$\frac{\partial P}{\partial t} + W \frac{\partial P}{\partial z} - K \frac{\partial^2 P}{\partial_z^2} = 0$$

where

P(z,t) = the relative concentration of the particles

W = the vertical velocity in the area of convergence or divergence

K = kinematic diffusivity coefficient

In the above equation the coefficient of kinematic diffusivity was assumed to be the same in the areas of convergence and divergence. This is an acceptable assumption since the two areas are close enough and they are under the influence of the same wind and the same wave activity. Using the following boundary conditions,

1) No sand flux through the surface after $t = 0$

2) The sum of all the sand in the water column is constant for $t > 0$

3) Initially the sand is all at the surface

we get the solution

$$P(z,t) = \frac{1}{2}\left[\operatorname{erfc}\left(\frac{z-Wt}{2K^{\frac{1}{2}}t^{\frac{1}{2}}}\right) + \operatorname{erfc}\left(\frac{-z-Wt}{2K^{\frac{1}{2}}t^{\frac{1}{2}}}\right)\right]$$

where:

$$\operatorname{erfc}(u) = \frac{2}{\sqrt{\pi}}\int_u^\infty e^{-u^2}du$$

In the above solution the vertical velocity W and the coefficient of diffusivity K are variables. In Figure 23, the normalized solution for W = 2.5 cm/sec and K = 1200 cm^2/sec has been plotted along with the normalized values of the sand concentration in the areas of convergence and divergence, obtained from Figures 19 and 20. From this figure it can be seen that the data obtained from the area of convergence coincide with the curve of 5 cm/sec and the data obtained from the area of divergence coincide with the curve of 2 cm/sec. In order to have the continuity of vertical velocities of the areas of convergence and divergence the following equations must be satisfied:

$$\overline{S} + W_c = 5$$

$$\overline{W} + W_d = 2$$

where:

$\overline{S}$ = average rate of sinking of the patch of 20 microns sand in the upper 15 meters of the water column, which was determined to be 2.8 cm/sec.

W_c = vertical velocity in the area of convergence caused by the Langmuir circulation.

W_d = vertical velocity in the area of divergence caused by the Langmuir circulation.

From these two equations the value of W_c and W_d can be obtained.

W_c = 2.2 cm/sec

W_d = -0.8 cm/sec

These two values show very clearly that there exists a downward current in the area of convergence of magnitude 2.2 cm/sec and an upward current of magnitude of 0.8 cm/sec in the area of divergence for the data obtained on 11 March.

Langmuir in 1939 reported the following: "A few measurements were made of the vertical components of motion by means of a large square sheet of aluminum suspended in a horizontal plane from a small lamp bulb so weighted as to give practically zero buoyancy. With a wind speed of 6 m/sec, it was found in the windrows two meters below the surface descending currents of about 2 to 3 cm/sec and rising currents of from 1 to 1.5 cm/sec midway between adjacent windrows."

Figures 21 and 22 of the previous chapter are based on the data obtained on 15 July 1971. No indication of the cellular motion of the Langmuir circulation can be derived from the curves of these two figures. Actually the maximum

concentration of the 20 microns sand in the areas of convergence and divergence exists at the same depth of 15 meters. This may be due to the following reason: in the first part of this chapter it was stated that no windrows can be formed below a wind speed of about 2.8 cm/sec. Since the data on 15 July were obtained with a wind speed of about 3.2 cm/sec is very likely that the Langmuir circulation was not well established.

C. RECOMENDATIONS

It is strongly recommended that the project of windrow investigation and Langmuir circulation be continued at the Naval Postgraduate School. Several corrections to the investigative technique are indicated. Our suggestions for future investigations fall into three categories: the need for better marking material, an observational study of the ratio of average row spacing to mixed-layer depth, and a complete study of the dependency of vertical velocities of Langmuir circulation upon the wind speed.

If there exists area of convergence more powerful than others, enough material should be scattered in the water to indicate the presence of both the major and minor convergences. The computer cards used in this investigation show the areas of strong convergence. Another method involves the use of small confetti like particles of paper, or powder. The second seeding method must be used in areas where no wave activity is present. As it was mentioned in the first part

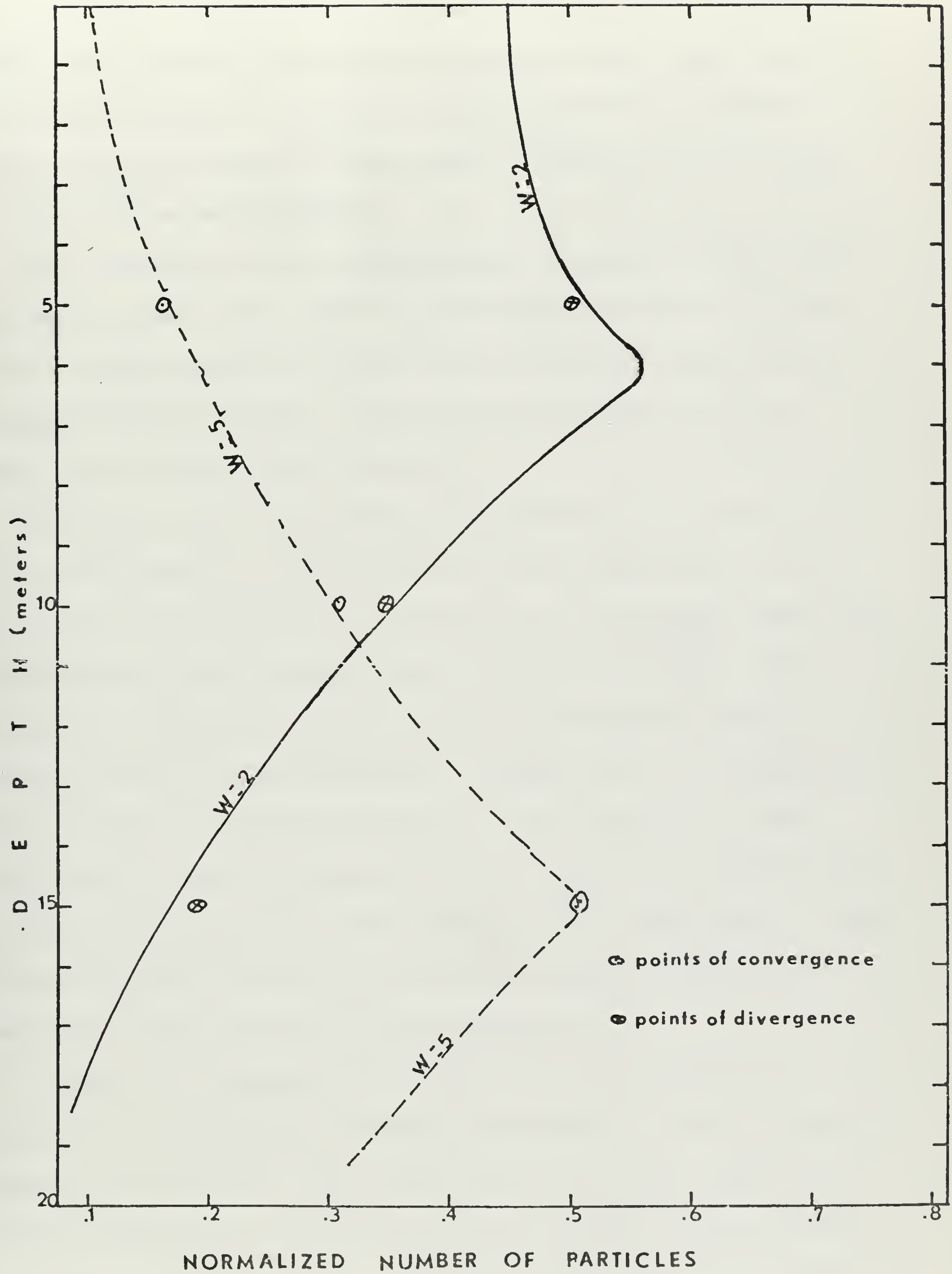

Figure 23. Diagrammatic Representation of the Solution to the Sand Diffusion Problem.

of the second chapter, the Sulfur Dust was first used in this study but was not easily distinguishable especially with wave activity. Also it is suggested that a movie camera could be used to advantage to obtain all the stages of the windrow development.

The accuracy of the relationship obtained between windrow spacing and wind speed can be tested using data taken over a longer period of time, and at various times within a given 24 hour period. Infrared photographs could be taken night or day, for example.

No final result was obtained concerning the ratio L/D. The investigation of this ratio is very important for the study of water pollution. Pollution is collected where the circulating cells converge and is driven downward. Dr. Arnold L. Gordon and Robert Gerard of Columbia Lamont-Doherty Geological observatory, working on the sea pollution near Bermuda announced in May 1971 the following: "The phenomenon, known as Langmuir Cells, previously was thought to extend no deeper than the depth of the mixed-layer. Our studies showed convoluting cells of water as large as 900 feet deep which drive pollution downward."

Also it is suggested the study of the dependency of vertical velocities of Langmuir circulation upon the wind speed be continued. This study has to be made with wind speeds exceeding 4 m/sec so that the Langmuir circulation will be well established. The best period for this study seems to be the months of February, March and April

according to this work. In order to get a better representation of the diffusion of the sand, four to six reversing Nansen bottles can be used at each depth. Each bottle would be reversed after a fixed time interval. This will give the diffusion of the sand at each depth and a value of the vertical velocity at each depth. A fluorescein solution can be used instead of the sand. Also the original method used by Langmuir, as described in reference 5 of the bibliography, can be used.

APPENDIX A

ADDITIONAL REFERENCES

Csanady, G. T., 1963. "Turbulent Diffusion in Lake Huron," J. Fluid Mech., V. 17, pp. 360-384.

Csanady, G. T., 1964. "On Windrows," Univ. of Waterloo, Dept. of Mech. Engr., (unpublished report).

Csanady, G. T., and H. K. Ellention, and R. E. Deane, 1962. "Slicks on Lake Huron," Nature, V. 196, pp. 1305-1306.

Faller, A. J., 1963. "An Experimental Study on Instability of the Laminar Ekman Boundary Layer," J. Fluid Mech., V. 15(4), pp. 363-370.

Ichiye, T., 1965. "Upper Ocean Boundary Layer Flow Determined by Dye Diffusion," Physics of Fluids, Supplement, 1965, pp. 5270-5277.

Kraus, E. B., 1967. "Organized Convection in the Ocean Surface Layer Resulting from Slicks and Radiation Stress," Physics of Fluids, Supplement, 1967, pp. 5294-5297.

Munk, W. H., 1947. "Effect of Earth's Rotation Upon Convection Cells," Ann. N.Y. Acad. Sci., V. 48, pp. 815-820.

Palm, E., 1960. "On Tendency Toward Hexagonal Cells in Steady Convection," J. Fluid Mech., V. 8, pp. 183-192.

Pearson, J. R. A., 1958. "On Convection Cells Induced by Surface Tension," J. Fluid Mech., V. 4, pp. 489-500.

Rayleigh, Lord, 1916. "On Convection Currents in a Horizontal Layer of Fluid, When the Higher Temperature is on the Upperside," Phil. Mag., V. 32, pp. 529-546.

Stommel, H., 1949. "Trajectories of Small Bodies Sinking Slowly through Convection Cells," J. Mar. Res., V. 8(1), pp. 24-29.

Woodcock, A. H., 1944. "A Theory of Surface Water Motion Deduced from the Wind-Induced Motion of the Physalia," J. Mar. Res., V. 5, 196-205.

APPENDIX B

Program for least-squares fit

```
CCMPUTER PROGRAM FCR SMOOTHING AND PLOTTING OF EXPERIMENTAL DATA
      IMPLICIT REAL*8(D)
      REAL*8 ITITLE(12)
      REAL*8 LABEL1/8H        /
      REAL LABEL2/4H    /
      DIMENSION WIND(20),SPACE(20),DWI(20),DFSPCE(20),DELY(20),
     CDTITLE(10),DB(21),DSB(20),X(801),Y(801),DWIND(20),DSPACE(20),
     CB(21)
      DATA DTITLE/10*' '/,DWI/20*1.0D0/
      READ (5,1000) N,KK
      READ(5,2000) (DWIND(K),DSPACE(K),K=1,N)
      DC 10 I=1,KK
      M=-I
      CALL LSQPL2(N,M,DWIND,DSPACE,DWI,DFSPCE,DELY,DB,DSB,DTITLE)
      AINCR=4.0/800.0
      DO 30 J=1,801
      AJ=J
      K=I+1
      X(J)=2.8+(AJ-1)*AINCR
      PCL=0.0
      DC 20 L=1,K
      B(L)=SNGL(DB(L))
   20 PCL=POL+B(L)*X(J)**(L-1)
   30 Y(J)=PCL
      DO 40 II=1,N
      WIND(II)=SNGL(DWIND(II))
      SPACE(II)=SNGL(DSPACE(II))
   40 CONTINUE
      READ(5,3000) (ITITLE(L),L=1,12)
      CALL DRAW(N,WIND,SPACE,1,5,LABEL1,ITITLE,0.0,0.0,0,0,0,0,9,9,1,
     CLAST)
      WRITE(6,4000) LAST
      CALL DRAW(801,X,Y,3,0,LABEL2,ITITLE,0.0,0.0,0,0,0,0,9,9,1,LAST)
      WRITE(6,4000) LAST
   10 CCNTINUE
 1000 FORMAT(2I5)
 2000 FORMAT(8F10.3)
 3000 FCRMAT(6A8)
 4000 FCRMAT('0',10X,'LAST=',I4)
      STOP
      END
```

APPENDIX C

SAND DIFFUSION PROBLEM

$$\frac{\partial P}{\partial t} + W\frac{\partial P}{\partial z} - K \frac{\partial^2 P}{\partial z^2} = 0 \qquad (1)$$

Introduce the following new variable

$$\eta = \frac{(z-Wt)^2}{Kt}$$

then,

$$\frac{\partial P}{\partial t} = \frac{\partial P}{\partial \eta}\left(\frac{\partial \eta}{\partial t}\right) = \frac{\partial P}{\partial \eta}\left[\frac{-2W(z-Wt)}{kt^2} - \frac{(z-Wt)^2}{Kt^2}\right]$$

$$\frac{\partial P}{\partial z} = \frac{\partial P}{\partial \eta}\left(\frac{\partial \eta}{\partial z}\right) = \frac{\partial P}{\partial \eta}\left[\frac{2(z-Wt)}{kt}\right]$$

$$\frac{\partial^2 P}{\partial_z{}^2} = \frac{\partial}{\partial t}\left(\frac{\partial P}{\partial \eta}\ \frac{\partial \eta}{\partial z}\right) = \frac{\partial^2 P}{\partial \eta^2}\left(\frac{\partial \eta}{\partial z}\right)^2 + \frac{\partial P}{\partial \eta}\ \frac{\partial^2 \eta}{\partial z^2} = \frac{\partial^2 P}{\partial \eta^2}\left[\frac{4(z-Wt)^2}{K^2t^2}\right] + \frac{\partial P}{\partial \eta}\ \frac{2}{Kt}$$

Substituting this back into the D.E. (1)

$$\left[- \frac{2W(z-Wt)}{Kt} - \frac{(z-Wt)^2}{Kt^2} + \frac{2W(z-Wt)}{Kt} - \frac{2}{t}\right]\frac{\partial P}{\partial \eta} - \frac{4(z-Wt)^2}{Kt^2}\ \frac{d^2 P}{\partial \eta^2} = 0$$

which reduces to

$$4\eta P'' + (\eta+2)P' = 0 \qquad (2)$$

Integrating this once gives:

$$\frac{P''}{P'} = -\left(\frac{\eta+2}{4\eta}\right) = -\frac{1}{4} - \frac{1}{2\eta}$$

Or,

$$\ell n\ P' = -\frac{1}{4}\eta - \frac{1}{2}\ \ell n \ + \ell n\ \frac{C_1}{4}$$

and this is equivalent to

$$P' = \frac{C1}{4} \eta^{-1/2} e^{-\eta/4} \tag{3}$$

Introduce the new variable

$$u = \frac{1}{2} \eta^{1/2}$$

then,

$$\frac{dP}{d\eta} = \frac{dP}{du} \frac{du}{d\eta} = \frac{dP}{du} \left(\frac{1}{4} \eta^{-1/2} \right)$$

Using this equation (3) becomes

$$\frac{dP}{du} = C_1 e^{-u^2}$$

And integrating gives

$$P = C_2 \int e^{-u^2} du + C_2 \tag{4}$$

Appropriate limits must now be determined by the boundary conditions, which are:

1) No sand flux through the surface after $t = 0$

2) The sum of all the sand in the water column is constant for $t > 0$

3) Initially the sand is all at the surface.

If the error function is defined as

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$

equation (4) becomes

$$P(u) = \frac{C_1}{2} \sqrt{\pi}\ \mathrm{erf}(u) + C_2$$

Or

$$P(\eta) = \frac{C_1\sqrt{\pi}}{2} \operatorname{erf}\left(\frac{z - Wt}{2K^{\frac{1}{2}}t^{\frac{1}{2}}}\right) + C_2$$

To match the boundary conditions we evaluate the constants to get:

$$P(z,t) = \frac{1}{2}\left[\operatorname{erfc}\left(\frac{z - Wt}{2K^{\frac{1}{2}}t^{\frac{1}{2}}}\right) + \operatorname{erfc}\left(\frac{-z-Wt}{2K^{\frac{1}{2}}t^{\frac{1}{2}}}\right)\right] \tag{5}$$

where

$$\operatorname{erfc}(u) = \frac{2}{\sqrt{\pi}} \int_u^\infty e^{-u^2}\, du.$$

BIBLIOGRAPHY

1. Csanady, G. T., 1965. "Windrow Studies," Baie Du Dore Report 1965, Great Lakes Institute Report No. PR, pp. 60-82.

2. Ewing, G., 1950. "Slicks, Surface Films, and Internal Waves," J. Mar. Res., V. 9, pp. 161-181.

3. Faller, A. J., 1963. "The Angle of Windrows in the Ocean," Tellus, V. 16(3), pp. 363-370.

4. Faller, A. J., and A. H. Woodcock, 1964. "The Spacing of Windrows in the Ocean," J. Mar. Res., V. 22, pp. 22-29.

5. Langmuir, Irving, 1938. "Surface Motion of Water Induced by Wind," Science, V. 87, pp. 119-123.

6. McLeish, W., 1968. "On the Mechanisms of Wind Slick Generation," Deep Sea Research, V. 15, pp. 461-469.

7. Sullivan, P. J., 1964. "Windrows; in Hydrodynamic Studies on Lake Huron at Baie Du Dore," Great Lakes Institute, Univ. of Toronto and Univ. of Waterloo, PR19.

8. Uttormark, P. D., 1968. "A Thermal-Convection Model of Langmuir Circulation," Unpublished PhD Thesis, Univ. of Wisconsin.

9. Wellander, P., 1963. "On Generation of Wind Streaks on the Sea by Action of the Surface Film," Tellus, V. 15(1), pp. 67-71.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library Naval Postgraduate School Monterey, California 93940	2
3.	Oceanographer of the Navy The Madison Building 732 N. Washington Street Alexandria, Virginia 22314	1
4.	National Oceanographic Data Center Washington, D.C. 20390	1
5.	Office of Naval Research Special Projects (Code 418) Department of the Navy Washington, D.C. 20360	1
6.	Office of Naval Research Geophysics Branch (Code 416) Department of the Navy Washington, D.C. 20360	1
7.	Department of Oceanography, Code 58 Naval Postgraduate School Monterey, California 93940	1
8.	Department of Meteorology, Code 51 Naval postgraduate School Monterey, California 93940	1
9.	Professor N. E. Boston Department of Oceanography Naval Postgraduate School Monterey, California 93940	5
10.	Hydrographic Service of Navy Paparrigopoulou 2 Athens, Greece	2

11. Lieutenant A. Maratos 2
Hydrographic Service of Navy
Paparrigopoulou 2
Athens, Greece

12. LT José Manuel P.B. Saldanha 1
Instituto Hidrografico
Ministerio Damarinha
Lisbon, Portugal

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

STUDY OF THE NEAR SHORE SURFACE CHARACTERISTICS OF WINDROWS AND LANGMUIR CIRCULATION IN MONTEREY BAY

4. DESCRIPTIVE NOTES (Type of report and, inclusive dates)

Master's Thesis; September 1971

5. AUTHOR(S) (First name, middle initial, last name)

Alexander Maratos; Lieutenant, Greek Navy

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1971	72	9

8a. CONTRACT OR GRANT NO. b. PROJECT NO c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Naval Postgraduate School Monterey, California 93940

13. ABSTRACT

Observations of the spacing and angle of windrows with respect to the wind speed and direction were conducted in Monterey Bay, using aerial photographs taken of windrow accumulations on 13, 20, 27 April and 3, 11 May 1971.

The spacing of windrows was found to depend upon wind speed. These windrows are indicative of the presence of helical vortices in the surface waters, and the data support Langmuir's contention that the vortices are wind-driven. Deflection angles showed small variation to the left and right of the wind with 0° being the most common angle. No correlation was found between depth of the thermocline and row spacing.

The Langmuir circulation investigated in Monterey Bay showed a cellular pattern with vertical velocities of 2.2 cm/sec downward in the area of convergence and 0.8 cm/sec upward in the area of divergence, at a wind speed of 6.0 m/sec.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
WINDROWS						
LANGMUIR CIRCULATION						