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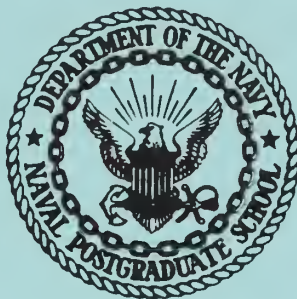
SURFACE CHARATERISTICS OF WINDROWS

by

Ralph William Ortengren, Jr.

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# UNITED STATES NAVAL POSTGRADUATE SCHOOL



## THESIS

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December 1968

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SURFACE CHARACTERISTICS OF WINDROWS

by

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Submitted in partial fulfillment of the  
requirements for the degree of

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ABSTRACT

Aerial photographs were taken of windrow accumulations in Monterey Bay on 1, 8, 15 and 22 October 1968. A Fairchild T-11 aerial mapping camera was used, with photographs taken approximately every two minutes over 40 to 60 minute periods. Windrows were marked with accumulations of computer cards, wind speed measured by cup anemometer, and wind direction taken with the aid of a MK. 6 Smoke Float. Sea surface temperature, depth of the thermocline, and surface air temperature measurements were taken concurrently.

An attempt was made to correlate windrow spacing and wind speed, to find mean deflection of windrows relative to the wind, to determine any relationship between row spacing and depth of the thermocline, and to find the response time of windrow orientation to a wind shift.

Windrow spacing was found to depend on other factors than wind speed. Deflection angles varied between  $20^{\circ}$  left and  $20^{\circ}$  right, with  $0^{\circ}$  being the most common angle. No correlation was found between depth of the thermocline and row spacing. Response time fell between two and four minutes.

TABLE OF CONTENTS

CHAPTER	PAGE
I. . . . .	7
Introduction . . . . .	7
Motivation. . . . .	12
II. EQUIPMENT AND INVESTIGATIVE PROCEDURE . .	13
Equipment . . . . .	13
Sampling technique and dates . . . . .	14
III. PRESENTATION AND DISCUSSION OF DATA . . . .	17
Daily results . . . . .	18
Discussion of statistical significance . . . . .	24
Individual photographs . . . . .	27
IV. CONCLUSIONS AND RECOMMENDATIONS . . . . .	45
Conclusions . . . . .	45
Recommendations . . . . .	47
BIBLIOGRAPHY . . . . .	50
APPENDIX I     Additional references . . . . .	51
APPENDIX II    Program for least-squares fit . . . . .	53
INITIAL DISTRIBUTION . . . . .	54





## LIST OF FIGURES

FIGURE		PAGE
1.	Least-Squares Fit, First Degree, for Spacing versus Wind Speed . . . . .	29
2.	Least-Squares Fit, Second Degree, for Spacing versus Wind Speed . . . . .	30
3.	Least-Squares Fit, Third Degree, for Spacing versus Wind Speed . . . . .	31
4.	Bathythermograph Traces for 1, 8, 15, 22 October . .	32
5.	Spacing Histograms for 1, 8, 15 October . . . . .	33
6.	Deflection Histograms for 1, 8, 15 October . . . . .	34
7.	S/D Histograms for 1, 8, 15 October . . . . .	35
8.	Histogram of Total Spacing Data . . . . .	36
9.	Histogram of Total Deflection Data . . . . .	37
10.	Histogram of Total S/D Data . . . . .	38
11.	Photograph 81 . . . . .	39
12.	Photograph 87 . . . . .	40
13.	Photograph 155 . . . . .	41
14.	Photograph 158 . . . . .	42
15.	Photograph 159 . . . . .	43
16.	Photograph 1519 . . . . .	44

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I would like to express my special appreciation for the help given me by Professor Ted Green of the Department of Oceanography. His efforts were instrumental in initially defining the problem and formulating the method of attack in order to obtain meaningful results.

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## CHAPTER I

### I. INTRODUCTION

Lines of confluence, denoted by foam, seaweed, or other floating material, are commonly observed on the surface of lakes and oceans. These lines are commonly called "windrows" or "wind slicks". They will be referred to as "windrows" hereafter in the body of this thesis. Windrows are thought to be formed by the horizontal convergence of surface waters, which then descend leaving any less dense, floating matter behind. Winds appear to cause windrows by setting up horizontal vortices in the upper waters of lakes and oceans. The axes of these vortices are roughly parallel to the wind, and adjacent vortices rotate in opposite directions. The existence of this particular situation is often indicated by the presence of lines of foam parallel to the direction of the wind, and lying directly above the region of downflow between two adjacent vortices.

Besides wind induced confluences, other flow conditions may give rise to lines of convergence. Stommel (1951) observed that a line often forms some distance from shore, where the surface water descends and flows out again at some depth. This occurs along shorelines where surface currents have an onshore component. Ewing (1950) found that where conditions cause the formation of internal waves on the thermocline, the internal waves are sufficient

to cause lines of confluence on the surface. These lines propagate along with the internal waves. Such confluences may or may not form in the presence of wind. They are usually easily distinguishable from windrows since they tend to parallel coasts, are often well-defined over several miles, are separated by fairly large distances, and finally are independent of wind direction provided wind speed is low. They are most easily seen in low to still wind conditions. They are caused by processes originating within the body of the ocean.

The mechanism of windrow formation is much different. The triggering agency seems to be the external stress exerted by the wind on the sea surface. The goal of this thesis is to present an analysis of the surface characteristics of these wind-formed lines of confluence.

Langmuir (1938) first noticed seaweed arranged in parallel lines at sea in 1927. These lines seemed to be oriented parallel to the wind. Through experiments on Lake George, Langmuir found several significant features. The streaks were caused by the wind on the water setting up longitudinal surface currents in the direction of the wind. The wind produced a series of alternating right and left helical vortices in the water having horizontal axes parallel to the wind. On the water's surface, water converges toward the streaks, and dives under them. Between the streaks, there are rising currents, which flow out laterally toward the streaks upon

reaching the surface. Langmuir's results led him to believe that the helical vortices were bounded on the bottom by the depth of the thermocline. In addition, he postulated that there might be some relationship between the depth of the thermocline and the spacing of the windrows.

At the present time the exact mechanism which generates Langmuir circulation is not known. Three possible mechanisms are presented in the literature, . . . shear flow instability, surface films, and thermal convection. Faller (1963) demonstrated that cellular rolls were formed in laminar flow due to instabilities of the Ekman boundary layer. By analogy he has suggested that shear flow instability is a possible generating mechanism for Langmuir circulation. As supporting evidence, Faller and Woodcock (1964) found that windrows are not exactly parallel to the wind, but lie at some small angle to the right of it.

Welander (1963) proposed a theory for Langmuir circulation, in which the motions are generated by the shearing effect of the wind upon an organic surface film of varying thickness. Stommel (1951) also suggested that the generating mechanism for Langmuir circulation was confined to a relatively thin surface layer because of the rapid response of windrow alignment to changing wind direction.

Csanady (1964) thought that the presence of windrows was invariably associated with a rapid vertical diffusion. On this basis, he assumed that Langmuir vortices were the principal causes of

the vertical mixing of epilimnion waters. During the summer of 1965, Csanady had boat crews perform routine observations of windrows on Lake Huron. His general conclusions confirmed the findings of Faller and Woodcock, i. e. , that windrows are not correlated with upward heat flux. He proposed that a convective, surface-cooling mechanism is at least a reasonable cause of Langmuir vortices. A doctoral candidate at the University of Wisconsin, P. D. Uttormark, is presently working on a thermal convection model of Langmuir circulation, but his results are not available at this time.

Recently McLeish (1968) has suggested that no other factor than wind induced water turbulence is necessary for the formation of windrow patterns. He further stated that the windrow patterns, although showing a dominance of lines parallel to the wind, are really continually changing networks with irregular line widths, spacings and directions. Although his paper is generously provided with excellent photographs, there is a dearth of quantitative results to support his conclusions.

Very little work has been done since Langmuir concerning the surface characteristics of windrows. Csanady (1965) reported on 246 observations of windrows, but noted only the basic occurrence of windrows versus upward heat flux. He did notice that only once were windrows observed below a wind speed of 2.1 meters/second. Csanady noted that windrows were much more noticeable and easier to identify in the presence of surface evaporation. Faller (1964)

made 25 observations of windrows, 12 from a small boat and 13 by aerial photography. He marked the windrows with several thousand sheets of 8-1/2 x 11 inch paper. With this small data base, he found an average angle of deflection of the windrows to be 12.9 degrees to the right of the wind, with a standard deviation of 6.6 degrees.

Faller and Woodcock (1964) used a data base of only 14 samples to postulate the dependence of windrow spacing upon wind speed as: spacing in meters equals 4.8 times the wind speed in meters/second. It was during this project that Faller and Woodcock attempted to find a correlation between the occurrence of windrows and upward heat flux. They found no such correlation. There was in addition only a small range of physical conditions present during the sampling, and seasonal and latitudinal variations were not tested.

Sullivan (1964) made 27 sampling runs on Lake Huron using a small boat. He obtained spacing measurements by dragging a marked polypropylene rope behind the boat and driving through the windrows perpendicularly. He found the windrows to be roughly parallel to the wind and independent of wave direction. He observed no windrows below a wind speed of 3.5 meters/second. He also noted the lack of occurrence of windrows on several occasions when the wind speed was significantly greater than 3.5 meters/second. In addition Sullivan measured 14 samples of windrow spacing versus depth of the thermocline. The ratios found varied between 1.0 and 1.72, indicating some relationship may exist, as Langmuir had forecasted.

## II. MOTIVATION

Prior to this thesis, investigations of the surface characteristics of windrows have suffered from two important inadequacies. Foremost has been the lack of a sufficiently large number of observations. As stated earlier, the empirical results of Faller, Woodcock, and Sullivan were based on samples ranging between 14 and 27 total observations. Secondly, and perhaps equally important, has been the lack of adequate measuring equipment. Spacing measurements were taken by "seaman's eye". Faller used aerial photography for 13 of his samples, but the camera was a hand-held movie camera which was not described.

The intent of this thesis is to present a study of windrows based on an adequate number of observations to be statistically significant, and with measurement of length, spacing and direction inherently more accurate than any previous work. The windrow characteristics investigated include the following:

- (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.



## CHAPTER II

### EQUIPMENT AND INVESTIGATIVE PROCEDURE

#### I. EQUIPMENT

The core of the data acquisition system was a Fairchild T-11 Aerial Mapping Camera. This is the primary camera used by the U. S. Air Force and U. S. Navy for accurate mapping, and has an accuracy of linear measurement to one part within 100,000. Coupled with this is the feature of extremely good resolution of small-scale objects. The camera was mounted in a U. S. Navy S-2 Grumman aircraft attached to the Naval Auxiliary Landing Field, Monterey. The camera uses a lens of fixed focal length and is mounted such that if the aircraft is in a level flight attitude, the lens is pointed directly down. As the shutter is tripped, the aircraft's altitude (by pressure altimeter) and the time of the shutter trip (by instrument panel clock) are printed on the margin of the negative. The camera operator has only to note the aircraft heading at the time of shutter release. Automatic film advance allows a picture to be taken every two seconds. The responsibility of the pilot is to maintain as level an attitude as possible during the actual photography. After the photo runs, the camera's magazine is unloaded and the film airmailed to the Miramar Naval Air Station for development into negatives. Due to the unofficial status of the project, contact prints of the negatives were not produced.

Surface wind speeds were obtained with a Cassella cup anemometer. The anemometer 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.

With the exception of the camera, all instruments were mounted on the Naval Postgraduate School's 63 foot oceanographic research boat. The marking of windrows was accomplished by dropping 3-1/2 x 7-3/8 inch computer cards from the aircraft and from the boat. Approximately 3,000 cards were used during each sampling period. Individual cards could be distinguished in the photographs made by the T-11 camera from a height of 300 feet.

## II. 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 occurrence in Monterey Bay, approximately two miles northwest of Monterey Marina. Voice communications would be established with

the aircraft, and shipboard instrumentation rigged. Upon arrival overhead, the aircraft would fly directly over the boat on a heading upwind and release the load of computer cards from the bomb bay at an altitude of approximately 200 feet. 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 aircraft would commence flying a racetrack pattern at an altitude of 300 feet, so as to pass over the smoke float and computer card pattern roughly every two minutes. The photographs would be taken directly overhead and the aircraft's heading and exact altitude noted. Any necessary changes to the flight pattern or any other segment of the sampling run could be communicated to all parties by means of frequency modulated transceivers located in the aircraft and in the boat. On the boat, the anemometer was firmly attached near the bow at a height of six feet four inches above the waterline. All wind speed readings were obtained with the boat lying to with all protrubances of ship structure being downwind of the anemometer. 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 1, 8, 15 and 22 October 1968. Further runs were precluded due to inclement weather and aircraft availability.

## CHAPTER III

### PRESENTATION AND DISCUSSION OF DATA

Data derived from the four 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 meteorological and bathythermometric conditions during the sampling process. Following the tables is a discussion of symbols used for the definitions of parameters. The chapter 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.

1 October 1968

<u>PHOTO NO.</u>	<u>TIME</u>	<u>WIND</u>	<u>NO. ROWS</u>	<u>SPACING</u>	<u>DEFL.</u>	<u>S/D</u>
12	1516	4.2	10	135.0	-----	4.36
13	1518	3.3	12	82.5	-----	2.66
14	1520	3.4	5	103.2	-----	3.34
15	1522	3.7	4	-----	-----	-----
16	1524	2.8	5	90.0	3°L	2.90
17	1526	3.0	5	121.9	9°R	3.92
18	1528	3.1	11	140.7	7°R	4.53
19	1530	3.0	8	-----	12°R	-----
110	1532	2.7	6	100.0	4°R	3.22
111	1534	2.6	3	123.8	3°R	3.99
112	1536	2.6	3	-----	8°R	-----
113	1538	2.8	6	145.0	5°R	4.68
114	1540	2.5	5	110.5	4°R	3.57
115	1542	2.4	--	-----	-----	-----
116	1544	2.6	4	-----	-----	-----
117	1546	2.2	2	-----	4°R	-----
118	1548	2.2	3	-----	12°R	-----
119	1550	2.5	5	-----	9°R	-----
120	1552	2.1	3	-----	5°L	-----
121	1554	2.1	1	-----	2°R	-----
122	1556	1.9	4	-----	-----	-----

Thermocline remained fixed at 31 feet during observational period.  $T_s > T_w$   
during entire period. Data taken in 250 feet of water; visibility unlimited;  
clear sky; 5 foot swell from southwest.

8 October 1968

<u>PHOTO NO.</u>	<u>TIME</u>	<u>WIND</u>	<u>NO. ROWS</u>	<u>SPACING</u>	<u>DEFL.</u>	<u>S/D</u>
81	1450	4.5	---	-----	-----	----
82	1452	4.1	---	-----	0°	----
83	1454	4.1	---	-----	0°	----
84	1456	4.8	5	-----	8°R	----
85	1458	5.1	6	106.9	-----	4.11
86	1500	4.3	4	-----	0°	----
87	1502	4.2	9	-----	5°R	----
88	1504	4.5	3	433.0	-----	16.70
89	1506	4.6	6	472.0	0°	18.10
810	1508	4.1	6	-----	-----	----
811	1510	4.2	11	150.0	4°L	5.77
812	1512	4.0	9	178.1	-----	6.81
813	1514	3.5	2	-----	6°L	----
814	1516	2.8	8	150.0	0°	5.78
815	1518	2.9	9	178.1	0°	6.85
816	1520	3.1	7	178.1	-----	6.85
817	1522	2.4	8	-----	-----	----
818	1524	3.3	9	142.6	20°L	5.49
819	1526	4.1	9	-----	0°	----
820	1528	4.0	6	-----	12°L	----
821	1530	3.7	8	-----	13°L	----

Thermocline fixed at 26 feet during observation period.  $T_s > T_w$   
during same period. Data taken in 270 feet of water: visibility unlimited;  
clear sky; calm sea (no detectable swell).

15 October 1968

<u>PHOTO NO.</u>	<u>TIME</u>	<u>WIND</u>	<u>NO. ROWS</u>	<u>SPACING</u>	<u>DEFL.</u>	<u>S/D</u>
151	1428	5.1	10	-----	19°R	----
152	1430	5.0	6	-----	----	----
153	1432	5.1	7	143.9	0°	4.11
154	1434	4.0	5	-----	----	----
155	1436	6.0	11	168.8	16°R	4.80
156	1438	5.7	3	-----	----	----
157	1440	5.3	6	420.0	3°R	12.00
158	1442	6.4	5	360.0	0°	10.30
159	1444	5.8	6	300.0	Wind Shift	8.58
1510	1446	5.7	6	420.0	6°L	12.00
1511	1448	5.2	4	281.0	----	8.03
1512	1450	6.4	7	-----	0°	----
1513	1452	4.8	5	-----	----	----
1514	1454	4.2	5	281.0	18°R	8.03
1515	1456	5.7	6	345.0	12°R	9.86
1516	1458	5.3	6	-----	3°R	----
1517	1500	4.4	5	317.0	4°R	9.06
1518	1502	4.9	5	440.0	0°	12.58
1519	1504	6.0	7	450.0	0°	12.88
1520	1506	6.3	4	441.0	----	12.61
1521	1508	6.4	5	480.0	11°R	13.71
1522	1510	6.4	5	231.5	0°	6.62
1523	1512	6.3	6	-----	0°	----

Thermocline remained at 36 feet during entire period.  $T_s > T_w$   
during same period. Data taken in 240 feet of water. Visibility unlimited;  
clear sky; approximately one foot swell from southwest.



22 October 1968

No useable data is available for this date. Observations were attempted between 1330 and 1530 local time, but no windrows formed. During this period the wind varied between full calm and 1.1 meters/second. The average and median speed was 0.4 meters/second. At no time did the computer cards begin to separate from their initial grouping. Between 1330 and 1530, the depth of the thermocline remained fixed at 31 feet, and there was absence of swell. Evaporative cooling was again present during the two hours, with  $T_s > T_w$  throughout.

Remarks on Symbols

- PHOTO - Number refers to date and sequence. PHOTO 11 is first photograph taken on 1 October; PHOTO 1520 is 20th photograph taken on 15 October.
- TIME - Local time on a 24 hour basis relative to midnight as time 0.
- WIND - Wind speed in meters/second during the two minutes immediately preceding the photograph.
- NO. ROWS - The number of windrows clearly distinguishable on the photograph.
- SPACING - The predominant or average spacing in feet between windrows.
- DEFL. - The angle between windrow orientation and the wind direction. Wind direction (relative) taken from plume of smoke float.
- S/D - The ratio of SPACING over depth of the thermocline. Thermocline depth used as depth where temp.  $1^{\circ}$  lower than surface temp. as taken by bucket thermometer.

$T_s$  - Surface water temperature

$T_w$  - Wet bulb temperature

Spacing measurements were determined by use of the standard optical equation:

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

The image and focal length of the T-11 camera are fixed at nine and six inches respectively. With the altitude of the aircraft 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 wherein 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.

#### 1 October 1968

Ten observations of windrow spacing yielded an average of 115.3 feet with an average wind speed of 6.8 m/sec. The average angle of windrow deflection was  $5.0^\circ$  to the right of the wind, with a standard deviation of  $5.0^\circ$ . During the observation period, wind speed decreased fairly steadily from 4.2 m/sec. to 1.9 m/sec.

During the last 15 minutes of observation, the rows became more irregularly spaced and seemed to converge upon one another. No spacing measurements were taken during this segment in order to avoid biasing the statistics. Deflection measurements of this 15 minute segment were made relative to the dominant windrow(s) in the particular photograph. The windrows nearest the smoke plume were weighted more heavily in deflection calculation. If windrows immediately adjacent to the smoke plume indicated a given deflection angle, while rows further away showed evidence of some other angle(s), the rows adjacent to the plume were taken as correct. Evidence was found that individual row orientation is closely related to the wind eddies immediately above the row. Thus the windrows at some distance from the smoke plume may be reacting to wind action different than that indicated by the smoke float. No measurable wind shift occurred during the photographic period, thus no calculation of windrow response to a wind shift could be made.

#### 8 October 1968

Only nine photographs were used for spacing analysis, with an average of 220.9 feet for an average wind speed of 3.8 m/sec. Mean windrow deflection was  $3^{\circ}$  to the left of the wind, based on 14 observations, with a standard deviation of  $7.2^{\circ}$ . Fully seven of the 14 measurements showed no angle of deflection, however. Once again, no wind shift occurred.

15 October 1968

15 measurements of spacing were used to obtain an average spacing of 338.6 feet with an average wind speed of 5.6 m/sec. Using 16 values, the average deflection was found to be  $5.0^{\circ}$  to the right, with a standard deviation of  $7.6^{\circ}$ . Once again the mode was  $0^{\circ}$ , occurring in seven of the 16 photographs. At 1444 a wind shift occurred. Two minutes later, the wind had completed its shift and had steadied. The angle of deflection at 1446 was  $6^{\circ}$ L. By 1450, the angle of deflection had become  $0^{\circ}$ . In addition, row spacing increased by over 100 feet during the shift, but was back to within 20 feet of its original value by 1450.

Summary of Statistics

	<u>1 October</u>	<u>8 October</u>	<u>15 October</u>
Average wind speed (m/sec.)	6.8	3.8	5.6
Average spacing (ft.)	115.3	220.9	338.6
Average deflection	$5.0^{\circ}$ R	$3.0^{\circ}$ L	$5.0^{\circ}$ R
std. deviation	$5.0^{\circ}$	$7.2^{\circ}$	$7.6^{\circ}$
mode	---	$0^{\circ}$	$0^{\circ}$
median	$5.0^{\circ}$ R	$0^{\circ}$	$3^{\circ}$ R

I. DISCUSSION OF STATISTICAL SIGNIFICANCE

Graphs and figures 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. Only 30 values of spacing versus wind speed have been used to generate the best-fit curves. These represent only 46.1% of the total number of observations. Since over 50% of the samples could not be used for determination of spacing/wind speed relationships, any statistics or empirical relationships derived from the remaining observations must necessarily be at best highly suspect. The reasons for using only 30 observations have been explained earlier. Since nearly 50% of the total sample represented windrows that were not reasonably parallel or straight, it would seem hazardous to acknowledge any relationship of spacing to wind speed derived from the remaining portion of the sample.

In the same vein, a study of the frequency of occurrence of various deflection angles reveals the danger of applying any high degree of confidence to the statistics that can be manufactured. Although the deflection angles varied within the small range of  $20^{\circ}$  left to  $20^{\circ}$  right, the angle of  $0^{\circ}$  predominated.

In the investigation of Faller, Woodcock, Sullivan, and Csanady, only Csanady refused to publish fairly sweeping empirical relationships derived from field observations. Yet Csanady was the only

one of the mentioned group who could reasonably lay claim to a sufficiently large sample (246). Faller (1964) proposed a linear relationship of spacing versus wind speed based on a very few observations. Faller used only 25 observations to derive a particular mean windrow deflection angle. Sullivan had available only 27 observations. It is the contention of this writer that samples of less than several hundred observations over a considerable range of meteorological and oceanic conditions cannot and should not be used to propose any relationships between wind speed versus spacing and deflection angle other than the following: (1) windrows are generally oriented in the direction of the prevailing wind over the sea surface, and (2) the spacing between windrows is highly variable and seems to be dependent upon other features than wind speed alone. Best-fit curves up to fourth degree yielded almost identical degrees of fit: poor. Again it is emphasized that even these curves are based on the best of the samples taken. Surely those samples showing spacing to be random or convergent are more "statistically significant" than that minority which showed only some correlation between spacing and wind speed.

A particularly interesting aspect concerning deflection can be noticed by close examination of the photographs used for this report. Although various angles of deflection were noted in the majority of cases, windrows near or on the plume of the smoke float tended to parallel the plume. This tends to strengthen the proposition that

windrows orient themselves parallel to the wind in the absence of other factors. In several photographs, there can be seen extremely good correlation between the meanders of the smoke plume and the track of adjacent windrows. This feature will be mentioned in the next section concerning significant individual photographs.

## II. INDIVIDUAL PHOTOGRAPHS

Photograph 81 is an excellent example of the forceful nature of Langmuir circulation. The card pattern in this picture had been seeded by boat, and the photograph taken 35 seconds after completion of card dumping. Already individual rows can be seen forming in large numbers and parallel to each other. In subsequent photographs, the number of visible rows was significantly smaller. This led to a possible conclusion that the various areas of convergence may attract the computer cards, overcoming the attraction of weaker areas. This in turn may lead to erroneous values of windrow spacing.

Photograph 87 shows 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.

The close correlation of windrow orientation and smoke plume meander can be seen in the lower portion of photograph 155. The

picture was taken at a considerable distance downwind of the smoke origin, yet one windrow directly underneath the plume follows the path of the plume almost identically.

Photograph 158 also indicates the close response of neighboring windrows to slight shifts in the wind. Where the plume appears to break up in the middle of the photograph, the row immediately above also appears to break up in the same interval and direction.

Photograph 159 is mentioned specifically, since it is used as the definition of a quick wind shift. The wind had shifted abruptly to the right only eight seconds prior to the time of shutter-trip.

Photograph 1519 is another good example of correlation between the smoke plume meanders and a neighboring windrow's orientation. The windrow just below the smoke plume follows the path of the plume quite well throughout its length.



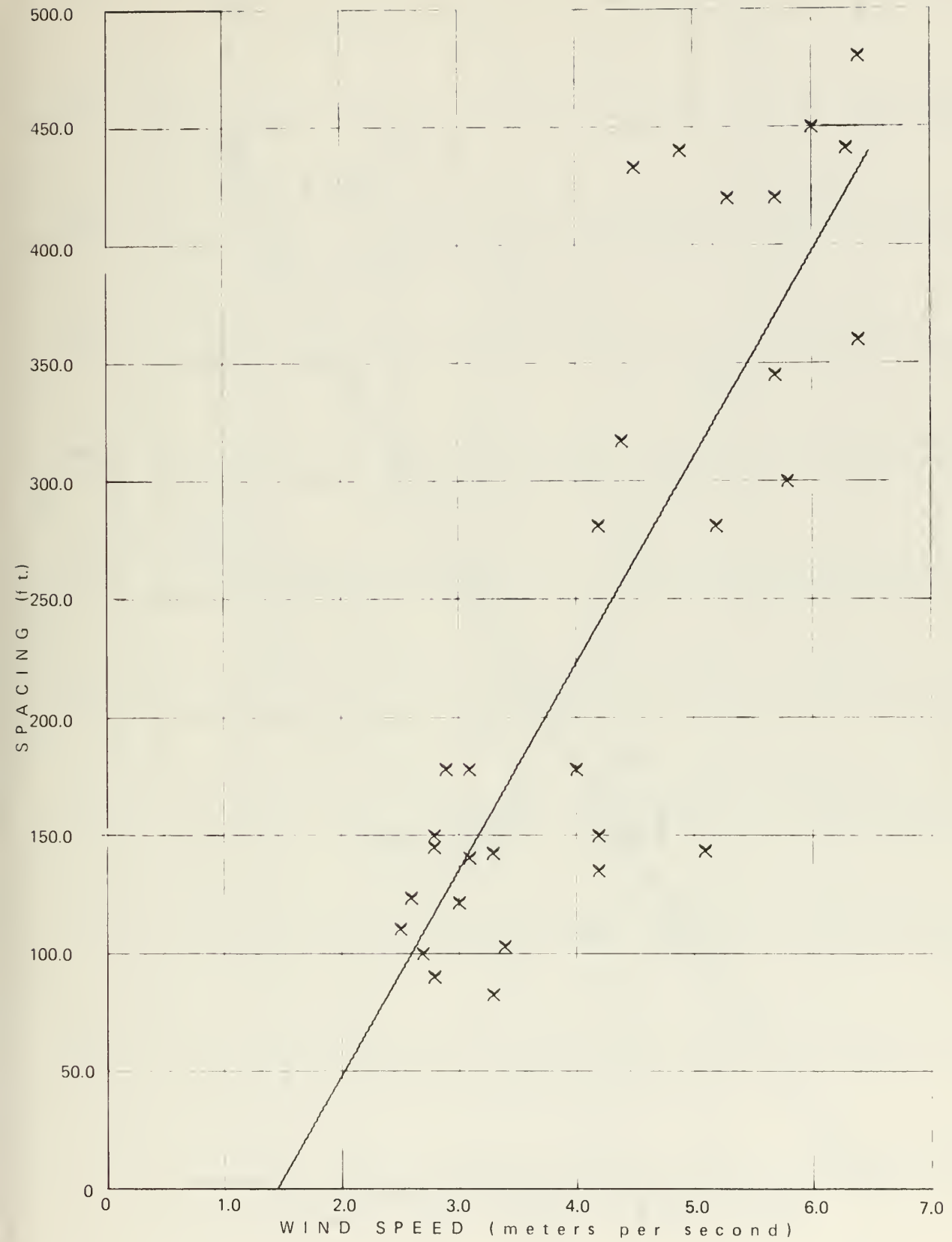


Fig. 1 Least-Squares Fit, First Degree, for Spacing versus Wind Speed

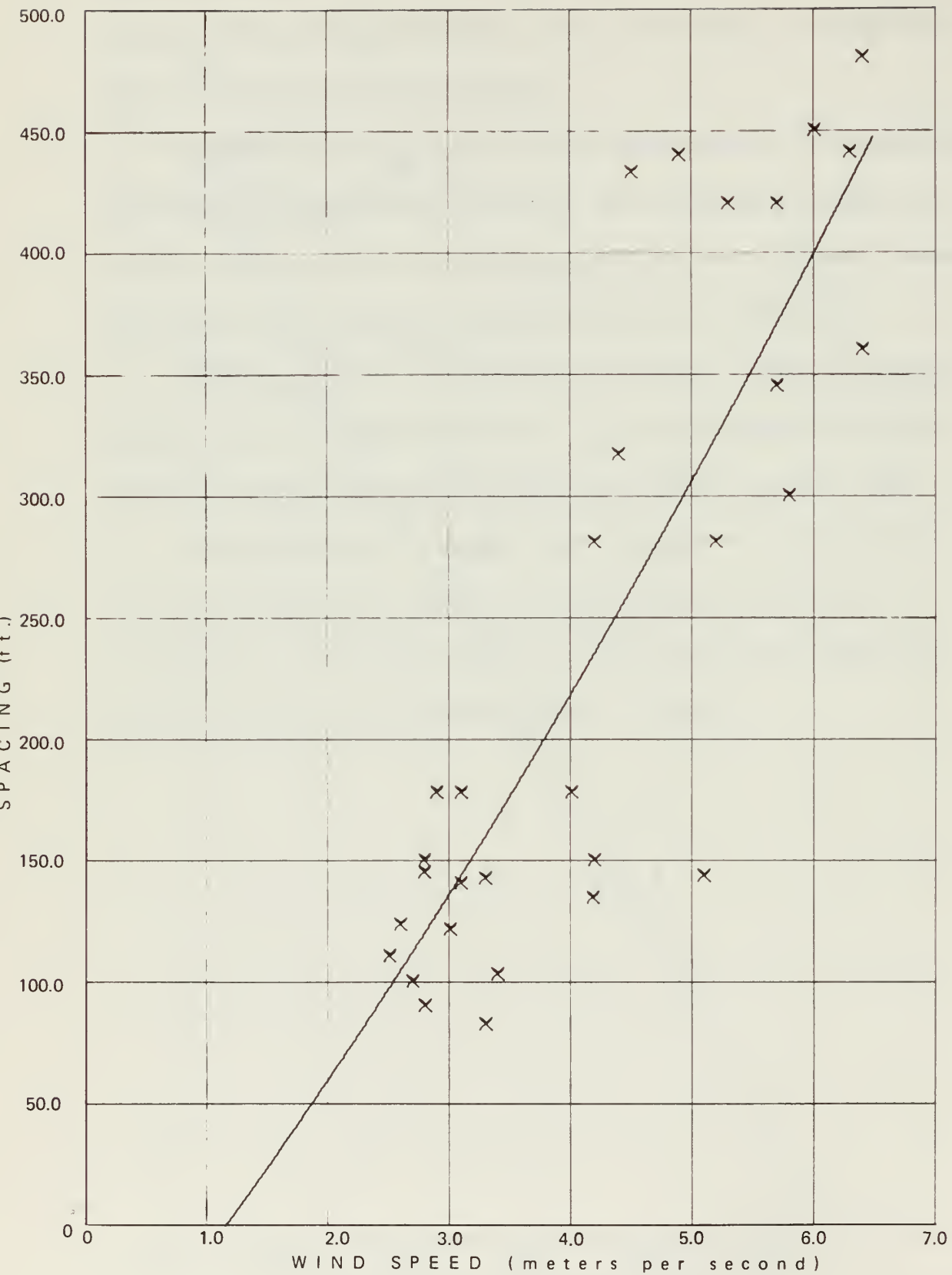


Fig. 2 Least-Squares Fit, Second Degree, for Spacing versus Wind Speed

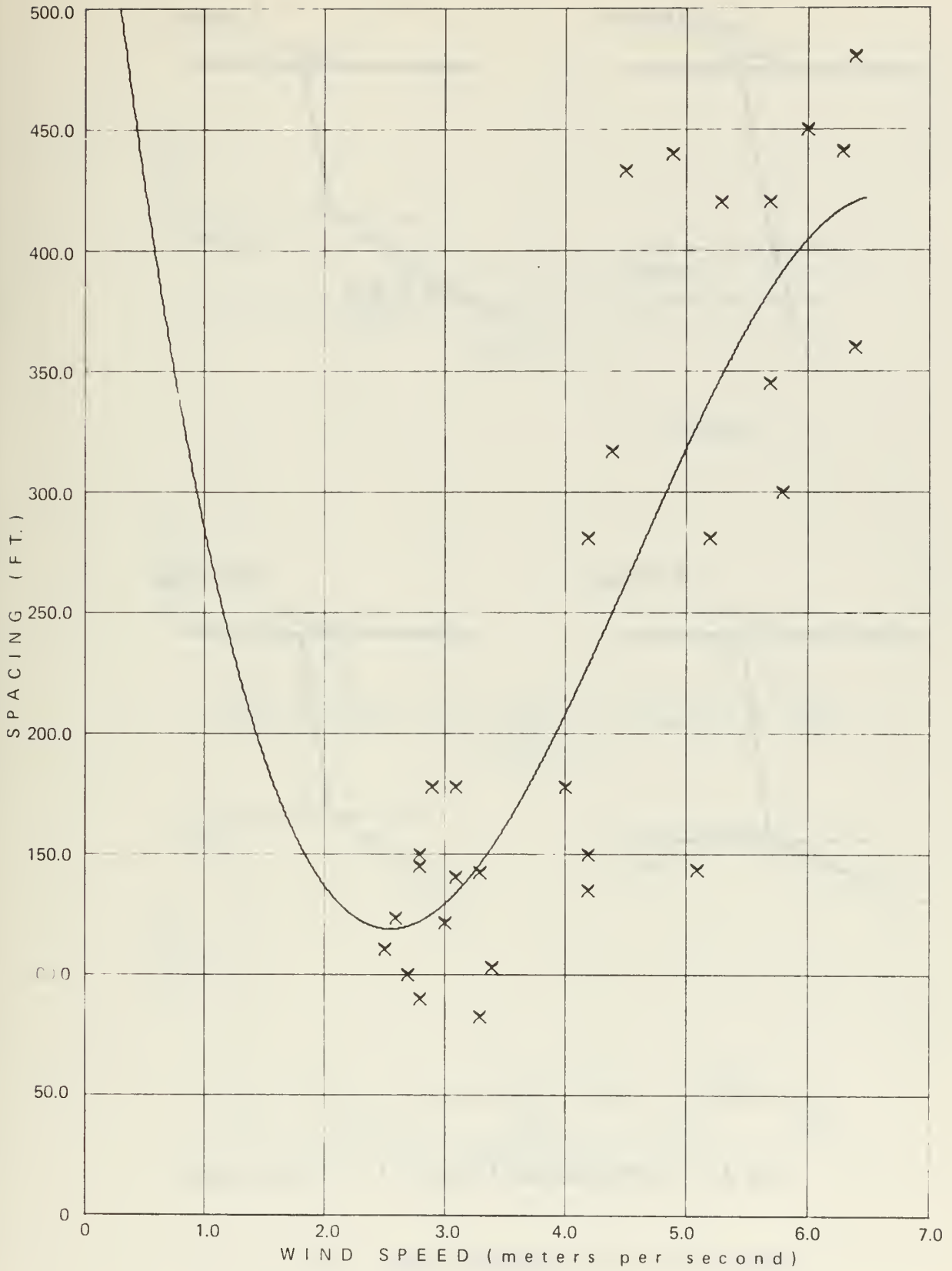


Fig. 3 Least-Squares Fit, Third Degree, for Spacing versus Wind Speed

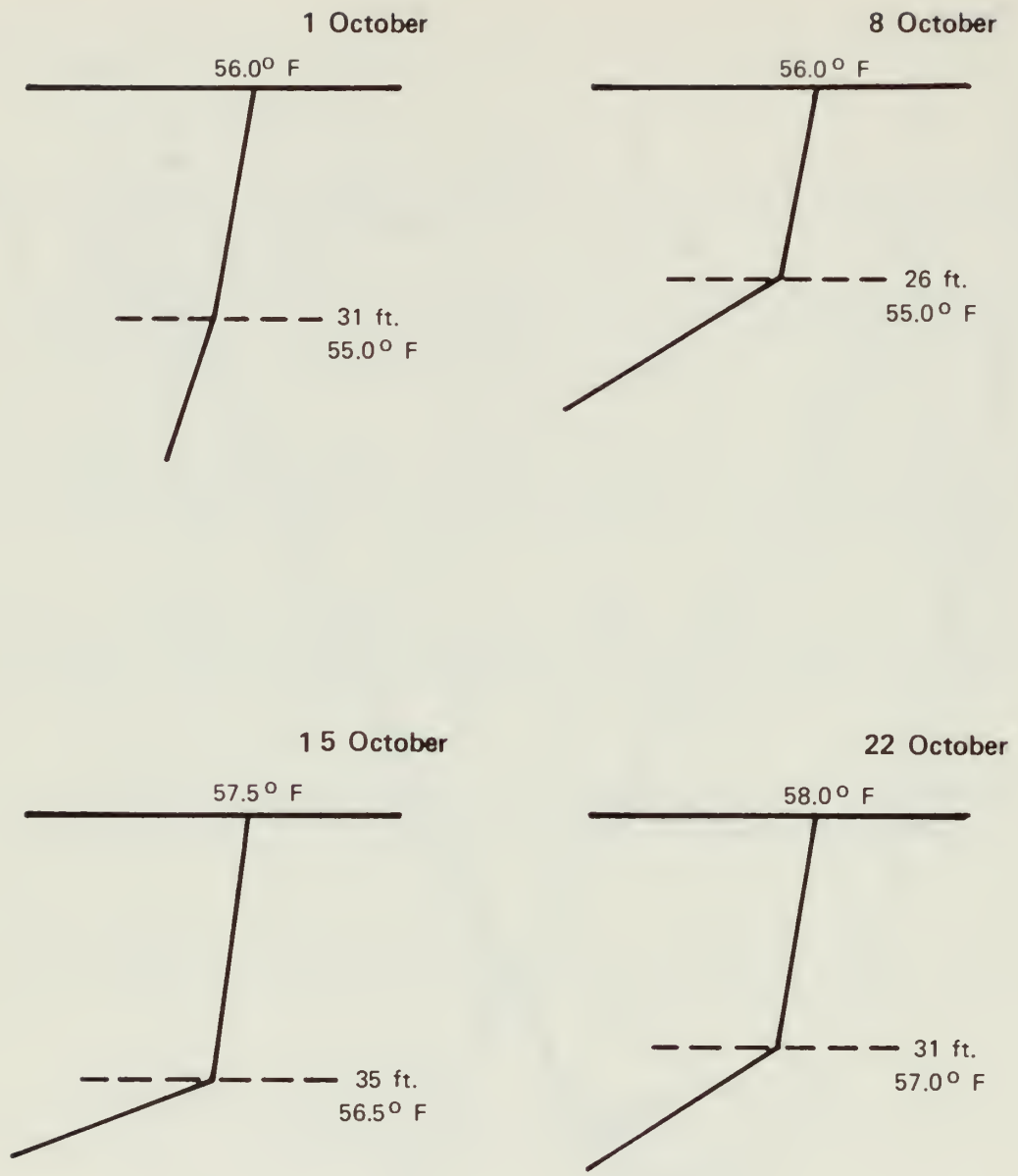


Fig. 4 Bathythermograph Traces for 1, 8, 15, 22 October

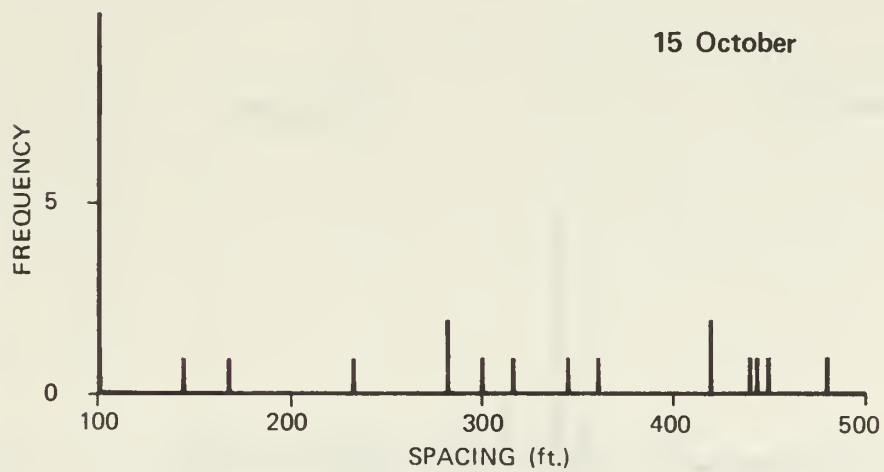
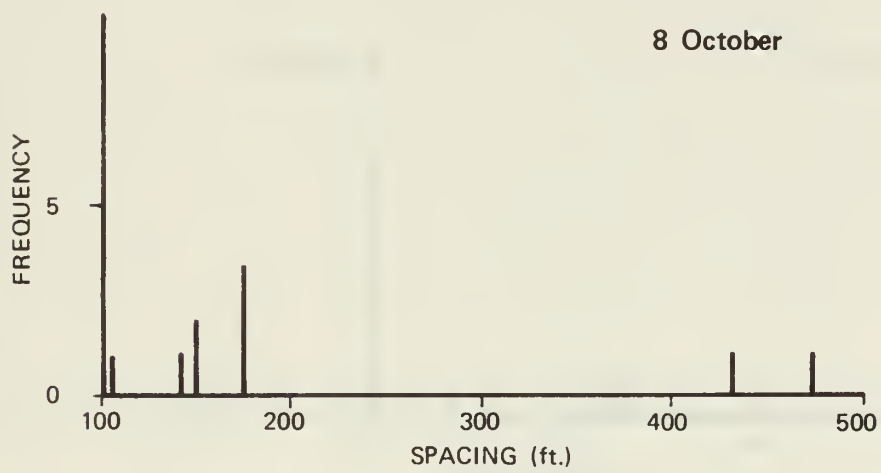
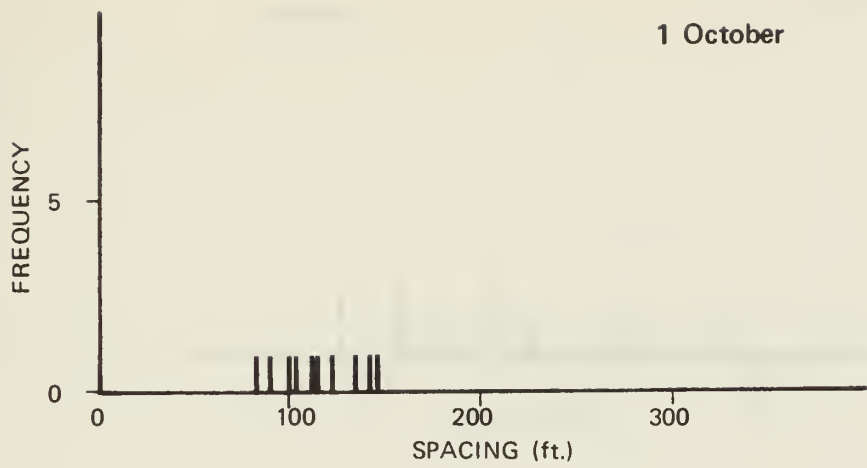


Fig. 5 Spacing Histograms for 1, 8, 15 October

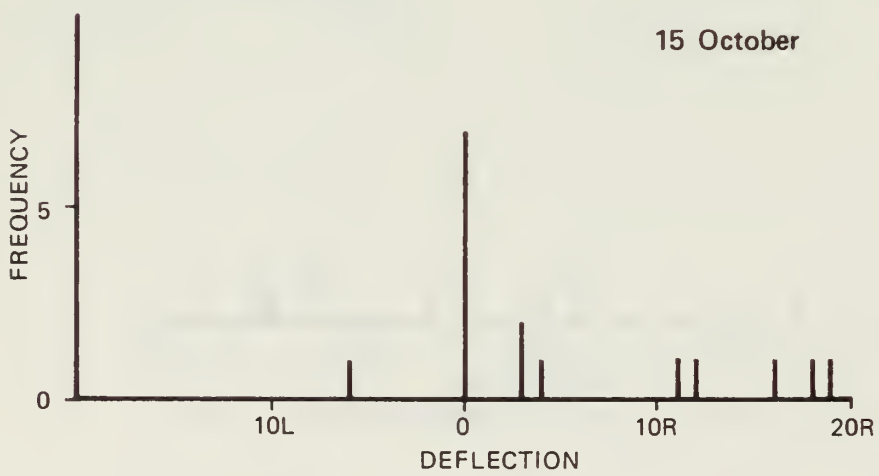
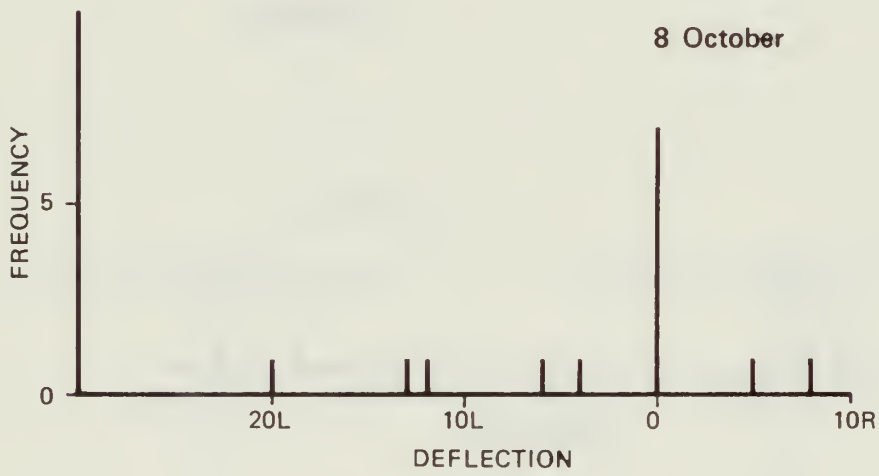
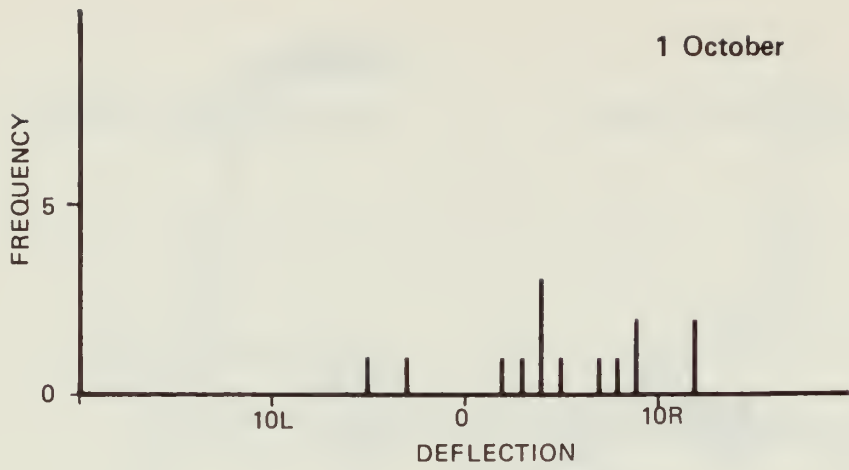


Fig. 6 Deflection Histogram for 1, 8, 15 October

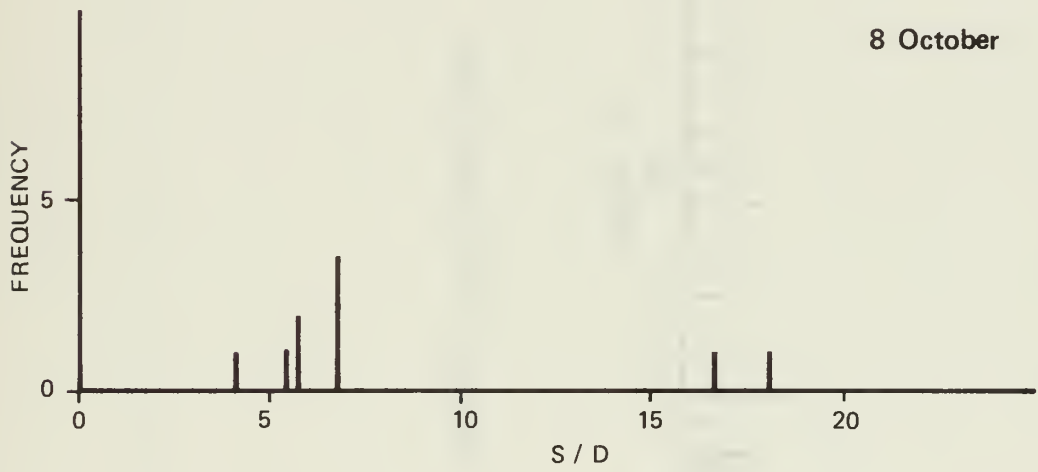
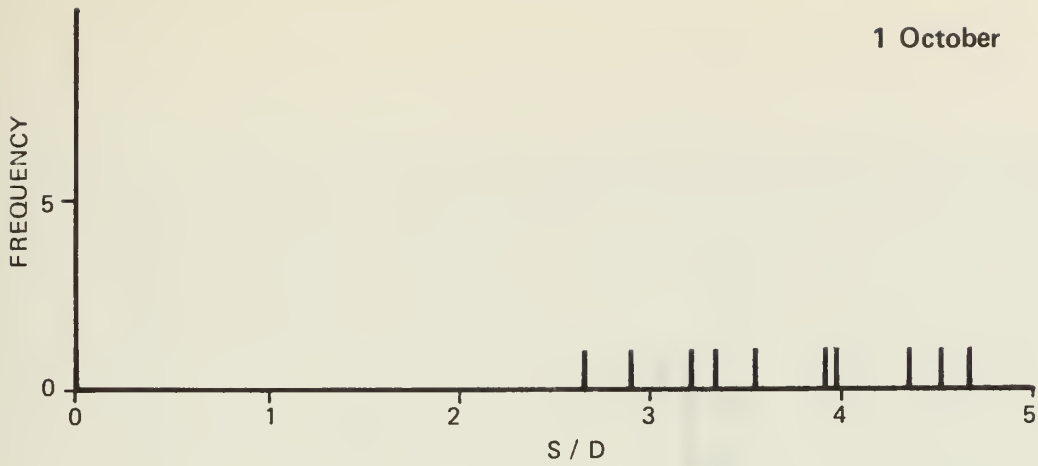


Fig. 7 S / D Histograms for 1, 8, 15 October



Fig. 8 Histogram of Total Spacing Data



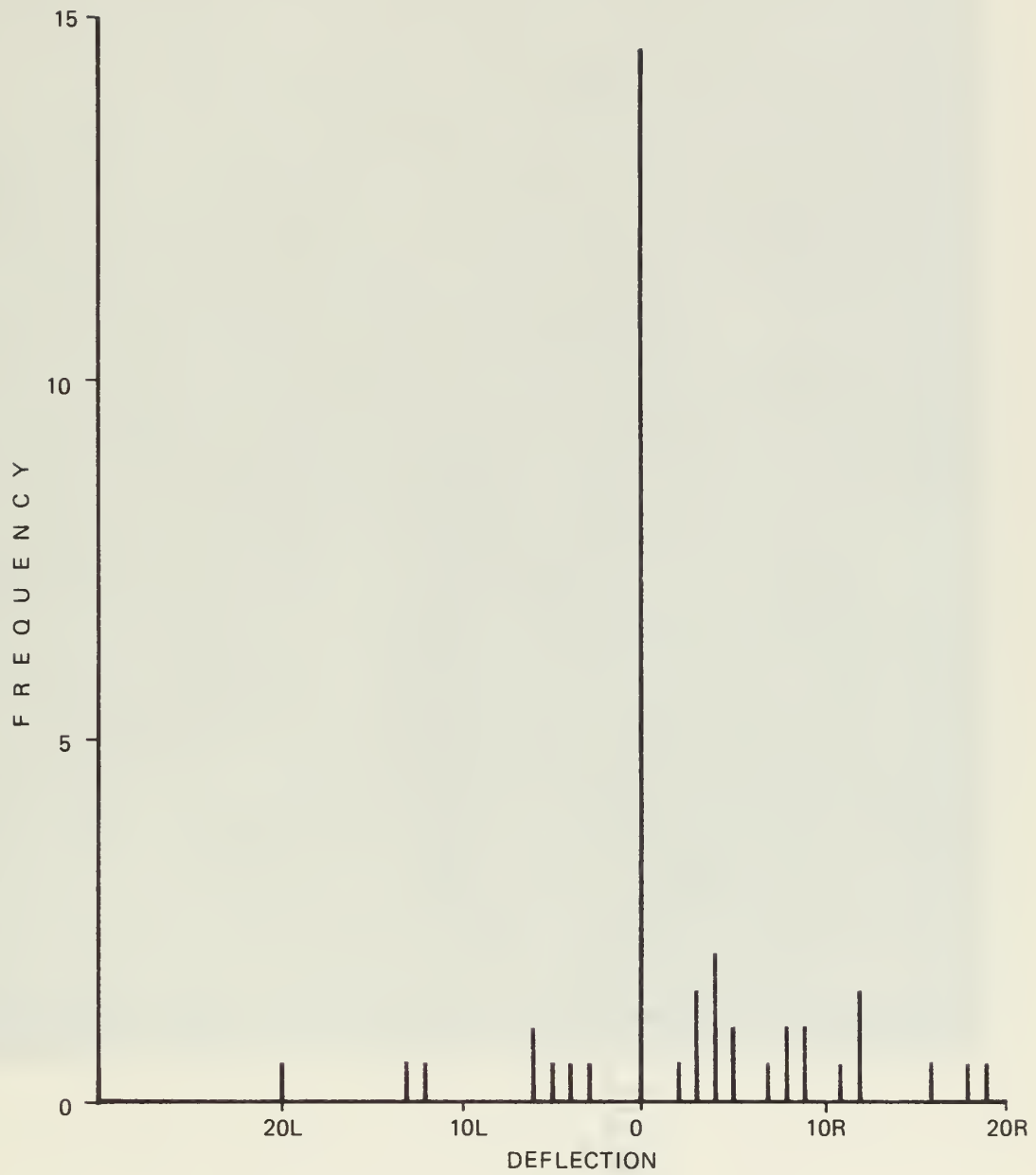


Fig. 9 Histogram of Total Deflection Data

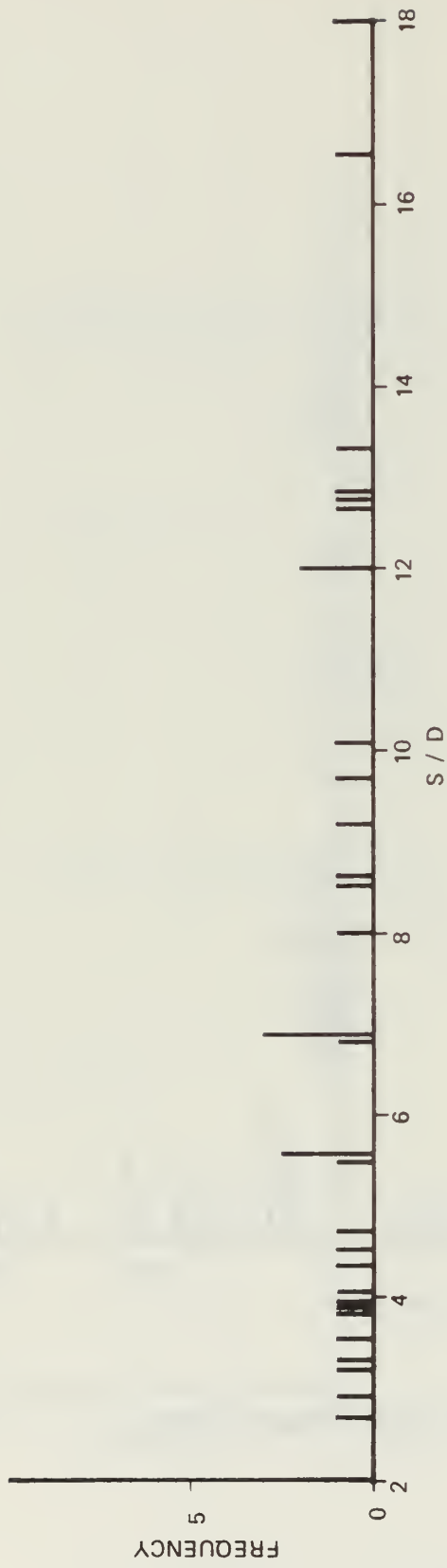


Fig 10 Histogram of Total S / D Data

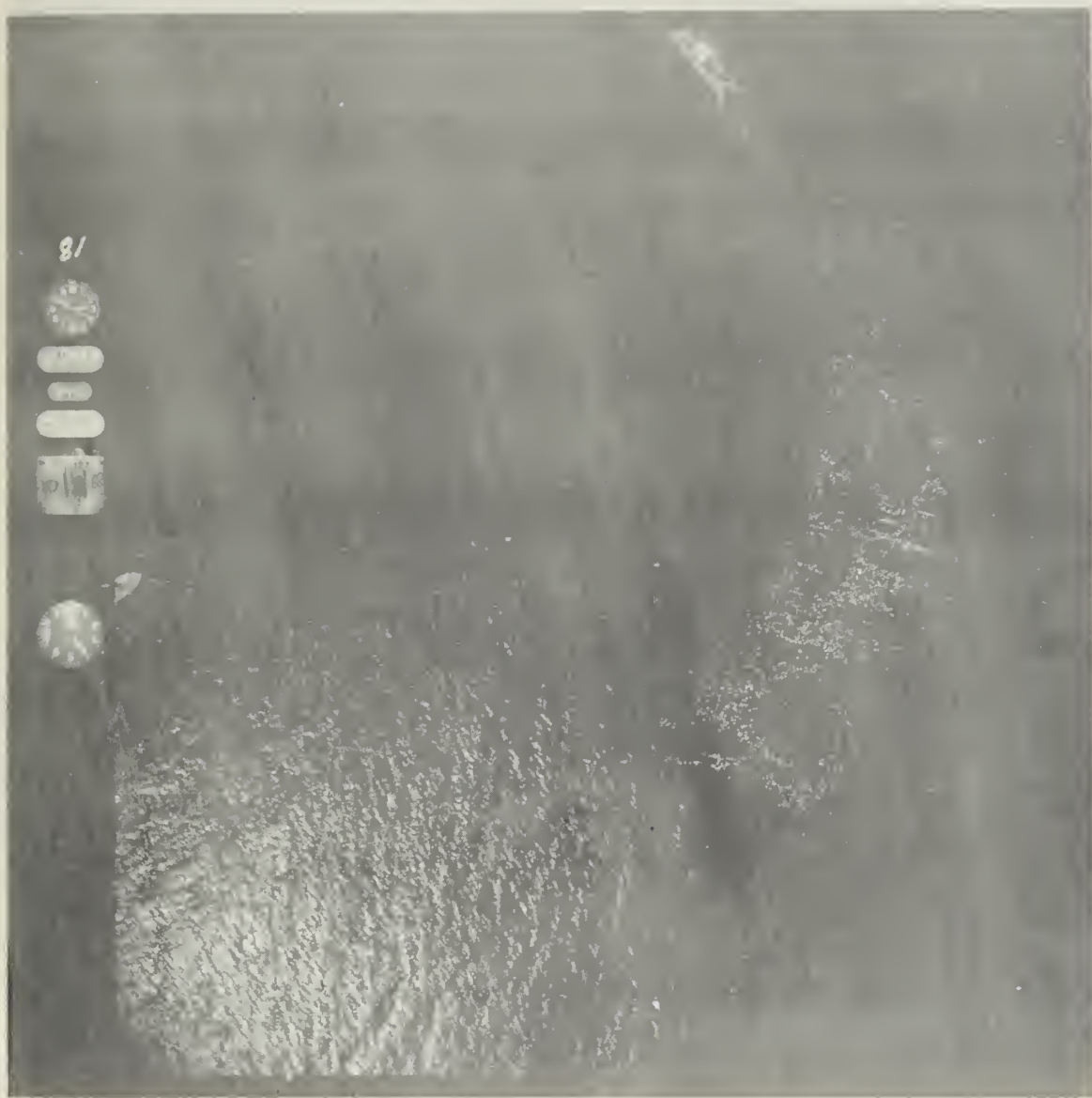


Figure 11. Photograph 81



Figure 12. Photograph 87



Figure 13. Photograph 155



Figure 14. Photograph 158

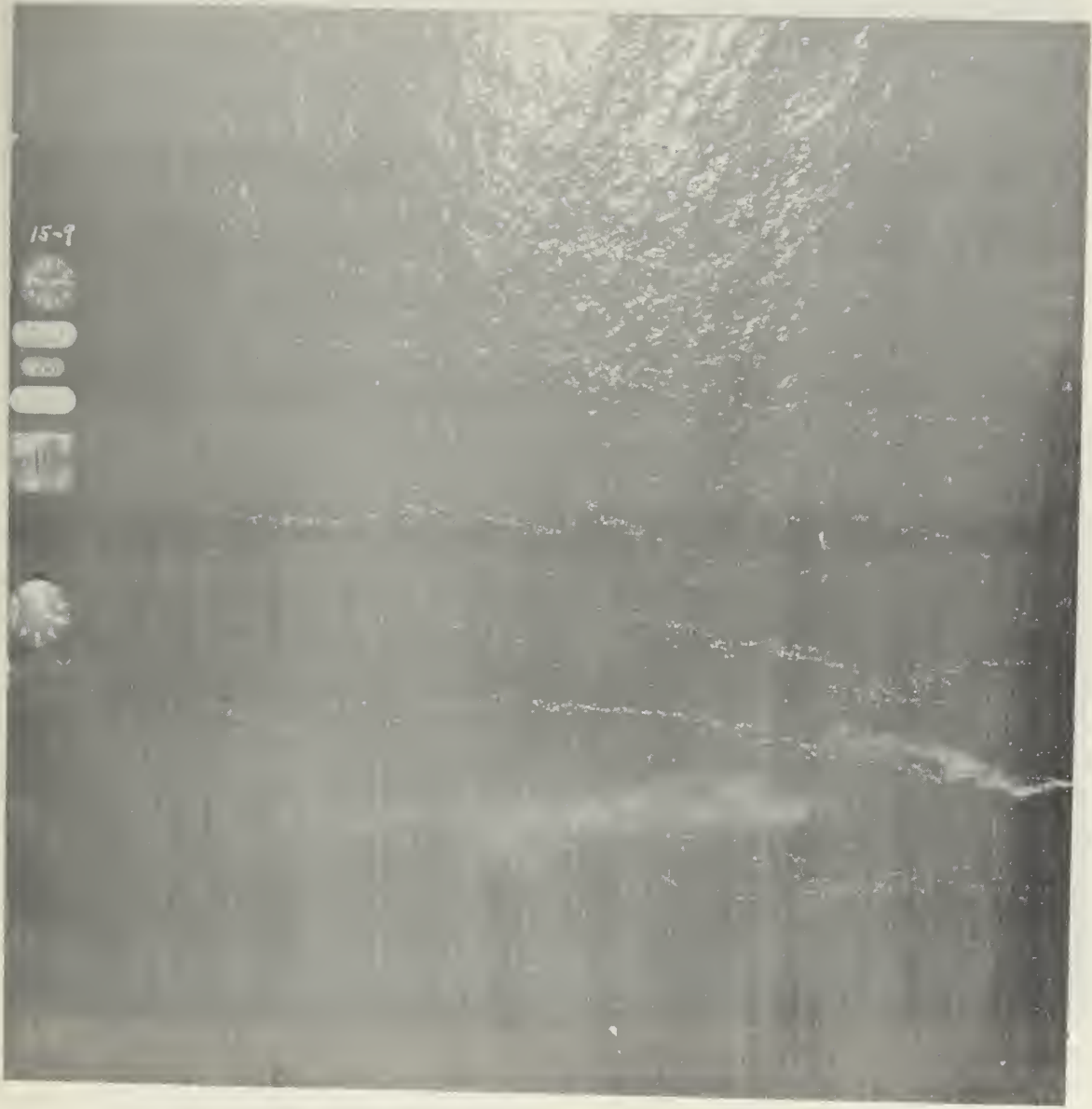


Figure 15. Photograph 159



Figure 16. Photograph 1519



## CHAPTER IV

### CONCLUSIONS AND RECOMMENDATIONS

#### I. CONCLUSIONS

The primary conclusion derived from the data of Chapter III is that a greater 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, windrow spacing must be considered variable and related to other factors than wind speed alone.

Deflection angle measurements indicate that windrows generally orient themselves roughly parallel to the wind. Although angles between  $20^{\circ}$  left and  $20^{\circ}$  right of the wind were observed, the angle of zero deflection was most common. 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 seem 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.

Although a particular row can be traced from one photograph to the next in several cases, there is sufficient photographic evidence to lend credence to the findings of McLeish (1968). McLeish postulated that the rows were constantly shifting in direction, spacing and width within some range of values. This range depended upon the turbulent conditions present within the surface waters.

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. Minor deviations of wind direction, as taken from the meanders of the smoke plume, are closely coupled with identical deviations of neighboring windrows.

No specific mention has been made in this report of the parameter  $S/D$ . No correlation could be found for spacing versus depth of the thermocline, and this may be due to one of three reasons. First, there may be no correlation. Secondly, the spacing evident in the photographs may not be indicative of the total number of rows present. Lines or paths of convergence weaker than their neighbors may lose the marking cards to possession by the more powerful areas of convergence. Third, there may be no well defined thermocline. This was the case on 8 October, when only a very weak negative temperature gradient was observed.

A summary of this writer's conclusions is as follows:

(1) Windrow spacing appears to be related strongly to factors other than wind speed alone.

(2) Deflection of windrows to the right or left of the wind's direction occurs, but these deflections are small and can be expected to be within  $20^{\circ}$  of the wind.

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

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

## II. RECOMMENDATIONS

It is strongly recommended that the project of windrow investigation be continued at the Naval Postgraduate School. The data derived in this report resulted in much less conclusive evidence than was anticipated, and several corrections to the investigative technique are indicated.

Foremost is the need for better marking material. If there exist areas 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. It was noted, however, that the number of visible rows decreased shortly after initial seeding of the cards. One way of overcoming this problem would involve second seeding of material between formed windrows. Another method involves the use of small confetti-like particles of paper, or powder. The second seeding method seems preferable, but the probability exists of disturbing the pattern

already formed. If reasonable care is taken, the recommended method consists of using confetti or a metallic powder for an initial planting, then following this at specific intervals with second and perhaps third seedings of the same material between rows already formed.

The second recommendation is to investigate the use of a helicopter incorporating the T-11 camera. Some of the most well-defined and prevalent windrows can be found just offshore of the Oceanography Beach Laboratory. This is an area impossible to be photographed by fixed wing aircraft due to the proximity of the Monterey County airport's traffic pattern. In such an area, convection plays an important role. If thermal convection is present, only a light wind seems required to produce windrows. In the absence of convection, a significantly stronger wind would probably be needed. McLeish postulated that turbulence alone could produce windrows, but the photographs of this thesis contain too many observations that contradict his conclusion, i. e. , observations of well-defined parallel rows. In addition, several sequences of photographs showed windrows retaining their identity over time. A beach-mounted movie camera could be well used in conjunction with the T-11 to confirm this fact. In conclusion a helicopter has the capability of hovering for close-coupled time sequenced photographs of the windrows. This should allow accurate observation of windrow response time to a wind shift plus the variability with time of windrow width, direction, and spacing.

In order to develop meaningful statistics, it is recommended that sample photographs be 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. The photographs of this report were taken invariably in the afternoon due to aircraft and boat availability. The number of observations should total in the hundreds to allow for poor camera placement.

Since the wind field immediately above the water's surface is turbulent, there is an eddying motion present. Thus at any instant in time, the rows may not be parallel over all parts of a photograph. Based on this conclusion, the only reliable deflection measurements would be related to rows adjacent to the smoke plume, and these are nearly always parallel. To confirm the coupling of windrow orientation and wind eddies, it is recommended that multiple smoke floats be used in future research. An array of some type would be best, provided it does not obscure the cards or other marking material.

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APPENDIX II

Program for least-squares fit

```

C THIS PROGRAM COMPUTES THE LEAST SQUARE FIT BY LEGENDRE POLYNOMIALS
C FOR WIND SPEED IN M/SEC VERSUS WINDROW SPACING IN FEET
C
IMPLICIT REAL*(A-H,P-Z)
REAL*8 LABEL/8H /, ITITLE(12)
REAL*4 SIGMA, DELY, SB, ST, SC, W
REAL*4 XX(900), YY(900), XXX(30), YYY(30)
DIMENSION VEL(30), SPACE(30)
DIMENSION W(30), Y(30), DELY(30), B(4), SB(4), V(4), ST(4), X(4), SC(4),
*U(30), KM=1,4
DO 11 I=1,900
  READ 1, VEL
  FORMAT 1, (13F4.1)
  1 READ 2, SPACE
  2 FORMAT 2, (13F6.1)
  DO 3 I=1,30
    XXX(I)=VEL(I)
    YYY(I)=SPACE(I)
  3 READ 25, ITITLE
  25 FORMAT 25 (6A8)
C PLOTTING OF INPUT DATA POINTS FOLLOWS.
C CALL DRAW(30,XXX,YYY,1,1,LABEL,ITITLE,0,50,0,0,0,0,9,10,1,LAST)
C COMPUTATION OF COEFFICIENTS OF LEGENDRE POLYNOMIALS.
  16 CALL LSQPOL(30,KM,0,0,0,SIGMA,VEL,SPACE,W,Y,DELY,B,SB,V,ST,X,SC,U)
  DX=6.5/900.0
  RR=0.0
  DO 8 I=1,900
    XX(I)=RR
    IF(KM.EQ.2) GO TO 20
    IF(KM.EQ.3) GO TO 21
    IF(KM.EQ.4) GO TO 22
    YY(I)=R(I) + B(2)*RR
    GO TO 10
  20 YY(I)=B(1) + B(2)*RR + B(3)*(RR**2)
  21 YY(I)=R(I) + B(2)*RR + B(3)*(RR*RR) + R(4)*(RR**3)
  22 YY(I)=B(1) + B(2)*RR + B(3)*(RR*RR) + R(4)*(RR**3) + B(5)*(RR**4)
  10 RR = RR + DX
  8 CONTINUE
C PLOTTING OF BEST FIT CURVE
C CALL DRAW(900,XX,YY,3,0,LABEL,ITITLE,0,50,0,0,0,0,9,10,1,LAST)
  11 RETURN

```

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3. ABSTRACT			
<p>Aerial photographs were taken of windrow accumulations in Monterey Bay on 1, 8, 15 and 22 October 1968. A Fairchild T-11 aerial mapping camera was used, with photographs taken approximately every two minutes over 40 to 60 minute periods. Windrows were marked with accumulations of computer cards, wind speed measured by cup anemometer, and wind direction taken with the aid of a MK. 6 Smoke Float. Sea surface temperature, depth of the thermocline, and surface air temperature measurements were taken concurrently.</p> <p>An attempt was made to correlate windrow spacing and wind speed, to find mean deflection of windrows relative to the wind, to determine any relationship between row spacing and depth of the thermocline, and to find the response time of windrow orientation to a wind shift.</p> <p>Windrow spacing was found to depend on other factors than wind speed. Deflection angles varied between 20° left and 20° right, with 0° being the most common angle. No correlation was found between depth of the thermocline and row spacing. Response time fell between two and four minutes.</p>			

14

KEY WORDS

LINK A

LINK B

LINK C

ROLE

WT

ROLE

WT

ROLE

WT

Windrows

Langmuir circulation

Wind streaks













thes05893

Surface characteristics of windrows.



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