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# The relationship between local wind and current in coastal waters of the British Isles

by

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and

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The substance of sections 4 to 7 of this report was embodied in a paper read before the Challenger Society on January 28th, 1954

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## ABSTRACT

The progress made towards the determination of the relationship between local wind and current, using data obtained at certain light vessels in 1939-41, is first outlined.

The main body of this Report describes the steps by which it was found possible, making use of data obtained since the War, to isolate that part of the observed current which fluctuates with local tidal conditions, allowing the wind-induced current, "untainted" by periodic terms, to be compared with the local wind. By this means it is possible to determine the value of what may be termed the basic current, which is independent of wind and tide.

It is shown that at three of the four light vessels considered the wind-induced water movement at approximately 14 feet below the surface is about 1.7% of the wind travel, but that local conditions may alter the percentage according to the direction from which the wind blows. At the fourth light vessel the value is only 0.9% but this is tentatively ascribed to the vessel's position.

Finally, the expression connecting the wind and water movement is shown to be linear for wind strengths up to about Beaufort 3, but above this it appears to be parabolic or to obey a different linear relationship.

# THE RELATIONSHIP BETWEEN LOCAL WIND AND CURRENT IN THE COASTAL WATERS OF THE BRITISH ISLES

## 1. INTRODUCTION

For some years before the War observations of the currents in the upper layers of the sea were made aboard British light vessels under the auspices of the Ministry of Agriculture & Fisheries Laboratory, Lowestoft, first with "Carruthers" drift indicators and later with "Carruthers" vertical log current meters. This work was undertaken by the Laboratory as part of its normal fisheries research programme.

From 1939 to 1941 six current meters were in operation, for more or less continuous periods, in light vessels stationed at points between Scilly and the Humber. By the time the work ceased owing to the War, some 2,000 daily observations had been made aboard them.

An investigation of these data was made in the Hydrographic Department of the Admiralty in 1950-51, under the direction of the Oceanographer, who was responsible ab origine both for the design of the vertical log current meter (see Appendix "A") and for the organisation of the programme of currents observations. A certain amount of progress was made towards discovering the relationship between the local wind and the observed current, and several papers were published on the subject (see Appendix "B").

The currents measurement programme was restarted late in 1950 as a combined commitment of the Hydrographic Department of the Admiralty, the Royal Naval Scientific Service and the National Institute of Oceanography. The object of the programme was to gain knowledge of the coastal water movements not only for fisheries research work, but also for such military purposes to which it could be applied.

By the middle of 1953 fourteen light vessels were making continuous observations in the waters surrounding Britain. The scheme had largely become internationalised, the vessels taking part being eight British, four Netherlands, one Belgian and one German.* Their positions are shown in Fig. 1. Since by this time five of the light vessels had completed at least two years of more or less continuous observations, it was possible to continue the investigation using the post-War data only. This gave a considerable advantage over the earlier investigation, for between 1939 and 1941 only three light vessels had made observations for more than twelve months continuously, and only one for more than two years.

## 2. CONDITIONS UNDER WHICH OBSERVATIONS ARE MADE

To obtain the observations which are the basis of this Report, the practice has been for the current meter to be read every lunar or mean tidal day of 24 hours 50 minutes. The local wind direction is estimated at three-hourly intervals to the nearest 2 points($22\frac{1}{2}°$) and its strength according to the Beaufort scale.

The water layer to which the observations refer is 5 feet in thickness, centred at approximately 14 feet below the sea surface in all but Netherlands light vessels, in which it is centred approximately 20 feet below.†

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* Since then, observations have been commenced in one French and three British light vessels, and discontinued in one British vessel.

† This has now been standardised at about 6m ($20\frac{1}{2}$ ft.) for all light vessels.

It must be emphasised that the conditions under which currents measurements are taken by light vessel personnel cannot compare with those of carefully controlled experiments conducted by trained scientific staff. The currents observations suffer from the added disadvantage that they must take second place to ordinary ship duties, particularly in bad weather, when faulty readings tend to increase for other reasons.

The possible errors, which are either inherent in the method, or generally unavoidable and frequently undetectable, are discussed in Appendix "C". Because of these difficulties, it was essential to have available for investigation as many daily observations as possible (at least 700 per light vessel) and to discard ruthlessly any which did not, in the course of the investigation, appear to fall into line. Under the circumstances, it argues well for the care with which the light vessel personnel performed their task that in fact only a small percentage of the data had to be so discarded.

## 3. INVESTIGATION OF 1939-41 DATA

In 1914 Thorade [1] concluded that in the open ocean water movement and wind are related by a parabolic expression at low wind speeds, but that with wind speeds above Beaufort 3 the relationship is linear.

As described in Appendix "A", the vertical log current meter records the sum of all water movements which occur in each of the 45° octants whose median lines are the cardinal and intercardinal magnetic directions. The residual water movement, or current, is obtained by vector addition of the octantal movements at the end of each period of observation.

Whatever fixed period of time is selected for the observation, part of the observed current is subject to tidal periodicity, part will be wind-induced and part "basic", or current which is present whatever the conditions of wind and tide.

Thus, modifying Thorade's linear expression for winds above Beaufort 3,

$$\overrightarrow{C_o} = \overrightarrow{x.\sin\phi} + \overrightarrow{y.W} + \overrightarrow{C_b} \qquad (1)$$

where $C_o$ is the observed current,

$x.\sin\phi$ is the periodic portion depending upon tidal conditions,

$y$ is the percentage of wind travel transmitted to the water,

$W$ is the wind travel

and $C_b$ is the basic current.

The determination of the variables and unknowns in the above expression was found to be by no means as simple as it might appear. Various methods, fully described in the papers listed in Appendix "B", were tried, but it was felt that the results obtained were not altogether conclusive.

Tentative values obtained for y, using pre-War data, are shown in Table I.

TABLE I - TENTATIVE VALUES FOR y OBTAINED BY VARIOUS MEANS

| Lt. V. | y (%) |
|---|---|
| Varne | 1.5 - 1.75 |
| Seven Stones ) Royal Sovereign ) North Goodwin ) | 1.5 |
| Cromer Knoll | 0.4 |

The similarity between the values for the four light vessels in the English Channel is striking, but their determination was carried out by consideration of selected observations only. The reason for y being so low at the Cromer Knoll is tentatively ascribed to shielding by the coast from the dominant S.W. wind.

Nevertheless, taking 1% as an average value for the wind travel transmitted to the water, and using monthly averages of geostrophic wind over large areas(2) instead of estimated local wind, it was found possible to discover expressions connecting wind conditions during the periods when fish larvae would have been pelagic with later yields of grown fish. What are considered to be good correlations were obtained between wind conditions and fish harvests for six different types of fish in eight separate fisheries. The relevant papers in which these findings were published are listed in Appendix "D".

Attention was next directed to the possibility of eliminating the periodic or tidal portion of the current by considering average values of water and wind movement for calendar months, on the grounds that a calendar month approximates roughly to a lunation. For this it was obviously essential to investigate data from light vessels at which current meters had been in operation for reasonably long periods, and of the available six light vessels only three — Varne, Royal Sovereign and Seven Stones — had taken observations for more than a year continuously.

Now at the Varne significant water movements occur in two octants only — N.E. and S.W. — whatever the wind direction, and the directions of the tidal streams diverge very little from the median lines of these octants. A graph was therefore constructed of the residual water movement (current) for each month, N.E. or S.W.*, against the component of the residual wind along the N.E. - S.W. line, as shown in Fig. 2(a)≠. Although there is considerable scatter, there is also more then a strong suggestion that the relationship between the two variables is linear; a tentative regression line has been drawn. Points marked with a query are for months where several days' observations are missing or where an inexperienced Master was in charge.

If the excursions of the points about the regression line be plotted chronologically (Fig. 2(b)) a half-yearly periodicity emerges. The determination of the amplitudes must be done by inspection, and it is obviously difficult, if not impossible, to predict their values for the future, the main difficulty being that there are too few points per cycle.

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* Directions given in point letters are magnetic; true dirdctions are indicated by the 0°- 360° scale.

≠ Fig. 2 refers to the post-War data, but follows the same lines as the plot obtained with the earlier results.

However, taking the curve as it stands and applying to the original points the corrections indicated by the amplitude of the curve at each month, this does have the effect of moving most of them closer to a regression line (Fig. 2(c)) which is very nearly the same as that drawn in Fig. 2(a).

Similar operations were performed upon the monthly averages for the Royal Sovereign and Seven Stones. At the former, the up-Channel water movement lay in the E. octant, and the down-Channel movement in the S.W. octant; both water and wind movements were therefore resolved along the reciprocal edges of these octants, E.N.E. and W.S.W. At the latter, water movements were recorded in all octants, but predominantly in the S. and N.W. Water and wind movements were therefore resolved first along the N.N.E. - S.S.W. line, then along the W.N.W. - E.S.E. line, and the two results combined.

It will be realised that the process described had the effect of telescoping Expression (1) to:-

$$\vec{C_o} = y\vec{W} + \vec{C_b} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where $C_o$ is the component of the observed current along the main tidal direction,
$y$ is the percentage of wind travel transferred to the water,
$W$ is the component of the wind travel along the main tidal direction,
and $C_b$ is the component of the basic current along the main tidal direction.

In the plots of Fig. 2, $y$ is represented by the slope of the regression line and $C_b$ by the intercept. The values of the unknowns thus obtained from pre-War data are shown in Table II*.

TABLE II - VALUES OF $y$ AND $C_b$ OBTAINED BY GRAPHICAL METHODS

| Lt. V. | $y$ (%) | $C_b$ (Miles per lunar day) |
|---|---|---|
| Varne | 1.2 | 1.2 : 035° |
| Royal Sovereign | 1.1 | 1.1 : 057° |
| Seven Stones | 1.0 | 0.8 : 157° |

4. PRELIMINARY WORK ON POST-WAR DATA

As the post-War programme progressed and data accumulated, plots of monthly averages of water and wind movement were constructed first for one light vessel and then for others. The only light vessel for which pre-War and post-War results were available for comparison was the Varne. (Observations at the Royal Sovereign were not restarted until the autumn of 1952, and no plot had therefore been constructed by the time this method of investigation was abandoned.)

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* A paper entitled "Studies of Wind and Water Movement in British Seas", giving these results and generally describing the above work, was read before the Challenger Society on October 17th, 1951.

The values of y and $C_b$ obtained from the post-War data are shown in Table III. It was found extremely difficult to evaluate the periodic terms at some light vessels, and at many of them it was impossible, due partly to scarcity of points and partly to the incidence of "bad" or unreliable monthly averages. Values enclosed in brackets in the table include the periodic terms. The table gives two sets of values for some light vessels, the one for mid-1951 to mid-1952, the other for the succeeding twelve months.

TABLE III - VALUES OF y AND $C_b$ for 1951/2 and 1952/3

| Lt. V. | y (%) | | $C_b$ (m.p.d.) | |
|---|---|---|---|---|
| | 1951/2 | 1952/3 | 1951/2 | 1952/3 |
| Varne | 1.98 | 2.02 | 1.87 : 037° | 1.53 : 037° |
| Smith's Knoll | 1.90 | 1.86 | 1.53 : 161° | 1.08 : 160° |
| Galloper | 0.90 | 0.85 | 0.63 : 2.7° | 1.05 : 217° |
| Dowsing | (1.13) | | (1.60 : 140°) | |
| S.2. | (2.06) | | (0.36 : 117°) | |
| North Carr | - | (1.43) | - | (0.27 : 116°) |
| Goeree (x) | - | (2.88) | - | (1.66 : 336°) |
| Texel (x) | - | (5.44) | - | (4.50 : 351°) |
| Terschellingerbank (x) | - | (7.41) | - | (4.26 : 027°) |

(x) = from end-1951 to mid-1953

The chief conclusion reached from these results was at the time becoming only too obvious from comparison both of the pre-War and post-War Varne results and of the 1951/2 and 1952/3 results for the first three light vessels in Table III. It was that in order to arrive at a reliable determination of y, the percentage of wind travel transferred to the water, and of $C_b$, the basic current, it was essential to eliminate not only the short term periodicity which existed within the lunation or calendar month, but also the periodics with half-yearly and longer cycles.

Secondly, it appeared desirable to take into account the local conditions obtaining at the position of each light vessel— principally the fetch of the wind from different directions and the general configuration of the bottom, since most light vessels lay close to the coast and in fairly shallow water.

To illustrate the effect which these conditions might be expected to have on the water movements, Fig. 3 shows a "theoretical" wind-water diagram from the Varne constructed on the lines followed by Wyrtki[3]. In this type of diagram the concentric circles represent wind travel starting from the centre and moving <u>with</u> the wind, and the contours, which at the Varne become straight lines because water movements are recorded in two reciprocal octants, represent the associated current travel, during a lunar or mean tidal day.

Apart from any consideration of variability of the basic current, if Expression (2) is assumed to hold good for winds from any direction all current contours should be parallel, equally spaced and running N.W.-S.E. and the zero (nil) current contour should be displaced to one side of the zero wind position — the centre of the diagram — by an amount equal to the basic current, $C_b$, which in this case is taken as 1.7 m.p.d. N.E., the intercept given by the graph in Fig. 2(c). Then a West wind of force 3, for example, should in theory be associated with the same current (3.1 m.p.d. N.E.) as a South wind of the same strength, since their components along the N.E.-S.W. line are identical. But inspection of the daily observations has shown that this is by no means the case. Other examples could be quoted, but in very few instances indeed was it found that equivalent winds from different directions produced equivalent currents.

Thirdly, as wind-water diagrams constructed on the above lines using monthly averages gave very inconclusive results, it seemed essential to revert to the examination of the daily observations.

## 5. INVESTIGATION OF POST-WAR DAILY OBSERVATIONS - "VARNE"

To avoid the dificulties already described, it was necessary to find, for use as what might be called an intermediate step, an oscillating variable whose phase and period corresponded, at least approximately, with the periodicity (both short and long term) which was apparent in the daily residual water movement or current. Van Veen (4) has shown that correlations could be made between the tidal range at Dover and the flood stream travel, the ebb stream travel and the total daily water movement (flood travel + ebb travel regardless of direction) respectively at the Varne. It was therefore decided to assume that there existed a like connection between the tidal range and the periodic term contained in the daily residual water movement (flood travel $\sim$ ebb travel).

The Varne observations, of which some 900 had now accumulated, were selected for "pilot" investigation. The first step was to group all observations according to the predicted mean tidal range at Dover for the period which each covered. The observations were next plotted — one plot for each foot of mean tidal range — by the method used by Wyrtki and described in (4) above. As a very large scale had to be used, it is not possible to reproduce the whole of each plot, but Fig. 4 shows the most significant part — the centre — of the plots for mean tidal ranges of 10, 13, 16 and 19 feet, covering residual wind travels with cardinal components of up to 150 miles per day.

These plots show that when the mean tidal range is 10 feet, zero wind is associated with a very slight N.E'ly current. As the mean tidal range increases, the magnitude of the N.E- going current associated with zero wind also increases, until at a mean tidal range of 19 feet it is of the order of 3 m.p.d. Alternatively, at 10 feet mean tidal range winds from south of the N.W.-S.E. line are associated with N.E- going currents, and winds from the north of it with S.W-going currents; at 19 feet winds from the south of the line are associated with much greater N.E-going currents, while weak winds from north of the line are associated with small N.E-going currents. This seems to justify, at least partially, the assumption made earlier.

It then became necessary to assess the mean value of the "no wind" current (or appropriate basic current) for each foot of tidal range. The most regular results seemed to be obtained from a combination of two methods - by plotting the current values of each point lying in a small arc on either side of the N.E.-S.W. line against the distance of the point from the N.W.-S.E. line and reading the intercept of the regression line, and by simply averaging the values of all points lying within a circle of small diameter with the "no wind" point as centre. The resulting plot (Fig. 5) is reasonably linear, the "no wind" current apparently varying from about 1 m.p.d. at 8 feet to 3 m.p.d. at 21 feet, both towards N.E.

Having got thus far, it seemed worthwhile to look for confirmation that a freak situation did not exist at the Varne. The whole process was therefore repeated using observations at the Galloper, where the water movements also run very close to N.E. and S.W., but predominantly towards S.W. A comparable result was obtained, the basic ("no wind") current apparently fluctuating between 1 m.p.d. S.W. at high tidal ranges and 0.3 m.p.d. S.W. at low tidal ranges.

The next move was to apply a correction to all current observations to make them applicable to one mean tidal range — in the case of the Varne, $14\frac{1}{2}$ feet at Dover was selected. This was readily done by adding to or subtracting from the observed currents the difference between the basic current for $14\frac{1}{2}$ feet and the basic current for the mean tidal range of each observation. All corrected observations were then put on to a wind-water plot of the usual type of construction.

As might be expected, although large "blocks" of currents of the same magnitude and duration appeared in the same areas, there were a number of cases, where, for instance, isolated high values showed up among low values, or where S.W-going currents were found in N.E-going current "territory", or vice versa. In view of the circumstances described in Appendix "C", it appeared not unreasonable to reject those observations which could not be reconciled with their surroundings, lest they should unduly colour the picture. In the event, not more than 5% had to be discarded.

The plot as it stood was still too complicated to permit current contours to be drawn in, and the final operation was to smooth the results and thus reduce the number of points. This was done by meaning the values in squares measuring 75 x 75 miles of wind travel, and giving those values lying within the central 25 x 25 miles twice the weighting of the remainder. The average current value thus obtained was assigned to the small central square. Fig. 6 shows the central portion, covering residual winds with cardinal components up to 200 miles per day, of the smoothed plot for the Varne.

From this smoothed plot, contour lines were constructed. They were drawn to pass roughly through the centre of large blocks of currents of the same magnitude and direction, isolated enclaves being largely disregarded and re-entrant curves, which might indicate <u>less</u> current for more wind in some areas, being avoided.

The complete wind-water diagram for the Varne, for winds up to Beaufort 5, is shown in Fig. 7; current observations associated with winds of greater strength are few and unreliable. The "no wind" or basic current is about 2 m.p.d. N.E., in agreement with the value given by Fig. 5. The <u>line</u> of no current, however, is very different from the NIL line of the "theoretical" diagram (Fig. 3); in effect, it lies much more nearly East-West, except with very strong winds. It is also evident that winds from different sides of the main tidal stream directions — N.E. and S.W. — which have components of the same numerical value are <u>not</u> associated with equivalent currents.

It will be apparent that the magnitude and direction of the so-called correction for any particular mean tidal range will depend upon the time at which the series of observations is started in relation to the local tidal conditions. That is to say, for example, that if at some position the series starts at H.W. when the water is about to move to the north, then the correction will be a northwards one; but if the series be started at L.W., when the water is about to move to the south, then the correction will be in the opposite direction. For other times of starting, the correction may have either direction, may be reduced in magnitude or may disappear. Thus this correction must now be discarded and no further use made of it in "hindcasting" current.

The diagram shows the combined basic and wind-induced current which may be expected to exist in a period of 24 hrs. 50 mins. It is important to remember, however, that if "hindcasts" are required over shorter lengths of time, the wind travel must be calculated on a basis of 24 hrs. 50 mins. and the appropriate current extracted; this must then be proportionally reduced to cover the appropriate time interval. For example, if a "hindcast" is required for a wind of W miles during a period of t hours, the wind travel to use on the diagram is $\frac{W}{t} \times 24\ 5/6$. Then if the current travel given by the diagram is X miles, the travel during the required period t hrs. is $\frac{X \times t}{24\ 5/6}$.

For periods greater than 24 hrs. 50 mins., a separate entry must be made with the wind travel appropriate to each lunar day, and any broken period remaining must be dealt with as above; the individual water travels can then be summed.

If it is desired to "hindcast" the position of a drifting object, then the effect of the tidal streams must of course be taken into account for all broken periods of less than 24 hrs. 50 mins.

The basic current of 2 m.p.d. N.E. compares reasonably well with the figure of 1.5 m.p.d. towards North which appears to be indicated by the similar diagram in Wyrtki's paper (3). The current observations used by him were obtained by Carruthers with one of his drift indicators at a depth of 33 feet (10 metres), while those from which Fig. 7 was constructed refer to a mid-depth of about 14 feet. His winds, moreover, are averages calculated for the Southern North Sea, as against estimated local winds at the Varne.

## 6. INVESTIGATION OF POST-WAR OBSERVATIONS - OTHER LIGHT VESSELS

The observations taken at three other light vessels were treated in the same manner as described above (Fig. 8). At the Galloper, off the Thames estuary, the basic current of 0.6 m.p.d. S.W. is much less than at the Varne. More wind is required to produce currents of comparable magnitude, possibly because of the Galloper's position.

Water movements at the Smith's Knoll, off Great Yarmouth, occur in all octants, the greatest in the north and south. To construct the diagram for this light vessel, it was therefore necessary to perform each operation twice --- once for the N.-S. current component and once for the E.-W. component --- and then to combine the two. The radial lines in the diagram represent current direction and the ellipses current travel. The Smith's Knoll is only shielded by the land to a certain extent to the west-south-westward. The current ellipses lie with their major axes along this direction, and the current direction radials are bunched together about the W.S.W.-E.N.E. line. This can be at least partly ascribed to the fact that more wind is needed to produce an onshore or offshore current than a current moving up and down the coast, and that a small change of wind direction, when onshore or offshore, is associated with a greater change of current direction than when the wind is up or down the coast. It can also be due in part to the tidal streams in this position spending more time in the N. and S. octants than in the remainder. This means that with winds at a considerable angle to the tidal streams, part of the wind-induced current will not be recorded unless the winds are very strong (see 7 below).

The German light vessel S.2 used to lie in the middle of the Southern North Sea, almost 100 miles from the nearest land. Her diagram should therefore show little distortion from the "theoretical", which in a position where the water moves in all octants consists of a series of concentric current magnitude circles with evenly spread current direction radials. It will be seen that at S.2 the magnitude contours are in fact more nearly circular, and the direction radials straighter and more regularly spaced, than at the Smith's Knoll.

## 7. RELATIONSHIP BETWEEN WIND AND CURRENT

Examination of the wind-water diagrams for Smith's Knoll and S.2 reveals that winds from different directions produce different percentage values of wind travel translated to water movement. If the water origin is transferred to the wind origin, thereby eliminating the basic current, the water movement can be plotted against wind travel for a particular wind direction and the relevant percentage value ascertained from the linear section of the graph. For example, at the Smith's Knoll the percentage value for a wind from 140° is 1.35, whilst for a wind from 240° it is 0.45 (Figs. 9(a) and (b)); these are the maximum and mininum values associated with this particular position. The difference between them can be ascribed to two effects:-

(i) The effect of fetch. The fetch to the S.W. at Smith's Knoll is only 25 miles, so that winds from that direction may possibly not produce such large water movements as those set up by S.E. and N.W. winds, for which the fetch is 80 miles and 130 miles respectively. Moreover, although there is a large fetch to the N.E. the water movement to the S.W. created by a N.E. wind may not be large owing to the land to leeward. However, the fetch is small over an arc between 210° and 290°, beyond which it suddenly increases, which might be indicated by a discontinuity in the current contours. No such discontinuity does in fact occur and hence fetch may not be the overriding factor.

(ii) The effect of the different times spent by the tidal movements in each octant. It must be remembered that the directions of the water movements are assumed to lie along the median lines of the octants and that the resultant of water movements in opposing octants are calculated from their scalar difference and not their vector sum. Hence theoretically, provided the wind is not strong enough to "twist" a water movement out of its octant, a N. (say) wind will not produce any recorded residual water movement whilst the tidal movements are in the E/W octants. Thus the magnitude of a resultant water movement whose direction lies in a particular octant will depend not only on the wind but on how long the tidal movement spends in that octant compared with the times spent in other octants. At Smith's Knoll the tidal movements spend most of the day in the N/S octants and little time in the E/W octants, and therefore it would be expected that the percentage value along the N/S water movement line would be much greater than the percentage along the E/W line.

To compute the overall percentage, neglecting the effect of fetch, the water movement is plotted against wind travel along axes about which the time spent in the various octants is evenly distributed; from the wind-water diagram of Smith's Knoll such axes appear to be NNE/SSW and WNW/ESE approximately. The overall percentage will be the sum of the individual percentages obtained for each axis, since the tidal movement spends half a day in the quadrants for which the median line is one of the axes. Fig. 9 (c) and (d) for the axes of Smith's Knoll give both the individual percentages as 0.80; hence the overall percentage is 1.60.

For S.2 the current contours are approximately circular, with maximum and minimum percentages of 1.00 and 0.75. This indicates that here the time spent in each octant is more nearly the same than at Smith's Knoll; this is borne out by reference to the Tidal Atlas. Figs. 10(c) and (b) for the axes of S.2 again give both individual percentages as 0.85, which results in an overall percentage of 1.70, which is very similar to the situation at Smith's Knoll.

At the Varne the tidal movements spend the whole time in the N.E. and S.W. octants, and it is therefore only necessary to plot along the lines which give the maximum wind/water percentages. Figs. 11(a) and (b), which were taken along the wind directions 186° and 007°, both reveal a percentage value of 1.75.

The procedure carried out for the Varne was used in the case of the Galloper. Figs. 12(c) and (b) were taken along the wind directions 182° and 015°, and give percentage values of 1.05 and 0.75; the mean overall percentage is therefore 0.90.

Whereas the values for Smith's Knoll, S.2 and Varne (1.60%, 1.70% and 1.75%) are in good agreement, the value for Galloper is very much lower. No complete explanation can be given for this, but it might be due to the Galloper's position, which is such that the surrounding wind-induced water movements may only produce a small resultant at the light vessel itself. It should be noted that all the above values agree well with those in Table III obtained from monthly means.

Scrutiny of the four wind/water plots shows that whereas for low wind speeds the relationship between wind travel and water movement is approximately linear (this is the section from which the percentage values were obtained), above certain speeds it tends to become curved or changes to another linear relationship of different slope. The latter is especially noticeable in the case of the Varne, where Figs. 11(a) and (b) each appear to consist of two straight lines. In most of the plots the numbers of points representing the second relationship are small, and it is impossible to decide whether this relationship is linear or curved.

Turning to Thorade's (1) conclusions mentioned in (3) above, his parabolic expression connecting water movement and wind travel for winds below Beaufort 3 does not seem to occur in the plots (or if it does the parabola is not discernible). With wind speeds above Beaufort 3 (250 miles per mean tidal day) he suggested that the relationship is linear, and in this the plots agree fairly well.

Thus if W is the wind travel, C the associated water travel and B the basic current, Thorade's conclusions can be represented by the following equations:-

Winds below Force 3 ................ $\vec{C} = \vec{B} + \overrightarrow{y_1 W}$ ........ (3)

Winds above Force 3 ................ $\vec{C} = \vec{B} + \overrightarrow{y_2 W}$ ........ (4)

The wind-water plots suggest the following alternative extensions:- Assuming a curved relationship, for winds above Force 3-4,

$$\vec{C} = \vec{B} + \overrightarrow{y_2 W} + \overrightarrow{y_3 W^2}, \text{ where } y_2 \gg y_3 \quad \ldots\ldots\ldots\ldots \quad (5)$$

or assuming a second linear relationship,

$$\vec{C} = \vec{B} + \overrightarrow{y_2 K} + \overrightarrow{y_3 (W-K)} \quad \ldots\ldots\ldots\ldots \quad (6)$$

where $y_2$ = percentage value obtained from the first linear relationship,

$y_3$ = " " " " " second " "

and K = value of wind travel at which the transition occurs from the first linear relationship to the second.

For the Varne the linear relationships and transition point are clearly defined. The mean values of $y_2$, $y_3$ and K from Figs. 11(a) and (b) are 1.75%, 4.25% and 310 m.p.d. It is conceivable that this transition point is the same as that observed by Thorade in his changeover from parabolic to linear relationship.

A suggestion regarding the curved extension appeared in the last paper listed in Appendix B. It was made very tentatively because the evidence consisted of one point only. The graphs now displayed give more weight to the suggestions, but more observations under conditions of high wind velocity will be needed before definite conclusions can be reached.

Certain of the wind/water plots suggest that the complete expression connecting wind travel and water movement may take the form

$$\vec{C} = \vec{B} + \overrightarrow{y_2 W} + \overrightarrow{y_3 W^2} + \overrightarrow{y_4 W^3} \text{ ------- etc.} \quad \ldots\ldots\ldots\ldots \quad (7)$$

where $y_2 \gg y_3 \gg y_4$ ------- etc.

The values of $y_2$ for the four light vessels were obtained from the initial linear sections of the wind-water plots in the manner described above. The following table shows the values of B and $y_2$:-

TABLE IV - VALUES OF B AND $y_2$ GIVEN BY WIND-WATER DIAGRAMS

| Light Vessel | Basic Current B in m.p.d. | Wind/Water $y_2$ |
|---|---|---|
| Smith's Knoll | 0.87 - 148° | 1.60% |
| S.2 | 0.58 - 070° | 1.70% |
| Varne | 2.05 - 037° | 1.75% |
| Galloper | 0.62 - 217° | 0.90% |

It should be noted that in every wind/water plot, when the water origin has been transferred to the wind origin, the direction of the water movement is to the right of the wind travel. This is in accordance with the theories of Ekman, who postulated that for an open ocean in the Northern Hemisphere the wind-induced water movement near the surface would run to the right of the wind. The angle between the wind and water directions varies from light vessel to light vessel, and also is variable at a particular light vessel according to the direction from which the wind blows. This may naturally be ascribed to the effect of neighbouring coastlines.

The foregoing also explains why, in the case of the Varne, winds having components of the same numerical value, but blowing from different sides of the main tidal stream directions, are associated with different currents (see 5 above).

## 8. VALIDITY OF RESULTS

The intention is that the wind-water diagrams should be used, inter alia, to "hindcast" the drift of floating objects from knowledge of the conditions of wind and tide.

Short of putting into the water drift floats so constructed as to be unresponsive to wind and tracking them from day to day, it is next to impossible to check the validity of the current values obtained by the method described. The most likely source of error is inherent in the system itself — the current meter measures the flow of water past a light vessel, and the direction of flow has to be assumed to remain constant whatever distance from the light vessel the water reaches. In fact, it is very probable that the water may change its direction and velocity only a few miles after passing the light vessel; at the Galloper, for instance, the current turns gradually through about 180°. Knowledge of the local current system can of course be used to some extent, in conjunction with the currents indicated by the diagrams, to obtain a more realistic idea of where an object will have drifted to in a given period.

Some sort of check has been made, however, on the Varne and Galloper diagrams by comparing the currents "hindcast" by them with the actual currents recorded aboard each lightship. Table V shows the differences between the "hindcast" and observed currents, expressed as percentages of the total number of observations, over a period of about one month.

TABLE V - DIFFERENCES BETWEEN "HINDCAST" AND OBSERVED CURRENTS

| DIFFERENCES (m.p.d.) | PERCENTAGE OF OBSERVATIONS | |
|---|---|---|
| | VARNE | GALLOPER |
| 0-1 | 33 | 56 |
| 0-2 | 26 | 24 |
| 2-3 | 19 | 12 |
| 3-4 | 7 | 0 |
| 4-5 | 11 | 8 |
| 5-6 | 0 | 0 |
| 6-7 | 4 | 0 |

The average difference for the Varne was 1.9 m.p.d., and for the Galloper 1.3 m.p.d. The greater differences for the Varne are due to the currents experienced being up to two or three times as great as at the Galloper for the same wind strengths. It is very probable that some of the greater differences were in each case due to incorrect operation of the current meter, but it is not possible to prove this.

The process of collecting observations and incorporating them in revisions of the wind-water diagrams can be continuous; each successive revision, being based on a greater number of observations than the last, is likely to be more reliable.

## 9. CONCLUSIONS

The conclusions reached as a result of the investigations described are:-

(a) The relationship between current travel (or velocity) and local wind travel (or velocity) is approximately linear for wind strengths up to Beaufort 3. On average, the water travel at a depth of about 14 feet is of the order of 1.7% of the wind travel, but this average is not invariable (see (c) below).

(b) For wind strengths greater than Beaufort 3, the relationship appears to become parabolic, i.e. equal increases in wind strength are associated with increasing increases of current, or to change over to another linear relationship of different slope.

(c) The percentage of wind travel transferred to the water may be influenced by local conditions, such as fetch, and the position of the light vessel.

## 10. FUTURE OBSERVATIONS AND INVESTIGATIONS

It will be apparent that the fluctuations in the basic current are in fact non-existent as true current, and are in reality small "left-overs" of tidal movement introduced through the use of a mean tidal (or lunar) day of 24 hrs. 50 mins. for each observation instead of the actual tidal day. The basic current, however, exists as true current.

As stated in Appendix "C", one of the major sources of error in the method of computing current described herein is the unavoidability of having to assume that the water movement takes place along the median lines of each octant. The error this introduces can be considerable, especially at lightships such as the Varne, where the water movements occur only in the N.E. and S.W. octants. To take an example, suppose the current meter readings on a particular day indicate a N.E. movement of 11 miles and an equivalent S.W. movement; the observed current will be the arithmetical difference of the two, which is nil. But if the actual directions of N.E 'ly and S.W 'ly water movements are in reality "bent", by a northerly wind, by only $2\frac{1}{2}$ degrees to the south of the N.E.-S.W. line, then the vector sum of the two movements results in a S.E.-going current of 1 m.p.d.

In an attempt to discover whether more realistic results could be obtained by a different method of observation, the recording procedure used in Netherlands light vessels was tried for two months during the summer of 1954, at the Varne and Smith's Knoll. In this method hourly readings of water travel and direction are taken, and it is assumed that the direction remains the same (or that the reading is the average direction) for the hour bracketing each observation. It was found that at both positions the current tended to run more strongly, and more nearly with the wind, than with the present method; this was generally in accordance with expectations.

The use of this method also allows actual tidal days to be considered instead of mean tidal days which, it is thought, eliminates most, if not all, of the periodicity.

A change was made to hourly observations in all British light vessels on January 1st, 1955. When sufficient observations have been collected, they will be analysed by the procedure described in 5 above in an attempt to re-assess the value of the basic current and the effect of the wind upon the water movement.

## 11. ACKNOWLEDGEMENTS

Acknowledgements are due to Dr. J.N. Carruthers, now Assistant Director of the National Institute of Oceanography, under whose direction the work was carried out, for access to certain papers, written when at the Ministry of Agriculture and Fisheries Laboratory, Lowestoft, which "pointed the way" in several instances.

Indebtedness is acknowledged to Dr. G. Böhnecke, President of the German Hydrographical Institute, for making available the daily observations taken at light vessel S.2; and to Dr. P. Groen, of the Royal Netherlands Meteorological Institute, for copies of the monthly summaries of observations taken at Netherlands light vessels.

## 12. REFERENCES

(1) von THORADE, H. - "The Velocity of Drift Currents and the Ekman Theory", Ann. d. Hyd. u. Mar. Met., No. 7, (Berlin, 1914). (ACSIL Trans. No. 480)

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APPENDIX "A"

BRIEF DESCRIPTION OF THE "CARRUTHERS" VERTICAL LOG CURRENT METER

AND THE METHOD OF COMPUTING CURRENT

The vertical log current meter consists essentially of a cup system, hung over the side of a vessel from a boom and rotated by the movement of passing water. The cup system is suspended by a chain from a ball race in a recorder box, and is kept as nearly vertical as possible by a heavy weight shackled to its foot. The rotation of the cup system is transmitted by gearing to two counters fitted in the recorder box.

One counter is left permanently in place and thus registers the total revolutions made by the cup system. The other counter is changed whenever the water direction shifts from one 45° octant to another; the octants are centred on the cardinal and intercardinal points.

To determine the direction in which the water is moving, and the moments at which to change the counters, a subsidiary instrument is provided embodying a dumb compass, over which moves a pointer revolved by a bicycle chain. The water direction is picked up by a tasselled chain hung from the end of a slat clamped to a toothed wheel at the end of a framework, and transmitted inboard to the pointer via the bicycle chain. Before reading the water direction the dumb compass is set to match the direction of the ship's head. The compass directions obtained are magnetic.

At the end of the desired period of observation (normally one lunar day of 24 hrs. 50 mins.) all counters which are or have been in use are read. Subtraction of the previous readings gives the number of revolutions collected by each.

The cup system turns 300 times for each mile of passing water and the counters throw two figures for each revolution of the cup system. The calibration curve of the instrument is linear over all water speeds normally encountered; this permits the counter revolutions to be readily converted in mileages run by the water. These mileages are assumed to have been run in the directions of the median lines of each octant, i.e. the cardinal and intercardinal directions.

The residual water movement, or current, is obtained by vector addition of the mileages run in the various octants.

APPENDIX "B"

PAPERS PUBLISHED ON THE RELATIONSHIP BETWEEN LOCAL WIND AND CURRENTS

(in the order in which they were written)

CARRUTHERS, J.N. and A.L. LAWFORD - "Water Movements and Winds at the Mouse Light Vessel, Thames Estuary", Weather, August, 1950

CARRUTHERS, J.N., A.L. LAWFORD and V.F.C. VELEY - "Studies of Water Movements and Winds at Various Light Vessels. II. At the Seven Stones Light Vessel near the Scilly Isles", J. Mar. Biol. Assoc., Vol. XXIX, February, 1951

——————— - "Water Movements at the North Goodwin Light Vessel", Marine Observer, January, 1951

——————— - "Studies of Water Movements and Winds at Various Light Vessels in 1938, 1939 and 1940. I. At the Varne Lightship and her Successors", Cons. Perm. Int. pour l'Explor. de la Mer, Ann. Biol. Vol. VI (1949), 1950

——————— - "Continuous Observations from Anchored Vessels on Water Movements in the Open Sea; Experiences at the 'Royal Sovereign' and 'Cromer Knoll' Light Vessels", Deutsche Hydrog. Zeitschr., Band 3, Heft 5/6, 1950

## APPENDIX "C"

## SOURCES OF ERROR IN THE OPERATION OF THE VERTICAL LOG CURRENT METER AND IN THE METHODS USED TO COMPUTE CURRENT AND WIND TRAVEL

The operation of the current meter, and the readings obtained from it, are subject to human error. Mistakes which may be made, especially by light vessel personnel new to the work, include changing the counters at the wrong time or failing to change them when the water direction changes, incorrect reading of the counters, and incorrect setting of the direction indicator compass card.

In bad weather — that is, when the wind velocity is great — the possibility of error increases to the point where it is dangerous to life to approach the instrument.

Wind strength and directions are estimated and are also liable to individual human error.

The wind is assumed to blow from the same direction and with the same strength for the three hours bracketing each of the eight daily estimations. The connection between the Beaufort scale of wind strength and wind travel is an arbitrary one.

The rotation of the cup system of the current meter may become slowed by fouling, and may be temporarily retarded, without detection, by drifting weed or nets.

While the water direction lies in any particular octant, its mean direction must perforce be assumed to lie along the median line of that octant. This can give considerable "colour" to the current obtained by vector addition of the movements in all octants.

## APPENDIX "D"

### PAPERS DEALING WITH THE RELATIONSHIP BETWEEN WIND AND FISH HARVESTS

(in the order in which they were written)

CARRUTHERS, J.N., A.L. LAWFORD, B.B. PARRISH and V.F.C. VELEY - "Variations in Brood Strength in the North Sea Haddock, in the light of relevant Wind Conditions", Nature, 169, No. 4302, (12.4.52)

CARRUTHERS, J.N., A.L. LAWFORD and V.F.C. VELEY - "Fishery Hydrography: Brood Strength Fluctuations in various North Sea Fish, with suggested Methods of Prediction", Kiel. Meeresforsch., Bd. VII, Heft 1, (1951).*

VELEY, V.F.C. - "Fishery Hydrography: Brood Strength Fluctuations in the Hake with a suggested Method of Prediction", Cons. Perm. Int. pour l'Esplor. de la Mer, Ann. Biol., Vol. VII, 1950 (1951)

__________ - "Year-Class Fluctuations in the Sprat", Cons. Perm. Int. pour l'Explor. de la Mer, R. et P.-V. CXXXI, Contributions to Special Scientific Meeting, 1951 - Fisheries Hydrography (June, 1952)

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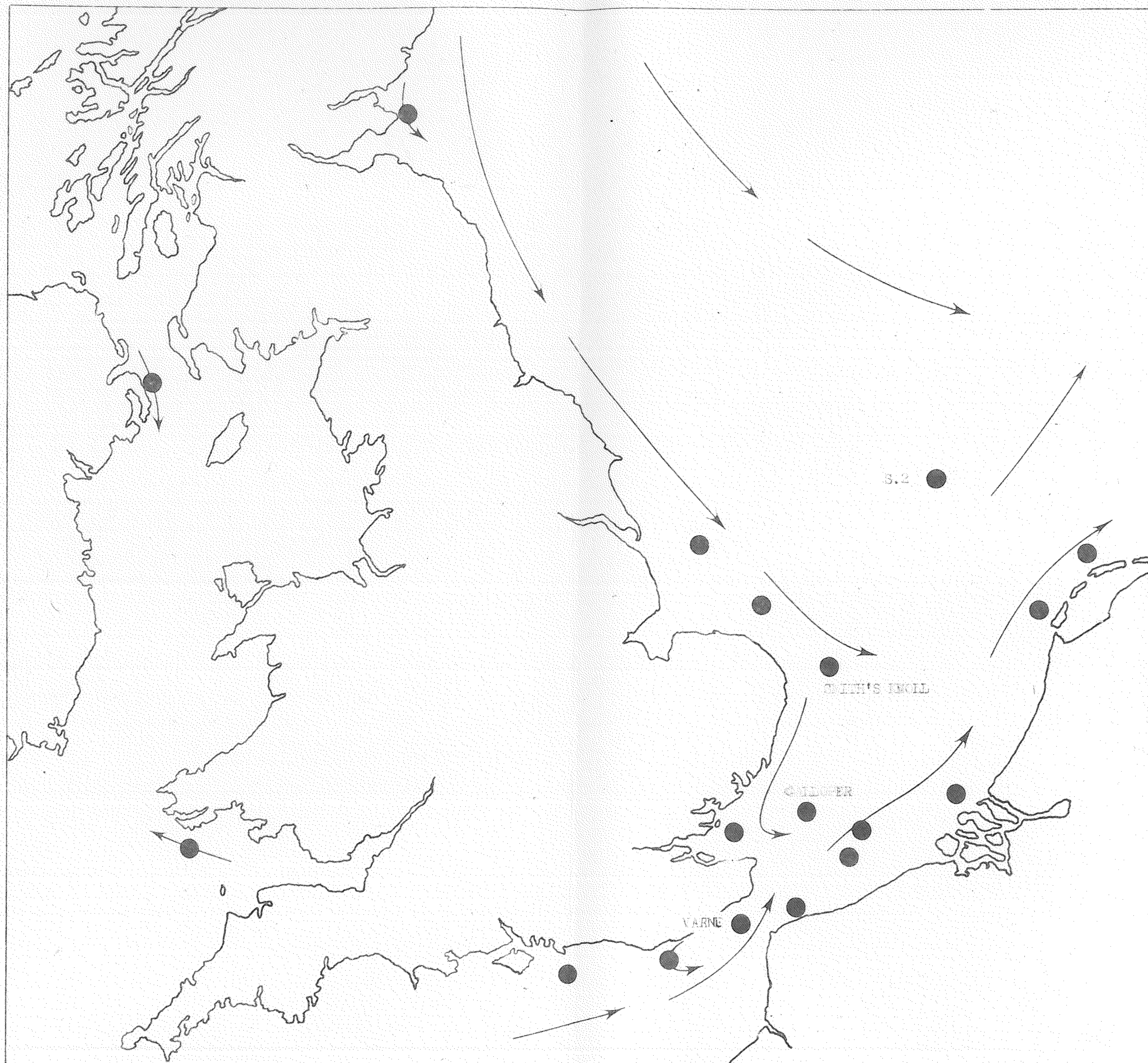
* This paper deals with the herring, plaice and cod.




POSITIONS OF LIGHTSHIPS OPERATING CURRENT METERS

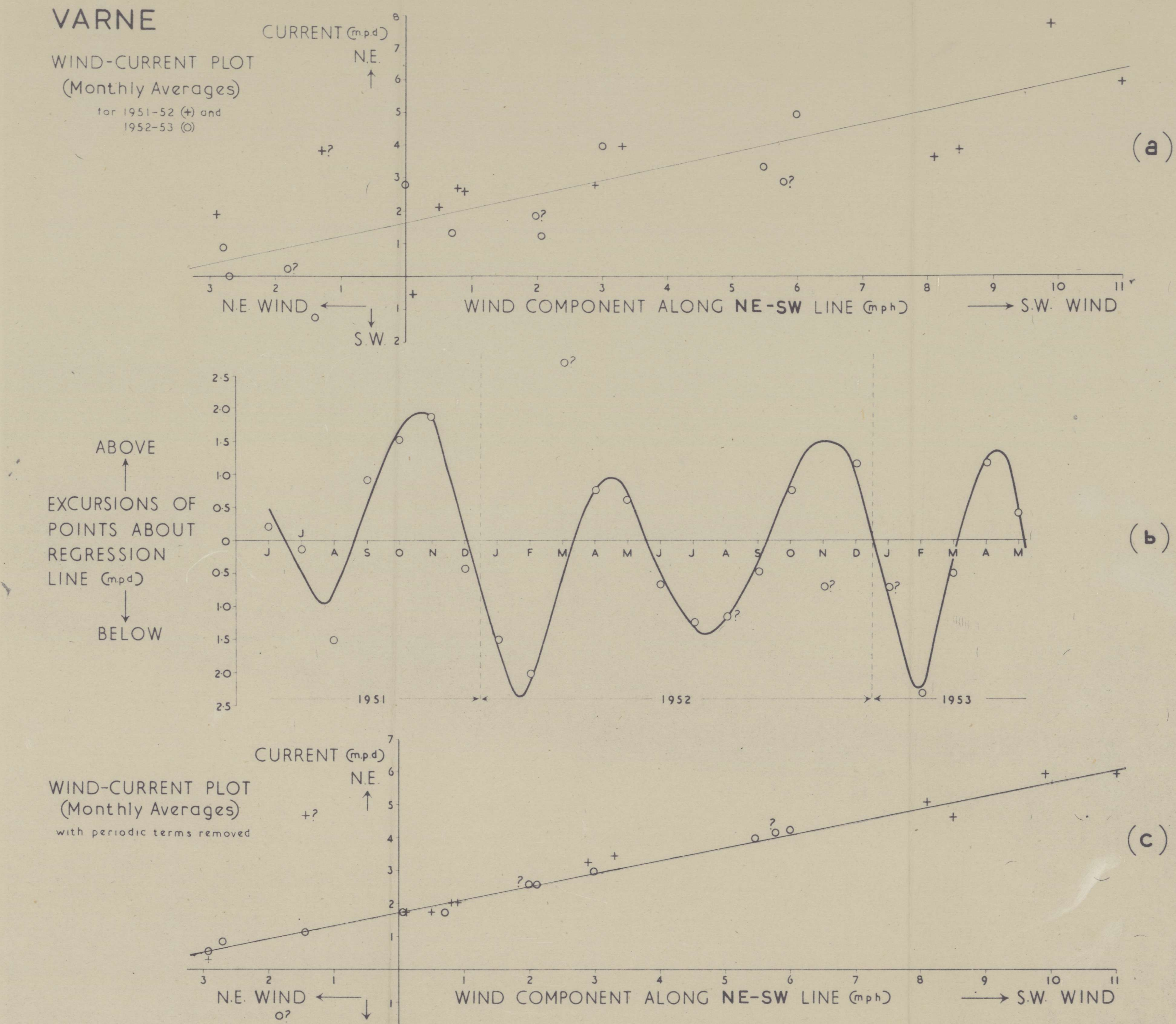

VARNE
WIND-CURRENT PLOT
(Monthly Averages)
for 1951-52 (+) and 1952-53 (O)
CURRENT (m.p.d)
N.E.
S.W.
N.E. WIND
WIND COMPONENT ALONG NE-SW LINE (mph)
S.W. WIND
(a)
ABOVE
EXCURSIONS OF POINTS ABOUT REGRESSION LINE (m.p.d)
BELOW
J J A S O N D J F M A M J J A S O N D J F M A M
1951
1952
1953
(b)
WIND-CURRENT PLOT
(Monthly Averages)
with periodic terms removed
CURRENT (m.p.d)
N.E.
S.W.
N.E. WIND
WIND COMPONENT ALONG NE-SW LINE (mph)
S.W. WIND
(c)

FIG. 2.

VARNE — THEORETICAL WIND-WATER DIAGRAM

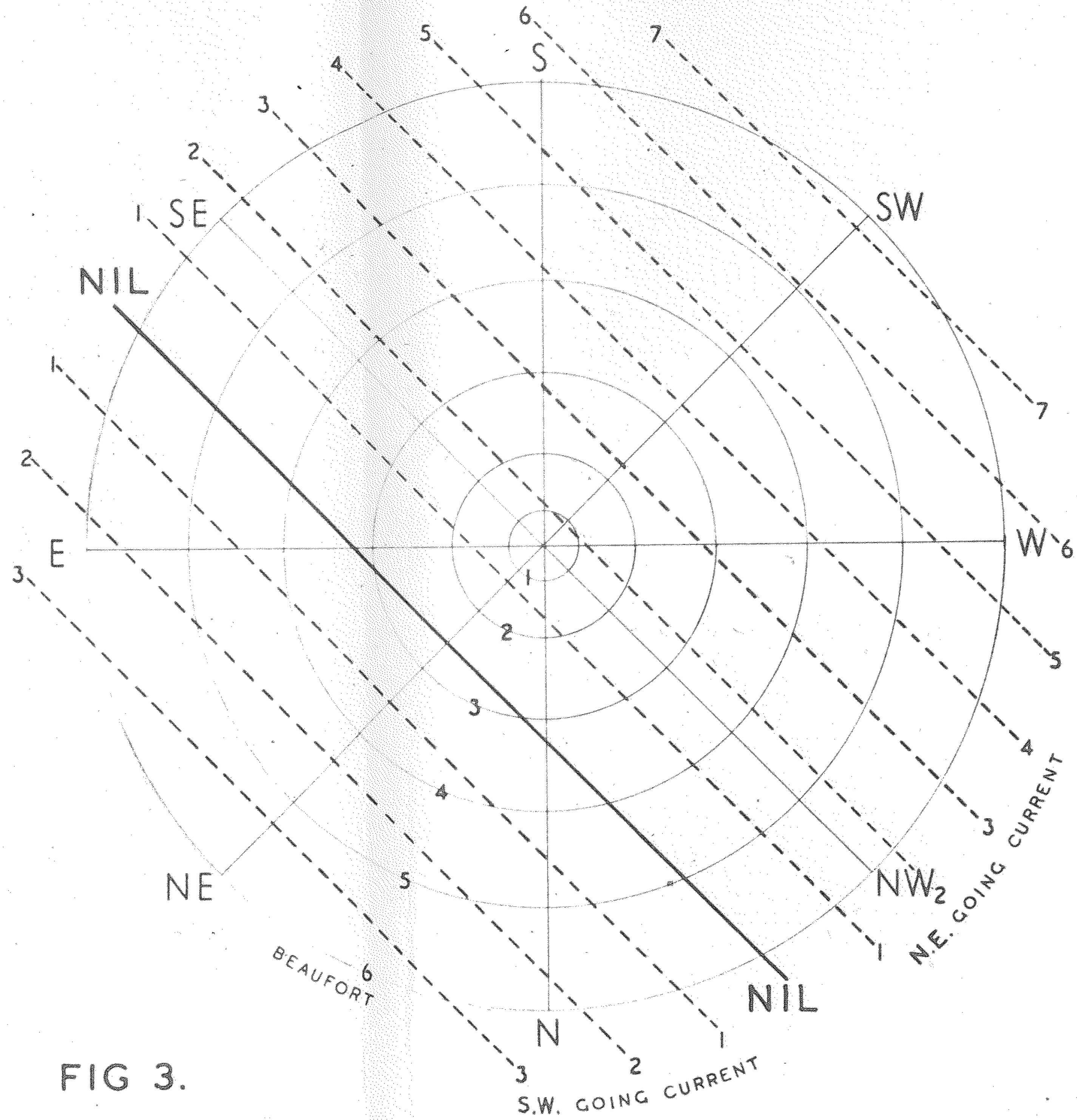



FIG 3.


VARNE —— WIND-WATER DIAGRAMS FOR VARIOUS MEAN TIDAL RANGES AT DOVER

FIGURES UNDERLINED ARE N.E. GOING CURRENTS, PLAIN FIGURES ARE S.W. GOING CURRENTS

FIG 4

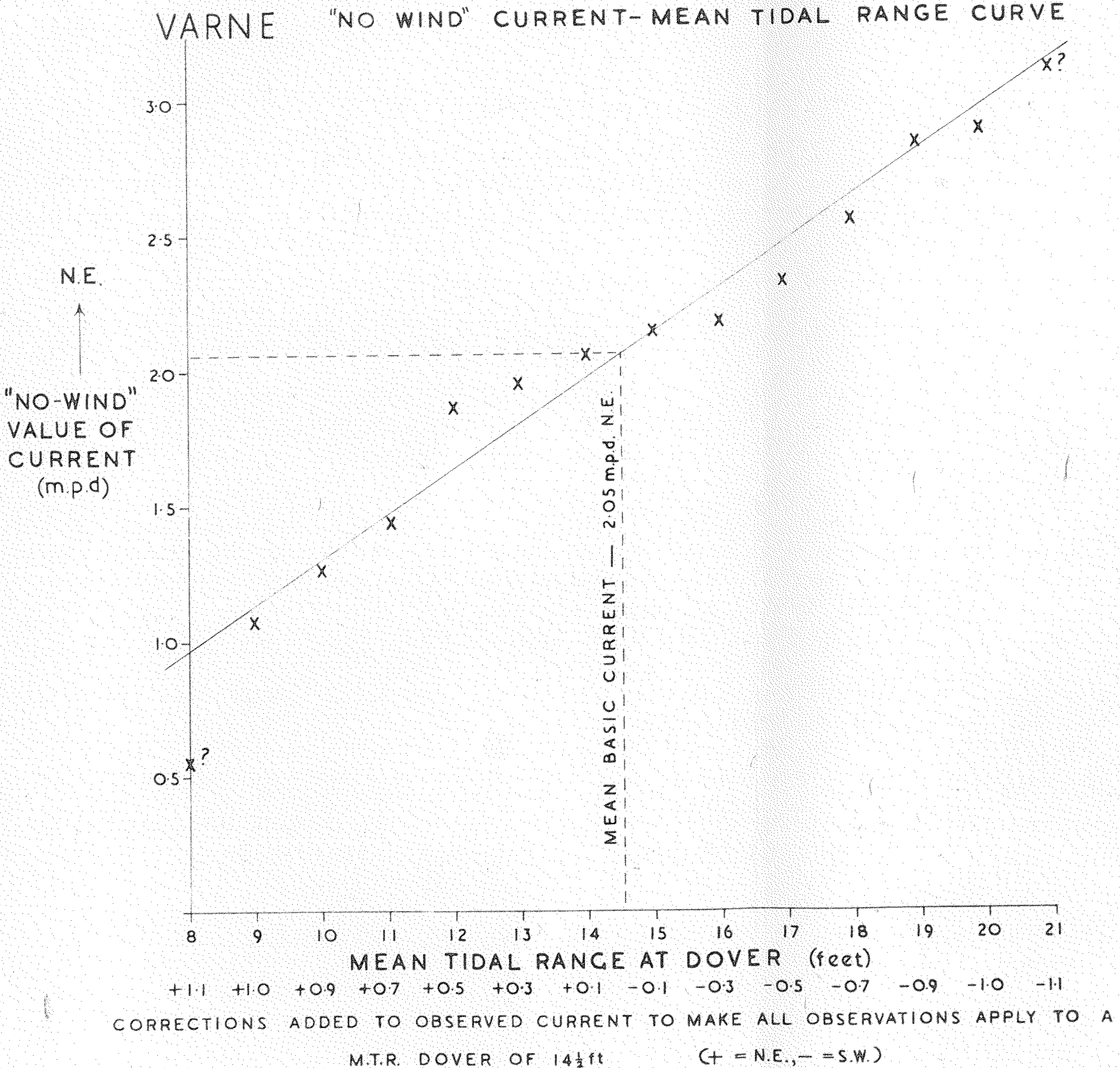

VARNE "NO WIND" CURRENT-MEAN TIDAL RANGE CURVE
N.E.
"NO-WIND" VALUE OF CURRENT (m.p.d)
3·0
2·5
2·0
1·5
1·0
0·5
MEAN BASIC CURRENT — 2·05 m.p.d. N.E.
8 9 10 11 12 13 14 15 16 17 18 19 20 21
MEAN TIDAL RANGE AT DOVER (feet)
+1·1 +1·0 +0·9 +0·7 +0·5 +0·3 +0·1 −0·1 −0·3 −0·5 −0·7 −0·9 −1·0 −1·1
CORRECTIONS ADDED TO OBSERVED CURRENT TO MAKE ALL OBSERVATIONS APPLY TO A
M.T.R. DOVER OF 14½ ft (+ = N.E., − = S.W.)

FIG 5.

# VARNE — SMOOTHED WIND-WATER DIAGRAM FOR MEAN TIDAL RANGE AT DOVER OF 14½ FEET

FIGURES UNDERLINED ARE NE-GOING CURRENTS, PLAIN FIGURES ARE SW-GOING CURRENTS

200   100   100   200

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\underline{2}$ | $\underline{2}$ | $\underline{4}$ | $\underline{5}$ | $\underline{6}$ | $\underline{5}$ | $\underline{5}$ | $\underline{4}$ | $\underline{5}$ | $\underline{5}$ | $\underline{6}$ | $\underline{6}$ | $\underline{6}$ | $\underline{6}$ | $\underline{7}$ | $\underline{7}$ |
| $\underline{2}$ | $\underline{4}$ | $\underline{3}$ | $\underline{3}$ | $\underline{6}$ | $\underline{5}$ | $\underline{4}$ | $\underline{4}$ | $\underline{5}$ | $\underline{5}$ | $\underline{4}$ | $\underline{5}$ | $\underline{5}$ | $\underline{5}$ | $\underline{5}$ | $\underline{6}$ |
| | $\underline{5}$ | $\underline{4}$ | $\underline{3}$ | $\underline{2}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{4}$ | $\underline{4}$ | $\underline{4}$ | $\underline{4}$ | $\underline{4}$ | $\underline{4}$ | $\underline{4}$ | $\underline{4}$ |
| $\underline{2}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{2}$ | $\underline{2}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{4}$ | $\underline{3}$ | $\underline{3}$ | $\underline{4}$ | $\underline{3}$ | $\underline{4}$ | $\underline{4}$ |
| $\underline{2}$ | $\underline{2}$ | $\underline{3}$ | $\underline{3}$ | $\underline{2}$ | $\underline{2}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{4}$ | $\underline{4}$ | $\underline{3}$ | $\underline{3}$ |
| $\underline{2}$ | $\underline{2}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ |
| $\underline{2}$ | $\underline{2}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{1}$ | $\underline{2}$ | $\underline{2}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ | $\underline{2}$ | $\underline{2}$ | $\underline{3}$ | $\underline{3}$ | $\underline{3}$ |
| $\underline{1}$ | $\underline{2}$ | $\underline{2}$ | $\underline{2}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{2}$ | $\underline{2}$ | $\underline{2}$ | $\underline{2}$ | $\underline{2}$ | $\underline{2}$ | $\underline{2}$ | $\underline{2}$ | $\underline{3}$ |
| $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ |
| $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | 0 | 0 | 0 | 0 |
| $\underline{1}$ | $\underline{1}$ | 0 | 0 | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | 1 | 1 | 1 | $\underline{1}$ |
| $\underline{1}$ | 0 | 0 | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | 0 | $\underline{1}$ | $\underline{1}$ | $\underline{1}$ | 0 | 1 | 1 | 0 | $\underline{3}$ |
| 0 | 0 | 0 | 0 | $\underline{1}$ | 0 | 0 | 0 | $\underline{1}$ | $\underline{1}$ | 0 | 0 | 1 | 2 | 2 | $\underline{2}$ |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | $\underline{1}$ | $\underline{1}$ | 0 | 2 | 2 | 2 |
| 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 2 | 3 |
| 2 | 2 | 2 | 1 | 0 | 0 | | 2 | 1 | 2 | 2 | 0 | 0 | 2 | 3 | 3 |

200   100   100   200

FIG 6.

## VARNE — CONTOURED WIND-WATER DIAGRAM

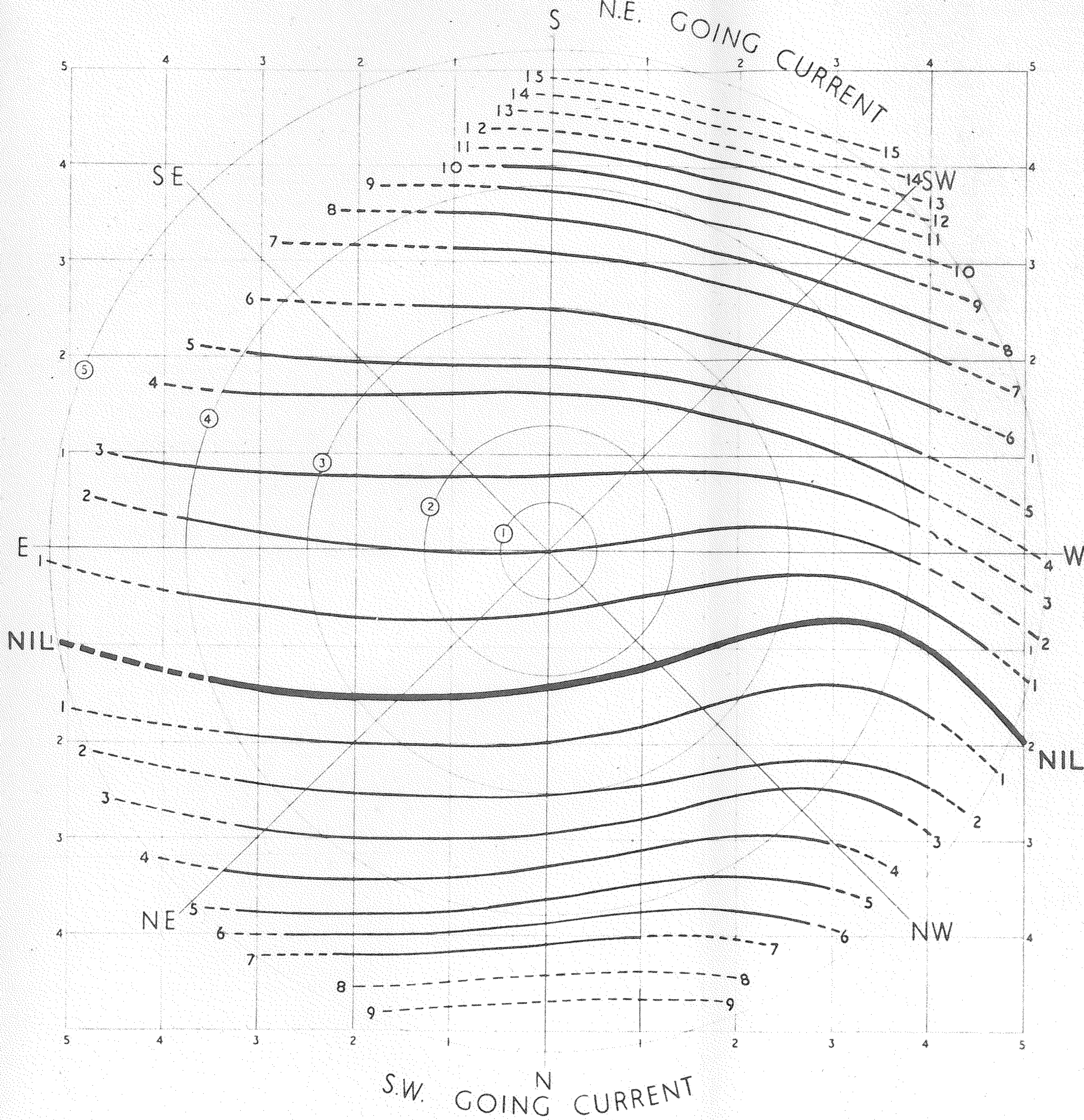
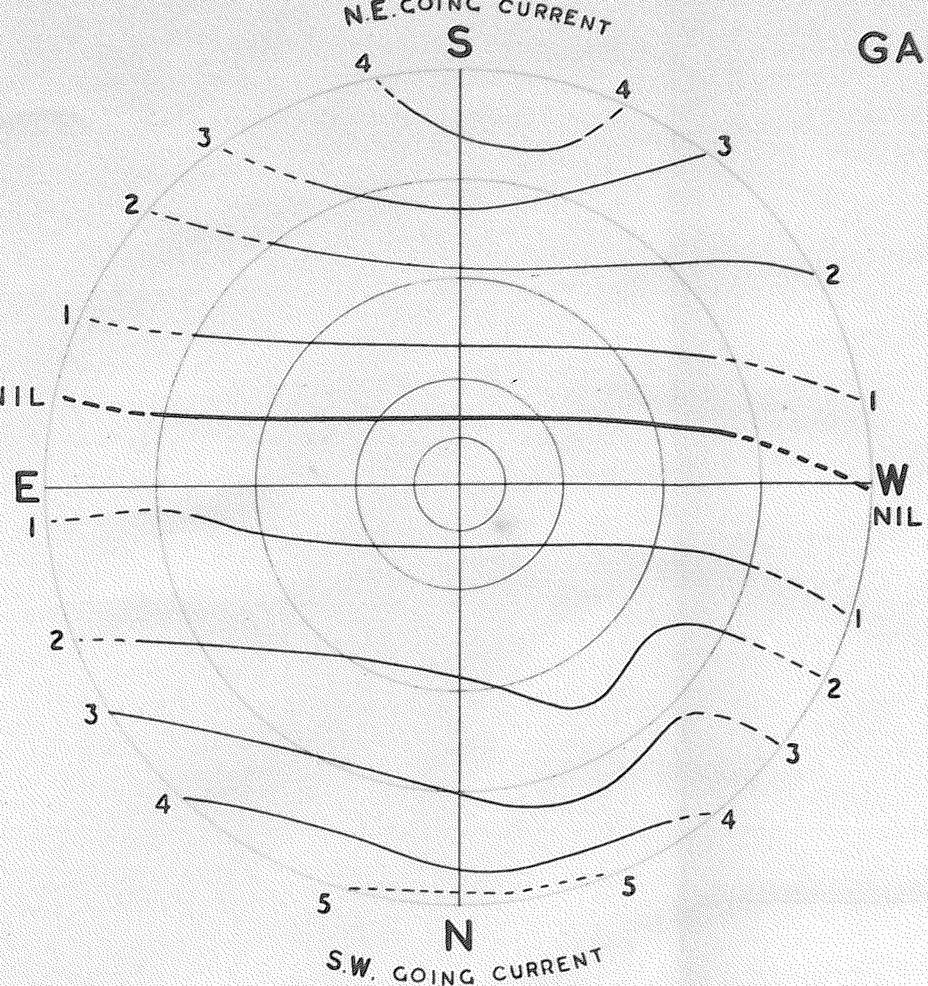


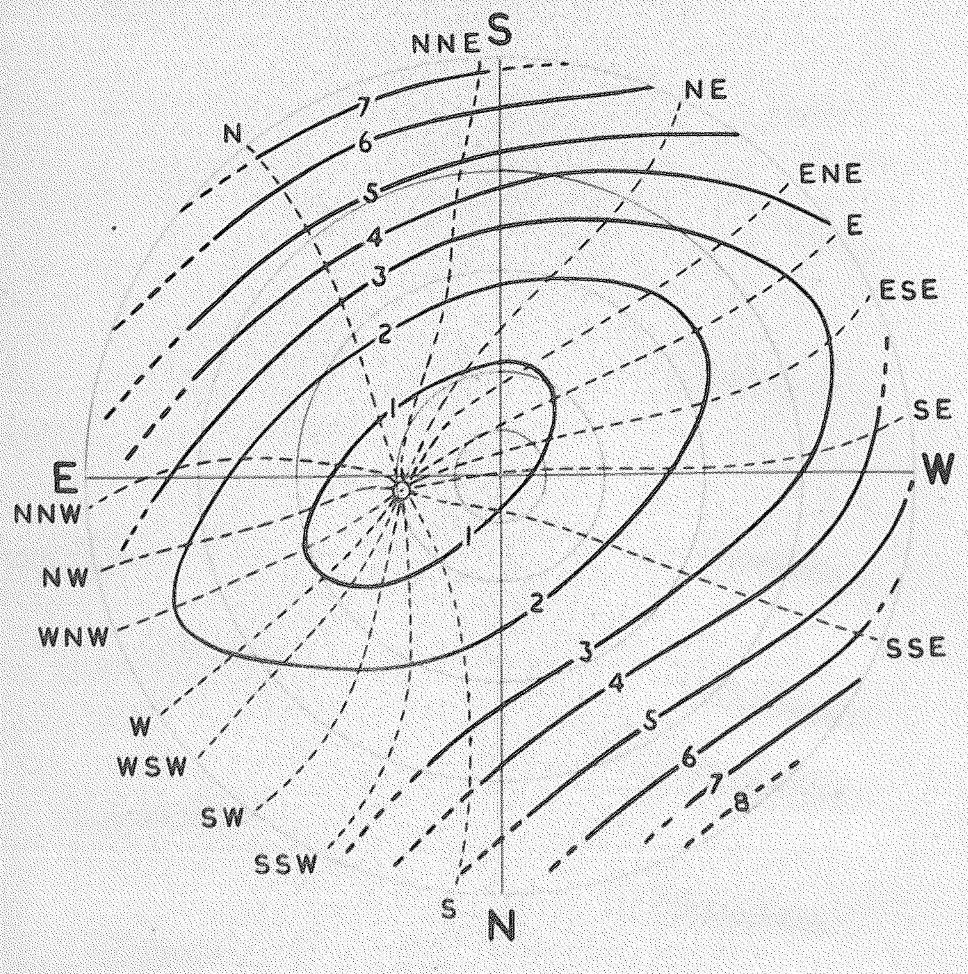

FIG 7.

WIND-WATER
DIAGRAMS FOR
VARIOUS LIGHTSHIPS

GALLOPER




SMITH'S KNOLL




S. 2

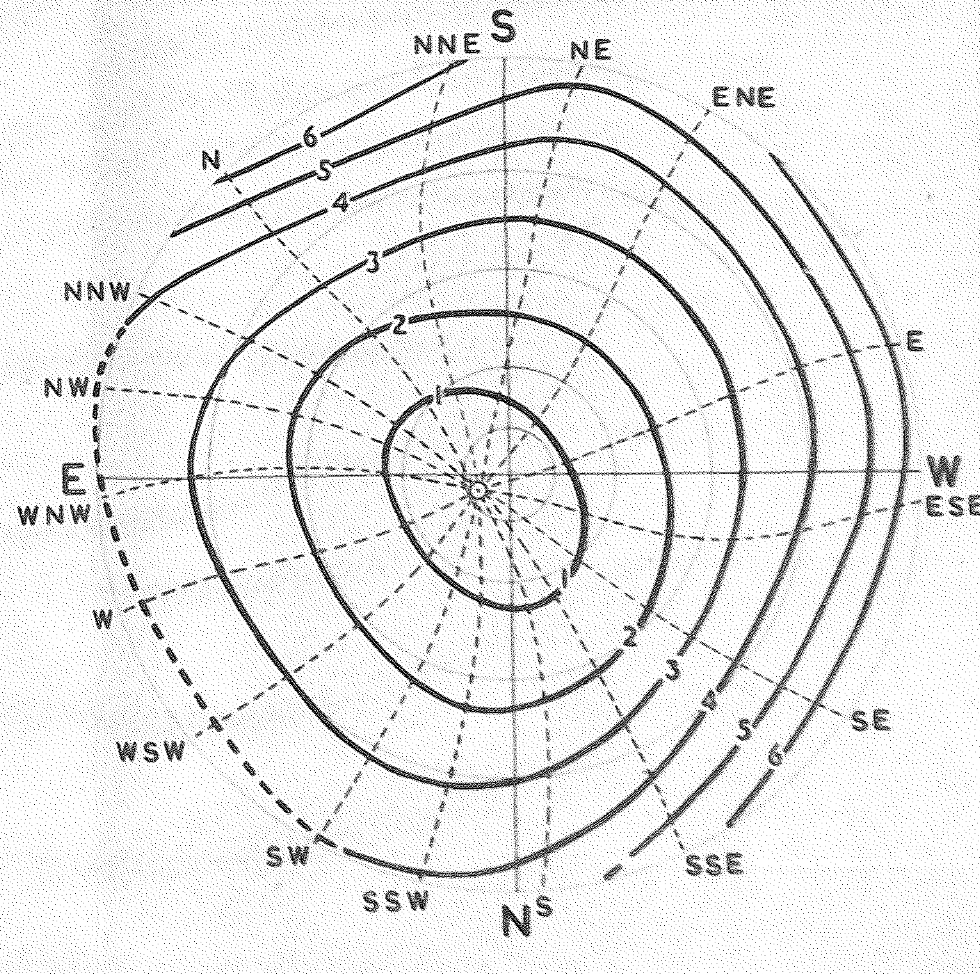
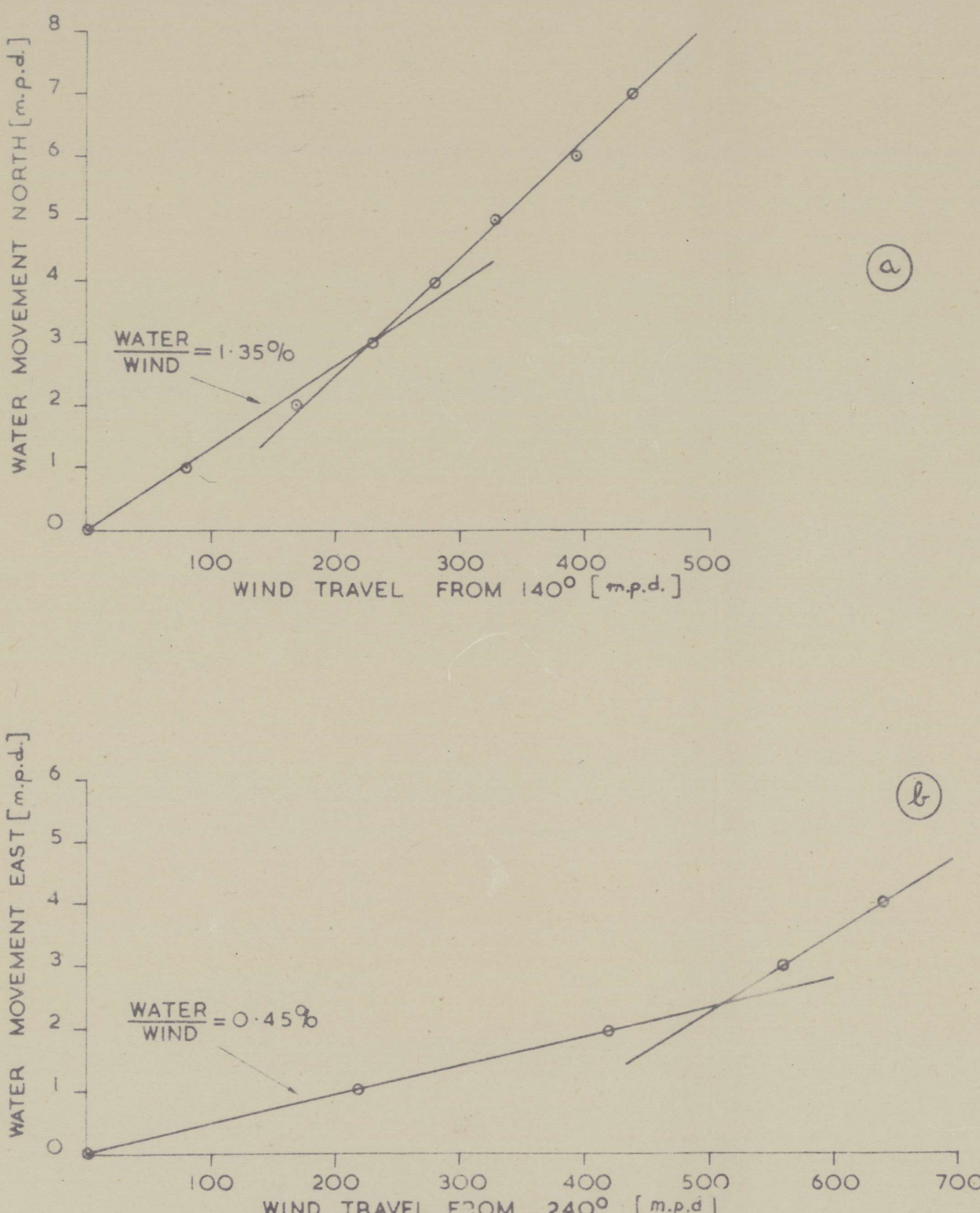



FIG 8.

SMITH'S KNOLL

WATER-WIND TRAVEL RELATIONSHIP

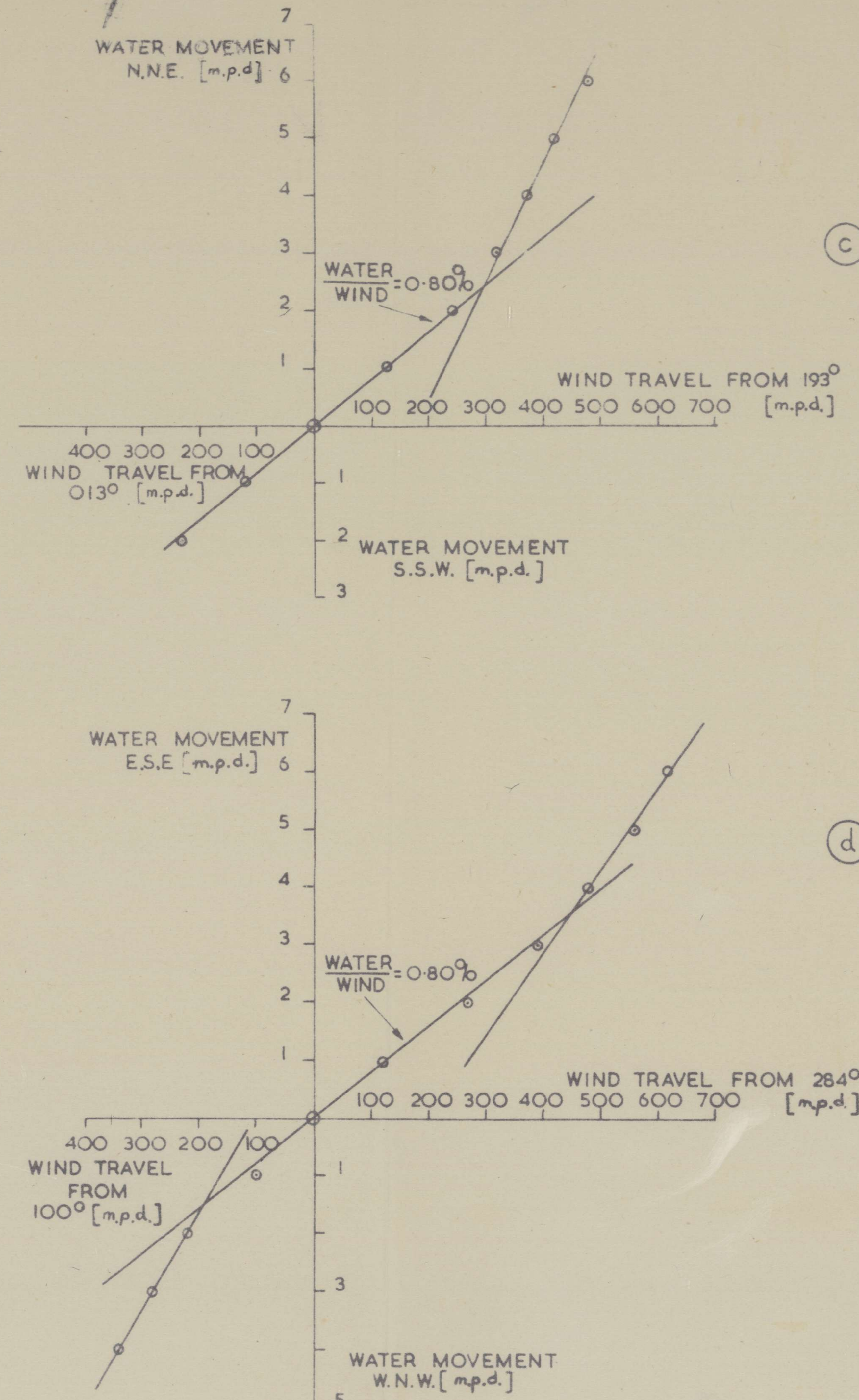
FIG 9




SMITH'S KNOLL

WATER-WIND TRAVEL RELATIONSHIP

FIG 9



THE RELATIONSHIP BETWEEN LOCAL WIND AND CURRENT IN
COASTAL WATERS OF THE BRITISH ISLES

by

A.L. Lawford and V.F.C. Veley, B.A.

N.I.O. Internal Report No. A3

CORRECTION to Figure 10(a)

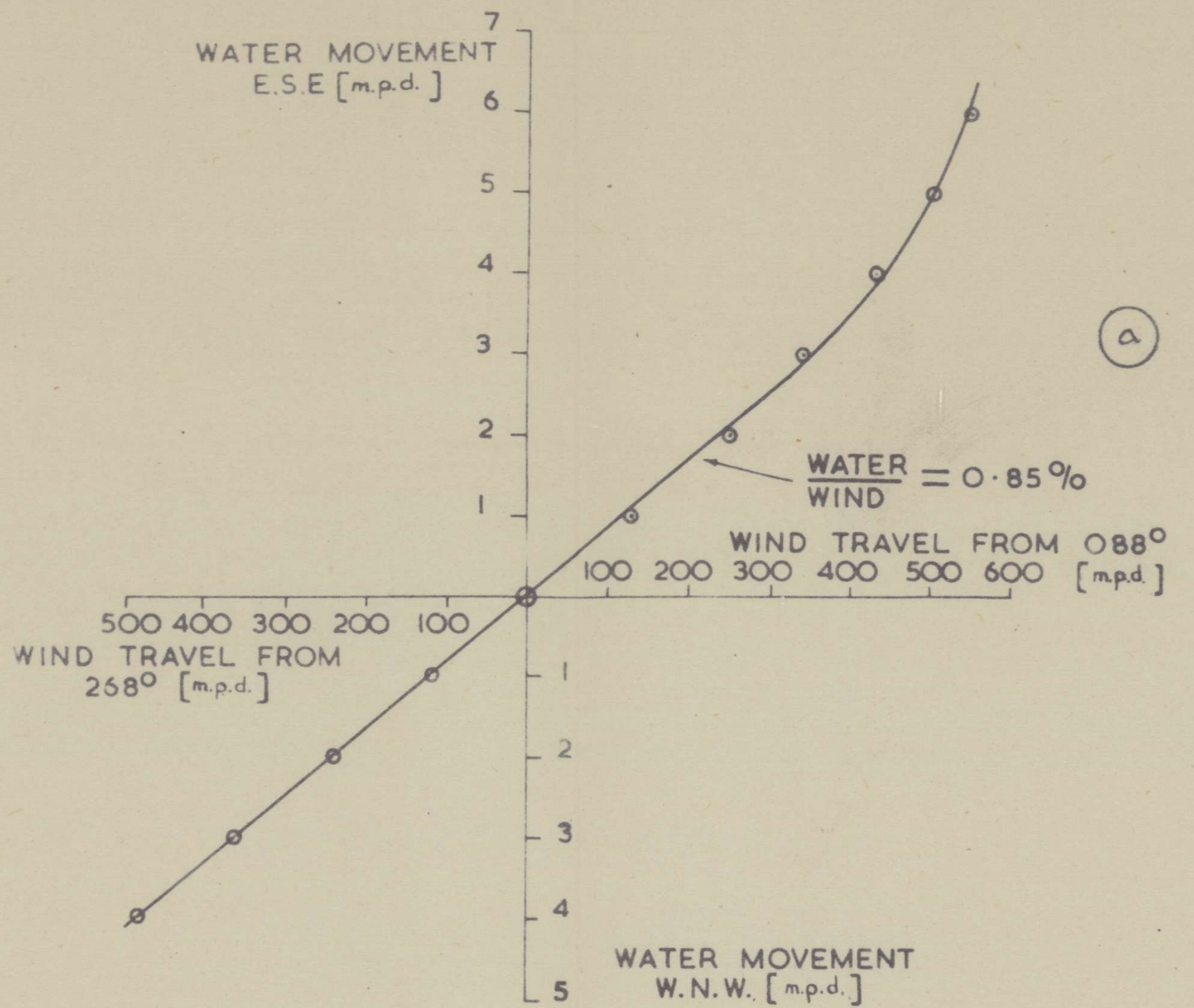
For "Water movement E.S.E." read "Water movement W.N.W.", and vice versa.

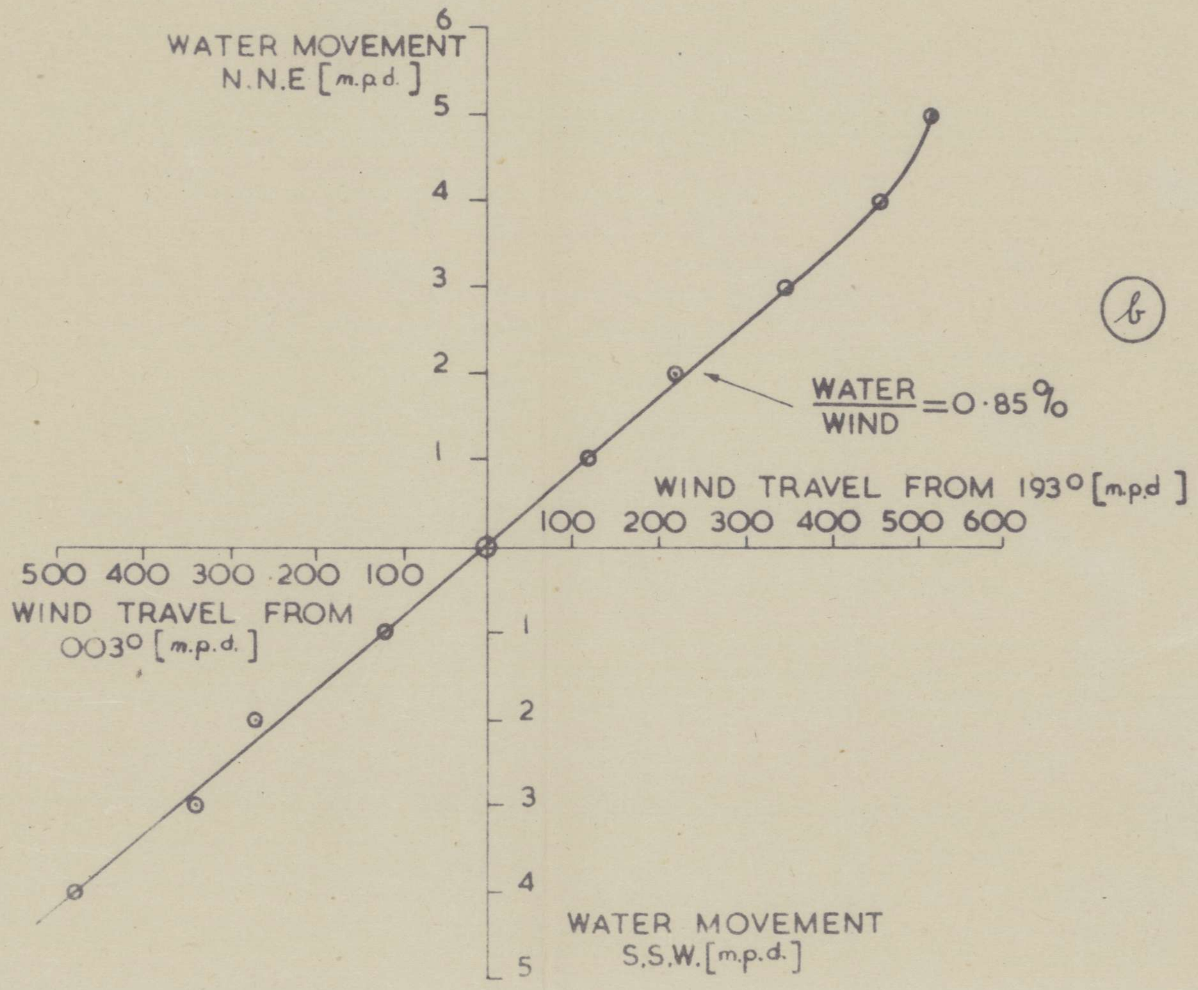
National Institute of Oceanography,
Wormley, Surrey.
17th July, 1956.

"S. 2"

WATER—WIND TRAVEL RELATIONSHIP

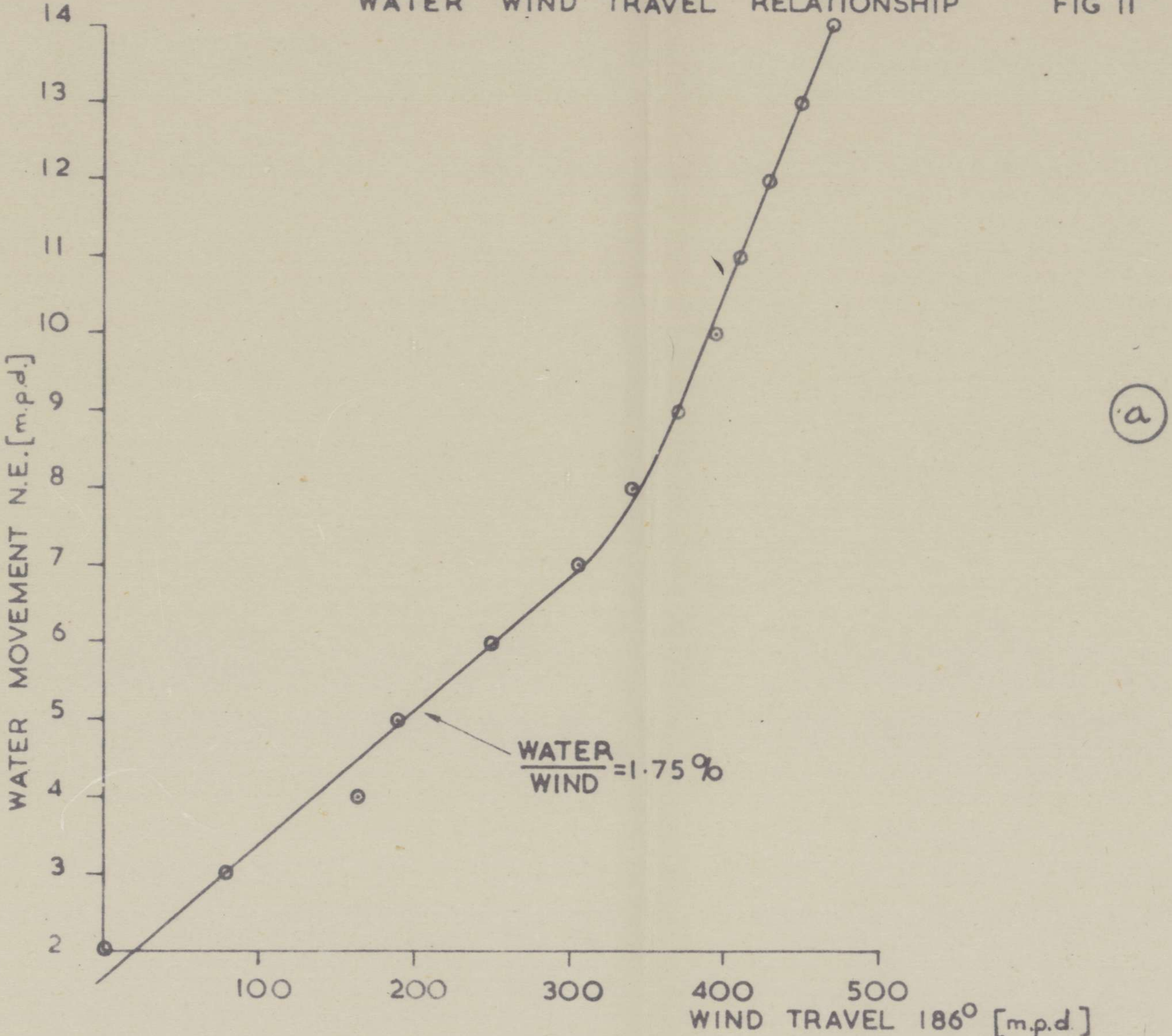
FIG 10

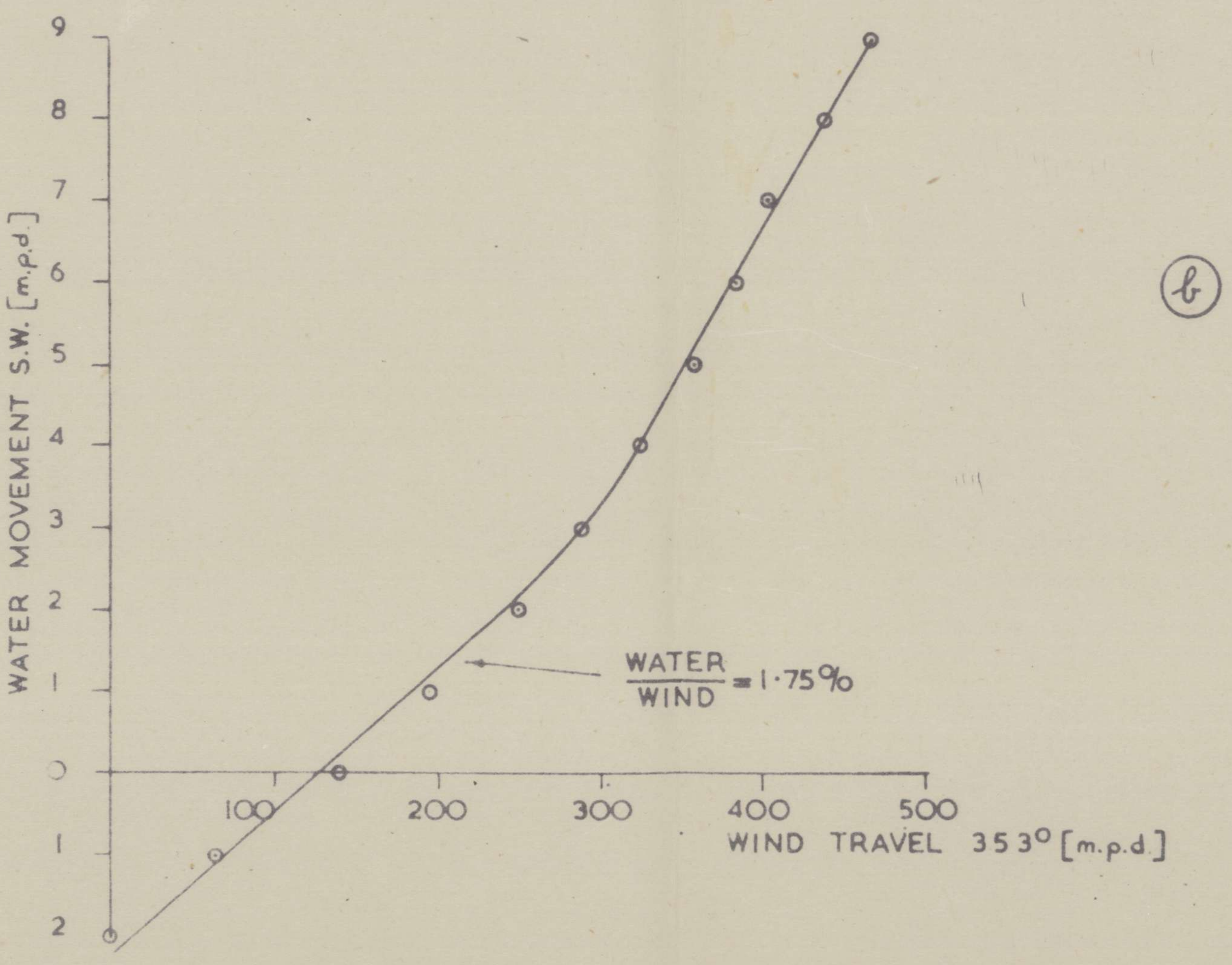


# VARNE

WATER WIND TRAVEL RELATIONSHIP FIG 11



# GALLOPER

WATER—WIND TRAVEL RELATIONSHIP

FIG 12