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The Spacing of Windrows of Sargassum in the Ocean

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ABSTRACT

The spacing of bands of Sargassum in the Atlantic Ocean is shown to be dependent upon the wind speed. These bands are indicative of the presence of helical vortices in the surface waters, and the data support Langmuir's contention that the vortices are wind-driven.

Introduction. The first adequate explanation of windrows in the surface layer of the oceans was that by Langmuir (1938). He reported the sighting of long lines of pelagic Sargassum in the Atlantic that were oriented in the direction of the wind and that changed direction with a change in wind direction. He studied similar windrows, marked by leaves and foam, on the surface of Lake George, New York, and confirmed experimentally his earlier deductions that the windrows are caused by water motions in the form of alternate left and right helical vortices that have their axes in the direction of the wind. Although Winge (1923) had noted the windrows of Sargassum in his study of the Sargasso Sea, his explanation is inadequate.

Langmuir believed that the energy of the vortical circulations is derived from the wind. His estimated values for the row spacings in Lake George are 5–10 m with a shallow thermocline and light winds in May and June and 15–25 m in October and November with stronger winds. He judged that the spacings are approximately proportional to the depth of the mixed layer (the epilimnion) and concluded that the wind-driven vortices are the principal mechanism of mixing.

Perhaps because no specific mechanism for wind-generated vortices was offered, there has been a tendency for oceanographers to assume that these circulations are convection cells, thermally driven by heat exchange at the ocean surface (e.g. Munk 1947, Montgomery 1947). Various investigators

1 Contribution Number 1389 from the Woods Hole Oceanographic Institution.
2 See page 29 for present addresses of authors.
3 These water motions are often simply termed "Langmuir circulations."
have demonstrated that, under laboratory conditions, convection may take the form of helical vortices (e.g. Graham 1933, Avsec 1939). Kuo (1963) has offered a theoretical treatment that indicates the possibility of thermal convection cells with their axes in the direction of the shear of the basic flow. Kraus and Rooth (1961) have attempted to describe the mixed layer in terms of thermal convective processes, quite the opposite point of view from that of Langmuir. But there has been no observational study capable of distinguishing between, or assessing the relative importance of, the wind-driven and thermally-driven mechanisms.

Woodcock (1944, 1950) showed that the Langmuir circulations might be of special biological significance for pelagic organisms such as Sargassum and Physalia (Portuguese Man-of-War). The surface-living alga Sargassum was observed to be carried far down into the sea by descending waters under convergence lines. He also found evidence that the helical vortices are asymmetrical (Fig. 1) and discussed the possibility that selective adaptation to this asymmetry might account for the predominant sailing characteristics and “right-handedness” of Physalia. He concluded that the Coriolis force might be responsible for the asymmetry and supported this hypothesis by noting that museum specimens of Physalia from the southern hemisphere were predominately “left-handed.”

4 Savilov (1961) has explored this hemisphere-dependence through study of extensive collections of Physalia made by the R. V. Vityaz.
Munk (1947) pointed out, however, that the asymmetry probably resulted from the interaction of the vortices with the wind drift of the surface layer rather than from a direct effect of the earth's rotation on the cellular motions. Sutcliffe et al. (1963) have emphasized other ways in which the Langmuir circulations may be biologically important, owing to their effects upon productivity within the surface waters of the sea.

\[ n \]

**Figure 2.** A typical histogram of the number of observations, \( n \), of the time interval between rows of *Sargassum*, \( \Delta t \). This set of observations was taken during 0815-0915 local time on August 18, 1941, 40°31' N, 60°00' W. Ship's speed normal to the bands was 3.4 m sec\(^{-1}\).

**Measurements of Row Spacing.** In 1941 the second author observed the spacings of *Sargassum* in the open ocean in the vicinity of 39° N, 60° W (ATLANTIS BT cruise No. 39, Hydrographic cruise No. 119). The primary data are in the form of time intervals between lines of weed as ATLANTIS sailed across the bands at known angle and speed. The measured time intervals vary considerably, and this is attributed to irregularities of the bands and to an occasional insufficient amount of *Sargassum* to reveal the lines of convergence. Fig. 2 is a typical histogram for one set of observations. The data fall into three natural divisions with average time intervals of 11.0, 21.7, and 32.7 sec. Therefore, this set is assumed to represent a fundamental time interval of 11.0 sec. The longer intervals have been reduced by the factors 2 and 3 before taking an average. In this manner each set has been reduced to a fundamental interval, and confidence limits, have been determined as twice the standard deviation of the mean. These values multiplied by the ship's crossing-speed give the band spacings, \( L \), as in Table 1 and the confidence limits (in parentheses). For the example in Fig. 2 this spacing is 37.2 ± 1.6 m.

Table 1 summarizes the meteorological and oceanographical data. Estimates of the mixed-layer depth, \( D \), and the vertical temperature difference between the bottom and top of the mixed layer, \( \Delta T \) (positive \( \Delta T \) indicating unstable stratification), were obtained from bathythermograms taken during the measurement of row spacing. Wind speeds were observed in terms of the Beaufort
TABLE I. Meteorological and Oceanographical Conditions During the Measurement of Row Spacings. Observations by A. H. Woodcock in the Vicinity of 39°N, 60°W. The quantity $\Delta T$ is a measure of the thermal stability of the mixed layer (see text), $D$ is the depth of the mixed layer, $W$ is wind speed, $L$ is row spacing, and $Q$ is the computed upward flux of sensible plus latent heat at the ocean surface.

<table>
<thead>
<tr>
<th>Sky Temperature</th>
<th>Date</th>
<th>Time</th>
<th>Cover (tenths)</th>
<th>Dry $T$ (°C)</th>
<th>Wet $T$ (°C)</th>
<th>Water $T$ (°C)</th>
<th>$\Delta T$</th>
<th>$D$ (m)</th>
<th>$W$ (m sec$^{-1}$)</th>
<th>$L$ (m)</th>
<th>$Q$ (cm$^{-2}$min$^{-1}$)</th>
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<td>25.8</td>
<td>22.8</td>
<td>25.2</td>
<td>-.01</td>
<td>32</td>
<td>7.4</td>
<td>40.5 (2.5)</td>
<td>.23</td>
<td></td>
</tr>
<tr>
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<td>26.6</td>
<td>22.5</td>
<td>27.2</td>
<td>0</td>
<td>26-48</td>
<td>8.6</td>
<td>38.0 (1.7)</td>
<td>.54</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 ...1245</td>
<td>20.4</td>
<td>16.9</td>
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<td>27</td>
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<td>15 ...1145</td>
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<td>17</td>
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<td>21.2</td>
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<td>49.5 (2.2)</td>
<td>.29</td>
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<td>19.9</td>
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<td>38.0 (1.6)</td>
<td>.55</td>
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<td>22.9</td>
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<td>8.6</td>
<td>26.2 (1.0)</td>
<td>.54</td>
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</table>

scale but are given in Table I in m sec$^{-1}$. The quantity $Q$ is the estimated upward flux of sensible plus latent heat at the water surface as determined with the formula of Kraus and Rooth (1961):

$$Q = (1 + R) L_tKW (1 - \frac{\epsilon_a}{\epsilon_w}) \epsilon_w.$$  

In this equation, $K = 1.5 \times 10^{-9}$ cm$^{-2}$ sec$^2$ mb$^{-1}$, $R$ denotes the Bowen ratio (e.g. see Sverdrup 1951), $L_t$ the latent heat of evaporation ($L_t = 585$ cal g$^{-1}$), $W$ the wind speed in cm sec$^{-1}$, $\epsilon_a$ the vapor pressure of the air, and $\epsilon_w$ the saturation vapor pressure at the ocean surface temperature; both $\epsilon_a$ and $\epsilon_w$ are expressed in mb.

Partial correlation coefficients between wind speed, $W$, row spacing, $L$, mixed-layer depth, $D$, and heat flux, $Q$, are given in Table II. Two sets of coefficients have been computed; one set ($N = 14$) includes all the data of Table I; the other set ($N = 13$) excludes the last observation, for which the value of $D$ is far from the range of the other values. A comparison of the correlation coefficients gives some estimate of reliability of the coefficients for this small sample. Values in parentheses are the number of standard deviations by which the correlations depart from zero, using Fisher's $z'$ transformation (Hoel 1947).
TABLE II. PARTIAL CORRELATION COEFFICIENTS BETWEEN WIND SPEED, \( W \), ROW SPACING, \( L \), MIXED-LAYER DEPTH, \( D \), AND HEAT FLUX, \( Q \). FOR EXAMPLE, \( r(WL \cdot QD) \) IS THE PARTIAL CORRELATION COEFFICIENT BETWEEN \( W \) AND \( L \) while \( Q \) AND \( D \) ARE IN EFFECT HELD CONSTANT. NUMBERS IN PARENTHESES ARE THE NUMBER OF STANDARD DEVIATIONS DEPARTURE OF THE CORRELATION FROM ZERO USING FISHER'S \( z' \) TRANSFORMATION (HOEL 1947).

\[
\begin{array}{cccc}
N = 14 & N = 13 \\
\end{array}
\]

\[
\begin{array}{l}
r(WL \cdot QD) + .724 (2.8) + .669 (2.0) \\
r(WD \cdot QL) + .576 (2.0) + .376 (1.0) \\
r(LD \cdot QW) -.502 (1.7) -.083 (0.2) \\
r(LQ \cdot WD) + .289 (0.9) + .396 (1.0) \\
r(DQ \cdot WL) + .200 (0.6) - .091 (0.2)
\end{array}
\]

In Table II the only correlation that is significant at the 5\% level is between the wind speed, \( W \), and the row spacing, \( L \). There is some indication that a relationship between \( W \) and \( D \), independent of \( L \) and \( Q \), may exist, but there appears to be no significant dependence of either \( L \) or \( D \) upon the heat-flux parameter, \( Q \). However, in viewing these correlations one should keep in mind the limited range of physical conditions represented by the data, namely, the seasonal limitation and the restricted geographical coverage. Thus the lack of dependence upon \( Q \) is thought to be of limited significance, and the single fact that may be emphasized is the relation between \( W \) and \( L \). This fact indicates that the row spacings are primarily determined by the wind and suggests that the Langmuir circulations are wind-driven.

Fig. 3 is a plot of \( L \) vs. \( W \). The two regression lines have been modified to take into account estimates of the variances in the random observational errors as suggested by Brooks and Carruthers (1953). Before correction for these errors, the correlation between \( W \) and \( L \) is \( r_{WL} = 0.71 \); after correction the correlation is \( r_{WL}^* = 0.82 \). Since the extrapolated regression lines pass evenly on either side of the origin, and since, after correction for the known errors of observation, neither line is preferred as a representation of the data, a line passing through the origin may be taken as the best linear approximation. This line is given by \( L = W \times 4.8 \) sec., where the coefficient of \( W \) may well be subject to seasonal or latitudinal variations. Selection of a line through the origin is not meant to imply that rows of Sargassum occur for all values of \( W \).

In the statistical technique suggested by Brooks and Carruthers (1953), the variances of the errors of observation (\( \sigma_e^2 \)) are subtracted from the variances of the respective variates (\( \sigma^2 \)). The slopes of the new regression lines and the new correlation coefficient are computed from these reduced values of the variances (\( \sigma_e^2 = \sigma^2 - \sigma^2 \)). The covariance of the variates remains unchanged if the errors are random, that is, if the errors of each variate are uncorrelated with the errors of the other variate or with the variates themselves.

In the present problem the errors of observation of \( W \) and \( L \) are believed to be random. For our calculation we have used \( \sigma_L = 1 \) m as the standard deviation of the errors of observation of \( L \), and \( \sigma_W = 1 \) m sec\(^{-1} \) as the corresponding estimate for \( W \). These values are conservative estimates, because not all possible sources of error have been taken into account.
Figure 3. Observations of row spacing, L, vs. wind speed, W. Open circles represent observations by Woodcock, and solid squares are from data of J. Beers. The lines are regression lines of W against L and of L against W after correction for random errors of observation (footnote 4).

down to $W = 0$. In fact, it is observed that, for winds of Beaufort 2 or less ($W < 3 \text{ m sec}^{-1}$), the Sargassum generally gathers into large patches rather than into rows. The solid squares represent observations taken by J. Beers of the Bermuda Biological Station, to whom we are greatly indebted. Additional observations by E. R. Baylor and W. H. Sutcliffe of the Woods Hole Oceanographic Institution (personal communication) are in general agreement with this equation.

Various studies have related the mixed-layer depth to the wind speed. Rossby and Montgomery (1935) arrived at the formula $D = W \times 2.38 \text{ sec/sin} \varphi$, where $\varphi$ is latitude. The data in the present study give the average relation $\bar{D} = \bar{W} \times 4.0 \text{ sec}$, which is in good agreement with the Rossby-Montgomery expression evaluated for the average latitude of those data, $\varphi = 39^\circ$. 
Concluding Remarks. The crucial question suggested by Langmuir, namely, to what extent do the helical vortices determine the mixed-layer depth, is not answered here. The ratio of average row spacing to mixed-layer depth is $L/D = 1.1$, which would be a reasonable ratio of cell width to depth, but the data exhibit no significant correlation between $L$ and $D$. As only one example of the complexity of the problem, we note that internal waves on the thermocline would cause horizontal divergence in the mixed layer (Ewing 1950) and might tend to produce a negative correlation between $L$ and $W$. In the presence of a steady wind the magnitude of this effect would depend on various factors including the amplitude, direction, and frequency of the internal waves, the mixed-layer depth, the response of the distorted vortices to the wind, and the rate of erosion of the thermocline by the vortices.

The relation between wind speed and row spacing supports Langmuir's hypothesis concerning the source of energy of the convergent motions. His conclusion that “the helical vortices set up by the wind apparently constitute the essential mechanism by which the epilimnion is produced” deserves further consideration and detailed observational study.

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SVERDRUP, H. U.

WINGE, ÖJVIND

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