On the Origins of Currents on the Southeastern Great Bahama Bank

by

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ABSTRACT

The Tongue of the Ocean, Bahama Islands, exhibits certain features of salinity and temperature variation which have been attributed to tidal currents entering the Tongue across the eastern and western Bahama Banks. To test the validity of this theory on the eastern bank, current measurements were made at a point on the narrowest portion of that bank.

The results of the measurements indicate that the tidal currents across the eastern bank are not directed so that they are the primary sources of water transport to the Tongue, but rather parallel the edge of the Tongue. The consistency of the measurements over the observed period indicates that tides are the primary origin of currents in the southeastern Bahama Bank, and that these currents are consistent throughout the depth of bank water and are not the result of laminar flow.

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INTRODUCTION

Measurements of temperature and salinity in deepwater open-ocean areas reveal certain recurring patterns which follow as a direct consequence of surface conditions and geographic location of the area under consideration. In general, these patterns yield the sufficient conditions to produce a "statical stability" (Proudman, 1953), due to continental interference with any possible latitudinal circulations which are caused by density gradients.

In tropical and subtropical open-ocean areas, these depth-dependent variations result from patterns of wind and insolation which are primarily seasonal in nature (Brown, 1965). Although extensive studies at all longitudes are lacking, specific studies using bathythermographs in the southern North Pacific Ocean show that salinity maxima occur in the upper two-hundred meters of depth at the stations considered (Brown, 1965). Similar studies, however, are lacking for the corresponding areas of either the South Pacific or the North or South Atlantic.

In the aforementioned study there is found to be a positive correlation between the salinity maximum and the depth at which the water temperature starts to decrease at a rate greater than its (approximately) uniform rate at shallower depths (Brown, 1965). Thus, as might be expected, the layer of maximum salinity coincides with the layer of suddenly decreasing temperature.

Such data are, in general, lacking for the Atlantic Ocean except in connection with studies made in the area of the Gulf Stream

(Iseline, 1936; Stommel, 1965). Although these have included deep-water areas, the presence of the strong surface current lessens the general applicability of the results. They are, however, useful in giving clues to the behavior of shallow-water currents, the subject of this study.

The problem first came under investigation during observations of data collected as part of an oceanographic survey by the U.S. Navy of the Tongue of the Ocean Basin and vicinity in the Bahama Islands.

The Tongue of the Ocean (see Fig. 1), is marked by a precipitous increase in depth as observed in an east-west section. The basin has, in general, a depth gradient of about 900 meters for each 5700 meters of horizontal distance. Immediately to either side of the boundaries of the Tongue, which are usually delineated by the line marking 183 meters or 100 fathoms of water depth, the Great Bahama Bank is an extremely shallow-water area, with no depths greater than about seven meters. Separating this bank from the deeper water to the east is a chain of small and narrow islands and cays, while to the west is the large Andros Island.

Exuma Sound, the basin to the east of the Great Bahama Bank, attainds depths equal to those of the Tongue of the Ocean, but has a smaller gradient of depth with horizontal distance. Thus, the picture obtained in an east-to-west section of the area is that of a deep basin which slopes upward to narrow channels between cays

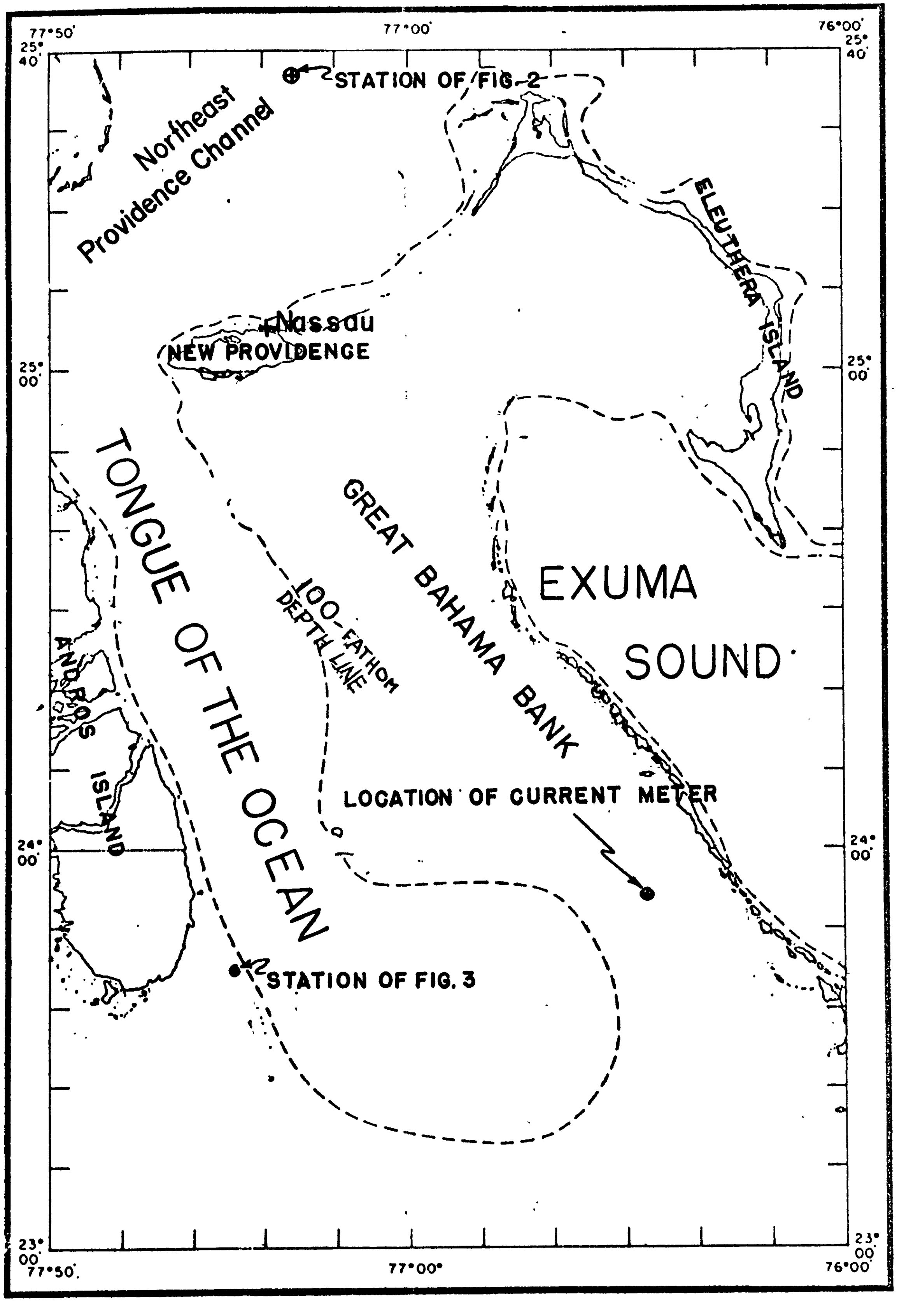

FIG. 1: TONGUE OF THE OCEAN AND ENVIRONS

which lead to an extremely shallow bank of between 40 and 80 kilometers width, ending in a precipitous drop into another deep basin.

At numerous stations in the norther Tongue area (the area under the direct influence of the south current entering the area) the salinity maximum was observed to occur in the depth range of 100 to 250 meters. It must be kept in mind, however, that these stations were located in the northern and northeastern neck of the Tongue of the Ocean, near the Northeast Providence Channel and the direct influence of the strong surface current entering from that channel and carrying water to refreshen the surface waters of the northern Tongue.

The salinity-depth sections yielded by these stations' data (of which Fig. 2, using data of February 21, 1962, is an example) indicate a consistent salinity maximum at the depths predicted by the type studies of Brown (1965) in areas of similar insolation and current structure. The sections are thus consistent with a picture of salinity maxima at depths below the surface due to refreshment of surface water by the currents. Investigations of a similar type in the southern and southeastern Tongue, the largest areas of the Tongue, have not been as extensively undertaken as they have been in the areas to the north, and the full sections done in the south have not been long-term in situ measurements, but rather shipboard soundings (see, for example, Figure 3, done from the USNS Silas Bent on March 2, 1966).

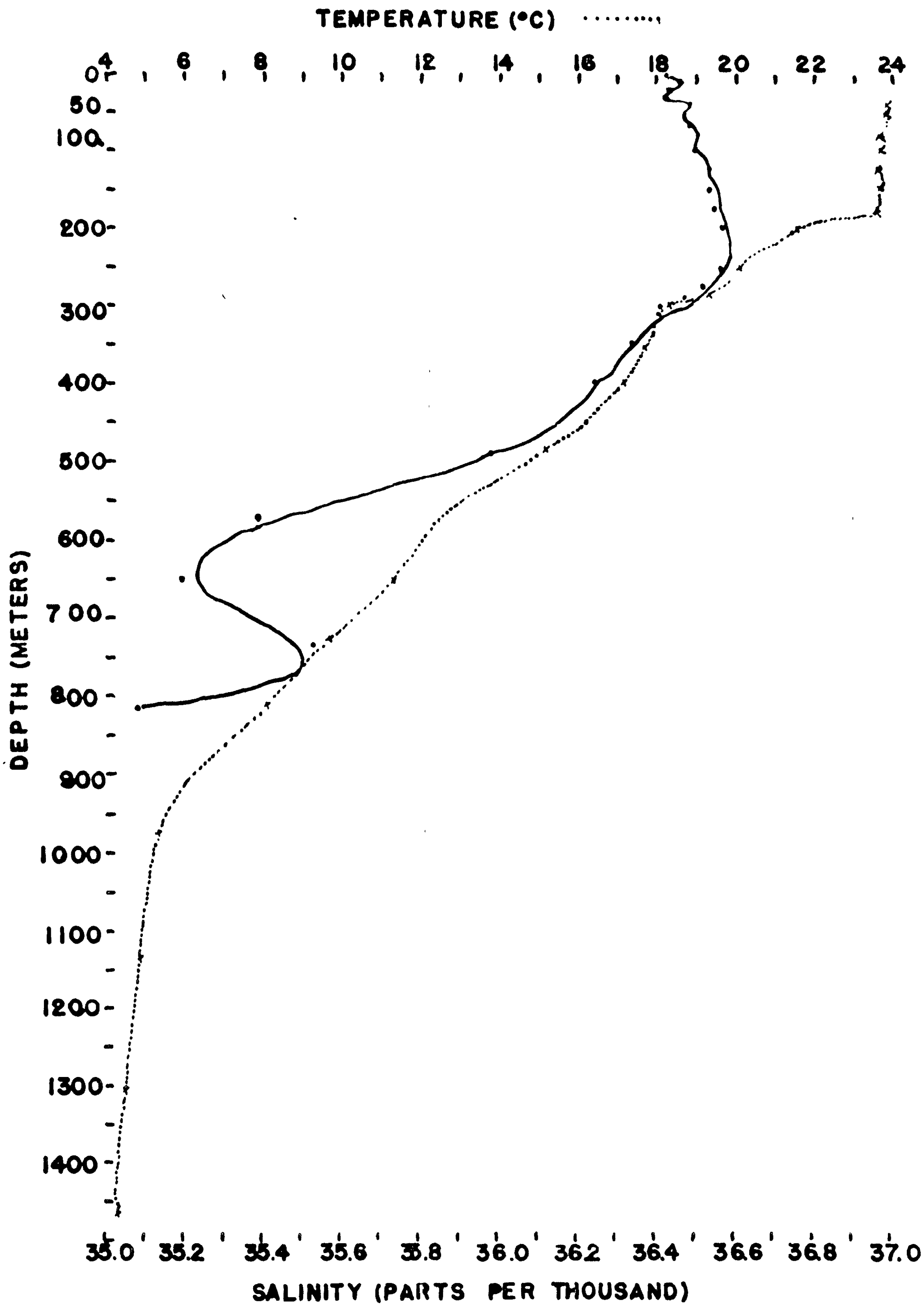

FIG. 2: STATION AT LAT. 25°37' N, LONG. 77°16' W

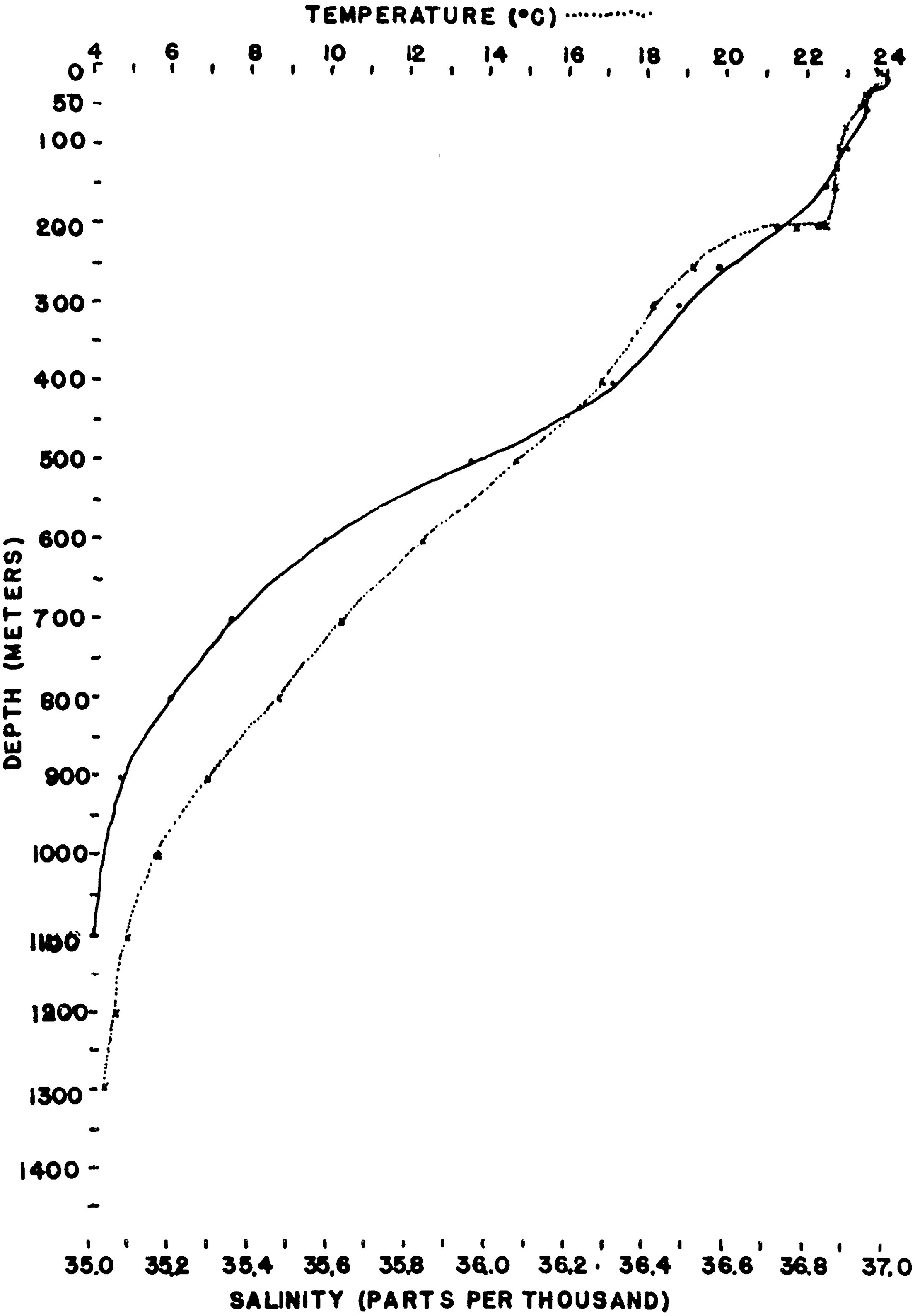

FIG. 3: STATION AT LAT. 23°44' N, LONG. 77°24' W

All such measurements in the south show a consistent recurrence of a pattern of salinity maxima in the upper thirty meters of depth. In addition, these maxima attain values consistently higher than the values observed for maximum salinities in the more open areas of the Tongue, sometimes reaching or exceeding thirty-seven parts per thousand.

Costin (1965), during studies of the residence time of water on the Bahama Bank to the northwest of the edge of the Tongue, cites evidence that the other major contributions to water movement on the Bahama Bank are tidal cycles; this evidence was gathered in field observations of the time of residence of dye emplacements on the Bank.

These studies, in addition to those conducted by the U.S. Navy and others, indicate a possible correlation between residence times and, more importantly, salinity and temperature observations, and tidal cycles in the area around the Tongue of the Ocean. The observations of Costin, and of previous authors cited in Costin's manuscript, tell of studies indicating the origins of Tongue near-surface water in tidal currents entering from the Great Bahama Bank.

THE STATION AND ITS RESULTS

In order to study the effects of currents across the East Bahama Bank, a current meter employing a savonius rotor and a Geodyne model A 100 film recorder was placed in the section of the bank which was of the narrowest width between the eastern barrier cays and the edge of the Tongue of the Ocean Basin. The meter was placed at a depth of five meters at latitude 23° 53.9' North, longitude 76° 28.0' West (See Fig. 1); recording started at 1130 hours (local time) on 12 February 1966 and ended at 1115 hours (local time) on 27 February 1966.

This position for the current meter was chosen for several reasons:

(i) The depth of the water at this location was 5.5 meters, a depth representative of most of the area of the bank adjacent to the edge of the Tongue of the Ocean;

(ii) The lack of any large land masses near the station allowed the observation of currents without correction for the surface and near-surface currents which would have been produced by the diurnal cycle of on-shore and off-shore winds near large islands;

(iii) The station, representing as it does the narrowest portion of the (East) Bank, should be more indicative of any currents entering the bank from the east or leaving from the west than stations located in wider bank;

(iv) The location of the meter near the southeastern terminus of the Tongue of the Ocean permitted observation of currents in an area which is not strongly affected by the south current on the surface of the more northern areas of the Tongue, thus providing a direct comparison with station data from these areas to give a more complete picture of the bank; and

(v) The location of the station is in an area in which few studies of this type have been undertaken.

Recordings of current speed and direction were made using a Gray binary code recorded as electrically-imprinted marks on film. The record is of current readings every ten minutes, but initial overexposure of the film resulted in all readings being obscured until the reading of 2305 hours on 13 February 1966. The total elapsed time of the record of current readings was 324 hours 10 minutes. In toto, there are 1943 readings, recording speed and direction every ten minutes.

The analysis of the data revealed a significant variation in the speed of the currents observed. Of the 1943 readings, 1098 or 56.4% were of speeds greater than or equal to 0.30 knot, while 845 or 43.6% were of less than 0.30 know (the reason for this demarcation point of 0.30 knot will be seen later). The significance of these figures becomes evident when the distribution of each speed interval versus angular interval is computed.

θ	0-44	45-89	90-134	135-179	180-224	225-269	270-314	315-359	
n	32	242	274	18	8	20	414	90	≥0.30
%	2.92	22.05	25.0	1.64	0.72	1.81	37.7	8.2	
n	103	136	159	86	60	85	117	99	<0.30
%	12.2	16.1	18.81	10.2	7.1	10.07	13.84	11.71	

The distribution of these data is shown graphically in Fig. 4 (for speeds greater than or equal to 0.30 knot) and Figure 5 (for speeds less than 0.30 knot). Indeed, even though the clustered nature of the higher speeds is shown in Fig. 4 as being quite noticeable, it must be remarked that many of the readings in the non-modal angular intervals for speeds in the higher range will be eliminated when anomalous readings of 48 hours duration, recording consistently high currents of highly variable direction, are removed from consideration.

As a secondary portrayal of this clustered nature of the higher speeds, a cumulative distribution for each speed range plotted the percentage of readings in each speed range up to and including the angle in question (Figs. 6 and 7). While the data curve for speeds of less than 0.30 knot varies in slope between 38° and 60°, a range of 22°, the curve for speeds in the higher range varies between 8° and 75°, a range of 67°. Once more, the highly modal nature of the two angular intervals {45°, 135°} and {270°, 315°} for the higher speed currents is evident.

Once it was established that the faster currents clustered significantly in two angular intervals, and that this clustering

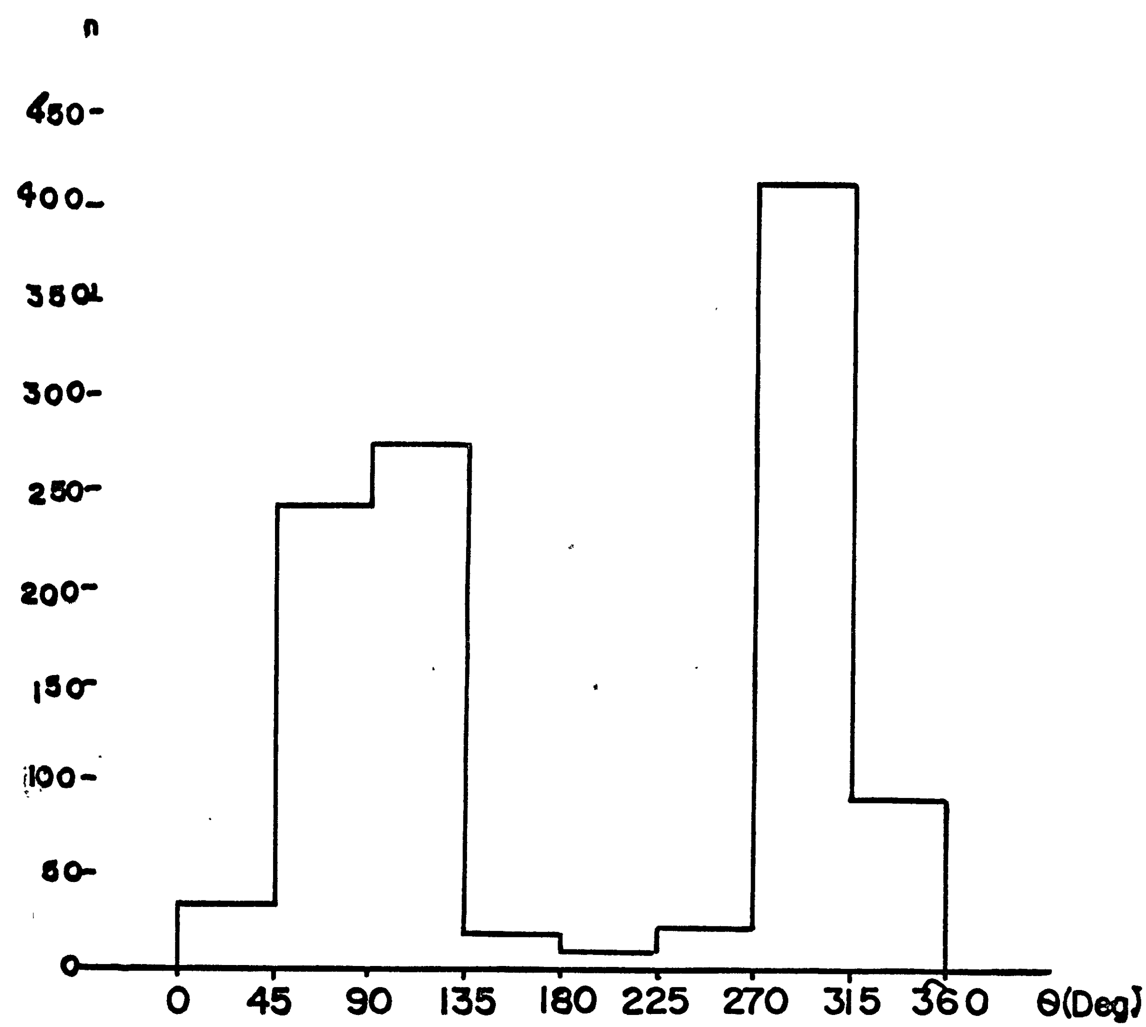

FIG. 4: FREQUENCY HISTOGRAM
BY ANGULAR INTERVAL OF CURRENTS
GREATER THAN OR EQUAL TO 0.30 KNOT

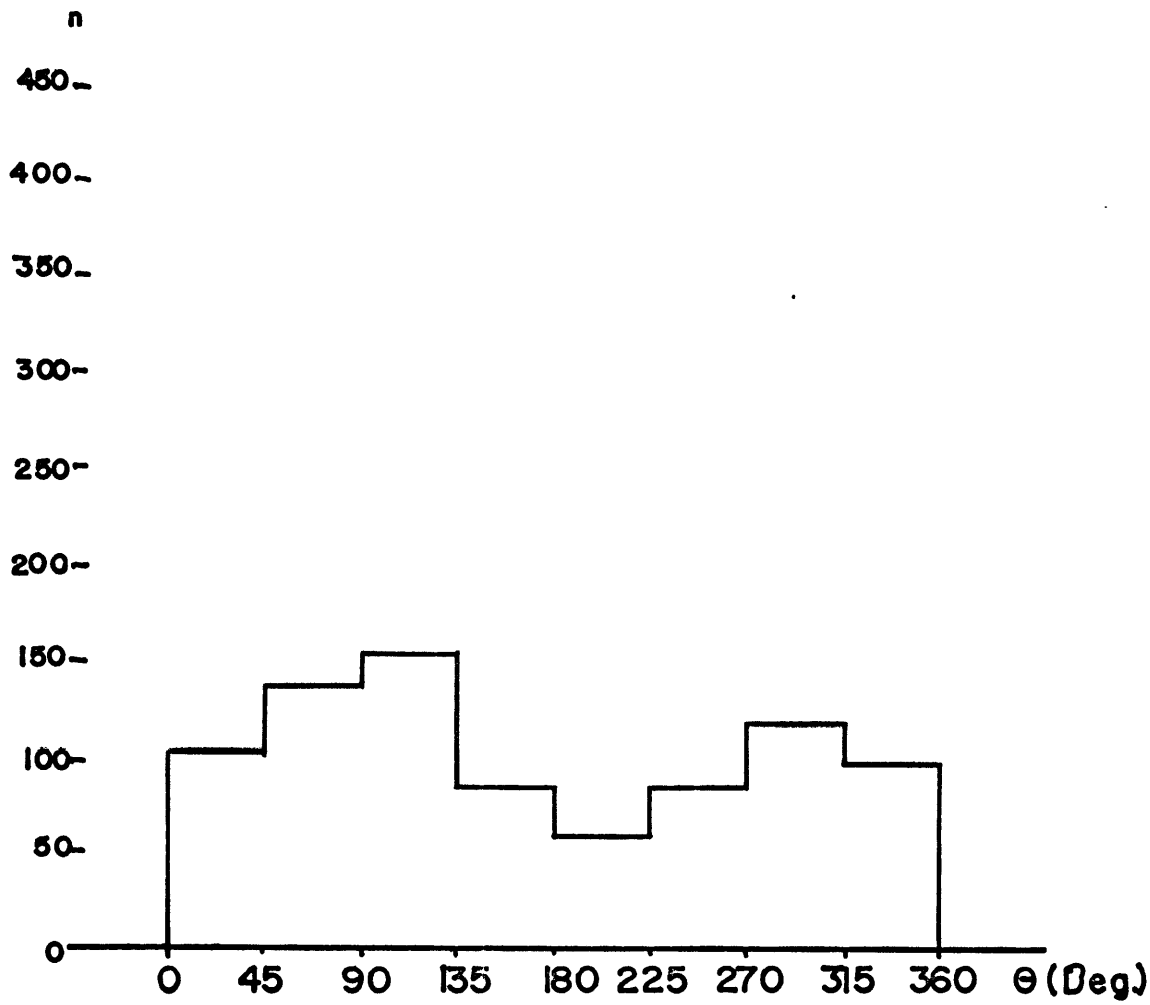

FIG.5: FREQUENCY HISTOGRAM

BY ANGULAR INTERVAL OF CURRENTS
LESS THAN 0.30 KNOT

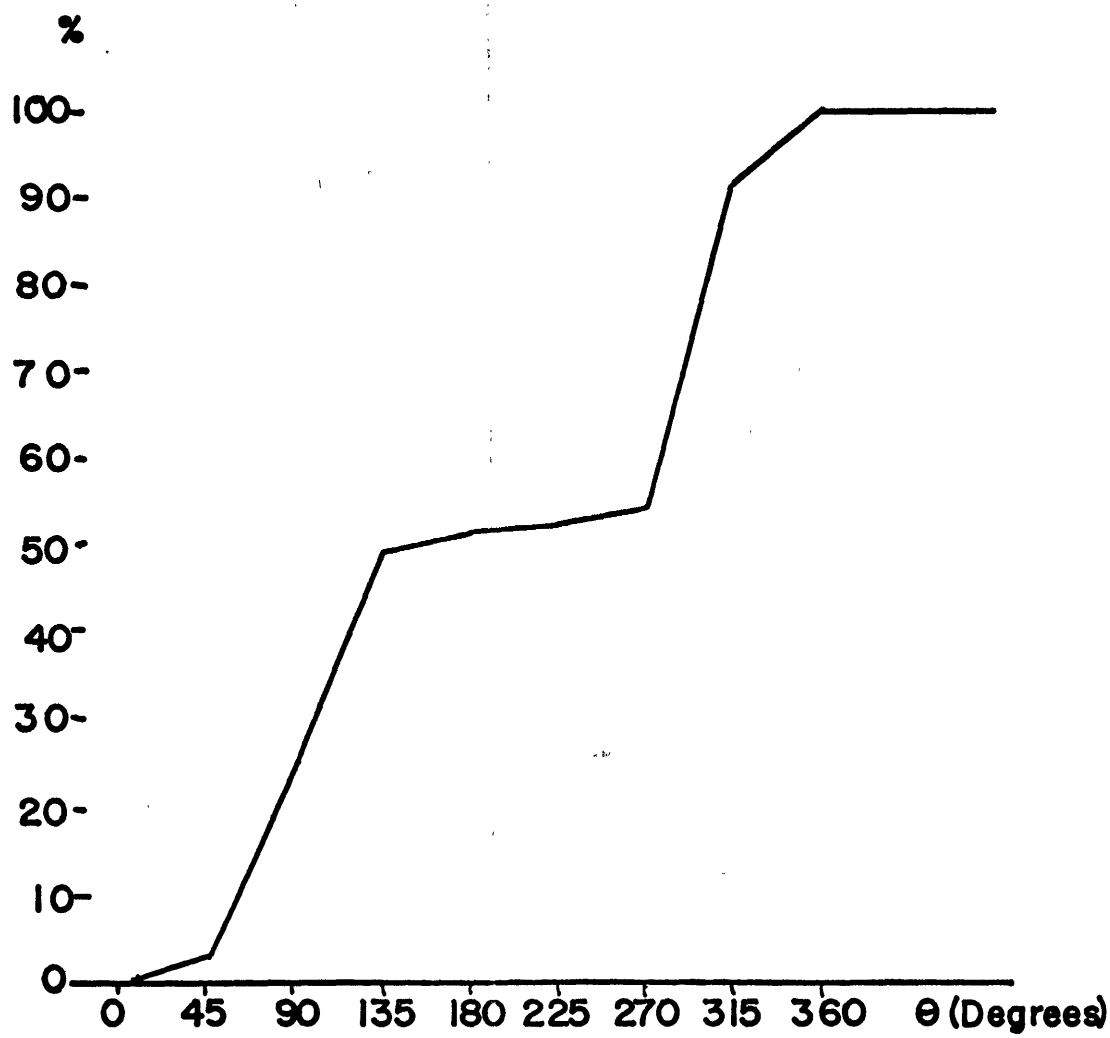

FIG.6: CUMULATIVE PERCENTAGE DIST.

ANGULAR INTERVAL FREQUENCIES FOR CURRENTS GREATER THAN OR EQUAL TO 0.30 KNOT

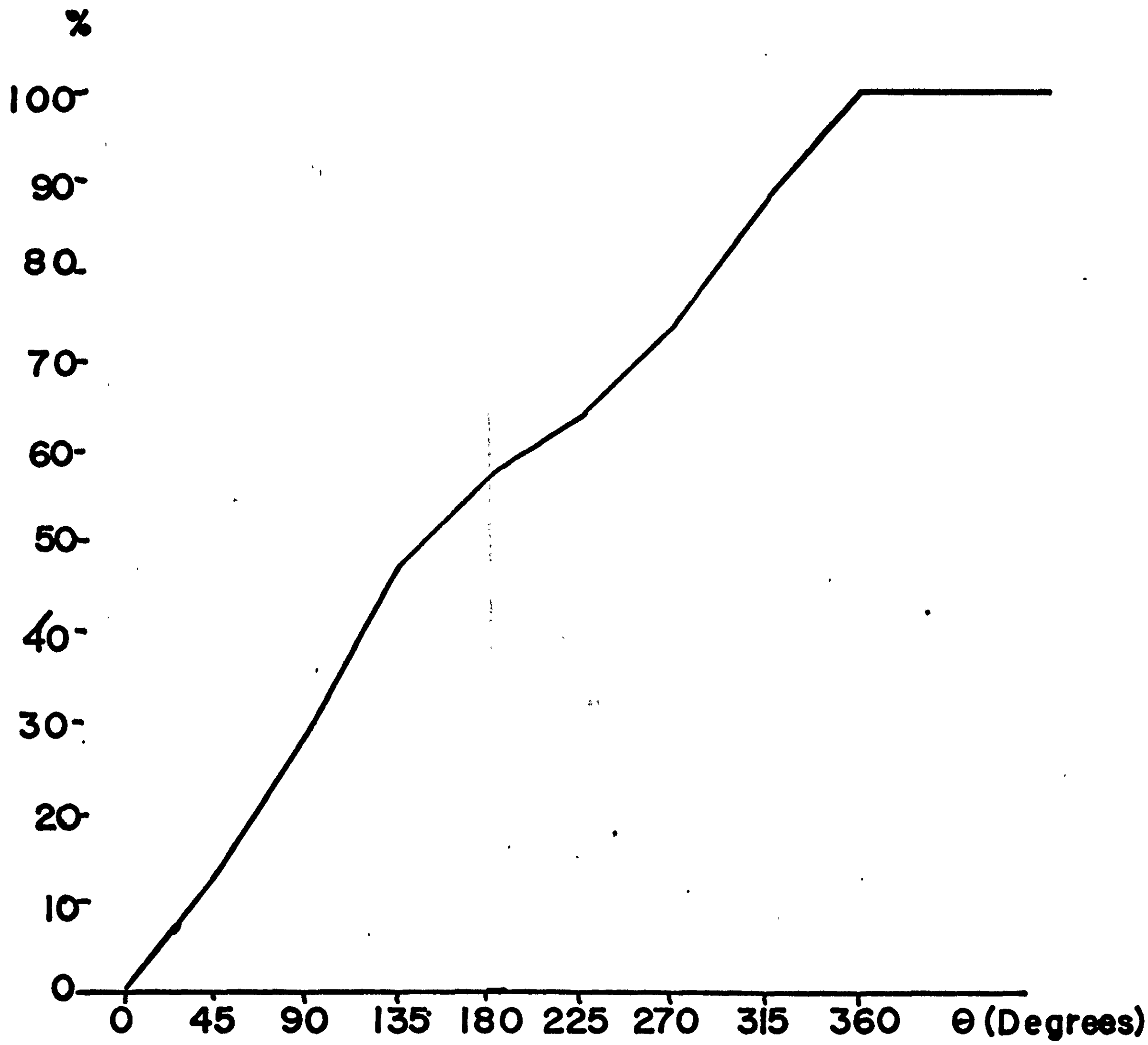

FIG. 7: CUMULATIVE PERCENTAGE DIST.

ANGULAR INTERVAL FREQUENCIES FOR CURRENTS LESS THAN 0.30 KNOT.

was in evidence for the entire body of data, it was necessary to correlate this bivariate data with a third variable: to the speed and direction data was added the variable of time. The question became: Is a positively correlated scatter of high speed and certain angular intervals also correlated with a recurring periodicity?

An initial search for such a periodicity necessitated using the previously correlated speed and direction as vectors and following these vectors' variation with time. The method used was a polar projection of the vectors, with radial distance from the center representing speed and angular interval representing direction. Such a plot involved linking sequentially the vectors within a given time interval; the result showed graphically the variation within this time interval of the vectors. One such plot is shown in Figure 8, with each point representing an hourly interval from the previous reading, and with certain key hours noted on the figure. The expressiveness of this exemplary diagram is enhanced when it is noted that the current vectors lying at the greatest radius (i.e., the currents of highest speed) are clustered in the angular intervals {100°, 130°} and {280°, 305°}--both subintervals of the previously noted modal intervals for high current speeds. In addition, these intervals contain current vectors representing speeds clustered in the range of 0.30 knot or greater.

The periodicity of the time interval portrayed in Fig. 8 (0000 hrs, 26 February 1966 to the last hour of the film, 1000 hours, 27 February 1966) is also evident: the slowest currents, clustered

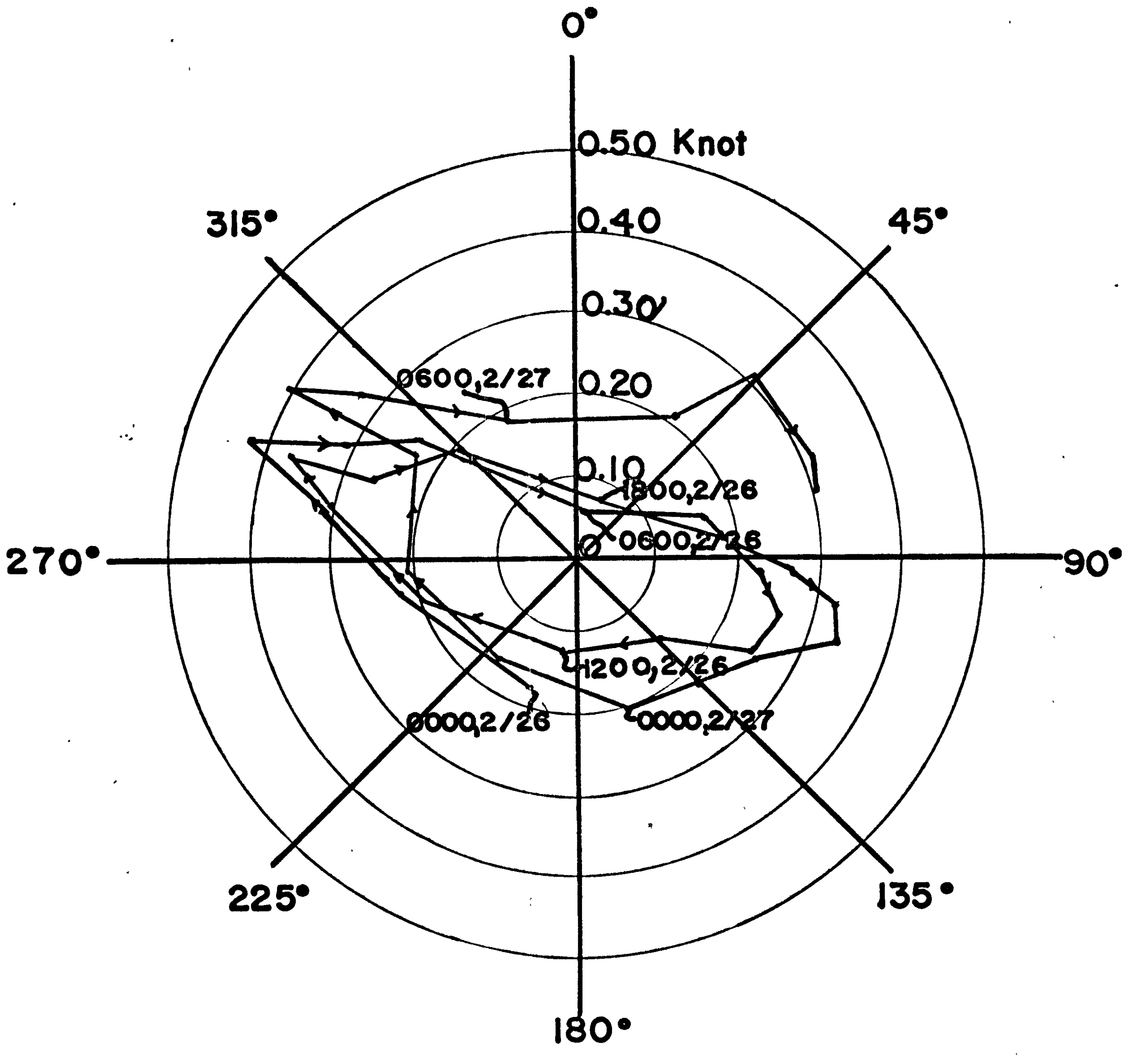

FIG. 8: HODOGRAPH OF CURRENT VECTORS FEBRUARY 26 & 27

(1-HOUR INTERVALS)

180° apart and at less than or equal to 0.20 knot, are also periodic in that there is a 180° shift in the directions of their vectors every six hours--repeated throughout the thirty-four hour period of Fig. 8, as is the repetition of the periodicity in the high-speed currents.

The example chosen for graphic exposition could only be considered a nontypical example if such highly correlative data was not repeated throughout the data. Investigation proves, however, that this highly positive correlation does not appear just once, or several times, but is consistent throughout the 324 hours of data.

Once the data were grouped by speed, this grouping was then subdiveided into the modal and non-modal angular intervals. Finally, the time intervals between such groupings were tabulated (once more discarding the approximately 48 hours' worth of anomalous data). There were 42 such intervals, representing the differences between 43 groupings of high-speed currents. Several of the observed groupings clumped together readings of greater-than) 0.30-knot currents with non-modal directions. Although such groupings meant approximately twelve-hour intervals between the beginnings of adjacent high-speed groups, there were only three such long-period intervals. The mean of the 42 intervals was 6.65 hours, and the standard deviation 1.5 hours. Of the 42 intervals, 24, or 57.14% lay in the interval {5.5 hours, 6.5 hours}. Extending the interval to {5 hours, 7 hours} includes a total of 78.5% of the intervals.

Just as evident as these interval correlations is the added correlation that, between every pail of current groupings tabulated, there was a shift of approximately 180° in the direction of the currents. ("Approximately" is used here because of the varying statistical nature of each current grouping and the consequent shifting within a range of directions of ± 25° from the mean of each group.) These shifts in the direction in every case proceeded through increasing angles, i.e., in a clockwise progression, and thus the readings in general followed the pattern of Fig. 8.

At the time that the current meter was placed in position and again when it was removed, samples of water were taken to note the salinity variation in the area of the station. These samples yielded the following results:

Salinity (parts per thousand)(± 0.04 ‰)

	Surface	Mid-depth	Bottom
12 February 1966	36.91	37.0	36.63
27 February 1966	36.93	37.04	37.0

Although its significance in such a shallow area is negligible for the formulation of any general statement, there is once more exhibited the feature of increasing, then decreasing, salinity with depth. (The temperature of the water in each section was uniform with depth, being 67.8°F on 12 February and 75.5°F on 27 February.)

THE PROPAGATION OF TIDAL CURRENTS

As was stated in the introduction, the area under study involves two deep basins separated by a very shallow bank, with one basin being segregated from this bank by a string of narrow islands. These islands are indeed so narrow in comparison to the width of the section of the Bahama Bank being studied that ideally they can be considered as unidimensional barriers on either side of the channels through them. They would therefore have only a vertical dimension, delineating the eastern terminus of the Bank before the descent into Exuma Sound.

The observed height versus time variations in sea level due to tidal forces can be analyzed through the use of harmonic analysis. This technique employs the determination of the coefficients a_0, a_1, $a_2, \ldots$, and b_1, $b_2, \ldots$ of the Fourier series

$$f(x) = \frac{a_0}{2} + \sum_{i=1}^{\infty} a_i \cos \frac{i\pi x}{L} + b_i \sin \frac{i\pi x}{L}$$

where L is the period of the wave. Tides approximated by cosine functions are expressed in the form

$$\eta = H_0 \cos(\xi_0 t - \chi_0) - \sum_{n=1}^{r} H_n \cos(\xi_n t - \chi_n)$$

$$= B_0 \cos\xi_0 t - C_0 \sin\xi t - \sum_{n=1}^{r} H_n \cos(\xi_n t - \chi_n)$$

where η is the sea level height (above mean sea level), $_n$ is the phase of the nth harmonic tide (the nth partial tide), ξ is the frequency or angular velocity of the tidal component, and H_n is the mean value of the height of the partial tide (Defant, 1961).

When tidal figures, or any other current data are solved for their harmonic components, what is yielded are the period, (relative) amplitude, and sin and cosine coefficients for the 1st through nth components. Knowing these separate terms, in turn, allows them to be summed at any point in time for any n harmonics to yield the prediction of the tidal (or other) wave height at that time. Herein lies the basis for tidal prediction machines, mechanical devices for summing individual harmonic terms.

The tidal components yielded are the various solar and lunar amplitude components. Normally, M_2, the principal lunar component of period 12.42 solar hours is assigned an amplitudinal coefficient of 100. Then, on this basis, it is found that the contribution of, for example, N_2 the larger lunar elliptic term, is 19.2, i.e., N_2's contribution to the total amplitude of the final tide is 19.2% of M_2's, although they will not occur at maxima at the same time, due to phase differences (Doodson, 1922).

In the Laplacian theory of tidal waves, the tides are seen as progressive waves moving in response to the basic harmonic forces but decisively modified by geographic and topographic factors. As such, it is seen that the tidal waves in open-ocean areas will appear as lines marking points of equal amplitude at equal times. Cotidal lines are lines connecting the points where maximum wave amplitude, i.e., points of high tide, occurs at the same time (von Arx, 1962; Proudman, 1953).

The cotidal lines in the southern North Atlantic are found to progress from south to north (Defant, 1961), changing to southeast to northwest in the area of the Bahamas due to an apparent amphidromic point (a point of radiation of the counterclockwise circulating cotidal lines) in the eastern Caribbean. In addition, land masses introduce frictional factors to this progressive wave, retarding its progress near these masses.

The plotting of the progress of the cotidal line with time through an area is equivalent to stating the time progression of a single wave through an area, since it is a representation of the progressive positions of the crest of the tidal wave. Thus, the knowledge of the cotidal lines in an area allows prediction of the tidal currents through that area. The proximity of the Tongue of the Ocean and the Bahamas in general to the eastern Caribbean amphidromic point implies a high angular velocity of the cotidal lines through the area. This is indeed found to be the case, as seen in Figure 9 (drawn up on the basis of data for high-water times in Tide Tables - 1966). This figure, in which the lines are labelled in terms of high tide

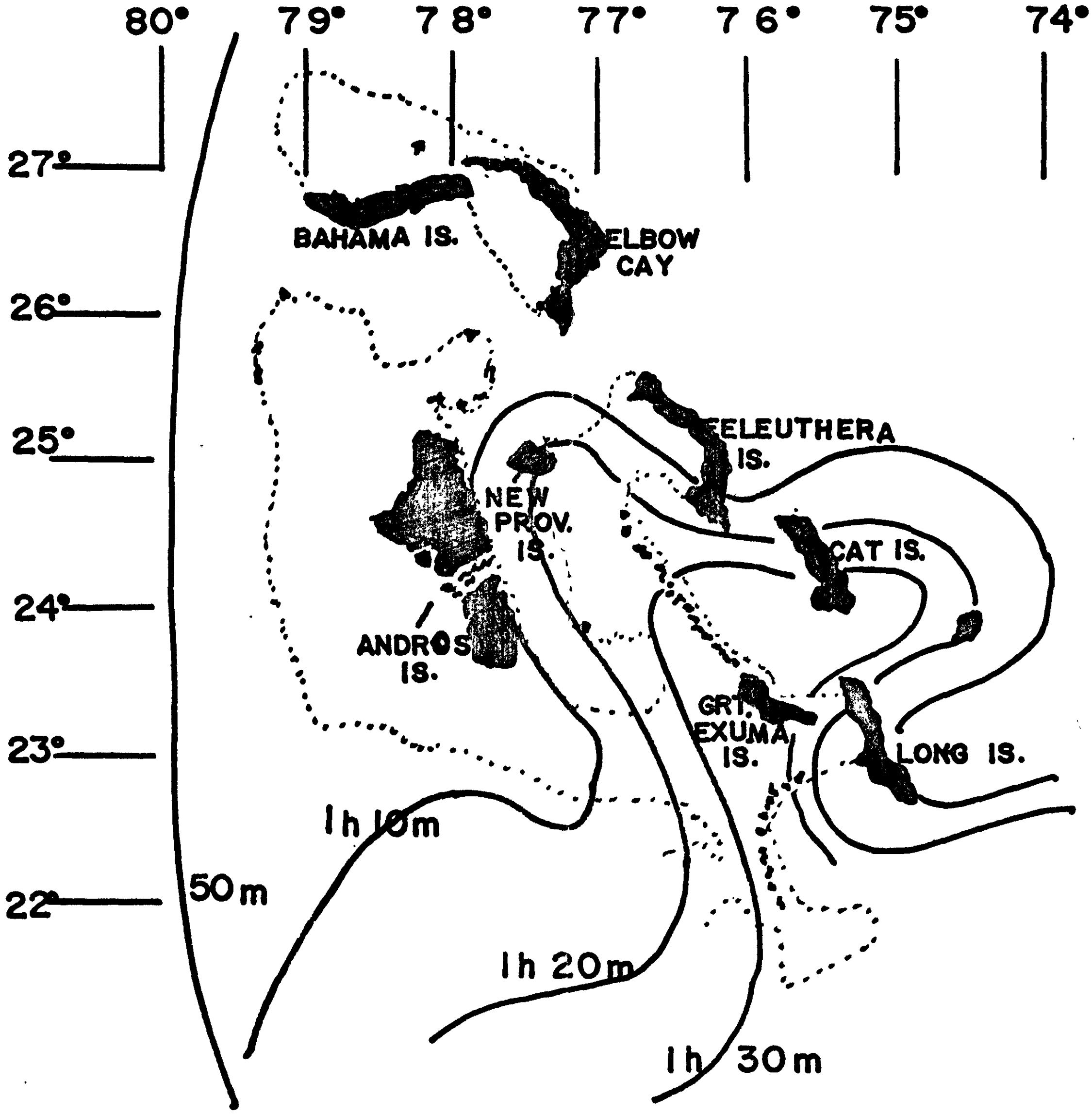

FIG. 9: COTIDAL LINES IN THE AREA OF THE BAHAMAS

[IN HOURS AND MINUTES BEFORE HIGH-TIDE TIMES AT HAMPTON ROADS, VIRGINIA] times before those times at Hampton Roads, Virginia, displays the theorized retardation of the progressive wave through the area by the bordering islands. It is apparent that the greatest linear progression of the tidal wave per unit time is over the eastern Tongue and eastern Bahama Bank.

Although the Bank and lower Tongue are somewhat enclosed by small chains of islands, there appears to be no seiching effect within the area. This is probably due to the presence on all sides of somewhat larger and freer-circulating channels. Thus, the nature of the progressive wave appears to be that of a wave which enters and leaves the bank through the same channel in response to advancing or receding crests of tidal waves (as opposed to a seich propagating by reflection from the borders of the basin).

The use of the theoretical equations for evaluating the propagation velocity depends on the determination of the harmonic coefficient involved in them, and this makes its use conceivable only in open-ocean, deep-water areas because of the complications introduced into shallow-water constituents by the differential in frictional forces in a wave entering shallow areas. The relatively shallow water has more effect on the trough than the crest of the wave due to the total amplitude of the wave, and the results are overtides, new constituents with angular speeds which are integral multiples of the astronomical constituents. These new shallow-water constituents have amplitudes which are inversely proportional to their angular speed, and have enough effect to make theoretical formulation of shallow-water effects arduous (Dronkers, 1964; Proudman, 1953).

The measurements of tidal flow across the shallow area allow the determination of total mass and volume of water transported by these flows through the area. The equations for volume transport by horizontal currents (as cited in Sverdrup, et al, 1942) are

$$T_x = \int_0^d v_x d_z, \qquad T_y = \int_0^d v_y d_z,$$

where v_x, v_y are the velocities in the x- and y-directions, and d is the water depth. For the purposes of this study, these equations may be combined and expanded into forms which are more directly applicable to tidal currents whose direction and speed vary with time.

During an ebbing flow across the Bahama Bank, i.e., a flow during which the tidal currents are moving off the bank, the direction of flow varies from θ_1 to θ_n. Since discrete time intervals are being dealt with, the range $\{\theta_1, \theta_n\}$ includes n angular readings $\theta_1, \theta_2, \ldots, \theta_i, \ldots, \theta_n$. With each θ_i is associated a velocity of v_i.

Then, at any particular station the volume transport expression becomes

$$T = \sum_{i=1}^{n} \int_0^d v_i dz$$

or, if an easterly current is here considered as 0_1 with 0 increasing clockwise, the component volume transports are

$$t_x = \sum_{i=1}^{n} \left[\int_0^d v_i dz \right] \cos \theta_1, = \quad t_y = \sum_{i=1}^{n} \left[\int_0^d v_i dz \right] \sin \theta_i ,$$

where T_x is the east-west contribution and T_y the north-south contribution to the volume transport.

If, instead of vectorial current points there is used the average measured current in an angular interval of mean value 0_k for each interval in the time period being considered, then the total volume transport per effluent cycle is the sum of the products of each interval's volume transport times the duration of flow in that interval. If the kth interval spans a time period t_k, the total transport per cycle is

$$V_x = \sum_{k=1}^{n} \left[\int_0^d v_i dz \right] t_k \cos \theta_k, \quad V_y = \sum_{k=1}^{n} \left[\int_0^d v_i dz \right] t_k \sin \theta_k .$$

Use of these formulas allows a numerical estimate of flow per effluent cycle on the Bahama Bank to be made. As an example, the volume transport for the period 1900 hours, 26 February, to 0000 hours, 27 February, was computed.

At 1900 hours, v is 6.08 meters/minute, $\theta = 78° - 90° = -12°$, and d is 5.5 meters (constant for all readings). The time interval will be considered as one hour, i.e., the hourly speed and direction will be considered average values for that time, plus or minus a half hour. Similar figures are found for each hour of this period. Then, summing over the entire period, it is found that

$$V_x = 12.251 \text{ cubic meters}, \; V_y = 4{,}257 \text{ cubic meters}$$

for the six hours represented by the cycle. V_x and V_y express the summed volume transport contributions of the x and y components of each velocity measurement.

For this period (February 26-27), the measured salinity and temperature at the location of the current meter yield a current-water density average of approximately 1.037 gm/cc, so that the contributions of total mass transported were approximately

$$M_x = 12.619 \times 10^6 \text{ kilograms}, \; M_y = 4.385 \times 10^6 \text{ kilograms.}$$

It must be emphasized that these figures represent total water mass transport past the station point, and not the actual mass effluent from the bank area. The actual effluence from the bank will be somewhat less than these values in the period considered, due to frictional forces acting on the flow through the cay channels. This force in the direction of flow will be of a shearing type produced by the walls and floor of the channel.

The question of the presence of a laminar flow across a shallow area can only be answered by current measurements at several depths in the water over a long period, combined with density and temperature measurements. The thermal measurements for the location of the current meter of this report, showing as they do a constant temperature gradient with depth, and the small variations in salinity with depth, indicate that an internal wave probably is not present. Rather, there would appear to be complete non-laminar flow across the entire section. Indeed, the current speed should ideally be found to increase with decreasing depth (and therefore decreasing bottom friction). For a bottom current with a velocity of form $v_r = f(r,t)$, it is found (Proudman, 1953; Sverdrup, et al, 1942) that the form of variation of this velocity with decreasing depth z is $v_r(z) = e^{\gamma z} f(r,t)$, where z is the vertical distance from the bottom and γ is a function of salinity, temperature, and depth.

COMMENTS AND CONCLUSIONS

The purpose of this study was to investigate the true nature of the current patterns in the southern part of the East Bahama Bank with a view towards determining any relationship between these patterns and the temperature-salinity profile of the Tongue of the Ocean. Specifically, it was to be determined whether the currents were of the form of a simple backing-up and subsequent intensification of currents in and through the cay channels on the east, or a more complex progressive wave across the bank consistent with the cotidal pattern thereon.

As is seen in Fig. 9, the general pattern of the perpendiculars to the cotidal lines in the area of the current meter was that of a generally southeast to northwest progression of the wave crests. This trend can be seen to be a result of the general patterns of islands and cays and of changing water depth in the Bahamas area, and not of the island-and-channel chain directly to the east of the Tongue.

The tidal flow is thus not primarily the result of hydrostatic pressure through the channel pattern, but rather results from a complex progressive wave whose velocity is intensified to only a slight extent by the "piling-up" effect in the channels. The direction of the wave in the neighborhood of the meter location takes it through chains of islands to the southeast, but the net effect is no more than that of a complex wavefront.

The many readings of speed and direction from the current meter are the major sources for verification of the true origins of any currents in the area. The two angular intervals with the highest frequencies of occurrence in the high-speed range coincide with the directions of the tidal wave entering and leaving the East Bahama Bank (as revealed by the cotidal plot), and also with the 6T-hour periodicity of a high-to-low tide cycle. The fact that all three variables (speed, direction, and periodicity) so closely concur with their predicted values by tidal flow leads to the conclusion that the far greatest proportion of observed flow originated with the progressive tidal wave through the area and past the station.

The excellent correlation between high current speeds and the direction of tidal flow is partly attributable to the relative lack of other, constant currents in the vicinity of the current meter, and also partly to the near-bottom position of the meter. This position, however, did serve to allow a closer inspection of currents common to all surface conditions.

Although it has been shown that the local currents are most directly caused by the tidal sweep across the bank, a more comprehensive survey is required to more accurately place the various tidal forces in a hierarchy of current-producing forces, i.e., there may indeed be a component of tidal flow which is most important in the surface structure of the water, but such a component would not be revealed by a meter near the bottom. In addition, the total transport past the meter can be more accurately defined only with similar speed and direction data for several stations arranged from surface to bottom in a section.

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