TECHNICAL REPORT

ASWEPS REPORT NO. 1

THE OCCURRENCE AND VELOCITY DISTRIBUTION OF SHORT-TERM INTERNAL TEMPERATURE VARIATIONS NEAR TEXAS TOWER NO. 4

ROY D. GAUL

Formulation Branch

Oceanographic Prediction Division

MAY 1961

U. S. NAVY HYDROGRAPHIC OFFICE
WASHINGTON, D. C.
Price 50 cents

ABSTRACT

This report describes a study of the occurrence, speed, and direction of short-term changes in water temperature near Texas Tower No. 4 off New York. Measurements made during two-week periods in the fall of 1959 and the spring of 1960 reveal common occurrences of internal solitary wave forms indicated by temperature changes at fixed levels of several degrees centigrade within several-minute intervals. Internal temperature wave forms observed in both seasons were typically moving onshore at speeds ranging from 0.75 to 1.30 knots. Comparison of observed speeds with values calculated from internal solitary wave theory exhibits reasonable agreement considering the limitations of the field experimental phase of the study.

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FRONTISPIECE—TEXAS TOWER NO. 4 OFF NEW YORK
(COLLAPSED 15 JANUARY 1961)

FOREWORD

Of great importance to a variety of naval operations is the knowledge of density distribution in the ocean at particular points in space and time. The field studies conducted at Texas Tower No. 4 in support of the AntiSubmarine Warfare Environmental Prediction System (ASWEPS) were designed to detect and provide a fund of field data for the analysis of regular and irregular variations in temperature structure beneath the water surface. The primary emphasis of this report is on anomalous short-term transitions giving the appearance of internal solitary waves.

E. C. STEPHAN
Rear Admiral, U. S. Navy
Hydrographer

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FIGURES

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I. INTRODUCTION

The Texas Tower No. 4 research operations during 1959-1960 were intended to provide data from a convenient and particular ocean region in sufficient detail to support analytically sound interpretation of long- and short-term environmental transitions. To expedite initial information acquisition in a largely unknown region, every attempt was made to use readily available techniques and instrumentation. The experience and information gained is now the basis for establishing more adequate field systems for fixed-station observation. This report is concerned with only one of the more readily observed phenomena: short-term, usually anomalous variations of the water temperature structure hereafter referred to as "signature" associated with a special variety of internal waves.

The existence of internal waves beneath the sea surface has long been known but only recently has observation technology advanced to the point of making controlled detection practical. Ekman (1904) theoretically explained "dead water" in terms of internal waves generated by a vessel moving slowly through a shallow overlying layer of low density water. Free wave speeds that he derived (which happen to closely correspond to results cited in this report) were shown to be inadequate to account for propagation of internal waves of tidal character until Haurwitz (1950) and Defant (1950) introduced the effect of earth rotation. Meanwhile, Fjeldstad (1933) developed a theoretical analysis of internal waves within a continuously varying density structure as opposed to the simplified two-layer system. These works and others too numerous to cite (see Davis and Patterson, 1956) were chiefly concerned with oscillatory waves of relatively long period. The works of Keulegan (1953) and Long (1956), which specifically consider the shallow-water internal solitary wave, will be given more detailed attention later in this report.

Several attempts have been made to use ships for observing internal waves in deep water over sufficient time periods to allow significant statistical analysis. Reid (1956) set up repetitive measuring stations off the southern California coast; a multiple ship survey was conducted in the Atlantic (Brown, Corton, and Simpson, 1955); and more recently, detailed time series were obtained in a special deepwater anchoring system (Magnitzky and French, 1960). The difficulty of performing these operations has intensified interest in use of shallower water fixed stations using bottom-mounted sensors (Haurwitz, Stommel, and Munk, 1959) and fixed platforms (LaFond, 1959) as well as photographic observation of sea slicks from shore sites (Dietz and LaFond, 1950; Ewing, 1950). The degree to which investigations of nearshore and deepwater internal wave phenomena are similar must await further scientific study.

II. RESEARCH OBJECTIVES AND PROCEDURE

Aside from operational development of fixed platform environmental research, an initial step in this study was to determine the existence of internal temperature variations and subsequently to gain sufficient knowledge to design an observation system. Minimal single-station measurement at a single level in July 1959 provided the basis for layout of the three-station system described in the following section. This was specifically arranged for detecting the passage of "discrete" internal temperature variations (or signatures) which retained sufficient identity of form to be recognizable at all three stations. Through observation over extended periods, continuity or regularity of occurrence could be established and a comparison could be drawn between fall and spring features of the internal phenomena. From the analysis of data collected during a multiple ship survey made in conjunction with observations at Texas Tower No. 4 during April 1960, it is intended in a future report to estimate the degree of horizontal uniformity within a distance of 15 miles from the tower.

III. FIELD MEASUREMENTS

Field data considered in this report were collected during the fall of 1959 and the spring of 1960 in the vicinity of Texas Tower No. 4. The tower (hereafter designated TT4) was located about 70 miles southeast of New York Harbor on the north shoulder of the Hudson Canyon in a water depth of 185 feet (Figure 1).

The sensing system consisted of a taut-wire submerged buoy with platinum resistance thermometers affixed at pre-selected levels (Figure 2). A spherical, 14-inch-diameter, Japanese, glass fishing float provided vertical lift. The net woven around the float was attached to a 3/32-inch steel cable which in turn was linked to a 100- to 150-pound gravity anchor. The 3/8-inch electrical lead cable from each resistance thermometer was taped or tied to the 3/32-inch cable and spliced near the anchor to a common cable laid on the ocean bottom to the tower.

The array used during the fall of 1959 consisted of two buoys 500 feet apart forming an equilateral triangle with the vertical guide cables below the hydrographic room of the tower (Figure 3). The two buoys on the east-west base of the 500-foot triangle supported resistance thermometers at nominal depths of 65 and 100 feet below mean water level (MWL). Thermometers at the tower were placed at 65, 80, 100, and 130 feet below MWL. During the spring of 1960, the array consisted of three buoys positioned as shown in Figure 4 with resistance thermometers placed at approximately 50, 70, 90, and 110 feet below MWL. Note that the equilateral triangle was 400 feet on a side instead of 500 feet and the vertex was 225 feet south of the tower to minimize influences of the structure.

The buoy arrays were manually installed from a 26-foot surfboat. Sextant angles taken from the boat, supplemented by sight lines relative to tower caissons, were used in the fall to position the two buoys. Considering drift rate, sea conditions, sextant and sighting errors, and the 40- to 50-foot freedrop of the buoy when cut loose over station, the actual positions of the buoys are estimated to be within 40 feet of the predetermined positions.

Two azimuth instruments accurately located at the end points of an east-west 100-foot baseline of the tower's flight deck were used for horizontal control in positioning the three buoys in the spring. Azimuth angles were computed to the nearest 15 minutes of arc —equivalent to the precision with which the sighting instruments could be preset. The relative locations of these buoys are estimated to be within 10 feet of the calculated stations.

Two 4-channel "Brown" balancing potentiometer recorders were used during the fall to record resistance thermometer output on a 0° to 30°C full scale. The sampling rate for a given channel depended on the temperature differences between the four channels and normally averaged 6 to 10 seconds. For the spring survey, the outputs from the four thermometer levels of all three buoy positions were recorded on a single Brown recorder modified to handle 12 different information channels. The sampling interval for an individual information channel was usually from 18 to 30 seconds. GMT marks were manually added to the records at one- to eight-hour intervals to serve as time control between recorders and supplementary observations. Precision of these marks is estimated to be ± 3 seconds for the majority of chart speeds.

The selection of resistance thermometers for temperature sensing was largely a matter of convenience. Thermometers and recorders were readily available and the normalized readout on a scaled strip chart promised a reduction in data processing effort. The main objection to the type of resistance thermometer used for this application is its long time constant as compared to those of other temperature sensors currently on the market. In the course of the TT4 field program, a step change calibration of the temperature recording system was accomplished by transferring the thermometers from a water bath at 18.5°C to a bath at 1.5°C. The lack of experimental control, normal to the laboratory, precluded exact determination of the response deviation from the exponential relationship,

$$T(t) = T_1 - (T_2 - T_1)e^{-t/\tau}, \tag{1}$$

where $T(t)$ is indicated temperature at time t, T_1 is the initial ambient temperature, T_2 is the secondary ambient temperature, and τ is the so-called "time constant." The results of field calibration indicated that the actual response curve differed from Equation (1) with τ becoming larger with increased time after the step change. It appeared that an equivalent time constant of about 60 seconds could be realistically taken for the system used in these studies.

In addition to fixed-level water temperature measurements, a variety of supplementary observations was made. Bathythermograph drops were made at the tower at intervals varying from hourly to daily. Many 15- to 30-minute surface wave records were obtained with a 15-foot resistance-wire wavestaff. Wind records were continuously recorded from an anemometer mounted on a bracket about 30 feet above the water surface on the hydrographic guide cables. Attempts to measure ocean currents with Roberts current meters were generally unsuccessful except for a 3-week period in April 1960 when a "Modified Roberts Current Meter II" furnished by Marine Advisers and Pruitt Manufacturing was used. These data are tabulated in Appendix I. Water samples at 3 to 6 levels were taken periodically during the spring for salinity analysis. Routine weather observations by Air Force weather observers rounded out the field program. All of these data are on file in the Oceanographic Prediction Division of the U. S. Navy Hydrographic Office.

IV. DATA PROCESSING AND ANALYSIS

Briefly, the data analysis technique consisted of subjectively selecting cases from the temperature records wherein identifiable "signatures," i.e., distinctive temperature variations related in form (but not necessarily amplitude), could be ascertained with a high degree of certainty to have occurred at all three measuring stations in a single horizontal plane. The times of passage at each known station were then used to calculate the speed and direction of the signatures. A total of 95 cases were selected during the fall period (28 September - 15 October 1959) and 201 cases from the spring period (13 May - 4 June 1960).

In an attempt to preserve some measure of statistical significance, all records were examined during each data period and every case was recorded where the signature relative to background "noise" was distinctive enough to almost completely assure nonambiguous occurrence at each station. In cases where a "train" of several signatures occurred, the most distinctive one was selected for analysis or several were averaged. The magnitude of temperature variation was not considered; distinctive features and uniform shape of the signature observed at each station was responsible for selection. The middle of the temperature peak or crest (internal wave trough) was normally used to index the time of passage at each station. Signature speed and direction were computed on an LGP-30 digital computer.

No attempt was made to ascertain the effect of horizontal water motion on signature speeds since accurate ocean current observations were normally not taken concurrently. Appendix I indicates the importance of accounting for the effect of field motion on individual signature velocities. The lack of simultaneous current observations leaves only the alternative of computing average speeds in each quadrant for the single two-week period of reasonably good data. This problem is further discussed in the following sections.

V. RESULTS AND DISCUSSION

A. SIGNATURE CHARACTERISTICS

Figures 5 through 12 are typical sections of temperature records selected to represent a cross section of observed activity. Figures 5 and 6 are samples of temperatures recorded in a single plane (or level) at all three stations during 1.5-hour time spans. Note that although the two records are separated by an interval of only 1.5 hours, Figure 5 contains distinctive large amplitude temperature variations while Figure 6 reveals little activity and no apparent correlation between stations. Figure 7 is an example of very well defined temperature variations at two levels, clearly signifying the passage of a regular wave form whereas the temperature changes at three levels shown in Figure 8 are small and show little coherence between measuring stations.

The case illustrated in Figure 9 is particularly interesting because there seems to be a temperature "node" at the 70-foot level. Inspection of the mean thermal structure reveals a dual thermocline and the measuring levels (50, 70, and 95 feet) are located such that if the entire thermal structure moved down about 15 feet there would be no temperature change at mid-depth while the upper and lower levels would change as observed. The fact that the changes are in phase significantly supports the argument for vertical migration of the water column as a unit. In many other cases, however, this phenomenon is by no means discernable. Lee (1960) has indicated the occurrence of similar cases at the U. S. Navy Electronics Laboratory's tower in 56-foot depth off Mission Beach, California.

Figure 10 is an example of close coherence between different levels in a constant thermal gradient—another indication of synchronous vertical movement of the water column. Two almost identical single temperature crests occurring at the same level on two different days are shown in Figures 11 and 12. Note that the mean thermal structure has the same form on both days. The computed travel directions of the two cases are somewhat different; viz., 335° for Figure 11 and 300° for Figure 12.

Comparison of individual signature forms recorded at each of the three stations raises the question of uniformity. Temperature amplitudes and "hump lengths" are not usually identical. Three possible explanations are offered: (1) the internal waves are short-crested relative to the 400- and 500-foot station spacings, (2) the preset elevations of sensing elements at each station were not uniform enough to initially be or to subsequently remain in horizontal planes, and (3) elevations along individual internal wave crests were not always constant. With regard to the second explanation, it is certainly unlikely that the prefabricated buoys would have been exactly uniform or the bottom perfectly flat but vertical tolerances of two feet in sensor planes seem quite reasonable and any error of this kind, other than current-induced dip of the taut wire buoy, would cause a consistent amplitude deviation at a particular station. From perusal of the records, it seems more reasonable to assume that the first and third explanations both apply. The internal wave surface or zone might therefore be analogous to the sea-swell regime of the air-sea interface.

B. SIGNATURE VELOCITY DISTRIBUTION

Computed signature speeds and directions are summarized in Appendix II for the fall data and in Appendix III for the spring data. Cumulative frequencies of occurrence of speed within 45° sectors of direction (set) have been calculated from these data and the results are graphically displayed in Figures 13 and 14 for the fall of 1959 and the spring of 1960, respectively.

The assessment of internal wave or temperature signature velocity distribution must be tempered by an estimate of the motion of the medium itself. The only reasonably reliable current data collected are given in Appendix I, and cover the period 12-25 April 1960. These data represent about five-minute averages observed every hour with a meter suspended at 100 feet from one of the guide cables. The meter support (bracket and cable) was not completely free from lateral movement. In tank tests, the meter was found incapable of orienting to within 30° at constant tow speeds less than about 0.15 knots. Both of these factors contribute to uncertainty of the data. In addition, the effect of the platform on magnetic reference of the meter was not determined.

The following averages for current speeds greater than 0.01 knot have been computed from the data in Appendix I: NE = 0.23 knot; SE = 0.27 knot; SW = 0.31 knot; and NW = 0.38 knot. Of the 268 observations used, 7.5% were in the NE quadrant, 26.0% in the SE, 27.5% in the SW, and 39.0% in the NW. Less than 8% of all hourly observations were at speeds below 0.1 knot. These ranges of speed correspond reasonably well to the vector spread of velocities summarized in Figures 13, 14, and 15.

The statistical treatment of the current data allows for the approximate nature of the basic data in that rough estimates are made of average speeds within broad bands of direction. There are several breaks in the hourly observations for which no adjustments were made. It is felt that the single record period of two weeks at least gives some notion as to probable speed ranges and can serve as a guide in the absence of better evidence. The consistency of the data definitely indicates a clockwise rotary current ellipse with the major axis oriented approximately NW-SE. The observations were made during a period of comparatively isothermal conditions so that maximum correlation of currents to tidal motion might be expected.

C. ANALYTICAL COMPARISONS OF SIGNATURE SPEED

The recorded internal fluctuations of temperature throughout this field study characteristically appear in groups of one to four temperature "humps" at irregular intervals. This strongly suggests the application of solitary internal wave theory after Long (1956) and Keulegan (1953) in order to compare observed speeds; both of these theoretical developments assume a two-layer system. Long further imposes a rigid boundary at the water surface as well as at the bottom. Keulegan's work was therefore selected as being most appropriate. His equations are summarized below and then applied to several observed cases of temperature-salinity structures for comparison with measured signature speeds.

Consider a two-layer fluid medium of thickness h_1 and density ρ_1 between the free surface and the internal density discontinuity overlying a layer of thickness h_2 and density h_2 between the discontinuity and a rigid bottom. It is shown that a solitary wave of infinitesimal height occurring at the internal discontinuity will travel at a phase speed, c_o, given

$$c_o \left[= \frac{g h_1 h_2}{h_1 + h_2} \left(\frac{\rho_2 - \rho_1}{\rho_2} \right) \right]^{1/2} , \tag{2}$$

where g is acceleration due to gravity. As a matter of interest this is the same equation as derived by Defant (1950) and Haurwitz (1950) for the oscillatory internal longwave neglecting the effect of earth rotation. Ekman (1904) also applied this equation to explain the "dead water" effect on vessels moving slowly in a shallow, low-density surface layer.

The phase speed, c, of the internal wave of finite amplitude η_o is found to be

$$c = c_o \left[1 + \frac{h_1 - h_2}{h_1 h_2} \eta_o \right]^{1/2} , \tag{3}$$

where η_o is referenced to the undisturbed level of the density discontinuity. From Equation (3), it is seen that when the discontinuity is at mid-depth the phase speed is independent of internal wave amplitude.

Since the above equations apply to a free surface, the internal wave crest or trough must be accompanied by a solitary surface wave trough or crest, respectively. In practically all observed cases near TT4, signature passage was indicated by positive humps or crests in temperature measured at a fixed level. Under normal conditions of a negative temperature gradient and positive salinity or isohaline profile, this would correspond to an internal wave trough accompanied by an imperceptible crest on the water surface.

A precise comparison of individually observed signature speeds to Keulegan's theory is not possible since salinity was neither measured continuously nor at the same depths as temperature. Water samples for salinity analysis were taken at several depths daily from 13 May to 3 June 1960 to provide a gross picture of the mean salinity structure. These data are tabulated in Appendix IV from which the average salinity is found to vary from 31.4‰ at the surface to about 32.5‰ at and below a depth of 90 feet. For purposes of two-layer calculation of wave speeds during the spring period, values of 31.5‰ for salinity in the upper layer (S_1) and 32.5‰ for salinity in the lower layer (S_2) have been assumed. Salinity is assumed to be 32.0‰ in both layers for calculated speeds during the data period in the fall of 1959.

The average speed given in Appendix II for the signatures shown in Figure 7 is 0.95 knot. Replacement of the mean thermal structure in Figure 7 with a sharp discontinuity at 70 feet, temperatures of 20°C in the upper layer and 10°C in the lower layer, and a constant salinity of 32‰ result in density values of $\rho_1 = 1.0225$ and $\rho_2 = 1.0247$. The mean temperature gradient at 65 feet as shown in Figure 7 is about 0.25°C per foot. The observed temperature changes at that level were approximately 7°C indicating an internal wave height, η_o, of 28 feet. Substitution of these values in Equations (2) and (3) gives an average speed of 0.96 knot as compared to the 0.95 knot observed.

A second direct comparison may be made for the wave shown in Figure 8. The discontinuity level at 60 feet is chosen and average temperatures and salinities are taken as follows: $T_1 = 10°C$, $S_1 = 31.5‰$, $T_2 = 4°C$, and $S_2 = 32.5‰$. The mean temperature gradient from 40 to 100 feet was approximately 0.1°C per foot and the temperature range at 70 feet was about 2.5°C inferring an internal wave height of 25 feet. The speed calculated from these assumptions is 0.85 knot as compared to the measured speed of 0.65 knot. Similar assumptions and calculations for the waves shown in Figures 9 through 12 provide the following comparisons:

Figure	Calculated Speed	Measured Speed
9	0.45	1.25
10	0.80	1.15
11	0.88	1.00
12	0.87	0.90

The cases shown in Figures 7 through 12 were selected to illustrate various wave forms rather than as a statistical basis for speed comparison. Computed speeds may not be truly representative but considering assumptions and data limitations the results are believed to be sufficiently indicative of reasonable agreement between observed and computed speeds.

The above comparisons are not intended to prove that observed temperature signatures correspond to internal waves that comply closely with solitary wave theory. The partially subjective simplifications required to reduce the actual density structure to a two-layer system preclude such expectations. Simultaneous and continuous measurement of ocean currents and a more detailed network of temperature and salinity sensing devices would also be required. It is believed, however, that sufficient evidence has been presented to strongly indicate a close correspondence of the measured temperature variations to internal wave theory presented by Keulegan.

VI. CONCLUSIONS

This report is pertinent to internal temperature variations observed at one site only — Texas Tower No. 4 in 185 feet depth off New York. The conclusions drawn from analysis of the data may be considered applicable only to that locality until studies elsewhere reveal the presence of similar "solitary signatures."

The following specific conclusions are drawn from the studies at Texas Tower No. 4:

1. Under conditions of vertical stability indicated by a negative thermal gradient, the passage of short-term internal disturbances resembling solitary waves is quite common.

2. These temperature wave forms or signatures occur irregularly in identifiable groups of one to four temperature humps (density troughs) moving onshore at a speed of approximately one knot.

3. The conspicuous onshore (normal to depth contours) orientation of the signatures as well as the reasonable agreement of travel speeds with shallow water internal wave theory verifies the direct association of signatures with long internal waves originating offshore from the measuring station.

4. Measured ocean currents are predominantly rotary clockwise; average speeds are about one-fourth those of the internal temperature signatures. This combination seems to account for most of the spread in signature velocities.

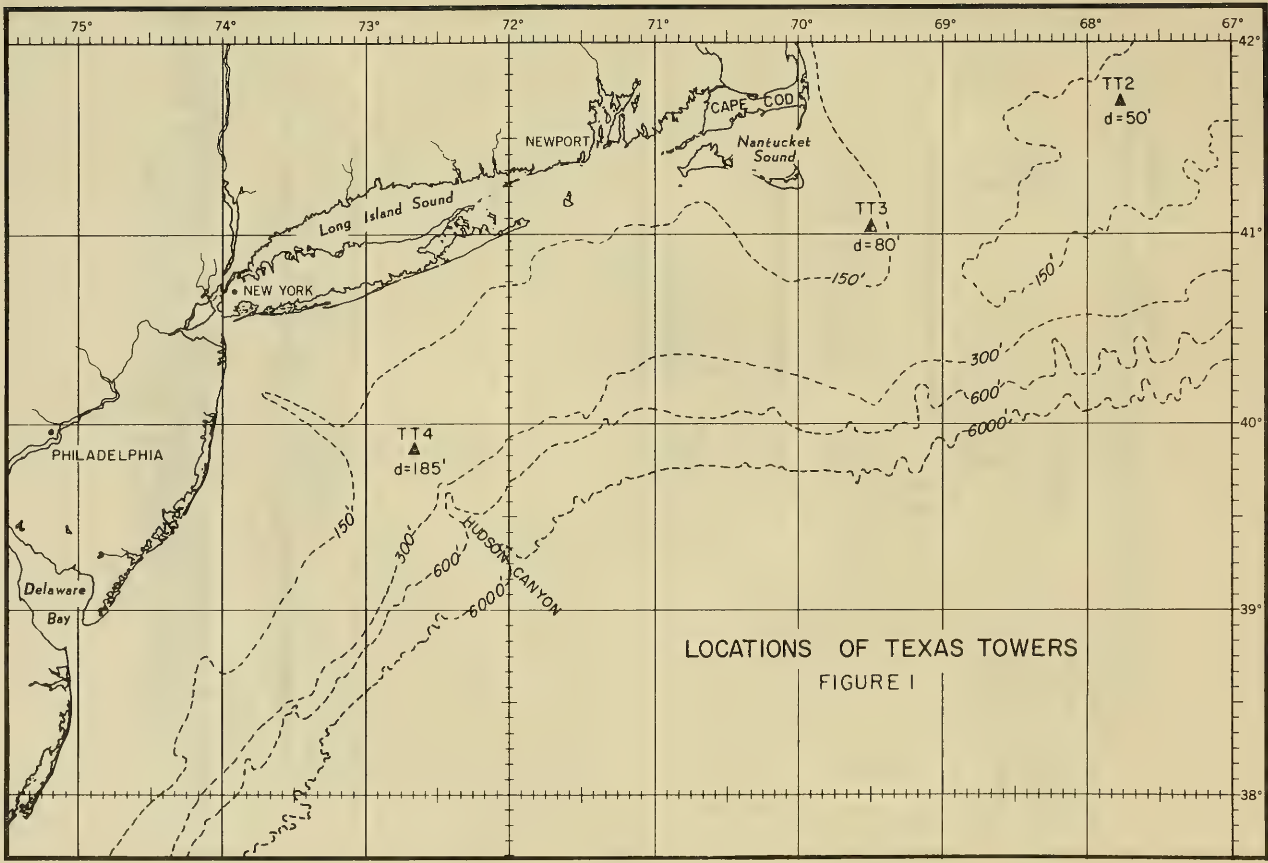
5. The design of future field experiments should include provisions for simultaneous and continuous measurement of temperature, salinity, and current velocity to a frequency resolution better than 10 seconds. A greater number of sensing units should be placed vertically at each measuring station. Additional observations should be made at positions up to several miles away from the main station to determine the horizontal uniformity of the water medium.

6. To establish the probability for predicting internal variations of the type discussed in this report, more detailed long-term descriptive and diagnostic field studies will be required in several different oceanic regions.

VII. ACKNOWLEDGEMENTS

Cooperation between the U. S. Navy Hydrographic Office and the Agricultural and Mechanical College of Texas has made possible the support and information exchange necessary for this work which was begun at the former and concluded at the latter. Among the many members of the oceanographic staff at the Hydrographic Office who have contributed to this study, particular note is due Mr. R. B. Elder for his major part in field operations and data analysis; Mr. H. V. French was a constant source of encouragement; and the field work of Mr. W. A. Garth is gratefully acknowledged.

This work could not have been performed without the cooperation and assistance of the 4604th Support Squadron at Otis Air Force Base, Massachusetts. Credit is especially due to Captain Gordon T. Phelan, USAF, the tower commander who rendered considerable service to this study. Captain Phelan was subsequently killed when the structure collapsed in January 1961.



LOCATIONS OF TEXAS TOWERS

FIGURE I

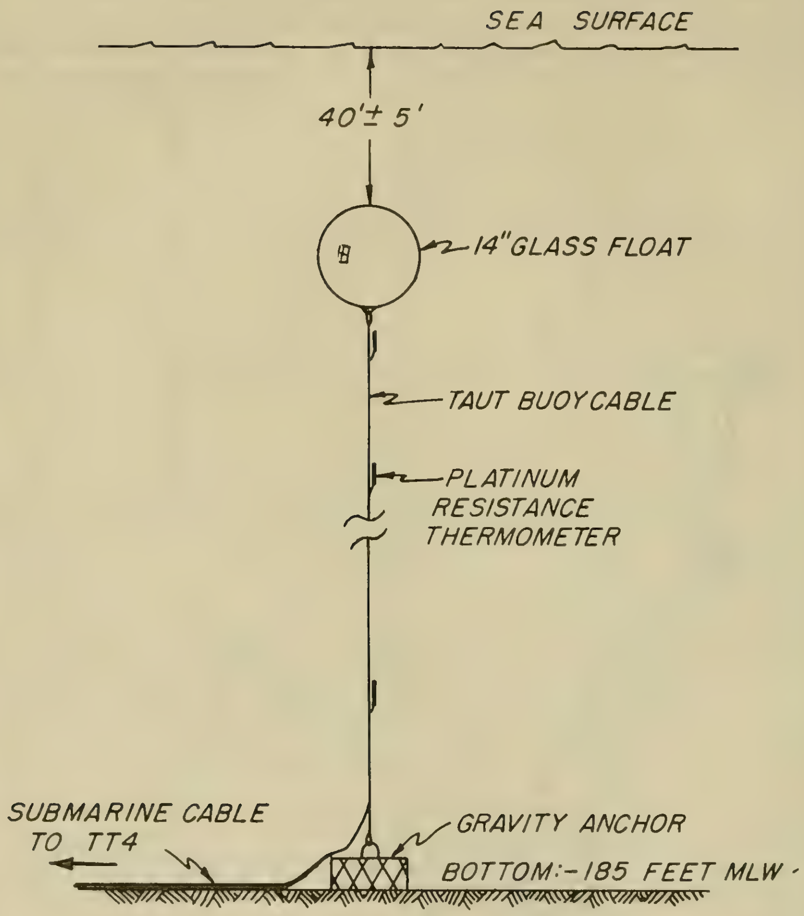


FIGURE 2 SCHEMATIC ELEVATION OF SUBMERGED BUOY STATION

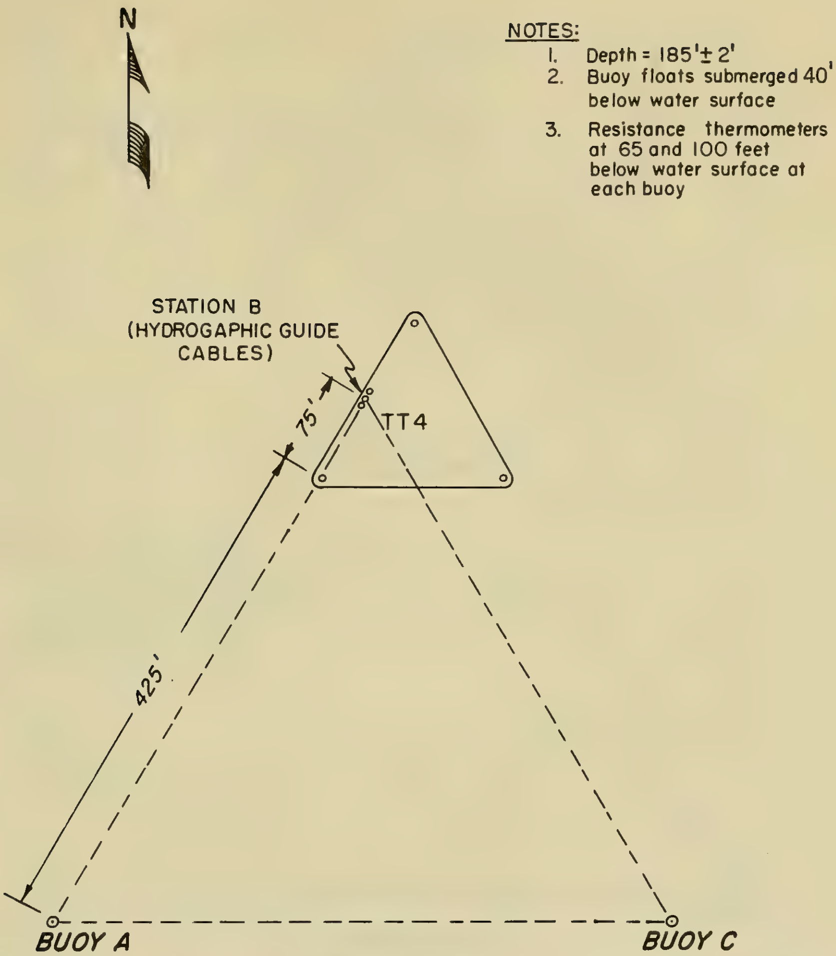


FIGURE 3 LAYOUT OF SUBMERGED TEMPERATURE MEASURING STATIONS, SEPT—OCT 1959

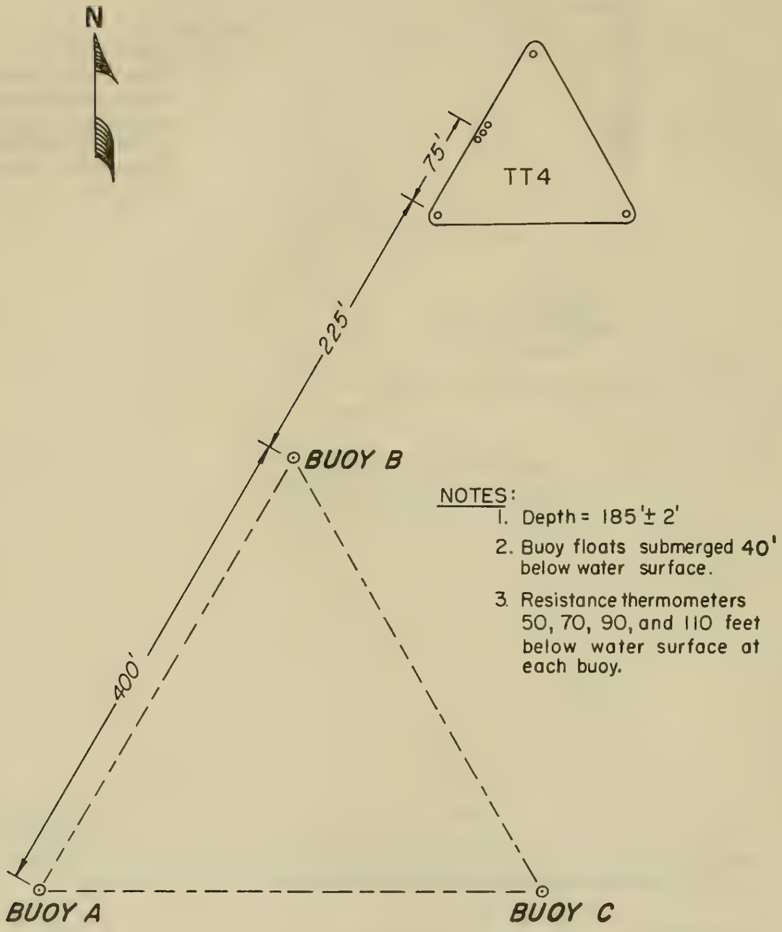


FIGURE 4 LAYOUT OF SUBMERGED TEMPERATURE MEASURING STATIONS, MAY—JUNE 1960

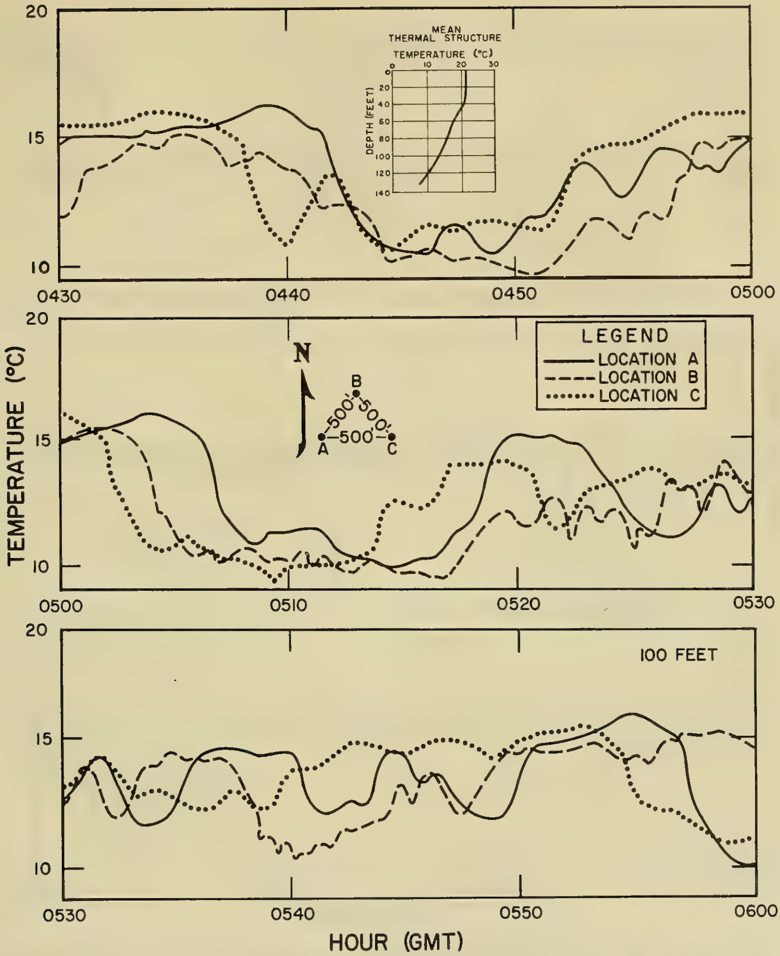


FIGURE 5 SAMPLE OF SINGLE-LEVEL THREE-STATION TEMPERATURE RECORDING— 30 SEPTEMBER 1959

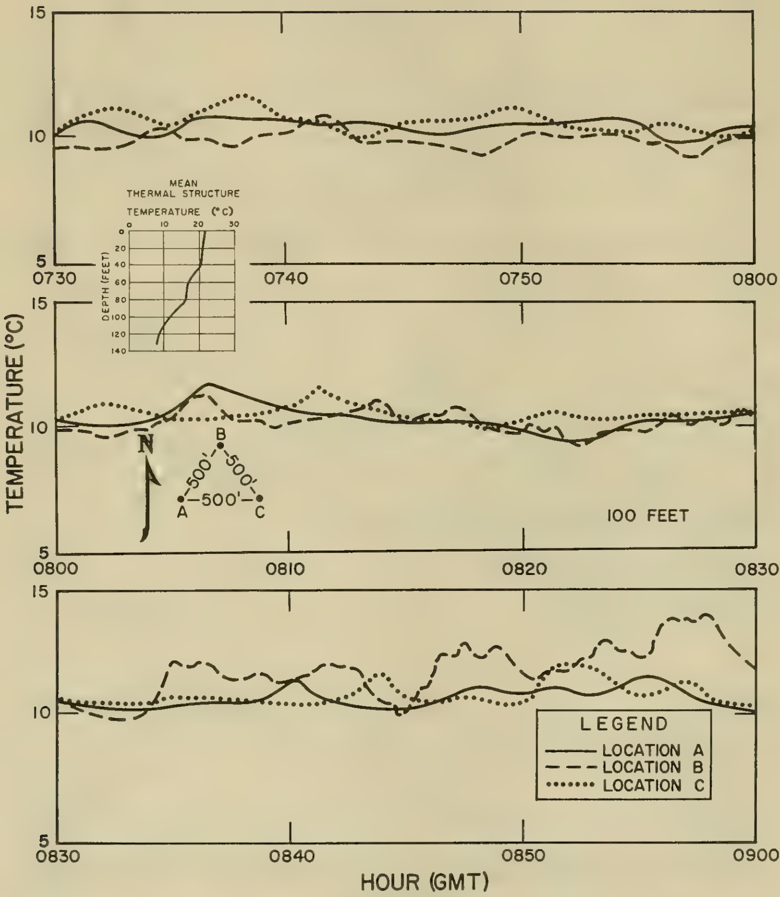


FIGURE 6 SAMPLE OF SINGLE-LEVEL THREE-STATION TEMPERATURE RECORDING— 30 SEPTEMBER 1959

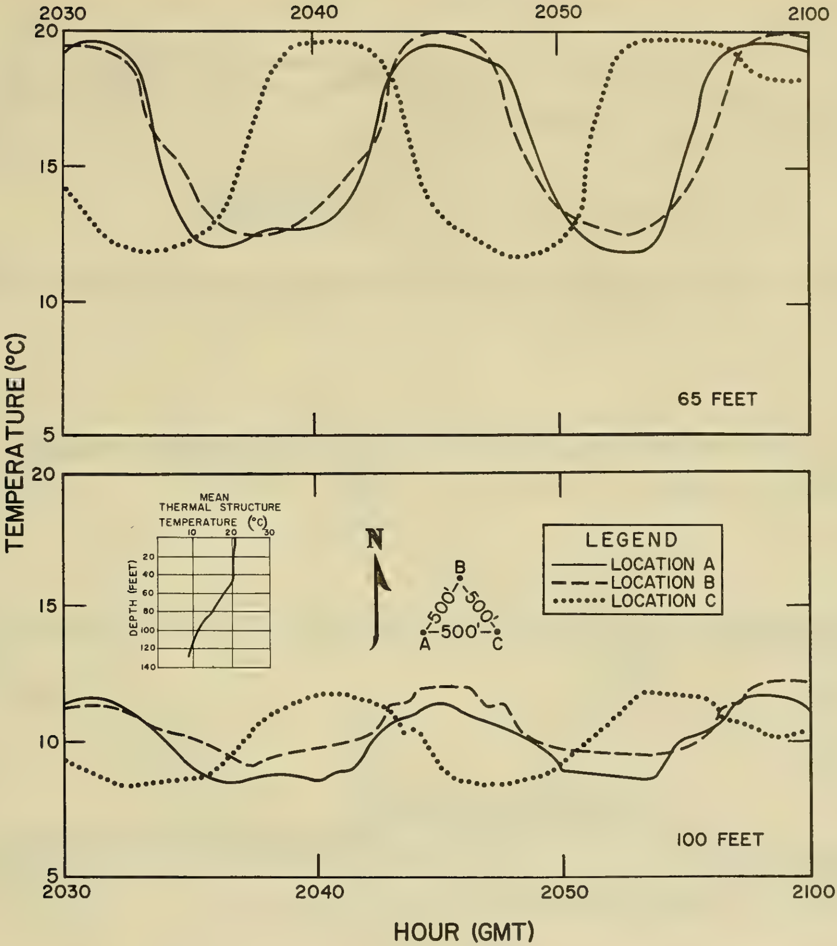


FIGURE 7 SAMPLE OF WELL-DEFINED TEMPERATURE VARIATIONS— 10 OCTOBER 1959

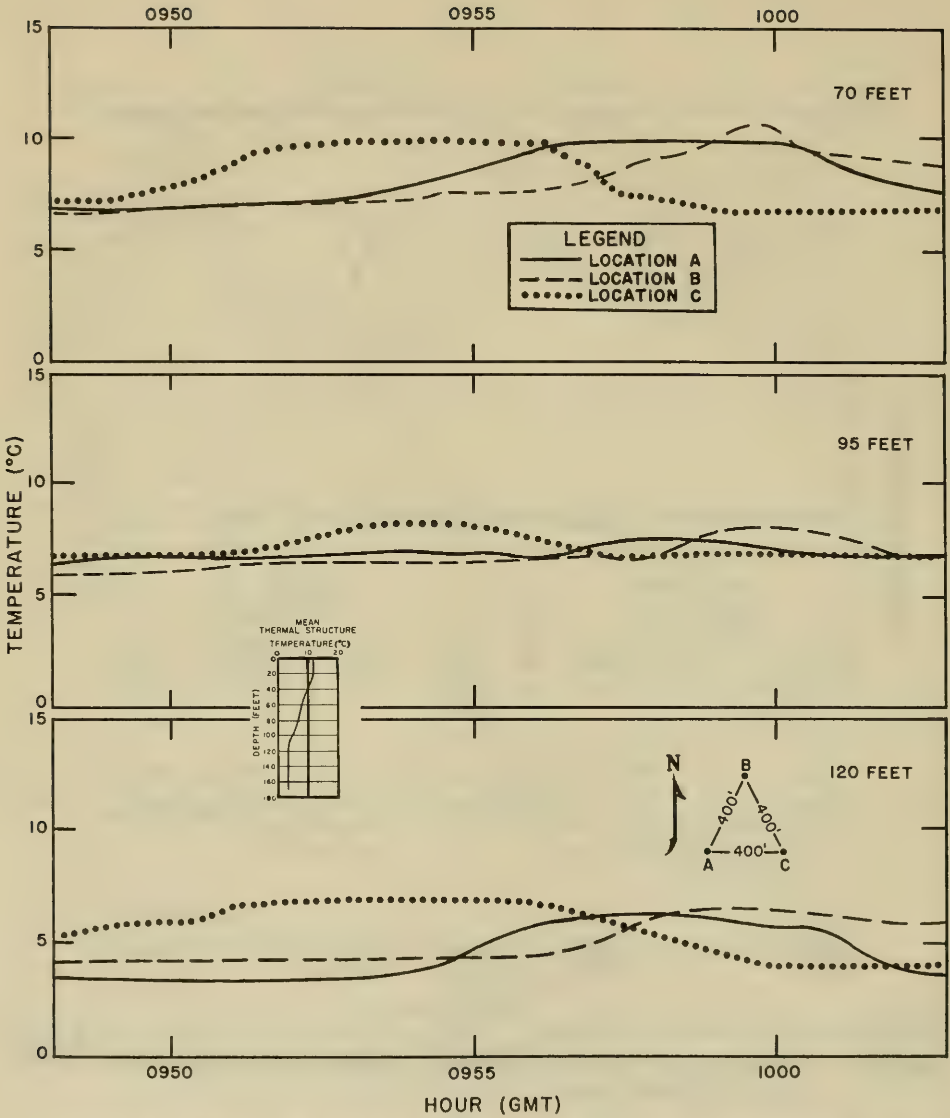


FIGURE 8 SAMPLE OF POORLY DEFINED TEMPERATURE VARIATIONS AT THREE LEVELS — 19 MAY 1960

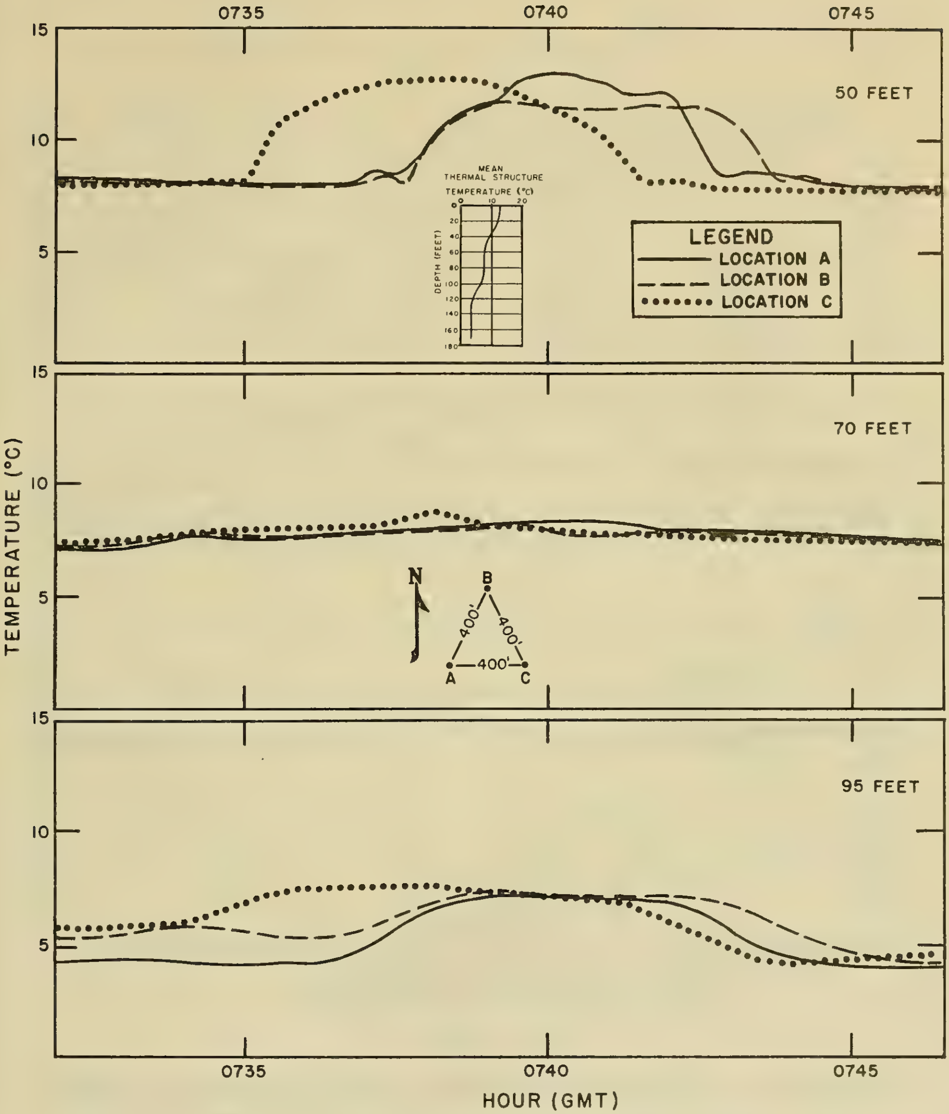


FIGURE 9 SAMPLE OF WELL-DEFINED TEMPERATURE VARIATIONS ABOVE AND BELOW A LEVEL OF LITTLE VARIATION — 20 MAY 1960

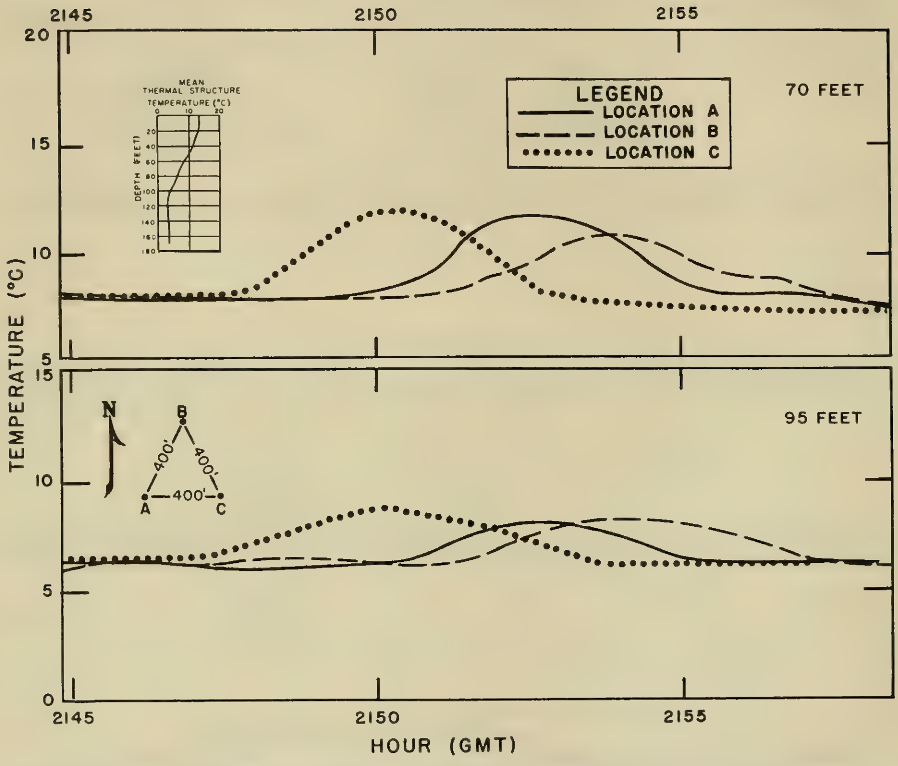


FIGURE 10 SAMPLE OF WELL-DEFINED TEMPERATURE VARIATIONS AT TWO LEVELS— 21 MAY 1960

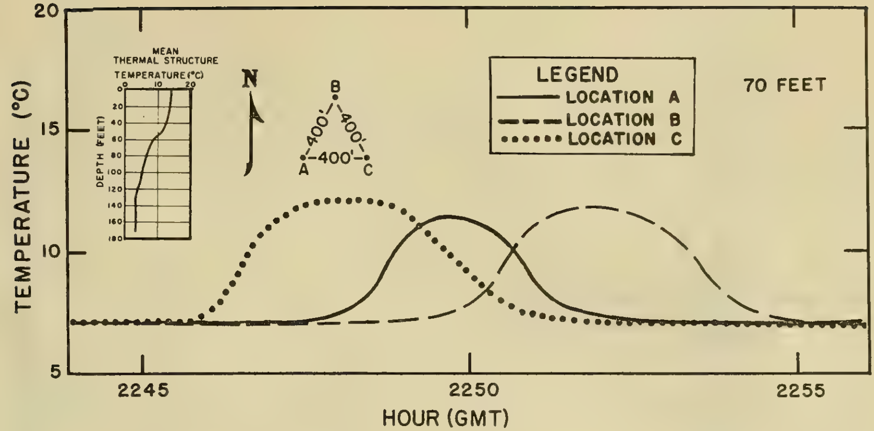


FIGURE 11 SAMPLE OF WELL-DEFINED TEMPERATURE VARIATIONS
30 MAY 1960

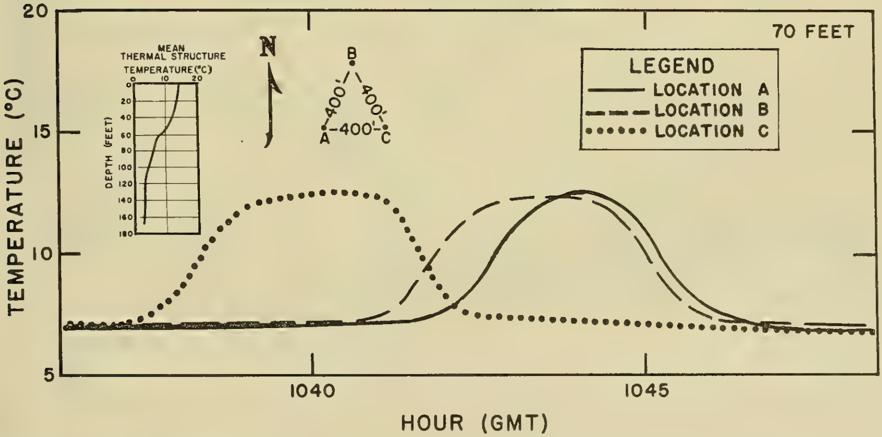


FIGURE 12 SAMPLE OF WELL-DEFINED TEMPERATURE VARIATIONS —
31 MAY 1960

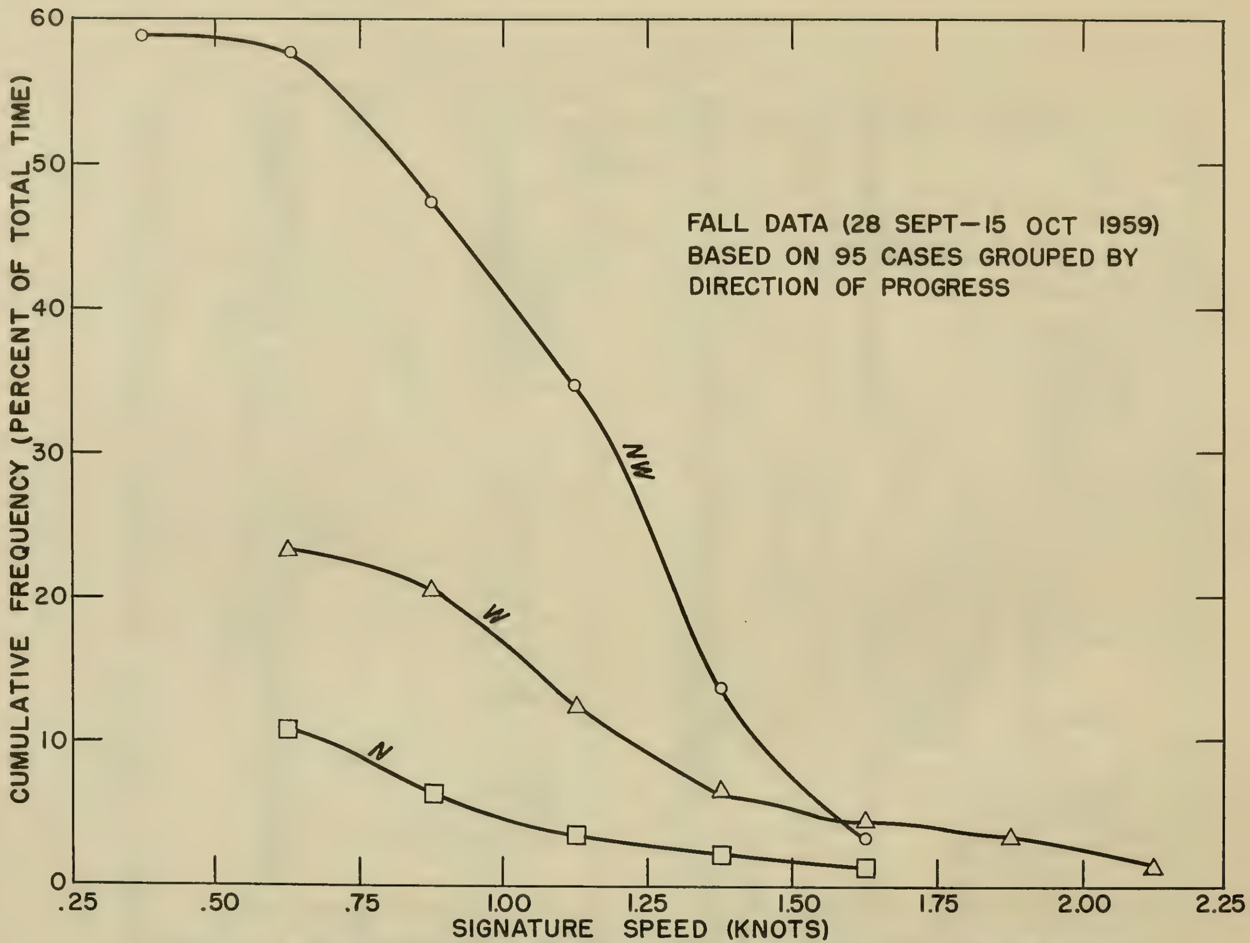


FIGURE 13 CUMULATIVE FREQUENCIES OF INTERNAL TEMPERATURE SIGNATURES

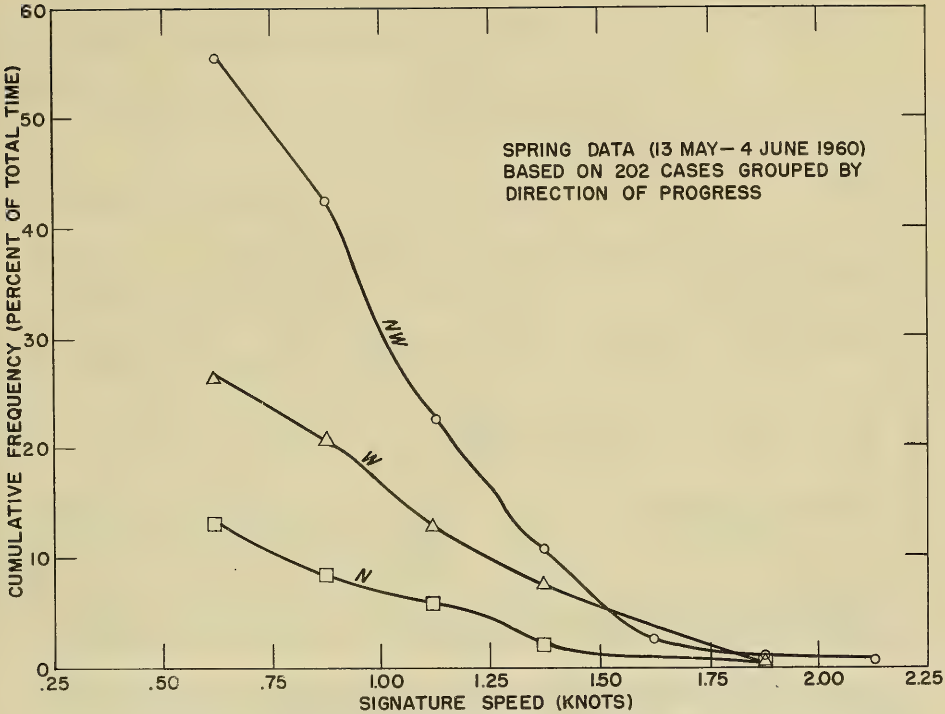


FIGURE 14 CUMULATIVE FREQUENCIES OF INTERNAL TEMPERATURE SIGNATURES

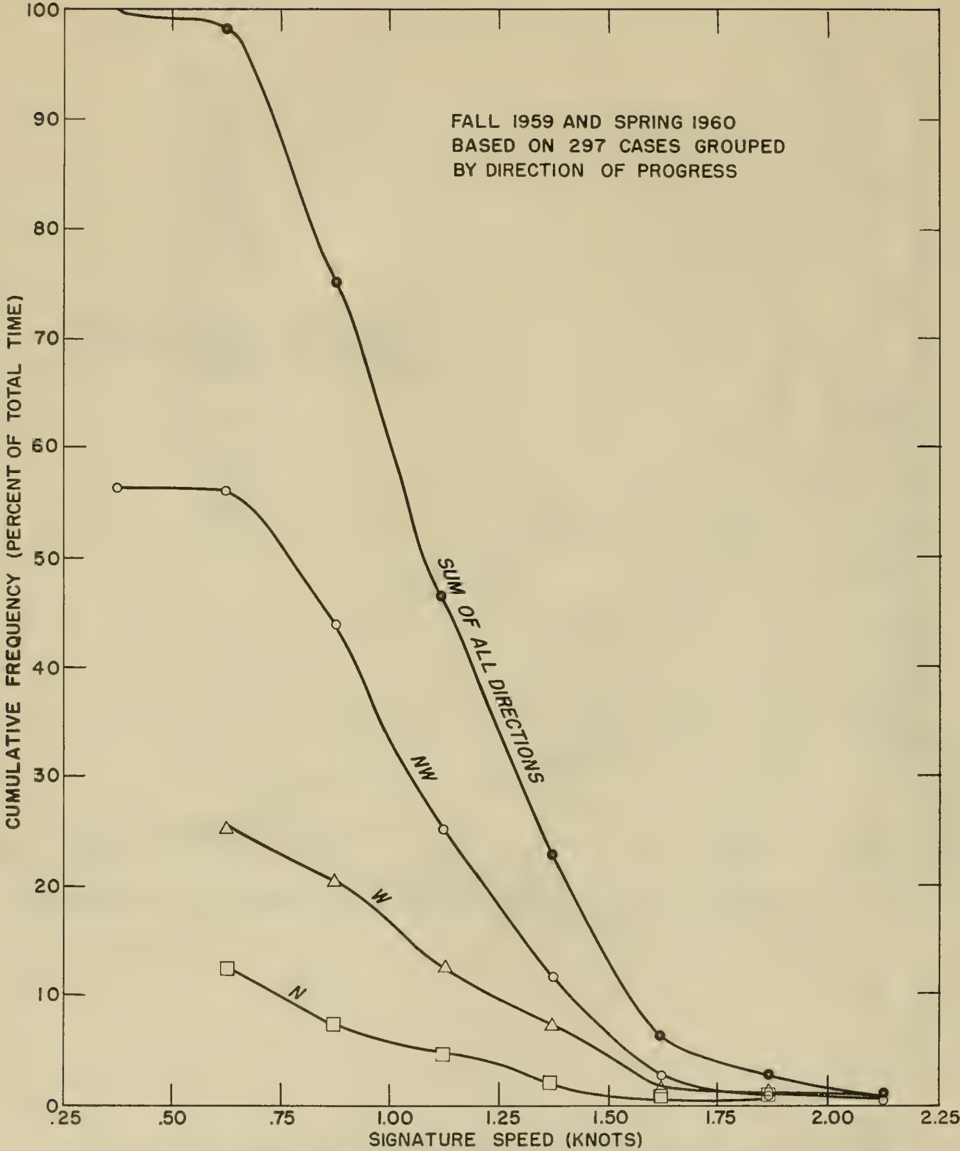


FIGURE 15 CUMULATIVE FREQUENCIES OF INTERNAL TEMPERATURE SIGNATURES

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APPENDIX I

OCEAN CURRENTS MEASURED 100 FEET BELOW THE WATER SURFACE AT TEXAS TOWER NO. 4

April 1960

OCEAN CURRENT OBSERVATIONS AT TT4 DURING APRIL 1960

Modified Roberts Current Meter II 100 feet below the water surface
Tabulated values for speed and set represent averages over approximately five-minute periods.

TIME (GMT) day/hr.	SPEED (knots)	SET (deg. mag.)	TIME (GMT) day/hr.	SPEED (knots)	SET (deg. mag.)	TIME (GMT) day/hr.	SPEED (knots)	SET (deg. mag.)
12/0205	.31	160	13/1505	.34	150	15/0305	.18	075
0305	.45	205	1605	.44	165	0405	.23	100
0405	.31	195	1705	.33	175	0505	.27	140
0505	.39	185	1805	.28	195	0605	.42	155
0605	.17	275	1905	.14	210	0705	.34	175
0705	.50	285	2005	.33	260	0805	.29	205
0805	.49	300	2105	.55	275	0905	.33	260
0905	.55	305	2205	.48	295	1005	.45	305
1005	.37	320	2305	.28	320	1105	.56	315
1105	.38	330	14/0005	.32	335	1205	.39	310
1205	.22	010	0105	.10	---	1305	.28	300
1305	.22	055	0205	.10	---	1405	.11	290
1505	.38	140	0305	.30	150	1505	.10	---
1605	.42	145	0405	.43	165	1605	.20	155
1705	.31	170	0505	.52	165	1705	.28	150
1805	.10	---	0605	.45	175	1805	.38	175
1905	.36	290	0705	.42	210	1905	.47	195
2005	.44	330	0805	.35	230	2005	.40	210
2105	.60	335	0905	.52	260	2105	.36	250
2205	.61	350	1005	.52	265	2205	.57	280
2305	.52	360	1105	.60	285	2305	.55	300
13/0005	.19	030	1205	.46	295	16/0005	.57	300
0105	.40	070	1305	.25	300	0105	.53	310
0205	.56	095	1405	.11	220	0205	.35	310
0305	.64	120	1505	.12	235	0305	.30	315
0405	.58	135	1605	.25	190	0405	.10	---
0505	.43	145	1705	.32	190	0505	.15	075
0605	.33	150	1805	.30	210	0705	.18	145
0705	.14	210	1905	.28	230	0805	.10	---
0805	.30	300	2005	.40	270	0905	.10	---
0905	.33	295	2105	.52	290	1005	.18	250
1005	.29	315	2205	.62	310	1105	.39	290
1105	.26	330	2305	.46	305	1205	.34	315
1205	.15	330	15/0005	.56	335	1305	.29	310
1305	.14	100	0105	.42	335	1405	.18	305
1405	.24	130	0205	.23	010	1505	.10	---

TIME (GMT) day/hr.	SPEED (knots)	SET (deg. mag.)	TIME (GMT) day/hr.	SPEED (knots)	SET (deg. mag.)	TIME (GMT) day/hr.	SPEED (knots)	SET (deg. mag.)
16/1605	.10	---	18/1405	.32	315	20/1100	.16	150
1705	.28	190	1505	.34	330	1200	.15	155
1805	.40	190	1605	.29	005	1300	.10	160
1905	.46	195	1705	.24	010	1400	.10	---
2005	.50	210	1805	.17	075	1500	.11	225
2105	.19	200	1905	.21	060	1600	.12	245
2205	.37	240	2005	.22	070	1700	.18	275
2305	.56	265	2105	.13	110	1800	.10	---
17/0005	.63	285	2205	.17	120	1900	.10	---
0105	.55	295	2305	.10	---	2000	.10	---
0205	.49	330	19/0005	.10	---	2100	.17	245
0305	.31	310	0105	.22	270	2200	.25	225
0405	.27	320	0205	.30	330	2300	.32	195
0505	.10	---	0305	.33	330	21/0000	.32	195
0605	.15	165	0405	.34	345	0100	.32	215
0705	.19	170	0505	.23	190	0200	.19	230
0805	.23	155	0605	.21	050	0300	.44	255
0905	.22	190	0705	.19	100	0400	.51	290
1005	.23	215	0805	.29	090	0500	.38	320
1105	.20	190	0905	.22	115	0600	.42	320
1205	.39	275	1005	.22	110	0700	.42	340
1305	.40	275	1105	.13	115	0800	.31	350
1405	.38	270	1205	.16	120	0900	.17	045
1505	.29	275	1305	.10	---	1000	.24	095
1605	.21	270	1405	.20	335	1100	.31	105
1705	.10	---	1505	.22	330	1200	.27	135
1805	.10	---	1605	.23	340	1300	.21	140
1905	.13	265	1705	.21	345	1400	.19	200
2005	.20	230	1805	.13	110	1500	.15	215
2105	.24	240	1905	.19	125	22/0400	.30	205
2205	.21	245	2005	.20	145	0500	.23	250
2305	.34	275	2105	.21	135	0600	.21	300
18/0005	.38	280	2205	.19	170	0700	.41	275
0105	.40	300	2305	.31	190	0800	.39	315
0205	.39	320	20/0005	.50	280	0900	.41	335
0305	.37	340	0100	.23	210	1000	.39	325
0405	.30	345	0200	.32	245	1100	.25	020
0505	.29	345	0300	.50	315	1200	.18	055
0605	.17	050	0400	.50	285	1300	.30	080
0705	.14	115	0500	.50	305	2100	.29	025
0805	.10	135	0600	.27	290	2200	.24	090
1005	.12	125	0700	.15	325	2300	.27	120
1105	.10	---	0800	.10	---	23/0000	.30	145
1205	.16	315	0900	.15	125	0100	.40	150
1305	.32	305	1000	.17	150	0200	.39	165

APPENDIX II

VELOCITIES OF INTERNAL TEMPERATURE SIGNATURES AT TEXAS TOWER NO. 4

28 September - October 1959

INTERNAL TEMPERATURE SIGNATURE VELOCITIES
28 September - 15 October 1959

Note: Time given is appropriate to all cases selected within the hour. Some values are average for several signatures in the same "train."

TIME (GMT) day/hr.	SPEED (knots)	SET (Degrees true)	TIME (GMT) day/hr.	SPEED (knots)	SET (Degrees true)	TIME (GMT) day/hr.	SPEED (knots)	SET (Degrees true)
28/1600	1.55	290	29/2200	.65	310	4/1800	1.55	320
1600	1.75	280	30/0100	.55	265	2000	.90	300
1700	1.40	310	0100	.60	280	2100	.80	315
1700	1.35	305	0200	.60	305	2100	.70	310
1700	2.05	290	0200	.60	300	5/1700	1.20	315
1900	1.50	225	0200	.80	310	1800	1.45	315
2000	.70	230	0400	1.55	300	2200	.70	265
2100	.75	200	0400	1.15	300	6/0500	.70	350
29/0300	.60	330	0500	..90	260	2200	1.25	020
0400	1.00	300	0500	1.15	270	7/2000	1.50	350
0500	1.05	275	0500	1.30	310	2200	1.00	295
0500	1.15	305	0500	1.10	320	8/0700	1.10	310
0600	1.20	300	0600	1.20	300	8/2100	.95	345
0600	1.00	285	1800	1.60	080	9/0700	1.10	305
0600	.95	280	1900	1.40	300	1100	.75	330
0700	1.20	300	1900	1.70	300	1200	.80	330
0700	.95	290	2100	1.20	305	10/0000	.75	325
0700	1.05	280	2100	1.35	320	0900	1.05	305
0800	.85	315	2100	1.40	320	1100	.75	315
0900	.80	270	1/0800	1.25	090	2000	.95	335
0900	.70	315	2/1100	.75	200	2100	1.15	310
1100	1.00	305	1100	1.35	310	11/1000	1.20	310
1800	1.25	290	1200	1.10	325	1000	1.15	300
1800	1.00	325	1900	.80	305	1300	.60	010
1800	1.00	235	2000	1.20	305	2200	.95	335
1900	1.20	290	3/1400	.90	290	12/1500	1.25	295
1900	1.10	285	1500	.85	275	13/1400	.65	325
2000	1.80	275	1800	.60	345	14/0500	.60	340
2000	.80	015	4/0100	1.25	290	1900	.90	265
2000	.95	360	0500	.65	330	15/1800	.50	335
2000	1.00	010	1200	.60	300	1900	.45	335
2100	.90	295	1700	1.25	335			

APPENDIX III

VELOCITIES OF INTERNAL TEMPERATURE SIGNATURES AT TEXAS TOWER NO. 4

13 May - 4 June 1960

INTERNAL TEMPERATURE SIGNATURE VELOCITIES
13 May - 4 June 1960

Note: Time given is appropriate to all cases selected within the hour. Some values are average for several signatures in the same "train."

TIME (GMT) day/hr.	SPEED (knots)	SET (degrees true)	TIME (GMT) day/hr.	SPEED (knots)	SET (degrees true)	TIME (GMT) day/hr.	SPEED (knots)	SET (degrees true)
13/1900	1.25	285	17/1800	.80	295	21/0900	1.30	280
1900	1.30	275	1800	.70	335	2100	1.15	320
2000	1.25	270	1900	.60	285	2200	.70	355
14/0100	1.30	330	18/0300	1.25	290	22/1500	.90	325
0200	.60	320	0300	1.20	295	24/0600	.55	315
1400	.80	320	0400	1.30	345	1800	1.25	325
1600	.80	315	0400	1.30	310	25/1800	1.40	315
1700	.55	300	0400	1.00	295	1900	1.40	315
1700	.85	280	0500	.90	305	1900	1.00	340
1700	1.25	290	0600	.80	295	2000	1.25	350
15/0200	.85	350	1200	.95	280	2300	1.05	340
0700	.60	350	1200	1.00	260	26/0100	.85	325
0700	.60	315	18/1600	1.45	330	0100	.85	330
1300	1.10	350	1600	1.00	345	0300	.90	295
1300	1.20	310	2000	.75	290	0800	.65	005
1300	.90	300	2100	1.50	305	1500	.60	345
16/0000	1.00	335	19/0400	1.35	325	1600	.70	325
0300	.75	305	0400	1.25	290	2000	1.15	300
0400	.80	305	0900	.65	315	2200	1.05	340
0500	.50	310	1100	.65	350	2300	1.25	310
1000	.70	270	1100	.55	325	2300	1.25	315
1000	.95	315	1200	.70	330	2300	1.95	305
1100	.65	360	1800	1.15	280	27/0200	.75	290
1800	.65	330	1900	1.30	310	0400	.65	320
2200	.95	260	2000	1.05	290	0700	.80	305
2200	1.10	280	2000	.85	280	1000	.60	000
2200	.85	320	20/0200	1.10	280	1200	1.25	290
17/0000	.95	270	0300	.70	265	1200	1.40	315
0500	.90	300	0500	1.05	285	1200	1.25	280
0500	.95	295	0600	.95	300	1900	1.05	290
0600	1.00	320	0700	1.25	290	28/0000	1.25	315
0600	.80	280	1800	1.30	280	0000	.85	315
0600	.85	280	1800	.90	280	0100	.90	305
0700	.65	310	21/0600	1.25	310	0400	.50	305
1000	.70	275	0700	1.45	290	0600	.40	215
1600	.95	310	0700	1.45	305	0700	.25	210
1800	.60	300	0800	1.15	290	0800	.65	260
1800	.50	330	0900	.95	270	1400	.95	305

TIME (GMT) day/hr.	SPEED (knots)	SET (degrees true)	TIME (GMT) day/hr.	SPEED (knots)	SET (degrees true)	TIME (GMT) day/hr.	SPEED (knots)	SET (degrees true)
29/0000	1.30	300	31/0700	.50	025	2/0200	1.05	340
0000	1.10	300	0900	1.05	340	0300	1.05	335
0100	2.10	300	1000	.90	300	0300	1.10	315
0100	1.25	290	1100	.90	305	0300	1.00	300
0600	.95	040	1100	1.00	310	0300	.95	325
1300	.95	345	1200	.75	305	0400	1.35	340
30/0000	1.00	310	1400	1.55	335	0500	1.05	310
0200	1.00	350	1500	.95	340	0500	.90	330
0300	.80	350	1600	.65	345	0600	.85	305
0400	.70	325	1700	.70	345	0700	.50	335
0500	.55	320	1800	.50	305	0800	.50	355
0700	.50	330	2000	.65	305	1000	.90	305
1100	.95	320	2000	.60	280	1100	.90	310
1200	.90	320	2100	.55	285	1200	1.45	275
1400	.90	320	2300	.70	320	1200	1.95	245
1500	1.15	335	1/0000	.95	310	1400	1.00	275
1500	.90	315	0100	1.30	325	1500	.70	260
1700	.65	325	0400	1.00	315	1600	1.20	315
1700	.70	325	0400	.80	325	2100	1.05	270
1800	.55	290	0400	.95	290	2300	.50	215
2200	1.75	285	1100	.50	045	3/0200	.90	325
2200	.90	350	1100	.90	310	0600	.80	325
2200	1.00	335	1100	1.25	260	1100	.55	225
2300	.95	290	1200	1.05	320	1200	.40	030
2300	1.20	300	1200	1.00	310	1300	.80	290
2300	1.20	315	1700	.80	290	1800	.50	275
31/0000	1.00	330	2100	.55	275	4/0000	.70	315
0000	1.95	340	2/0000	1.30	295	0100	.95	280
0200	.90	295	0100	1.55	310			
0700	.50	285	0200	1.05	310			

APPENDIX IV

DAILY SALINITIES AT TEXAS TOWER NO. 4

13 May - 3 June 1960

DAILY TITRATED SALINITIES AT TEXAS TOWER NO. 4
13 May - 3 June 1960

	Depth below MWL (feet)					
	0	45	90	120	150	170
May 13	31.56	31.70	32.10	32.48	32.55	31.62
14	31.35	31.38	32.14	32.52	32.56	32.54
15	31.50	31.63	32.28	32.00	31.54	31.52
16	31.50	31.90	32.47	32.60	32.61	31.85
17	31.64	31.60	32.38	32.54	32.53	32.54
18	31.68	32.32	32.64	32.62	32.58	32.66
19	31.48	31.44	32.52	32.55	32.52	32.56
20	31.22	31.80	32.35	32.62	32.60	32.31
21	30.96	31.87	32.54	32.64	32.63	32.64
22	31.21	31.92	32.56	32.56	32.52	32.56
23	31.34	31.42	32.63	32.64	32.63	32.63
24	30.99	31.98	32.64	32.62	32.62	32.62
25	31.07	31.78	32.62	32.58	32.61	32.60
26	31.08	32.14	32.61	32.62	32.60	32.55
27	31.53	32.25	32.60	32.68	32.69	32.65
28	31.90	31.94	32.58	32.67	32.66	32.67
29	32.00	32.07	32.65	32.68	32.68	32.69
30	31.67	32.40	32.71	32.69	32.68	32.68
31	31.31	32.61	32.76	32.73	32.70	32.71
June 1	31.25	32.68	32.74	32.76	32.72	32.73
2	31.18	32.65	32.70	32.69	32.68	32.65
3	31.03	32.49	32.65	32.77	32.70	32.67
Average	31.4	32.0	32.5	32.6	32.6	32.5

U. S. Navy Hydrographic Office.
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1. Internal waves
2. Internal temperature
3. Oceanography
4. ASWEPS

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3. Oceanography
4. ASWEPS

i. title: The occurrence and velocity distribution of short-term internal temperature variations near Texas Tower No. 4
ii. author: Roy D. Gaul
iii. H. O. TR-107

U. S. Navy Hydrographic Office.
THE OCCURRENCE AND VELOCITY DISTRIBUTION OF SHORT-TERM INTERNAL TEMPERATURE VARIATIONS NEAR TEXAS TOWER NO. 4, by Roy D. Gaul, May 1961. 45 p. including 15 figs. (H. O. TR-107, ASWEPS REPORT No. 4).

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