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Reference No. 54-76

Short Term Fluctuations in the Structure and Transport of the Gulf Stream System

by

William S. von Arx, Dean F. Bumpus
and
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Technical Report
Submitted to Geophysics Branch, Office of Naval Research
Under Contract N6onr-27701 (NR-083-004)
and Nonr-769(00)

November 1954

APPROVED FOR DISTRIBUTION ____________

SHORT TERM FLUCTUATIONS IN THE STRUCTURE AND TRANSPORT OF THE GULF STREAM SYSTEM

By

William S. von Arx, Dean F. Bumpus and William S. Richardson
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

ABSTRACT

Studies of the fluctuations of surface velocity and volume transport of the Gulf Stream System by means of aircraft, serial sections from shipboard, and a laboratory model of the wind-driven ocean circulation indicate that marked changes occur during the course of one week, one half week and less than one day. These results are discussed together with other new evidence obtained through measurements of the motional electromotive force developed by the volumes of water transported through the Straits of Florida with fixed and drifting apparatus. Thus far no clear correlations have been established between the tides in the Gulf of Mexico and the modulations of flow in and beyond the Straits of Florida. Still some influence of this kind may be present together with others which require identification, explanation and further examination.

INTRODUCTION

This paper summarizes the present information concerning the fluctuations of the Gulf Stream during intervals of less than a day together with some indications of weekly or semi-weekly fluctuations. Evidence of fluctuations reported in the literature will be compared with recent results of airplane studies of the geography of the frontal outcrop, serial sections from shipboard of the surface velocity profile and transport near the coast of North Carolina, and laboratory experiments with a rotating model. Further information is available in the recent work of Wertheim (1953) who has measured the transport of the current in the section between Key West and Havana throughout nearly a year by observing the motional electromotive force; observations by Murray (1952) and Wagner and Chew (1953) of the transverse velocity profile and volume transport measured from shipboard by the Loran-G.E.K. method (Malkus and Stern, 1952); and from data obtained during the multiple ship survey of the Gulf Stream (Fuglister and Worthington, 1951). The fluctuations may be due to instability or related to the combination of tides (in the Gulf of Mexico, North Atlantic Ocean and possibly also the Caribbean Sea) which act to modulate the otherwise more or less slowly changing transport of water produced by the atmospheric circulation over the North Atlantic Ocean. An account of the many hypotheses that have come to mind concerning the possible causes of the modulation of the flow in the Gulf Stream will not be given because none has yet seemed capable of relating all the observable indications of rapid change, not to say facts because of the many observational uncertainties. It does seem clear, however, that each day conspicuous fluctuations occur which require explanation and further examination.

THE TIDES

The first bit of evidence which drew the attention of one of us to the short term fluctuations of the flow in the Gulf Stream appeared in the earliest successful run of the rotating model of northern hemisphere oceans built at Woods Hole. In this experiment (von Arx, 1952a) there were distinct pulsations of the flow both through and downstream from the Straits of Florida which could not be accounted for other than as a modulation of the current by resonances in the Gulf of Mexico and perhaps also in the Caribbean Sea. Resonances are thought to be of the closed pipe sort in the Gulf of Mexico and open pipe sort in the Caribbean Sea. The amplitudes of the fluctuations in the rotating model were irregular, but suggested that a beat frequency might be present, and the period was sometimes approximately "diurnal", if one rotation of the model is taken as equivalent to a day.

Pillsbury (1880) detected fluctuations of possibly tidal frequency in the flow in the Straits of Florida and also at current meter stations across the main current along a line southeast of Cape Hatteras. Parr (1937) reported similar fluctuations of salinity and temperature related to changes of surface velocity observed with a taffrail log. The changes in salinity and temperature, however, were small compared with the changes of velocity so that it seemed unlikely that geostrophic equilibrium might be fully maintained.

The tides of the Gulf of Mexico are predominantly diurnal in character. This fact has been examined by Harris (1897, 1900), Endrös (1908), Wegemann (1908) and Sterneck (1921) and explained as a consequence of partial excitation of the seiche period (24.8 hours, Wegemann) of the Gulf by the principal luni-solar constituent of the tides (23.93 hours, Schureman, 1940) in the Atlantic Ocean and Caribbean Sea. According to most of these authors the nodal line of the K_1 tide lies some distance to the East of the Straits of Florida and it is generally agreed that the diurnal tidal oscillation is almost in phase at all stations around the

Gulf Coast (Grace, 1932). Inasmuch as the volume of the prism of the diurnal tide in the Gulf of Mexico is considerably less than equal to the daily volume of flow through the Yucatan Channel and through the Straits of Florida, and the current in both channels always flows in the same direction, one may expect that the volume of water involved in the diurnal rise of tide is provided by the flow through the Yucatan Channel. As a consequence the flow through both the Straits of Florida and Yucatan Channel may vary with the stage of the diurnal tide in the Gulf of Mexico and Caribbean Sea. The effects of the diurnal tide in the Gulf of Mexico on the flow through the Straits of Florida will be considered.

The flow through both the Yucatan Channel and the Straits of Florida is given by Sverdrup, et al (1942) as 26×10^6 m^3/sec and by Parr (1937) as between 30 and 34×10^6 m^3/sec. If the average diurnal rise of tide in the Gulf of Mexico is taken to be .4 meters and its area to be 1.3×10^{12} m^2, the volume that must enter to supply this rise is approximately 0.5×10^{12} m^3. If the average rate of inflow through the Yucatan Channel is 30×10^6 m^3/sec, the rise can be effected in a matter of about 5 hours. Since there are 12 hours during which the diurnal tide may rise, approximately 5/12 of the total flow during 12 hours may be stored in the diurnal tidal prism of the Gulf of Mexico when the tide is rising, 7/12 being discharged through the Florida Straits. On the diurnal ebb the total discharge in the Straits of Florida may increase to 17/12 of the average flow. Due to the numerical uncertainties in this estimate and the bimonthly change in the amplitude of the diurnal tide, it may be expected that the maximum amplitude of modulation could be as great as

40% but that the root mean square modulation of approximately ± 1/3 of the average flow (a factor of 2) would be most frequently observed.

Wertheim's observations (1953) encourage this point of view since he has observed a daily fluctuation of potential, related to volume transport, which increases with the amplitude of the diurnal tide in the Gulf of Mexico and varies by a factor of about 2 when the diurnal components dominate the tidal regime. Wertheim also finds an influence due to the semidiurnal tide entering the Straits of Florida as a progressive wave. With suitably chosen travel times he has succeeded in matching the combination of the tide at Tampico/Galveston less the tide at Miami with the electromagnetic measurements of transport through the Key West-Havana section.

LONGITUDINAL VARIATIONS

In the results of the multiple ship survey of 1950 (Fuglister and Worthington, 1951) it was noted that the core of the Gulf Stream was abnormally warm at intervals of something like 300 km. While it may be purest coincidence, this distance is nearly idential with the length of some continuous segments of the Gulf Stream front traced from the air (Figure 1) (von Arx and Richardson, 1953). If this correspondence is assumed to be due to a physical mechanism relating to the tidal modulation of the flow of the Gulf Stream to the tidal regime of the Gulf of Mexico-Caribbean Sea system, one is led to infer that each pulse is propagated downstream at something like 300 km per day, or at a rate of approximately 3 m/sec. At this rate seven days would have been required for the warm "gobs" observed in 1950 to have reached the positions at which they were observed. Inspection of the tide tables revealed that during the week prior to the dates of observation the tidal signature in the Gulf of Mexico had been predominantly diurnal. Similarly, the signature was predominantly diurnal during and for a few days prior to the flight of 26-27 February 1953. It was also noted from shipboard during the period 7 May to 21 June 1953, that the maximum current speeds did reach 3 m/sec in mid-current and that the range of variation of current speeds was approximately 2, but with a much greater (possibly a factor of 14) fluctuation of the volume transport. But as with many investigations, closer observation of related variables brings to light evidence that is hard to fit into a simple picture such as that provided by the tidal modulation hypothesis. It seems prudent, therefore, to do no more than review the facts of recent observation in some detail.

LONGITUDINAL PATTERN SEEN FROM THE AIR

During 26-27 February 1953, an attempt was made to fly along the length of the Gulf Stream front between Miami, Florida, and 70°W longitude. On this flight, as during the earlier flight made in November 1952 (Stommel, et al, 1953), the Stommel-Parson airborne radiation thermometer was used together with photographic (von Arx, 1953a) and visual observations to determine the position of the frontal outcrop of the sea surface. It was possible to follow phenomena apparently related to the Gulf Stream front throughout most of the distance between Miami and 70°W, but it was found that both the photo-visual and thermometric evidences of the front were discontinuous. Figure 1 shows the manner in which the frontal outcrop was

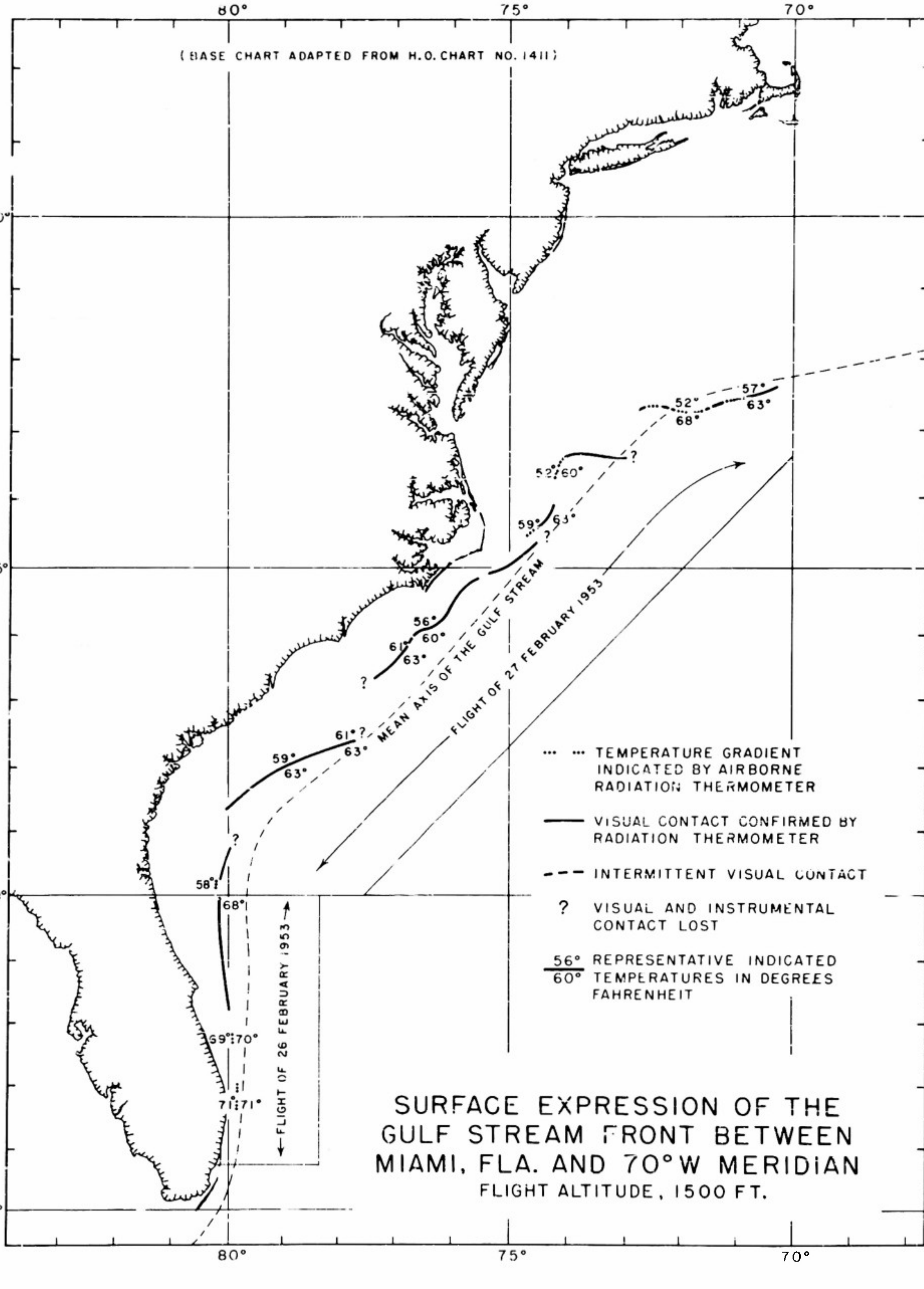
(BASE CHART ADAPTED FROM H.O. CHART NO. 1411)
80°
75°
70°
40°
35°
30°
25°
MEAN AXIS OF THE GULF STREAM
FLIGHT OF 27 FEBRUARY 1953
FLIGHT OF 26 FEBRUARY 1953
TEMPERATURE GRADIENT INDICATED BY AIRBORNE RADIATION THERMOMETER
VISUAL CONTACT CONFIRMED BY RADIATION THERMOMETER
INTERMITTENT VISUAL CONTACT
? VISUAL AND INSTRUMENTAL CONTACT LOST
56° / 60° REPRESENTATIVE INDICATED TEMPERATURES IN DEGREES FAHRENHEIT
SURFACE EXPRESSION OF THE GULF STREAM FRONT BETWEEN MIAMI, FLA. AND 70°W MERIDIAN
FLIGHT ALTITUDE, 1500 FT.

Fig. 1

broken. When approaching a discontinuity, one had the experience that both the temperature gradient at the surface and the change of sea state and sea color coincident with the temperature change grew fainter as observations were pursued downstream until in each case none of these clues were sufficiently pronounced to direct the airplane further. It was learned in November 1952 that the frontal phenomena generally reappeared nearer shore. This was found to be so in every case on the more recent flight. The surface expressions of the Gulf Stream front are therefore considered to be a succession of traceable surface evidences arranged on echelon. In some ways this pattern is like the much larger scale multiple Gulf Stream proposed by Fuglister (1951, 1954) from evidence obtained by Bathythermograph in the upper 200 m layer and also resembles in some ways the results of Wexler's studies (1947) of atmospheric fronts. From the accumulation of Sargassum along the visible segments of the front and the shredded appearance of the terminations it is thought that segments are made visible by horizontal convergence and the diffuse condition of available clues in the gaps is a consequence of either horizontal divergence, or perhaps simply inactivity at the free surface.

Observation from the airplane has also indicated a fine structure which interrupts the continuity of the frontal outcrop at intervals from 1/2 to 10 miles. When horizontal visibility is good it is possible to fly across these individual irregularities without losing track of the larger-scale trend.

At present it is difficult to understand how the surface evidence obtained from the air may be related to the meander structure such as that observed from shipboard. It is quite possible, for example, that the discontinuities observed from the airplane are only superficial phenomena. It is also possible, however, that the relatively wide spacing between successive Bathythermograph observations and between successive crossings by ships have led to a smoother representation of the frontal structure than is actually the case.

The validity of photo-visual and radiant signals from the sea surface as a means for tracing the frontal outcrop of the Gulf Stream is open to some question. It is known, for example, that the steepest temperature gradients at the sea surface are usually found a few miles shoreward of the steepest horizontal gradients 100 to 200 m below the surface in winter and may be as much as 50 miles or more shoreward of the deeper temperature gradients in summer (Strack, 1953). Therefore, the evidence of the radiation thermometer is probably most reliable during the winter months. Visible evidence consists of a number of factors which include a change in the water color, a change in the sea state due to the horizontal shear of the surface currents (von Arx, 1952a), and possibly, accumulations of Sargassum or, in calm weather, characteristic patterns of surface slicks parallel to the front. Slicks alone are unreliable indices of the front but when accompanied with a change in water color it is usually found that a strong temperature gradient is also associated. In rough weather the slicks, even those so strongly developed in slope water, are no longer visible but the sea state may change abruptly across the frontal outcrop (especially when near force 3) together with a change of water color and temperature. Therefore, the flights along the front are guided by an association of visible signs and evidence of an abrupt change of surface temperature. From a study of earlier Bathythermograph sections through slope water it seems possible that these clues may remain useful from Cape Hatteras eastward during June and possibly early July before surface heating destroys the correlation of temperature gradients with the other physical factors.

It would be desirable to repeat many of these observations when it might be expected that the discharge was related to a sequence of predominantly semidiurnal tides in the Gulf of Mexico. It is difficult to anticipate the characteristic patterns accompanying semidirunal tidal sequences. For example, twice as many segments might be observed, or they may blend so as to produce a relatively continuous surface outcrop. Since, at the same time, it is expected that the average current velocity will prevail, being slightly more than 2 m/sec (midway between the diurnal maximum 3 m/sec and the diurnal minimum 1.5 m/sec), the length of each semidiurnal segment may be in the order of 100 km. On one flight made between Cape Romain and Cape Lookout on 4 June 1953, a segment of this length was traced out but it was not possible to verify the presence of a temperature gradient due to trouble with the radiation thermometer. On the following few days poor visibility blocked further attempts.

However, it was on these days that the front detected visually from the airplane could be confirmed by observations from a research vessel on the sea surface directly below. Two checks were made on 5 and 6 June 1953. On 5 June the position of the sharp frontal outcrop was within 5 miles of the position indicated by the Baththermograph in the upper 20 meters

(Section W). The qualitative agreement was also good to the extent that a sharp outcrop located from the air was represented by closely packed isotherms on the temperature section. On the occasion when the airplane could find no clear evidence of a front as on 6 June, none was clearly defined in the corresponding temperature section (Section Y).

If this vague frontal structure was related to a gap between two frontal segments it seems clear that such gaps are not the site of countercurrents or conspicuous eddies. Measurements by G.E.K. and Loran indicate a general braodening and slowing of the surface current and the associated volume transport is about average (Sections A and Y).

SERIAL SECTIONS FROM SHIPBOARD

For six weeks during May and June 1953, an attempt was made to detect the fluctuations of the Gulf Stream flow near Onslow Bay, North Carolina. This site was chosen because the Gulf Stream there flows in relatively shallow water over the northeast portion of the Blake Plateau and at the same time is close to the coast where it is to be expected that the meander pattern is not free to develop. It is also a place where the coastal water mass abuts the Gulf Stream directly, and is indeed fed by Gulf Stream water from time to time (Bumpus, 1954).

Originally it was planned to anchor on the Blake Plateau about 20 km southeast of the mean axis of the Gulf Stream; in a relation to the mean axis similar to the site where Pillsbury had found the greatest fluctuations of velocity off Cape Hatteras. On arrival, however, this seemed an undesirable procedure because one could not then distinguish between actual variations in velocity and apparent variations caused by lateral migrations of the current due to instability or with the ebb and flow of North Atlantic semidiurnal tides. It was decided, instead, to cross and recorss the current as frequently as possible in the area shown in Figure 2 making sections with Loran, G.E.K. and Bathythermograph. Twenty-six such sections labeled A through Z were completed in four Groups, A-I, J-O, P-U and V-Z. The interruptions were caused by unfavorable weather, insufficient fuel reserve, and other difficulties peculiar to small ships.

The results of these serial section samplings are given in Figures A through Z which are plotted with the current running into the paper. Observations were made at hourly intervals during each traverse, and the courses steered were calculated to hold the ship on a geographic line (von Arx, 1951) bearing 130°T from the sea buoy located in the center of Onslow Bay. At times it was necessary to turn the bow of the ship as much as 40° upstream from the intended line of section to counteract the set of the current. Generally the departures from the intended line of section were greatest in mid-current but did not often exceed 5 nautical miles in either direction. The nominal point of intersection of the ship's track with the mean axis of the Gulf Stream given on H.O. chart 1000-L is indicated by the symbol (A) on each of the figures mentioned above. Distances in nautical miles from this point are also indicated as is the direction of traverse. The volume transport for each traverse was computed by the Malkus-Stern method (1952) from the transverse surface velocity profiles measured by G.E.K. and the Loran-D.R. method, together with the

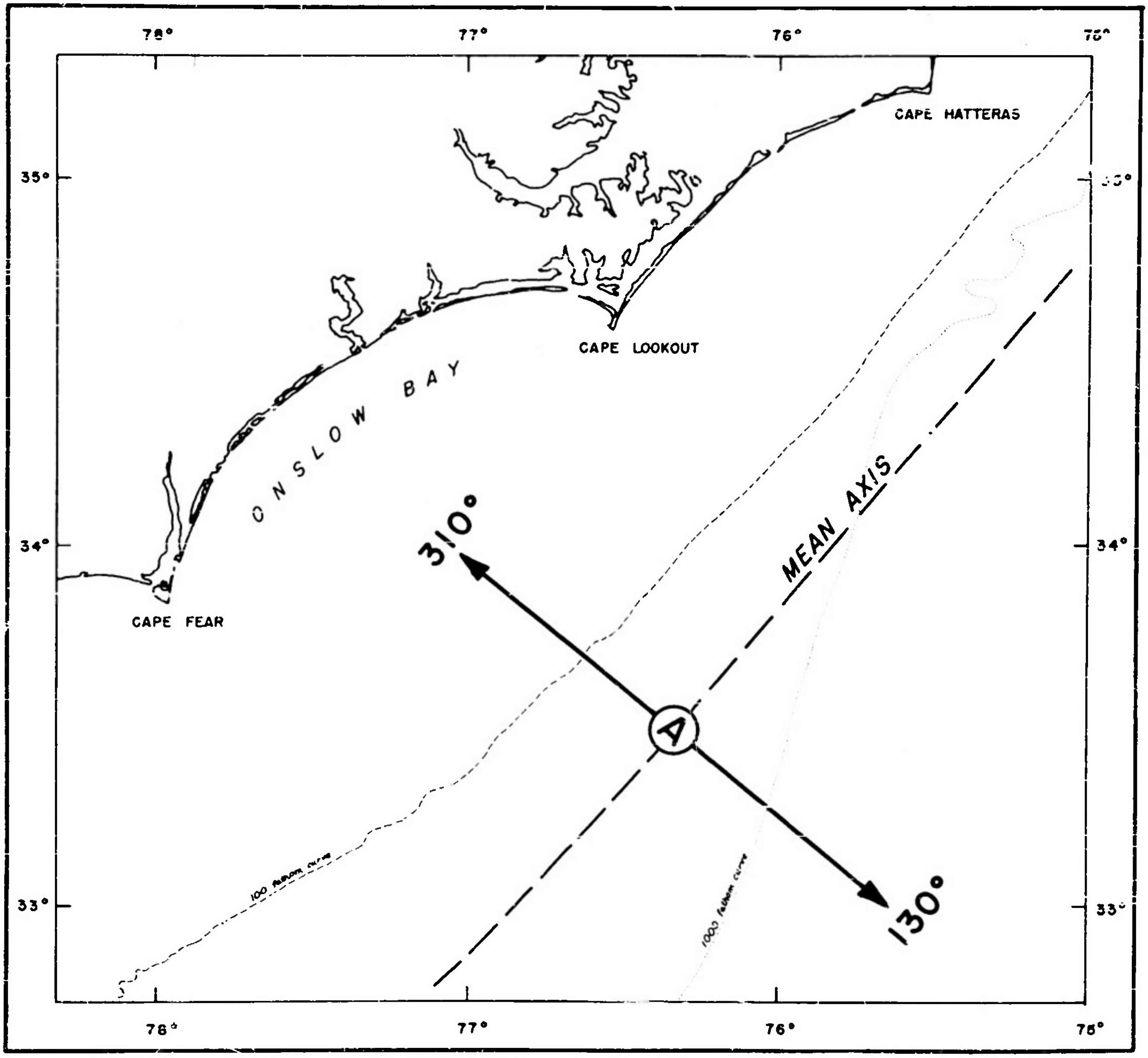
78°
77°
76°
75°
35°
34°
33°
CAPE HATTERAS
CAPE LOOKOUT
ONSLOW BAY
CAPE FEAR
MEAN AXIS
310°
130°
A
100 fathom curve
1000 fathom curve

Fig. 2

corresponding temperature section obtained by Bathythermograph. Current directions are shown relative to the line of sections. Currents perpendicular to this line are parallel with the mean axis of the Gulf Stream.

The most striking feature of this collection of observations is that each section differs from its neighbors to such an extent that one would be at a loss to arrange them in chronological sequence by qualitative inspection alone. Some of the changes are too rapid for even as many as three sections per day to indicate progressive changes in the structure of the flow beyond observational uncertainties. Inspection of individual observations indicates that upon reversal of course at the end of one section and beginning of the next, observations of current and temperature will repeat recognizably only for the first two or three hours. (In view of this it seems necessary to section the current (a distance of approximately 100 km) as many as six times each day to trace the continuity of change. The semimonthly sequence of tides in the Gulf of Mexico makes it desirable to continue sectioning at this rate for a period of more than 14 days to test the tidal modulation hypothesis. It would also be desirable to have aerial reconnaissance of the front 600 km upstream and downstream from the site of serial sections. The difficulties already experienced in trying to carry out this plan suggest that, in the future, it would be well to be prepared to make several fresh starts.)

The evidence already obtained clearly indicates a rapid fluctuation of the maximum velocity, temperature structure and volume transport. In addition there is a slower lateral migration of the front as evidenced by the 200 meter isotherms when plotted in time sequence, Figure 3, and a clearly systematic alternation of the position of both surface isohalines and isothermes at 0, 100 and 200 m with the surface current direction presumably related to the meander pattern (Figures 3a, b, c, d) not yet free to develop in amplitude. In that the direction of flow in these incipient meanders occasionally makes large angles with the mean axis (Sections G, H, I-Y, Z) one is led to expect that the flow rolls over on a horizontal axis alternatly as a right then a left-hand screw insofar as vertical stability permits, and that this motion contributed directly to the appearance of Gulf Stream water on the continental shelf southwest of Cape Hatteras (Bumpus op. cit.). For example, in sections A, B and C, the flow is slightly to the right of the mean axis of the Gulf Stream, but in sections D through I the direction of surface flow is away from the coast making an angle approximately 25° with the mean axis. While sections J through O were being made, the flow changed from slightly inshore during the course of making section J, to slightly offshore during sections K, L and M, to more offshore during section N. All of this occurred during a period of 40 hours. Taken together with the next group of sections, P through U, this transition is logically consistent as the recovery from the surface motions being directed strongly inshore. A similar reversal from onshore flow to offshore flow was observed during sections V through Z which were made over a period of 50 hours. From this evidence it is expected that one complete oscillation of the direction of current flow with respect to the mean axis requires approximately one week or possibly one half week.

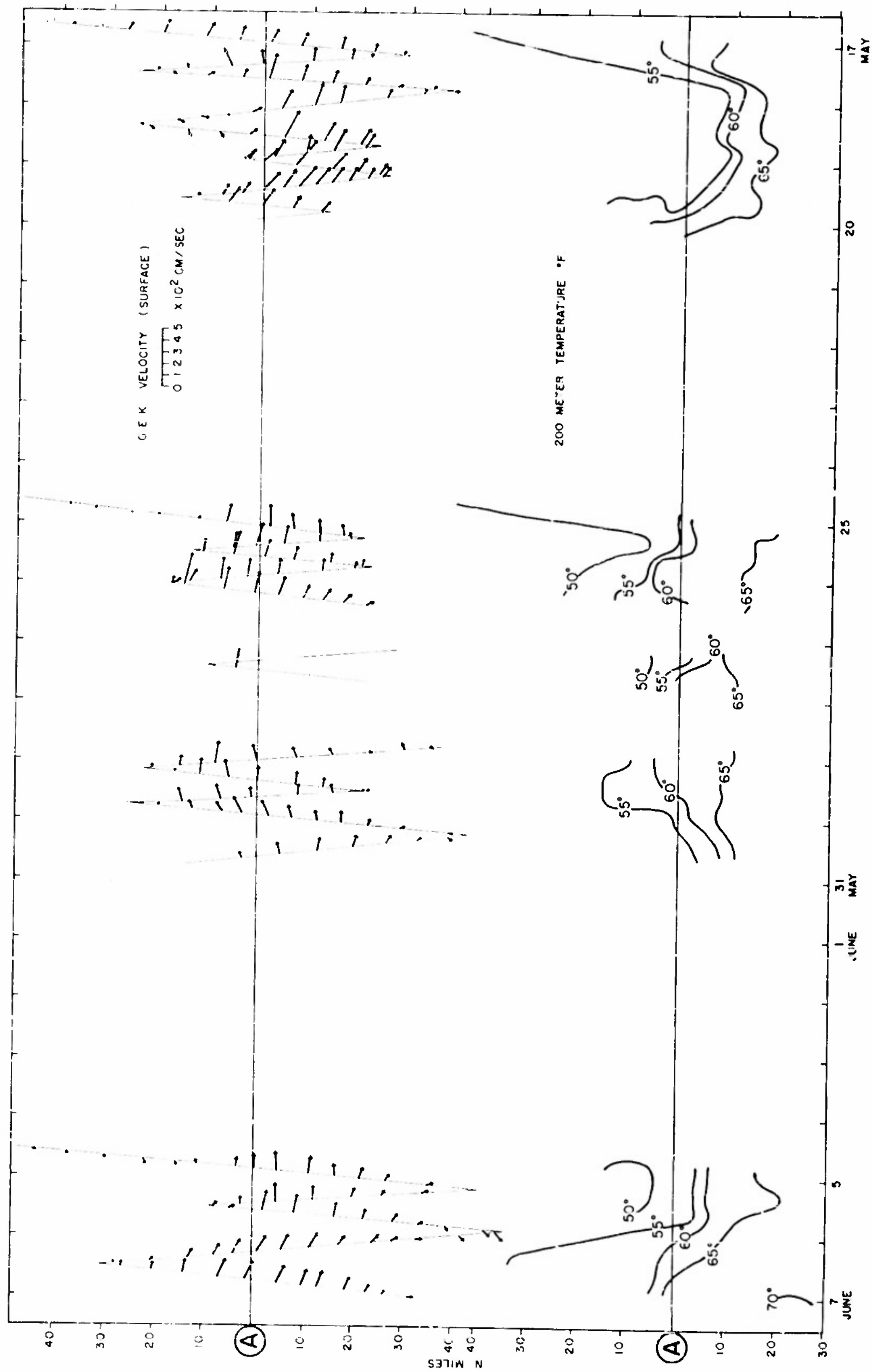
GEK VELOCITY (SURFACE)
0 1 2 3 4 5 X 10² CM/SEC
200 METER TEMPERATURE °F
N MILES
17 MAY
20
25
31 MAY
1 JUNE
5
7 JUNE
55°
60°
65°
50°
70°

Fig. 3

SALINITY IN ‰ AT SURFACE. CARYN 64

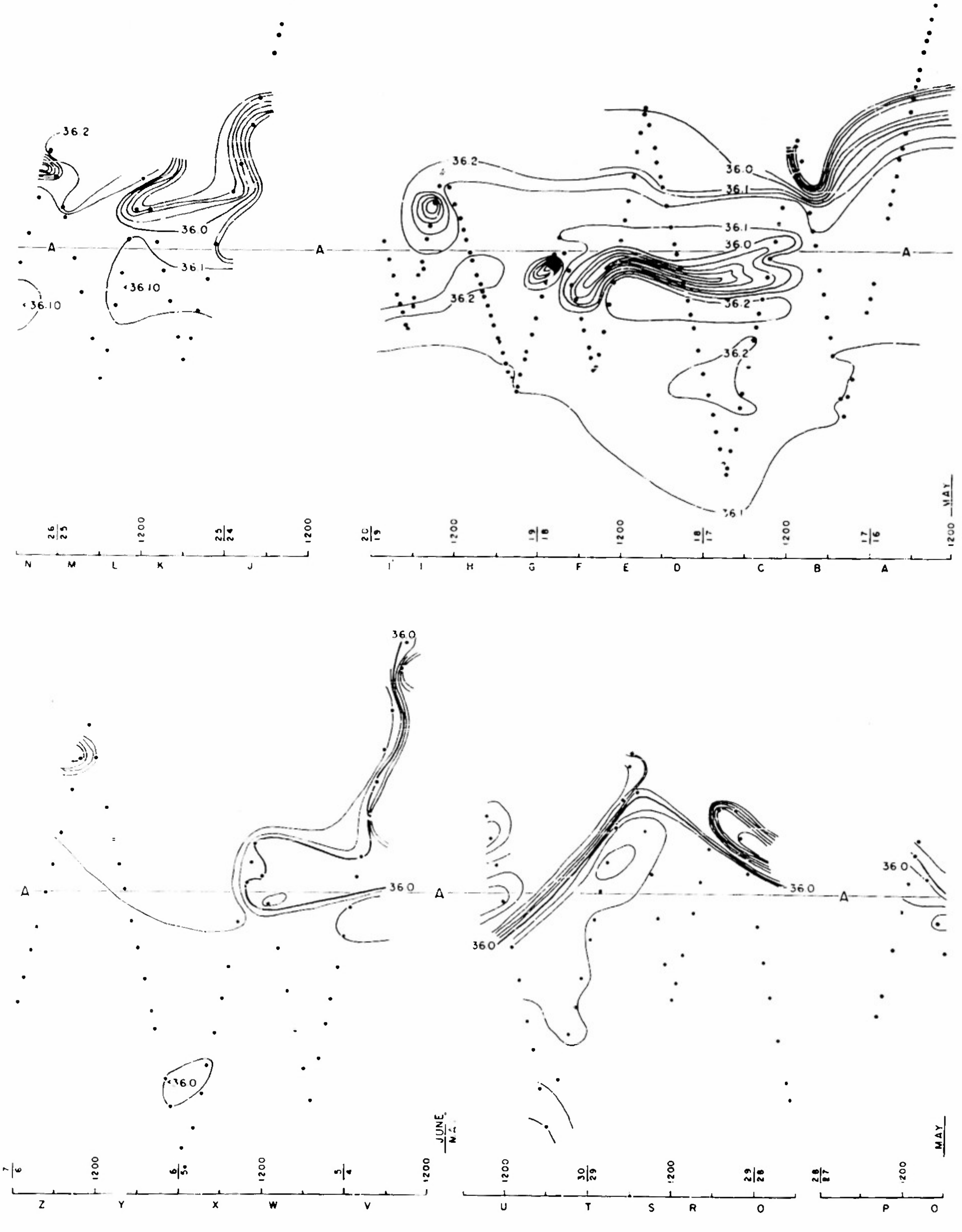

Fig. 3a

TEMPERATURE °F AT SURFACE. CARYN 64

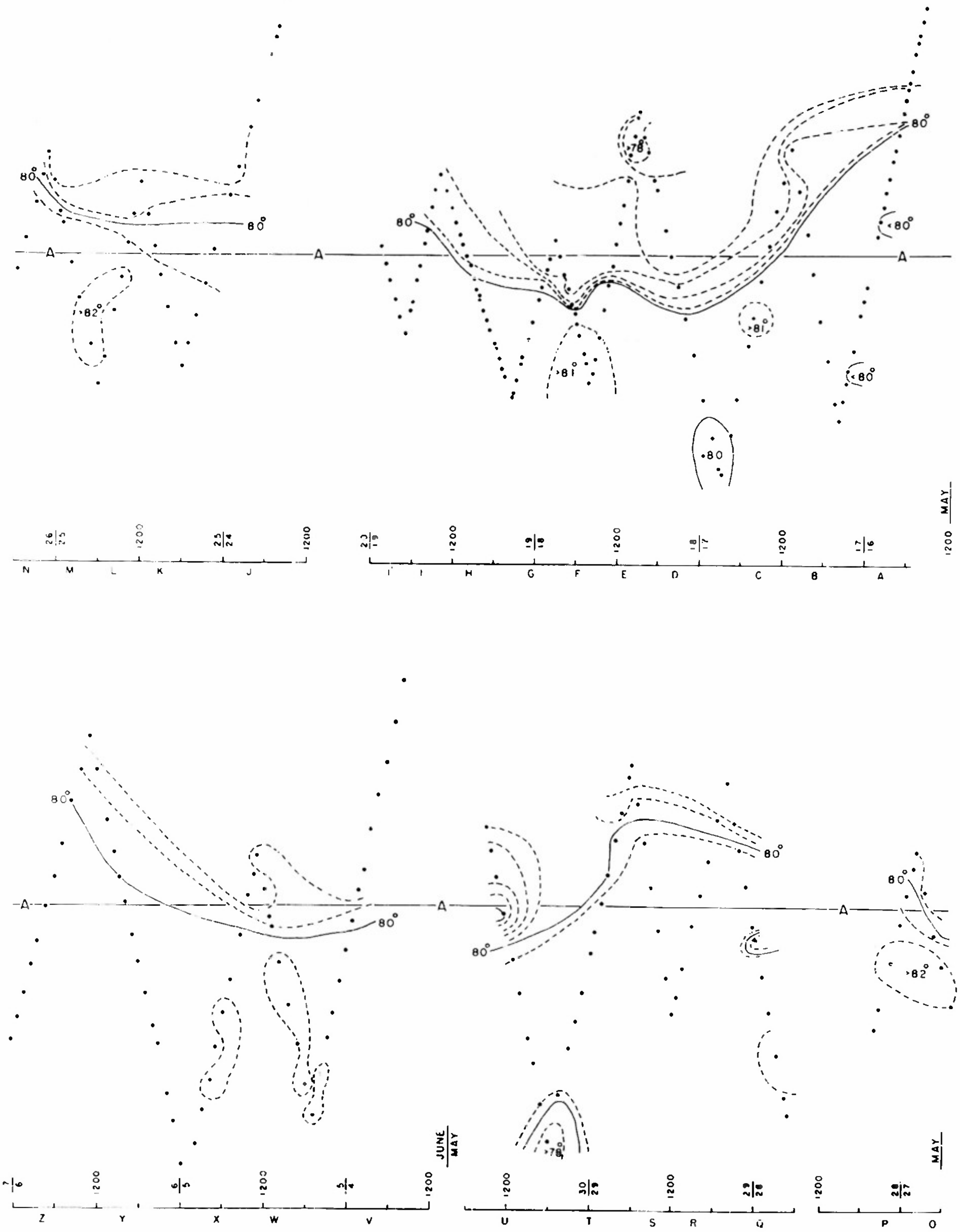

Fig. 3b

TEMPERATURE °F AT 100 M. CARYN 64

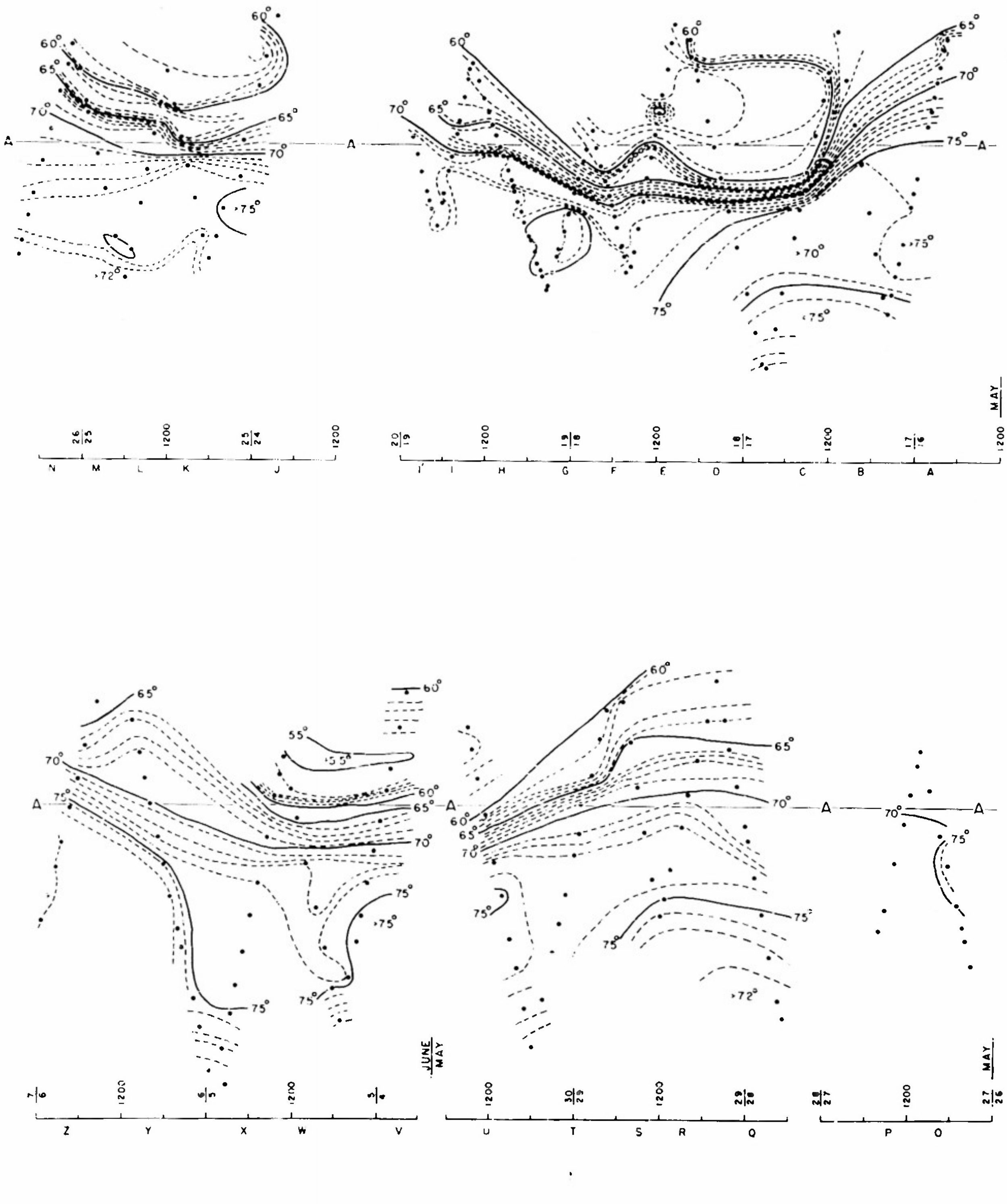

Fig. 3c

TEMPERATURE °F AT 200 M. CARYN 64

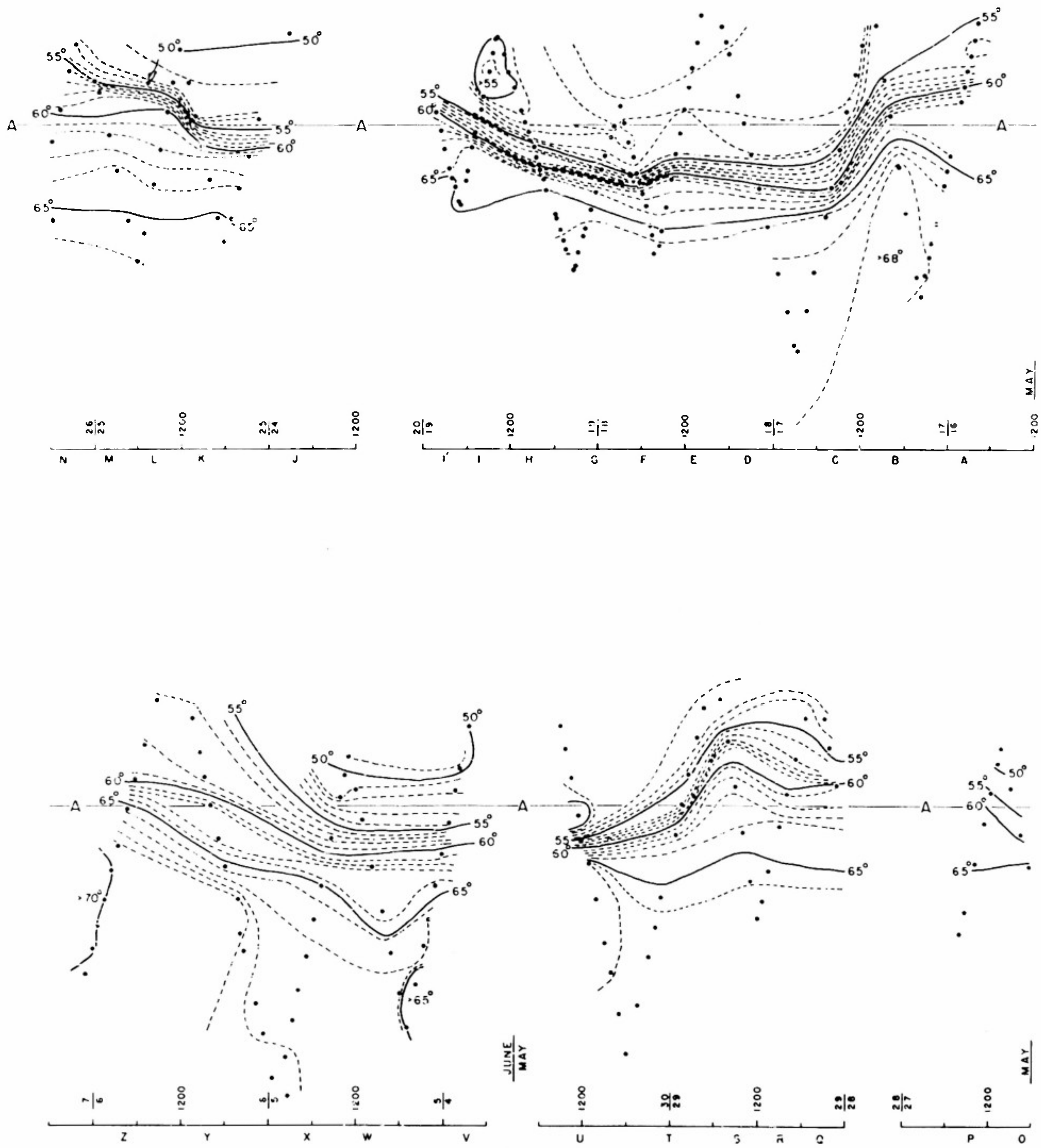

Fig. 3d

Such a figure is in fair agreement with indications of meander motions obtained during the multiple ship survey of 1950.

There is also evidence that the direction of surface flow is associated with the lateral shift of the position of maximum velocity and maximum surface temperature. The shift of the position of maximum velocity with respect to the mean axis of flow may have an amplitude as great as 28 miles. Due, however, to the fact that the surface velocity profile often becomes bimodal one cannot be sure that the peak velocity observed in successive profiles is the consequence of the motion of a single streak of high speed water or is seemingly offset due to the arrival of neighboring streaks. Similar problems have arisen in establishing the continuity of atmospheric jet streams (Cressman, 1950).

The change from mono to bimodal profiles of surface velocity in the Gulf Stream seems to progress without a clear relationship existing between the adjacent high speed zones except for the fact that the zone on the right of the current seems generally less swift than that on the left. Due to the increased depth of water under the right-hand mode it seems possible that the two may represent approximately equal transports; in other words, that the left-hand mode is more conspicuous on the surface due to the requirements of continuity.

VOLUME TRANSPORT

A comparison of the fluctuations in volume transport measured at the Onslow Bay section with the tidal signature at Galveston, Texas, was unavailing. Galveston was chosen as a reference station because the tidal signature there (or at Tampico) is predominantly diurnal in character, and it is the rise and fall of the diurnal tide that requires a net change in the volume of water in the Gulf of Mexico. After many trial displacements of the tidal trace drawn from data in the Tide Tables for the East Coast of North and South America (U. S. Coast & Geodetic Survey, 1953) with the volume transport measurements no clear agreement of fluctuations was seen except that with a lag of 4 1/2 days the amplitudes of fluctuations in volume transport at Onslow Bay are largest when the tidal amplitudes are large, and smallest when the tidal amplitudes are small and predominantly semidiurnal. The scatter of individual transport measurements (Table II) is not easily fitted to the tidal curve.

Clearly it would be desirable to review this possible relationship more closely; preferably through comparison of actual tidal records with observations of transport through the Florida Straits and with more frequent transport measurements off Onslow Bay. One difficulty is likely to remain, however, concerning the accuracy of volume transport measurements from shipboard by the Loran-G.E.K. method. The reliability of these measurements is low because they depend on the evaluation of small differences between large quantities, and upon a subjective estimate of the proper limits of integration (Malkus and Stern, 1952). For practical purposes during the work at sea an effort was made to terminate each section when the velocity of the surface layer was either negligibly small or had turned parallel to the line of the section. The term "negligibly small" must be qualified because it was found in these waters that velocities in the order of 50 cm/sec might exist near the continental edge of the Gulf Stream due to the influence of tides. If, through experience and the character of the water mass, it was decided that the ship had entered water moving under the influence of the tide rather than of the Gulf Stream itself, the section was terminated. In the final plot of the data the curves were arbitrarily extrapolated to zero velocity by continuing the downward slope from the maximum current near mid-stream in a manner that seemed consistent with observations made on other occasions in the Gulf Stream east of Cape Hatteras where tides presumably have only a very small influence on the transverse velocity profile. It is recognized that this introduces an element of uncertainty, which in terms of volume transport, may amount to as much as $\pm$ 30 x 10^6 cm^3/sec. Fluctuation of the volume transport at the Onslow Bay section ranged between 6.8 x 10^6 m^3/sec and 101 x 10^6 m^3/sec and averaged 50.8 x 10^6 m^3/sec. (While three figures are given above, even the first figure should be regarded as uncertain.) In the figures showing the results of sections A through Z the volume transport is indicated within the limiting values given in Table I. Table II presents the observed values, subject to the uncertainty mentioned earlier, together with the position of the Gulf Stream front at a depth of 100 meters relative to point A on Figure 2.

Table I

$T >> \bar{T}$	>70
$T > \bar{T}$	55-70
$T = \bar{T}$	45-55
$T < \bar{T}$	30-45
$T << \bar{T}$	<30

Table II

								100 m. front R or L of A
A	1630	16 May	-	0400	17 May 1953	49.3 x 10^6 m^3/sec		8 mi. L
B	0400	17	-	1100	17	25.0		0 -
C	1100	17		2100	17	96.5		6 mi. R
D	2100	17		0900	18	42.7		7 mi. R
E	0900	18		1600	18	101.7		6 mi. R
F	1600	18		2100	18	38.3		9 mi. R
G	2100	18		0330	19	64.9		7 mi. R
H	0330	19		1400	19	70.6		5 mi. R
I	1400	19		1900	19	16.4		1 mi. L
I'	1900	19		0330	20	-		? mi. L
J	1530	24		0600	25	26.7		3 mi. L
K	0600	25		1200	25	24.6		2 mi. L
L	1200	25		1800	25	-		5 mi. L
M	1800	25		0100	26	12.8		7 mi. L
N	0100	26		1000	26	49.8		12 mi. L
O	0300	27		1000	27	-		0 -
P	1000	27		1700	27	-		3 mi. L
Q	1700	28		0400	29	19.9		0 -
R	0400	29		1100	29	30.6		9 mi. L
S	1100	29		1800	29	6.8		10 mi. L
T	1800	29		0600	30	93.9		5 mi. L
U	0600	30		1500	30 May	36.7		3 mi. R
V	1500	4 June	-	0500	5 June	85.2		1 mi. L
W	0500	5		1300	5	39.6		4 mi. R
X	1300	5		2300	5	90.8		1 mi. R
Y	2300	5		1300	6	70.3		1 mi. R
Z	1300	6		0100	7	76.1		7 mi. L

There are further qualifications of these results which arise from ship handling. Upon entering the Gulf Stream from the continental side there was often a marked increase in sea state which reduced the accuracy with which a given heading could be steered and thus increased the uncertainty of current measurements by the Loran dead-reckoning method. Frequently there was a change in the wind force which required resetting both engine revolutions and the sails which in turn contributed a change in the leeway of the vessel. Such effects enter the computations in a variety of ways for the integrations are weighted in proportion to the depth of water. For example, the total discrepancies at the end of a traverse between Loran dead-reckoning method and the G.E.K. profile of velocity are known with fair precision but the distribution of individual contributions measured by the Loran-D.R. method might be overestimated in deep water and underestimated by corresponding amounts in the shoal water portion of the section (von Arx, 1953b). This case would result in an overestimate of the volume transport for two reasons: first, that the difference between Loran dead-reckoning and G.E.K. current velocity would be largest in deep water and the mean velocity obtained from them would be assumed to apply to a larger cross sectional area than was actually the case. The reverse would occur if the estimated Loran dead-reckoning current measurements were erroneously largest in the shoal water portion of the traverse. Were the distribution of such errors to be associated with the direction of traverses, as seems possible, one would expect that southeastward sections might give consistently larger or smaller volume transport measurements than northwestward sections. There is no clear evidence of such an effect. Thus for the time being it is assumed in spite of the very large uncertainties in the volume transport estimates that the fluctuations are real although the amplitudes highly uncertain.

In conclusion, it seems significant that while marked fluctuations in volume transport were being observed at the Key West-Havana section and at the Onslow Bay section, only small variations of temperature and salinity were noted by observers from the Marine Laboratories, University of Miami who occupied an anchor station at 25°41'N, 79°53'W, near the site of Parr's station No. 2. This suggests either changes occurred farther to the East in the Florida Straits or that the fluctuations of volume transport are not accompanied by correspondingly complete adjustments of the density distribution. In view of the existence of fluctuations of velocity and transport it is at first surprising that the classic comparison of direct measurements and dynamic computations of the current structure in the Florida Straits by Wüst (1924) turned out so favorably, until it is realized that in all probability these effects were averaged out through the combination of many observations almost randomly spaced in time.

ACKNOWLEDGMENTS

Most of the new field work reported in this paper was made possible by funds supplied by the Office of Naval Research, under Contracts N6onr-27701 (NR-083-004) and Nonr-769 (00), which support is gratefully acknowledged.

We are indebted to members of a number of groups who have cooperated in these efforts, namely: the University of North Carolina Institute of Fisheries Research, the U. S. Fish and Wildlife Service, U. S. Fisheries Laboratory, Beaufort, North Carolina, U. S. Marine Corps Air Station, Cherry Point, North Carolina, U. S. Coast Guard Air Station, Elizabeth City, North Carolina, and University of Miami, Marine Laboratory, Coral Gables, Florida.

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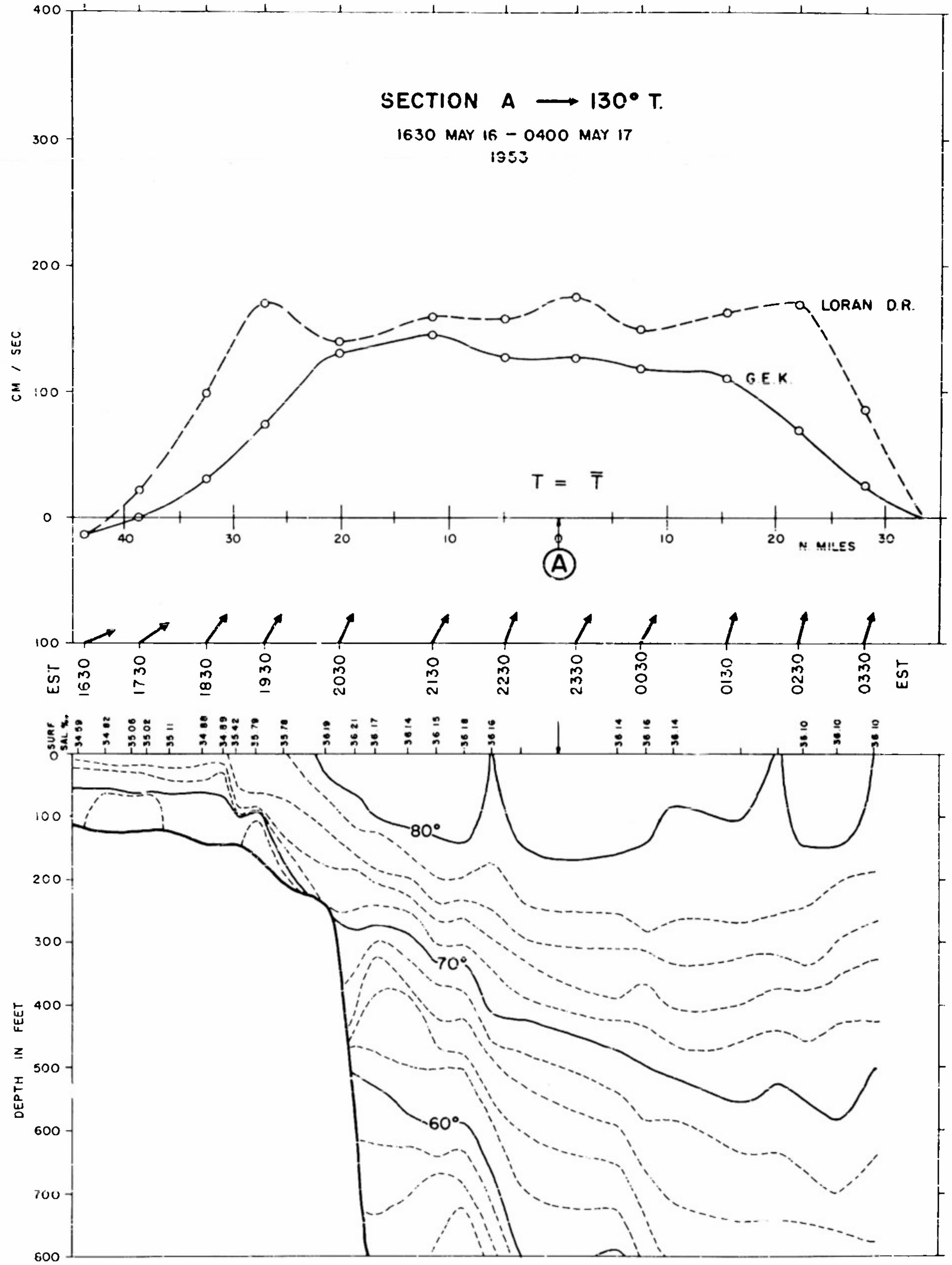
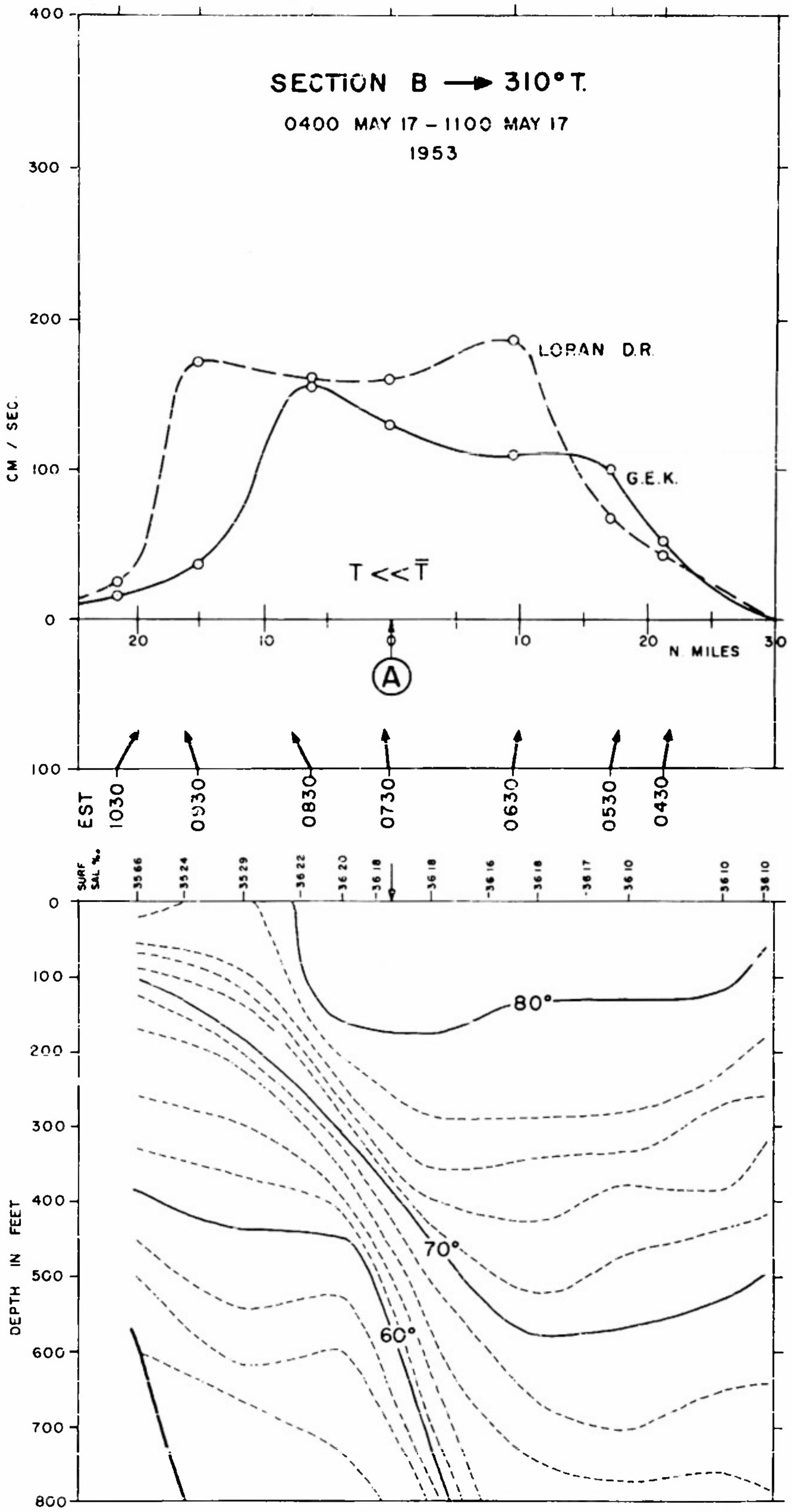
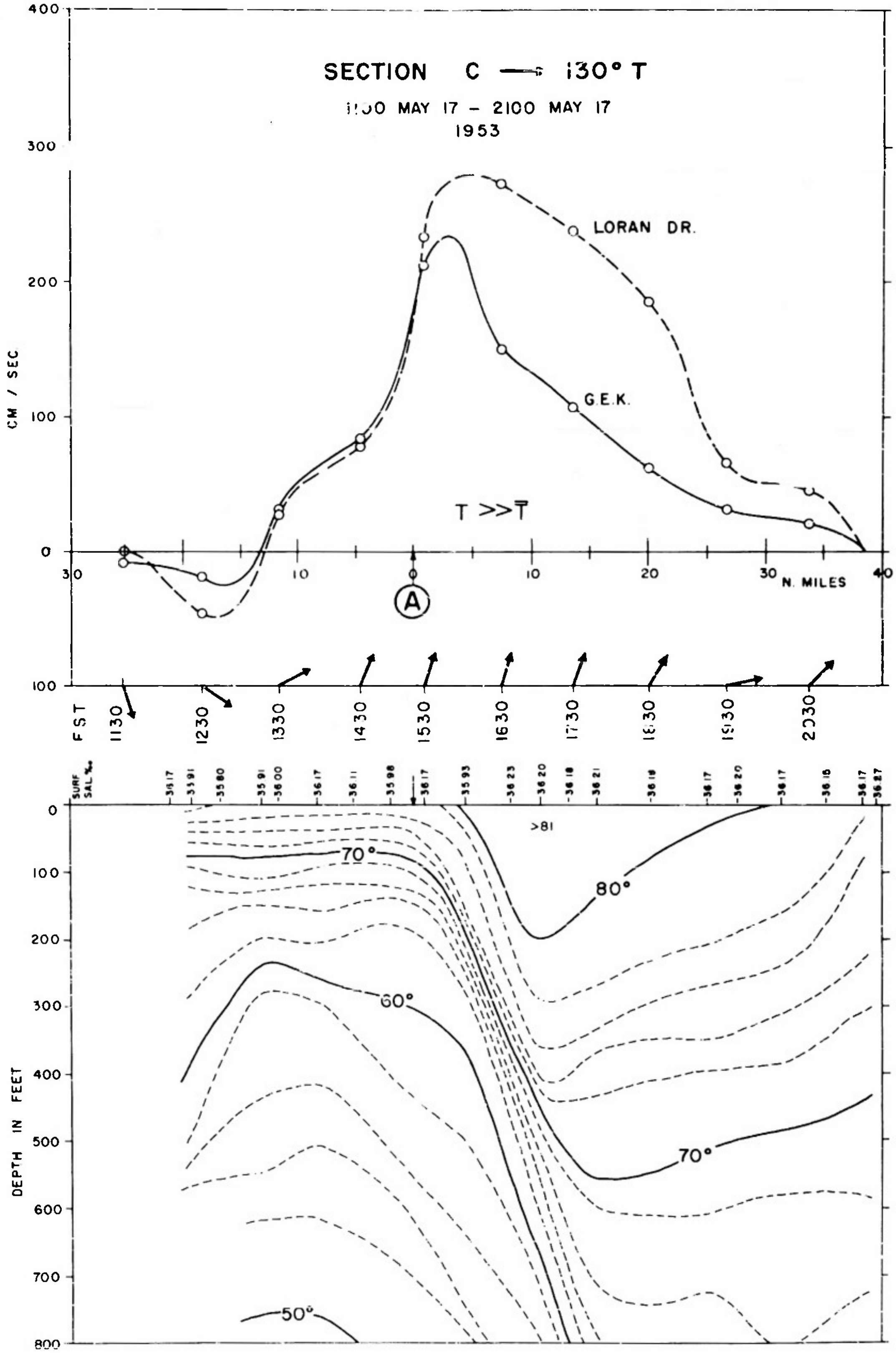
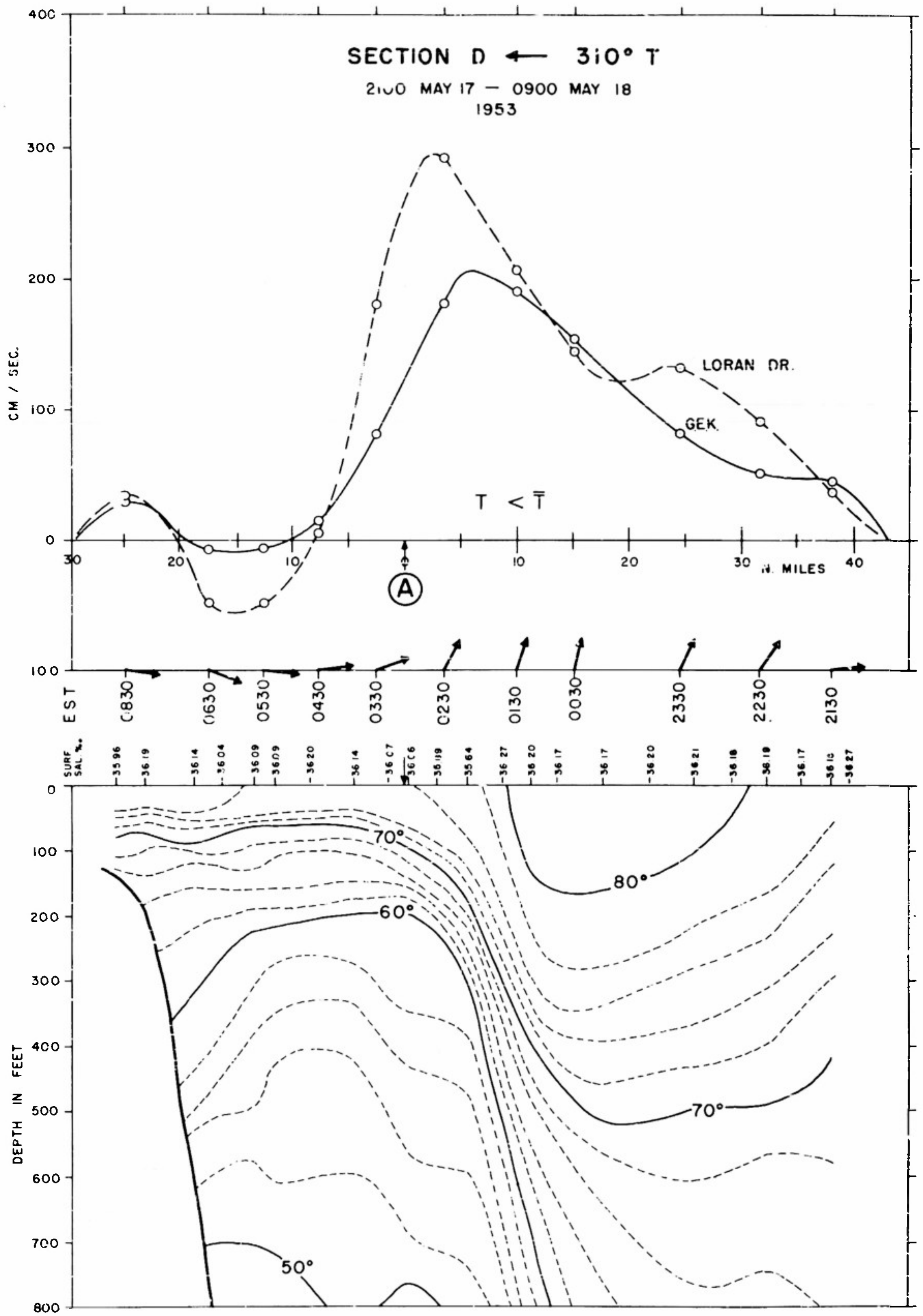
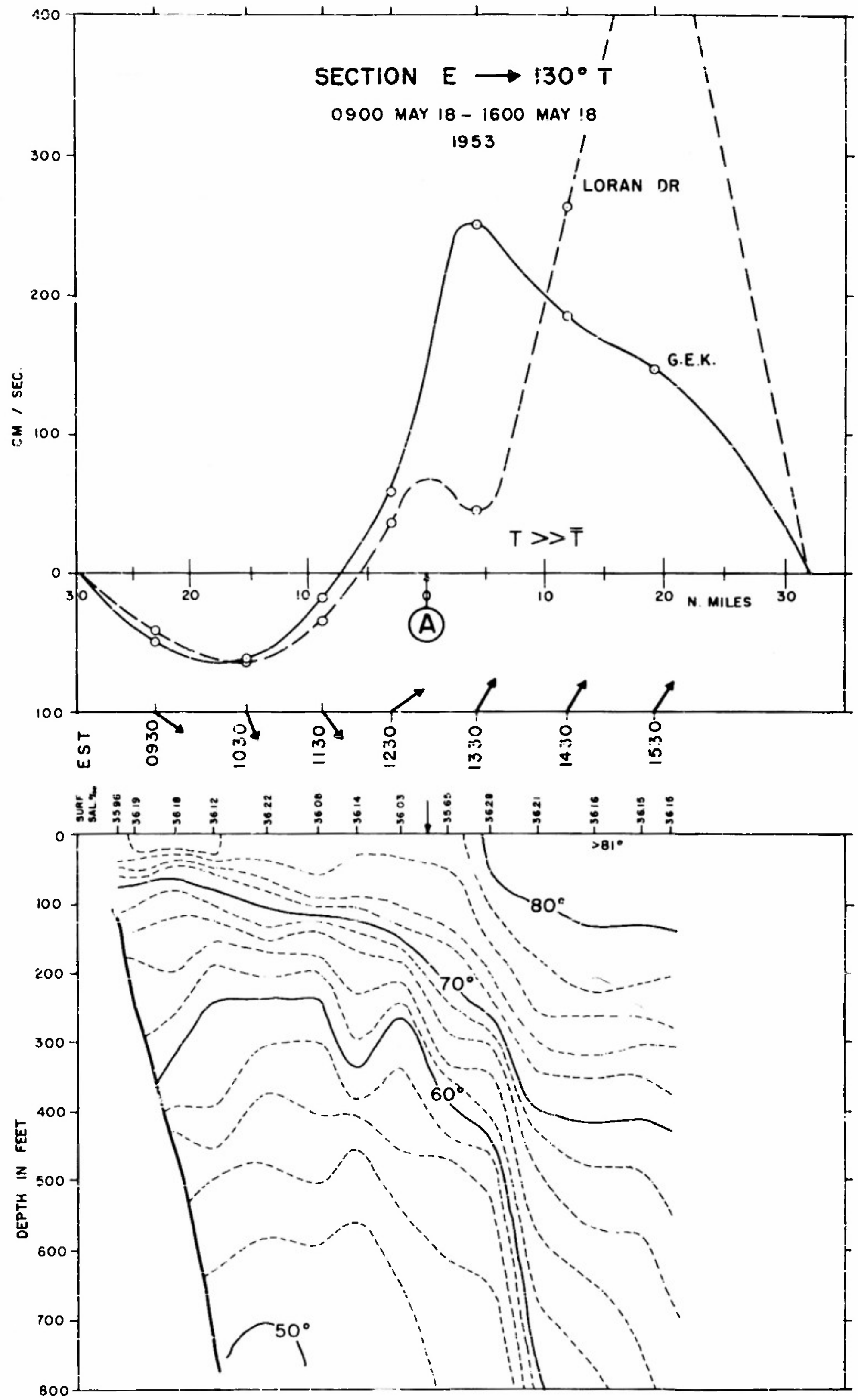

SECTION A ⟶ 130° T.
1630 MAY 16 – 0400 MAY 17
1953
CM / SEC
LORAN D.R.
G.E.K.
T = T̄
N. MILES
A
EST
1630
1730
1830
1930
2030
2130
2230
2330
0030
0130
0230
0330
EST
SURF SAL ‰
DEPTH IN FEET
80°
70°
60°



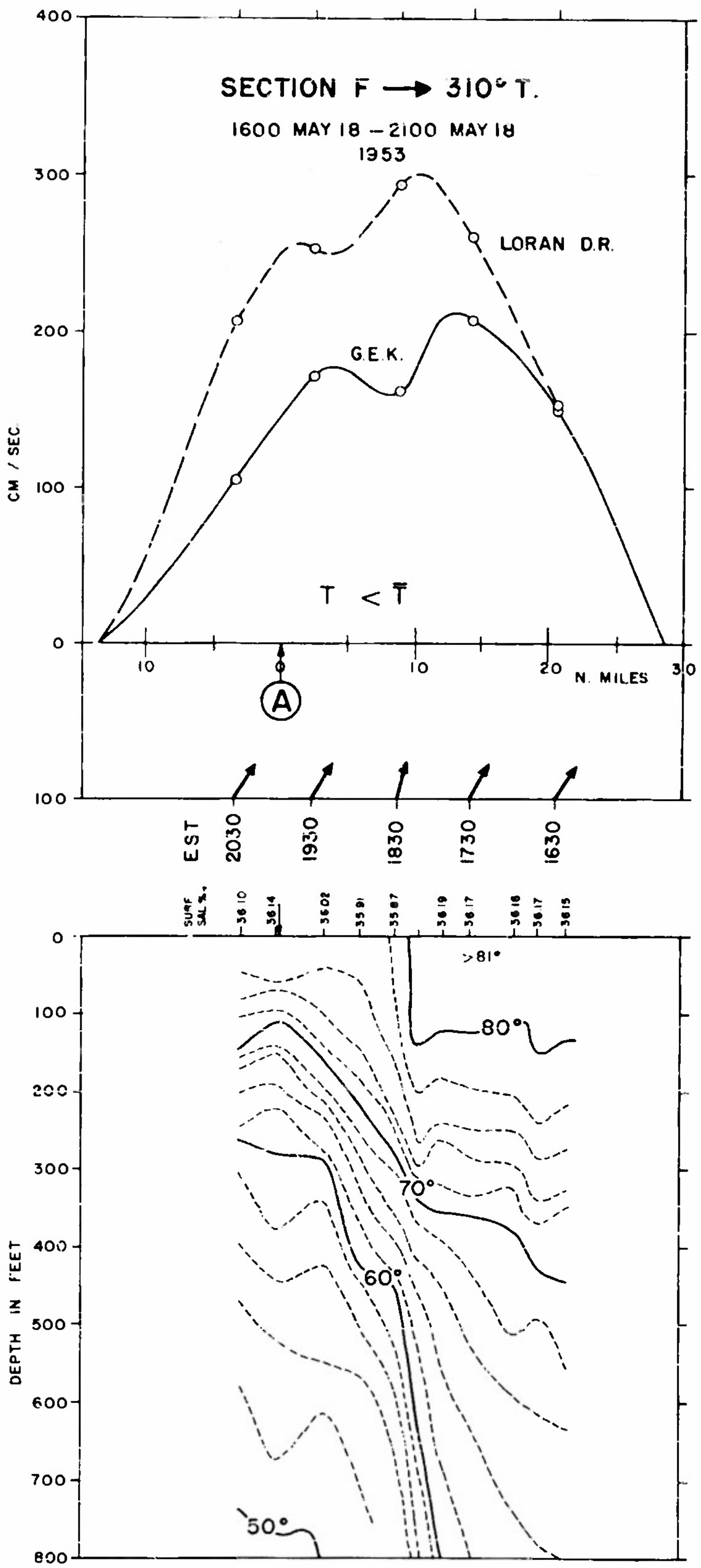
SECTION B → 310° T.
0400 MAY 17 – 1100 MAY 17
1953
CM / SEC.
400
300
200
100
0
100
LORAN D.R.
G.E.K.
T << T̄
20
10
0
10
20
30
N. MILES
A
EST
1030
0930
0830
0730
0630
0530
0430
SURF SAL ‰
35 66
35 24
35 29
36 22
36 20
36 18
36 18
36 16
36 18
36 17
36 10
36 10
36 10
DEPTH IN FEET
0
100
200
300
400
500
600
700
800
80°
70°
60°

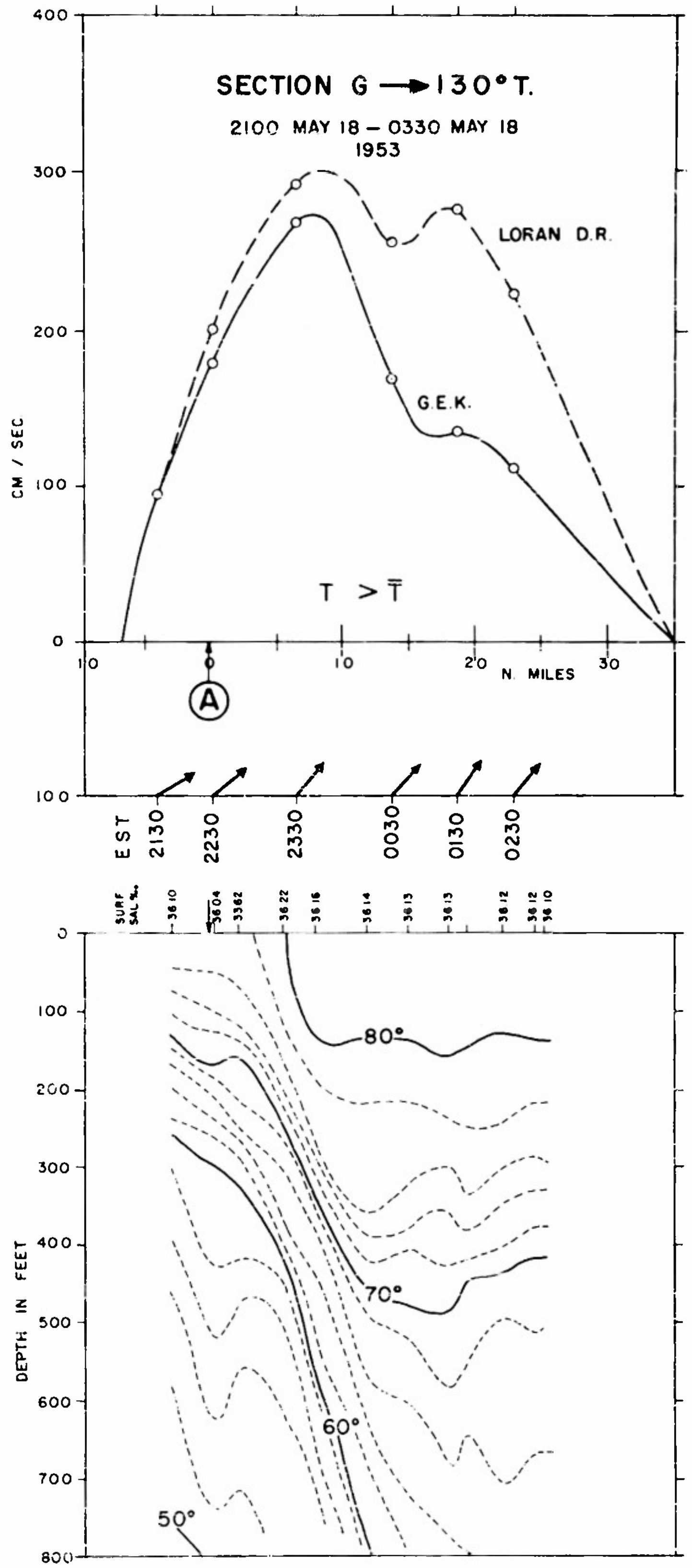

SECTION C → 130° T
1100 MAY 17 – 2100 MAY 17
1953
LORAN DR.
G.E.K.
CM / SEC
T >>T̄
N. MILES
A
FST
1130
1230
1330
1430
1530
1630
1730
1830
1930
2030
SURF SAL ‰
>81
70°
80°
60°
70°
50°
DEPTH IN FEET

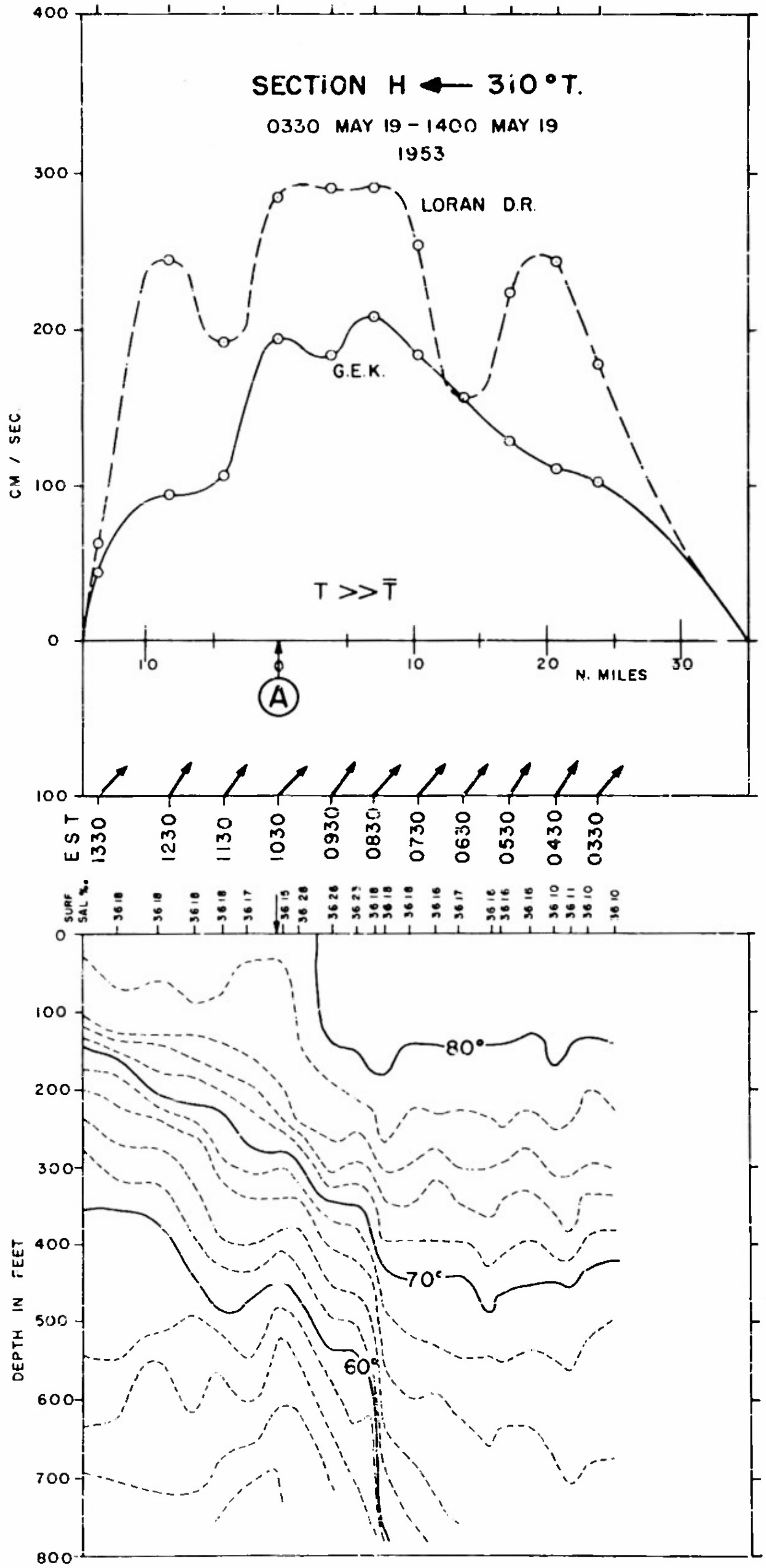

SECTION D ← 310° T
2100 MAY 17 — 0900 MAY 18
1953
CM / SEC.
LORAN DR.
GEK.
T < T̄
N. MILES
A
EST
0830
0630
0530
0430
0330
0230
0130
0030
2330
2230
2130
SURF SAL ‰
DEPTH IN FEET
70°
60°
80°
70°
50°



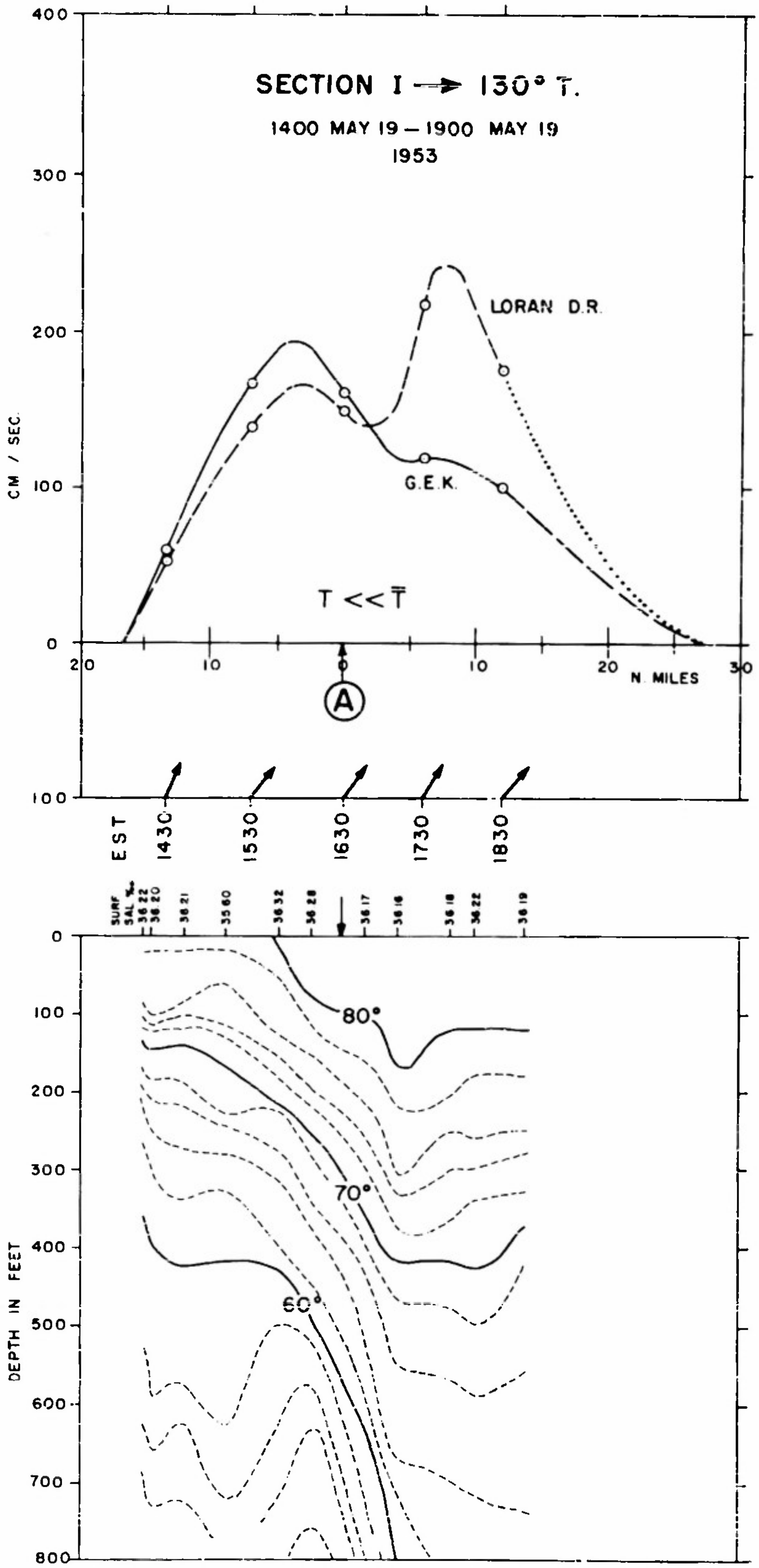
SECTION E → 130° T
0900 MAY 18 – 1600 MAY 18
1953
LORAN DR
G.E.K.
T >> T̄
CM / SEC
N. MILES
EST
0930
1030
1130
1230
1330
1430
1530
SURF SAL ‰
DEPTH IN FEET
80°
70°
60°
50°
>81°


SECTION F → 310° T.
1600 MAY 18 – 2100 MAY 18
1953
LORAN D.R.
G.E.K.
T < $\bar{T}$
CM / SEC
N. MILES
A
EST
2030
1930
1830
1730
1630
SURF SAL ‰
36.10
36.14
36.02
35.91
35.87
36.19
36.17
36.18
36.17
36.15
>81°
80°
70°
60°
50°
DEPTH IN FEET

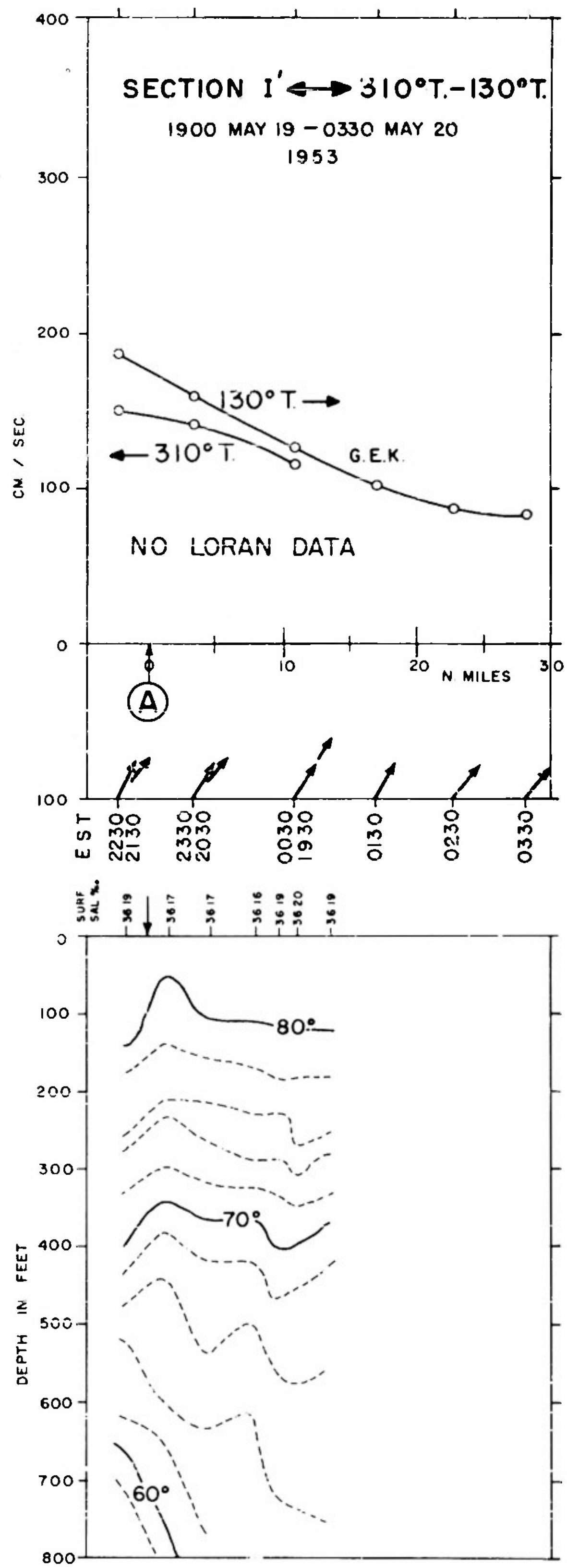

SECTION G → 130° T.
2100 MAY 18 – 0330 MAY 18
1953
LORAN D.R.
G.E.K.
T > T̄
CM / SEC
N. MILES
A
E S T
2130
2230
2330
0030
0130
0230
SURF SAL ‰
DEPTH IN FEET
80°
70°
60°
50°



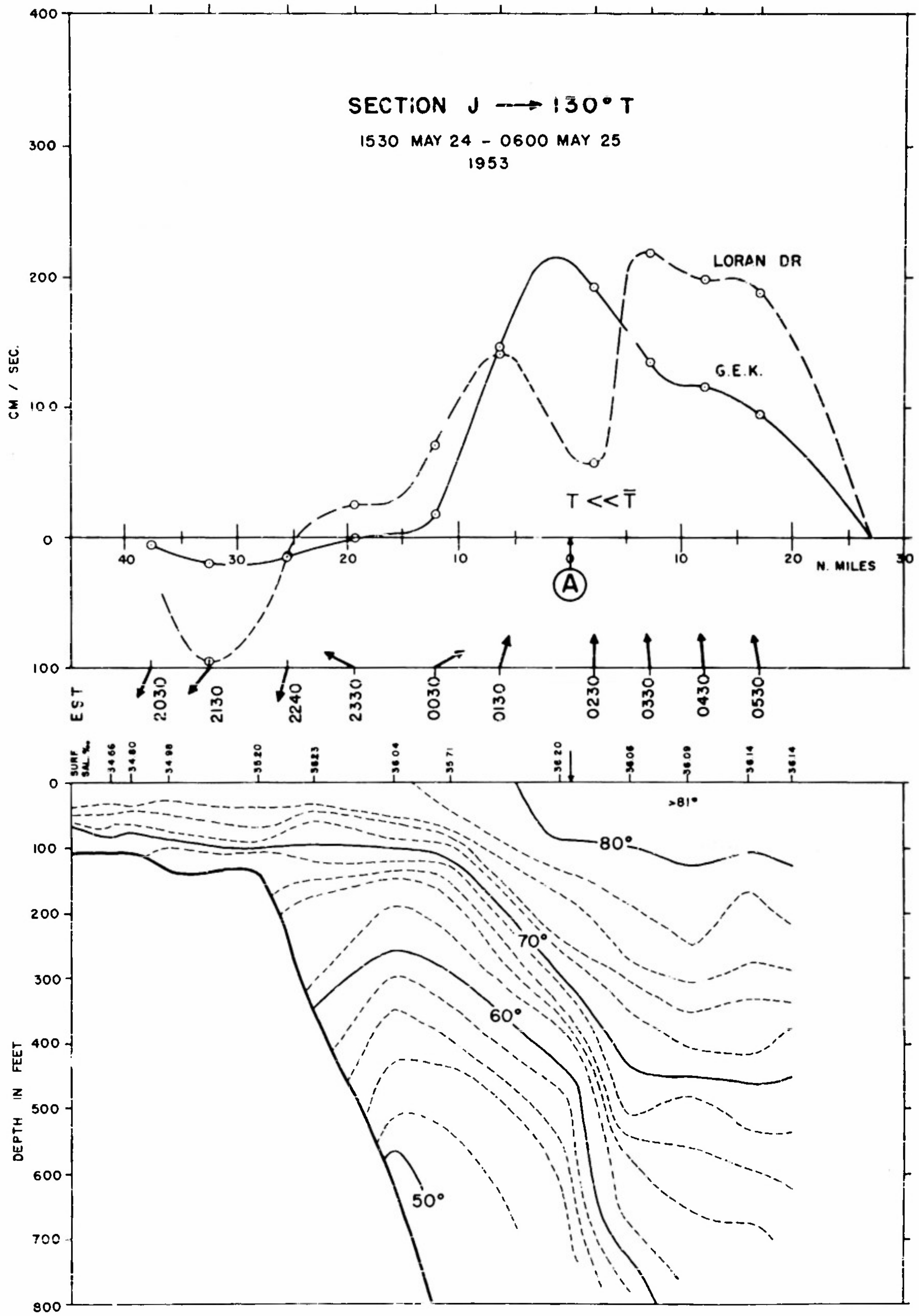
SECTION H ← 310°T.
0330 MAY 19 - 1400 MAY 19
1953
LORAN D.R.
G.E.K.
CM / SEC
T >> T̄
N. MILES
A
E S T
1330
1230
1130
1030
0930
0830
0730
0630
0530
0430
0330
SURF SAL ‰
80°
70°
60°
DEPTH IN FEET



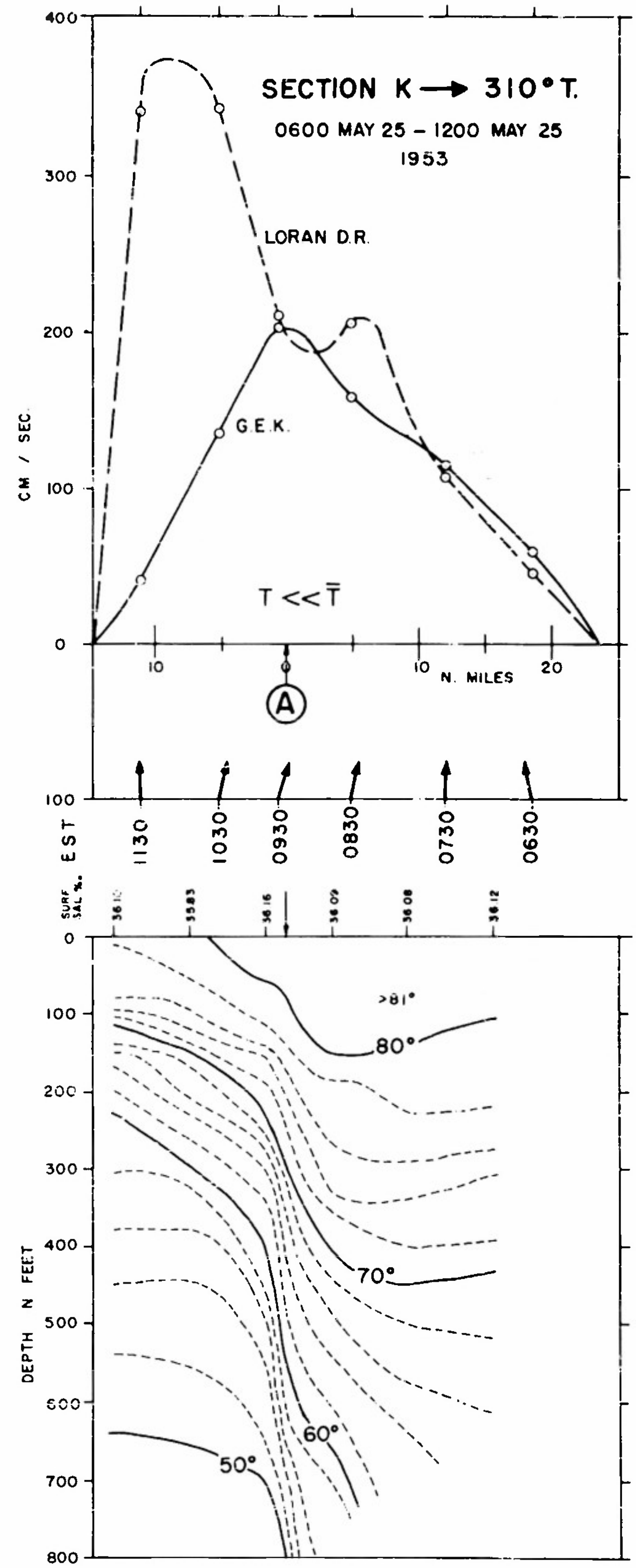
SECTION I → 130° T.
1400 MAY 19 — 1900 MAY 19
1953
LORAN D.R.
G.E.K.
T << T̄
CM / SEC.
N. MILES
A
EST
1430
1530
1630
1730
1830
SURF. SAL. ‰
DEPTH IN FEET
80°
70°
60°



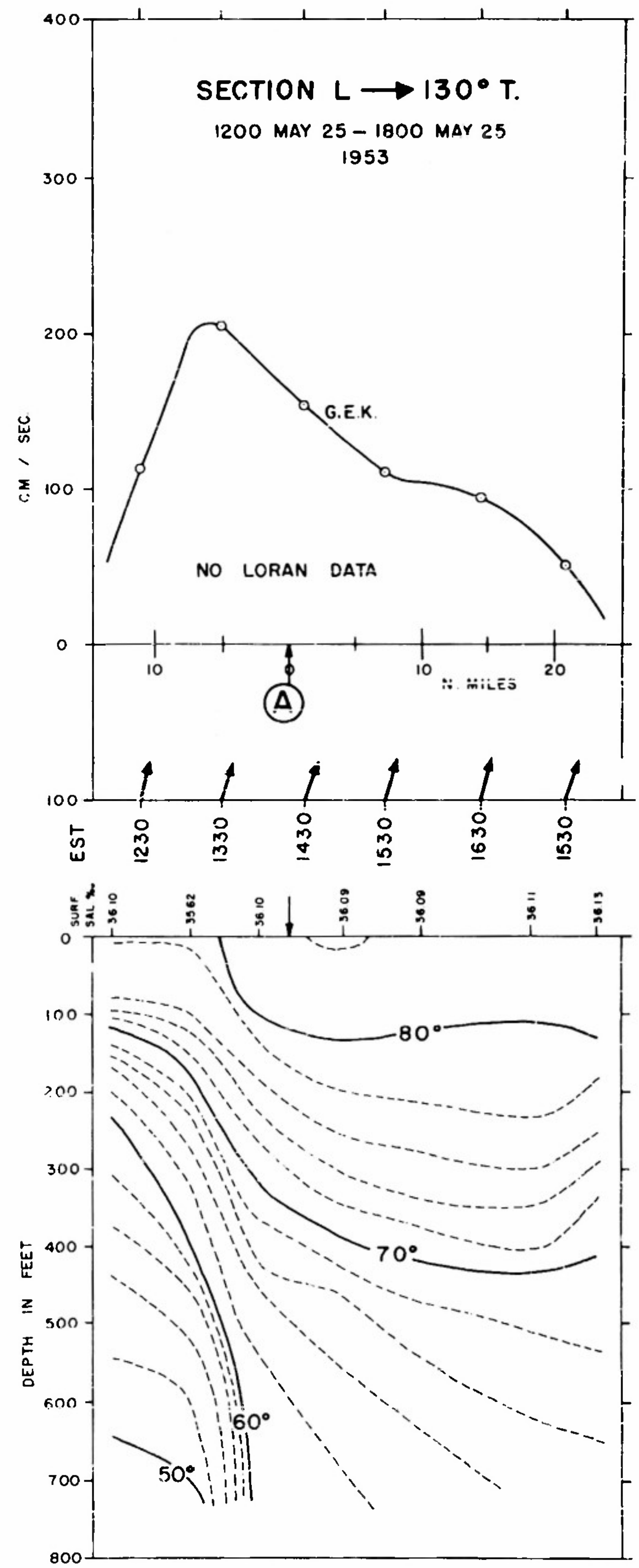
SECTION I' ⟷ 310°T.-130°T.
1900 MAY 19 — 0330 MAY 20
1953
130° T.
310° T.
G.E.K.
NO LORAN DATA
CM. / SEC.
N. MILES
A
EST
2230 2130
2330 2030
0030 1930
0130
0230
0330
SURF SAL ‰
80°
70°
60°
DEPTH IN FEET

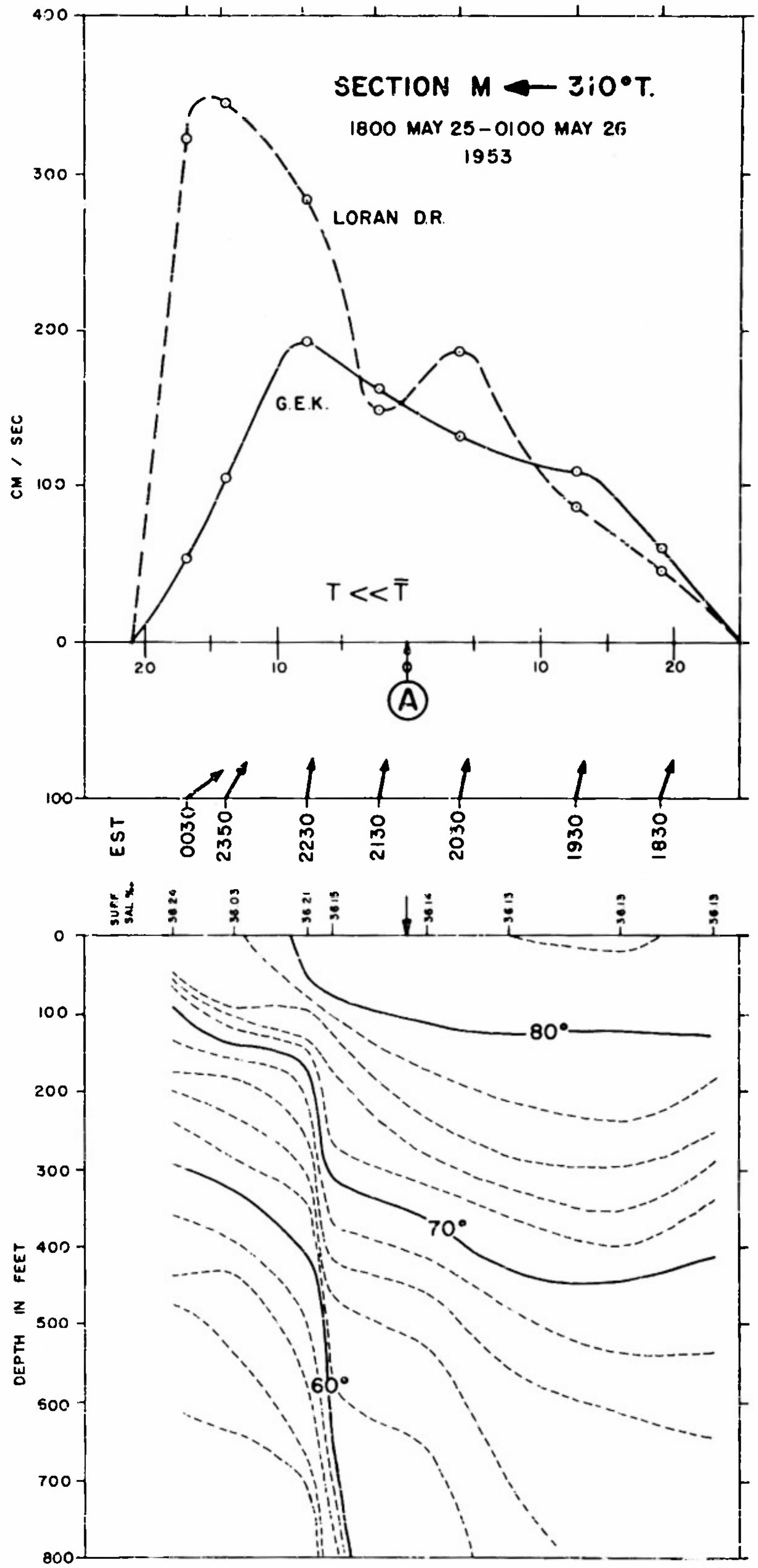


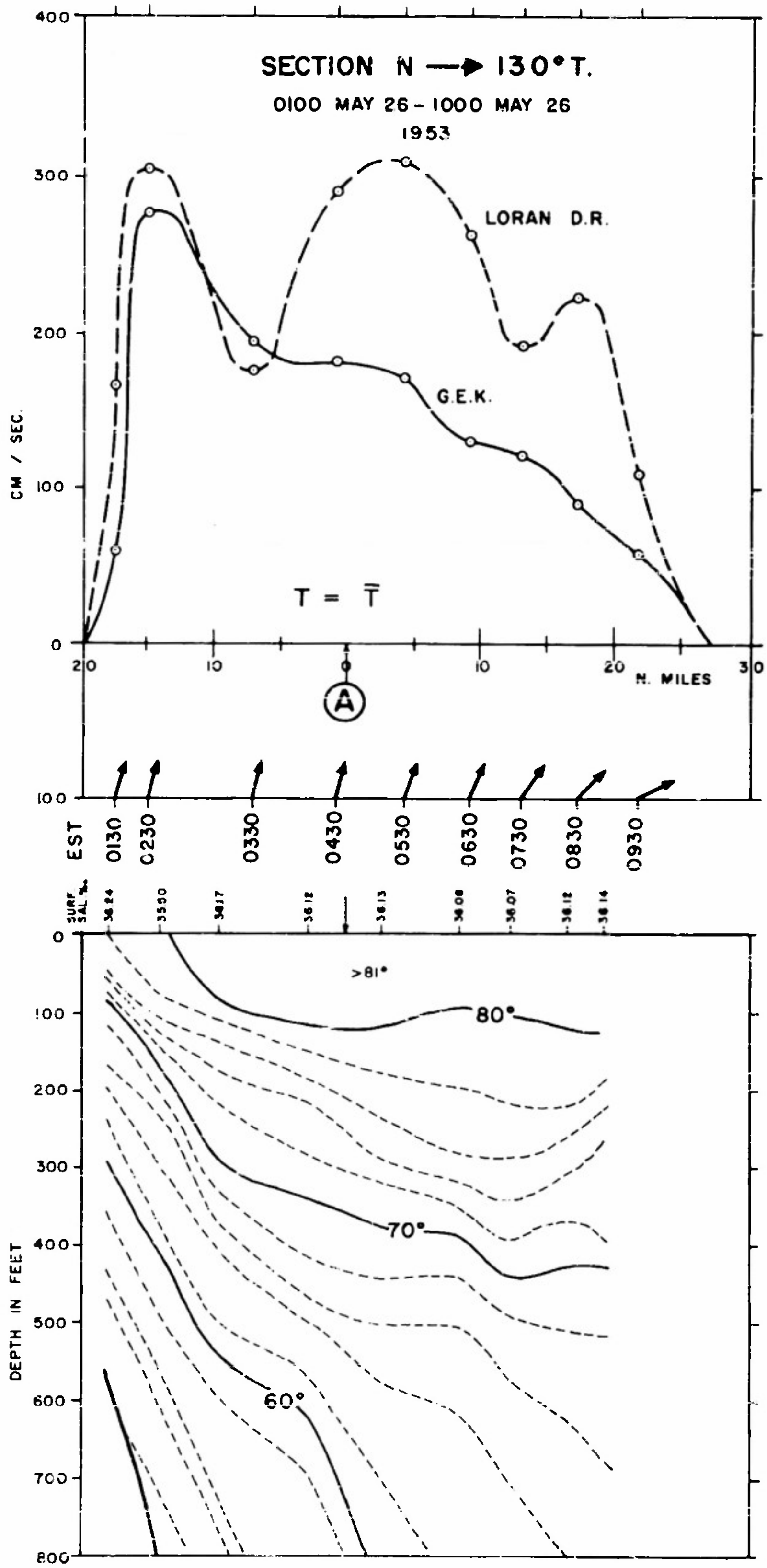
SECTION J ⟶ 130° T
1530 MAY 24 - 0600 MAY 25
1953
LORAN DR
G.E.K.
CM / SEC.
T << T̄
N. MILES
A
EST
2030
2130
2240
2330
0030
0130
0230
0330
0430
0530
SURF. SAL. ‰
34.66
34.80
34.98
35.20
35.23
36.04
35.71
36.20
36.06
36.09
36.14
36.14
>81°
80°
70°
60°
50°
DEPTH IN FEET

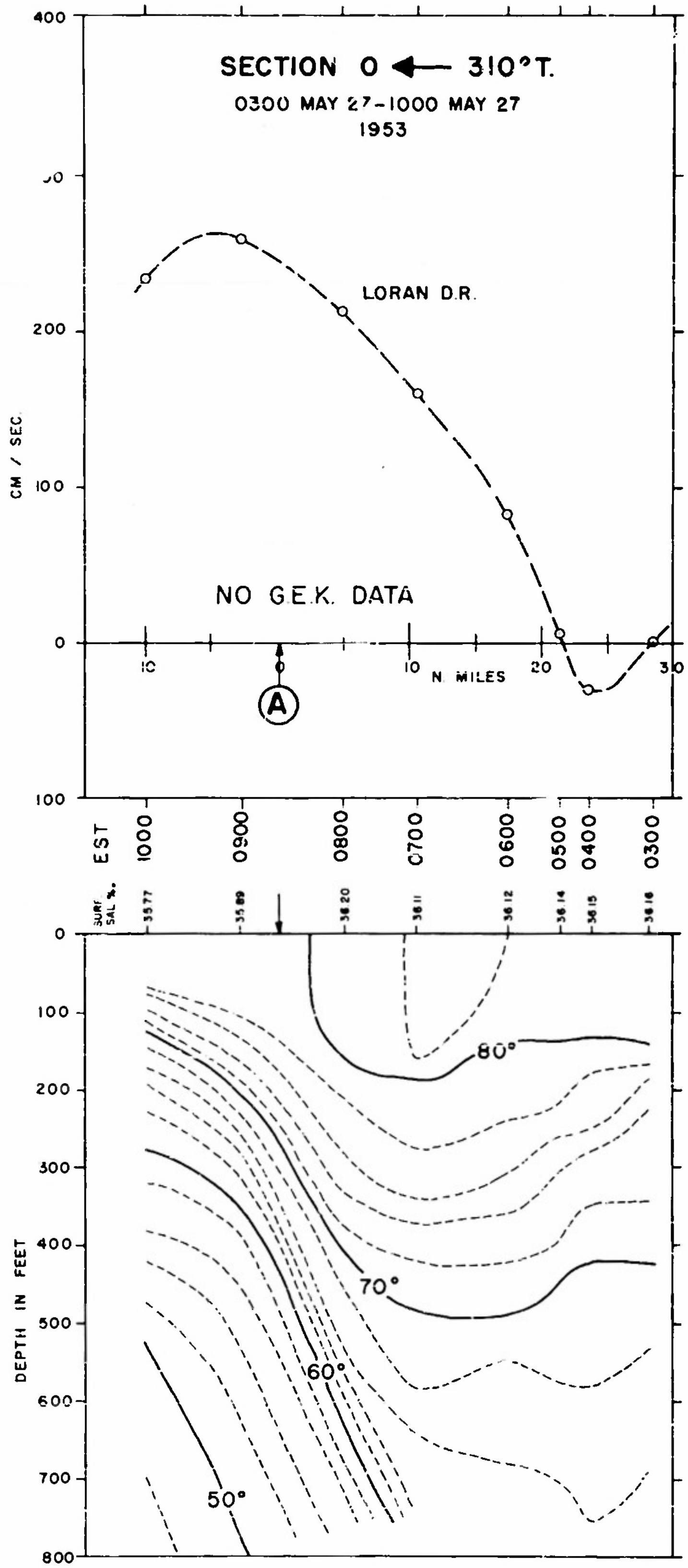


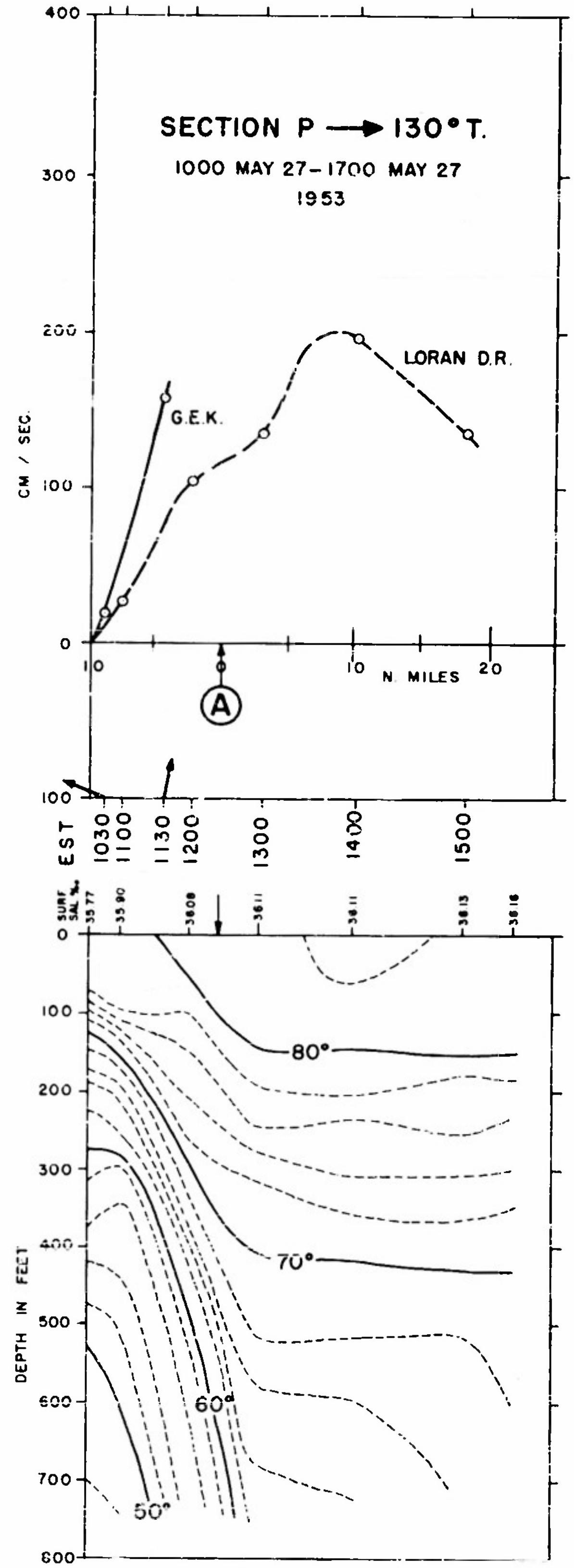
SECTION K → 310° T.
0600 MAY 25 – 1200 MAY 25
1953
LORAN D.R.
G.E.K.
T << T̄
CM / SEC.
N. MILES
A
EST
1130
1030
0930
0830
0730
0630
SURF SAL ‰
>81°
80°
70°
60°
50°
DEPTH IN FEET

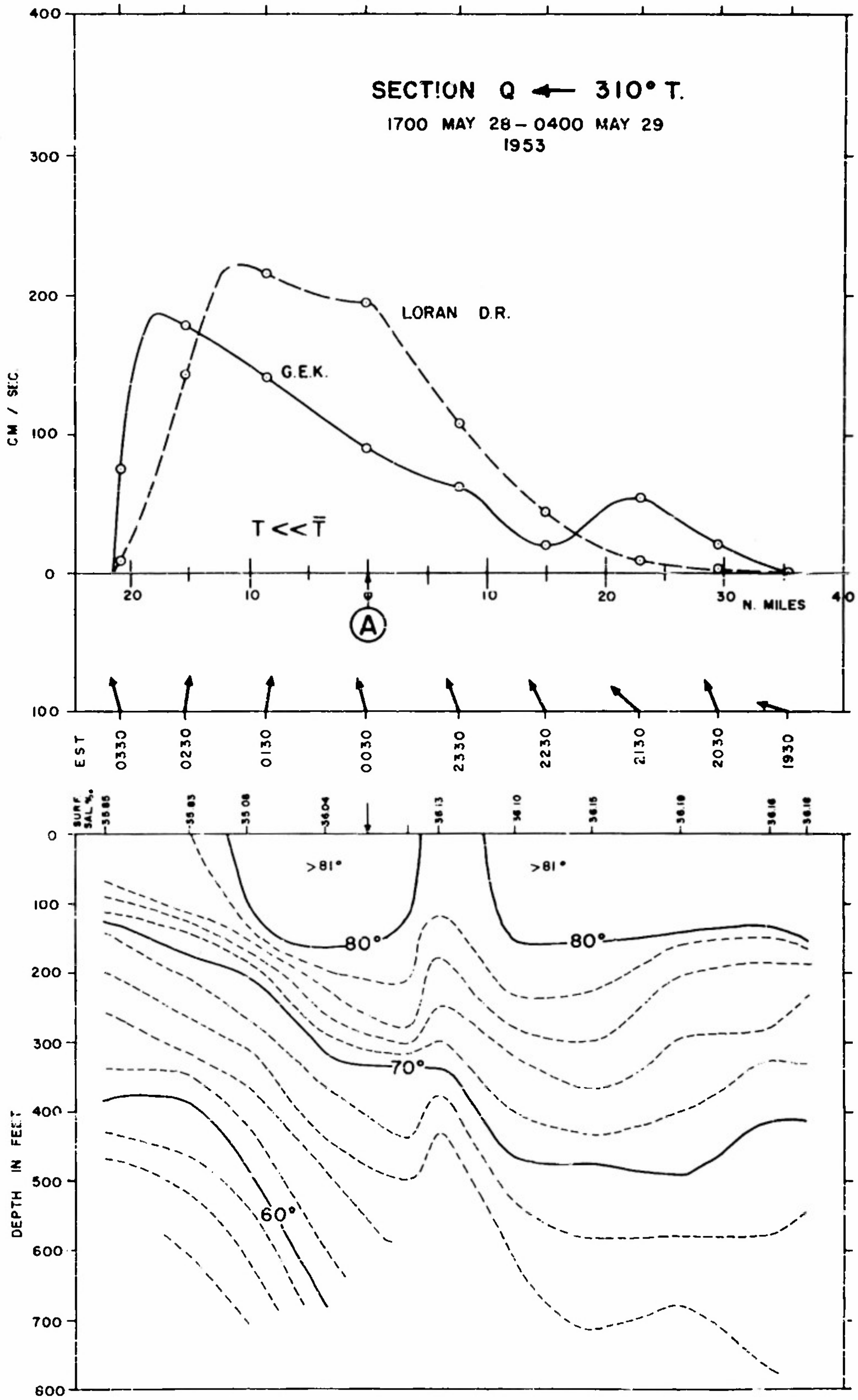

SECTION L → 130° T.
1200 MAY 25 – 1800 MAY 25
1953
CM / SEC.
G.E.K.
NO LORAN DATA
N. MILES
A
EST
1230
1330
1430
1530
1630
1530
SURF SAL ‰
DEPTH IN FEET
80°
70°
60°
50°


SECTION M ← 310°T.
1800 MAY 25 – 0100 MAY 26
1953
LORAN D.R.
G.E.K.
T << $\overline{T}$
CM / SEC
A
EST
0030
2350
2230
2130
2030
1930
1830
SURF SAL ‰
80°
70°
60°
DEPTH IN FEET

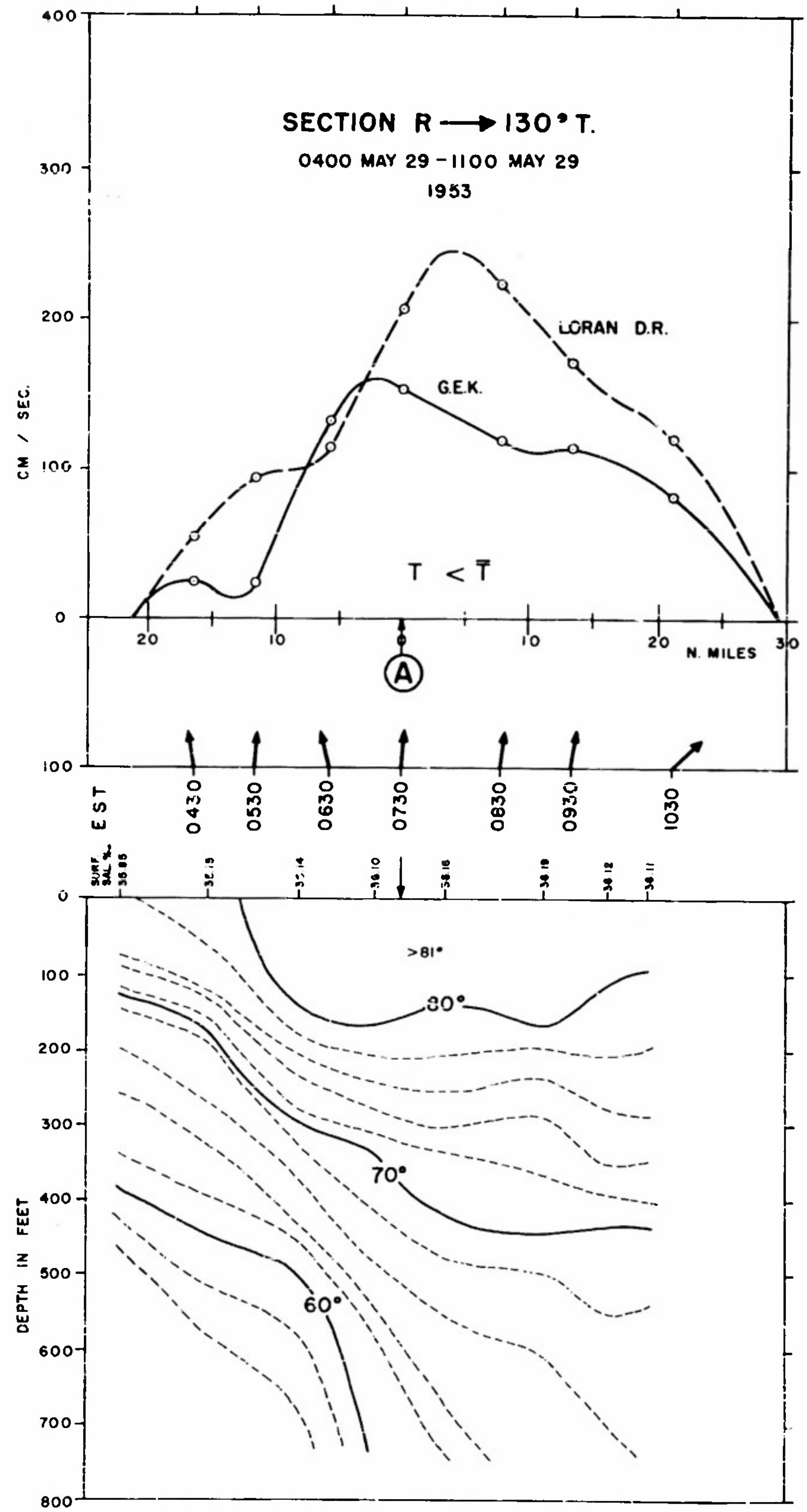

SECTION N → 130° T.
0100 MAY 26 - 1000 MAY 26
1953
LORAN D.R.
G.E.K.
T = T̄
CM / SEC.
N. MILES
A
EST
0130
0230
0330
0430
0530
0630
0730
0830
0930
SURF SAL ‰
>81°
80°
70°
60°
DEPTH IN FEET

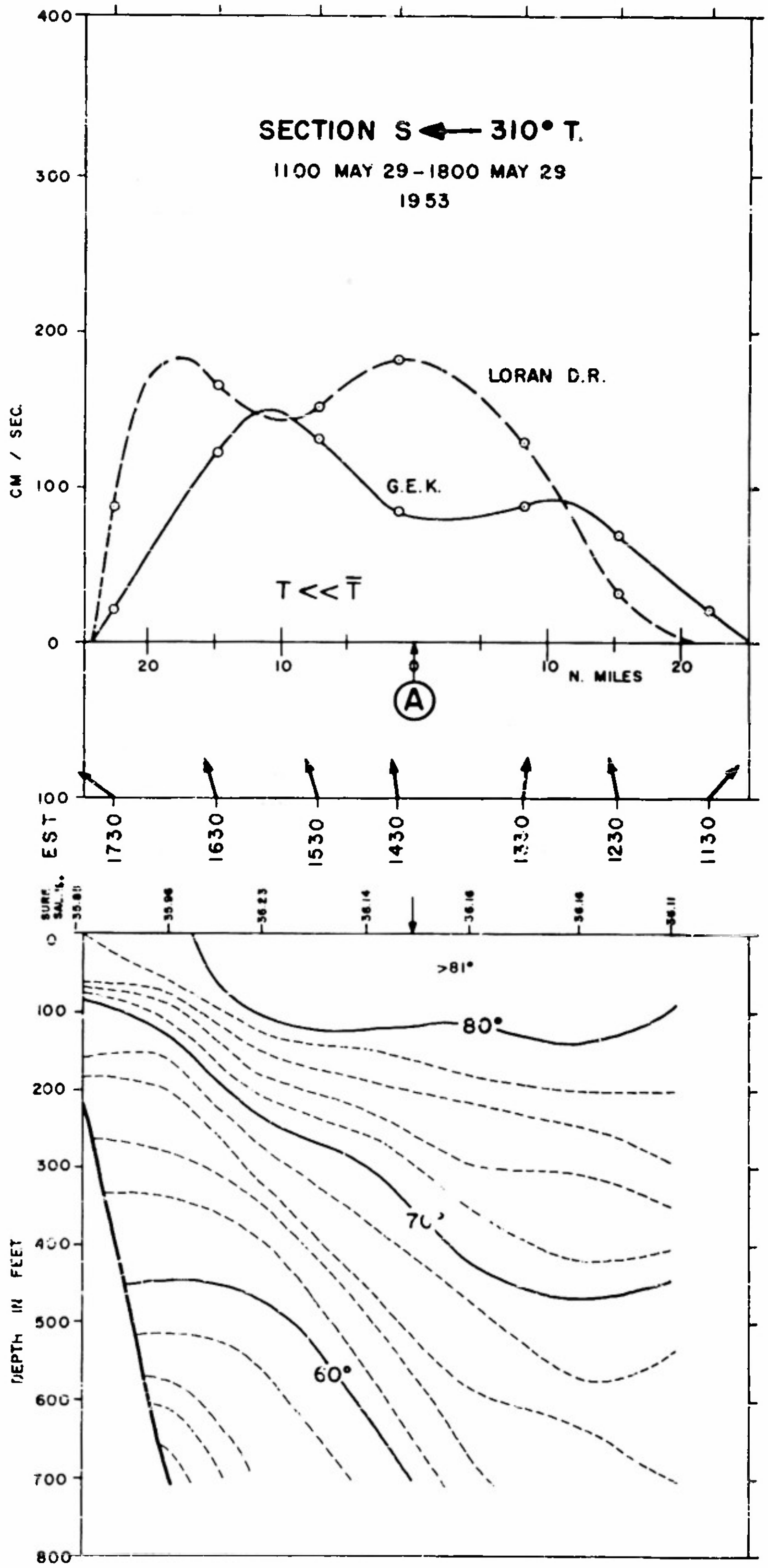

SECTION O ← 310°T.
0300 MAY 27-1000 MAY 27
1953
LORAN D.R.
NO G.E.K. DATA
CM / SEC.
N. MILES
A
EST
1000
0900
0800
0700
0600
0500
0400
0300
SURF. SAL ‰
80°
70°
60°
50°
DEPTH IN FEET


SECTION P → 130° T.
1000 MAY 27 – 1700 MAY 27
1953
LORAN D.R.
G.E.K.
CM / SEC.
N. MILES
A
EST
DEPTH IN FEET
80°
70°
60°
50°

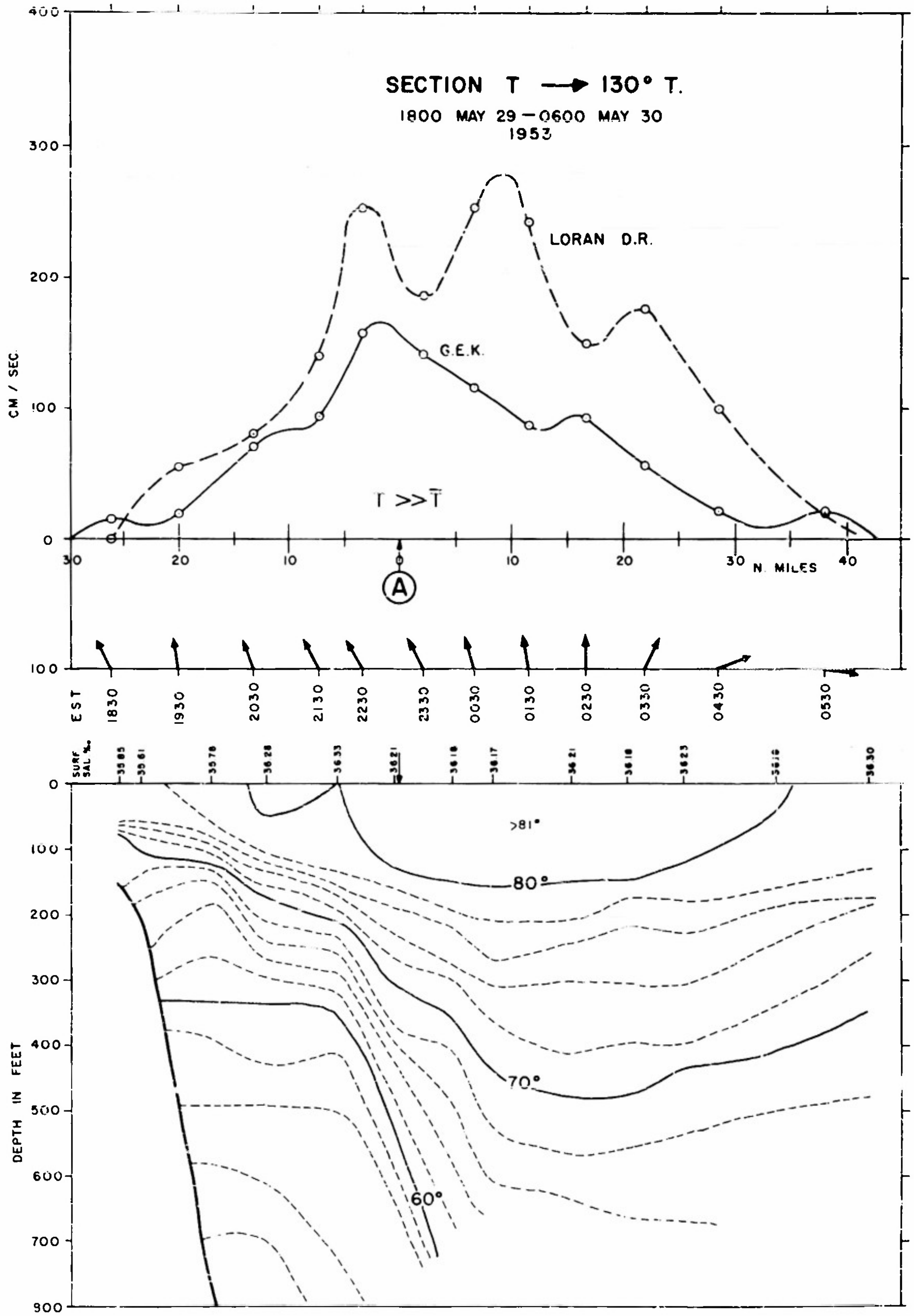


SECTION Q ← 310° T.
1700 MAY 28 – 0400 MAY 29
1953
LORAN D.R.
G.E.K.
CM / SEC
T << $\bar{T}$
N. MILES
A
EST
0330
0230
0130
0030
2330
2230
2130
2030
1930
SURF. SAL ‰
>81°
80°
70°
60°
DEPTH IN FEET

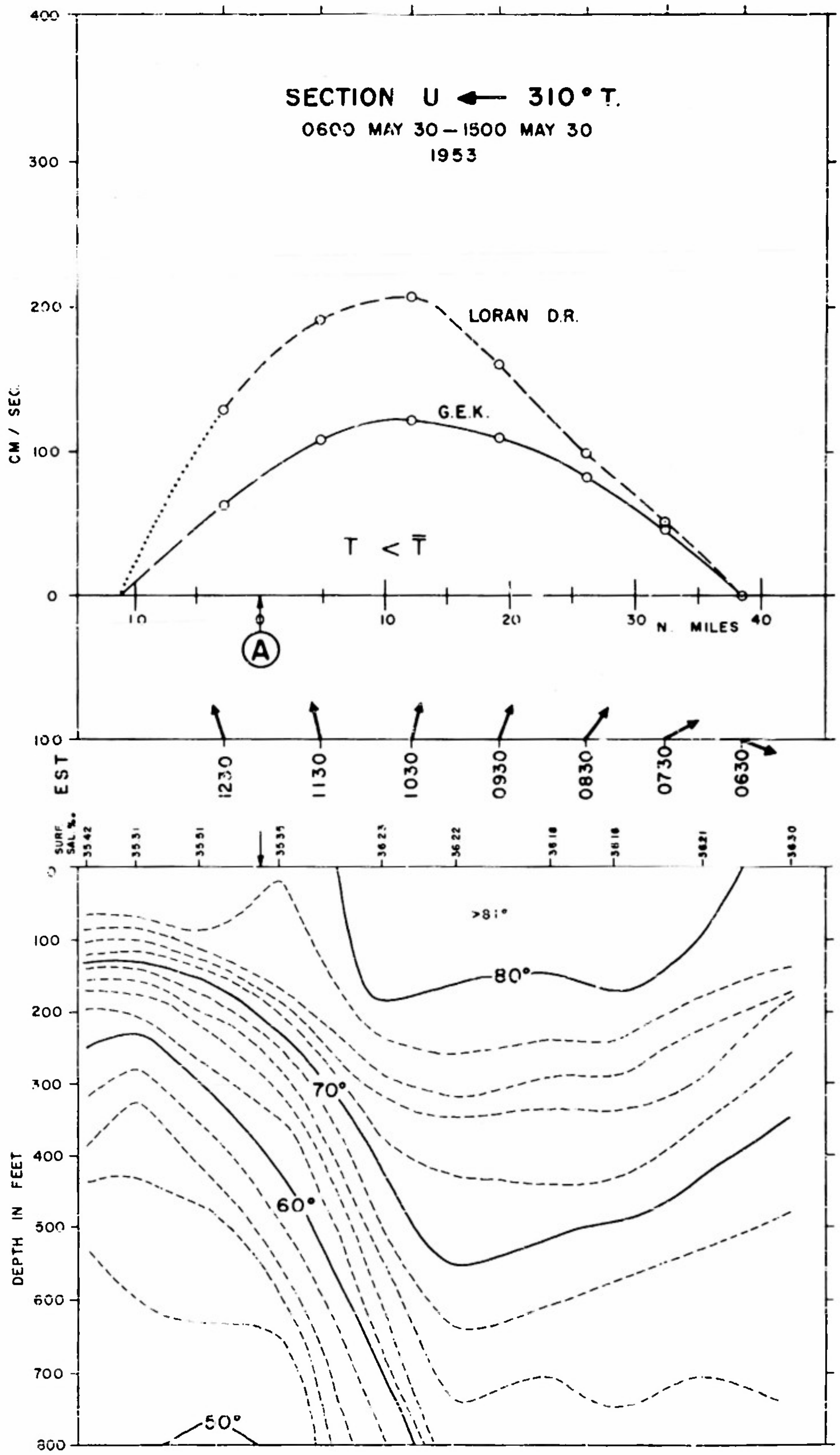

SECTION R ⟶ 130° T.
0400 MAY 29 – 1100 MAY 29
1953
LORAN D.R.
G.E.K.
T < T̄
CM / SEC.
N. MILES
A
EST
0430
0530
0630
0730
0830
0930
1030
>81°
80°
70°
60°
DEPTH IN FEET



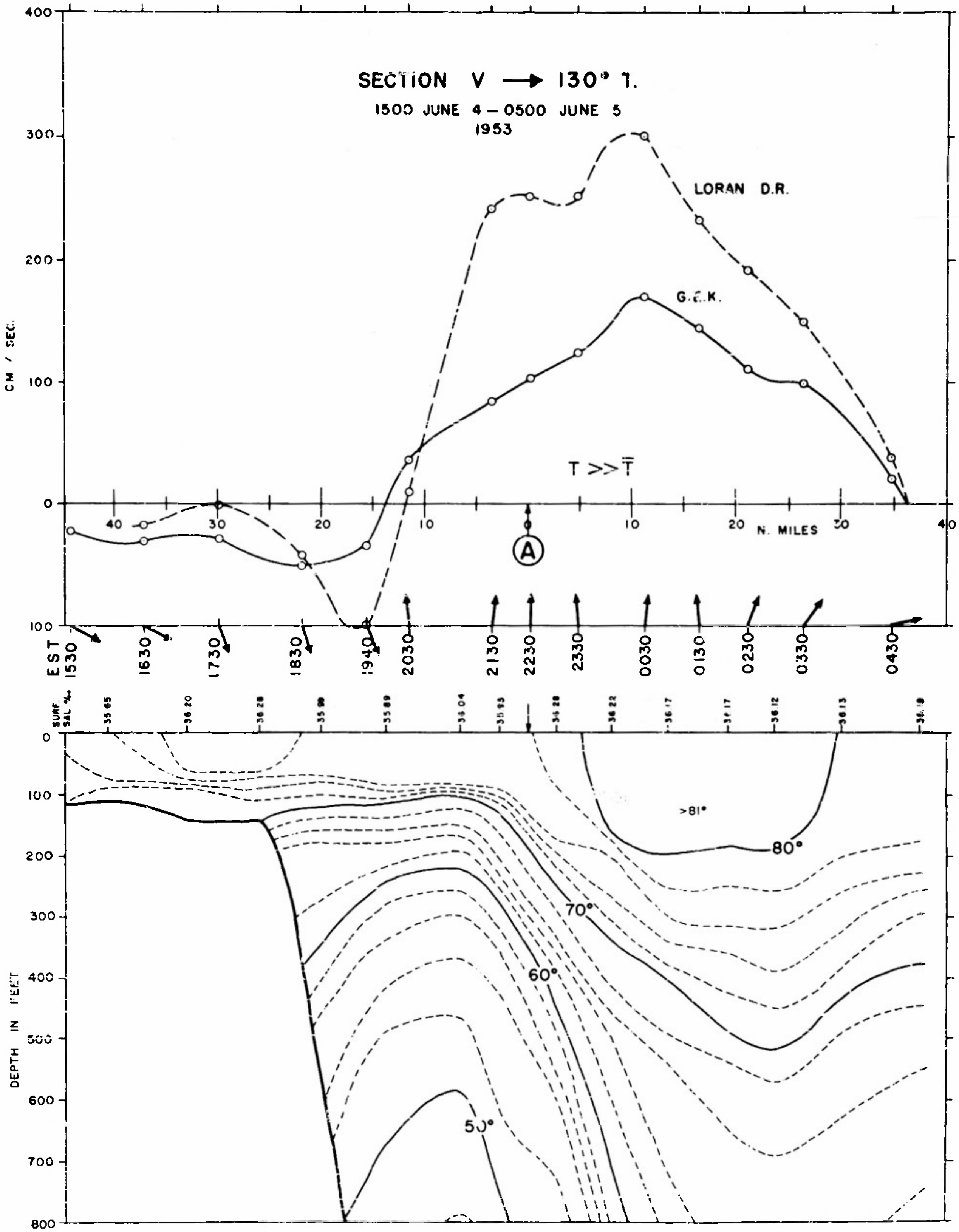
SECTION S ← 310° T.
1100 MAY 29 - 1800 MAY 29
1953
LORAN D.R.
G.E.K.
T << T̄
CM / SEC.
N. MILES
A
EST
1730
1630
1530
1430
1330
1230
1130
>81°
80°
70°
60°
DEPTH IN FEET

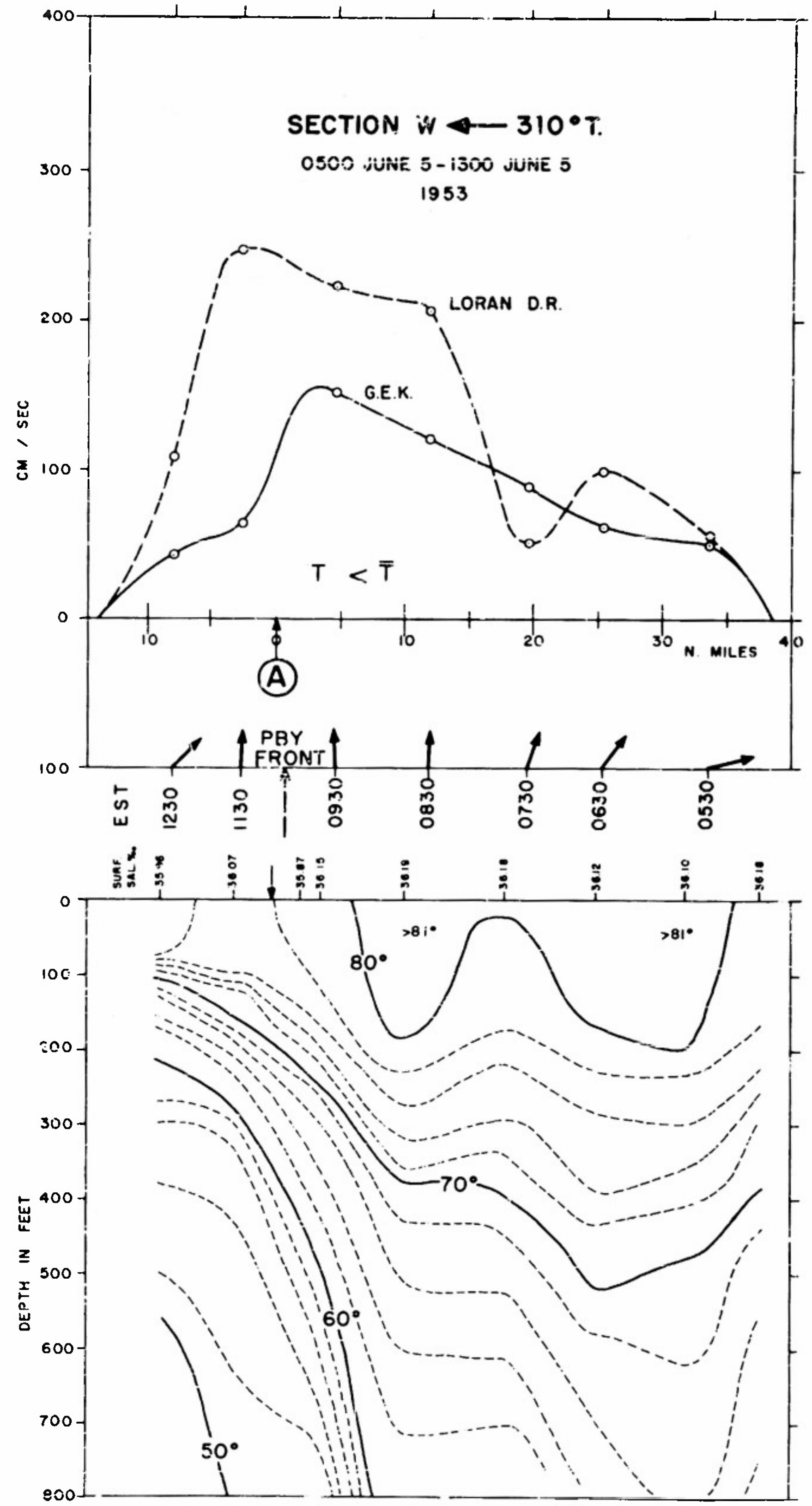


SECTION T → 130° T.
1800 MAY 29 — 0600 MAY 30
1953
LORAN D.R.
G.E.K.
T >> T̄
CM / SEC.
N. MILES
A
EST
1830
1930
2030
2130
2230
2330
0030
0130
0230
0330
0430
0530
SURF SAL ‰
35.85
35.61
35.78
36.28
36.33
36.21
36.18
36.17
36.21
36.18
36.23
36.30
>81°
80°
70°
60°
DEPTH IN FEET

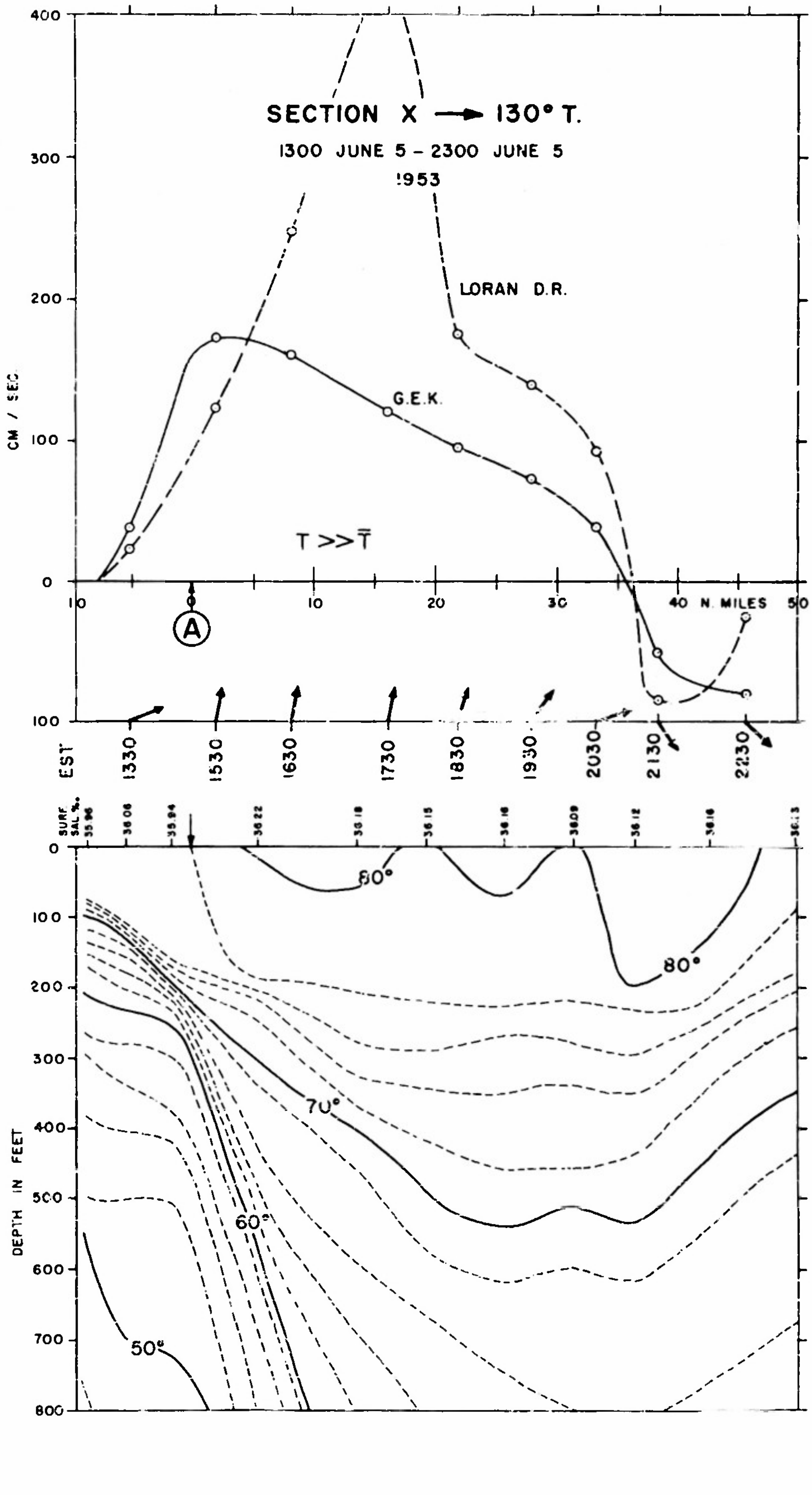


SECTION U ← 310° T.
0600 MAY 30 — 1500 MAY 30
1953
LORAN D.R.
G.E.K.
CM / SEC
T < T̄
N. MILES
A
EST
1230
1130
1030
0930
0830
0730
0630
SURF SAL ‰
DEPTH IN FEET
>81°
80°
70°
60°
50°

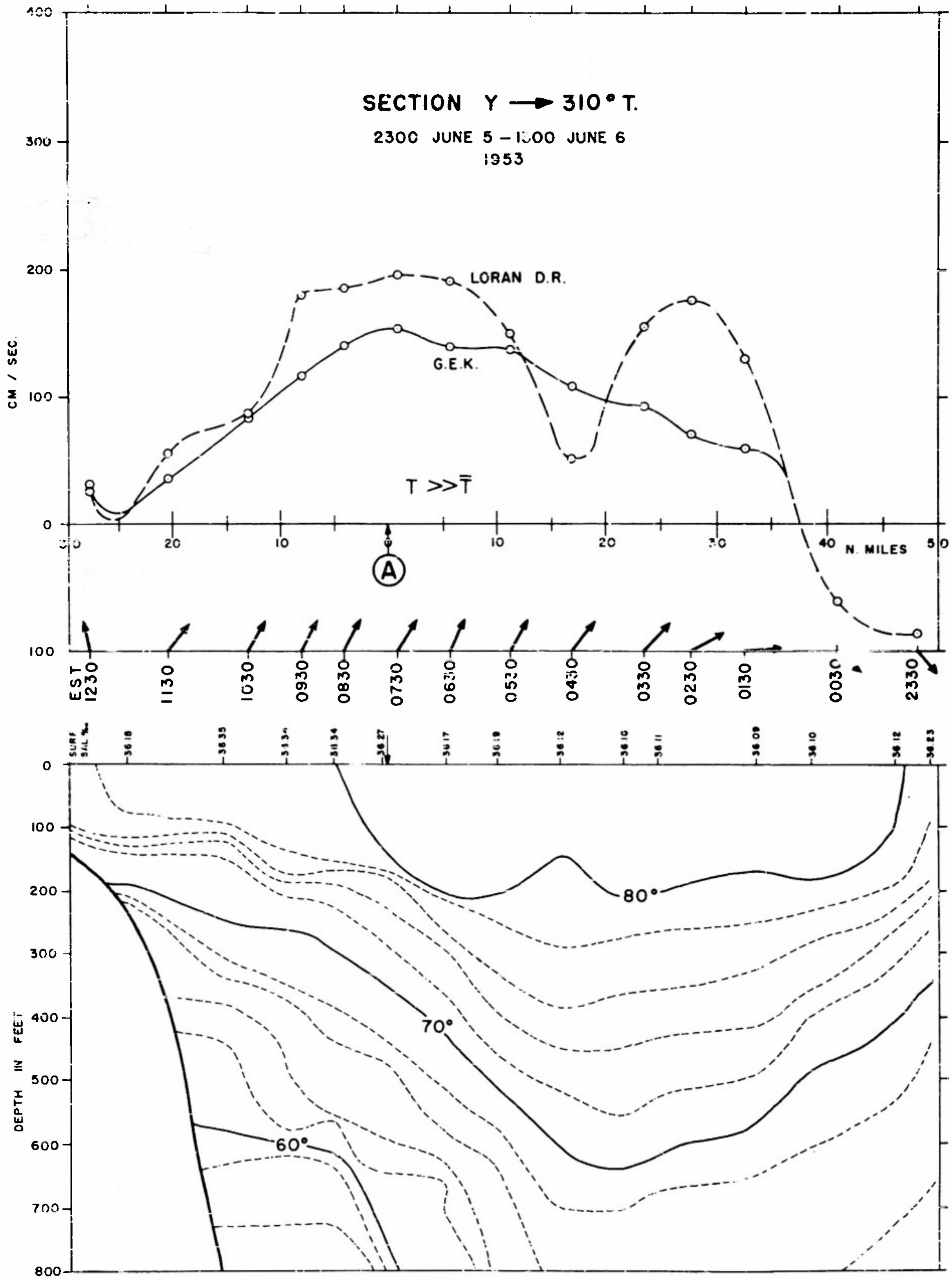

SECTION V → 130° T.
1500 JUNE 4 – 0500 JUNE 5
1953
LORAN D.R.
G.E.K.
T >> T̄
CM / SEC.
N. MILES
A
EST
1530
1630
1730
1830
1940
2030
2130
2230
2330
0030
0130
0230
0330
0430
SURF SAL ‰
DEPTH IN FEET
>81°
80°
70°
60°
50°



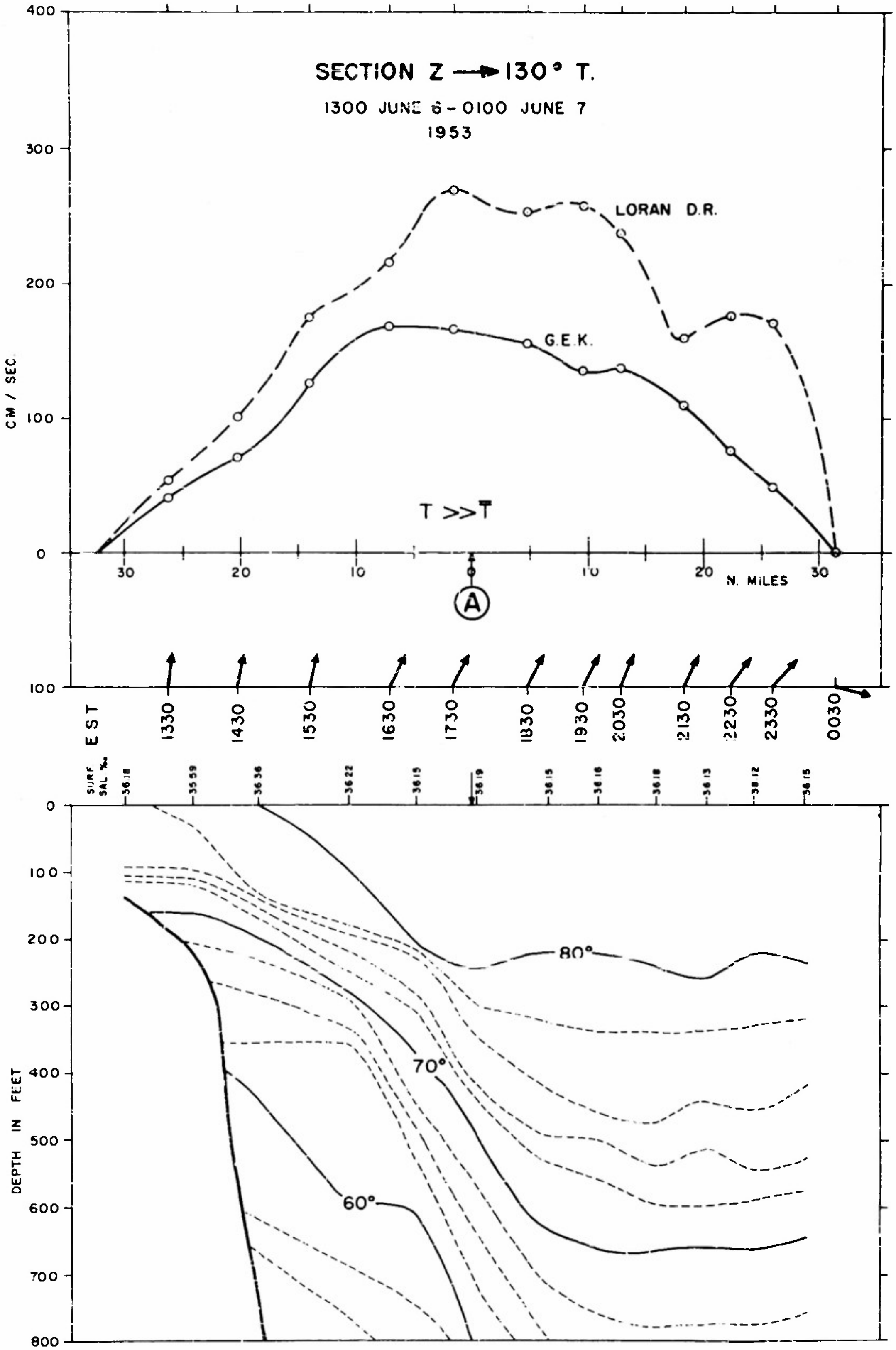
SECTION W ← 310°T.
0500 JUNE 5 - 1300 JUNE 5
1953
LORAN D.R.
G.E.K.
T < T̄
CM / SEC
N. MILES
A
PBY
FRONT
EST
1230
1130
0930
0830
0730
0630
0530
SURF SAL ‰
>81°
80°
70°
60°
50°
DEPTH IN FEET



SECTION X → 130° T.
1300 JUNE 5 - 2300 JUNE 5
1953
LORAN D.R.
G.E.K.
T >> T̄
CM / SEC.
N. MILES
A
EST
1330
1530
1630
1730
1830
1930
2030
2130
2230
SURF. SAL ‰
80°
70°
60°
50°
DEPTH IN FEET



SECTION Y → 310° T.
2300 JUNE 5 – 1300 JUNE 6
1953
LORAN D.R.
G.E.K.
T >> T̄
CM / SEC.
N. MILES
A
E.S.T.
80°
70°
60°
DEPTH IN FEET


SECTION Z → 130° T.
1300 JUNE 6 - 0100 JUNE 7
1953
LORAN D.R.
G.E.K.
T >> T̄
CM / SEC.
N. MILES
A
EST
1330
1430
1530
1630
1730
1830
1930
2030
2130
2230
2330
0030
SURF. SAL. ‰
80°
70°
60°
DEPTH IN FEET

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