

A DESCRIPTION AND AN ANALYSIS  
OF MEANDERS IN THE GULF STREAM

by

THOMAS FERRIS WEBSTER

B.Sc., University of Alberta  
(1956)

M.Sc., University of Alberta  
(1957)

SUBMITTED IN PARTIAL FULFILLMENT  
OF THE REQUIREMENTS FOR THE  
DEGREE OF DOCTOR OF  
PHILOSOPHY

at the  
MASSACHUSETTS INSTITUTE OF  
TECHNOLOGY

February, 1961

Signature of Author . . . . .  
Department of Geology and Geophysics. *January 13, 1961*

Certified by . . . . . Thesis Supervisor

Accepted by . . . . .  
Chairman, Departmental Committee  
on Graduate Students

1

A DESCRIPTION AND AN ANALYSIS  
OF MEANDERS IN THE GULF STREAM

by

Thomas Ferris Webster

Submitted to the Department of Geology and Geophysics on January 9, 1961, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

Data from a month of continuous surface observations across the Gulf Stream show a periodic time variation in the position of the current. The region studied is off Onslow Bay, North Carolina, where the current is close to the edge of the continental shelf. The dominant periods of the position variations correspond to the periods of the offshore winds between Charleston, S. C. and Cape Hatteras, N. C. There is, however, no indication of resemblance between the periods of the stream positions and the more persistent downstream winds.

The dominant variations in position, referred to here as meanders, have amplitudes of 10 km. Lunar components, either monthly or diurnal, have amplitudes which are, at most, small in comparison with those of the principal meanders.

Although the meanders off Onslow Bay may be analogous to the multiple currents found downstream, their periods eliminate them as incipient forms of the large-scale meanders. An average section for the month of observations is presented, and shows a stream profile much more broad than is found on any individual crossing.

Using surface velocities, calculations of the transfer of kinetic energy from meanders to mean flow were made both off Onslow Bay and in the Straits of Florida

between Miami and the Bahamas. In both cases, it was found that the meanders transferred momentum against the velocity gradient, exactly opposite to what would be expected if they were frictionally driven. The observations suggest that the mean flow of the Gulf Stream is enhanced by the kinetic energy of meanders, and that the meanders should therefore derive their energy from sources other than the kinetic energy of the mean flow.

Thesis Supervisor: William S. von Arx

Title: Professor of Oceanography

## PREFACE

This thesis consists primarily of two papers. The first is a description of Gulf Stream meanders off Onslow Bay; the second is an inquiry into the balance of kinetic energy in the Florida Current. Though related, it is believed that these papers are of sufficiently different character to warrant separate publication. Because each is given here substantially in the form that will be submitted for publication, there is a certain amount of duplication.

In addition, the thesis contains supplementary material which is not intended for separate publication, but which is added to provide background and to indicate directions of inquiry which have been pursued during the development of the thesis.

The author wishes to acknowledge the assistance of the following:

W. S. von Arx, who initiated and directed the program of observations which are analyzed here, for his encouragement and help throughout the preparation of the thesis.

K. Bryan, Jr., for suggesting that eddy kinetic energy calculations be tried, and for further suggestions in the course of many stimulating discussions.

V. P. Starr, for encouragement and advice

during the preparation of the second part of this thesis.

B. A. Warren, for critically reading the thesis.

Helen F. Phillips, for typing the manuscript through many drafts, and for many useful suggestions on the presentation of the material.

D. F. Bumpus and C. G. Day, for work done during CRAWFORD Cruise 18, on which the data were collected.

Much of the data included here were reduced and checked by Nellie Andersen.

Diagrams 1 through 23 were drafted by Richard von Dannenberg and Charles Innis.

The one hundred and twenty cross-sections were drafted by Gale Pasley and Mary Minot.

Most of the funds supporting this research were provided by the Office of Naval Research, under contract Nonr2196(00). In addition, the author wishes to acknowledge the award of an MIT Canadian Trust Fund Scholarship.

TABLE OF CONTENTS

	PAGE
ABSTRACT . . . . .	2
PREFACE . . . . .	4
TABLE OF CONTENTS . . . . .	6
LIST OF FIGURES . . . . .	8
LIST OF TABLES . . . . .	9
HISTORICAL INTRODUCTION . . . . .	10

PART I

A DESCRIPTION OF GULF STREAM MEANDERS OFF ONSLOW BAY .	24
1. Introduction . . . . .	25
2. Basic Data . . . . .	27
Surface temperature	
100-meter temperature	
Depth of 20-degree isotherm	
Surface salinity	
General features of the space-time diagrams	
3. Analysis of the Data . . . . .	37
Cold tongues	
Periodic components of meanders	
Characteristics of an average Gulf Stream	
Comparison with meanders farther downstream	
An idealized meander	
References . . . . .	53

PART II

THE KINETIC ENERGY OF GULF STREAM MEANDERS . . . . .	56
1. Introduction . . . . .	57

2. Observations . . . . .	57
GEK Data	
Onslow Bay	
Florida Straits	
3. Energy Calculations . . . . .	65
Onslow Bay	
Florida Straits	
Statistical significance of results	
4. Discussion of Results . . . . .	68
Scale of perturbations	
Regeneration time	
Atmospheric similarities	
Austausch coefficients	
5. Kinetic Energy Equation . . . . .	80
6. Conclusions . . . . .	86
References . . . . .	88

APPENDIX

1. Surface Velocities . . . . .	92
Downstream surface velocity	
Stream function	
2. Correlation between surface velocity and subsurface	
temperature . . . . .	97
3. Variations in Flow . . . . .	99
4. Advection of Mean Kinetic Energy by Eddies . . . . .	105
5. Reynolds Stress as a Correlation Coefficient . . . . .	107
6. Suggestions for Future Research . . . . .	110
7. CRAWFORD 18 Cross-sections . . . . .	114
BIBLIOGRAPHY . . . . .	135
BIOGRAPHICAL NOTE . . . . .	143

LIST OF FIGURES

FIGURE		PAGE
1	Onslow Bay Area . . . . .	26
2	Surface temperature, CRAWFORD Cruise 18 . . . . .	30
3	100-meter temperature, CRAWFORD Cruise 18 . . . . .	31
4	Depth of 20-degree isotherm, CRAWFORD Cruise 18 . . . . .	33
5	Surface salinity, CRAWFORD Cruise 18 . . . . .	34
6	Position of stream center, CRAWFORD Cruise 18 . . . . .	36
7	Harmonic components of meanders . . . . .	42
8	Atmospheric pressure difference between Cape Hatteras and Charleston, and position of stream center during CRAWFORD Cruise 18 . . . . .	44
9	Lagged atmospheric pressure and meanders . . . . .	45
10	Cross-section of average current . . . . .	47
11	Idealized meander structure . . . . .	51
12	Florida Current region . . . . .	59
13	Florida Straits . . . . .	62
14	Average surface velocity, Florida Straits . . . . .	64
15	Production of mean kinetic energy, Onslow Bay . . . . .	67
16	Production of mean kinetic energy, Florida Straits . . . . .	70
17	Production of zonal kinetic energy, atmosphere . . . . .	77
18	GEK velocity, CRAWFORD Cruise 18 . . . . .	93
19	Surface stream function, CRAWFORD Cruise 18 . . . . .	96
20	Half-width . . . . .	100
21	Maximum velocity . . . . .	101
22	Shape factor . . . . .	102
23	Transport . . . . .	103
24 to 43	CRAWFORD 18 Cross-sections . . . . .	115 to 134



LIST OF TABLES

TABLE		PAGE
I	Comparison between lightship surface salinities and temperatures and those found in cold tongues . . . . .	38
II	Energy flux, Onslow Bay . . . . .	66
III	Energy flux, Florida Straits . . . . .	69
IV	Florida Straits velocities as determined by Pillsbury . . . . .	72
V	Eddy advection of mean kinetic energy . . . . .	106
VI	Reynolds stress as correlation coefficient . . . . .	108

## HISTORICAL INTRODUCTION

The object of this thesis is to study the surface structure and kinetic energy of meanders of the Gulf Stream south of Cape Hatteras. The region south of Cape Hatteras is of interest for two reasons. (1) Because little is known about meanders in that area; there is common belief that meanders do not become developed until the stream passes Cape Hatteras. However, it is now known that meanders south of Cape Hatteras do exist, and further description of them is needed. (2) Because the meanders upstream from Cape Hatteras are smaller than those found downstream, observations and analyses of the former can be more easily undertaken. It is hoped that the analysis of data taken upstream from Cape Hatteras will provide information of a fundamental character which can have application downstream as well.

The following brief historical outline is intended to review those studies which have revealed or analyzed the meandering flow of the Gulf Stream.

Observational Studies. Investigations of the Gulf Stream have, until recently, been mostly centered on a description of broad, average features. Only after a large number of cruises did it become apparent that the flow was, in fact, not smooth and continuous, but irregular, possibly interrupted, and of variable strength.

Pillsbury (1891), an oceanographer of the United States Coast and Geodetic Survey, made a thorough study of the current between the Gulf of Mexico and Cape Hatteras. His study produced evidence of fluctuations in transport, which he attempted to relate to the declination of the moon. He also noted lateral variations in the position of the current, and that the amplitude of these variations increased downstream. He speculated that the variations would increase beyond Cape Hatteras, and eventually result in the obliteration of the boundaries of the Gulf Stream. He concluded, moreover that the current was not divided by irregular bottom topography. Bache (1860) had suggested this from an earlier study, which revealed veins of cold water, which he supposed were indications of a division of the stream, produced by an irregular bottom. Pillsbury's soundings revealed that the bottom was too regular to be the source of branching of the current.

After Pillsbury's measurements, little new was done until about thirty years later when advances in instrumentation stimulated fresh investigations. The development of the continuously recording thermograph provided a means for rapid surface surveys of large ocean areas. Thermographs were installed on commercial ocean liners running between Bermuda and North America. The resulting surface temperatures provided evidence of time variations of the position of the Gulf Stream. Church (1937) analyzed such data and

concluded that the Gulf Stream executed "lateral wanderings" or meanders, which increased in amplitude as the Gulf Stream progressed northeastward from Cape Hatteras. He reported, moreover, that onshore migrations of Gulf Stream water occasionally occurred at Diamond Shoals Lightship, near Cape Hatteras, with a meander amplitude of about thirty or forty miles, in good accord with the latest measurements.

Hachey (1939) made a study of ten years of thermograph records obtained between Halifax, Boston, and Bermuda. He detected what seemed to be a seasonal migration of the Gulf Stream axis, with southerly excursions of the stream occurring at the equinoxes. However, his data show wide deviations from this rule in certain years. In addition, he calculated the intensity of the current flow from considerations of the sea level difference between Bermuda and Charleston, and found a seasonal variation. He went on to relate the variations in transport with the seasonal migrations of the stream axis, concluding that in periods of weakening flow, the position of the Gulf Stream moved closer to the American continent.

Iselin made an extensive study of the circulation of the western North Atlantic in the 1930's. The Gulf Stream System, as portrayed by Iselin (1936), is fed by additions of water from the Sargasso Sea region as it flows between the Straits of Florida and Cape Hatteras. Beyond Cape Hatteras, the current attains its maximum transport and then

continues with relative uniformity until it passes the Grand Banks. Beyond this point it seems gradually to dissipate into a number of divergent branches.

In a further study of the Gulf Stream System Iselin (1940) investigated the variations in transport. He assumed that the current system in the North Atlantic was a single clockwise eddy, whose central core was the Sargasso Sea, and that an increase in transport would cause the eddy to deepen and contract. Weakening currents, on the other hand, would result in expansion of the eddy with some shoaling and spreading of the central core. Iselin supposed that such a mechanism might explain the apparent seasonal migrations of the current.

The development of the bathythermograph (BT) during the Second World War made rapid surveys of the upper water layers possible. While making BT temperature sections across the Gulf Stream, Spilhaus (1940) found a feature in the thermal structure which he described as an eddy. A later study by Spilhaus (1941), in which he mapped the fine structure of the surface temperature over an area of about five hundred square miles, showed an interfingering of warm and cold water along the inshore edge of the current. The complexity of the temperature structure led him to conclude that the supposed smoothness of the onshore edge was merely a statistical view of many such interfingerings.

Another technological advance made during the

Second World War was the development of Loran, a navigational system which enabled the position of a ship to be determined by electronic means. The scales of time-variations of Gulf Stream structure made such a position-finding device necessary before quantitatively significant studies could be made of them. By providing nearly continuous and reasonably accurate knowledge of a ship's position in the Gulf Stream region, Loran permitted more detailed determinations of currents, by comparison of radio and dead-reckoned positions, than had been possible with celestial navigation.

Surveys over large regions, using Loran, revealed new aspects of the time variations of the Gulf Stream system. In post-war studies, Iselin and Fuglister (1948) found eddies on both side of the Gulf Stream: cyclonic eddies to the right of the main current and anti-cyclonic eddies to the left, looking downstream. These eddies appeared to be meander loops which had broken off from the Gulf Stream proper. An eddy observed during June, 1947 had an east-west length of 200 miles and a north-south length of 60 miles. Iselin and Fuglister also found meanders with increasing amplitude downstream from Cape Hatteras, in accord with Church's conclusions. Because of these meanders, they concluded that it was not possible to tell from a single section whether the regional trend of the Gulf Stream was north or south of its mean position. Consequently, it became doubtful that the stream really underwent seasonal north-south migra-

tions, as Hachey had concluded on the basis of data from individual sections.

The development of the geomagnetic electrokinetograph (GEK) by von Arx (1950) provided a swift method for measuring surface currents from a ship while underway. Together, the GEK and the bathythermograph could be used to determine the velocity and the temperature structure of the surface layer from a research vessel cruising at normal speed.

These newly developed methods of measurement and navigation were combined in Operation CABOT, a multi-ship exploration of the surface layer of the Gulf Stream between Cape Hatteras and the Grand Banks of Newfoundland, during June, 1950. The observations (Fuglister and Worthington, 1951) showed a meander structure which increased in amplitude beyond Cape Hatteras. The formation of an anti-cyclonic eddy, from the breaking off of a meander to its separate identity, was followed step-by-step during a twelve day period. In addition, cyclonic eddies were observed north of the stream. Data from Operation CABOT revealed "gobs" of warm water in the Gulf Stream which seemed to the authors to indicate a pulsing action, perhaps related to some short period variations in the transport.

In a further examination of the CABOT data, Ford, Longard and Banks (1952) noted a narrow filament of cold, relatively fresh water along portions of the left-hand side of the stream. From the temperature and salinity it seemed

evident that this water did not come from depth, but originated on the continental shelf north of Cape Hatteras, possibly as river run-off. Although a cold filament was not observed on every crossing along the whole length of the left hand edge, it might have been missed because the interval between half-hourly BT's is long enough to completely miss a filament whose width is less than five miles. In a study of the surface temperature profiles of one hundred crossings of the Gulf Stream, Strack (1953) found the cold filament to be present generally, but often wider than observed by Ford, et al.

von Arx (1952) and Worthington (1954) made a detailed study of the velocity profile and density structure on several crossings of the Gulf Stream south of Cape Cod. Their studies were intended both to provide typical details of surface velocity and density across the Gulf Stream and to test and compare the newly developed techniques for current measurement. Their characteristic profile had a sharp region of cyclonic shear to the left of the current maximum (looking downstream) and a broad region of anti-cyclonic shear to the right. The cyclonic shear was usually greater than the value of the Coriolis parameter and the anti-cyclonic shear less.

Fuglister (1951), showed that the data collected during Operation CABOT could be interpreted as a series of laterally overlapping currents separated by weak counter-currents. Re-analysis of several additional sets of data taken in the Gulf Stream region (Fuglister, 1955) demonstrated



that the interpretation of hydrographic observations of conventional horizontal scale was ambiguous; instead of giving a unique picture of current structure, these measurements cannot be used to distinguish between a single meandering current and a set of loosely connected currents and counter-currents. This ambiguity leaves an element of subjectivity to the scientist.

Partly in an effort to resolve this ambiguity, optical measurements of sea-surface temperature were undertaken from an airplane (Stommel, von Arx, Parson, and Richardson, 1953). A two-day aerial survey of the Gulf Stream System from the Florida Straits to longitude 70°W (von Arx, Bumpus, and Richardson, 1955) revealed a pattern of sea-surface temperatures corresponding to a shingled structure of overlapping, discontinuous segments, having lengths of a few hundred kilometers. So far as could be determined from the air, there was no continuous stream. The discontinuities were found both downstream and upstream from Cape Hatteras, and the general pattern was compatible with a multiple-current theory.

A different approach to the study of the Gulf Stream current was devised by Malkus and Johnson (1954). In an attempt to determine the nature of possible formation of multiple branches of the current, a ship was allowed to drift with the current while measurements of the water properties were taken. It was hoped that, during the drift, changes in

the structure of the stream relative to the ship would indicate a possible branching or meandering and thus partially resolve the ambiguity of the data. They found that the ship eventually drifted out of the main current, and that a run of several tens of kilometers westward was generally necessary to find a strong current again. The cruise underscored the need for more than one ship at any one time in order to produce unambiguous results.

Stimulated by the temperature pattern observed from the air, von Arx, Bumpus and Richardson (1955) developed a procedure for observing the continuous passage of the Gulf Stream across a section. Sailing back and forth along a single line, they charted the changes with time of temperature, salinity and velocity. The observations, taken near Onslow Bay, just south of Cape Hatteras, again gave evidence of a meander structure, but the sparseness of the data prevented its clear definition.

The character of the flow through the Florida Straits as revealed by an extensive series of observations is apparently different from that farther downstream off Cape Hatteras. Most investigators have concluded that the principal variations in the flow are produced by tidal influences. Pillsbury made time studies of the variations in current strength which led him to conclude that they were tidally induced. In a series of anchor stations made in the Straits of Florida between Miami, Florida and Gun Cay, Bahamas, Parr

(1937) also found what he considered to be strong diurnal, and hence tidal, variations in the temperature and salinity fields.

The University of Miami Marine Laboratory has conducted an extensive program of GEK measurements of velocity in the Straits of Florida during the past ten years. Their studies (Murray, 1952; Wagner and Chew, 1953; Hela, Chew and Wagner, 1954; Chew, 1958) have indicated an apparent tidal fluctuation in the velocity and transport as well as tidal transverse motions. In addition, they note non-tidal variations which are difficult to isolate.

von Arx, Bumpus and Richardson (1955) calculated that the Straits of Florida transport could vary by as much as a factor of two as a result of the changing hydraulic heads associated with the rise and fall of the diurnal tide in the Gulf of Mexico. They went on to speculate that the daily variation in the flow through the Straits of Florida might be related to the formation of the discontinuous "shingles" which had been observed further downstream. It was possible, they suggested, that each shingle represented a single day's outflow from the Gulf of Mexico.

Theoretical Studies. Theoretical studies which aim to explain the behaviour of the Gulf Stream meanders have been conducted mostly during the last fifteen years. Rossby (1936) postulated that the Gulf Stream flow was

analogous to that of a turbulent jet. Such a flow would interact with the surrounding water by turbulent mixing. One might expect to find eddies, or meanders, which would dissipate energy. Observations have failed to disclose a consistent downstream increase in the stream or the counter-currents necessary to sustain such a flow.

Stommel (1948) developed dynamical reasons for an intensification of western boundary currents. The currents should provide a mechanism for the dissipation of large amounts of kinetic energy. Munk (1950) developed a relation between such currents and the regional wind stress. In these models, meanders could possibly provide the necessary frictional dissipation. However, though the theoretical models of Stommel and Munk required that the North Atlantic currents should be concentrated in the west, the required currents did not need to be filamentary. The western boundary current could be entirely satisfied by the statistical or climatological mean Gulf Stream, and the narrow, filament-like structure could be induced by other causes. Thus, although it was possible to incorporate meanders into a frictional boundary current theory, their role was uncertain.

The possibility that a mathematical model based on the unstable flow of a narrow current might provide a dynamical explanation of the observations encouraged some theoretical studies. Haurwitz and Panofsky (1950) constructed a mathematical model of a narrow current flowing

near a wall (representing the edge of the continental shelf) in which the cross-stream profile of downstream velocity was specified. They supposed that the character of the horizontal shear of the mean flow might render it unstable to small perturbations, and found that waves could grow by drawing energy from the mean flow provided that the current had left the vicinity of the continental shelf. This result was in accord with the belief that the meanders south of Cape Hatteras were negligible. Haurwitz and Panofsky did not take any account of bottom topography.

Stommel (1953) investigated the meanders which could occur in a wide current in a two-layer ocean. He specified the steady current velocity by giving the form of the interface. He then examined the effect of infinitesimal perturbations of the mean current. Stommel did not intend his theory to be realistic; he merely was attempting to determine the effect of horizontal divergence in stratified currents. Nevertheless, characteristic values of physical parameters did yield a critical wavelength (180 km) which corresponded to that of a meander observed during Operation CABOT (Fuglister and Worthington, 1951).

Saint-Guilly (1957) made a theoretical study of the formation of meanders and their development into eddies, in an attempt to explain the observed break-off of an eddy from the main stream during Operation CABOT. Saint-Guilly defined general criteria which might lead to stability or

instability of a meandering current, but did not make particular applications to the observed Gulf Stream.

Newton (1959), stimulated by a suggestion of Rossby that atmospheric and oceanic current systems are similar, made a comparison between the Gulf Stream and the atmospheric jet stream. He found equivalences between distance and velocity scales, meander sizes, lateral shears, and thermal structure in the two systems.

Summary. The picture of the Gulf Stream which has emerged at the present is that of a narrow discontinuous current which begins to meander somewhere in the region of Cape Hatteras. As it progresses northeastward from Cape Hatteras, the meanders increase in amplitude.

The results of ship observations can be interpreted in more than one way. Equally valid patterns ranging from a single contorted unbroken current to a whole series of independent unconnected currents can be obtained depending on the choice of the analyst. The only means for resolving this ambiguity seems to be an extensive, nearly simultaneous network of observations.

Whatever interpretation one chooses to give to ship observations, it is apparent, at least beyond Cape Hatteras, that the Gulf Stream does not flow regularly or smoothly. The behaviour of the Gulf Stream upstream from Cape Hatteras may be basically similar, but because the mean

flow is so close to the shore, there is little opportunity for large amplitude meanders to develop. This restriction of amplitude may be a benefit for the oceanographer, since small amplitude meanders can be sectioned more frequently and studied with a far higher degree of control than is possible farther downstream.

The present study reports on a month's surface observations of the current off Onslow Bay, south of Cape Hatteras. It was hoped that these continuous observations would answer the questions: (1) Does the Gulf Stream meander south of Cape Hatteras, and if so, what is the structure of the meanders? (2) What is the role of the meanders with respect to the mean flow?

## PART I

### A DESCRIPTION OF GULF STREAM MEANDERS OFF ONSLOW BAY

#### ABSTRACT

Data from a month of continuous surface observations across the Gulf Stream show a periodic time variation in the position of the current. The region studied is off Onslow Bay, North Carolina, where the current is close to the edge of the continental shelf. The dominant periods of the position variations correspond to the periods of offshore winds. The amplitude of these dominant variations, or meanders, is 10 km. Lunar components, either monthly or diurnal, have amplitudes which are, at most, small in comparison with those of the principal meanders.

Although the meanders off Onslow Bay may be analogous to the multiple currents found downstream, their periods eliminate them as incipient forms of the large-scale meanders. An average section of velocity and temperature during the month of observation is presented.



## 1. Introduction

Meanders are among the most intriguing and baffling aspects of the Gulf Stream System. Although meanders north of Cape Hatteras have been the subject of a certain amount of study, little is known of their behaviour between the Florida Straits and Cape Hatteras, where the Gulf Stream flows close to shore over the Blake Plateau. This region would probably be a fruitful one for study, since the amplitude of meanders is constrained by the nearness of the main current to the continental shelf.

In order to seek information on meanders in this region, a month-long cruise was made in the research vessel CRAWFORD by W. S. von Arx, D. F. Bumpus and C. G. Day during May and June, 1958. The ship made 120 consecutive crossings of the axis of the Gulf Stream during a 28-day period. Figure 1 shows the path of the sections. Point "A" is the intersection of the path with the axis of the climatological mean Gulf Stream, as estimated by the United States Coast and Geodetic Survey. Measurements were made of the surface salinity and velocity, and of the temperature to a depth of 200 meters. The general procedure of this cruise was similar to one undertaken by von Arx, Bumpus, and Richardson (1955) in the research vessel CARYN, but the duration and concentration of measurements were much greater.

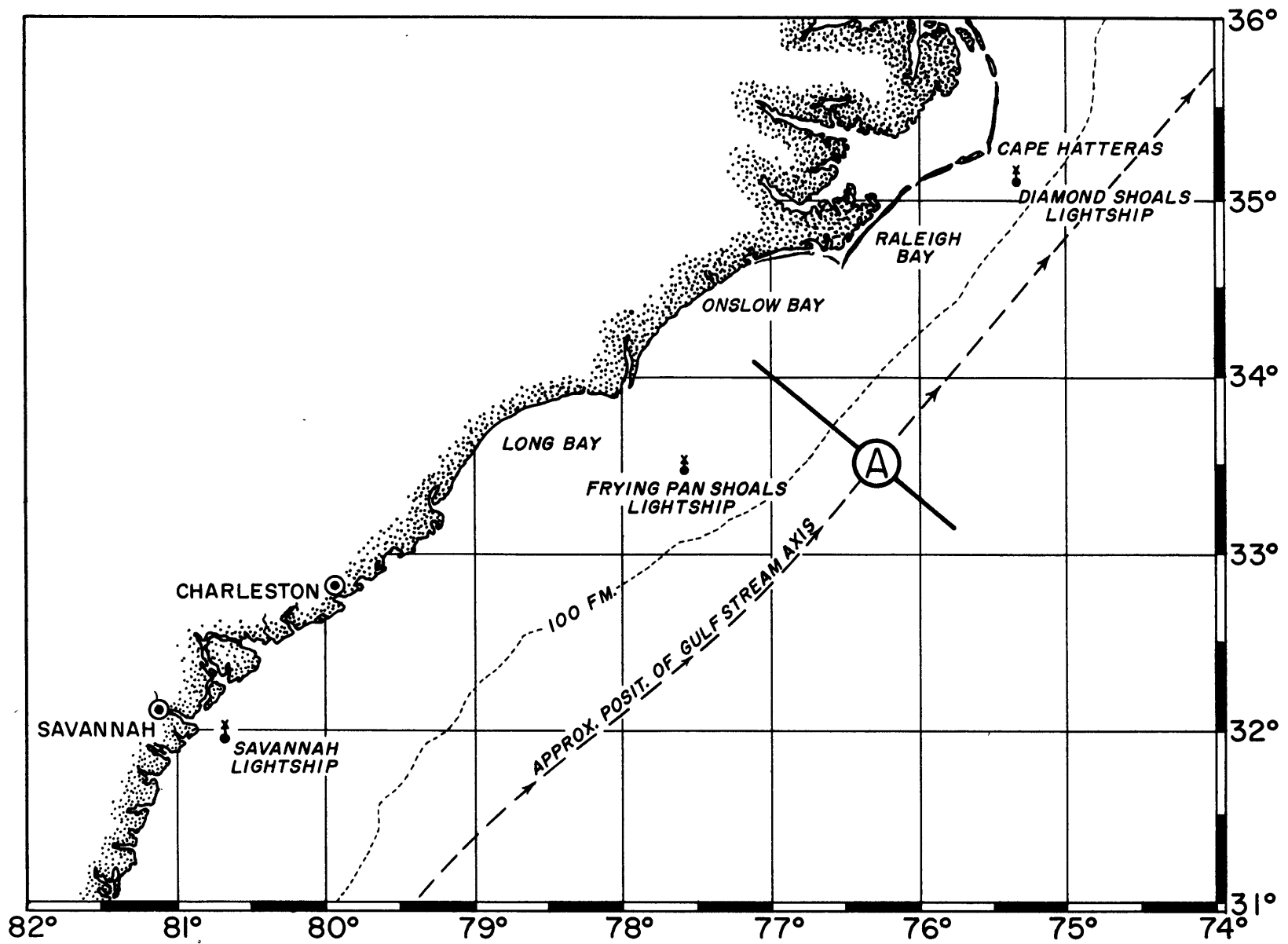


Figure 1  
Onslow Bay area

Because the observations were restricted to a single lunar month, only a relatively small portion of the spectrum of Gulf Stream time variations could be sampled. Moreover, the time necessary to complete a single crossing of the current was about six hours, and hence the frequency of sections was too low to permit semidiurnal tidal effects to be measured. By extending the duration of measurements to 28 days, it was hoped that the lunar monthly effects, if any, could be observed. Hence, the data are most useful for determining the characteristics of time variations having periods greater than a day and less than a month.

## 2. Basic Data

Throughout the cruise, a bathythermograph (BT) measurement, giving temperature as a function of pressure to a depth of 200 meters, was taken every half-hour. At the time of each BT lowering, a bucket sample of surface water was taken, to be analyzed later for salinity. The surface water velocity vector was determined hourly, by means of the geomagnetic electrokinetograph (GEK) (von Arx, 1950). The position of the ship at each BT and GEK observation was determined by a LORAN fix, to confirm the choice of ship's course to keep as close as possible to the planned cruise line. Each crossing was continued across the current as far as was necessary to define the onshore edge of the band of maximum velocity.

The observations were plotted to form a set of space-time diagrams: namely those in which the values along the line of traverse were plotted against time of observation. Isopleths were drawn to connect the sections. These space-time diagrams bear some resemblance to the pattern of the stream as it might be if viewed from above. This resemblance is easily misinterpreted when analyzing the data, since there is an erroneous tendency to interpret the time axis as a space axis. Changes of the current in time at a point are not, of course, necessarily dependent upon the spatial variation of the current. Hence, when reading a space-time diagram, it is well to remember that the long axis represents time, not distance.

First, the particular features of each of the space-time diagrams will be discussed. Then, the diagrams will be considered as a group, and their general features will be described.

Surface Temperature. The surface temperatures were measured by means of a thermistor bead mounted in the bow of the CRAWFORD about two feet below the water line. The resistance of the bead was recorded continuously on a strip chart recorder calibrated for temperature. This permitted the sharp temperature gradients to be well located in space and time. The temperature records for the crossings were plotted as profiles on the cross-sections (see Appendix,

Section 7). From these 120 profiles, the space-time diagram, Figure 2, has been constructed. The straight, slanting lines across the face of the diagram represent the path of the ship in space and time. Along this path, the temperature was measured continuously; between path lines, the isotherms were contoured smoothly.

The surface temperatures were particularly susceptible to seasonal warming during the period of CRAWFORD Cruise 18. The maximum temperature at the beginning of the cruise was about twenty-five degrees Centigrade, and at the end of the cruise, the maximum temperature was about twenty-eight degrees. This seasonal, or vernal, warming tends to diminish the surface-temperature contrast across the Gulf Stream and make the definition of the stream edges more difficult. In spite of the major handicap of vernal warming, the surface temperatures are nevertheless useful because they can be compared with the other physical quantities such as current velocity and salinity which were in general measured only at the surface.

100-meter Temperature. The 100-meter temperatures on the space-time diagram (Figure 3) are bathythermograph (BT) data. Since BT lowerings were made at half-hourly intervals, the actual temperature gradients at a depth of 100 meters may have been much sharper than the necessarily smoothed contours indicate. However, the temperature at 100 meters is

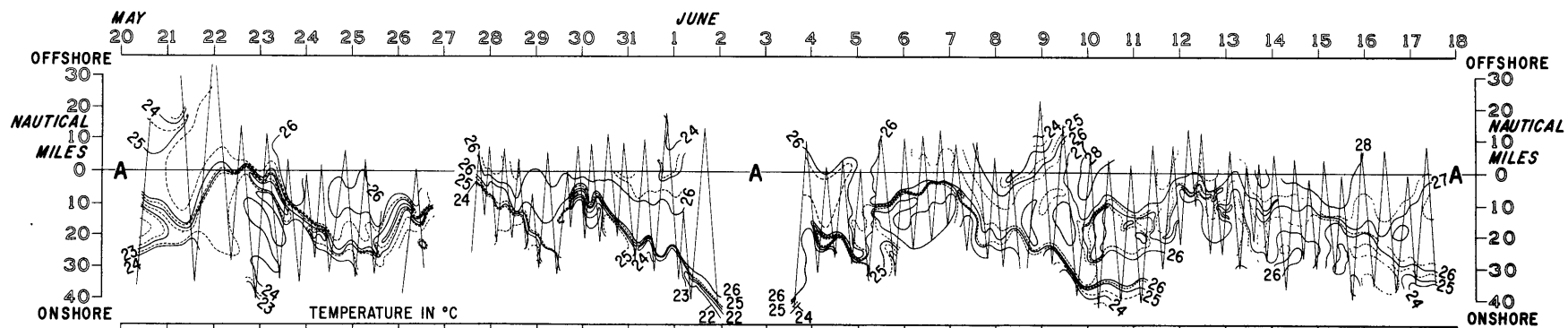


Figure 2

Surface temperature, CRAWFORD Cruise 18

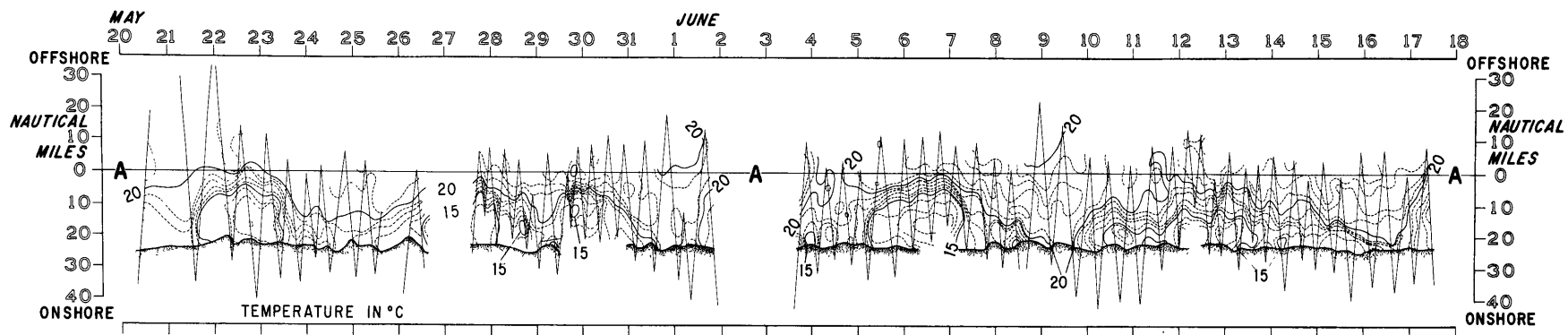


Figure 3

100-meter temperature, CRAWFORD Cruise 18

relatively unaffected by vernal warming, so that it is more useful than surface temperature for comparison of the structure of the current between different portions of the cruise.

The lower stippled boundary of this diagram represents the position of the continental slope at a depth of 100 meters. The fluctuations in its position are due to uncertainties in position measurements and deviations of the ship's course from the cruise line.

Depth of 20-degree Isotherm. The topography of the 20-degree (Centigrade) isotherm (shown in Figure 4) was also drawn from BT observations. It was plotted as an attempt to determine the internal motions associated with meanders of the current. 20°C was chosen because shallower isotherms were subject to the distortions of vernal warming and deeper isotherms often dropped below the depth accessible to the BT.

Surface salinity. The surface water samples, which were routinely taken at the time of each BT lowering, were analyzed on a Schleicher-Bradshaw conductivity bridge. (Schleicher and Bradshaw, 1956.) The surface salinity, shown in Figure 5, is determined on the assumption of a direct relation between conductivity and salinity, for which the conductivity bridge is calibrated.



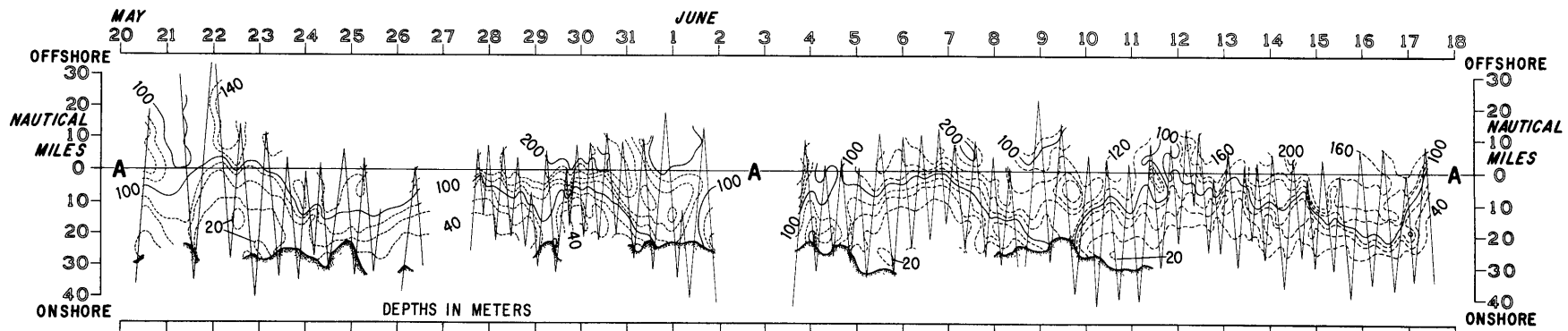


Figure 4

Depth of 20-degree isotherm, CRAWFORD Cruise 18

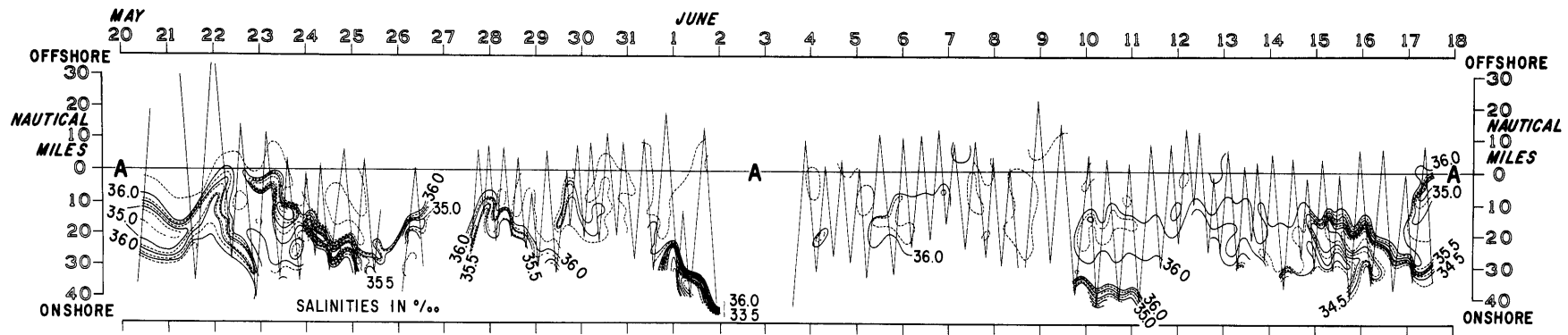


Figure 5

Surface salinity, CRAWFORD Cruise 18

General Features of the Space-Time Diagrams.

Each of the space-time diagrams shows a series of meanders of the stream. The surface temperature diagram shows periodic occurrences of a sharp temperature gradient across the section. These sharp temperature gradients seem to form at an offshore position and to move onshore as time increases, generally becoming more intense. Since the direction of current flow is exactly opposite to the direction of increasing time, the current is actually flowing offshore, decreasing in intensity as it does so. A region of sharp temperature gradient is followed by a broad diffuse temperature gradient region which once again reforms into another offshore sharp gradient.

Surface readings, though suggestive, are not sufficient for delineating the meanders because the surface layer is influenced both by vernal warming and by shifting winds. Consequently, the temperature at a depth of 100-meters and the depth of the 20°C isotherm, are more useful in defining the center of the Gulf Stream and its edges. It is found, upon comparing the surface velocity with the 100-meter temperature, that the position of the 20°C isotherm at 100 meters depth corresponds closely with the path of maximum downstream velocity as defined by the GEK on each crossing (Figure 6). Hence, it is possible to define a center of the stream using either the BT or the GEK; either the 20°C isotherm at 100 meters depth or the maximum velocity across the

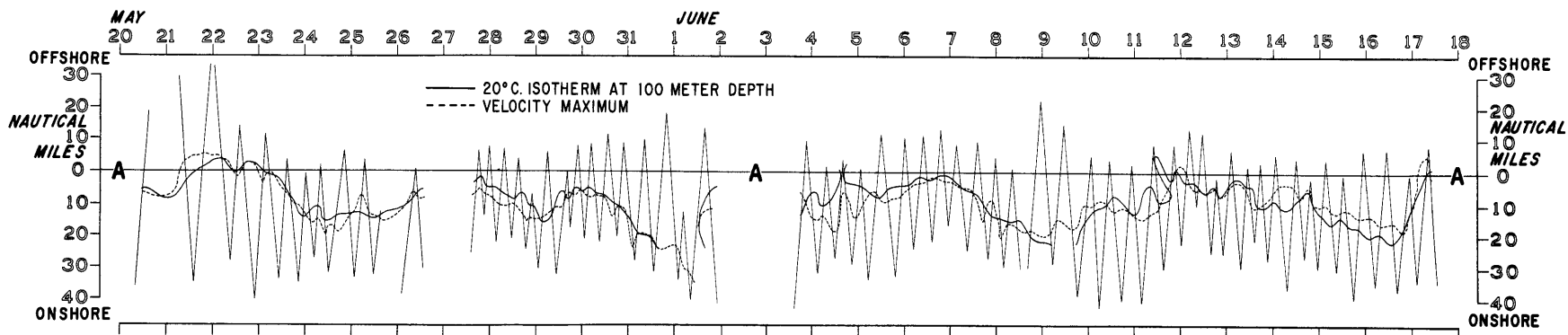


Figure 6

Position of stream center, CRAWFORD Cruise 18

section may be chosen as the center of the stream in Onslow Bay.

### 3. Analysis of the Data

Cold Tongues. Together, the surface temperature and salinity define bands, or tongues, of water both colder and less saline than that on either side.

These tongues are found shoreward of the stream center. It will be noted that towards the end of the cruise, the salinity record shows another of these offshore-running tongues, but that the surface temperature record defines it only poorly. This is probably an effect of vernal warming, which gives a clue to the origin of the water in the tongues. A similar warming during this period was noted at Frying Pan Shoals Lightship, between Long Bay and Onslow Bay, where, between May 15 and June 15, the surface temperature increased from 19°C to 25°C.

In addition to the temperature, the salinity also gives a clue to the origin of the water in the tongues. Both the water temperature and salinity correspond generally to that of the onshore Carolina Bays: Raleigh, Onslow and Long Bays. The temperature and salinity of the water in these regions were recorded during the cruise at lightships and have been tabulated by Day (1959).

Table I shows the temperatures and salinities as measured in the fresh cold tongues in the Gulf Stream and at

TABLE I

Comparison between lightship surface salinities and temperatures  
and those found in cold tongues during CRAWFORD 18 Cruise.  
(salinities in parts per thousand, temperatures in degrees Centigrade)

DATE	CRAWFORD 18 tongue	Frying Pan Shoals 2 days earlier	Frying Pan Shoals	Savannah	Diamond Shoals
May 24 - 25	34.5	33.0	34.0	31.0	32.0
	22.5	21.5	22.0	24.0	21.5
May 28 - 29	34.0	34.0	35.0	31.0	-
	23.0	22.5	22.0	24.0	-
May 31 - June 2	32.5	33.0	35.0	31.5	31.5
	22.0	22.0	24.0	24.0	22.0
June 10 - 11	34.0	34.0	35.0	30.0	31.5
	23.5	23.0	24.0	27.0	21.5
June 15 - 17	33.5	33.5	33.0	32.0	33.5
	26.0	26.0	25.0	26.0	25.5

the same time of the waters at Frying Pan Shoals and Savannah Lightships, both south of Onslow Bay, and at Diamond Shoals, north of Onslow Bay (Figure 1). The water at Savannah Lightship is warmer and fresher than the water in the tongues, which eliminates it as a source of tongue water. The salinity of the water at Savannah a few days before the appearance of a cold tongue is always fresher than that in the tongue by about three parts per thousand. The temperature and salinity are generally less at Diamond Shoals than in the tongues. Temperatures and salinities more compatible with those found in the tongues are found in the waters at Frying Pan Shoals. If this is indeed the source, best agreement is found when the values of temperature and salinity at Frying Pan Shoals are compared with those in the tongue at Onslow Bay two days later.

To illustrate the contrast between the shelf water and the water characteristic of the Gulf Stream in this region, note that the salinity of the water on the seaward side of the stream is consistently about 36.25 ‰ and the temperature ranges from 25° to 28°C. This is also typical of water in the main current on the shoreward side of the maximum flow. Hence, it appears that the water in the tongues is shelf water which has been entrained into the shoreward edge of the Gulf Stream current. The source of the tongue water is just south of the section under observation - probably Long Bay. This agrees with the con-

clusions of Bumpus (1955), and Bumpus and Pierce (1955), that when the Florida Current moves inshore it will entrain shelf water. Other investigators have found similar occurrences of fresh and/or cool water. Ford, Longard, and Banks (1952) reported a slender filament of cold water along the shoreward edge of the Gulf Stream, downstream from Cape Hatteras. From the salinity of the filament, they concluded that its source was river runoff from the shelf near Cape Hatteras. Similarly, Hela, and Wagner (1954) report the occurrence of relatively fresh water on the western side of the Florida Current, off Miami, which seems to originate in the north-east area of the Gulf of Mexico.

The structure of the meanders as shown in the space-time diagrams suggests that each meander forms onshore and moves offshore as it flows downstream. As each meander flows offshore shelf water remains entrained along its shoreward side. If the meanders in the Onslow Bay region are characteristic of those throughout the Gulf Stream System, then we should expect to find water from a near-shore region generally present along the inshore edge of the current.

Periodic Components of Meanders. The Fourier components of the fluctuation positions of both the velocity maximum and the 20-degree isotherm at 100 meters depth were calculated. The lunar month of 27.55 days was chosen as a basic period, and the positions of these features were



determined at 48 equi-distant points during the month to establish a 48-ordinate scheme for harmonic analysis, as outlined by Conrad and Pollak (1950). The amplitudes of the components, up to the 12th harmonic, are shown in Figure 7. The dominant harmonics are the fourth and the seventh, corresponding to periods of 6.9 and 3.9 days. There is no apparent reason to expect that the dominant harmonic components should be exact sub-multiples of a lunar month; hence the periods showing this characteristic should be regarded only as approximate. However, the prominent components have periods of the order of a week and amplitudes of about ten kilometers. It should be stressed that these harmonic components refer only to the CRAWFORD Cruise 18 data; there is no evidence to indicate that these same periods and amplitudes would be found on another cruise.

Significantly, the amplitudes of the monthly (first harmonic) and fortnightly (second harmonic) components are comparatively small, being less than 2 nautical miles (3.7 km). Their unimportance indicates that the meanders are not induced primarily by long-period lunar effects.

A possible cause of the seven-day and four-day recurrence of meanders is revealed in a comparison of the meander positions, as indicated by the 20°C isotherm, with the atmospheric pressure field during the period of observations. The sea-level barometric pressure difference be-

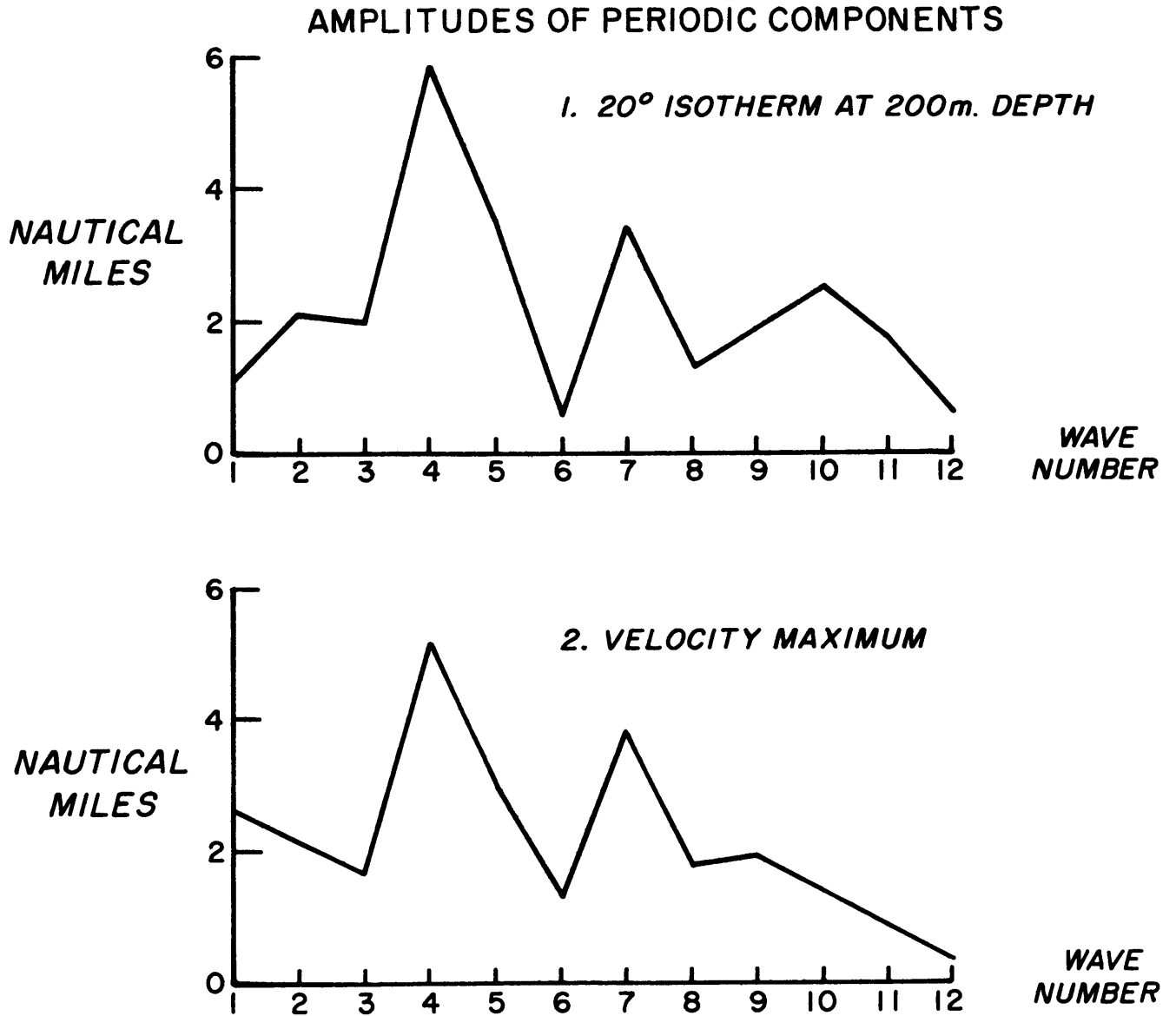


Figure 7

Harmonic components of meanders

tween Charleston, South Carolina, and Cape Hatteras was used as an index of the offshore wind. A higher pressure at Hatteras corresponds to an onshore wind. Figure 8 shows the position of the 20-degree isotherm at 100 meters and the Hatteras-Charleston atmospheric pressure difference. There is an obvious similarity in periods, but no clear indication of synchronism. If it is assumed that there is a delay in the response of the stream position to persistent winds, then the atmospheric pressure difference can be lagged. Figure 9 shows the result of introducing a lag of four and a half days, which gives the best correlation between atmospheric pressure and stream position. The stream position shown in Figure 9 was obtained by combining the dominant harmonic components (4th, 5th, and 7th) found in the Fourier analysis. The downstream wind was, during the cruise, more persistent than the offshore wind. An attempt to find a similarity in periods between the downstream wind and meanders failed, suggesting that the physical significance of the correlation between offshore winds and meanders is open to question.

Although the data are not suitable for analysis of diurnal components, it is evident from the space-time diagrams that the passage of each of the principal meanders (or shingles) is not a diurnal phenomenon, but requires a period of several days. It seems likely that, because of their relatively long time of passage, the meanders off

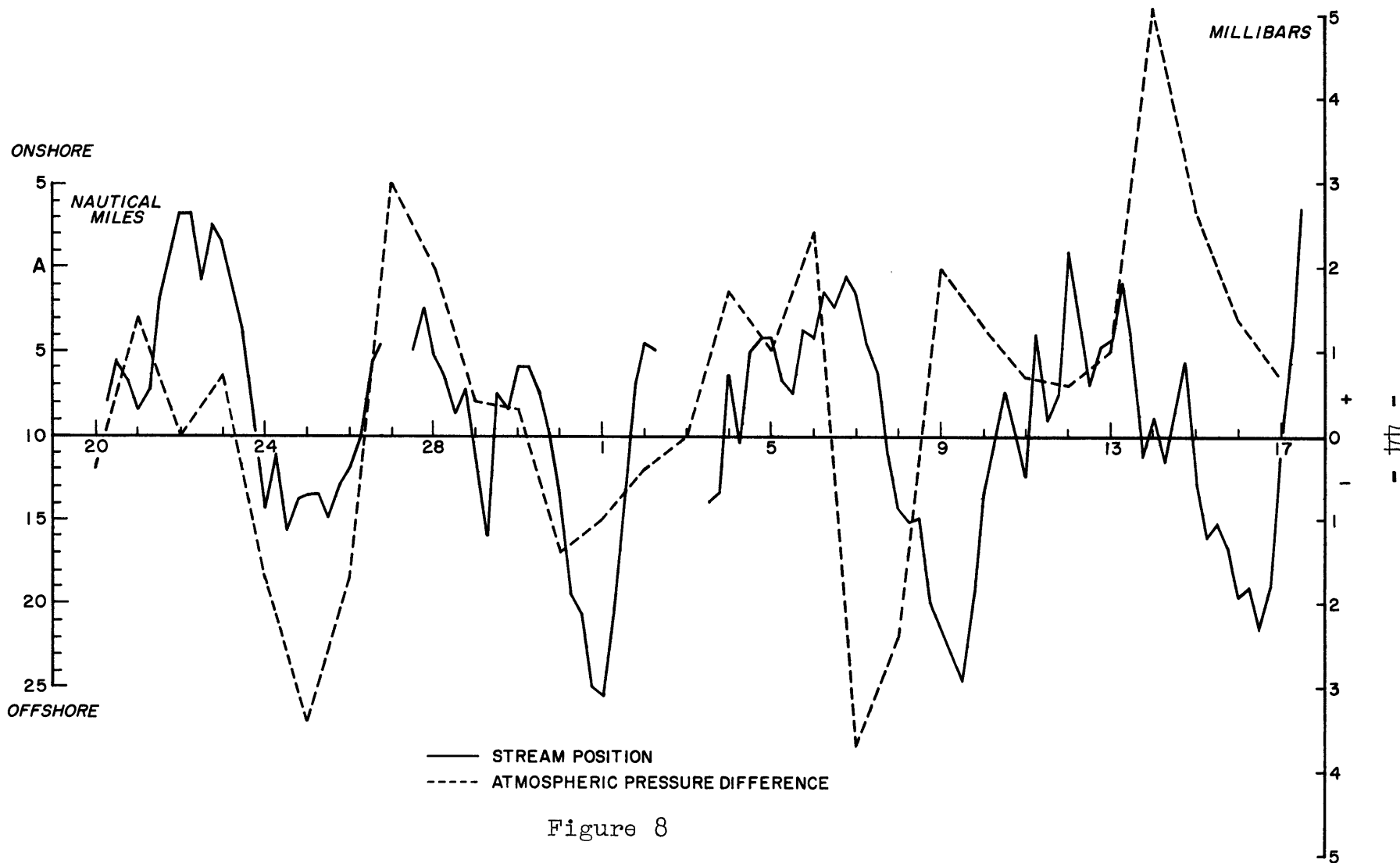


Figure 8  
 Atmospheric pressure difference between Cape Hatteras  
 and Charleston, and position of stream center  
 during CRAWFORD Cruise 18

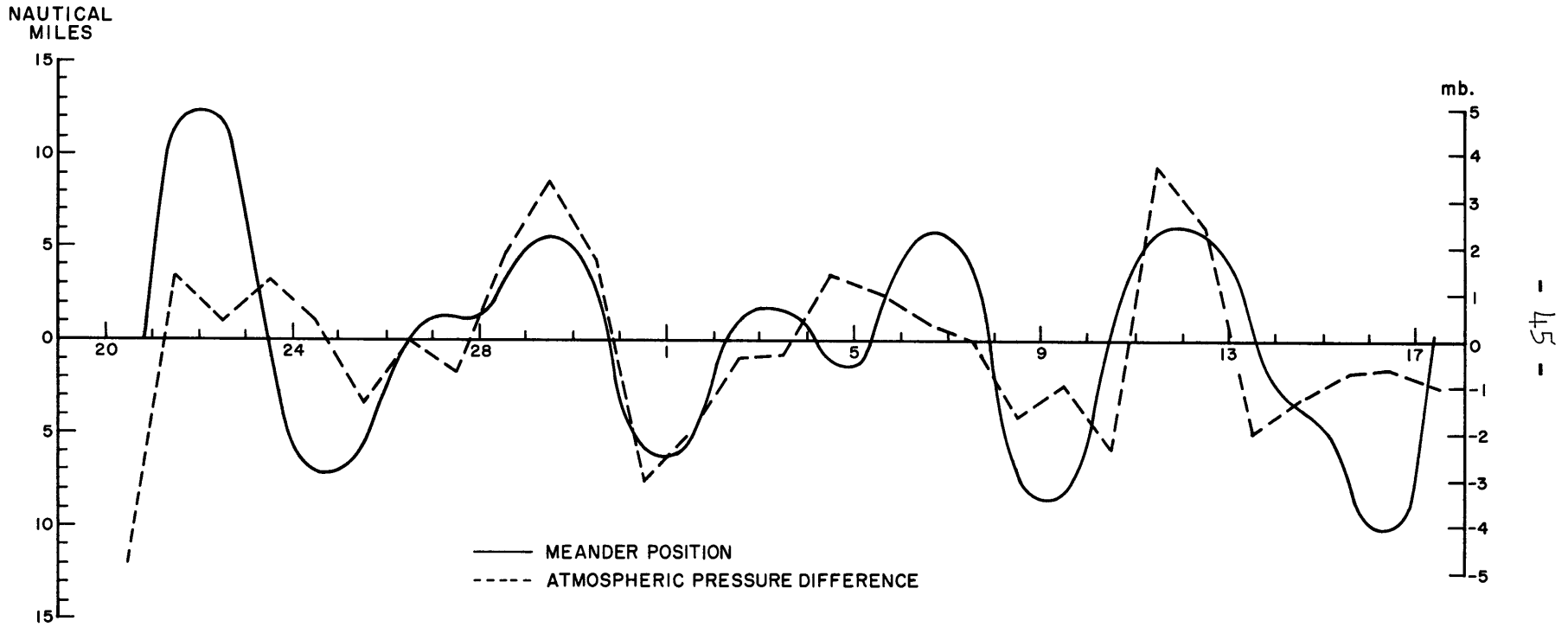


Figure 9

Lagged atmospheric pressure and meanders

Onslow Bay are not related to the daily outflow from the Gulf of Mexico, as suggested in the hypothesis advanced by von Arx, Bumpus, and Richardson (1955).

Characteristics of an average Gulf Stream. The Onslow Bay observations were further combined to portray an average cross-section of the surface layer temperature structure and the surface velocity profile for the period of the survey. The average velocity profiles ( $\bar{u}$ ), ( $\bar{v}$ ), and the average temperature structure are shown in Figure 10. Any characteristic instantaneous profile would have much steeper temperature and velocity gradients, for when time averages are taken of a shifting steep gradient, the gradient is blurred and tends to flatten out. This has been illustrated by Fuglister (1954) with respect to climatological temperature averages.

Any velocity, when measured with the GEK, is less than the actual surface water velocity by a factor which depends upon the depth of moving water in relation to the total depth of water. Because these depths cannot readily be measured, the factor is commonly determined empirically by calculating surface velocities from the discrepancies between Loran and dead-reckoned positions. For the region of the Gulf Stream off Onslow Bay, it was found (von Arx, Bumpus, and Richardson, 1955) that the GEK velocities should be multiplied by  $1.46 \pm 0.09$  to correspond with the

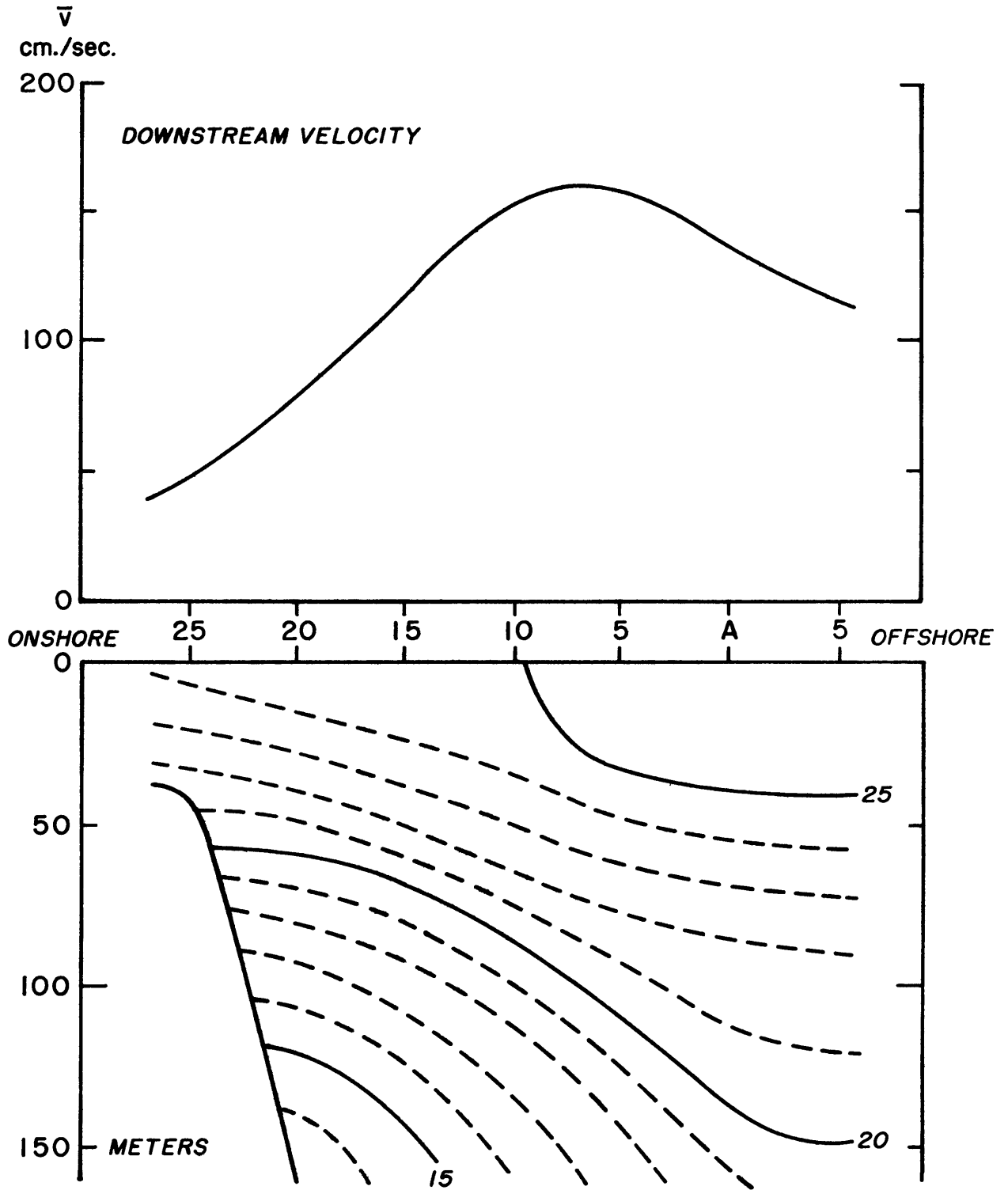


Figure 10

Cross-section of average current

velocities as determined by dead-reckoning. All the GEK velocities obtained during CRAWFORD Cruise 18 have been multiplied by this factor.

The cyclonic shear of the average velocity inshore of the velocity maximum is about  $4.4 \times 10^{-5} \text{sec}^{-1}$ , and the anti-cyclonic shear of the average velocity offshore is about  $3.0 \times 10^{-5} \text{sec}^{-1}$ . For comparison, the Coriolis parameter at this latitude is  $8 \times 10^{-5} \text{sec}^{-1}$ . The cyclonic shear of the average velocity is much lower than the cyclonic shear of individual crossings. von Arx (1951) gives individual values as high as  $50 \times 10^{-5} \text{sec}^{-1}$  for instantaneous cyclonic shears, and some instantaneous shears encountered on CRAWFORD Cruise 18 were as large. The lower value results from the long-term averaging, so that the cyclonic shear of the average current for the month observed is less than the Coriolis parameter. To be realistic, a theory of the Gulf Stream should probably not imply a climatological average cyclonic shear in excess of about  $5 \times 10^{-5} \text{sec}^{-1}$  in this region.

Comparisons with meanders farther downstream.

The surface meander pattern in Onslow Bay as shown in the space-time diagrams has some similarity with the large-scale current pattern farther downstream. Fuglister (1951) presented an interpretation of the Gulf Stream beyond Cape Hatteras as a set of multiple currents. The meanders shown



here are similar to the multiple currents because they appear to be more nearly a set of disconnected currents than a single current; each offshore-running current maximum seems to evolve anew rather than to be a continuation of a pre-existing current maximum. However, the space and time scales of the meanders off Onslow Bay are far different from those of the multiple currents beyond Cape Hatteras. There are only three or four currents comprising the multiple current system between Cape Hatteras and the Grand Banks. The length of each current is a thousand kilometers or more, whereas the meanders off Onslow Bay probably have a length of the order of a hundred kilometers. The multiple current pattern is either a permanent structural feature of the flow, or persists for a period of several months; the Onslow Bay meanders, on the other hand, pass by at a rate of one each week.

Although there is uncertainty about the interpretation of the Gulf Stream currents between Cape Hatteras and the Grand Banks, (Fuglister, 1955) it seems likely that currents in the region contain large-scale meanders (Iselin and Fuglister, 1948; Ford and Miller, 1952; Fuglister and Worthington, 1951). Such large-scale meanders are not an evolved form of the meanders observed off Onslow Bay. The meanders downstream from Cape Hatteras give the appearance of an amplifying disturbance (Fuglister and Worthington, 1951, Figure 4). Were this assumption to be valid, the

meanders excited upstream from Cape Hatteras and those which become amplified downstream would have similar periods. Since the time scale of the large-scale meanders appears to be at least an order of magnitude larger than the week-long periods observed off Onslow Bay, the meanders observed at Onslow Bay during the course of one month are probably not an incipient form of the larger meanders found farther downstream. If the large-scale meanders do have their origin upstream from Cape Hatteras, and have a period longer than a month, observations should be extended over several months to distinguish them.

An idealized meander. The thermal structure of the upper 200 meter layer may be determined from the BT data. In order to show this structure more clearly, an idealized diagram has been drawn, in space and time, which combines some features common to all the meanders. Figure 11 is a diagram of the thermal structure of an idealized meander, in which the period of the meander was chosen to be seven days. Each of the meanders resembles a sort of skewed wave motion and consists of an intense offshore-running current, followed by a broad, confused flow onshore, then followed by another intense offshore current. The observations taken were not suitable to determine whether the cold subsurface water coinciding with the farthest offshore positions of the current maximum represents upwelling or not.

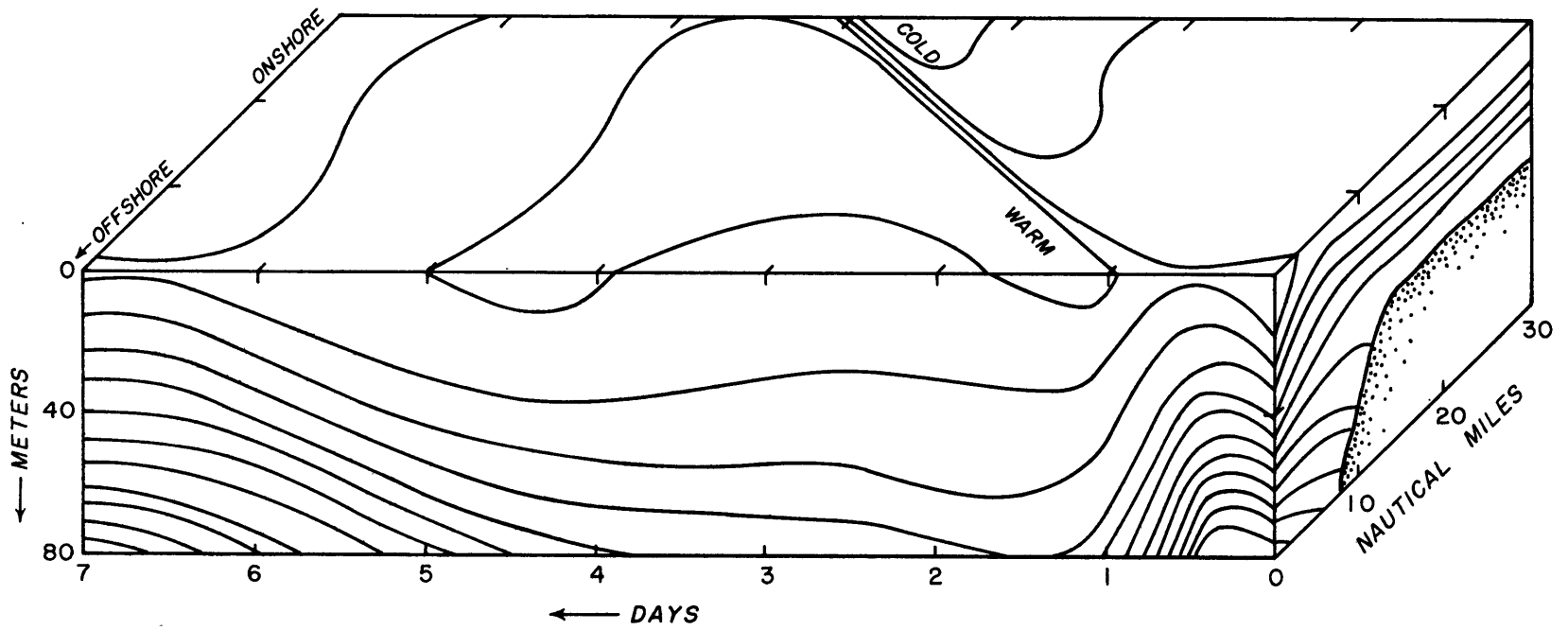


Figure 11

Idealized meander structure

### Acknowledgements

The writer wishes to acknowledge the advice and encouragement of W. S. von Arx, who first suggested that this study be undertaken. Thanks are also due to B. A. Warren for helpful criticisms. The data used were collected under the direction of W. S. von Arx, with the assistance of D. F. Bumpus and C. G. Day. Much of the data reduction was performed by Mrs. N. Andersen. The work was made possible by funds supplied by the Office of Naval Research, under contract Nonr2196(00).

References

- Bumpus, D. F. (1955), The circulation over the continental shelf south of Cape Hatteras. Trans. Amer. Geophys. Union, 36 (4), 601-611.
- Bumpus, D.F., and Pierce, E.L. (1955), The hydrography and the distribution of chaetognaths over the continental shelf of North Carolina. Pap. Mar. Biol. and Oceanogr., Suppl. Deep-Sea Res., 3, 92-109.
- Conrad, V., and Pollak, L.W. (1950), Methods in Climatology, Cambridge, U.S.A., Harvard University Press, 459 pp.
- Day, C.G. (1959), Oceanographic observations, 1958 East Coast of the United States. United States Fish and Wildlife Service, Special Sci. Rept., Fisheries No. 318, 119 pp.
- Ford, W.L., Longard, J.R., and Banks, R.E. (1952), On the nature, occurrence and origin of cold low salinity water along the edge of the Gulf Stream. Jour. Mar. Res., 11 (3), 281-293.
- Ford, W.L., and Miller, A.R. (1952), The surface layer of the Gulf Stream and adjacent waters. Jour. Mar. Res., 11, (3), 267-280.
- Fuglister, F.C. (1951), Multiple currents in the Gulf Stream System. Tellus, 3 (4), 230-233.

Fuglister, F.C. (1954), Average temperature and salinity at a depth of 200 meters in the North Atlantic. Tellus, 6 (1), 46-58.

Fuglister, F.C. (1955), Alternative analyses of current surveys. Deep-Sea Res., 2 (3), 213-229.

Fuglister, F.C., and Worthington, L.V. (1951), Some results of a multiple ship survey of the Gulf Stream. Tellus, 3 (1), 1-14.

Hela, I., and Wagner, L.P. (1954), Note on tidal fluctuations in the Florida Current, in: Marine Lab., Univ. of Miami, Tech. Rept., No. 54-7, 14-24.

Iselin, C. O'D., and Fuglister, F.C. (1948), Some recent developments in the study of the Gulf Stream. Jour. Mar. Res., 7 (3), 317-329.

Schleicher, K.E., and Bradshaw, A.L. (1956), A conductivity bridge for measurement of the salinity of sea water. Journ. du Cons., 22 (1), 9-20.

von Arx, W.S. (1950), An electromagnetic method for measuring the velocities of ocean currents from a ship under way. Pap. Phys. Oceanogr. Meteor., 11 (3), 1-62.

von Arx, W.S. (1951), Some measurements of the surface velocities of the Gulf Stream. Woods Hole Oceanogr.

Inst., Tech. Rept. Ref. No. 51-96 (unpublished  
manuscript).

von Arx, W.S., Bumpus, D.F., and Richardson, W.S. (1955),  
On the fine structure of the Gulf Stream front.  
Deep-Sea Res., 3 (1), 46-65.

## PART II

### THE KINETIC ENERGY OF GULF STREAM MEANDERS

#### ABSTRACT

Calculations have been made, using surface velocity observations, of the transfer of kinetic energy from meanders to mean flow at two separate localities in the Gulf Stream System. In both cases, it was found that the meanders transferred momentum against the velocity gradient, exactly opposite to what would be expected if they were frictionally driven. The observations suggest that the mean flow of the Gulf Stream is enhanced by the kinetic energy of meanders, and that the meanders should therefore derive energy from sources other than the kinetic energy of the mean flow.



## 1. Introduction

Calculations have been made, for two separate regions, of the surface transfer of momentum by meanders in the Florida Current section of the Gulf Stream System. In both regions, it was found that the meanders transferred momentum against the velocity gradient, exactly opposite to what would be expected if they were frictionally driven. Or, in other words, there was at the surface, a net transfer of kinetic energy from the meanders to the mean flow.

Since no other such observations have been made of the transfer of momentum in ocean currents, it has not been possible to determine the source of kinetic energy of meanders. It has been supposed by some (e.g.: Rossby, 1936, p. 6; Stommel, 1958, p. 107; von Arx, 1954) that the eddies draw their energy from the kinetic energy of the mean flow and represent a mechanism for frictional dissipation of the mean flow. The observations here suggest that the opposite is true: that the mean flow is enhanced by the kinetic energy of meanders, and that the meanders should, therefore, derive their kinetic energy from sources other than the kinetic energy of the mean flow.

## 2. Observations

The data used to calculate eddy momentum fluxes were obtained from two separate sections across the axis of

the Gulf Stream. One section is located off Onslow Bay, North Carolina, near Cape Hatteras, and the other is located in the Straits of Florida, running across the channel between Miami and Gun Cay, Bahamas. Figure 12 shows the location of these sections and their relation to the mean surface axis of the Gulf Stream, as estimated by the United States Coast and Geodetic Survey.

GEK data. The necessary velocity measurements were made with the geomagnetic electrokinetograph (GEK), first described by von Arx (1950). These measurements are usually less than the true surface velocity, depending mainly on the depth of moving water in relation to the total depth of water (Longuet-Higgins, Stern, and Stommel, 1954). It is general practice to determine the reduction of GEK velocities for any region by calculating the average ratio between surface velocities measured by dead-reckoning methods and surface velocities measured with the GEK. This ratio (called "k") has been determined for the Onslow Bay area from several hundred measurements by von Arx, Bumpus, and Richardson (1955), who found for k,  $1.46 \pm 0.09$ . In the Straits of Florida it has been calculated by Hela and Wagner (1954) to be  $1.68 \pm 0.30$ . That the Straits of Florida have a somewhat higher k-value than does Onslow Bay is a result of the shallower depth of water in the Straits. All GEK observations presented here have been corrected by

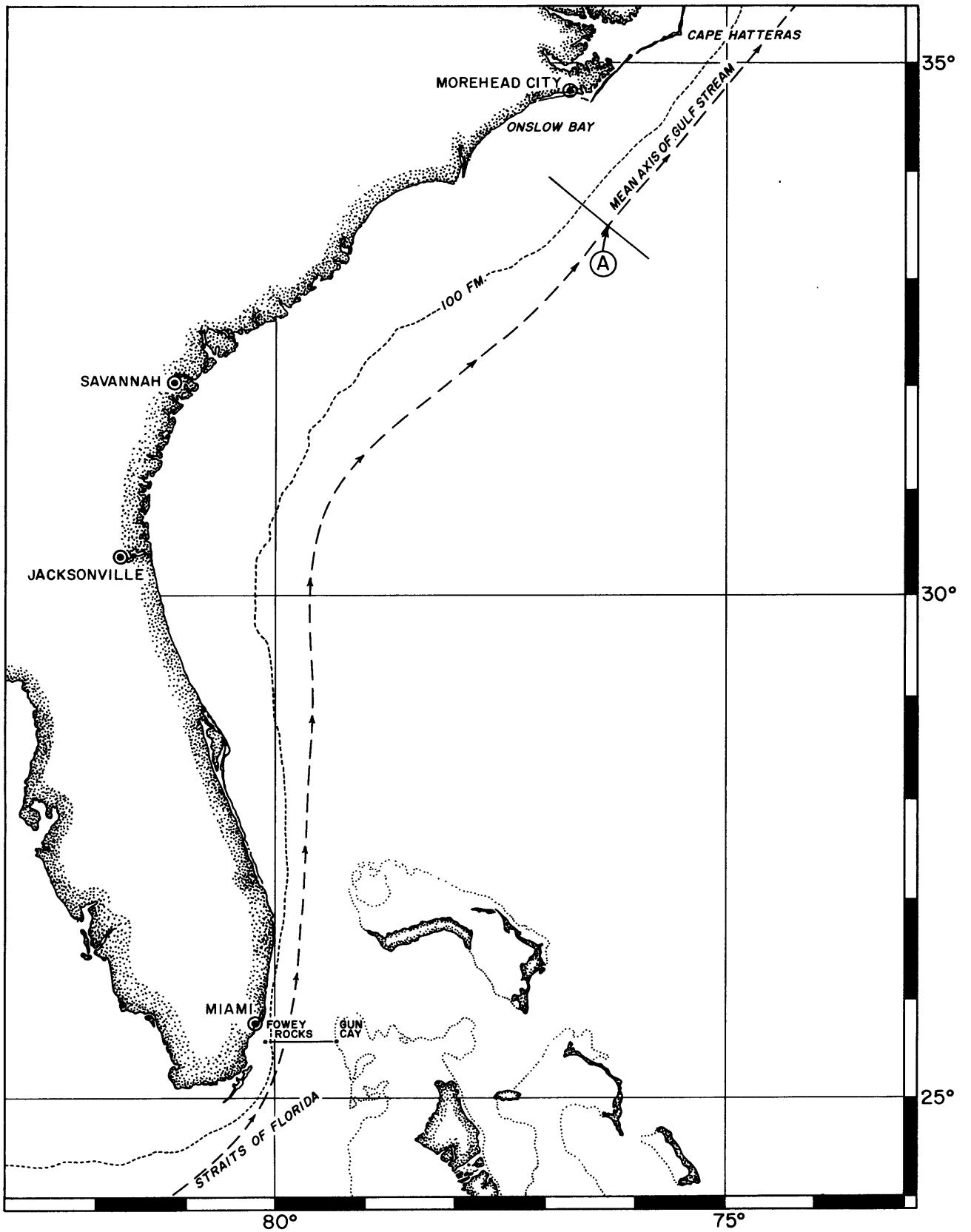


Figure 12

Florida Current region

the appropriate value of  $k$ .

Onslow Bay. The data off Onslow Bay were collected by W. S. von Arx, D. F. Bumpus, and C. G. Day on Cruise 18 of the research vessel CRAWFORD during May and June, 1958. The CRAWFORD sailed back and forth along a single line at right angles to the mean axis of the Stream. An observation of the surface water velocity was made each hour by means of the GEK. During the twenty-eight days of the cruise, 620 separate measurements, or fixes, of the surface water velocity were made. Between fixes, the component of surface velocity at right angles to the course of the ship was recorded continuously. Since the ship's track was across the mean axis, this component was equivalent to the downstream surface velocity. For this portion of the Stream, "downstream" means in the direction  $040^{\circ}\text{T}$ .

The time-average downstream surface velocity ( $\bar{v}$ ) profile determined from CRAWFORD Cruise 18 data is shown in Figure 10, and has a cyclonic shear of approximately  $4.4 \times 10^{-5} \text{sec}^{-1}$ , and an anticyclonic shear of approximately  $3.0 \times 10^{-5} \text{sec}^{-1}$ . The Coriolis parameter at this latitude has a value of  $8.0 \times 10^{-5} \text{sec}^{-1}$ . Because the averages of the cross-stream surface velocity ( $\bar{u}$ ) are generally less than their standard deviations, the averages are not significantly non-zero. If there are mean cross-stream motions, they are less than 4 cm/sec.

Florida Straits. Between 1952 and 1958, the Marine Laboratory of the University of Miami was engaged in part of a long-term program to determine the characteristics of the Florida Current as it flows through the channel between Fowey Rocks, Florida (near Miami), and Gun Cay, Bahamas. The channel at this point is about 43 nautical miles (80 kilometers) wide. A total of 632 GEK observations of velocity in the surface layer from 42 of the cruises made by the Marine Laboratory were available for analysis (Hela, Chew, and Wagner, 1954, 1955; Chew and Wagner, 1957).

The region surveyed by the University of Miami was divided into longitudinal zones, in a manner similar to that used by Chew (1958), except that a somewhat closer spacing than his was used where observations were more plentiful. Only the observations made between latitudes 25°30'N and 25°59'N were used in calculating the averages for each zone. The zones and the region are shown in Figure 13. The limits of the zones are as follows:

<u>Zone</u>	<u>From</u>	<u>To</u>	<u>Width</u>
1	80°05'.5 W	80°01'.5 W	4'.0
2	01'.4	79°58'.5	3'.0
3	79°58'.4	55'.5	3'.0
4	55'.4	52'.5	3'.0
5	52'.4	49'.5	3'.0
6	49'.4	44'.5	5'.0
7	44'.4	39'.5	5'.0
8	39'.4	34'.5	5'.0
9	34'.4	29'.5	5'.0
10	29'.4	24'.5	5'.0
11	24'.4	19'.5	5'.0

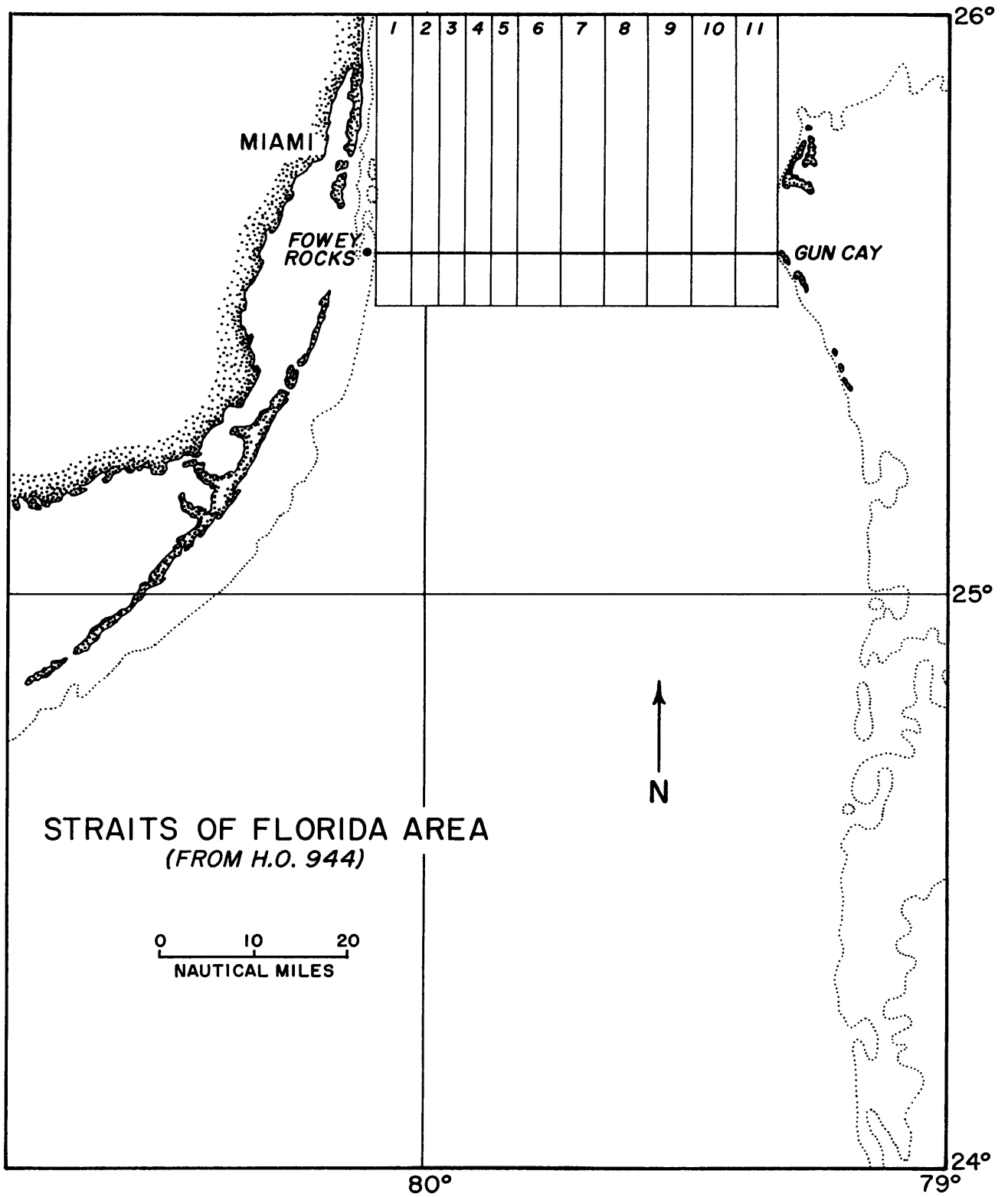


Figure 13  
Florida Straits

The western boundary of the channel, Fowey Rocks, is at  $80^{\circ}06'.5$  W, and the eastern boundary, Gun Cay, is at  $79^{\circ}18'.5$  W, so that the zones chosen cover nearly the entire channel, and include all the observations available. In the Straits of Florida region, one minute of longitude is equal to 0.911 nautical miles (1.69 km). Therefore the width of the widest zones is 4.55 nautical miles (8.45 km).

The averages of the northward component of surface velocity ( $v$ ) and the eastward component ( $u$ ) were calculated for each zone using all the GEK observations lying in that zone. These averages are tabulated in Table III, and plotted in Figure 14.

The mean downstream velocity profile is asymmetrical, with a cyclonic shear region about 15 nautical miles (28 km) wide having a shear of approximately  $3 \times 10^{-5} \text{sec}^{-1}$ . The anticyclonic shear region is about 32 nautical miles (59 km) wide and has a shear of approximately  $2 \times 10^{-5} \text{sec}^{-1}$ . For comparison, the value of the Coriolis parameter at this latitude is  $6.9 \times 10^{-5} \text{sec}^{-1}$ . The cyclonic shear of the average stream is significantly less than that of the instantaneous stream, because variations in position of the latter produce a wide distribution of average velocity, and hence a profile more gentle than that which would be found on any particular crossing.

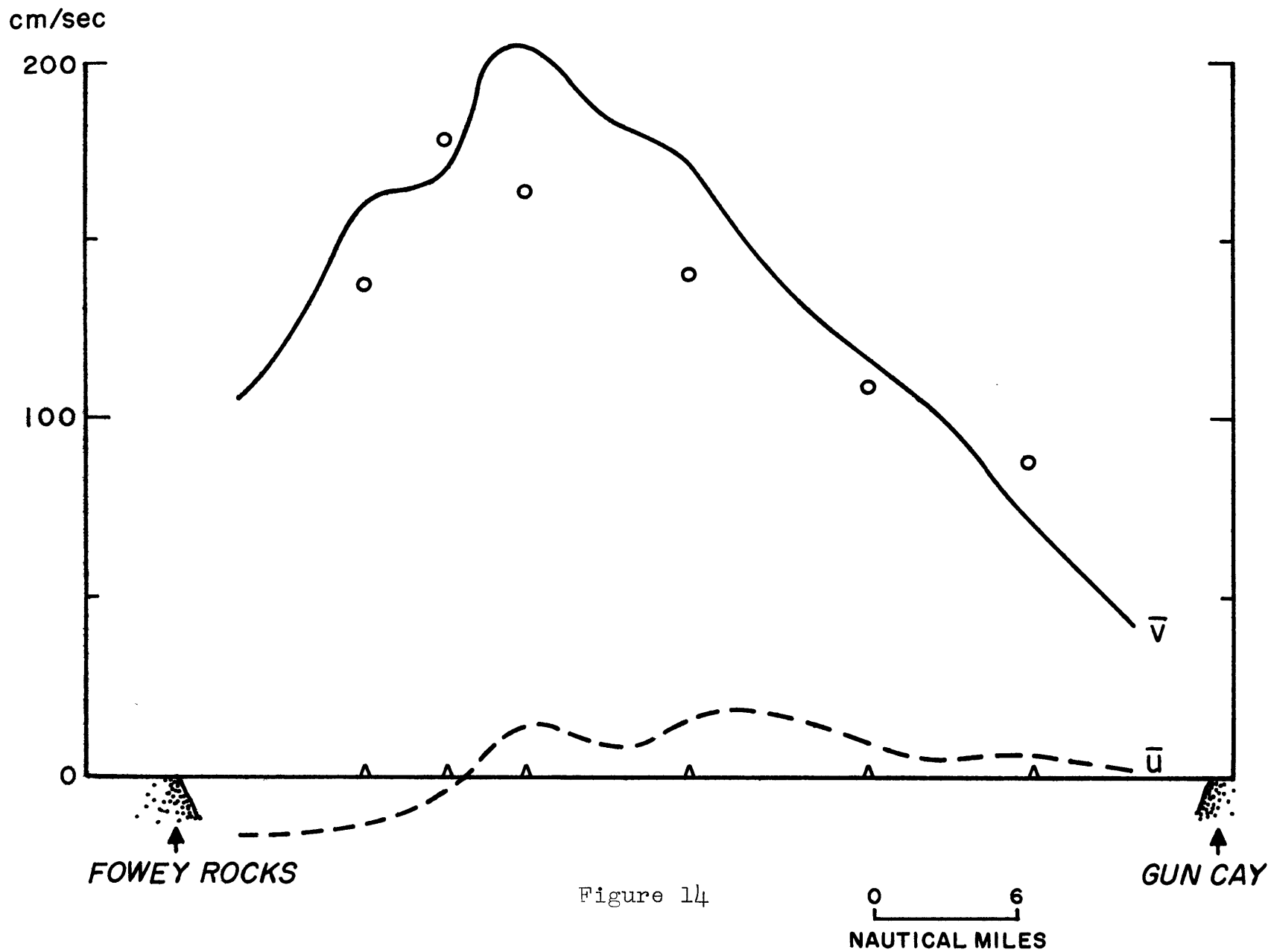


Figure 14

Average velocity profile, Florida Straits



### 3. Energy Calculations

The transfer of kinetic energy from the eddies to the mean flow can be expressed as

$$\rho \overline{u'v'} \frac{\partial \bar{v}}{\partial x} \quad (1)$$

where a bar represents a time average of a quantity, a prime represents a deviation from the time average, u and v are the velocity components in the cross-stream (x) and downstream (y) direction, and  $\rho$  is the density of the water. This method for treating perturbations of a mean flow was first developed by O. Reynolds (1895), and is outlined by Lamb (1932).

Onslow Bay. For the Onslow Bay region, the data were divided into twelve zones across the current, each zone being 3 nautical miles wide.  $\overline{u'v'}$  was calculated by applying Simpson's rule to the values of  $u'v'$ , over the total time of observation, for each of the twelve zones. The value of  $\overline{u'v'}$  was calculated for each zone from the profile of average velocity (v). Table II shows for each zone:  $\overline{u'v'}$ , the average transport of eddy momentum;  $\frac{\partial \bar{v}}{\partial x}$ , the shear of the average velocity; and the term (1) representing the production of mean kinetic energy by meanders. ( $\rho$  was assumed constant, and equal to one gram per cubic centimeter.)

Figure 15 shows the distribution of (1) across the width of the current off Onslow Bay. The cross-stream

TABLE II

		Onslow Bay				$k = 1.46$			
Zone	$u'$		$v'$		$\overline{u'v'}$	$\frac{\partial \bar{v}}{\partial x}$	$\overline{\rho u'v'} \frac{\partial \bar{v}}{\partial x}$		
	cm/sec		cm/sec					cm <sup>2</sup> /sec <sup>2</sup>	$\times 10^{-5} \text{sec}^{-1}$
6	+5.4	$\pm 6.3$	39.6	$\pm 7.9$	+210.2	$\pm 279$	2.13	+0.45	$\pm 0.6$
7	+2.6	$\pm 7.2$	53.6	$\pm 13.0$	-72.1	$\pm 503$	2.68	-0.19	$\pm 1.3$
8	+10.4	$\pm 5.5$	70.2	$\pm 12.7$	+236.3	$\pm 341$	4.35	+1.03	$\pm 1.5$
9	+6.9	$\pm 6.6$	95.9	$\pm 9.1$	+482.0	$\pm 481$	4.35	+2.10	$\pm 2.1$
10	-4.8	$\pm 8.0$	118.1	$\pm 8.8$	+640.6	$\pm 558$	4.35	+2.79	$\pm 2.4$
11	+8.0	$\pm 9.8$	143.5	$\pm 7.4$	+648.8	$\pm 364$	3.84	+2.49	$\pm 1.4$
12	-11.2	$\pm 10.1$	156.8	$\pm 6.1$	+335.6	$\pm 409$	0.71	+0.24	$\pm 0.3$
13	+2.2	$\pm 6.0$	157.2	$\pm 6.4$	+268.5	$\pm 271$	-0.36	-0.10	$\pm 0.1$
14	-12.8	$\pm 7.2$	153.4	$\pm 7.9$	-74.3	$\pm 349$	-1.10	+0.08	$\pm 0.4$
15	+6.9	$\pm 5.8$	139.3	$\pm 8.9$	-169.4	$\pm 279$	-3.00	+0.51	$\pm 0.8$
16	-3.8	$\pm 5.4$	126.0	$\pm 8.3$	-61.9	$\pm 253$	-2.21	+0.14	$\pm 0.6$
17	-11.7	$\pm 6.9$	114.9	$\pm 11.1$	+72.4	$\pm 349$	-2.85	-0.21	$\pm 1.0$

Average Energy Flux:  $79 \times 10^{-4} \text{ ergs/cm}^3/\text{sec}$ .

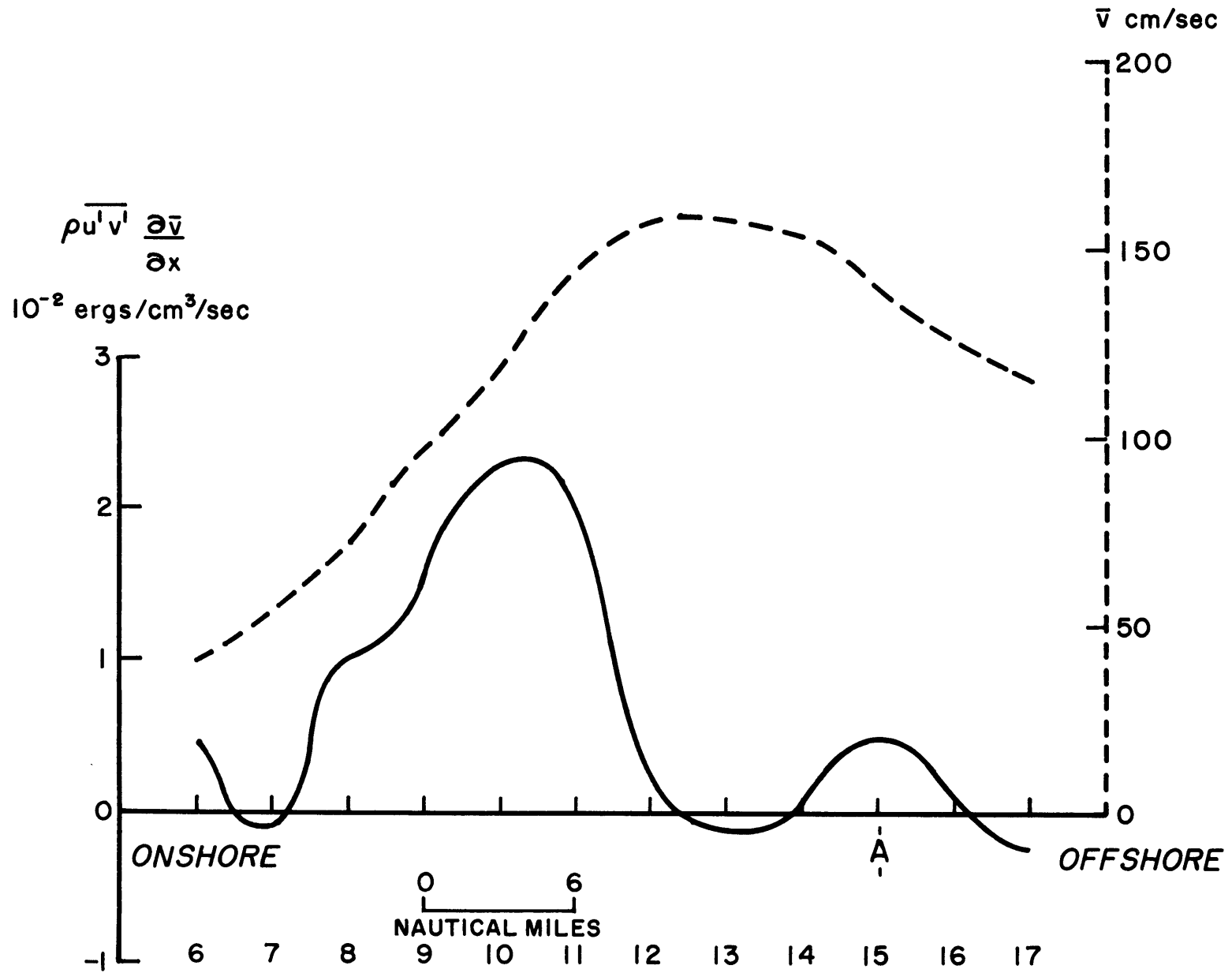


Figure 15

Production of mean kinetic energy, Onslow Bay

integral of (1) is positive, indicating a net transfer of kinetic energy from the meanders to the mean current.

Florida Straits. The averages for the Florida Straits section were calculated by taking ensemble averages in each of the zones. That is, a barred quantity was evaluated as:

$$\overline{(\ )} = \frac{1}{N} \sum_{i=1}^N (\ )_i$$

where N is the total number of observations in the zone. The results of the calculations are tabulated in Table III, and the profile of the term (1) across the current is shown in Figure 16. In this region, although there are points in the current where (1) is positive, the net production of mean kinetic energy across the stream is not significantly non-zero.

Statistical significance of results. The standard error of the means of  $\bar{u}$ ,  $\bar{v}$ , and  $\overline{u'v'}$  are given for each value in Tables II and III. The standard error of a mean is defined, for large N, as  $\sigma / \sqrt{N}$ , where  $\sigma$  is the standard deviation of the sample from which the mean is calculated, and N is the number of individual observations.

#### 4. Discussion of Results

Scale of perturbations. The conclusions which

TABLE III

		Florida Straits			k = 1.68				
Zone	$\bar{u}$ cm/sec	$\bar{v}$ cm/sec	$\overline{u'v'}$ cm <sup>2</sup> /sec <sup>2</sup>	$\frac{\partial \bar{v}}{\partial x}$ x 10 <sup>-5</sup> sec <sup>-1</sup>	$\overline{\rho u'v'}$ 10 <sup>-2</sup> ergs/cm <sup>3</sup> /sec	$\frac{\partial \bar{v}}{\partial x}$			
1	-18.1 ±3.5	103.1 ±8.9	-411.7 ±184	+4.27	-1.76 ±0.78				
2	-17.6 ±6.4	129.9 ±10.4	+259.0 ±371	+5.68	+1.47 ±2.11				
3	-11.2 ±5.7	160.7 ±12.3	+270.0 ±392	+3.60	+0.97 ±1.41				
4	-6.4 ±4.5	164.8 ±5.8	+975.4 ±277	+4.27	+4.16 ±1.18				
5	+11.0 ±6.7	202.8 ±9.2	+357.0 ±498	+1.97	+0.70 ±0.98				
6	+9.9 ±4.2	188.0 ±4.5	+333.2 ±322	-2.35	-0.78 ±0.76				
7	+16.5 ±5.7	167.0 ±7.4	+15.2 ±361	-3.34	-0.05 ±1.21				
8	+14.4 ±4.2	131.4 ±5.5	-13.2 ±217	-3.55	+0.05 ±0.77				
9	+5.1 ±4.4	107.2 ±6.6	+140.6 ±171	-3.43	-0.48 ±0.59				
10	+5.8 ±4.5	73.5 ±6.9	+122.7 ±123	-3.75	-0.46 ±0.46				
11	+2.1 ±4.4	43.9 ±7.4	+281.2 ±102	-3.49	-0.98 ±0.36				

Average Energy Flux:  $3.0 \times 10^{-4}$  ergs/cm<sup>3</sup>/sec.

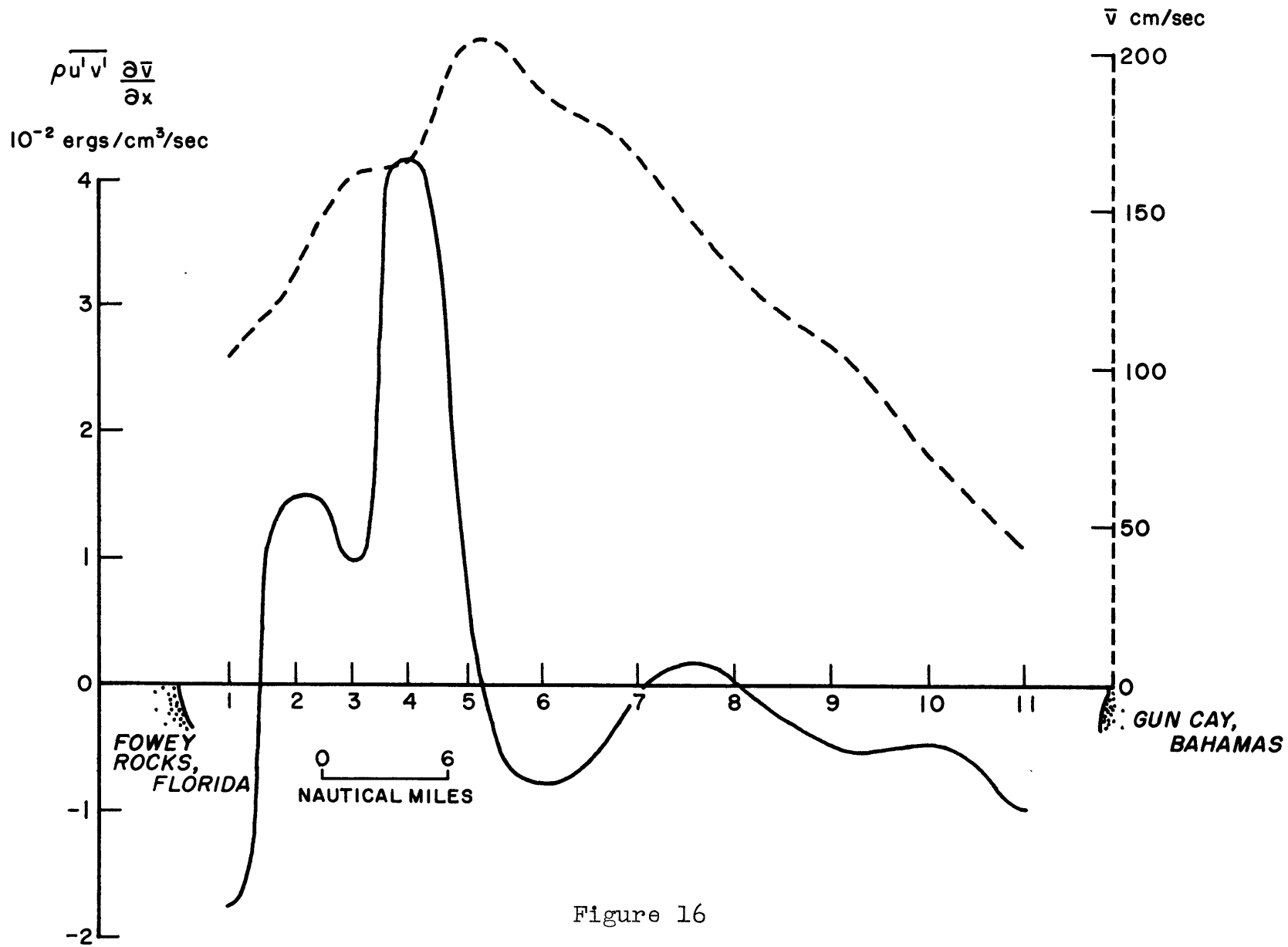


Figure 16

Production of mean kinetic energy, Florida Straits

can be derived directly from the evaluation of (1) across the Florida Current apply only to the surface layer of moving fluid, and only to the time scale of perturbations which the  $u'$  and  $v'$  characterize. That is, the results obtained say nothing directly about the energy balance below the surface nor about the eddy motions of other time scales. However, on the basis of earlier observations, some estimate can be made of the subsurface velocity structure and of the time scale of the perturbations in the Straits of Florida.

Pillsbury (1891) made a detailed study of the Florida Current at six anchor stations between Fowey Rocks and Gun Cay. His average velocity measurements for each station are shown in Table IV, together with the change in velocity with depth, relative to a surface velocity of unity. Pillsbury's average surface velocities are plotted as circles in Figure 14 where they can be compared with the averages from the University of Miami GEK measurements. His observations show that the subsurface velocities are not greatly less than those at the surface, and suggest a qualitative similarity between surface and subsurface velocity fields. If so, then the energy transfer between eddies and mean flow calculated for the surface layers from GEK data may be representative of the whole current in the Florida Straits.

Pillsbury also made a study of the time variations

TABLE IV

Florida Straits Velocities  
as determined by Pillsbury (1891)

(a) Velocities in cm/sec

Station No.	Miles East of Fowey Rocks	3 1/2 fm	15 fm	30 fm	65 fm	130 fm
1	8	137	121	116	82	32
1 1/2	11 1/2	178	149	151	124	83
2	15	163	157	164	152	113
3	22	140	137	138	128	96
4	29	109	108	109	101	75
5	36	88	81	73	80	77

(b) Velocity drop-off

Surface (3 1/2 fm) Velocity = 1.00

1	8	1.00	.89	.81	.60	.24
1 1/2	11 1/2	1.00	.84	.85	.70	.47
2	15	1.00	.97	1.01	.93	.70
3	22	1.00	.98	.99	.92	.68
4	29	1.00	.99	1.00	.93	.69
5	36	1.00	.92	.82	.91	.88



of current position, velocity, and width in the Florida Straits, and found monthly variations related to the declination of the moon, as well as daily, tidally-influenced oscillations. He concluded that the tidal components of the variations were significantly larger than those which could be attributed to non-tidal causes.

Parr (1937) analyzed a set of five anchor stations which were successively occupied for 24-hour periods in the Straits of Florida between Fowey Rocks and Gun Cay. He found that lunar periodicities were strongly indicated in the data, and he even combined data from station to station, by referring them to corresponding lunar hours.

More recently, Murray (1952) analyzed velocity fluctuations in the same region. These fluctuations, as determined with the GEK, had periods between a few hours and a day. Murray was unable to confirm Pillsbury's conclusion that there was a relationship between the transport and the declination of the moon, and found only inconclusive evidence of lunar effects. A further analysis of additional GEK data by Hela and Wagner (1954) indicated that some tidal variations in velocity did exist, but that they were strongly masked by non-tidal effects. Wertheim (1954) from electromagnetic measurements of total transport, found conclusive evidence of diurnal tidal influence in the transport through the Florida Straits.

In conclusion, although it is probably rash to

ascribe the velocity fluctuations of the current through the Straits of Florida predominantly to tidal causes, the periods of the fluctuations are of the order of a day, and the deviations from the mean which are used here to calculate the eddy transport of momentum most likely are representative of meandering motion.

In Onslow Bay, the data were taken continuously for a month, in contrast to the Florida Straits, where the data were obtained at intervals over the course of several years. The eddy momentum transfer calculated from the perturbations has periods ranging between a few hours and a week; this is the range of meander periods which were described in Part I. Unfortunately, no systematic velocity measurements at depth, similar to those of Pillsbury in the Florida Straits, have ever been made in the Onslow Bay region.

We may conclude that both in the Florida Straits and in Onslow Bay, the calculated lateral surface transfer of momentum is produced by perturbations having periods of a day or longer. No observations have been made of perturbations of other time scales, in particular of small-scale perturbations, having periods which are small compared with the length of a day. Consequently, there is no evidence to suggest that small-scale perturbations would transport momentum in a manner similar to the meanders.

Regeneration Time. Figures 15 and 16 show the

rate of transfer of energy from the meanders to the mean flow. In both localities, the maximum production of mean kinetic energy occurs in the region of cyclonic shear; in the anti-cyclonic shear regions there is little significant exchange of energy between the meanders and the mean flow. The magnitude and the lateral scale of the eddy kinetic energy release off Onslow Bay are similar to those in the Florida Straits. This apparent similarity between the two profiles suggests that there might be a characteristic scale of energy release throughout the whole region between the Straits of Florida and Cape Hatteras. However, a calculation of the time scales of the energy transfer reveals that the kinetic energy plays a different role in the mean kinetic energy balance in each region.

If the curves are integrated over their lengths, the average rate of surface transfer of energy from the meanders to mean flow is  $79 \times 10^{-4}$  ergs/cm<sup>3</sup>/sec for Onslow Bay and  $3.0 \times 10^{-4}$  ergs/cm<sup>3</sup>/sec for the Florida Straits. If the kinetic energy of the mean surface flow is averaged by integrating across the stream, the result is  $7.3 \times 10^3$  ergs/cm<sup>3</sup> for Onslow Bay and  $8.55 \times 10^3$  for the Florida Straits. If no other actions were present, the calculated rate of energy transfer would double the mean surface kinetic energy in 11 days in Onslow Bay and in 329 days in the Florida Straits.

The difference between the regeneration time of

the surface kinetic energy in Onslow Bay and that in the Florida Straits may perhaps be explained partly by the confining channel of the latter. Near each shore there is a region where the meanders draw energy from the mean flow. This boundary layer effect is not so noticeable in the Onslow Bay region where the current is not closely confined by physical barriers.

In addition, the current through the Florida Straits may be more directly driven by a downstream pressure gradient. If so, then the meanders would contribute less to the mean flow than they do farther downstream where, possibly, the current is maintained by the cross-stream density field through the mechanism of meanders. At present, the measurements necessary to evaluate the role of downstream pressure gradients are not available.

Atmospheric Similarities. There is a similarity between the role of meanders in the Gulf Stream and the role of large-scale eddies in the atmosphere. Figure 17, adapted from Starr (1953) shows the production of zonal kinetic energy in arbitrary units, and the relative angular velocity as a function of latitude. When Figure 17 is compared with Figures 15 and 16, it can be seen that, for both systems, the maximum countergradient flow of momentum occurs in the region of maximum shear.

Several years' study of atmospheric transfer

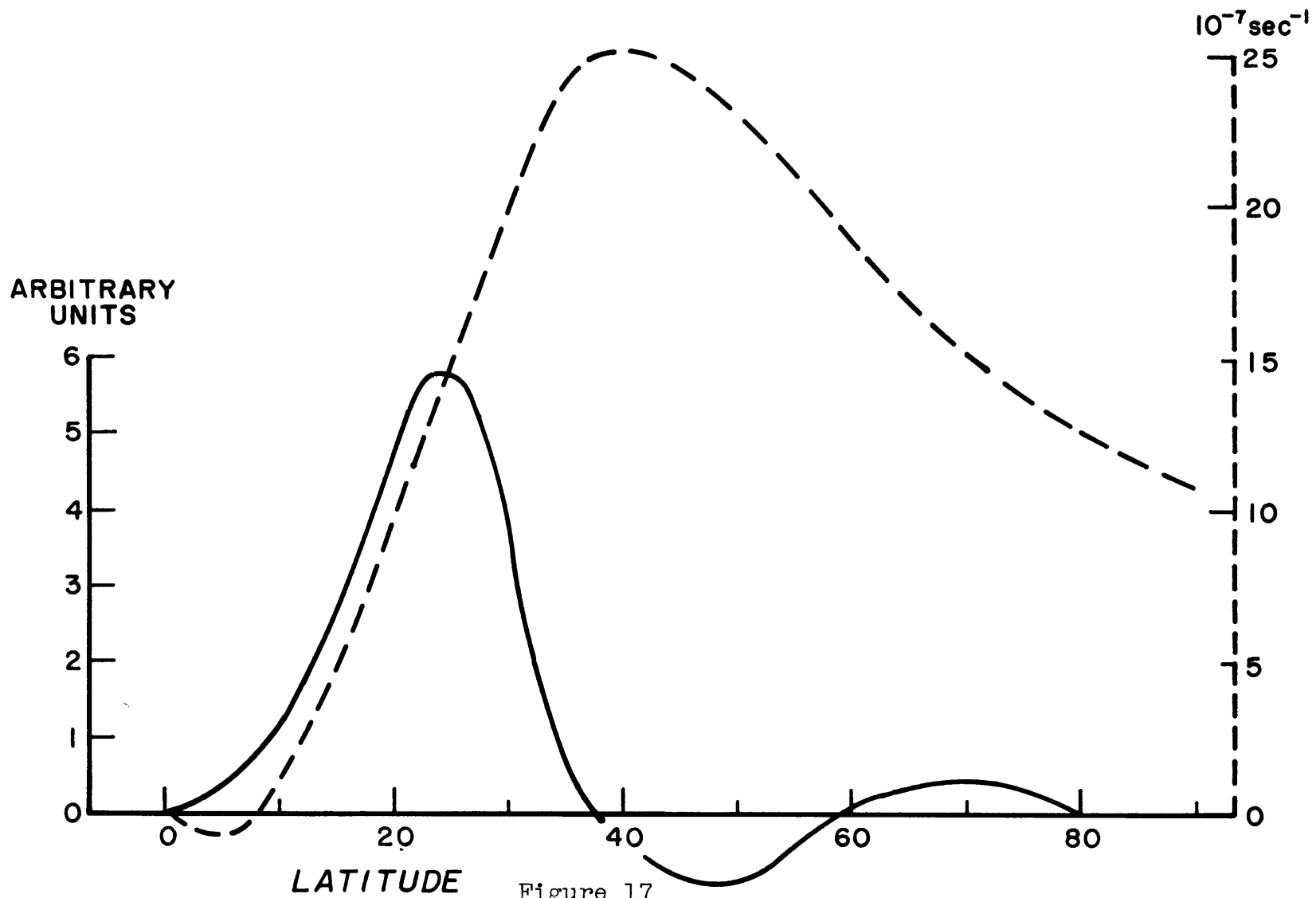


Figure 17  
 Production of zonal kinetic energy, atmosphere  
 (from Starr, 1953, Figure I)

processes have established that the mean zonal flow is sustained by large-scale disturbances (Starr, 1953), and that the necessary meridional transports of momentum are effected by horizontal eddy exchange processes (Starr, 1954). The question of whether mean current systems in the ocean are maintained in an analogous manner cannot be answered until further observations are made. These preliminary observations suggest at least, however, that meanders in the regions studied do not tend to dissipate the kinetic energy of the mean flow.

The conversion of eddy kinetic energy, at the surface, into kinetic energy of mean flow suggests that the meanders derive their energy from the potential energy of the density field. Frictional models of the Gulf Stream (Stommel, 1948; Munk, 1950) require some sort of eddy dissipation which could conceivably be supplied by perturbations of meander scale. It is possible that the necessary frictional dissipation is carried out by perturbations of a scale smaller than the meanders. If so, then the energy balance is analogous to that in the atmosphere, where the mean zonal flow is sustained by large-scale eddies, but dissipated by small-scale eddies and molecular viscosity.

Austausch Coefficients. A coefficient of lateral eddy viscosity, or Austausch coefficient, may be defined on the assumption that the perturbations of the mean

flow are analogous to an eddy frictional mechanism. However, the perturbations of the Gulf Stream flow, observed here, act exactly opposite to friction, so that a viscosity coefficient calculated using them would be negative. A negative viscosity coefficient has questionable physical significance.

When the perturbations do act to dissipate the mean flow, an Austausch coefficient can be calculated, using a series of velocity measurements. Stommel (1955) has made a calculation of the Austausch coefficient in the Florida Straits using surface velocities measured by Pillsbury. In two calculations, he found Austausch coefficients of  $9(\pm 5) \times 10^5 \text{ cm}^2/\text{sec}$  and  $2(\pm 6) \times 10^5 \text{ cm}^2/\text{sec}$ , at a point where the present data would indicate a negative coefficient. The value of mean shear used by Stommel was  $10^{-4} \text{ sec}^{-1}$ . University of Miami GEK measurements indicate that the average shear at this point is only about a third as large. Furthermore, the calculation by Stommel was made near the western boundary, eight miles from Fowey Rocks. If there is some sort of frictional "boundary zone" on each side of the channel, then it is possible that positive values of the Austausch coefficient would be found in those areas. In any case, it appears that the Austausch coefficient obtained in any such calculation will depend strongly on the scale of the perturbations used in the analysis. The small-scale perturbations which might be expected to provide a dissipating action probably cannot be measured by standard techniques of cur-

rent measurement.

## 5. Kinetic Energy Equation

The equation expressing the flux of energy in a turbulent flow was originally developed by O. Reynolds for a parallel non-rotating dissipative flow (Lamb, 1932). The corresponding general equation for the atmosphere has been given by Kuo (1951). The equations for ocean current systems are similar to those for the atmosphere because the coordinate frame for both systems is rotating, but dissimilar because the atmosphere is cyclic and centered about the axis of rotation, whereas ocean currents are a more local phenomenon. The action of winds upon the surface of the ocean is a mechanism whose atmospheric analogue is negligible.

The following model is a simple version of the Reynolds model, intended to provide an orientation. Better models may follow later.

Let us consider an ocean current flowing in the y-direction, with velocity components u, v, and w in the x, y, and z directions, x being directed to the right of y, and z being directed downward. Let us consider only the equation of downstream momentum, which is:

$$\rho \frac{dv}{dt} = -\rho fu - \frac{\partial p}{\partial y} - d \quad (2)$$

where  $\rho$  is the density of the water, f is the Coriolis



parameter,  $p$  is the pressure, and  $d$  is a dissipative force, which includes the effect of wind stress on the surface. We shall omit explicit reference to the wind stress. Equation (2) may be expanded and, with the aid of the continuity equation, written:

$$\frac{\partial}{\partial t} \rho v + \frac{\partial}{\partial x} \rho u v + \frac{\partial}{\partial y} \rho v v + \frac{\partial}{\partial z} \rho v w = -\rho f u - \frac{\partial p}{\partial y} - d \quad (3)$$

Now the quantities  $u$ ,  $v$ , and  $w$  can be separated into mean motion and deviations as:

$$u = \bar{u} + u'$$

$$v = \bar{v} + v'$$

$$w = \bar{w} + w'$$

where the bars represent time averages, and the primes are deviations from the average. Terms of the form  $\overline{u'v'}$  become  $\bar{u} \bar{v} + \overline{u'v'}$ .

Consider a unit cross-section. We may write the mean kinetic energy equation by multiplying equation (3) by  $\bar{v}$  and integrating with respect to  $x$ ,  $z$ , and  $t$ . To express the equation in terms of a time average, we divide the integral by the length of the time interval,  $\Delta T$ :

$$\begin{aligned}
 \frac{1}{\Delta T} \iiint \frac{\partial \rho}{\partial t} \frac{\bar{v}^2}{2} dx dz dt &= -\frac{1}{\Delta T} \iiint \bar{v} \frac{\partial}{\partial x} \rho uv dx dz dt \\
 &\quad -\frac{1}{\Delta T} \iiint \bar{v} \frac{\partial}{\partial y} \rho v v dx dy dz dt \\
 &\quad -\frac{1}{\Delta T} \iiint \bar{v} \frac{\partial}{\partial z} \rho v w dx dz dt \\
 &\quad -\frac{1}{\Delta T} \iiint \bar{v} \rho f u dx dz dt - \frac{1}{\Delta T} \iiint \bar{v} \frac{\partial p}{\partial y} dx dz dt \\
 &\quad -\frac{1}{\Delta T} \iiint \bar{v} d. dx dz dt \tag{4}
 \end{aligned}$$

The left hand side of this equation by definition is zero for a given fixed time period, so there is a balance between the terms on the right hand side. If we integrate (4) with respect to time, we will form barred averages:

$$\begin{aligned}
 0 = & -\iint \rho \bar{v} \frac{\partial}{\partial x} \overline{u'v'} dx dz \quad -\iint \rho \bar{v} \frac{\partial}{\partial x} \overline{u\bar{v}} dx dz \\
 & -\iint \rho \bar{v} \frac{\partial}{\partial y} \overline{v'v'} dx dz \quad -\iint \rho \bar{v} \frac{\partial}{\partial y} \overline{v\bar{v}} dx dz \\
 & -\iint \rho \bar{v} \frac{\partial}{\partial z} \overline{v'w'} dx dz \quad -\iint \rho \bar{v} \frac{\partial}{\partial z} \overline{v\bar{w}} dx dz \\
 & -\iint \rho \bar{v} f \bar{u} dx dz \quad -\iint \bar{v} \frac{\partial p}{\partial y} dx dz \\
 & -\iint \rho \bar{v} d. dx dz \tag{5}
 \end{aligned}$$

This gives an equation for the balance of mean downstream kinetic energy. With the limited amount of information available now, it is not possible to evaluate each term in (5) for the Gulf Stream. However, an estimate of the role of some of the terms can be made.

First, consider the term (1):

$$-\rho \bar{v} \frac{\partial}{\partial x} \overline{u'v'}$$

which includes the expression used in the surface calculation of this study. It may be re-written as

$$\begin{array}{cc} \text{(a)} & \text{(b)} \\ -\rho \frac{\partial}{\partial x} (\bar{v} \cdot \overline{u'v'}) & + \rho \overline{u'v'} \frac{\partial \bar{v}}{\partial x} \end{array}$$

The term  $-\rho \frac{\partial}{\partial x} (\bar{v} \cdot \overline{u'v'})$  represents an eddy advection across the boundaries of mean kinetic energy and can be integrated easily across a stream to become:

$$\rho [\bar{v} \cdot \overline{u'v'}]_A - \rho [\bar{v} \cdot \overline{u'v'}]_B$$

If the stream is bounded by walls,  $u'$  will be zero at the walls, or if the mean stream velocity drops to zero at each side of the current,  $\bar{v}$  will be zero, and the term (a) is zero. Off Onslow Bay, where the current is not bounded by walls and the observations did not cover the whole width of the current, calculation of the term (a) has revealed that its integral across the width of observations is zero. (See Appendix, Section 4.) Hence, the cross-stream integral of

the term:

$$+ \rho \overline{u'v'} \frac{\partial \bar{v}}{\partial x} \quad (1)$$

is a measure of the increase of mean kinetic energy at the expense of kinetic energy of horizontal eddy motion.

The term (5):  $\rho \bar{v} \frac{\partial}{\partial z} \overline{v'w'}$  represents contributions of kinetic energy to the mean flow by vertical perturbations. Since observations of vertical motions are not available, this term has not been calculated. It might represent an important contribution to the mean downstream kinetic energy.

The terms (2) and (6) containing  $\bar{u} \bar{v}$  and  $\bar{w} \bar{v}$  include contributions of kinetic energy to the mean motion by standing waves. In addition, they include energy transfers by mean cross-stream motions. A systematic program of downstream observations would permit a resolution between the standing wave components and the mean cross-current components. An analysis of the role of these components, as applied to the atmosphere, has been presented by Starr and White (1951).

The terms  $\frac{\partial}{\partial y} \overline{v'v'}$  and  $\frac{\partial}{\partial y} \bar{v} \bar{v}$  (3) and (4) represent the downstream increase in mean kinetic energy across the unit cross-section. In order to evaluate the derivatives, velocity measurements in the direction of the stream are needed.

The quantity  $\frac{\partial p}{\partial y}$  is not known well enough to

calculate its contribution, in term (8), to the mean downstream kinetic energy. Indications are that this downstream pressure gradient is important in the Florida Straits, but little is known about it in Onslow Bay. More reliable measurements are needed in both areas. The terms (3), (4), and (8) all represent time-independent geographic increases in mean downstream kinetic energy.

The term (7) ( $\rho f \bar{u} \bar{v}$ ) represents conversion of mean cross-stream energy to mean downstream energy by the action of Coriolis forces. The present data indicate a value of  $\bar{u}$  which is not significantly different from zero. Term (7) might be important in those regions where there are large mean cross-stream velocity components.

The frictional dissipation term, (9), was included in the equation to represent the general action of frictional stresses. Included in the term is the effect of wind stress on the surface. An order of magnitude calculation shows that the energy provided by the wind stress is one or two orders of magnitude less than the transfer of kinetic energy from the meanders to the mean flow. That is, if we assume a maximum wind stress of half a dyne/cm<sup>2</sup>, a maximum velocity of 50 cm/sec, and a current depth of 500 meters, the energy transfer will be  $5 \times 10^{-4}$  ergs/cm<sup>3</sup>/sec, for total correlation between winds and currents. Assuming only partial correlation, or more characteristic values of wind stress and meander velocity, the energy contributed to

the meanders by the wind is about  $1 \times 10^{-4}$  ergs/cm<sup>3</sup>/sec. In comparison with the transfer of energy between meanders and mean flow of  $80 \times 10^{-4}$  ergs/cm<sup>3</sup>/sec, the wind would appear to be eliminated as a significant source of kinetic energy for the meanders.

## 6. Conclusions

The similarity between these results and those in the atmosphere provides hope that a general study of the energy, momentum, and heat transfers in ocean currents would be as fruitful as such studies in the atmosphere have been. Perhaps, to some extent, meanders are to an ocean current what cyclones are to atmospheric circulation: a mechanism which sustains the mean flow and which provides transfers necessary for climatological balances.

A further program of systematic measurements in the Gulf Stream System is necessary to illuminate the large-scale balances. Downstream from Cape Hatteras, especially, the tortuous course of the Gulf Stream has only recently been discovered, and the processes determining its nature are unknown. An extensive observation program might be undertaken initially with GEK surface velocity measurements. Hydrographic station data probably would not be suitable for velocity measurements because non-geostrophic and/or non-baroclinic velocity components might be an important constituent of the transfer process. A system which at present seems promising, and which ultimately might provide the vast

amount of data necessary for an oceanic study comparable to that in the atmosphere, is that of anchored buoys, which record data at predetermined time intervals. Such a system could be scattered throughout the ocean, and could record data at any depth.

#### Acknowledgements

The writer is indebted to Dr. Kirk Bryan, Jr. for suggesting this study. Thanks are also due to Prof. V. P. Starr for encouragement and helpful suggestions, and to Bruce Warren and Prof. William von Arx for helpful criticisms.

References

- Chew, F., 1958: An interpretation of the transverse component of the geomagnetic electrokinetograph readings in the Florida Straits off Miami. Trans. Amer. Geophys. Union, 39, 875-884.
- Chew, F., and Wagner, L.P., 1957: Tropical Oceanography, semi-annual report, March, 1957. Marine Lab., Univ. of Miami, Tech. Rept., No. 57-9, 128 pp.
- Hela, I., Chew, F., and Wagner, L.P., 1954: Some results of the Florida Current Study, 1953. Marine Lab., Univ. of Miami, Tech. Rept., No. 54-7, 100 pp.
- Hela, I., Chew, F., and Wagner, L.P., 1955: Some results of the oceanographic studies in the Straits of Florida and adjacent waters. Marine Lab., Univ. of Miami, Tech. Rept., No. 55-1, 74+ pp.
- Hela, I., and Wagner, L.P., 1954: Note on tidal fluctuations in the Florida Current, in: Marine Lab., Univ. of Miami, Tech. Rept., No. 54-7, 14-24.
- Kuo, H.L., 1951: A Note on the kinetic energy balance of the zonal wind systems. Tellus, 3, 205-207.
- Lamb, Sir H., 1932: Hydrodynamics, 6th ed. Cambridge, England, Cambridge University Press, 738 pp.



- Longuet-Higgins, M.S., Stern, M.E., and Stommel, H.M., 1954:  
The electrical field induced by ocean currents and  
waves, with applications to the method of towed  
electrodes. Papers in Physical Oceanography and  
Meteorology, 13:1, 1-37.
- Munk, W.H., 1950: On the wind-driven ocean circulation. Jour.  
Meteor., 7, 79-93.
- Murray, K.M., 1952: Short period fluctuation of the Florida  
Current from geomagnetic electrokinetograph observa-  
tions. Bull. Mar. Sci., Gulf and Caribbean, 2, 360-375.
- Parr, A.E., 1937: Report of hydrographic observations at a  
series of anchor stations across the Straits of Florida.  
Bull. Bingham Oceanogr. Coll., 6, 1-62.
- Pillsbury, J.E., 1891: The Gulf Stream, a description of the  
methods employed in the investigation and the results of  
the research. Rept. Supt., U.S. Coast and Geodetic  
Survey, 1890, App. 10.
- Reynolds, O., 1895: On the dynamical theory of incompressible  
viscous fluids and the determination of the criterion.  
Phil. Trans. Roy. Soc. London, A, 186, 123-164.
- Rossby, C.-G., 1936: Dynamics of steady ocean currents in the  
light of experimental fluid mechanics. Papers in  
Physical Oceanography and Meteorology, 5:1, 1-43.

- Starr, V.P., 1953: Note concerning the nature of the large-scale eddies in the atmosphere. Tellus, 5, 494-498.
- Starr, V.P., 1954: Commentaries concerning research on the general circulation. Tellus, 6, 268-272.
- Starr, V.P., and White, R.M., 1951: A hemispherical study of the atmospheric angular momentum balance. Quart. J. Roy. Meteor. Soc., 77, 215-225.
- Stommel, H.M., 1948: The westward intensification of wind-driven ocean currents. Trans. Amer. Geophys. Union, 29, 202-206.
- Stommel, H.M., 1955: Lateral eddy viscosity in the Gulf Stream System. Deep-Sea Res., 3, 88-90.
- Stommel, H.M., 1958: The Gulf Stream. Berkeley, U.S.A., Univ. of California Press, 202 pp.
- von Arx, W.S., 1950: An electromagnetic method for measuring the velocities of ocean currents from a ship under way. Papers in Physical Oceanography and Meteorology, 11:3, 1-62.
- von Arx, W.S., 1954: Measurements of the oceanic circulation in temperate and tropical latitudes. Oceanographic Instrumentation, Nat. Res. Counc. (U.S.) Publ., No. 309, 13-35.

von Arx, W.S., Bumpus, D.F., and Richardson, W.S., 1955:  
On the fine structure of the Gulf Stream front. Deep-  
Sea Res., 3, 46-65.

Wertheim, G.K., 1954: Studies of the electric potential  
between Key West, Florida and Havana, Cuba. Trans.  
Amer. Geophys. Union, 35, 872-882.

## APPENDIX

This portion of the thesis contains supplementary material developed during the preparation of Parts I and II.

### 1. Surface Velocities

Surface velocities determined from GEK measurements have been depicted in two different space-time diagrams. The first shows a single component, the second a stream function derived by integrating one component. Neither provides a completely satisfactory method for presenting spatial vector observations in a frame having one space and one time co-ordinate.

Downstream Surface Velocity. The term "downstream surface velocity" is used here to mean the component of surface velocity parallel to the axis of the mean Gulf Stream. A GEK fix was made at hourly intervals throughout CRAWFORD Cruise 18 to determine the surface current vector. Between fixes, a continuous record of the velocity normal to the ship's direction, which is approximately the downstream component, was obtained. Its space-time diagram is shown in Figure 18. Since these are the uncorrected GEK data, the values should be multiplied by the empirical correction factor,  $k$ , so that they will correspond more closely to true surface velocities. von Arx, Bumpus, and Richardson (1955) found the factor for this region to be

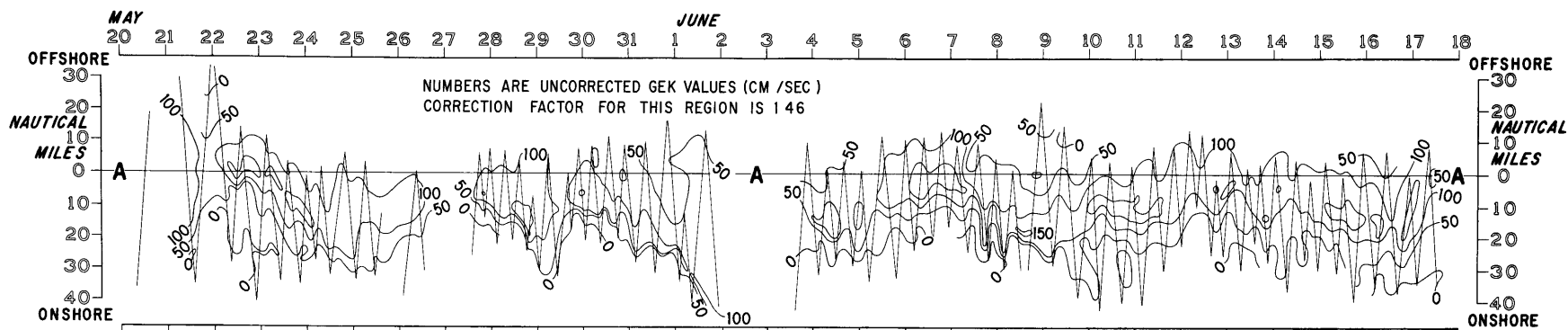


Figure 18

GEK velocity, CRAWFORD Cruise 18

1.46.

The space-time diagram of the downstream component of surface velocity serves principally to define the position of the velocity maximum, or the core of the stream.

Stream Function. In an attempt to represent the two-dimensionality of the surface velocity field better than is possible with the downstream component of velocity alone, a surface stream function was calculated. Such a stream function,  $\psi$ , can be defined for horizontally non-divergent flow as follows:

$$u = \frac{\partial \psi}{\partial y} \quad (5)$$

$$v = - \frac{\partial \psi}{\partial x} \quad (6)$$

where  $u$  and  $v$  are components of velocity in the  $x$  and  $y$  directions. When lines of constant  $\psi$  are plotted in an  $x$ - $y$  plane, they are everywhere parallel to the horizontal velocity vector. If the velocity field is known, then the stream function may be determined from

$$\psi = \int u \, dy + c \quad (7)$$

or, 
$$\psi = - \int v \, dx + c \quad (8)$$

where  $c$  is an arbitrary constant of integration, which may be a function of time.

If the axis of the stream in Onslow Bay is taken as the  $y$ -direction, positive downstream, the cruise path to

the right of  $y$  as the  $x$ -direction, then the downstream velocity ( $v$ ) is known along each cruise path ( $x$ ). If we assume that the flow is horizontally non-divergent, and that each crossing of the stream takes place instantaneously, then the stream function can be determined from equation (8) within an arbitrary constant. In this calculation the arbitrary constant of integration was chosen so that the stream function was continuous at the ends of adjoining sections. Equal values of  $\psi$  were contoured between sections to form a space-time diagram, shown in Figure 19.

The resultant pattern of isopleths is not a streamline pattern, because the stream function, though defined for a single instantaneous crossing, is not explicitly defined as a function of time. However, the pattern shows the regions of countercurrents and cross-currents more graphically than any of the other space-time diagrams.

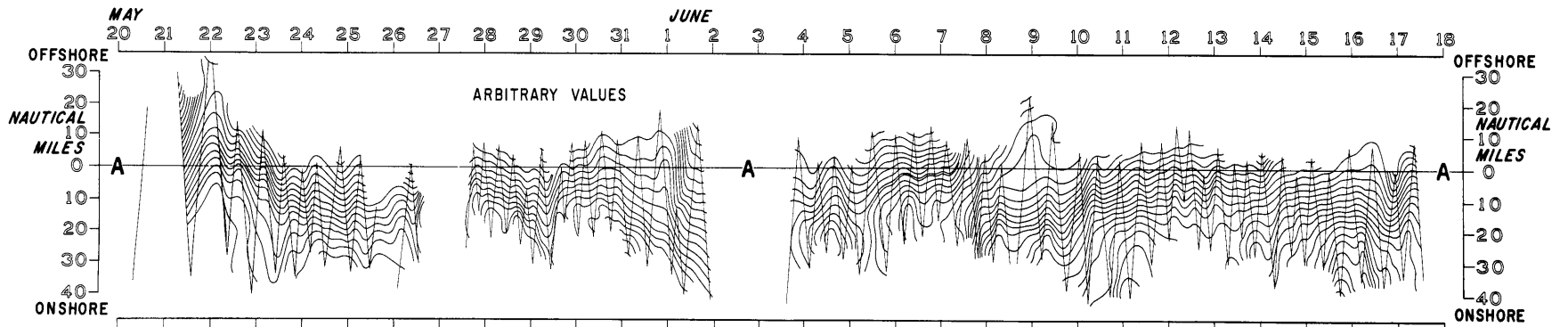


Figure 19

Surface stream function, CRAWFORD Cruise 18



## 2. Correlation between Surface Velocity and Sub-surface Temperature.

It was stated, in Part I, that the position of the 20-degree isotherm at 100 meters depth corresponded closely with the position of the maximum surface velocity. An attempt to find a regular relation between the temperature at a depth of 100 meters and the magnitude of the downstream surface velocity failed. However, when the surface velocities were made non-dimensional by dividing each measurement by the maximum downstream surface velocity recorded on the particular section, a regular relationship between velocity and temperature was found in the cyclonic shear region, which is the onshore side of the velocity maximum. Linear correlation coefficients and regression lines were computed between the non-dimensional velocity in this region and the corresponding temperatures at 30, 60, 100, and 150 meter depths, with the temperature as independent variable. These are summarized below, where T is the centigrade temperature, V is the non-dimensional downstream surface velocity, and r is the correlation coefficient.

### 30-meter temperature

$$V = -131.74 + 7.58 T$$

$r = 0.49$ , with 95% confidence limits of 0.40 and 0.58.

60-meter temperature

$$V = -134.55 + 9.49 T$$

$r = 0.75$ , with 95% confidence limits of  
0.71 and 0.75.

100-meter temperature

$$V = -101.99 + 9.31 T$$

$r = 0.69$ , with 95% confidence limits of  
0.73 and 0.64.

150-meter temperature

$$V = -59.29 + 8.07 T$$

$r = 0.56$ , with 95% confidence limits of  
0.43 and 0.65.

### 3. Variations in Flow

Parameters characterizing the width, transport and shape of the current were defined, and then calculated for each crossing of the stream during CRAWFORD Cruise 18. It was hoped that regular relationships could be found between the parameters, say between maximum velocity and current width; no such relations were found. The characteristic parameters which are presented here have special definitions as follows:

Half-Width. The distance between the points on either side of the velocity maximum where the downstream velocity is half the maximum value found on the stream crossing. (A similar parameter is used in spectroscopy to define the width of a spectral line.) Figure 20 shows the half-width as a function of time.

Maximum Velocity. The maximum downstream velocity found on each stream crossing. Figure 21.

Shape Factor. The maximum velocity divided by the half-width. A large value of shape factor should correspond to a sharp, peaked velocity profile, and a low value to a broad, flat profile. Figure 22.

Transport. The product of the maximum velocity and the half-width. Figure 23.

The correlation coefficients which were calculated between maximum velocity and half-width and between maximum velocity and stream position did not suggest the

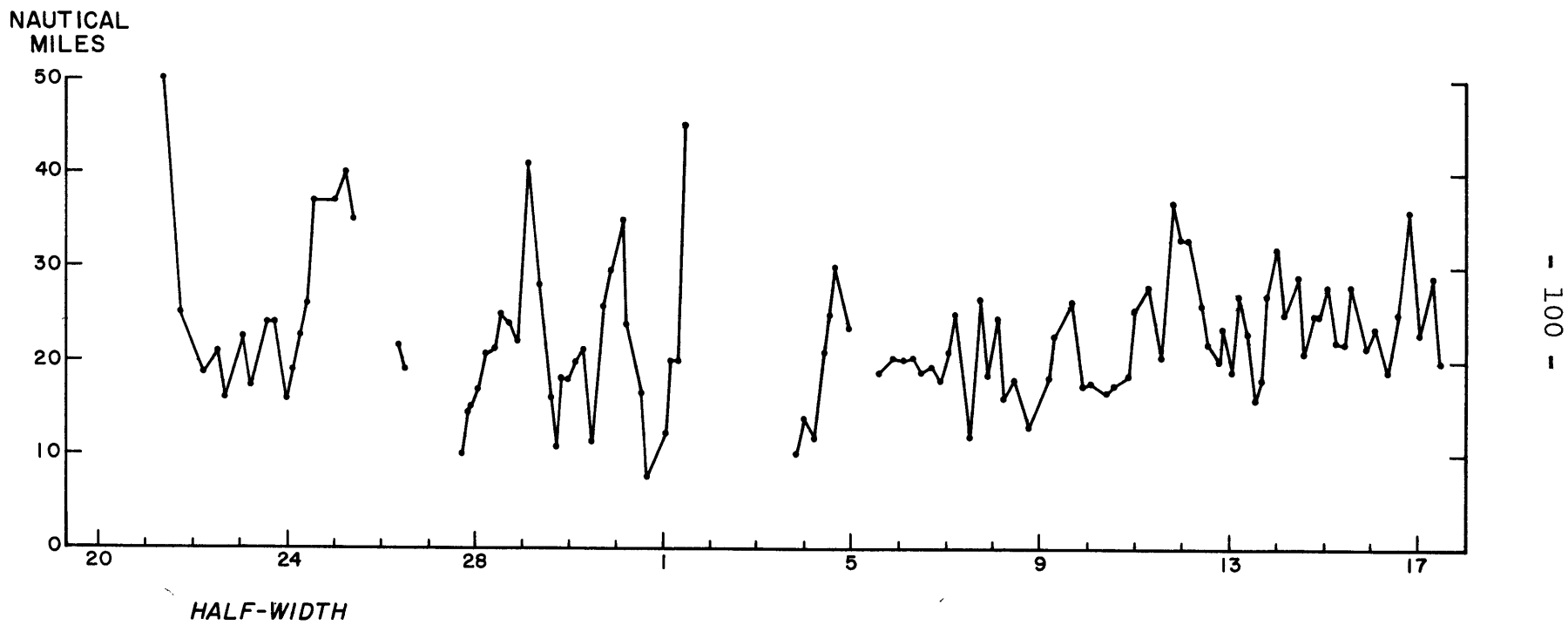


Figure 20

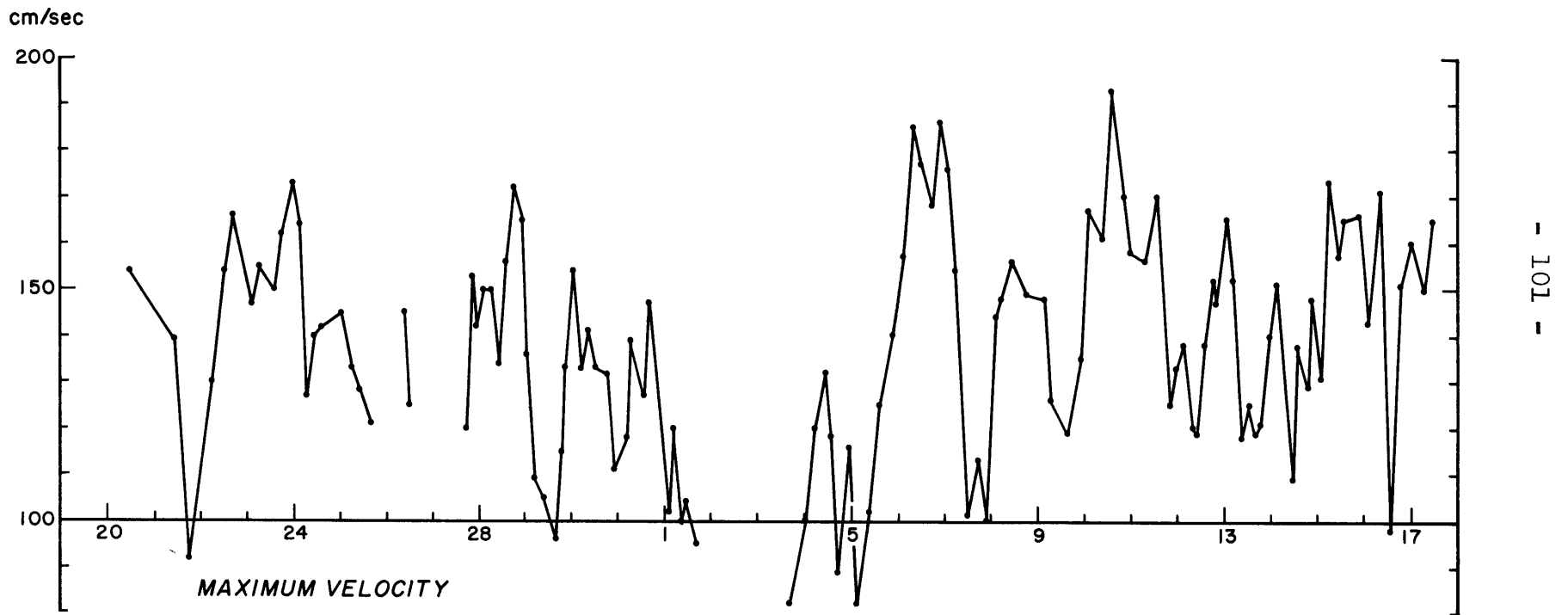
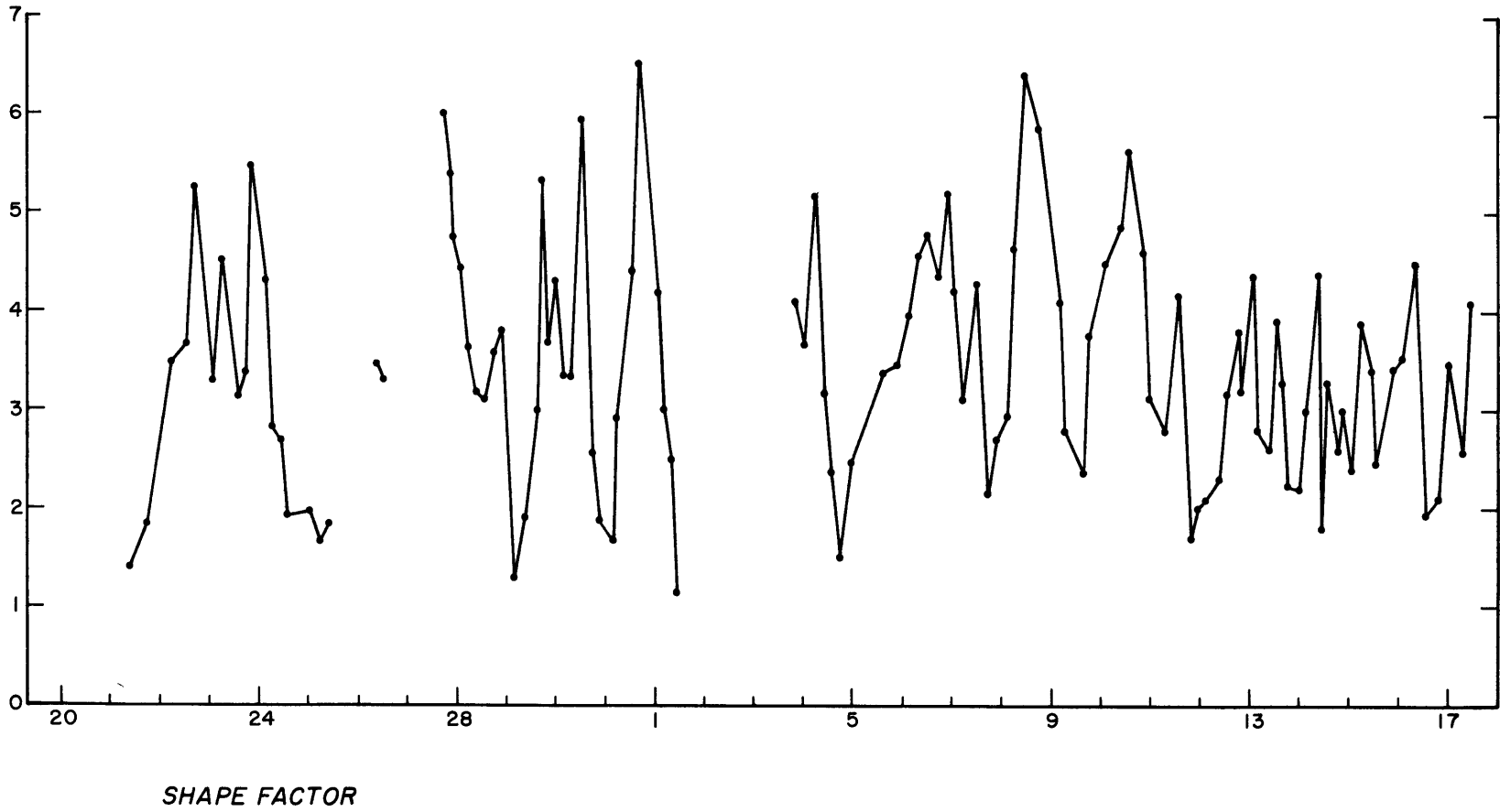


Figure 21

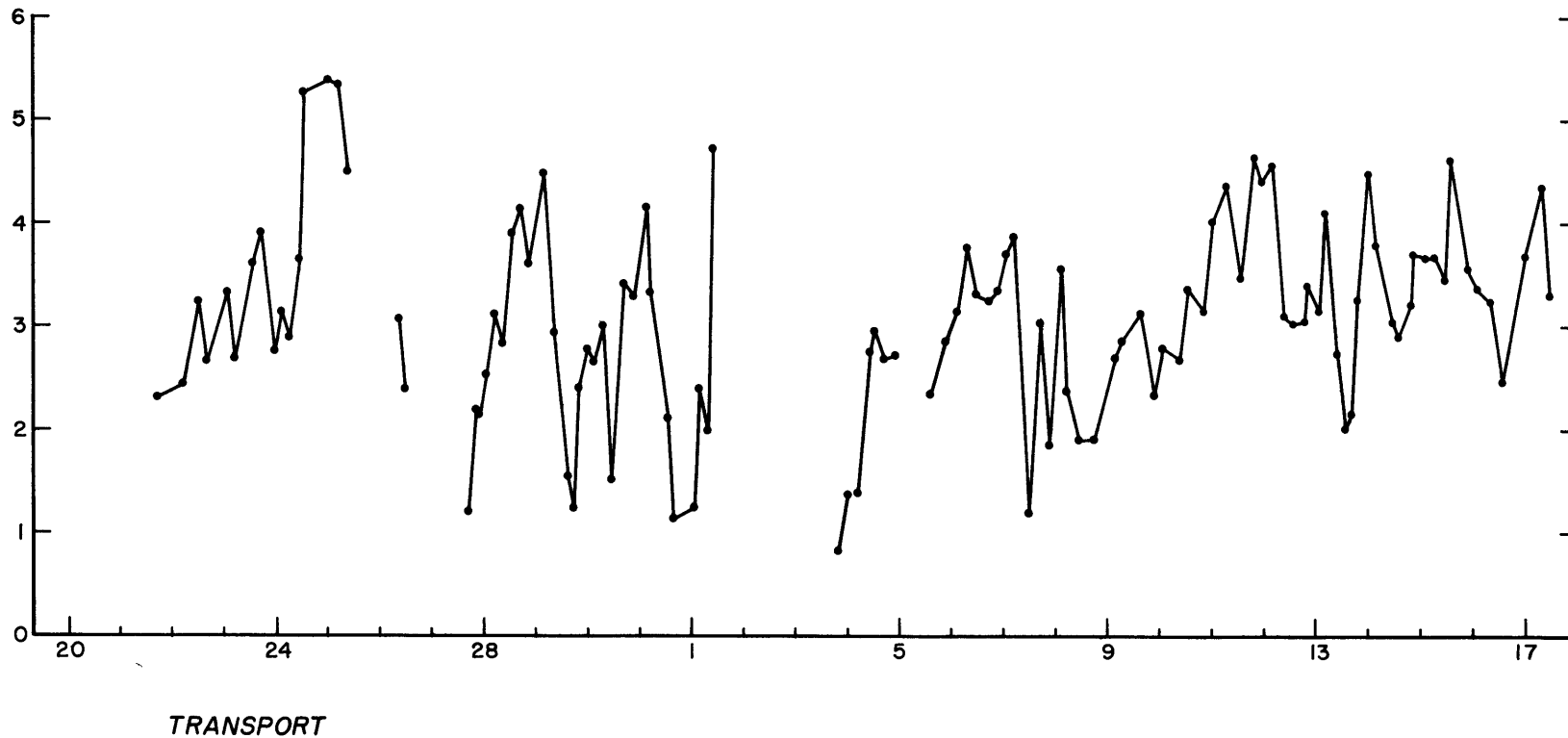
ARBITRARY  
UNITS



- 102 -

Figure 22

ARBITRARY  
UNITS



- 103 -

Figure 23

existence of any physical relationships. Because the time scales of variations in the parameters are not similar to each other, there also would be no significant results if lagged correlations were computed.



#### 4. Advection of Mean Kinetic Energy by Eddies

It was shown, in Part II, that the term (1) of equation (5) can be split into two parts:

$$\textcircled{1} \qquad (a) \qquad (b)$$
$$-\rho \bar{v} \frac{\partial}{\partial x} \overline{u'v'} \equiv -\rho \frac{\partial}{\partial x} \bar{v} \overline{u'v'} + \rho \overline{u'v'} \frac{\partial \bar{v}}{\partial x}$$

The integral of term (1) represents the rate of increase of mean downstream kinetic energy by the action of horizontal eddies. The integral of (a) is the rate of advection by horizontal eddies of mean kinetic energy across the boundaries of a region, and the integral of (b) is the rate at which the horizontal eddies within the region are losing kinetic energy to the mean flow.

If the current is bounded by walls, as is the Florida Current between Fowey Rocks and Gun Cay, then  $\bar{v}$  and  $u'$  are both zero at the walls and the cross-stream integral of (a) is zero. Where the current is not bounded, as is the Florida Current off Onslow Bay, (a) must be integrated across the stream to determine its net contribution to the mean kinetic energy.

The terms (a), (b), and (1) have been calculated independently of one another for each zone across the Onslow Bay section. It is found that the integral of (a) across the stream is zero, so that the integral of (1) is equivalent to the integral of (b). Table V shows (a), (b), and (1) for each zone and the integral of each across the stream.

TABLE V

Eddy Advection of Mean Kinetic Energy

(All values are  $10^{-2}$  ergs/cm<sup>3</sup>/sec)

(1)	(a)	(b)
$-\rho \bar{v} \frac{\partial}{\partial x} \overline{u'v'}$	$-\rho \frac{\partial}{\partial x} (\bar{v} \cdot \overline{u'v'})$	$\rho \overline{u'v'} \frac{\partial \bar{v}}{\partial x}$
+2.37	+2.20	+0.17
-3.44	-3.69	+0.25
-3.68	-5.34	+1.66
-3.06	-5.30	+2.25
-0.19	-3.14	+2.95
+8.45	+7.30	+1.18
+1.90	+1.88	+0.02
+9.59	+9.66	-0.07
+2.51	+2.20	+0.31
-2.57	-2.85	+0.28
-2.91	-2.90	-0.01
Sum +8.97	+0.02	+8.99
Average +0.81		+0.81

### 5. Reynolds Stress as a Correlation Coefficient

The Reynolds stress,  $\rho \overline{u'v'}$ , represents the eddy transport of momentum. The expression for the correlation coefficient between the horizontal eddy velocity components,  $u'$  and  $v'$ , is:

$$r = \frac{\overline{u'v'}}{(\overline{u'^2})^{\frac{1}{2}}(\overline{v'^2})^{\frac{1}{2}}}$$

where  $(\overline{u'^2})^{\frac{1}{2}}$  and  $(\overline{v'^2})^{\frac{1}{2}}$  represent the standard deviations of the perturbation velocity components. This correlation coefficient is a convenient method for expressing the magnitude of the Reynolds stress in relation to the magnitude of the eddy velocity components. The correlation coefficient was calculated from the GEK data for both Onslow Bay and the Florida Straits, and is tabulated in Table VI.

Between two random sets of observation, it is possible to obtain by chance a sizable correlation coefficient, whose magnitude will decrease with the number of observations. The value which the chance correlation coefficient may be expected to exceed five per cent of the time, or the 5% significance level, is shown in Table VI for each zone. Although most values of the Reynolds stress correlation coefficient are less than the statistically significant level, the predominance of positive values in the cyclonic shear region, and of negative values in the anticyclonic shear region indicates a significant transfer

TABLE VI

Reynolds Stress as Correlation Coefficient

Onslow Bay			Florida Straits		
zone	r	5% significance level	zone	r	5% significance level
6	+.08	.22	1	-.16	.22
7	-.03	.20	2	+.08	.28
8	+.09	.20	3	+.09	.30
9	+.17	.19	4	+.48	.22
10	+.23	.19	5	+.19	.36
11	+.24	.19	6	+.18	.20
12	+.12	.19	7	+.01	.27
13	+.10	.19	8	-.01	.27
14	-.03	.19	9	+.10	.28
15	-.06	.20	10	+.08	.28
16	-.02	.21	11	+.15	.25
17	+.03	.24			

of momentum against the velocity gradient.

Unfortunately, the maximum correlation coefficients which can be expected from comparisons with similar physical situations, are about the same magnitude as the 5% significance level for samples of the size available. The largest correlation found in the present data is 0.4, but generally, maximum values are about 0.2, which is typical of similar coefficients in the atmosphere, calculated from thousands of observations (Buch, 1954). In a dissipative turbulent shear flow, maximum values of  $r$  are approximately 0.3 (Goldstein, 1938). Therefore, while further extensive observations of surface velocity may increase the statistical significance of the Reynolds stresses, they should not be expected to increase the magnitude of the correlation.

## 6. Suggestions for Future Research

The kinetic energy calculation of Part II suggests that the meanders play a significant role in maintaining the mean Gulf Stream. If this role is to be evaluated properly, an extensive program of velocity observations must be undertaken, the aim of which should be to collect data from all depths, along several hundred kilometers of the Gulf Stream axis. The data should be sufficient to provide a description of the current system in space and time adequate to derive the statistical balance of momentum, and energy throughout the region. Such an ideal observational program is not likely to be realized within the near future, because of the expense of gathering data and the limitations of present techniques of measurement. In the meantime, certain restricted observational programs might be undertaken whose aim is to delineate particular aspects of these balances.

More surface observations, similar to those analyzed here, are desirable. Data from several sections, at intervals along the Gulf Stream axis, can be gathered relatively easily. Such data would improve the description of downstream changes in Gulf Stream surface structure, and provide further information on the surface production of mean kinetic energy by meanders. If shipboard sections are made, as on CRAWFORD Cruise 18, care should be taken to make velocity observations across the whole width of the mean Gulf

Stream in that region, not just across the particular instantaneous stream width.

The effects of standing eddies in the balance calculations can be determined by making observations along the length of the current. This will enable space, as well as time averages to be found, and the deviations from these averages will specify the action of the standing eddies.

The sectional balance of linear momentum may be calculated if the horizontal velocity field is known beneath the surface on a single cross-section. The CRAWFORD Cruise 18 data were confined to the surface layer, but a less rapid cruise of a similar nature might be used to determine subsurface velocities.

These restricted observational programs can be used to provide an initial indication of the order of magnitude of the momentum and energy transfers in the Gulf Stream System. Ultimately, a simultaneously recording system of instruments, spread regularly throughout the region of the mean Gulf Stream, are needed to provide the statistical information necessary for a complete analysis of the momentum and energy transfer of meanders. Such a system would need to record at least temperature, salinity, and horizontal velocity. Horizontal velocities could be measured by a direct-reading rotor-type meter, which would record total magnitude and direction. Together, the temperature and salinity would specify the density field,

from which could be calculated the horizontal pressure gradients with respect to a reference surface. The reference surface could probably be determined by comparing geostrophic velocities computed from the density distribution with the directly measured velocities. Because of the difficulty of directly measuring vertical velocities, they would have to be calculated from the continuity equation, using the horizontal velocities. Once calculated, a time series of such vertical velocities, together with density measurements can be used to find the conversion from potential energy to meander kinetic energy.

A theoretical model describing the generation of meanders which is not based on a shearing instability is needed. If the meanders were the consequence of shearing instability, they would derive kinetic energy from the mean flow. The present study indicates that the source of meander kinetic energy is either the potential energy of the density field or a variable wind stress. Therefore, it seems that a successful theoretical model might be one in which the baroclinic (gravitational) instability is dominant in comparison with the barotropic (Rayleigh) instability. Up to the present time, those stability theories of the Gulf Stream which have had even limited success have been deduced from models which assume that the generation of meanders is the consequence of barotropic instability. Perhaps if a baroclinic Gulf Stream model could be constructed, much



along the lines of successful atmospheric models, a stability criterion could be formulated which would have a greater correspondence with reality.

## 7. CRAWFORD 18 Cross-sections

Figures 24 to 43 show the basic data gathered on each crossing of the Gulf Stream during CRAWFORD Cruise 18.

Above the temperature cross-section, plotted from BT data, are shown the profiles of surface temperature as recorded with the thermograph, surface salinity from bucket samples, and downstream surface velocity from GEK records. The GEK velocities have been left uncorrected. At the position of each GEK fix, an arrow has been drawn at the top of the temperature section, showing the direction of the surface velocity vector at that fix. At each BT lowering position, a black dot is shown.

The wind arrow in the lower left corner shows the direction and magnitude of the wind as recorded on the ship during the crossing.

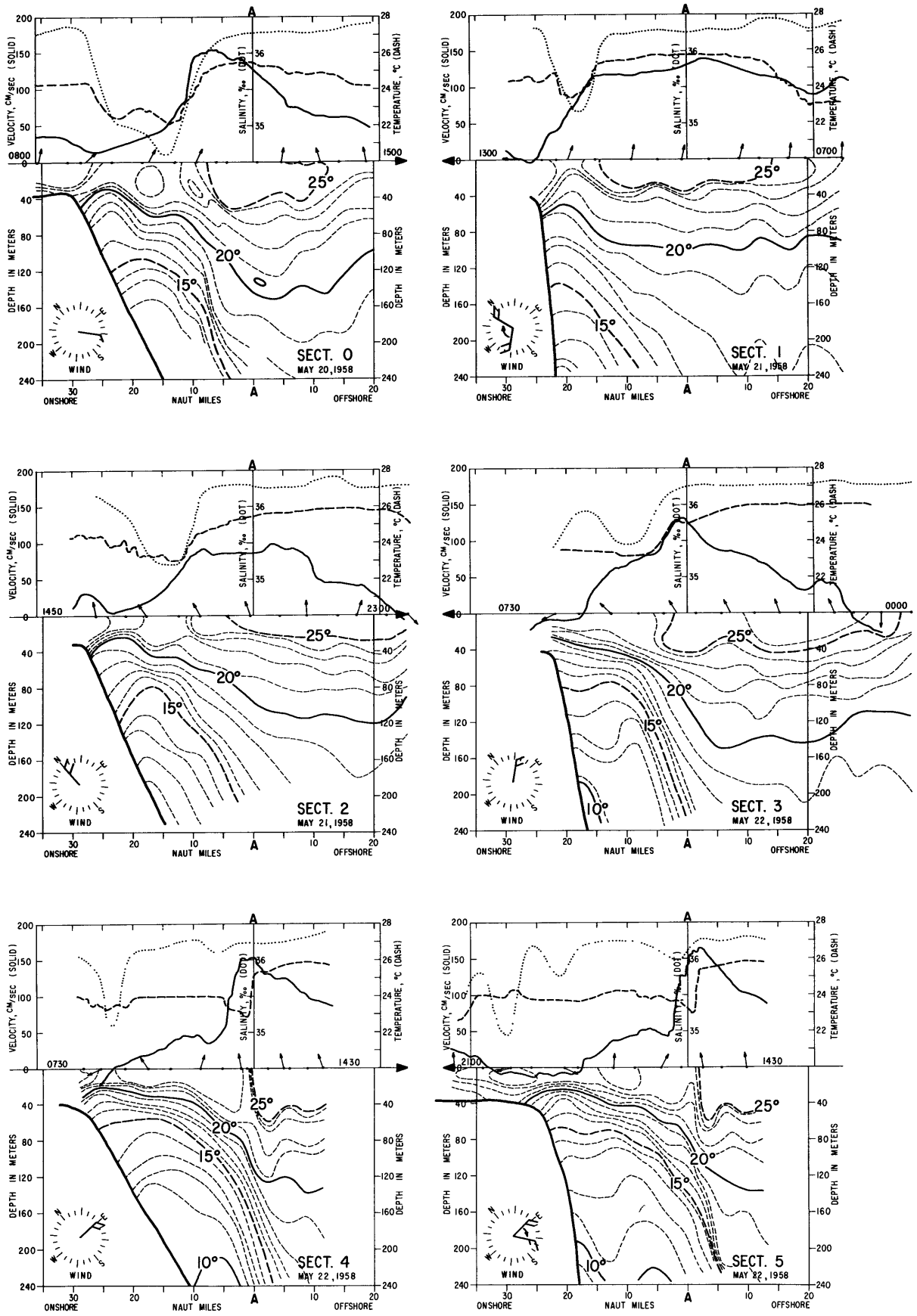


Figure 24

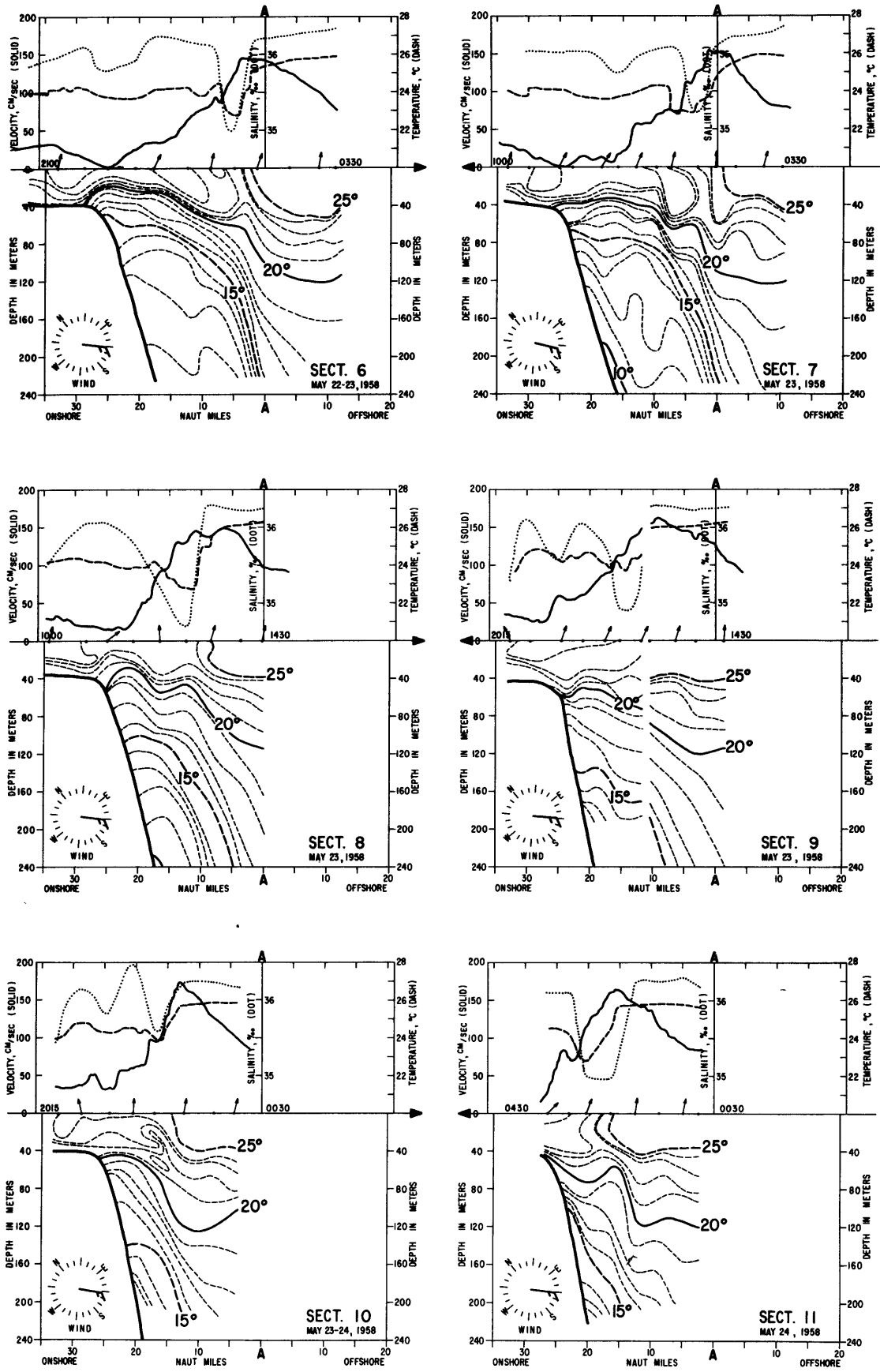


Figure 25

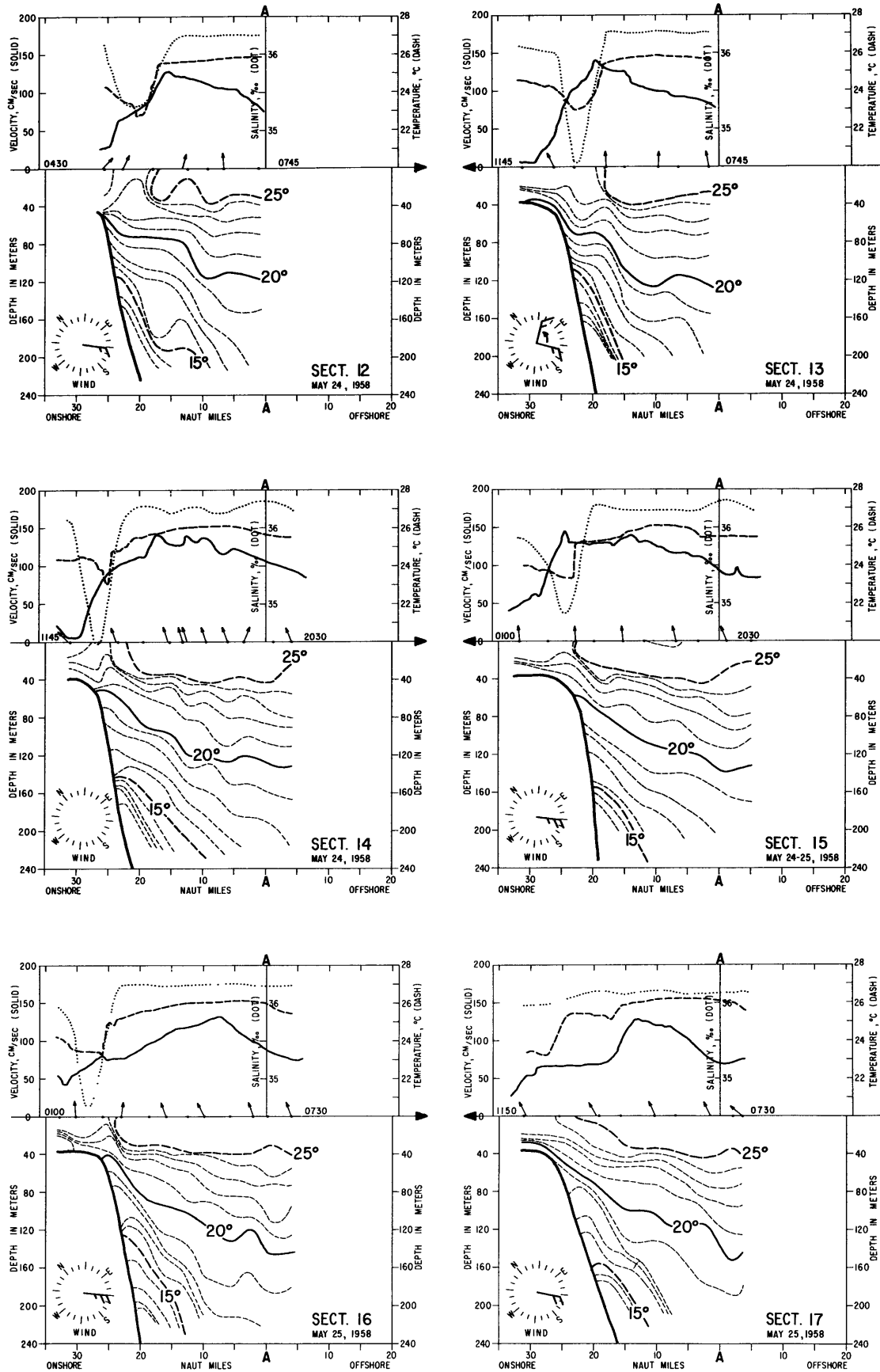


Figure 26

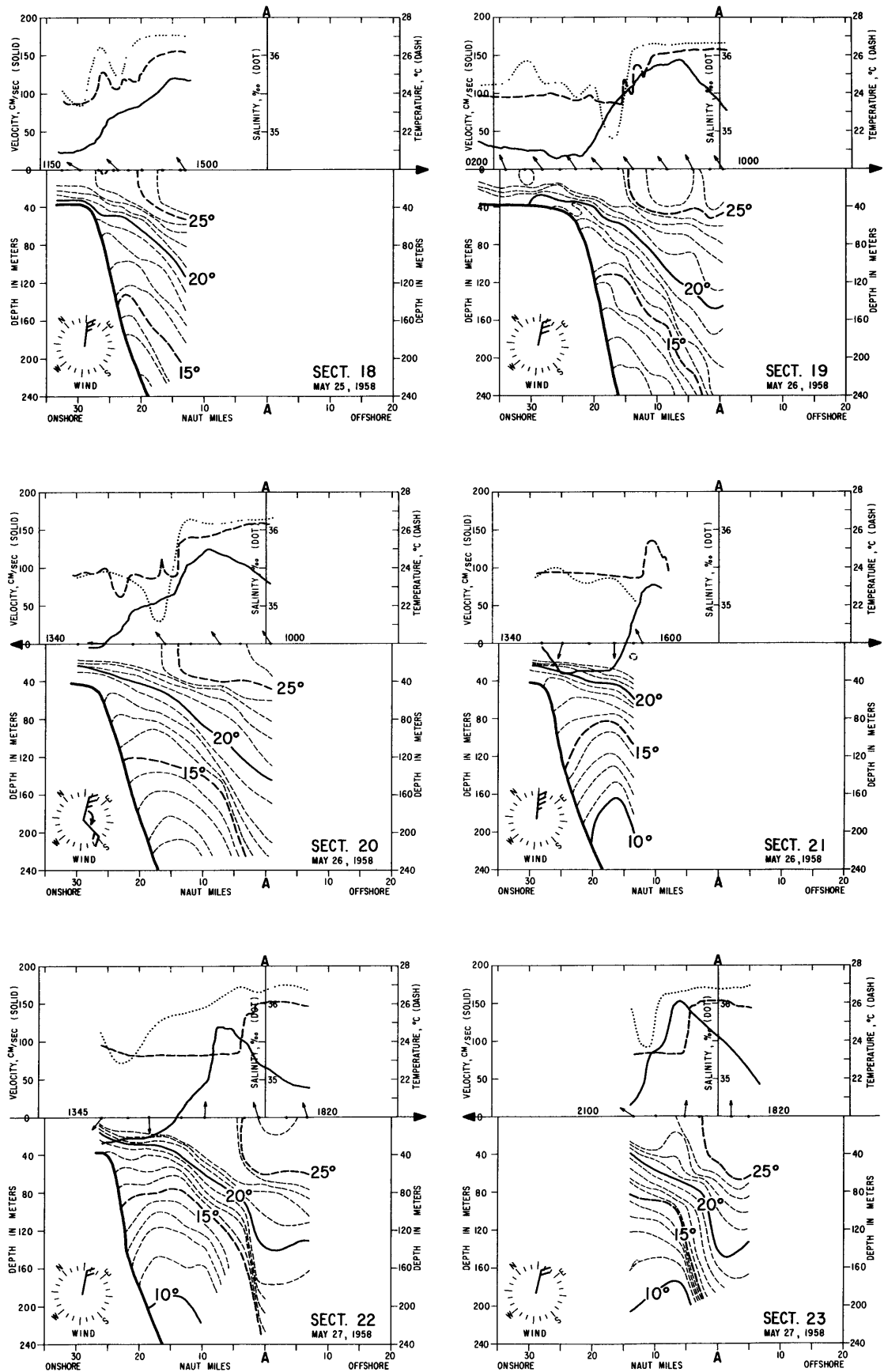


Figure 27

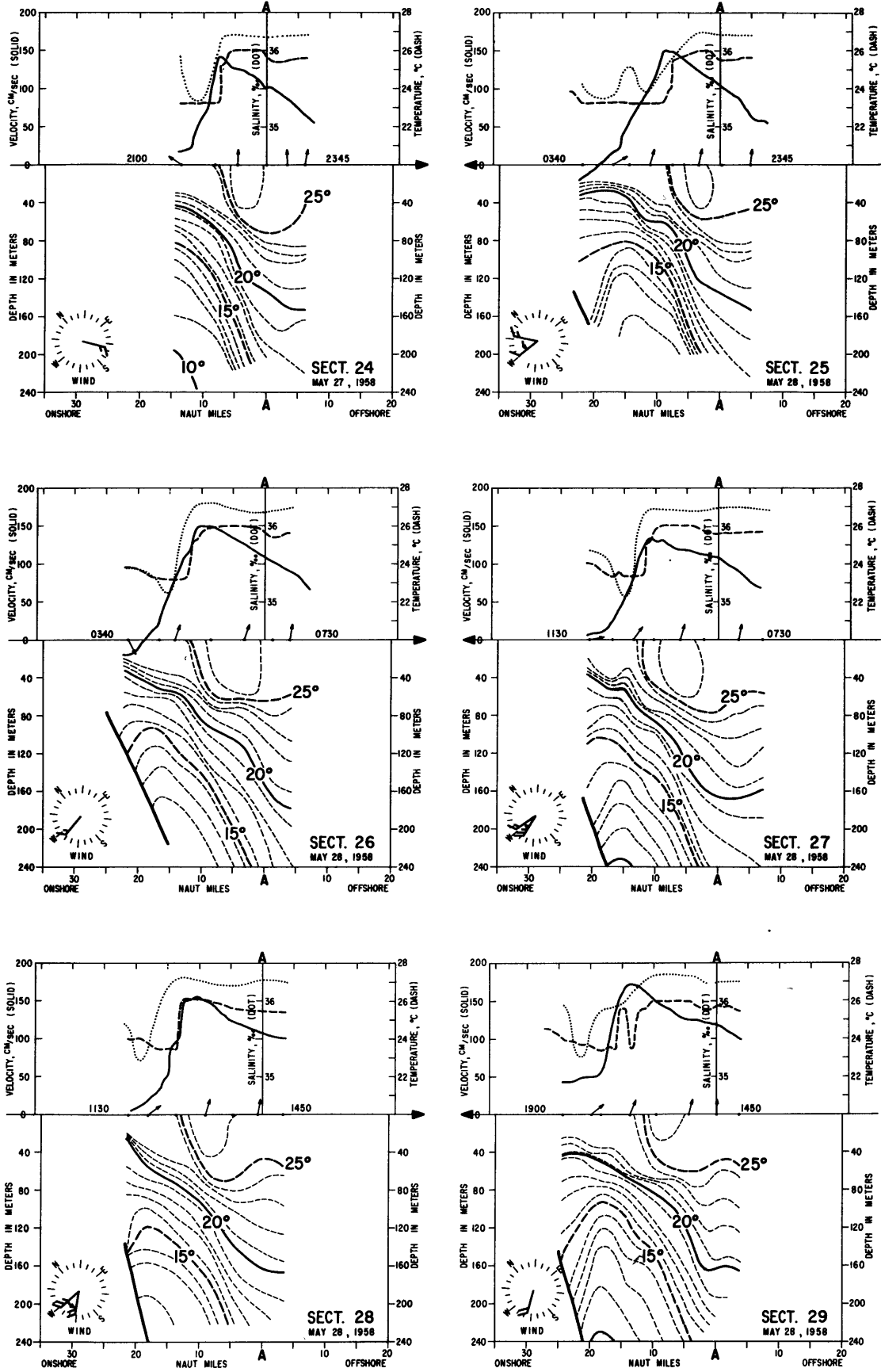


Figure 28

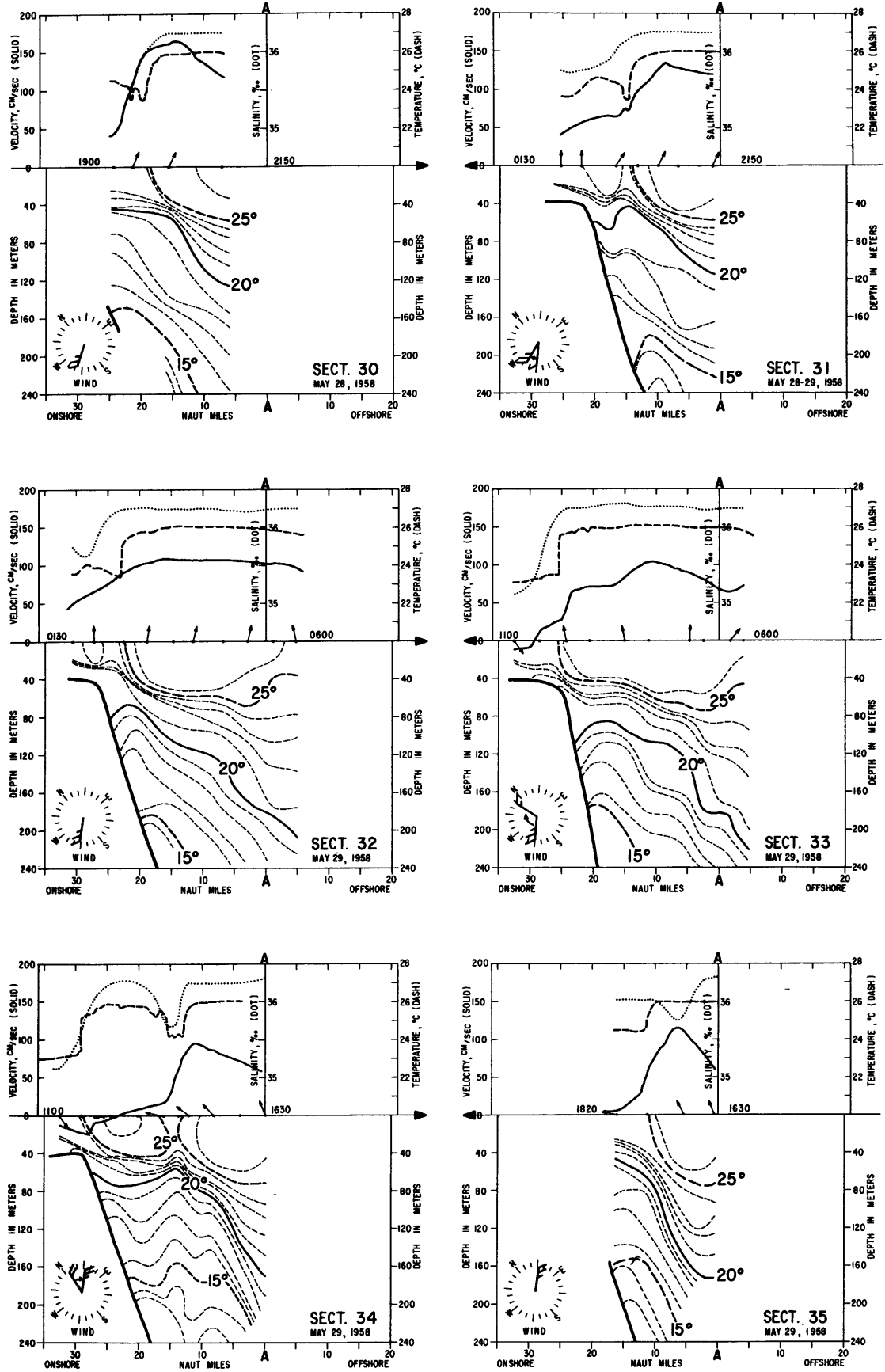


Figure 29



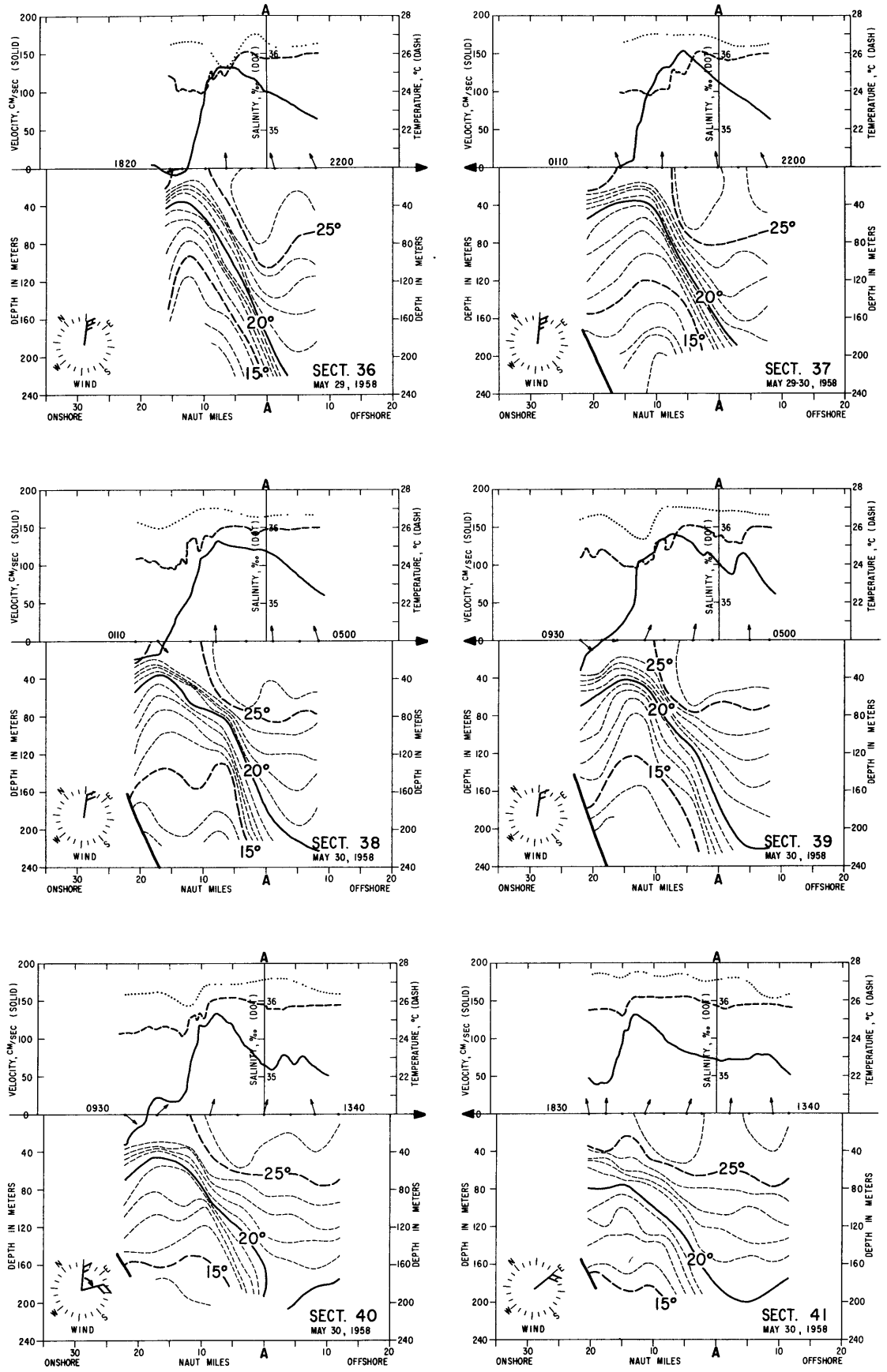


Figure 30

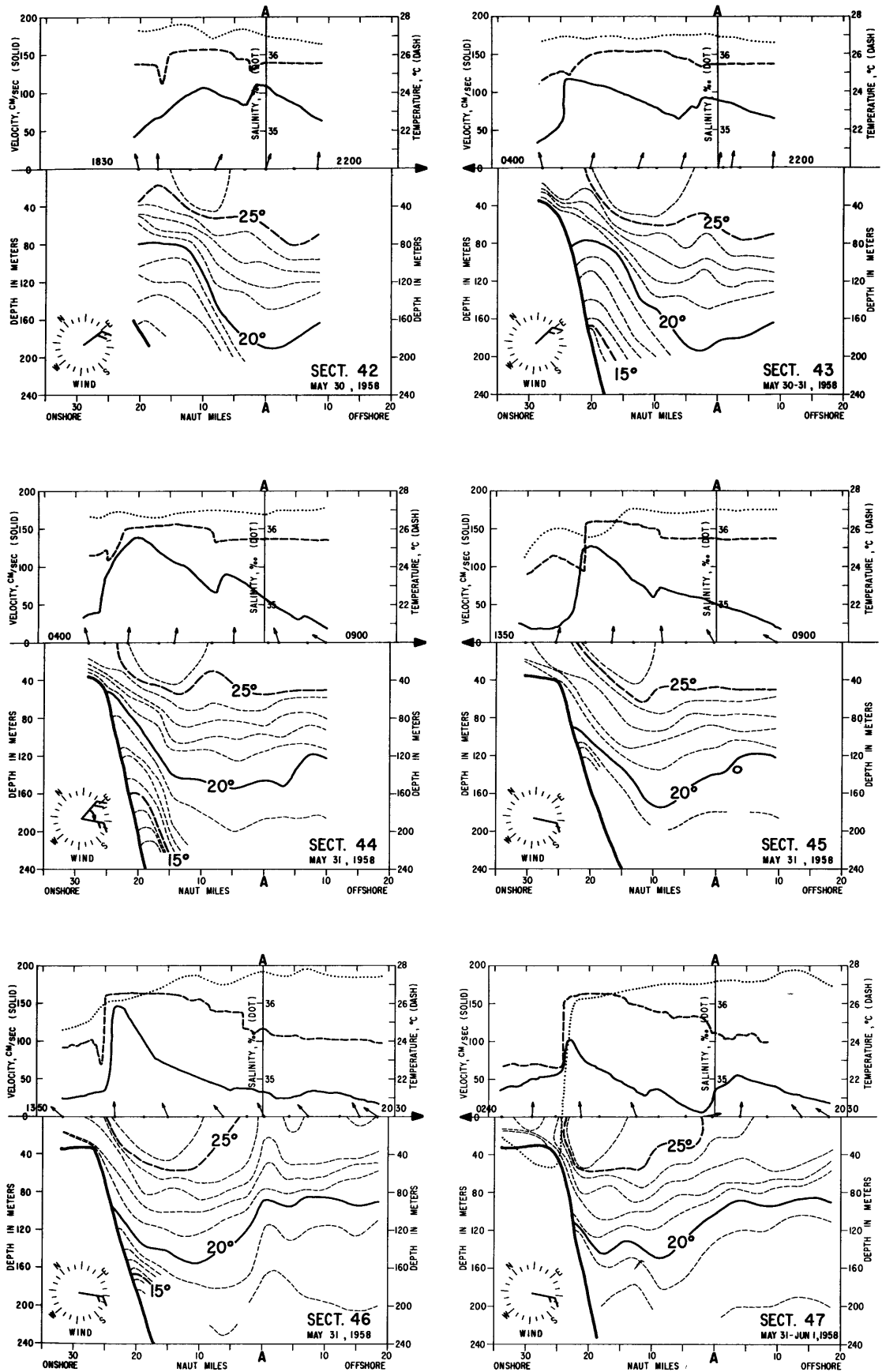


Figure 31

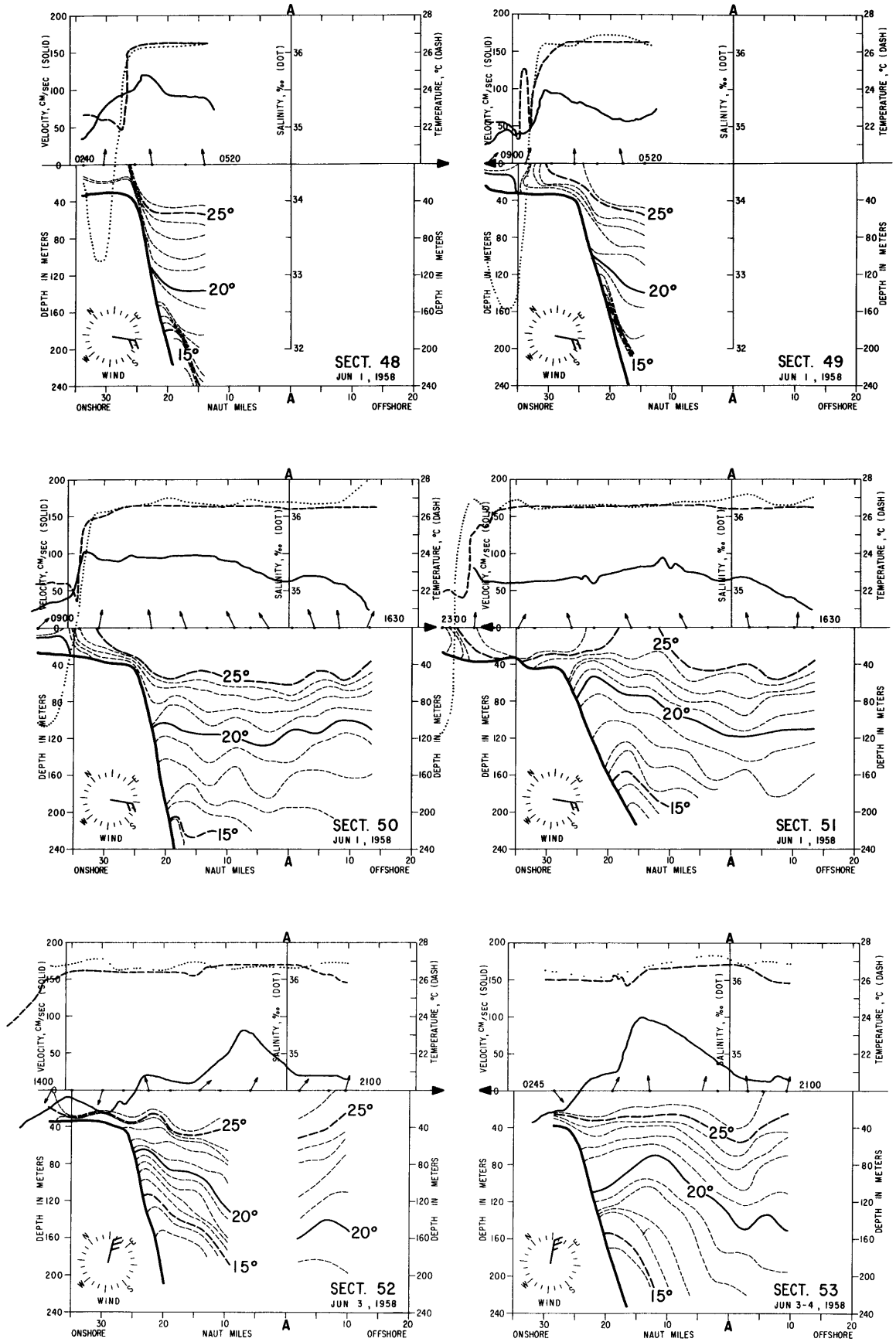


Figure 32

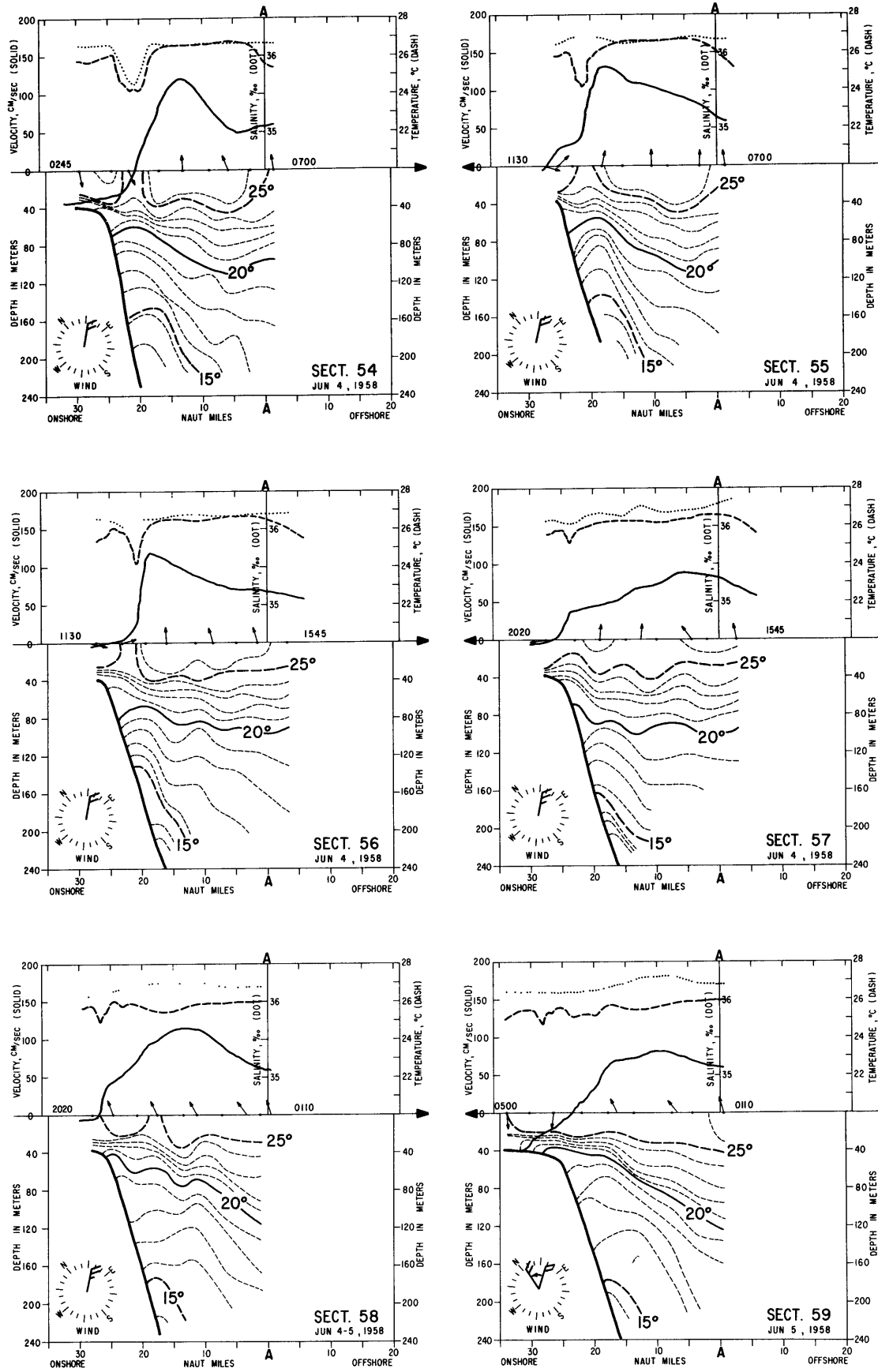


Figure 33

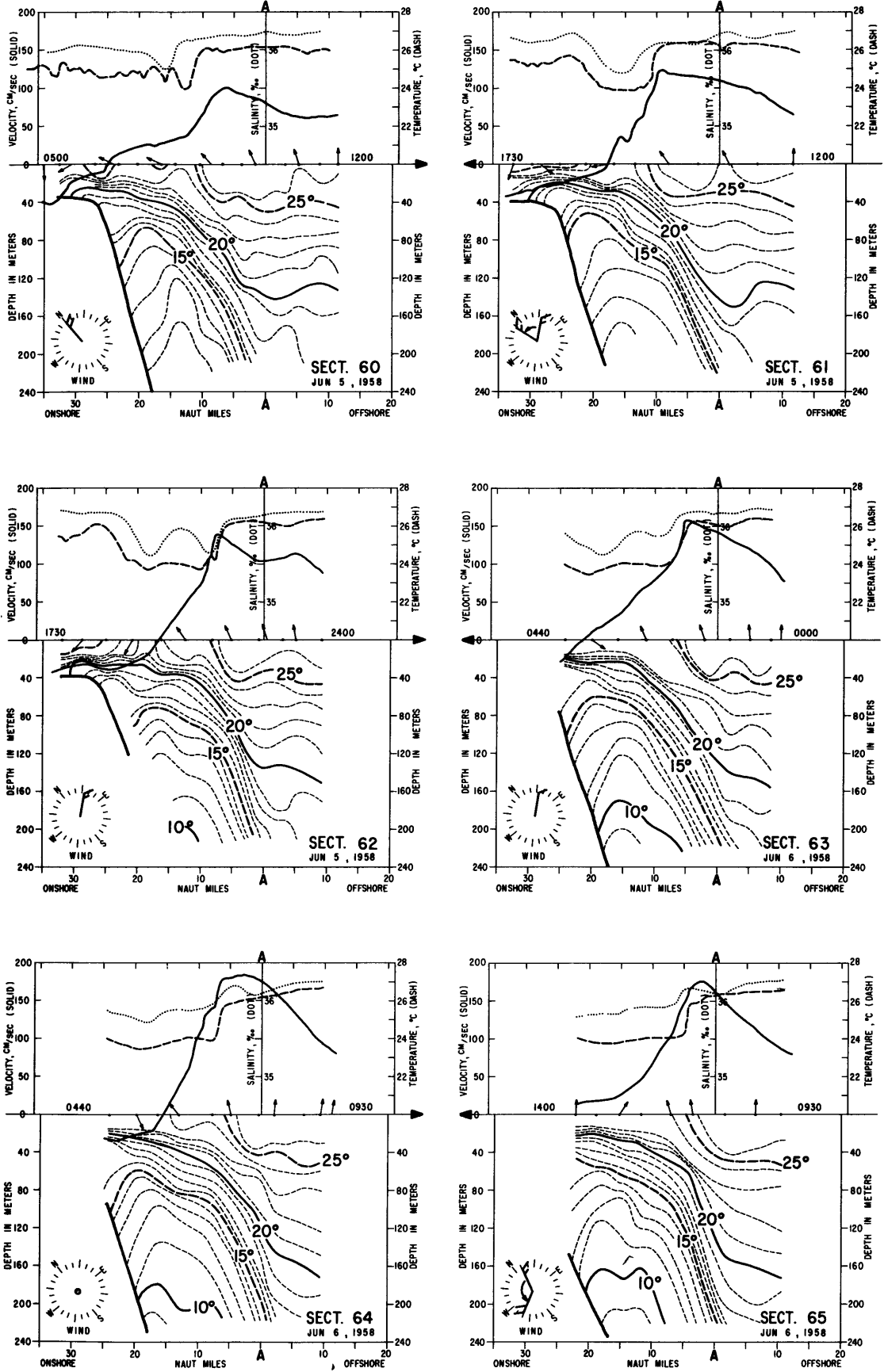


Figure 34

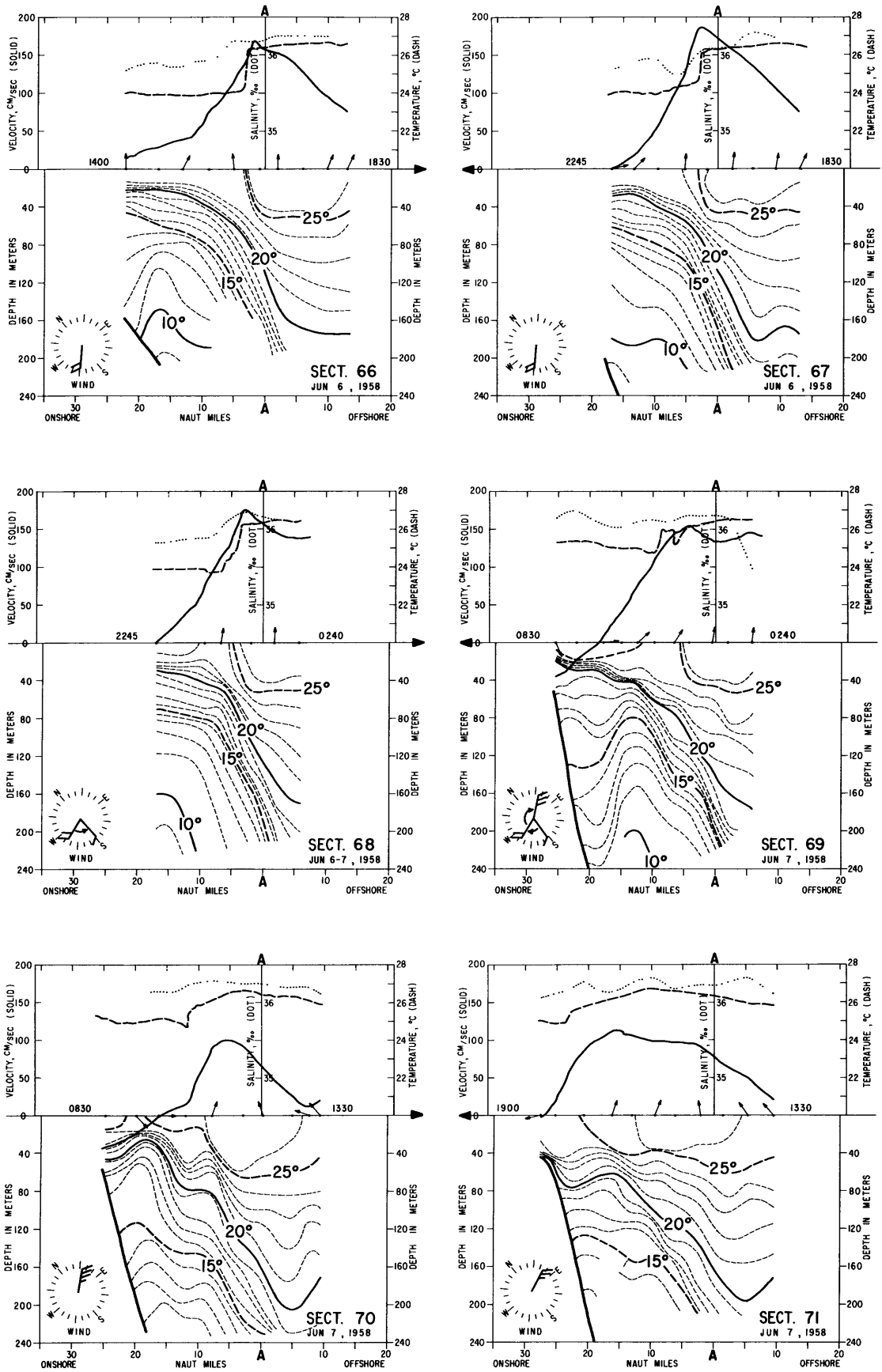


Figure 35

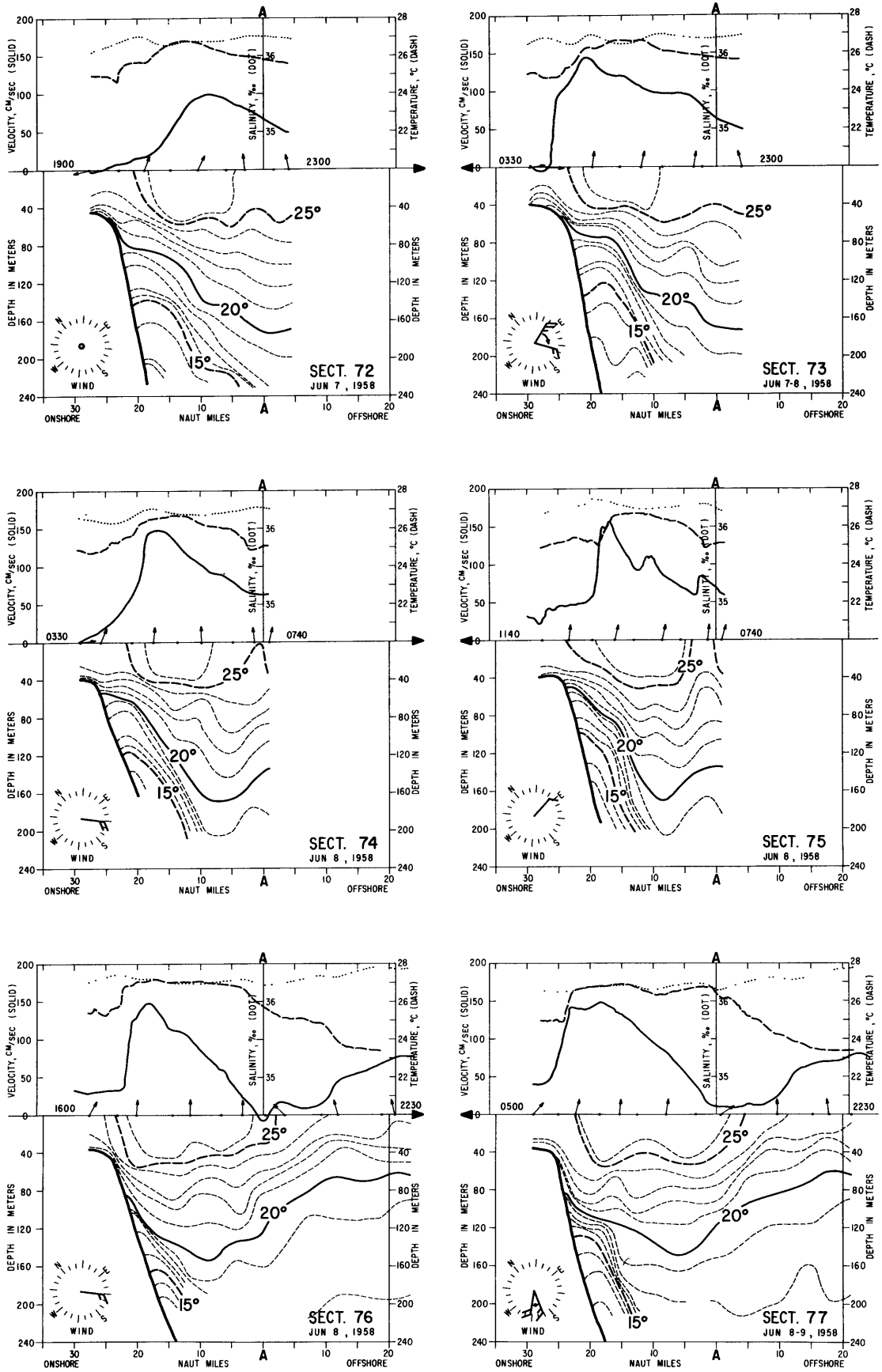


Figure 36

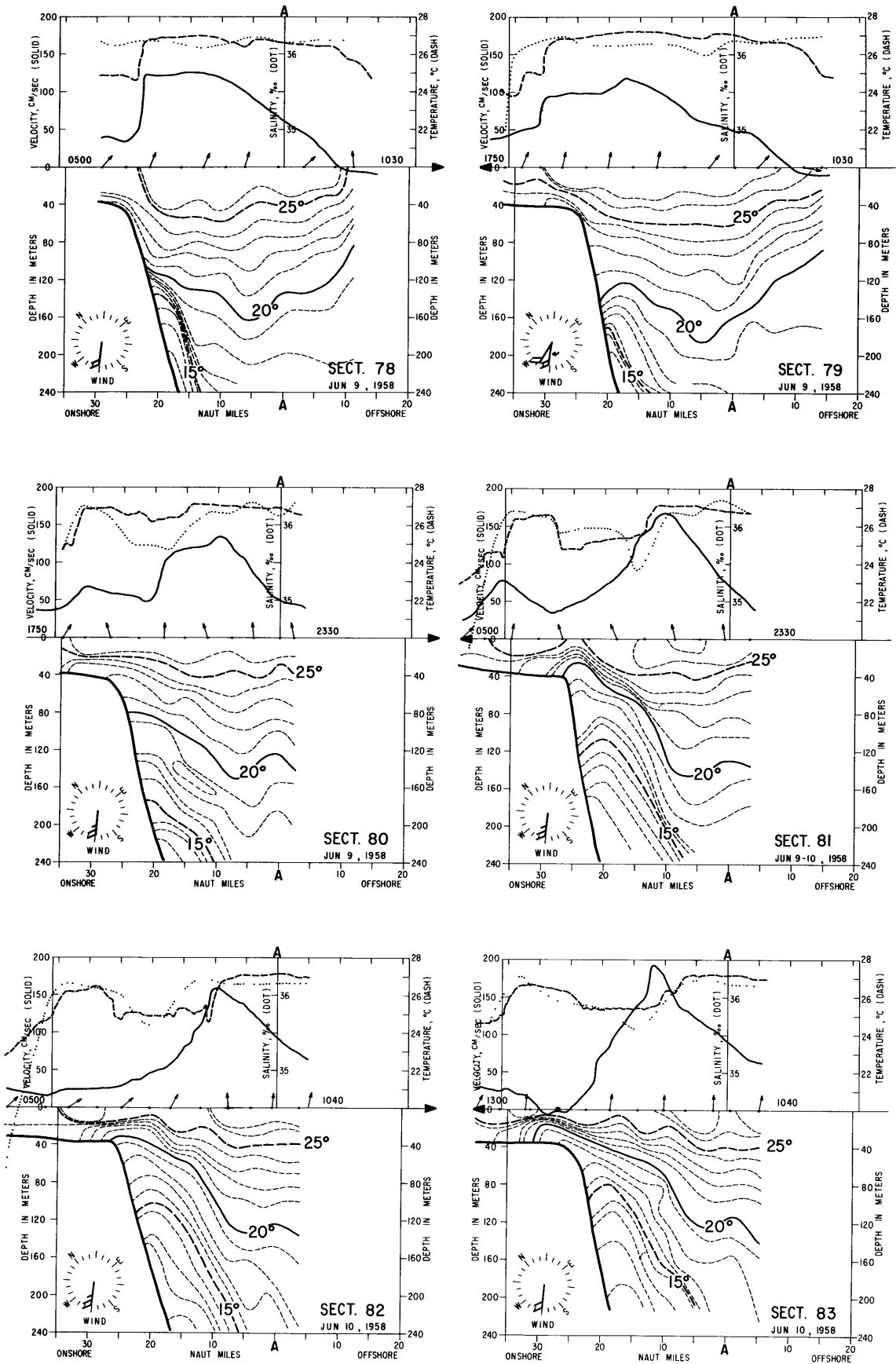


Figure 37



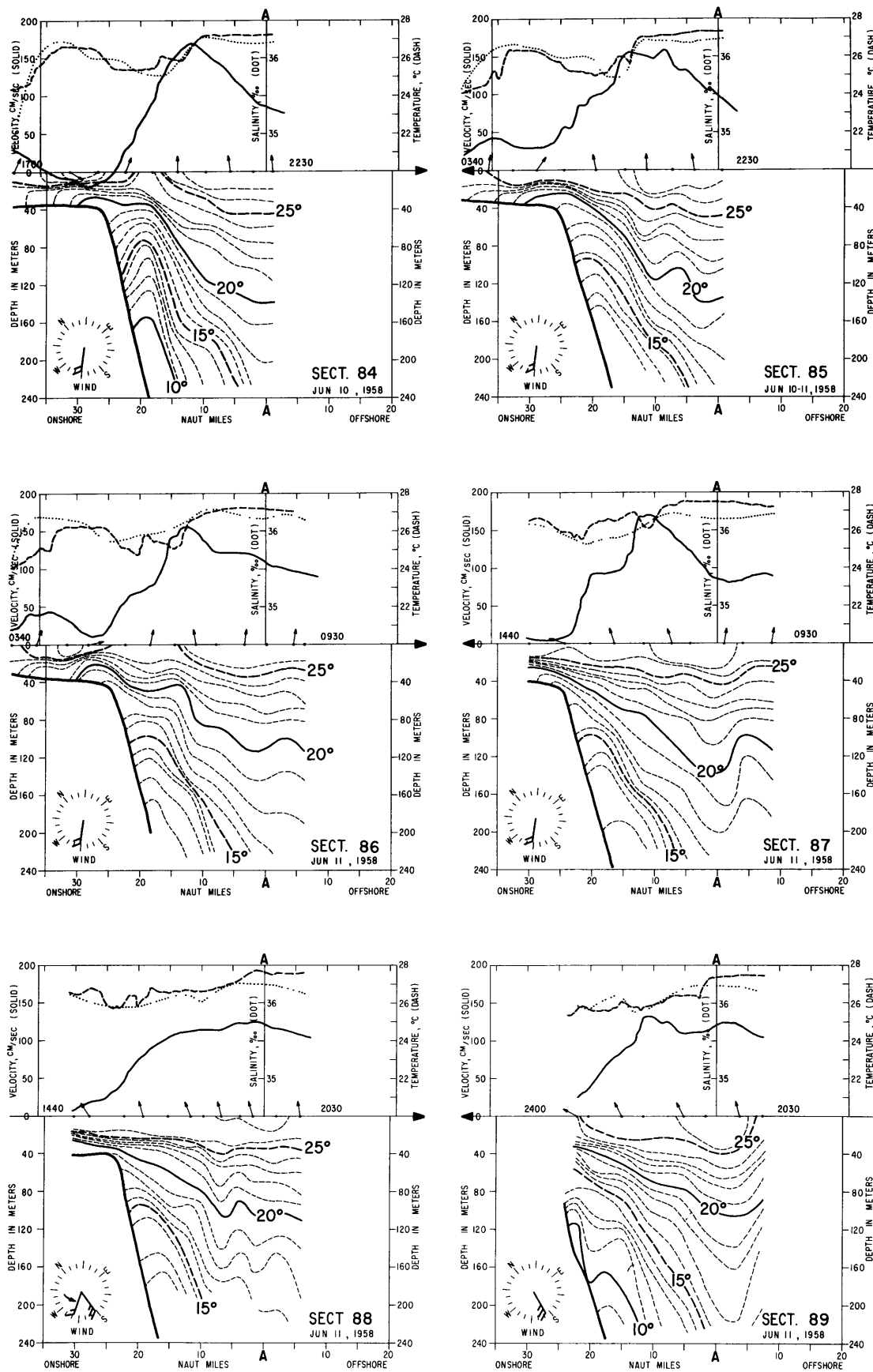


Figure 38

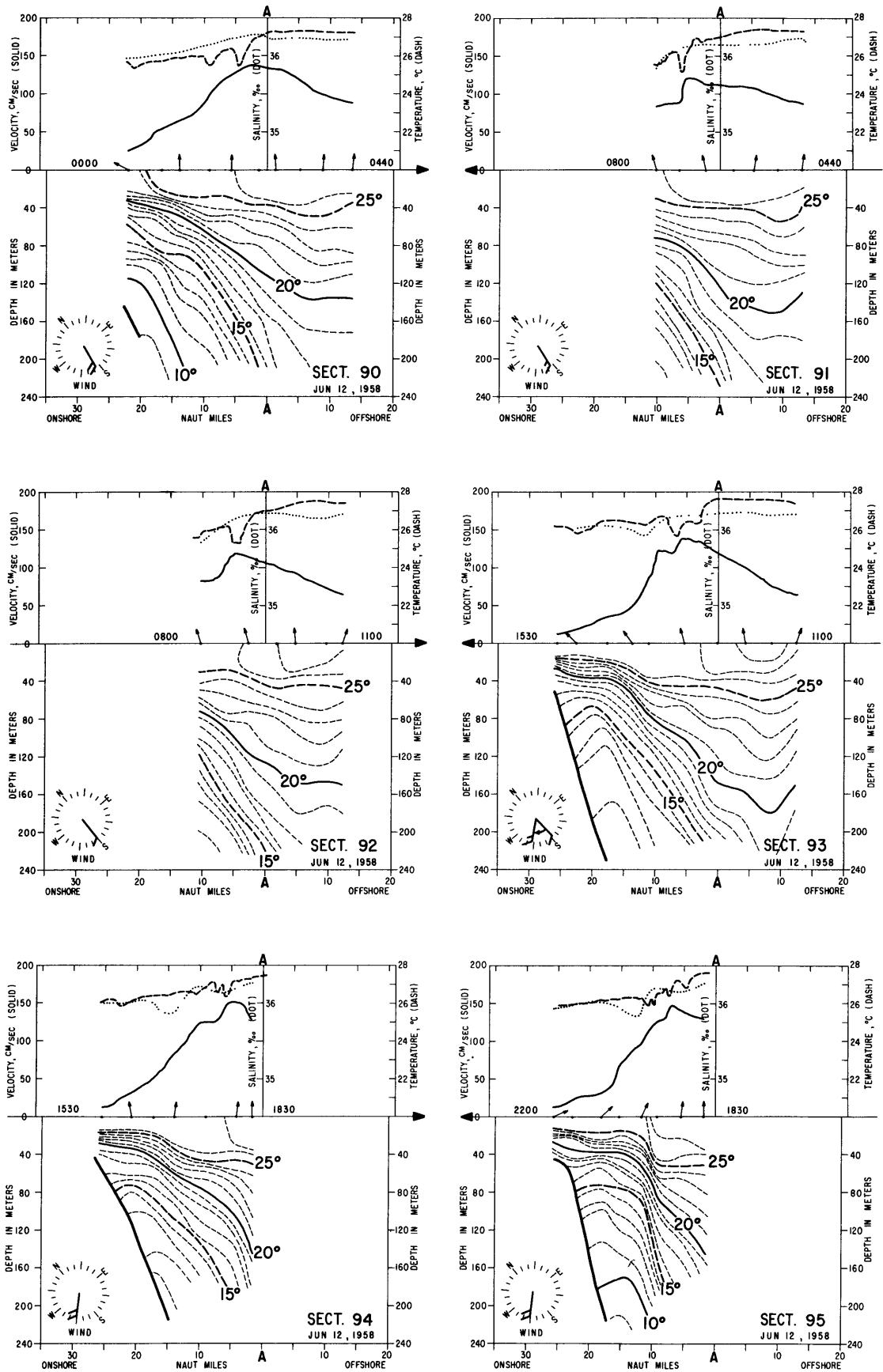


Figure 39

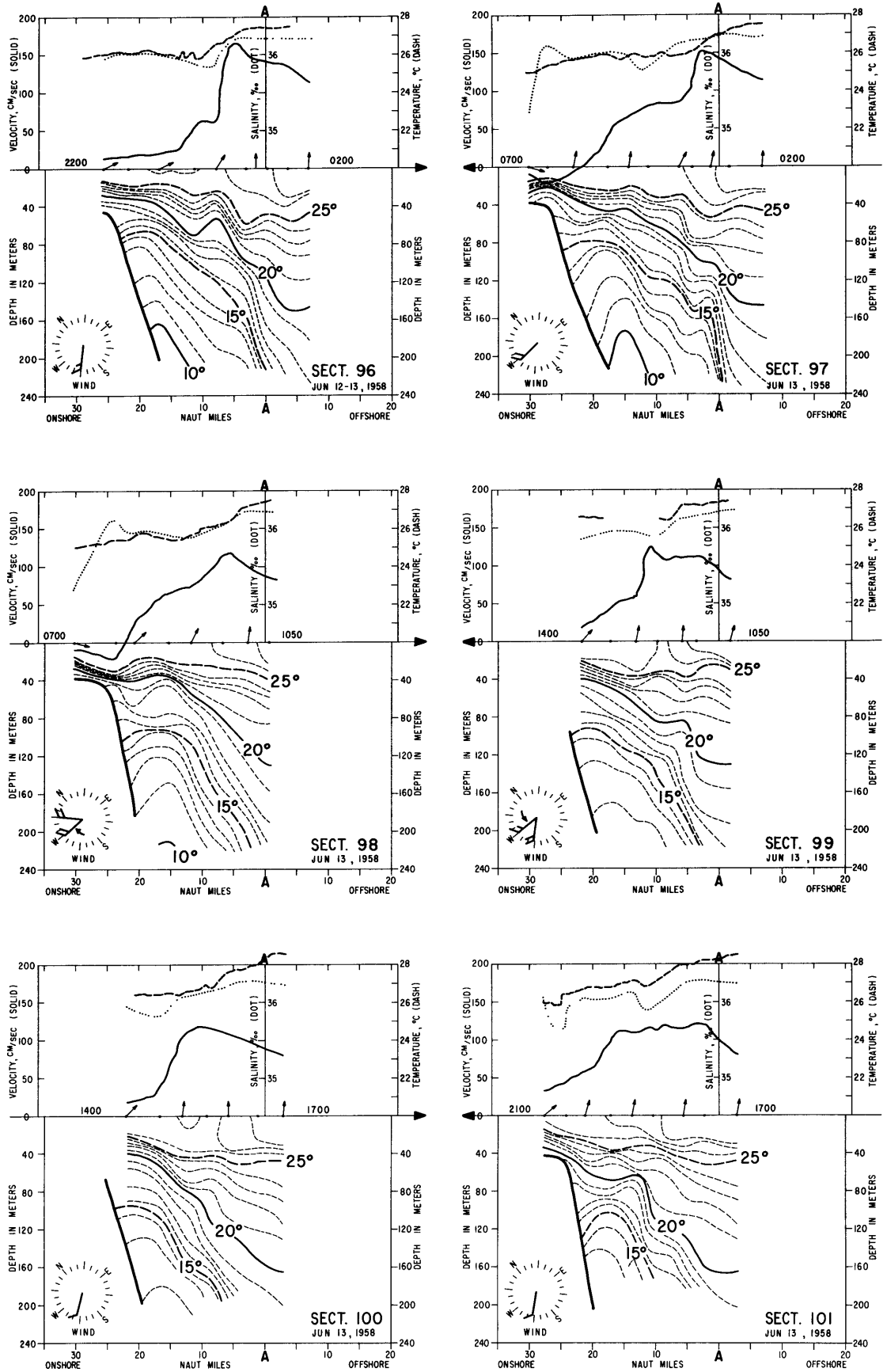


Figure 40

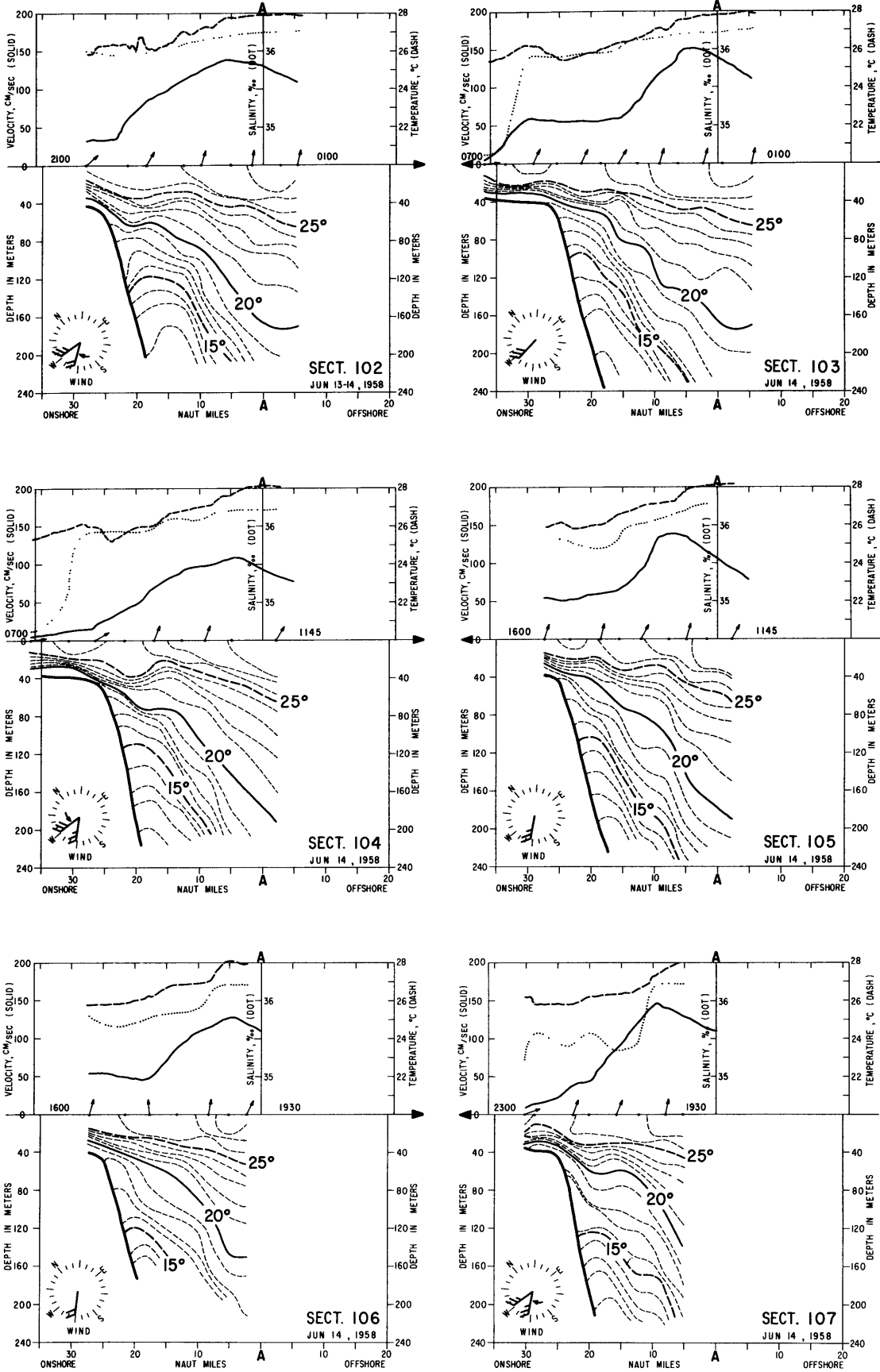


Figure 41

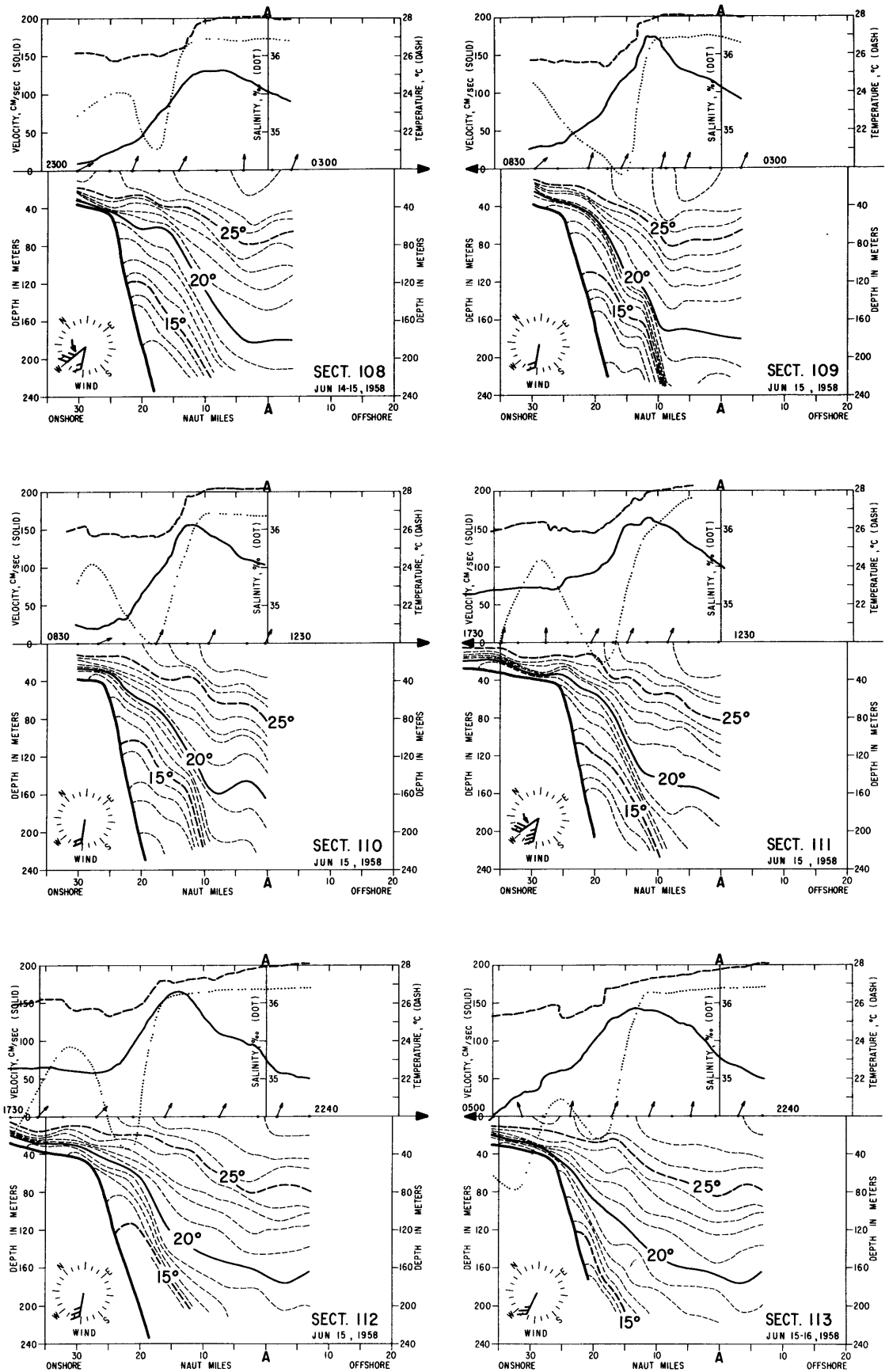


Figure 42

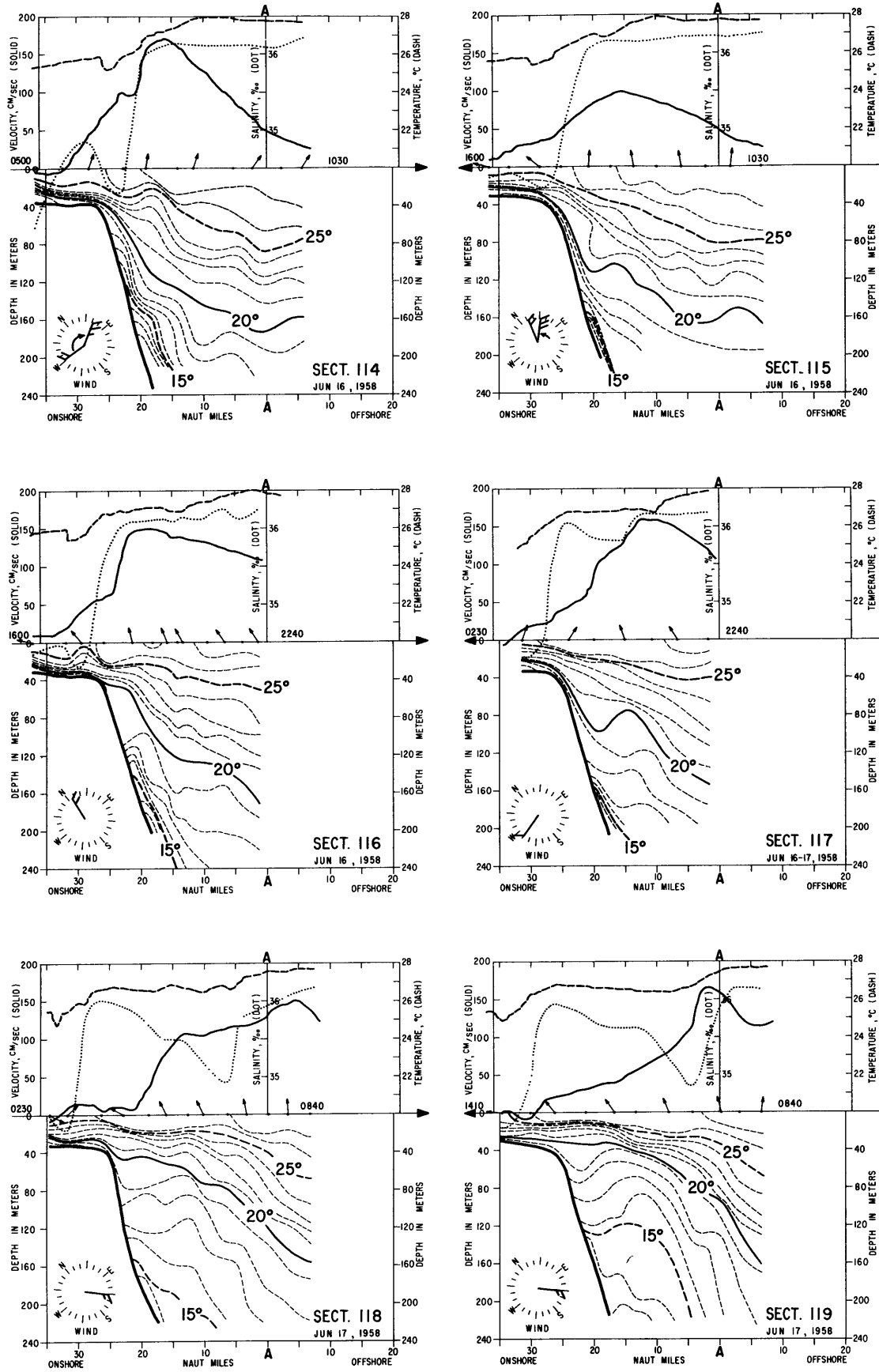


Figure 43

## BIBLIOGRAPHY

- Bache, A.D., 1860, Lecture on the Gulf Stream. Amer. J. Sci., 2 (31) 313-329.
- Buch, H.S., 1954, Hemispheric wind conditions during the year 1950. Final Report, M.I.T. General Circulation Project, Part 2, 126 pp.
- Bumpus, D.F., 1955, The circulation over the continental shelf south of Cape Hatteras. Trans. Amer. Geophys. Union, 36 (4) 601-611.
- Bumpus, D.F., and Pierce, E.L., 1955, The hydrography and the distribution of chaetognaths over the continental shelf of North Carolina. Pap. Mar. Biol. and Oceanogr., Suppl. Deep-Sea Res., 3, 92-109.
- Chew, F., 1958, An interpretation of the transverse component of the geomagnetic electrokinetograph readings in the Florida Straits off Miami. Trans. Amer. Geophys. Union, 39 (5) 875-884.
- Chew, F., and Wagner, L.P., 1957, Tropical Oceanography, semi-annual report, March, 1957. Marine Lab., Univ. of Miami, Tech. Rept., No. 57-9, 128 pp.
- Church, P.E., 1937, Temperatures of the western North Atlantic from thermograph records. Assoc. Océan.

Phys., Union Geodes. Geophys. Int., Publ. Sci.,  
4, 1-32.

Conrad, V., and Pollak, L.W., 1950, Methods in Climatology,  
Cambridge, U.S.A., Harvard University Press, 459 pp.

Day, C.G., Oceanographic observations, 1958 East Coast of the  
United States. United States Fish and Wildlife  
Service, Special Sci. Rept., Fisheries No. 318,  
119 pp.

Ford, W.L., Longard, J.R., and Banks, R.E., 1952, On the  
nature, occurrence and origin of cold low salinity  
water along the edge of the Gulf Stream. Jour. Mar.  
Res., 11 (3) 281-293.

Ford, W.L., and Miller, A.R., 1952, The surface layer of the  
Gulf Stream and adjacent waters. Jour. Mar. Res.,  
11 (3) 267-280.

Fuglister, F.C., 1951, Multiple currents in the Gulf Stream  
System. Tellus, 3 (4) 230-233.

Fuglister, F.C., 1954, Average temperature and salinity at a  
depth of 200 meters in the North Atlantic. Tellus,  
6 (1) 46-58.

Fuglister, F.C., 1955, Alternative analyses of current sur-  
veys. Deep-Sea Res., 2 (3) 213-229.

Fuglister, F.C., and Worthington, L.V., 1951, Some results of



a multiple ship survey of the Gulf Stream. Tellus,  
3 (1) 1-14.

Goldstein, S., 1938, Modern developments in fluid dynamics.  
Vol. I. Oxford, Oxford Univ. Press, 330 pp.

Hachey, H.B., 1939, Temporary migrations of Gulf Stream water  
on the Atlantic seaboard. Jour. Fish. Res. Bd. Can.,  
4 (5) 339-348.

Haurwitz, B., and Panofsky, H.A., 1950, Stability and  
meandering of the Gulf Stream. Trans. Amer. Geophys.  
Union, 3 (5) 723-731.

Hela, I., Chew, F., and Wagner, L.P., 1954, Some results of  
the Florida Current Study, 1953. Marine Lab., Univ.  
of Miami, Tech. Rept., No. 54-7, 100 pp.

Hela, I., Chew, F., and Wagner, L.P., 1955, Some results of  
the oceanographic studies in the Straits of Florida  
and adjacent waters. Marine Lab., Univ. of Miami,  
Tech. Rept., No. 55-1, 74+ pp.

Hela, I., and Wagner, L.P., 1954, Note on tidal fluctuations  
in the Florida Current, in: Marine Lab., Univ. of  
Miami, Tech. Rept., No. 54-7, 14-24.

Iselin, C. O'D., 1936, Study of the circulation of the North  
Atlantic Ocean. Pap. Phys. Oceanogr. Meteor.,  
4 (4) 1-101.

- Iselin, C. O'D., and Fuglister, F.C., 1948, Some recent developments in the study of the Gulf Stream. Jour. Mar. Res., 7 (3) 317-329.
- Kuo, H.L., 1951, A note on the kinetic energy balance of the zonal wind systems. Tellus, 3 (3) 205-207.
- Lamb, Sir H., 1932, Hydrodynamics, 6th ed. Cambridge, England, Cambridge University Press, 738 pp.
- Longuet-Higgins, M.S., Stern, M.E., and Stommel, H.M., 1954, The electrical field induced by ocean currents and waves, with applications to the method of towed electrodes. Pap. Phys. Oceanogr. Meteor. 13 (1) 1-37.
- Malkus, W.V.R., and Johnson, K., 1954, A drift study of the Gulf Stream. Woods Hole Oceanogr. Inst., Tech. Rept., Ref. No. 54-67 (unpublished manuscript).
- Munk, W.H., 1950, On the wind-driven ocean circulation. Jour. Meteor., 7 (2) 79-93.
- Murray, K.M., 1952, Short period fluctuation of the Florida Current from geomagnetic electrokinetograph observations. Bull. Mar. Sci., Gulf and Caribbean, 2 (1) 360-375.
- Newton, C.W., 1959, Synoptic comparisons of jet stream and Gulf Stream systems. The Atmosphere and the Sea

in Motion, edited by B. Bolin, New York, Oxford University Press, pp. 288-304.

Parr, A.E., 1937, Report of hydrographic observations at a series of anchor stations across the Straits of Florida. Bull. Bingham Oceanogr. Coll., 6 (3) 1-62.

Pillsbury, J.E., 1891, The Gulf Stream, a description of the methods employed in the investigation and the results of the research. Rept. Supt., U.S. Coast and Geodetic Survey, 1890, App. 10.

Reynolds, O., 1895, On the dynamical theory of incompressible viscous fluids and the determination of the criterion. Phil. Trans. Roy. Soc. London, A, 186, 123-164.

Rossby, C.-G., 1936, Dynamics of steady ocean currents in the light of experimental fluid mechanics. Pap. Phys. Oceanogr. Meteor., 5 (1) 1-43.

Saint-Guilly, B., 1957, Les méandres des veines de courant dans les océans. Bull. de l'Inst. Oceanogr., No. 1108, 11 pp.

Schleicher, K.E., and Bradshaw, A.L., 1956, A conductivity bridge for measurement of the salinity of sea water. Journ. du Cons., 22 (1) 9-20.

- Spilhaus, A.F., 1940, A detailed study of the surface layers of the ocean in the neighborhood of the Gulf Stream with the aid of rapid measuring hydrographic instruments. Jour. Mar. Res. 3 (1) 51-75.
- Spilhaus, A.F., 1941, Fine structure of the edge of the Gulf Stream. Trans. Amer. Geophys. Union, 22nd Ann. Meet., Pt. 2, 478-484.
- Starr, V.P., 1953, Note concerning the nature of the large-scale eddies in the atmosphere. Tellus, 5 (3) 494-498.
- Starr, V.P., 1954, Commentaries concerning research on the general circulation. Tellus, 6 (3) 268-272.
- Starr, V.P., and White, R.M., 1951, A hemispherical study of the atmospheric angular momentum balance. Quart. J. Roy. Meteor. Soc., 77 (332) 215-225.
- Stommel, H.M., 1948, The westward intensification of wind-driven ocean currents. Trans. Amer. Geophys. Union, 29 (2) 202-206.
- Stommel, H.M., 1953, Examples of the possible role of inertia and stratification in the dynamics of the Gulf Stream System. Jour. Mar. Res., 12 (2) 184-195.
- Stommel, H.M., 1955, Lateral eddy viscosity in the Gulf Stream System. Deep-Sea Res., 3 (1) 88-90.

- Stommel, H.M., 1958, The Gulf Stream. Berkeley, U.S.A., Univ. of California Press, 202 pp.
- Stommel, H.M., von Arx, W.S., Parson, D., and Richardson, W.S., 1953, Rapid aerial survey of Gulf Stream with camera and radiation thermometer. Science, 117 (3049) 639-640.
- Strack, S.L., 1953, Surface temperature gradients as indicators of the position of the Gulf Stream. Woods Hole Oceanogr. Inst., Tech. Rept. Ref. No. 53-53, (unpublished manuscript).
- von Arx, W.S., 1950, An electromagnetic method for measuring the velocities of ocean currents from a ship underway. Pap. Phys. Oceanogr. Meteor., 11 (3) 1-62.
- von Arx, W.S., 1951, Some measurements of the surface velocities of the Gulf Stream. Woods Hole Oceanogr. Inst., Tech Rept. Ref. No. 51-96 (unpublished manuscript).
- von Arx, W.S., 1952, Notes on the surface velocity profile and horizontal shear across the width of the Gulf Stream. Tellus, 4 (3) 211-214.
- von Arx, W.S., 1954, Measurements of the oceanic circulation in temperate and tropical latitudes. Oceanographic Instrumentation, Nat. Res. Council. (U.S.) Publ., No. 309, 13-35.

von Arx, W.S., Bumpus, D.F., and Richardson, W.S., 1955, On the fine structure of the Gulf Stream front. Deep-Sea Res., 3 (1) 46-65.

Wagner, L.P., and Chew, F., 1953, Some results of the Florida Current survey. Marine Lab., Univ. of Miami, Tech. Rept., No. 53-9, 1-53.

Wertheim, G.K., 1954, Studies of the electric potential between Key West, Florida and Havana, Cuba. Trans. Amer. Geophys. Union, 35 (6) 872-882.

Worthington, L.V., 1954, Three detailed cross-sections of the Gulf Stream. Tellus, 6 (2) 116-123.

\* Iselin, C. O'D., 1940, Preliminary report on long-period variations in the transport of the Gulf Stream System. Pap. Phys. Oceanogr. Meteor., 8 (1) 1-39.

## BIOGRAPHICAL NOTE

The author, Thomas Ferris Webster, was born in Saint Boniface, Manitoba, Canada, on August 7, 1934. He attended public schools in Winnipeg, Calgary, Saskatoon, and Edmonton, Canada, and entered the University of Alberta in 1952, receiving a Bachelor of Science degree in Honours Physics in May, 1956. During his senior year there, he was awarded the California Standard Company Scholarship.

He obtained his Master of Science degree in Physics in October, 1957, at the University of Alberta. While enrolled there as a graduate student, he was awarded a California Standard Company Graduate Fellowship. His master's thesis was a study of the relation between electric and magnetic components of the geomagnetic field in relation to subsurface geological structure. Results from this study have been published in: Garland, G.D., and T.F. Webster, "Studies of natural electric and magnetic fields", Jour. of Research, N.B.S., 64D (4) 405-408, 1960. During the summers of 1956 and 1957, he was engaged in geophysical field measurements in western Canada.

The author was admitted to the Graduate School of M.I.T. in September 1957 as a doctor's candidate. During the school years 1957-58 and 1958-59, he was employed as a Research Assistant in the Geochronology Project under the direction of Prof. P. M. Hurley. In the summers of 1958-59, he received a summer fellowship from the Woods Hole Oceanographic Institution, where, in 1959, he attended the summer course in Geophysical Fluid Dynamics. In 1960-61, he was awarded an M.I.T. Canadian Trust Fund Scholarship. During his final two years as a graduate student at M.I.T., he was a research assistant at the Woods Hole Oceanographic Institution under the supervision of Prof. W. S. von Arx.