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PHYSICAL CHARACTERISTICS OF OCEAN FRONTS AND EDDIES IN THE NORT--ETC(U)

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PHYSICAL CHARACTERISTICS OF OCEAN FRONTS AND EDDIES IN THE NORTH ATLANTIC

R. W. JAMES
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Ocean fronts and eddies are defined, described and typical locations given. Their formation, surface and vertical characteristics, variability, and operational system display are discussed. How to analyze and map fronts is described.

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FOREWORD

This Technical Note presents material prepared at the request of Commander in Chief, Atlantic Fleet in connection with a project concerning ocean fronts and their effect on ASW operations. The object of the project, which was funded by the Navy Science Assistance Program (NSAP), was to document the present status of knowledge concerning frontal acoustics. A three-part report was presented to CINCLANTFLT; Part I (NAVOCEANO) concerning the physical characteristics and mapping of ocean fronts and eddies; Part II (NUSC, Newport) dealing with the effects of fronts/eddies on short range tactical sonars, and Part III (NUC) regarding the effects on surveillance systems. The complete report will be published as a joint paper of the three groups in June 1977.

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PHYSICAL CHARACTERISTICS OF OCEANIC FRONTS AND EDDIES IN THE NORTH ATLANTIC OCEAN

1.0 INTRODUCTION

The ability to detect a submarine is dependent upon, among other factors, the environmental conditions between the target and the sensor. Usually it is assumed that these conditions are stable; that is, one thermal profile (BT) is taken to be representative of the entire acoustic path. This is not a valid assumption in many of the world's oceans owing to the existence of horizontal thermal and haline discontinuities associated with oceanic fronts and eddies. These anomalous oceanographic conditions modify sound transmision and, in many instances, produce significant variances in sonar ranges, area of insonification and the optimum sensor mode and depth. In addition, there may be an icrease in ambient noise, reverberation levels, and bearing errors (James-1).

Two separate but related operational problems are created:

(1) Target and sensor on same side of front

An ASW unit transiting a frontal region will often find that sonar conditions on one side of the front differ considerably from those on the other side. These differences are often of such a nature as to require a revision in tactics. For example, VP operations south of the Gulf Stream in the spring can obtain maximum coverage by using shallow hydrophones, while deep settings are better to the north due to differences in the thermal profiles. The problem: What changes should be made in sensor deployment and depth, sonar mode, and other tactics when an ASW unit crosses a front or eddy?

(2) Target and sensor on opposite sides of a front or eddy

When the target is on the opposite side of a front or eddy from the sensor there are modifications to the transmission of sound propagating through the front which are in addition to, and separate from, the differences in sonar conditions existing on the two sides of the front. For example, sound tends to be refracted below the front when propagating from cold to warm water. This affects the convergence zone range, which will be shorter than that occurring entirely in the warm water, but longer than those found in the cold water side of the front. Other changes take place leading to bearing errors for long range surveillance, revision of criteria for selecting optimum detection depth for a sensor, and anomalous propagation losses for certain target/sensor depth combinations. The problem: What procedures should be followed to ensure maximum (or minimum if desired) sonar capabilities?

The first step to understanding and considering the ASW consequences of oceanic fronts and eddies is to learn the exact nature of these phenomena. To that end this paper discribes physical characteristics of fronts in the North Atlantic. Since real-time surveillance of these features must be maintained if operational applications are to be made, techniques for tracking fronts/eddies are also discussed.

2.0 IDENTIFYING FRONTS AND EDDIES

Oceanic fronts are rather narrow regions separating waters of different physical characteristics and usually exhibiting large horizontal gradients of temperature and/or salinity as well as a degree of current shear. A precise definition is difficult since some fronts which have weak horizontal gradients at the surface may have strong gradients at 200 m (650 ft). In some cases gradients are weak at all levels but variability across the front as reflected by the shape of the thermal profile is sufficient to complicate sound ranging. Fronts are found in every ocean, in surface as well subsurface layers, and on scales varying from tens to hundreds of km (Roden-2). Cheney and Winfrey (3) have classified ocean fronts as strong, moderate or weak as a function of criteria significant to ASW operations:

Table 1. CRITERIA FOR RATING THE RELATIVE STRENGTH OF OCEAN FRONTS

	Maximum change in sound velocity (ft/sec)	Change in SLD (ft)	Depth (ft)	Persistence
Strong	>100	>500	>3000	year-round
Moderate	50-100	100-500	300-3000	year-round
Weak	< 50	<100	<300	selected seasons only

Because fronts exhibit both seasonal and short-term variability, all the characteristics of one category may not be present at the same time.

Eddies are a special form of fronts. Since eddies are rotating masses of water that have broken off from a strong front (such as the Gulf Stream) they can be considered circular fronts with the waters trapped inside having different physical properties than the surrounding waters through which the eddies move. Eddies are large, occur frequently, and produce acoustic anomalies in a fashion similar to fronts. Accordingly, eddies are also important to ASW operations.

In a general sense an eddy is any parcel of fluid within a larger mass but having a circulation and life history of its own. As such, the eddy concept can be applied to phenomena ranging from momentary vortices in the sea surface flow to the slow steady circulation of a basin-wide gyre. For ASW applications however, mesoscale features with diameters of 100 to 400 km (55 to 215 nmi) are of significant importance and it is these eddies that will be considered in this report.

3.0 TYPICAL LOCATION OF FRONTS

Approximate mean positions of fronts in the North Atlantic are indicated in Figure 1; the dashed lines are weak fronts and may not be significant to ASW operators. The cross-hatched indicates the general region within which Gulf Stream warm and cold eddies form. Ocean fronts are of varying dimensions; some can be identified for well over 1000 km (540 nmi) while others are less a tenth of that length.

The Gulf Stream is a strong front (see Table 1) and dominates circulation in the western North Atlantic. East of 50°W it weakens and is known as the North Polar Front (or North Atlantic Current). The Slope Front follows the shelf break between Cape Hatteras and Nova Scotia and is classified as a moderate front. The Sargasso Sea Front, or Subropical Convergence as is it known further to the east, is a weak front which only exists during late winter and early spring. The Denmark Strait Front is a moderate front and the Icelandic-Faeroe Front separates relatively warm water carried northward by the extension of the Gulf Stream from the cold, subarctic water of the Norwegian Sea. Another front in that area is the Greenland-Norwegian Sea Front. The Huelva Front found along the southern coast of Spain, is weak, owing to its seasonal nature and limited dimensions.

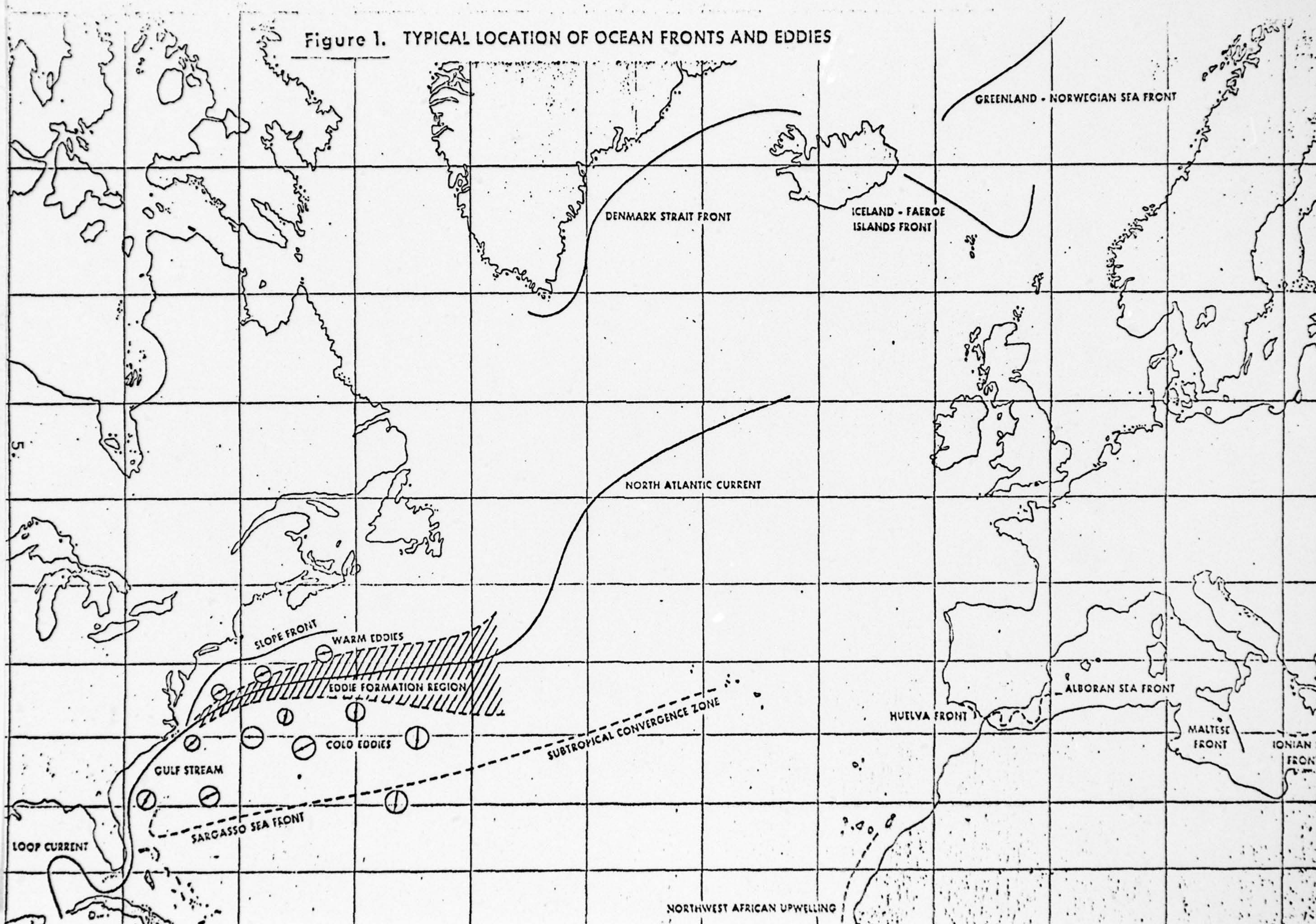

Figure 1. TYPICAL LOCATION OF OCEAN FRONTS AND EDDIES

IV. FORMATION AND LOCATION OF EDDIES

Eddies are spawned from the Gulf Stream when a meander becomes elongated and begins to close off at the neck (Figure 2). In the case of a warm eddy a northward protrusion of warm Sargasso Sea Water is trapped within the encircling Gulf Stream. Eventually the warm eddy separates and drifts off on its own as a large ring of water rotating in a clockwise fashion. In a similar, but reversed pattern, the cold eddy breaks off to the south. This eddy rotates counterclockwise and contains a cold core. Eddies maintain their independent circulations over their lifetimes, although their energy gradually decreases with time due to friction and mixing.

It is estimated that three to four warm eddies and 10 to 15 cold eddies may exist at any one time (Cheney-4). This is based on the number of eddies that form each year and their typical lifetimes. Fuglister (5) suggests that 5 cold and 5 warm eddies form each year. On the basis of several surveys of eddies over their lifetimes it is concluded that warm eddies persist as long as 12 months (Gotthardt-6, Potocsky-7, Thompson and Gotthardt-8). Cold eddies last longer, with life spans of 2 to 3 years (Cheney and Richardson-9, Barrett-10). The accuracy of these estimates is substantiated by recent observations of 13 distinctly different eddies (10 cold and 3 warm) during a four month period in 1975 (Figure 3). These positions were based on data gathered from ships, aircraft, and satellite imagery (Cheney and Richardson-11).

In addition to these major thermal features it appears that less well-defined, non-Gulf Stream eddies are also common in what has here-to-fore been considered quiet regions of the North Atlantic. Discoveries

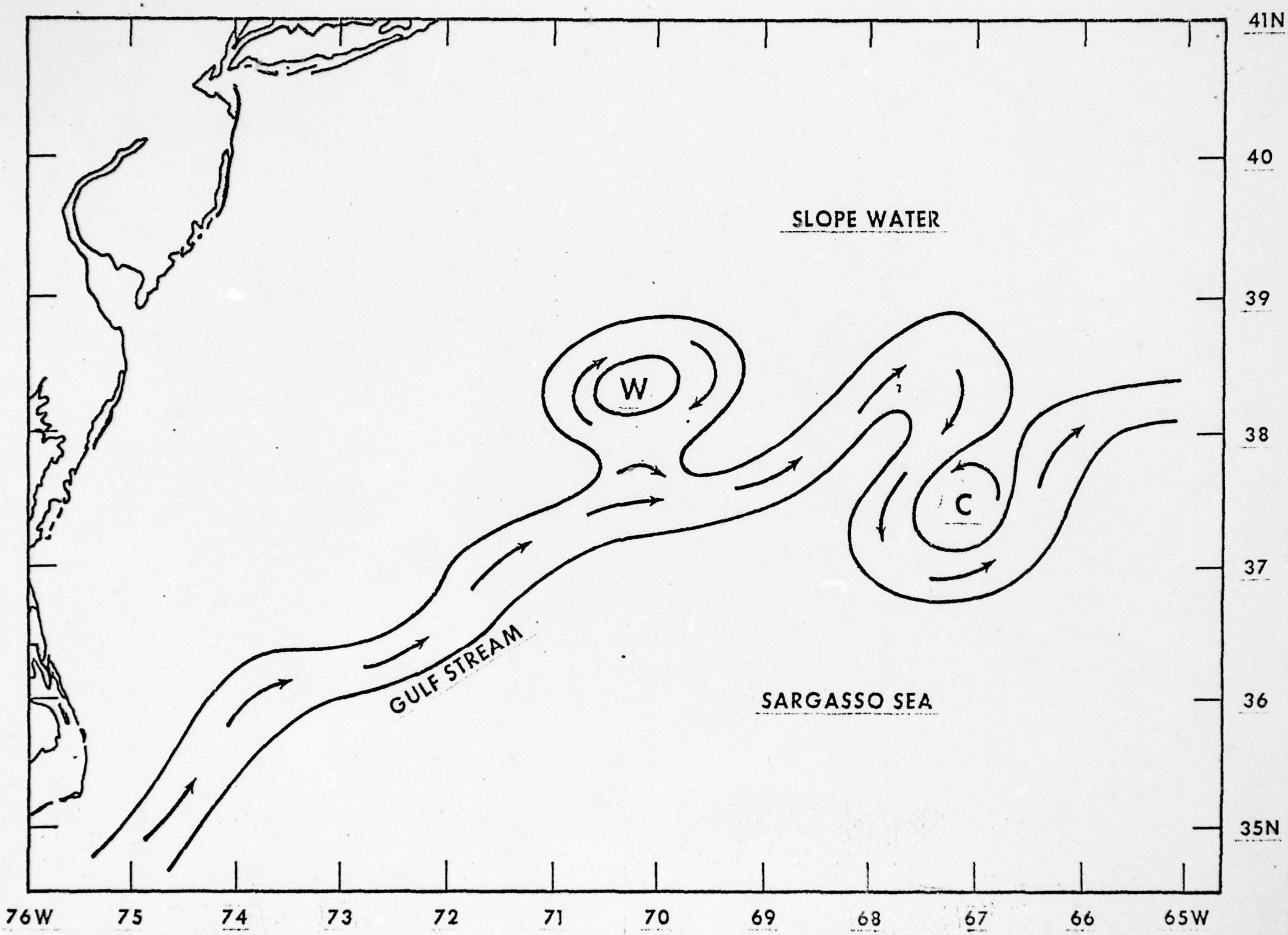

Figure 2. Formation of warm and cold eddies

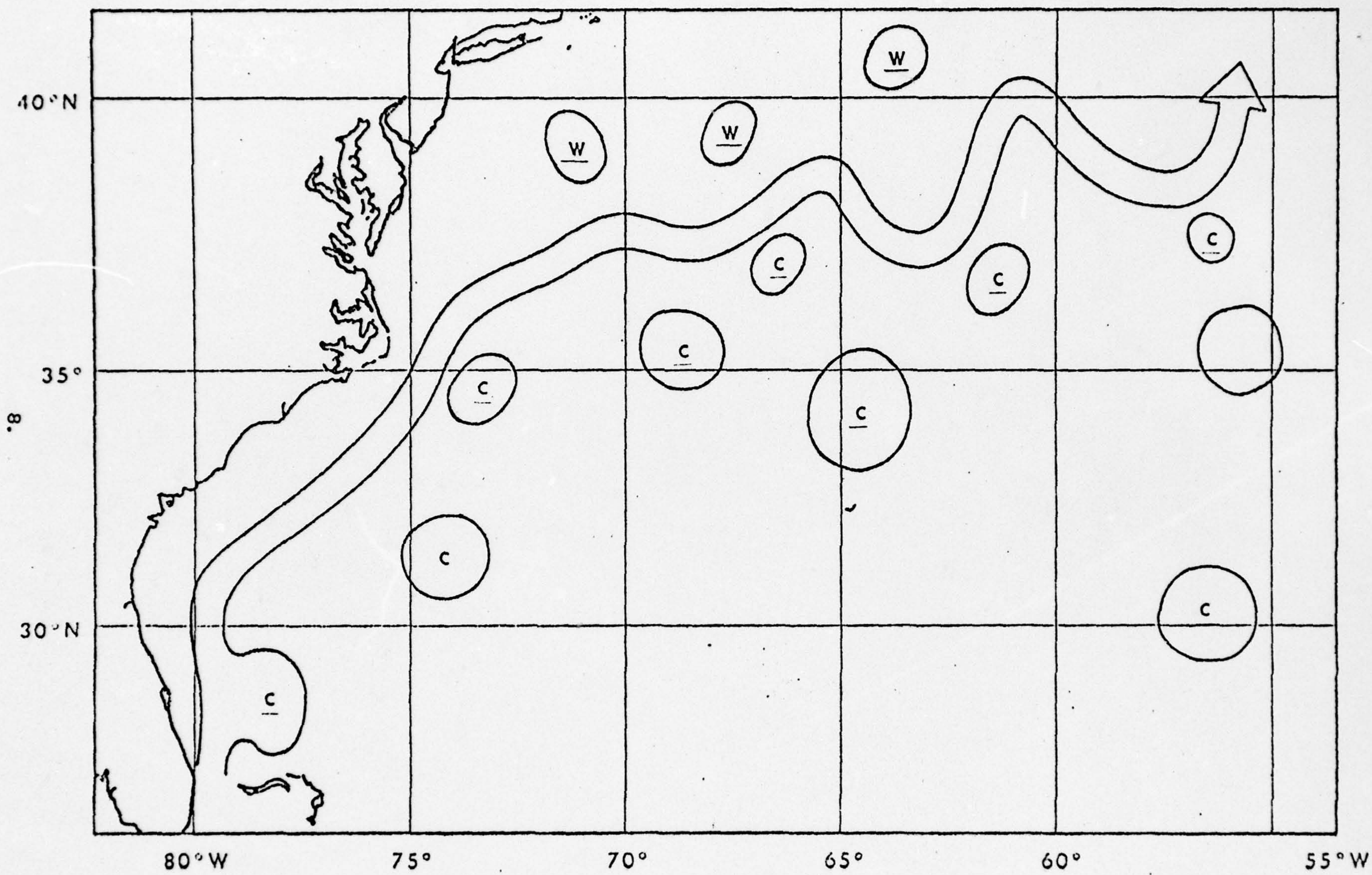

Figure 3. Positions and approximate sizes of Gulf Stream eddies, April - July 1975

of large-scale, mid-ocean eddies during the USSR POLYGON experiment in 1970 and the US MODE program in 1973 have created a new awareness of the ocean's variability (Robinson-12). An analagous event in meteorology would be the discovery of the pattern of highs and lows which make up our weather. Recently, Dugan (13) reported five cold eddies with diameters of 100-175 km (55-95 nmi) in the area southwest of the Azores. These were identified from a survey of a swath of ocean 220 km (120 nmi) wide and 2700 km (1460 nmi) long; in most cases the features did not display surface temperature gradients.

5.0 SURFACE CHARACTERISTICS OF FRONTS AND EDDIES

The most obvious indication of ocean fronts and eddies is the sea surface temperature pattern. Although not present in all frontal areas, the existence of a sharp surface thermal gradient is still the easiest and most reliable method for identifying a front or eddy. In major fronts the gradient may be as large as 10°C in 20 km (18°F in 11 nmi); for weak fronts 1.0° (1.8°F) in the same distance may be the only indication.

The pattern of surface temperature gradients across a frontal system can be complex, as shown by the Gulf Stream in Figure 4. This is a typical winter case: during summer, heating of the surface waters on both sides of the Gulf Stream significantly reduces the surface gradient. This latter effect is well illustrated by measurement of the Icelandic Front (Figure 5). The surface isotherm pattern in July shows a relatively broad temperature change from north to south between Iceland and the Faeroe Islands. At 200 m, (655 ft.) however, there is revealed an intense thermal gradient which could seriously influence the performance of ASW sensors.

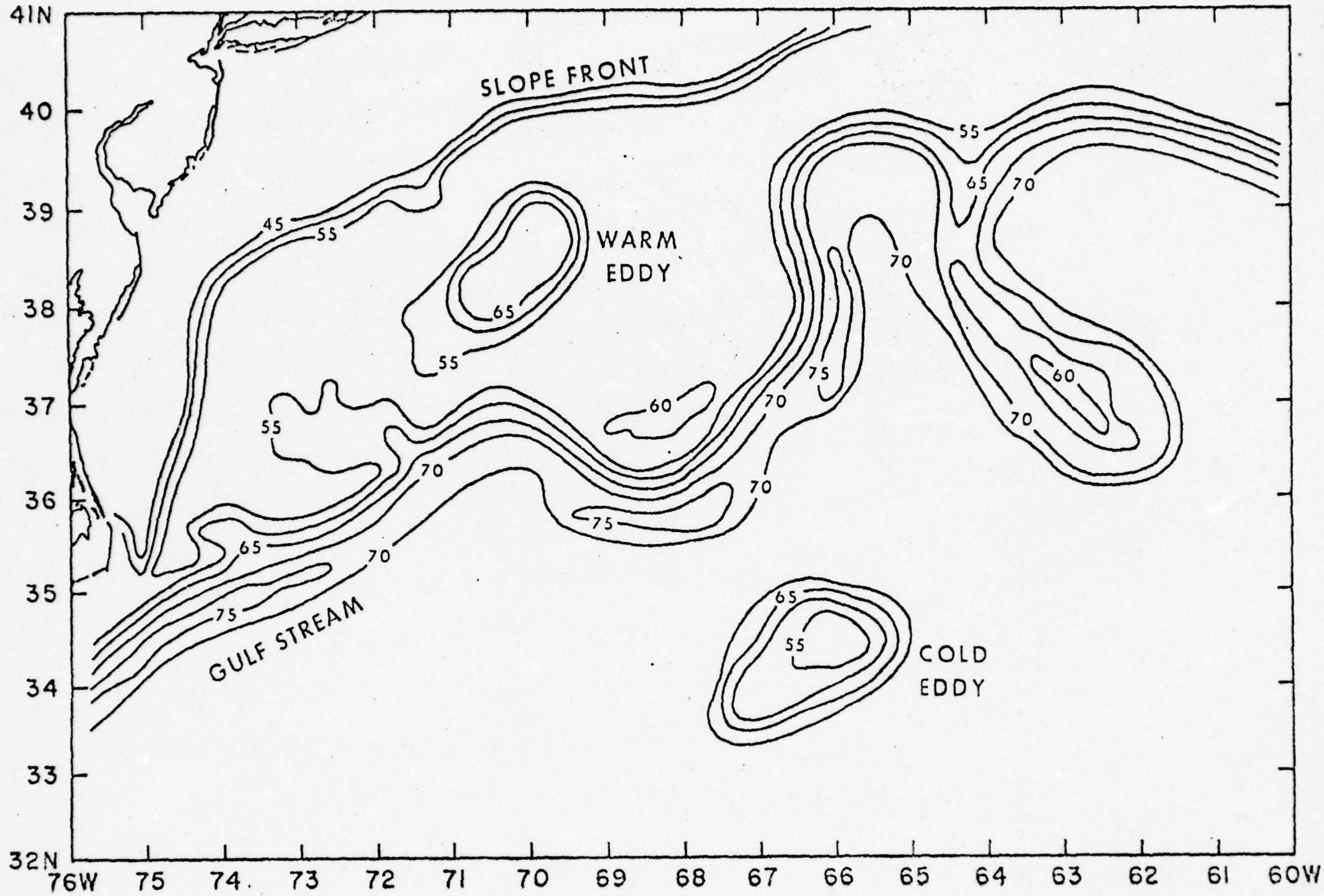

Figure 4. Surface temperatures (°F) in the Gulf Stream system

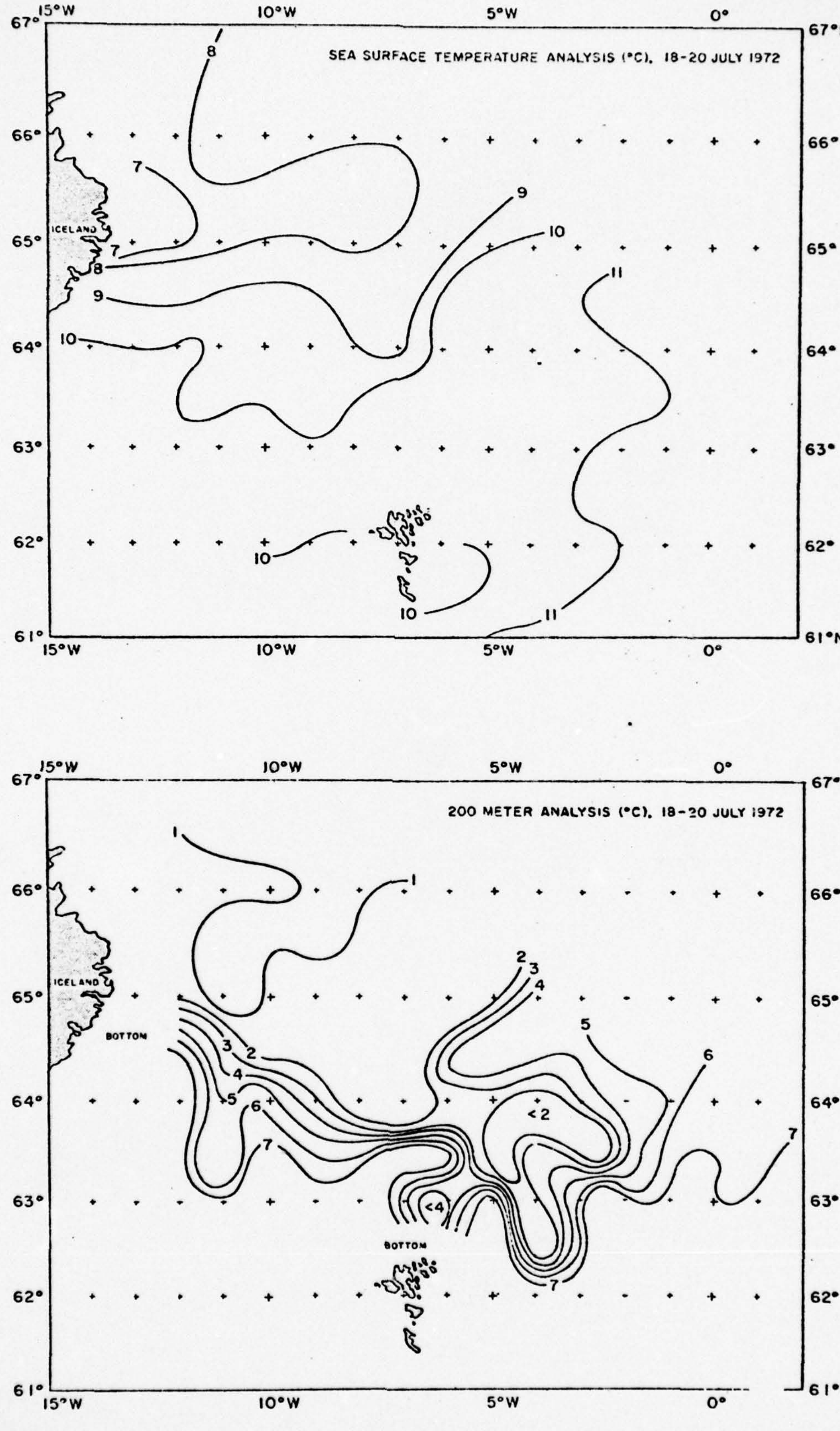

Figure 5. Icelandic - Faeroes front

Also shown in Figure 4 are surface isotherm patterns for a warm and cold eddy. Warm eddies are typically 100-200 km (55-110 nmi) in diameter while the cold eddies are larger, averaging 150-250 km (80-135 nmi). Oceanic fronts vary in width from a few kilometers (Sargasso Sea transients) to 150 km (80 nmi) in the Gulf Stream. The latter averages approximately 100 km nm (55 nmi) in width.

Cold eddies are characterized by counterclockwise currents which remain fairly strong for the lifetime of the eddy. Surface currents reach a maximum of 2-3 knots at a radius of 45-90 km (25-50 nmi) and gradually decrease to zero at the outer perimeter. A clockwise circulation is found in the warm eddies, with currents comparable to the cold eddy; maximum speeds are found only 30-50 km (15-25 nmi) from the center of warm eddies because of their smaller size. In both eddies the currents are zero at the center (Khedouri and Gemmill-14).

The Gulf Stream's flow is strongest and most persistent west of 65°W. East of this point significant changes in speed and direction of currents are likely owing to the complexity of meanders. Off Cape Hatteras the surface currents in the Gulf Stream average 2-3 knots although in the 20 km (10 nmi) wide axis of maximum current, speeds of 4-5 knots are common (Boisvert-15). The zone of maximum currents is generally displaced some 20-40 km (10-20 nmi) seaward of the surface location of the front which is marked by a strong horizontal sea surface temperature gradient. As with most fronts a velocity shear exists along the northern and southern edges of the Gulf Stream. Countercurrents of generally less than 0.5 knots flow to the west both in Slope Water and in the Sargasso Water. Currents weaken as the Gulf Stream flows to the east and broadens out into the North Atlantic Drift.

The complex patterns formed by meanders occasionally result in currents flowing to the west for limited portions of the frontal system. Surface currents in moderate fronts are weaker and less consistent with speeds generally below 2 knots.

6.0 VERTICAL CHARACTERISTICS OF FRONTS AND EDDIES

6.1 FRONTAL PROFILES

Figure 6 illustrates the variability that can be found in thermal profiles in a frontal area (Athey-16). An ASW platform following the indicated track would cross the front on four occasions, moving through alternating regions of warm and cold water. However, the accompanying BT's indicate that more than just two types of thermal profiles would be encountered. Profiles B, F, and G are all in cold water but because of their varying separation from the frontal boundary they exhibit significant variability in surface duct characteristics, and below layer gradients. Similarly the conditions in warm water show variability in layer depth and in-layer gradients. These differences are sufficient to necessitate different tactics, particularly regarding choice of sensor depth.

More important for long range propagation are the deep profiles. Figure 7 illustrates the major differences to be found in temperature, salinity and sound velocity as one crosses the Gulf Stream from Slope Water (north of Gulf Stream) to Sargasso Water (south of Gulf Stream). At all depths between the surface and 1000 m, Sargasso Water is shown to have dramatically higher temperatures and salinities; sound velocity profiles show correspondingly higher values. Changes in the deep sound channel are most significant, with the deepest axis occurring on the Sargasso side of the front at a mean depth of 1300 m (4265 ft) and a minimum sound velocity value of 1490 mps (4895 fps). Water to

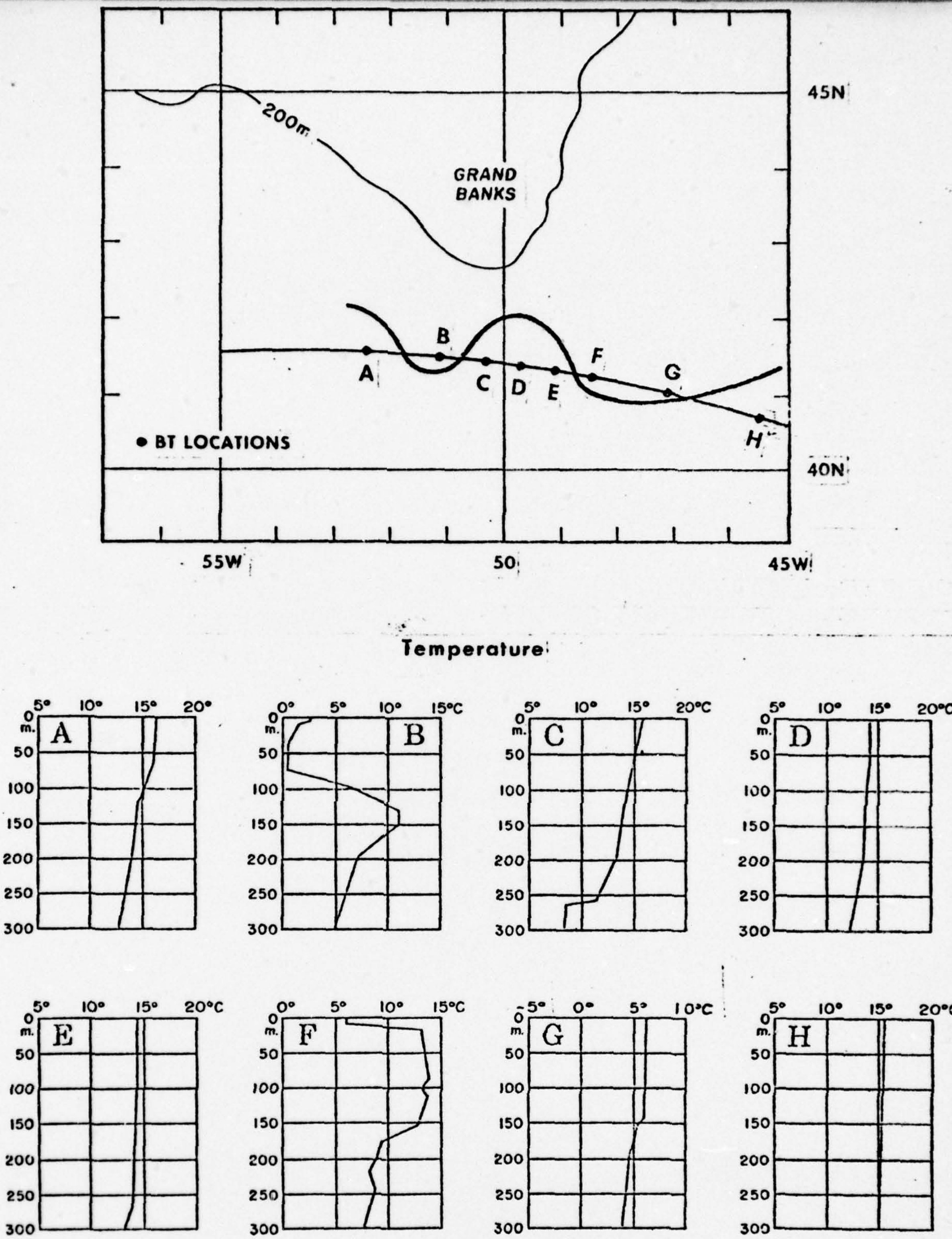

Figure 6. Variability of bathythermograms along ocean front

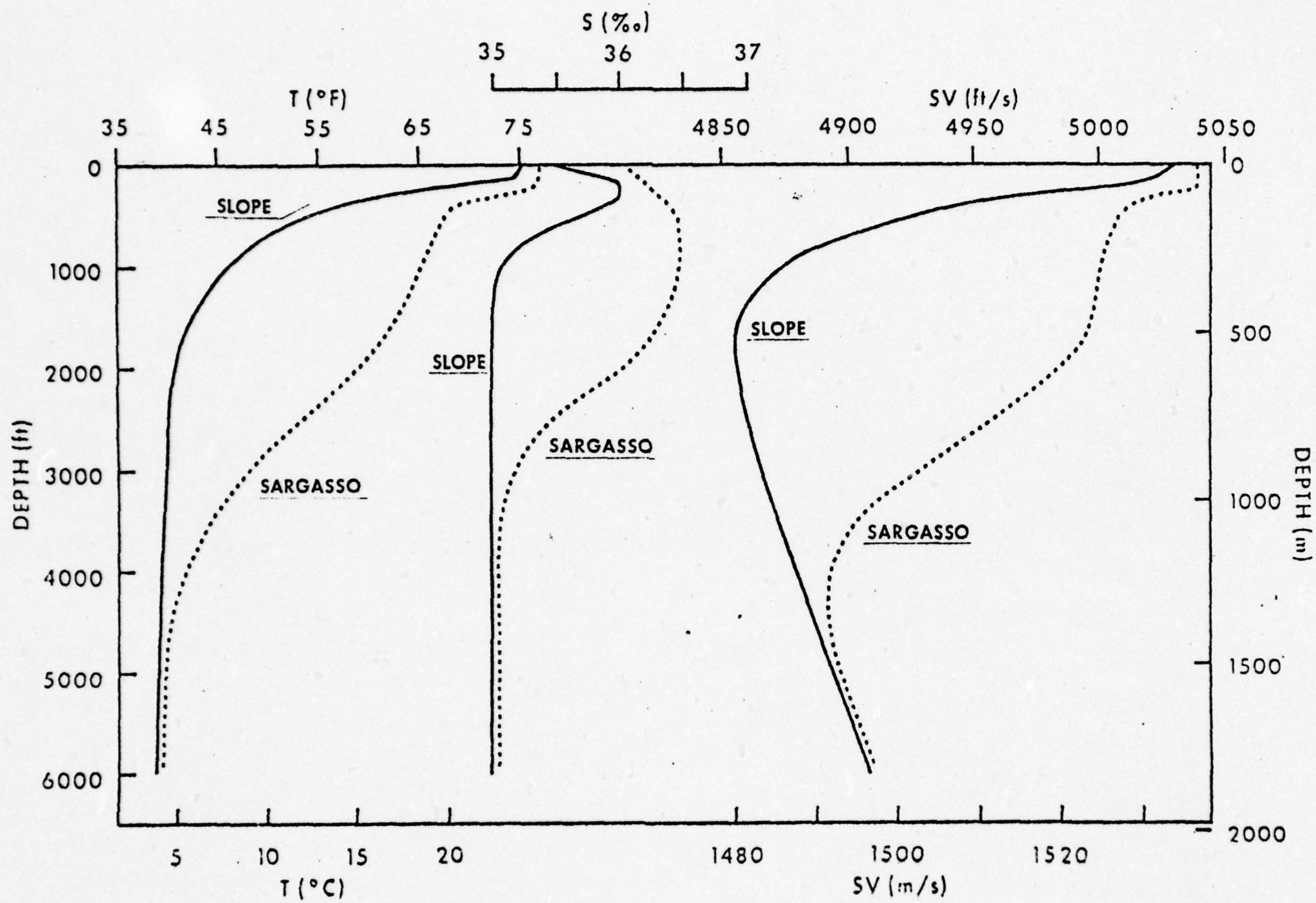

Figure 7. Typical profiles

the north of the Gulf Stream has a much shallower sound channel, 500 m (1640 ft) and lower minimum velocity; 1480 mps (4855 fps). As a mixture of the two water masses, the Gulf Stream has sound velocity values in between the two extremes.

6.2 FRONTAL CROSS SECTIONS

Figure 8 shows a thermal cross-section of the Gulf Stream looking downstream (flow into page) during the winter. Significant features are the warm core, the high gradient area which is called the North Wall, and the depth to which the Gulf Stream extends. Moderate and weak fronts have the same pattern of isotherms but exhibit progressively weaker gradients and lesser overall dimensions in width and depth.

As shown by Figure 8 the isotherms in the Gulf Stream slope upward toward the cold Slope Water. Although the slope appears steep in Figure 8 (where there is vertical exaggeration of scale) the isotherms generally slope at an angle of $0^{\circ}17'$ to $0^{\circ}21'$, or approximately 30 feet for every mile.

Isopleths of sound velocity in Figure 9 correspond to the Gulf Stream temperature section discussed above. In regions of large temperature gradients, such as the Gulf Stream, salinity plays a minor role in determining sound velocity; as a result, isovels follow the same general pattern as isotherms. In this example sound velocity across the Gulf Stream changes by about 25 mps (75fps) at the surface; a maximum difference of about 40 mps (130 fps) occurs at depths of 300-450 m. Sonic layer depth (SLD) at the North Wall is only 10 m (35 ft) compared to 150 m (490 ft) in Slope Water and 250 m (820 ft) in the Sargasso Sea. Maximum sound velocity occurs in the warm core.

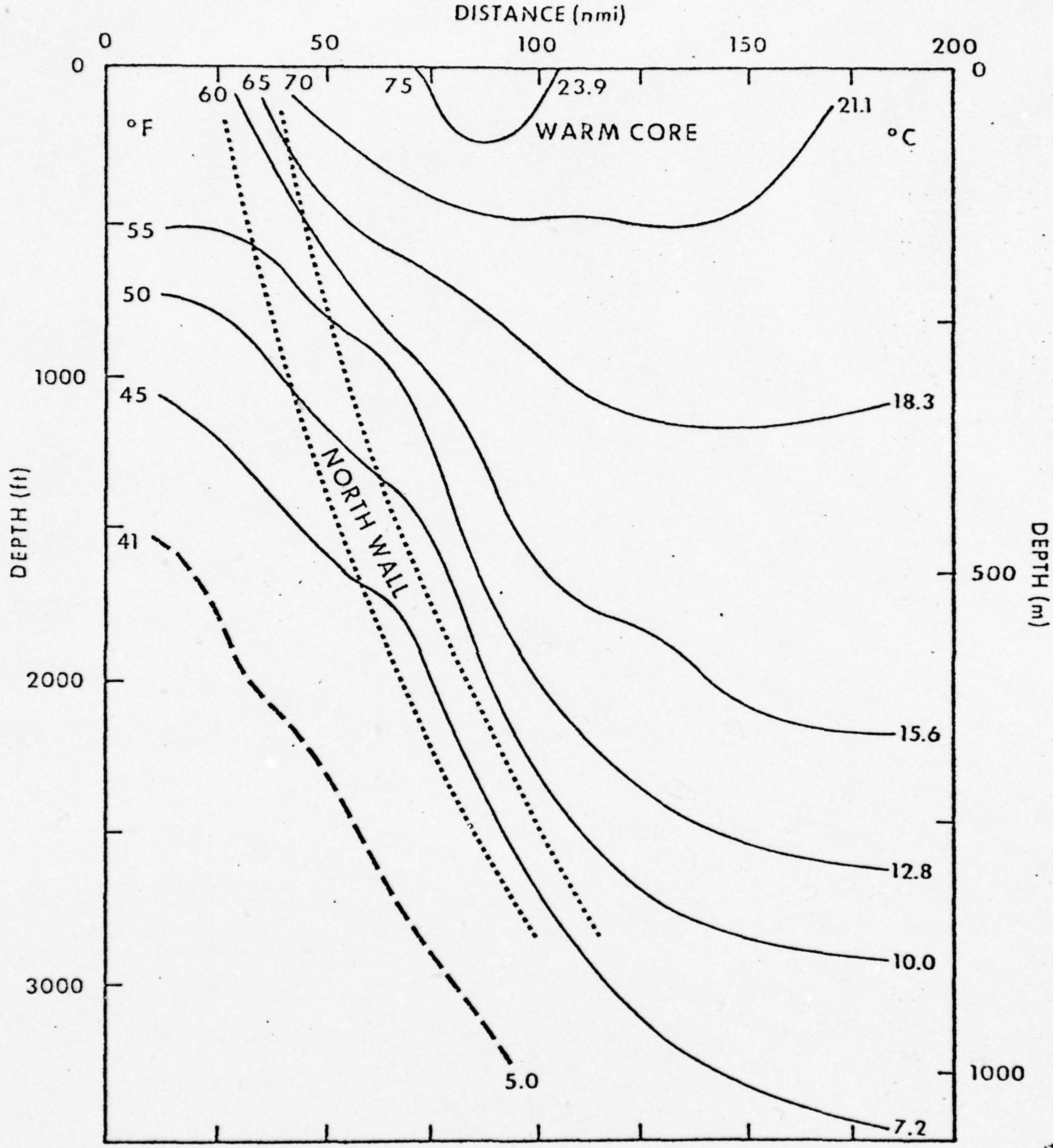

Figure 8. Gulf Stream temperature section

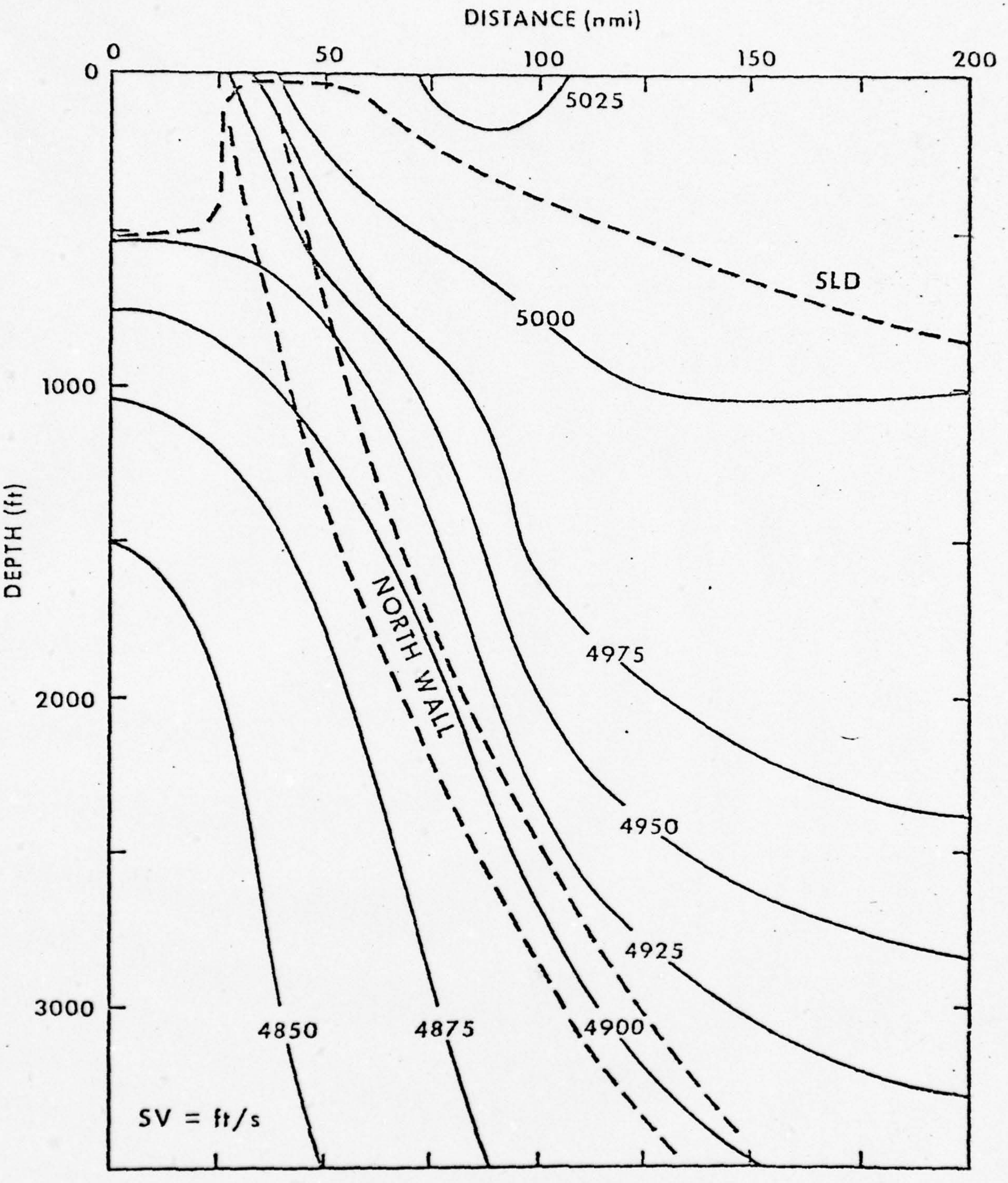

Figure 9. Sound velocity across the Gulf Stream

6.3 COLD EDDIES

A cold eddy is a dome of cold Slope Water which has been transported to the warm side of the Gulf Stream with a ring of Gulf Stream water surrounding the core. As seen in Figure 10 the center of the main thermocline, in this eddy indicated by 12.8°C (55°F), is 450 m (1475 ft) shallower in the core than in the surrounding Sargasso Water. This is a relatively new eddy as indicated by the presence of a surface outcrop of cooler water. With time, the cold water sinks deeper so that the dome becomes less accentuated and the eddy cannot be detected from surface measurement alone.

The sound velocity pattern of a cold eddy parallels that of the isotherms (Figure 11). Sound velocities are low within the core and high in the surrounding waters, with the maximum change across the eddy exceeding 30 mps (100 fps). Depending on the depth at which the sound rays penetrate the eddy the refractive changes may be minimal or highly significant. Sonic layer depth is generally shallow at the eddy center due to the raised thermocline. Outside the eddy the SLD in the Sargasso Sea varies during the year from zero in summer to 450 m (1475 ft) in winter. The change in SLD across the eddy therefore varies from an insignificant difference in summer to a dramatic change in winter.

To illustrate the influence of a cold eddy on long range sound propagation Figure 12 presents the same eddy on a larger scale. Because the core is a region of low sound velocity the deep sound channel (DSC) is 610 m (200 ft) shallower at the eddy center than outside. The sound velocity pattern is not generally modified below 1500 m (4920 ft), although modified surface conditions within the eddy do cause a change in critical depth of 450 m (1475 ft).

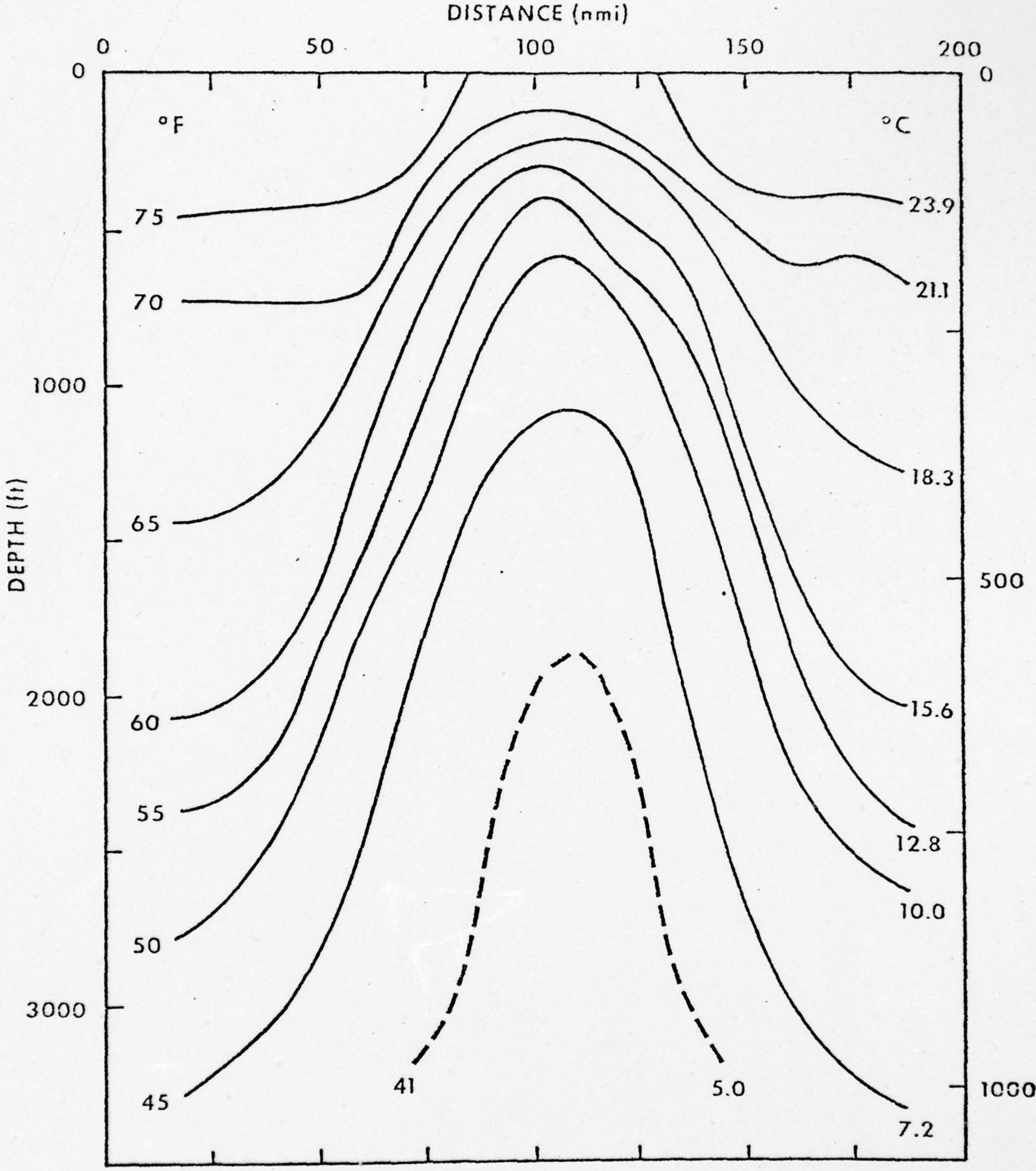

Figure 10. Temperature section through a Gulf Stream cold eddy

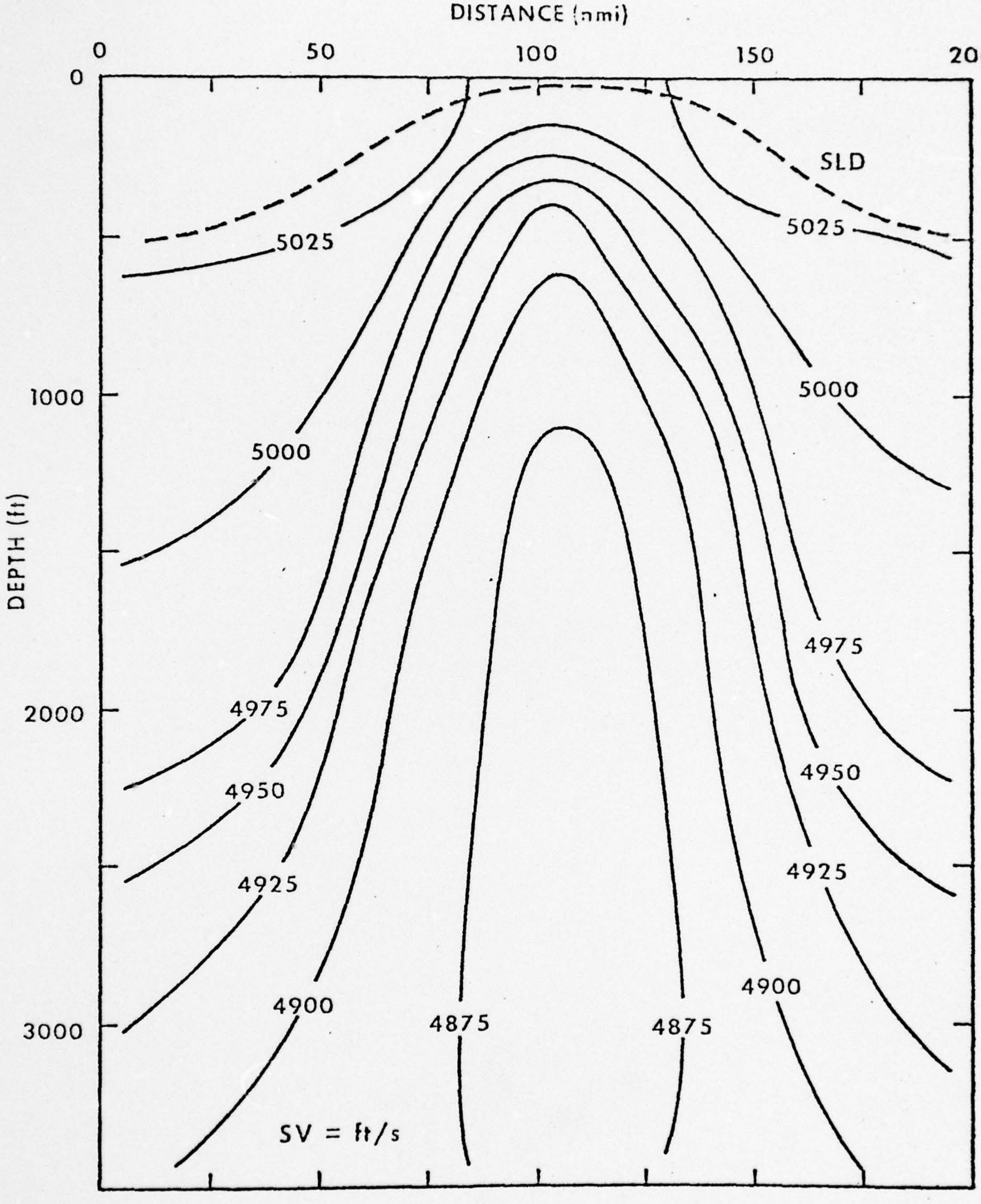

Figure 11. Sound velocity in a Gulf Stream cold eddy

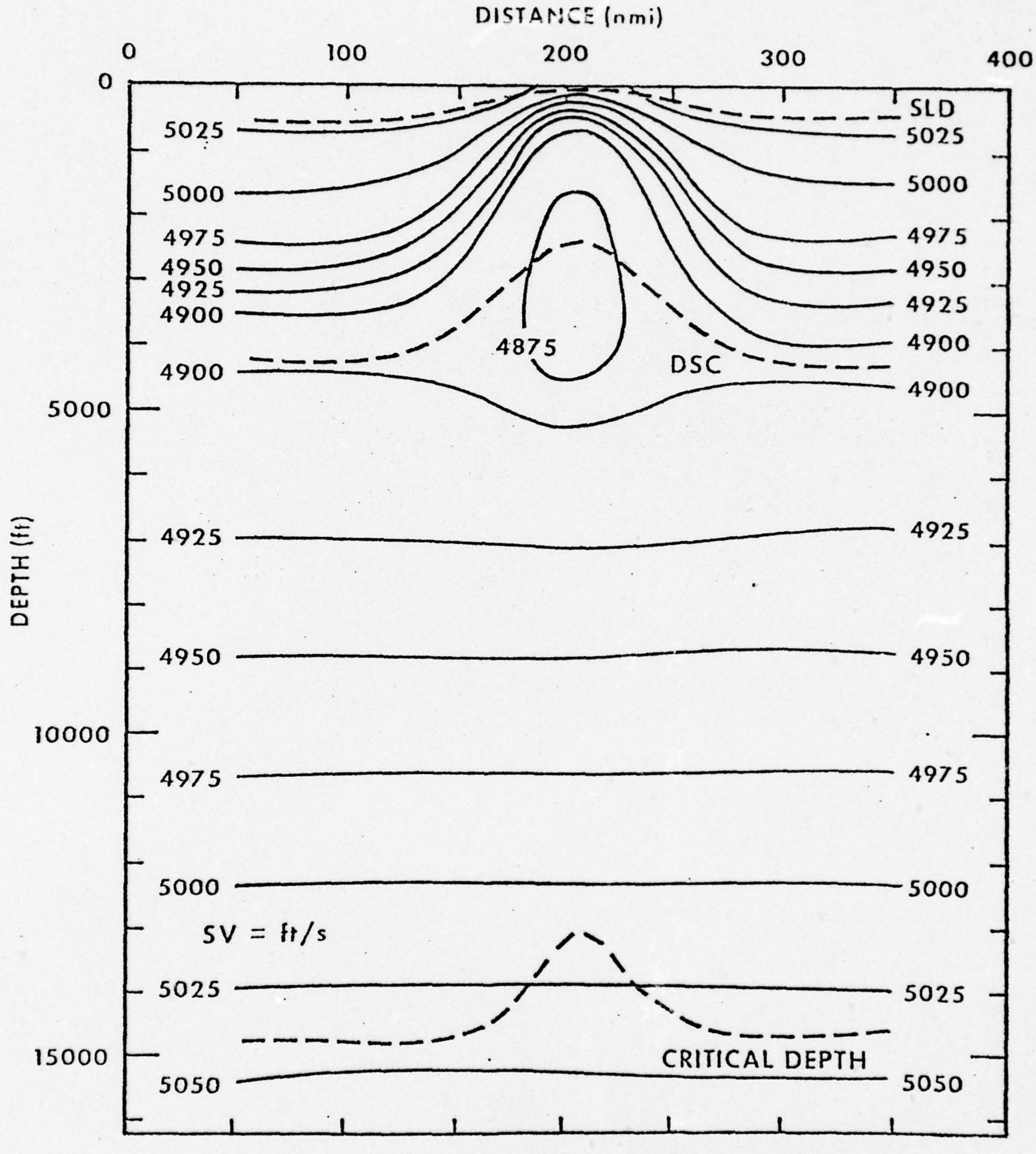

Figure 12. Sound velocity (deep) in a Gulf Stream cold eddy

6.4 WARM EDDIES

A warm eddy in winter is illustrated by Figure 13. This is the reverse of a cold eddy, with a core of warm Sargasso Water floating in the cooler Slope Water north of the Gulf Stream. Because the main thermocline is deep at the center of a warm eddy, mixing in winter has created an unusually thick isothermal layer down to 450 m (1475 ft). Temperatures inside the eddy are 9°C (16°F) warmer than in Slope Water outside. Warm eddies generally extend no deeper than 1000 m (3280 ft) and are physically restricted to the area between the Gulf Stream and the Continental Shelf, shown at left in Figure 13.

Sound velocities in a warm eddy are also opposite to those of the cold eddy. Maximum sound velocity occurs at the top of the thermocline in the warm core, as shown by Figure 14. The SLD varies from relatively shallow values at the edge of the eddy to 450 m (1475 ft) in the center of the eddy. Along horizontal surfaces the warm eddy is seen as a region of high sound velocity with a maximum change of 30 mps (100 fps) at 450 m (1475 ft).

6.5 SURSURFACE CURRENTS

Currents decrease with depth in both warm and cold eddies. Due to its deeper penetration the cold eddy may still have currents of one knot at 600 m (1970 ft) where in the warm eddy such speeds would seldom be found below 300 m (985 ft) (Khedouri and Gemmill-14). Subsurface flow in the Gulf Stream is in the same direction as the surface currents but, as with the eddies, velocity decreases with depth. Deep observations indicate currents at 3000 m (9840 ft) of approximately 0.2 knots beneath the Gulf Stream. Counter currents of up to 0.4 knots have been observed at the bottom on the Continental Slope just to the west of the Gulf Stream.

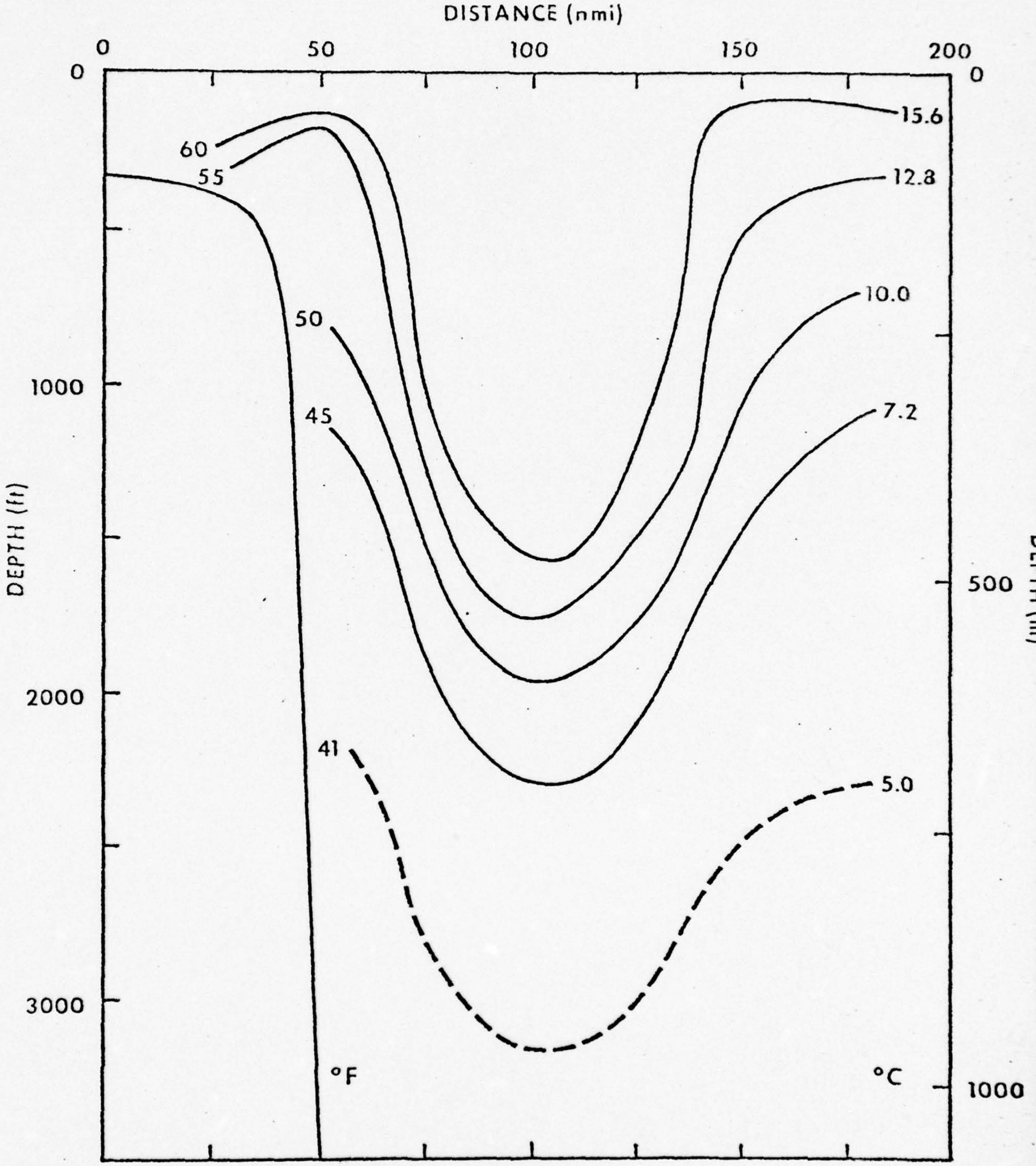

Figure 13. Temperature section through a Gulf Stream warm eddy

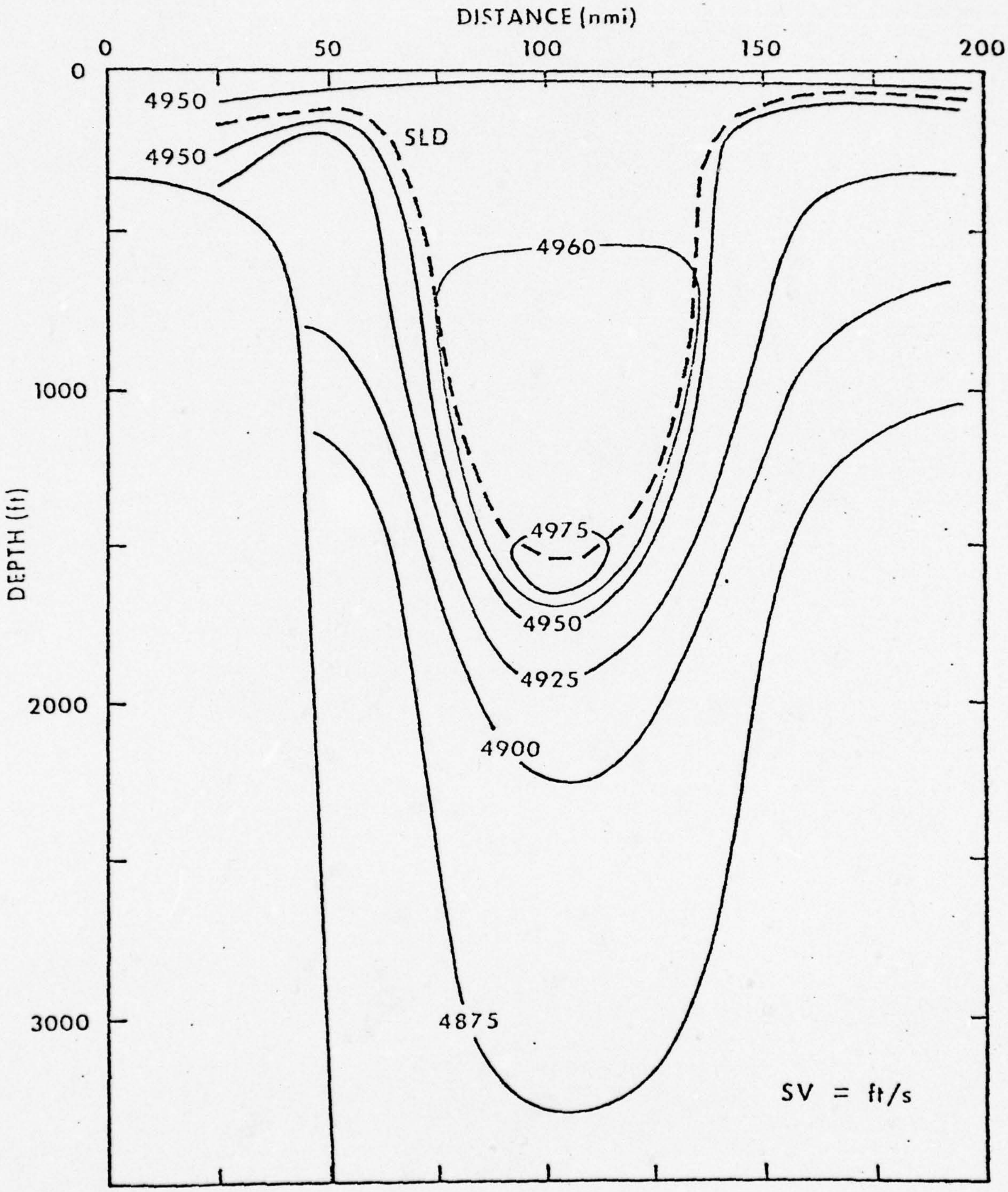

Figure 14. Sound velocity in a Gulf Stream warm eddy

7.0 VARIABILITY IN FRONTS AND EDDIES

All fronts exibit some variability in their location. Part of this is due to meanders that move along the front and part is due to displacement of the overall system from its mean position. Figure 15 indicates the type of frontal variability due to meandering of the Gulf Stream (Corton-17). Frontal positions were measured by aircraft surveys at approximately 10-day intervals as the meander moved to the northeast. Average speed was about 0.5 knot, which is typical for meander movement in this area. Further east the meanders slow down as they elongate, become unstable, and often generate eddies.

The variability in position for the Gulf Stream's northern edge according to Fisher (18) is shown in Figure 16. Based on a number of surveys made in all seasons, the outer limits define the area in which the front is found 95 percent of the time, the inner boundaries, 50 percent of the time. No definitive seasonal shift in the mean frontal position has been established although Stommel-(20) indicates a maximum in current speed in early summer. Gotthardt-(19) found considerable variability in the Icelandic-Faeroe front both short-term (10 days) and seasonally. He found movements of 90 km (50 nmi) in the position over 10 days and twice this amount seasonally.

Because of surface heating of both warm and cold water masses, and the lack of sufficient wind speeds to mix the water, the horizontal temperature gradient across fronts is always less in summer than in winter. On occasions the gradient may be so diffuse that the surface position of the front is difficult to locate. However, strong horizontal gradients still exist at depths below the layer of surface heating, within the range of submarine operating depths.

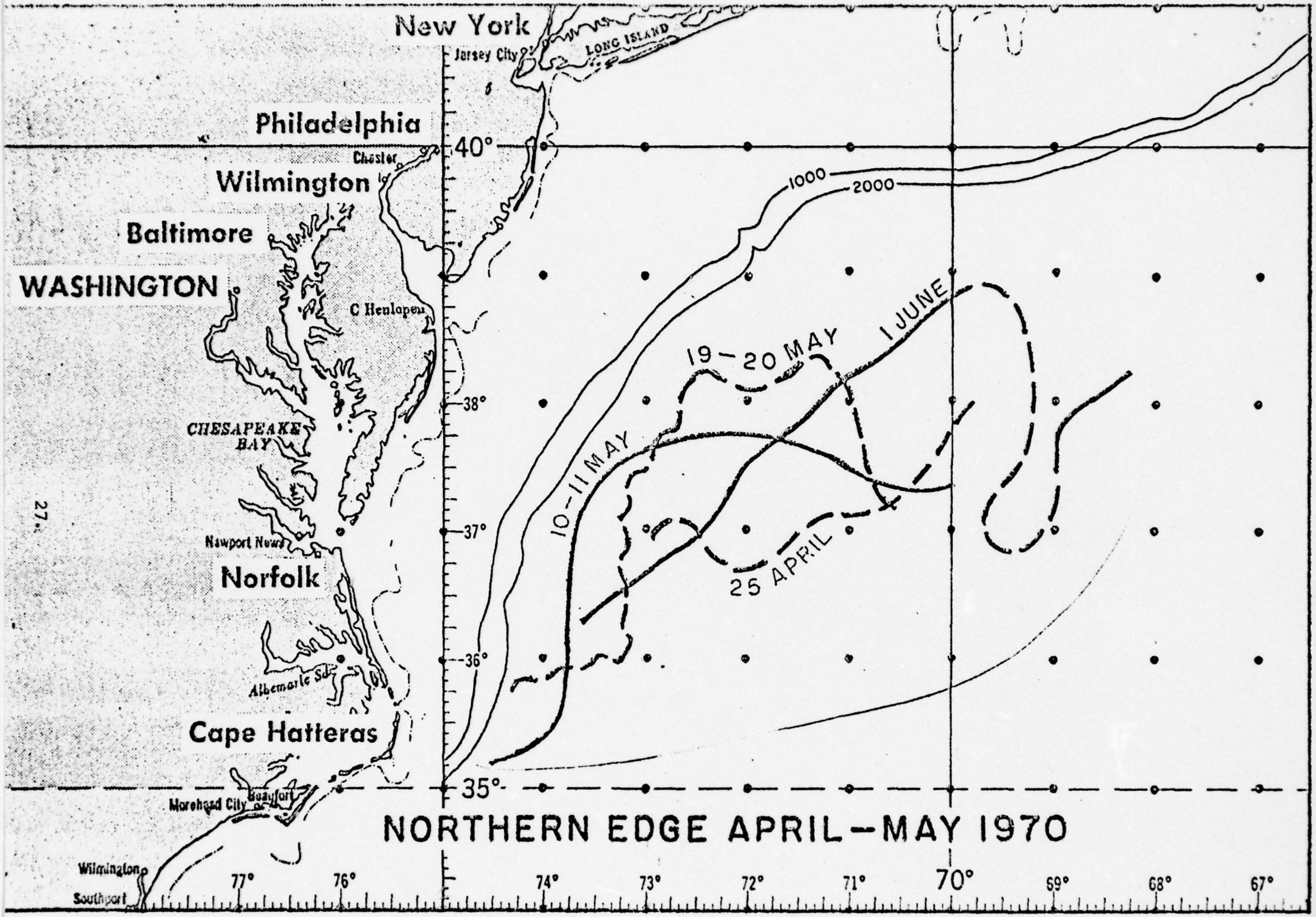

Figure 15. Progression of a Gulf Stream meander

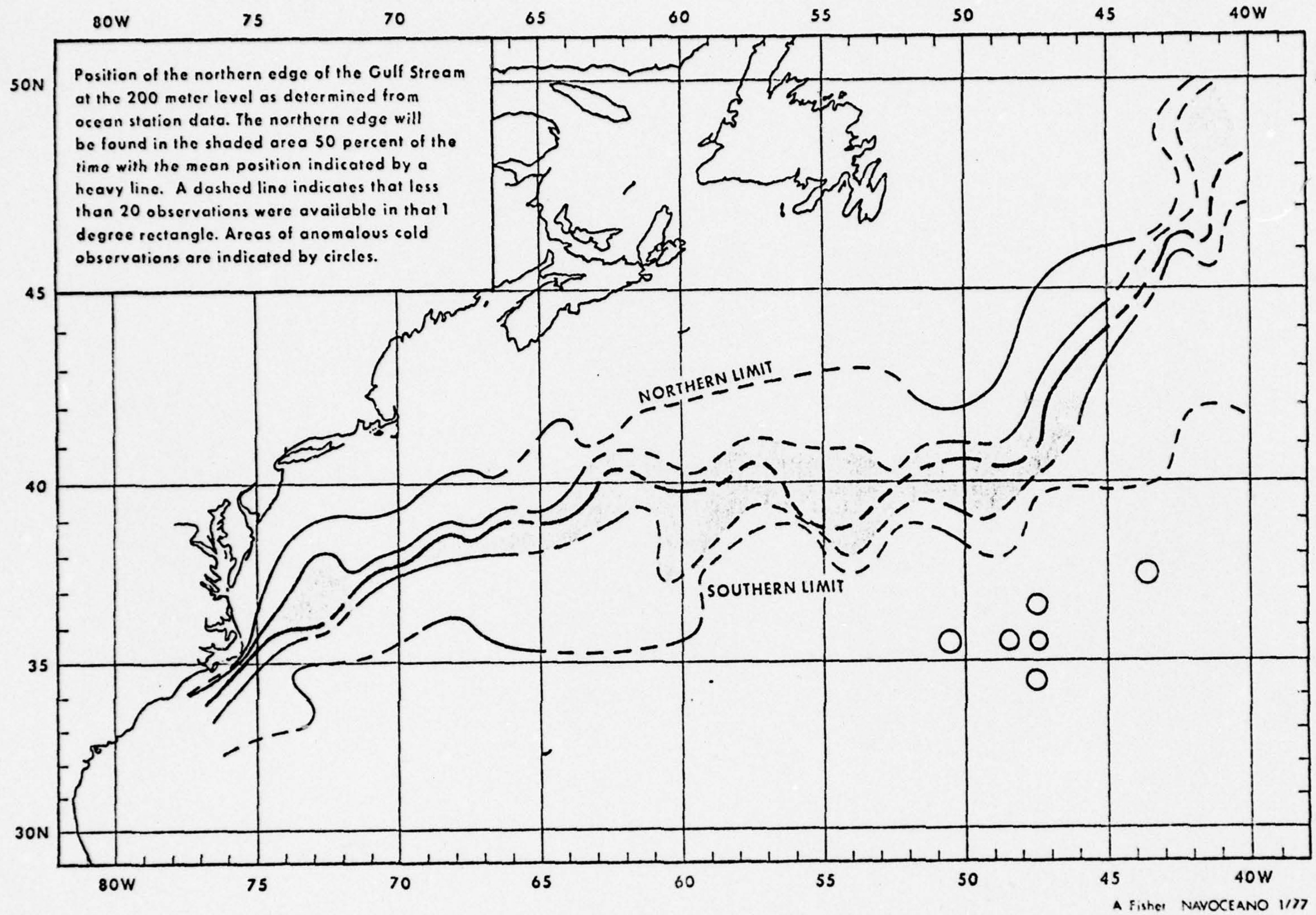

Figure 16. Variability in Gulf Stream location

Numerous eddies have been tracked for periods up to two years by combining survey data from ships and aircraft with infrared satellite imagery. In general, cold eddies migrate to the west or southwest (Figure 17) at speeds of 2-15 km/day (1-8 nmi/day) (Gotthardt and Doblar-21, Cheney and Khedouri-22). Their paths usually display complicated, spiraling trajectories. In some cases they move too close to the Gulf Stream and are reabsorbed.

Warm eddies are constrained in their movement by the Gulf Stream on one side and the continental shelf on the other as shown by Figure 18. (Thompson and Gotthardt-8). The average speed of these eddies is 4-6 km/day (2-3 nmi/day). It usually takes 6 months from the time a warm eddy forms until it is re-absorbed into the Gulf Stream off the Virginia Capes, although early recapture of warm eddies often occurs east of 68°W by passing meanders (Gotthardt-23).

Figure 19 illustrates seasonal variation in the thermal profiles of waters north and south of the Gulf Stream and in a warm and cold eddy. The solid line indicates winter conditions, the dashed, summer conditions. In all cases the layer between the surface and the top of the main thermocline becomes thoroughly mixed during winter; this results in much deeper layer depths in Sargasso Water (and the warm eddy) than in Slope water (and the cold eddy). Starting in April (earlier in the south) surface heating, combined with lighter winds, produces shallow layer depths which persist throughout summer.

8.0 MAPPING OCEAN FRONTS AND EDDIES

It has been estimated that frontal systems occupy nearly one-fourth of the ocean's surface area (Johannassen-24). In addition, numerous warm and cold eddies of various sizes and depths are found

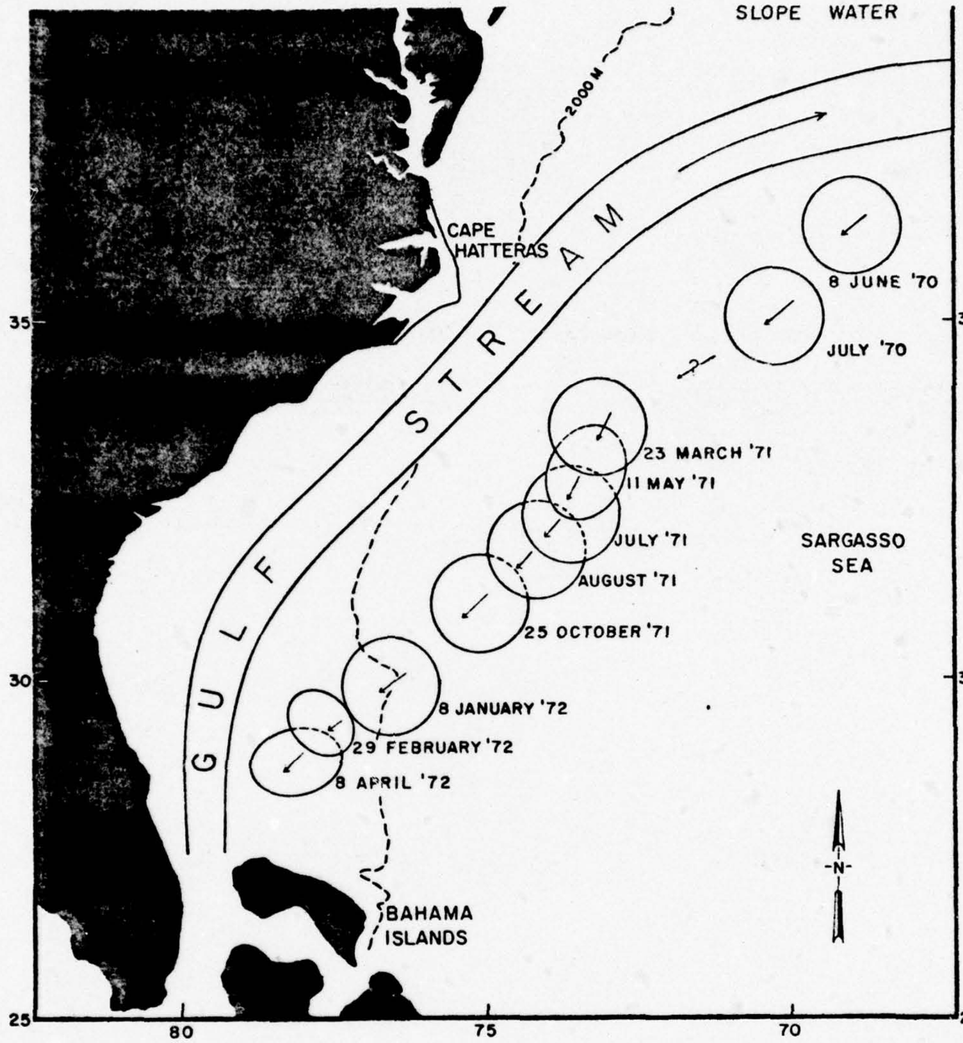

Figure 17. Movement of a cold eddy

Cheney and Richardson (9)

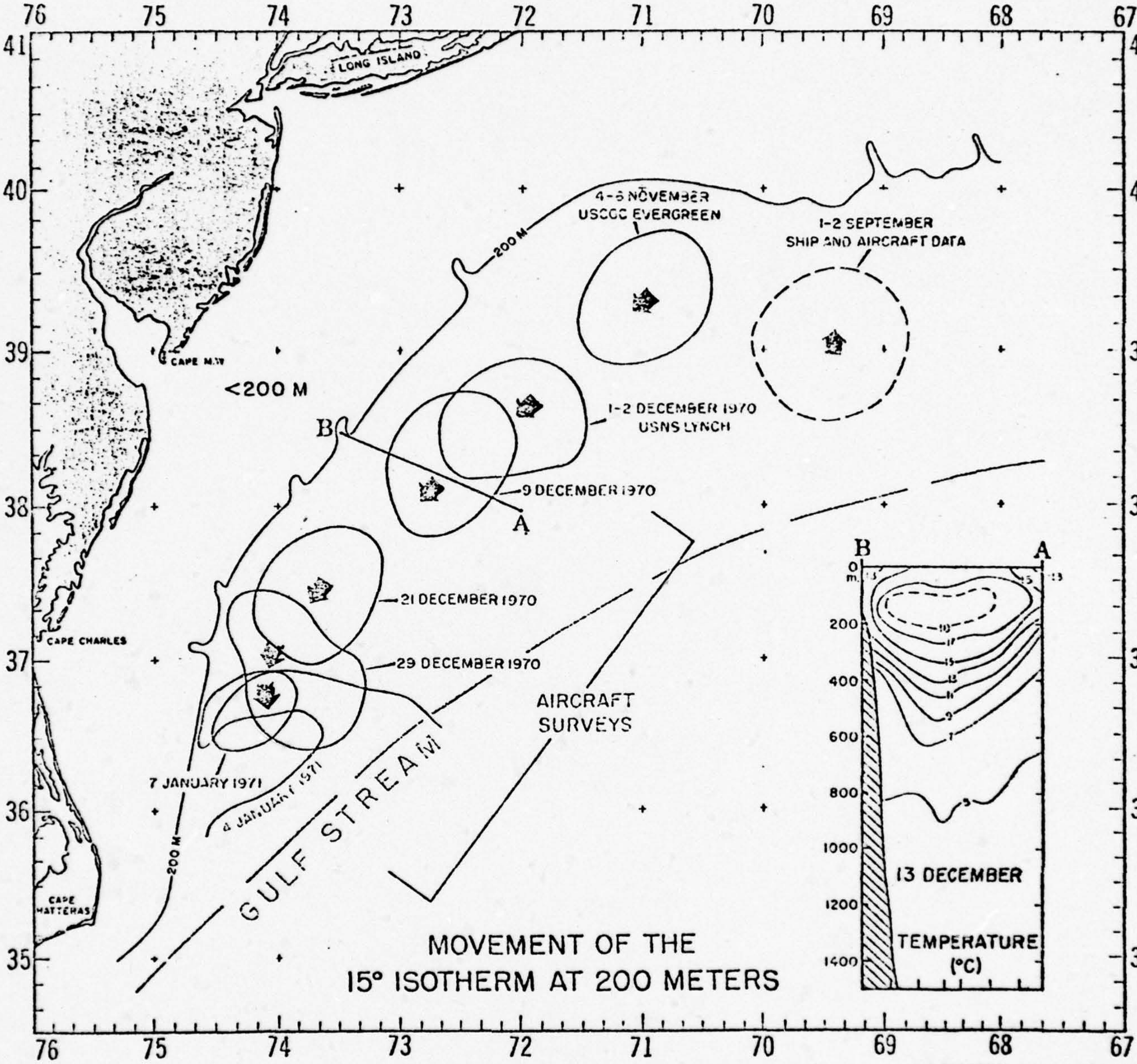

Figure 18.. Movement of a warm eddy

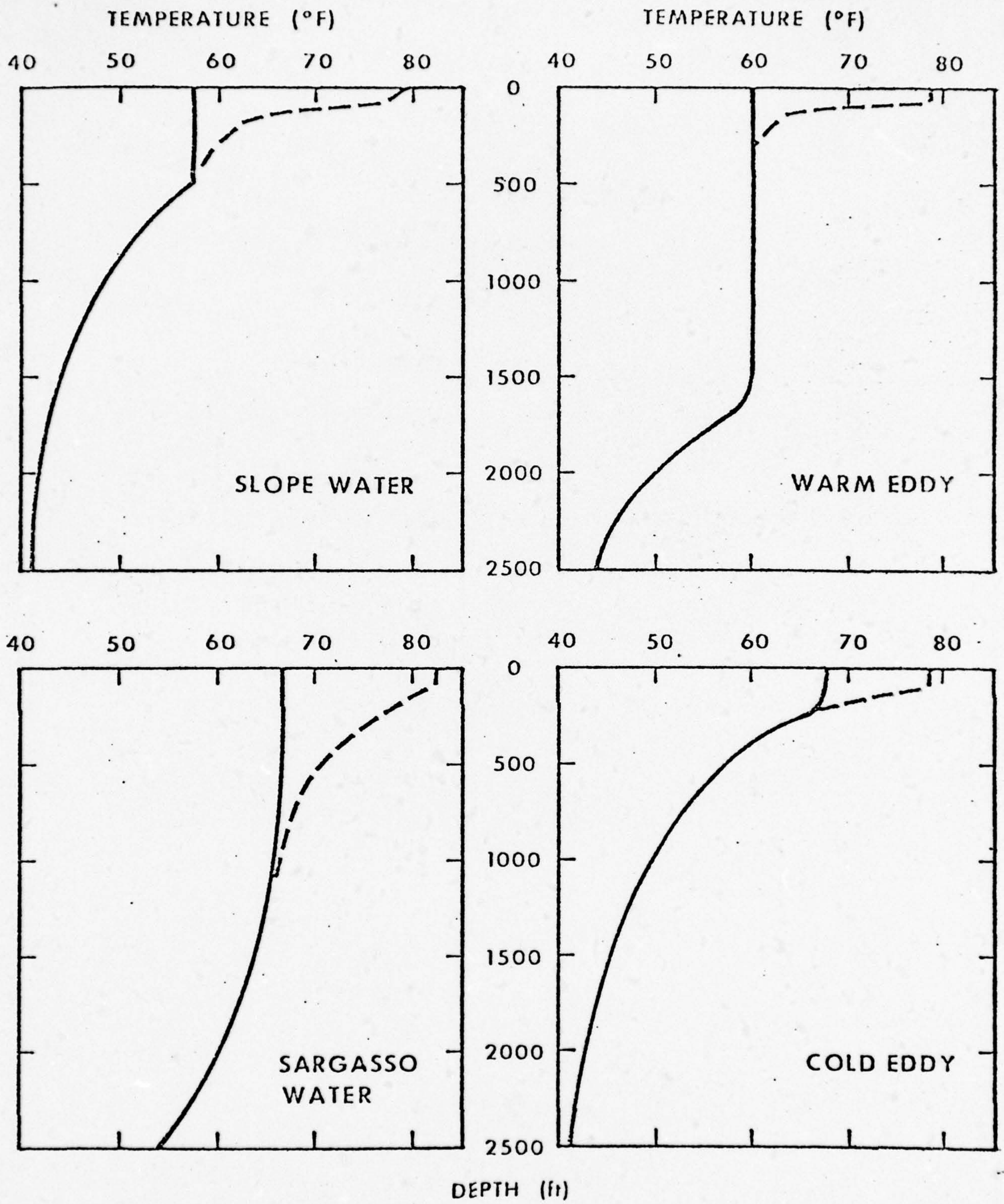

Figure 19. Winter and summer temperature profiles

in otherwise homogeneous regions. As many of these thermal features as possible should be mapped on a real-time basis if the Navy is to take advantage of the knowledge that has been gained concerning frontal acoustics.

There are several methods that can be used to maintain a continuous surveillance of oceanic fronts and eddies. The most economical approach, and one that is already established, is to use sea surface temperature reports from ships-of-opportunity. Although hundreds of such reports are received daily from ships operating in the North Atlantic, the poor accuracy of some of the temperature readings plus a non-random distribution of data along shipping lanes makes it necessary to composite the data over several days in order to derive a meaningful isotherm analysis. Even then, only major fronts can be identified and the accuracy of the frontal location is very poor in the vicinity of meanders. Cold eddies are not generally located at all, since they are only detectable at the surface during the first few months after their formation.

A thorough, near-synoptic analysis of a frontal system can be accomplished by means of aircraft surveys using special instrumentation. Surface features can often be located using an airborne radiation thermometer (ART) and airborne expendable BT's (AXBT's) are used to measure the subsurface thermal structure. In two or three days an aircraft can map much of the frontal system and associated eddies in the western North Atlantic. More complete measurements can be made by use of oceanographic ships since deeper measurements are obtained, including both temperature and salinity. However the length of time required to make the measurements is excessive and often the front moves during the survey period. Either of these platforms is valid for studies of a specific frontal area, or for one-time

ASWEX support. For routine mapping of ocean thermal features over extended periods of time, however both approaches are too costly and the platforms are not always readily available.

The most feasible approach to wide-spread, continuous mapping of ocean fronts and eddies is through the use of satellite data. Both visual (photographic) and very high resolution radiometer infrared (VHRR-IR) data are available and can be utilized to derive information concerning sea surface temperature patterns (DeRyche and Rao-25). Sea surface radiation sensed by the satellite radiometer is recorded by the satellite and read out by a data acquistion station on command. These data are then generally relayed to a central site for processing, including corrections for atmospheric conditions and instrument noise, and oriented to a geographic grid. Outputs are in the form of VHRR-IR pictures (distribution in grey scales), digitized values of IR sensings, or absolute mean temperatures for larger regions of the ocean surface. A number of different satellites operated by NASA, NOAA or DOD carry sensors yielding data useful for identification of oceanic fronts.

The Naval Oceanographic Office is presently producing a weekly analysis of fronts and eddies in the western North Atlantic, Figure 20, primarily on NOAA-5 satellite IR imagery. Because of interference in satellite imagery by clouds, the analysis is supplemented by inclusion of sea surface temperatures from ship weather reports and any available bathythermograms (Fisher-26). These data also provide ground truth for the satellite data. Although subjective to a degree, owing to the difficulty in distinguishing between small gradiations of grey scale, the frontal analysis has proved to be an extremely useful product for operations groups. Copies of this experimental chart are telecopied to

Figure 20. Experimental Ocean Frontal Analysis Chart

FNWC Monterey, FWC Norfolk, and is provided to other interested commands. A comparison of satellite-determined frontal boundaries to those obtained by aircraft during support of a recent submarine Fleet exercise was made by Perchal-(27). He found the frontal positions agreed within an accuracy of 7-14km (4-8 nmi).

In an attempt to reduce the subjectivity and the time necessary to analyze IR imagery for thermal discontinuities NAVOCEANO plans to automate production of the oceanic front analysis. Input to the automated program at present is IR data from NOAA's geostationary operational environmental satellites (GOES), which can provide five IR images per day with a scan resolution of 7 km. Other possibilities are the Defense Meteorological Satellite Program (DMSP) or SEASAT satellites. In all cases digital grey-scale values are manipulated through use of several pattern-recognition techniques and statistical approaches to display high-gradient areas or other indications of fronts.

Both NOAA and NASA have developed programs for obtaining sea surface temperatures from infrared data although fronts or eddies are not specifically delineated. NASA used TIROS radiation data and prepared isotherm analyses for a number of ocean areas around the world (Graves-28) to show the feasibility of deriving sea surface temperatures from satellite data. They were sucessful but no operational product is presently available. NOAA does have an operational program, (global operational sea surface temperature computation - (GOSSTCOMP) which provides sea surface temperatures as derived from scanning radiometer infrared data from NOAA polar orbiting satellites. This program provides several products on a daily basis for areas from the size of the Great Lakes to a global scale (Brower-29). Most useful is a plot of absolute temperature values at half-degree intervals of latitude and longitude and an isotherm analysis of these data. Both products are creditable presentations of sea surface temperatures but lack resolution of high-gradient areas, and are not oriented toward frontal location as much as a general temperature distribution.

The Director, Naval Oceanography Meteorology (DNOM) conducts a program using data from the DMSP satellite. Infrared imagery is received by direct read-out at vans located at several Fleet Weather Centrals and/or Facilities. Although the emphasis of this program has not been on oceanography the Facility at San Diego has made great progress in identifying patterns of water temperature off the coast of California. They have become particularily adept at using enhancement techniques (manipulation of grey scale imagery) to better locate regions of increased sea surface temperature gradients (Blackstone and Whritner-30). As with NAVOCEANO, San Diego FWF has had success in providing frontal and eddy information to the Fleet in support of ASW exercises. In addition, several aircraft carriers (USS CONSTELLATION, USS KENNEDY) have satellite readouts available aboard ship that permit identification of local thermal features.

Despite the above progress there are problems in the use of satellite imagery to map ocean fronts and eddies. The first problem is that the IR sensors respond to cloud radiation as well as to that from the ocean surface, thus if clouds are present in the scanning area the derived temperature is low since the contribution from the cloud tops is at a lower temperature value than would have been sensed from the water.

If the area of interest is completely cloud-covered thermal features cannot be identified.

Potocsky-(31) analyzed daily satellite IR imagery over a three year period to ascertain the reliability of satellites for identifying fronts on an operational basis. He found that in the spring significant portions of the Gulf Stream (or eddies) could be located on 14 out of 30 days. During winter, however, the reliability fell to only 6 out of 30 days, and there were periods when no thermal feature was visible for two weeks at a time. According to Shenk and Salomonson-(32) approximately 40 to 50 percent of the earth is obscured by clouds on any given day.

There are possible solutions to this problem. Improved sensors, such as microwave scanning may be able to "see through" the clouds. Processing techniques also offer means for circumventing the problem as long as the clouds have breaks and are moving. A series of satellite passes over an area is used and the clear portion of each pass combined in a composite to remove cloud contamination. One technique is to eliminate temperatures on a given scan below a set value (determined by seasonal water temperature). Another method is to use other sensors, such as visible imagery, to identify clouds and then discard values at those scan points. NOAA recalculates the mean value of data from a large area on the basis of fitting the observed histogram (sensed data) to the histogram representative of the area when no clouds are present.

Assuming that cloud contamination can be solved, and this is a valid assumption, there remains another problem in that satellites measure only the surface temperature pattern. Cold eddies lose their surface characteristics in the first few months of their estimated two year lifetimes, and although strong horizontal gradients exist below the surface, satellite imagery would show no anomalous thermal pattern. One possibility is to track the cold eddy as long as possible and then extrapolate its position thereafter at an average speed along a typical track. At intervals AXBT drops could be made by a VP aircraft to re-adjust and correct the eddy's predicted movement.

Another possibility is to tag the eddy with a buoy or float dropped in its center. Cheney, et al.-(33) described a recent attempt at tracking a cold eddy with three SOFAR (sound fixing and ranging) floats placed in its center. Positions of each float were determined from land stations by cross-fixing on an acoustic signal emitted by the float at six-hour intervals. Two of the floats remained in the eddy for three months, thus providing a continuous record of the eddy's movement. A second method using satellite-tracked buoys has been found to be easier and more effective. In a preliminary test Richardson, et al.-(34) used a buoy drogued at 200 m to track a cold ring for four months. Perfection of these techniques could make it possible to simultaneously monitor the movement of a number of eddies at a reasonable cost.

In addition, as NAVOCEANO experience has shown, it is possible to prepare an analysis including cold eddies by utilizing satellite data supplemented by ship SST reports and ship BT data. One reason for this success is that the thermal features move slowly. Occasional observations of various thermal features plus the consolidation of several days of data permits a fairly reliable analysis.

Location of the surface position of thermal features is only the first step, of course. Acoustic performance is a function of the three-dimensional thermal structure and an estimate of the sound velocity profiles at several points across the thermal feature is required before acoustic calculations can be made and tactical inferences drawn.

Fortunately, fronts and eddies conform to a generalized structure representing a balance of forces. Given a starting point, such as the surface position of a front, or the initial dimension of an eddy, one can apply a model to reconstruct reasonable temperature profiles and eventually SV profiles.

Khedouri-(35) showed that a statistical model of the Gulf Stream together with a given position of the North Wall, could be used to accurately predict isotherm distribution. Eddies also have somewhat predictable structures which are functions of their size and age. Such models exist in only very generalized form at present; a library of typical SV profiles across thermal features of various intensities, sizes, and locations needs to be developed.

9.0 OPERATIONAL SYSTEM DESIGN

The problem of how to best utilize fronts and eddies to improve ASW operations is complex. This is because a given thermal feature can either increase or decrease the propagation loss values or probability of detection, depending on the distance of source or receiver from a front, or the range from the source to receiver. Also the magnitude of propagation loss variation will depend on factors such as the bearing of propagation to the front, the source/receiver depths, frequency, topographic effects, etc. The number of combinations of these possibilities is so large that a tactical manual in a conventional sense is not practical. What may be possible is to have models of SV conditions across fronts and eddies which can be adjusted to the latest frontal position and any recent profile data. If these models are part of an automated system that also includes acoustic models (such as ICAPS) then one should be able to calculate propagation loss and other sonar information for any desired transit (at any depth and for any frequency) of the thermal feature.

What should an operational frontal information system look like, and where should it be situated? There is no simple answer to this since fronts and eddies affect ASW operations (and other warfare areas) at all levels of command. Since these features are wide-spread and may affect operational capabilities anywhere or everywhere in the Atlantic it is imperative that CINCLANTFLT be provided this information. A frontal information display and applications system could be incorporated into WWMCCS or ASWCCCS for instance. FLEWEACEN Norfolk would be the likely group to be responsible for providing the real-time mapping of the fronts and eddies. Monterey FNWC has recently established a satellite processing center which will permit the acquisition and processing of environmental data from both defense (DMSP) and national environmental satellites (NOAA-5, SEASAT, GOES). FNWC could process these data to locate fronts and eddies, utilizing techniques now under development, and transmit these data to FWC NORVA. Norfolk would then apply local information to complete the analysis, and pass the information into the appropriate display system for use of local commands.

Also available in the above display system would be a program which would permit the duty officer to request CRT display of any fronts or eddies in the vicinity of a given contact or other points of interest. Upon review of the information he could then request display of propagation loss, lateral range curves, or other acoustic indices for a given input of frequency, target and sensor depth. These calculations will be based on the appropriate SV profiles for the area and type of thermal feature, as stored in the computer memory or as a function of observed BT reports. If desired the Duty Officer can ask questions such as "what is the optimum depth for sonobuoys in the frontal areas?" or other tactical considerations.

For surveillance problems the propagation loss to selected arrays can be displayed and these data can, in conjunction with the known frontal pattern and the anticipated track of the suspected submarine, be used to alert an array when they might hear an improved signal. A similar system could be established at CINCPACFLT and through ASWCCCS be made available to the VP-TSC installations. Because of the demand for CPU time on the central computer other options might be considered.

In addition to this overall command-oriented support there is a requirement for frontal information and application packages aboard command ships. ICAPS is available aboard most aircraft carriers at present and will eventually be installed on all of them. By using the SMQ-10 shipboard read-out equipment (SROE) to obtain local IR imagery from the DMSP satellite the ASW office will have the capability to locate local fronts or eddies, and then apply the same type of sub-routines as above to obtain sonar indices necessary to make tactical decisions.

In addition, all ships should be provided with a tactical manual that presents typical SV profiles, by season, for both sides of all major fronts. The manual should include propagation loss curves for standard target/sensor depth combinations and frequencies for the two water masses and tabulated information concerning changes in operating on either side of a front.

10.0 RECOMMENDATIONS

As a follow-up to the above discussions the following actions are recommended:

RECOMMENDATION (1) Establish a program to map ocean fronts and eddies in the North Atlantic on a real time basis. This can initially be an expansion of the present NAVOCEANO frontal analysis, but eventually should be the responsibility of FLEWEACEN Norfolk or FNWC, Monterey.

RECOMMENDATION (2) The Navy Environmental Remote Sensing Coordinating and Advisory Committee (NERSCAC) should review and coordinate efforts within the Navy as to the use of satellites for frontal mapping, with particular emphasis on compatibility of outputs.

RECOMMENDATION (3) Develop oceanographic models of fronts and eddies for use in a command and control display routine that provides SV profiles for any desired thermal feature. Document and interface with ICAPS and frontal locations so that sonar indices can be computed for any frequency and target/sensor depth.

RECOMMENDATION (4) Develop a system for shipboard utilization of locally derived (shipboard satellite readout) or relayed frontal locations in conjunction with ICAPS to obtain tactical aids.

RECOMMENDATION (5) Continue experiments with research platforms and Fleet units to ascertain the effects of fronts and eddies on ASW operations with particular emphasis on the tactical options. Develop relationships between vertical and horizontal thermal gradients and their acoustic effects.

RECOMMENDATION (6) Establish procedures within CINCLANT so that routine environmental briefs contain information on important ocean parameters.

RECOMMENDATION (7) Design and execute fleet exercises across a major ocean front, such as the Gulf Stream, to familiarize the fleet units with the effect of fronts on their tactics and operations.

RECOMMENDATION (8) Continue research concerning the physical nature of fronts and eddies, their formation, movement and decay with particular emphasis on prediction of these phenomena.

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