On the Acoustic Characteristics of a Gulf Stream Cyclonic Ring

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(Manuscript received 9 April 1973, in revised form 11 July 1973)

ABSTRACT

The acoustic properties of a cyclonic Gulf Stream ring have been studied with field data and ray computations. Cyclonic rings represent relatively low sound velocity regions with large horizontal gradients of sound velocity embedded in the Sargasso Sea. Ray computations have shown the development of deep sound-channel-axis propagation from a near-surface source within a cyclonic ring.

1. Introduction

The Sargasso Sea was described by Iselin (1936) as a region of characteristic uniformity within the North Atlantic gyre that is maintained by steady climatic and mixing processes. The physical characteristics of the Sargasso Sea are warm and saline relative to North American slope water with small horizontal variations which contrast with the large gradients in the Gulf Stream. The formation of a Gulf Stream cyclonic ring introduces a major anomaly into the physical structure of the Sargasso Sea. Depending on the season of generation and ring age, cyclonic rings are roughly circular features of the order of 100 km in diameter with isotherms and isohalines elevated by hundreds of meters in the ring core. Although the temperature and salinity surface expressions of the core and encircling Gulf Stream remnant are gradually erased by seasonal effects, field observation and energy estimates indicate life spans of several years (Barrett, 1971). Fuglister (1972) has suggested that as many as eight cyclonic rings could be produced annually and two have been studied coincidentally in the North Atlantic. The geographical distribution of cyclonic rings derived by Parker (1971) encompasses a formation area south of the Gulf Stream between 60 and 70W and a drift region extending southward in the western Sargasso Sea to 25N. Mesoscale eddies on both sides of the Gulf Stream were studied by Iselin (1940) who made reference to the accompanying disturbance of the density structure encountered across the Gulf Stream from the slope water to the Sargasso Sea. It is presently clear that rings are frequent and strong expressions of mesoscale turbulence that affect the water mass characteristics and dynamic balance of the western North Atlantic.

2. General acoustical environment

Just seaward of the continental shelf and northeastward of Cape Hatteras three major features are evident in the waters of the North Atlantic Ocean. With increasing seaward distance these are slope water, the Gulf Stream, and the Sargasso Sea. In terms of *T-S* relations over the depth of the main thermocline, a clear distinction exists between North American Slope Water (NASW) and the North Atlantic Central Water (NACW) of the western Sargasso Sea. The Gulf Stream, moving between these water masses, appears as a transition region in *T-S* diagrams. Temperature, the primary acoustic variable over the main thermocline or upper layer, has a large horizontal gradient from the cooler NASW through the Gulf Stream to the warmer NACW. The gross structure of this overall temperature transition brings a unique acoustical character to cyclonic Gulf Stream rings in the Sargasso Sea and to anticyclonic rings in slope water.

The cyclic changes induced in the sound velocity profile by seasons in the mid-latitude North Atlantic reach to the depths of the main thermocline. With the exception of near-surface effects, these changes can be briefly surveyed on the basis of the depths of the sound channel axis and the minimum sound velocities which occur at the axis. Sound velocity profiles on geographic and seasonal bases as well as associated variances are available in Section VI of the series, *Oceanographic Atlas of the North Atlantic Ocean* (U. S. Naval Oceanographic Office, 1967), which has been compiled from data files of the National Oceanographic Data Center. The total variance of the sound channel velocity as a function of the sound channel depth is shown in Fig. 1 for the major water masses. Three overlapping characteristic regions are present, each drawn by connecting points representing extreme coordinate pairs by straight lines. The coordinate pairs were formed by associating minimum and maximum sound velocities with the respective minimum and maximum depths of the sound channel.

Several implications can be drawn from comparisons of the characteristic regions in Fig. 1. In response to the temperature field, there is a definite progression of

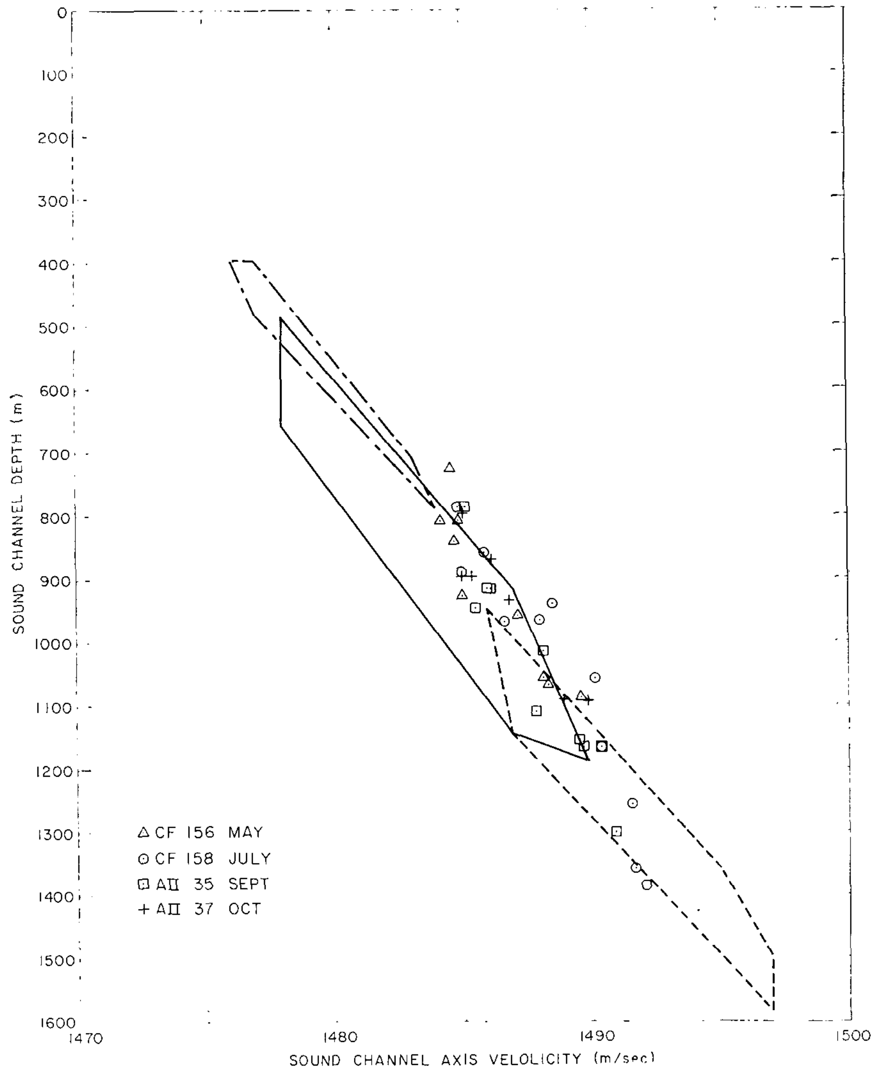

FIG. 1. Characteristic regions for sound channel parameters in North American Slope Water (long-short dashes) Gulf Stream water (continuous line) and North Atlantic Central Water (short dashes). Sound-channel-axis velocities and corresponding depths are shown for the 1967 cyclonic ring.

the sound channel velocity from high values for NACW to lower values for the Gulf Stream and NASW. The upper and lower bounds of these regions tend to occur in the summer months and are responsible for the overlaps. Since the designation of regions in the atlas is made on geographic and seasonal lines, it is logical that the overlaps are, in part, due to meanders of the Gulf Stream and the presence of anticyclonic and cyclonic rings on either side of the Gulf Stream. The simplest explanation for the summer overlap is the prevalence of observations during this season. A study of Gulf Stream meanders (Hansen, 1970) shows large meanders during the summer of 1966. Although no seasonality has been proven, a tendency for meanders to reach extreme latitude ranges during the summer could be reflected in the overlapping characteristic regions of Fig. 1.

A significant number of hydrographic stations have been taken in cyclonic rings within the Sargasso Sea. Ring core stations are taken in a water mass representing a mixture of slope water and Gulf Stream water at some stage of turbulent interaction with the surrounding waters and interaction with the atmosphere. These stations carry with them positions geographically associated with the Sargasso Sea. Fuglister and Worthington (1947) warned of the danger of incorrect interpretation of a single hydrographic section passing through a ring area. Since oceanographic interest is growing in these mesoscale features, field experiments will certainly increase in number. Unless sufficient care is taken in utilization of large data banks, however, there will be a corresponding danger of misinterpreting studies of physical parameters that characterize major water masses.

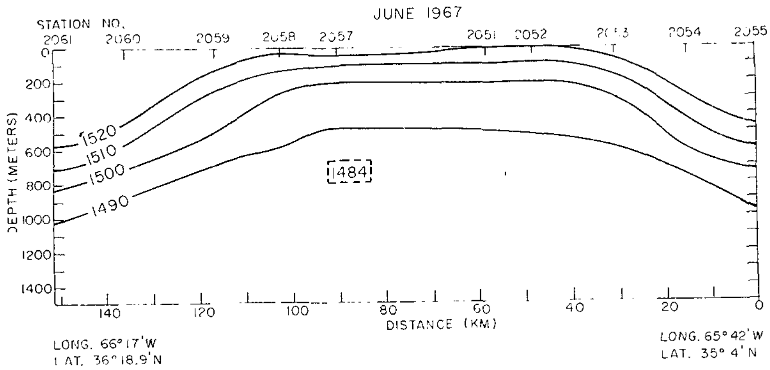

FIG. 2. Sound isovel section (m sec^{-1}) for cruise CF 156.

3. The 1967 cyclonic rings

During the aerial survey of the Gulf Stream on 1 March 1967, the formation of a cyclonic ring near 37N, 66W was detected with an infrared radiation thermometer (Bratnick *et al.*, 1968). The detachment of the ring took place over a 15-day period and was studied on ASWEPS aircraft flights by the Naval Oceanographic Office. The collection of shipboard data by the Woods Hole Oceanographic Institution (WHOI) was initiated in May and extended through October of that year. Hydrographic stations supplemented by expendable bathythermographs (XBT's) were gathered during cruises of the vessels RV *Atlantis* II (AII) and RV *Crawford* (CF). The cruises involved were CF 155, CF 156, CF 157, CF 158, AII 35, AII 37 and AII 38. The RV *Crawford* cruises took place in May, June and July; and the RV *Atlantis* II cruises were in August, September and October. On each cruise, an attempt was made to cross the ring with one or more lines of hydrographic stations and/or XBT's. The data taken on these cruises were obtained from the National Oceanographic Data Center and through the generosity of the principal investigator at WHOI, F. C. Fuglister. Sound velocities were calculated from the data by an application of Wilson's formula (Wilson, 1960). From these values, cross sections of sound velocities through the ring were drawn for each of the following cruises: CF 156, CF 158, AII 35, AII 37 and AII 38. The contours are given in Figs. 2–6. A pocket of minimum sound velocities associated with the cool core of the ring is illustrated quite well.

The serial sets of data taken during five of the WHOI cruises provide an opportunity to evaluate the stability of the sound velocity perturbation introduced by the ring. Two cruises, CF 158 and AII 35, took a sufficient number of deep hydrographic stations to delineate a lens-like cell of low acoustic velocity shown in the isovel patterns of Figs. 3 and 4. These and the remaining patterns illustrate an elevation of the isovels in the central portion of the ring. This is primarily a result of the cool core water. The minimum value of sound velocity and its approximate location is given for each section in the dashed rectangles. Values of minimum sound velocity for slope water profiles (Kaufman, 1965) correlate with the sound velocity in the ring centers. It should be noted that the analysis deals with a core subjected to alteration by surrounding Gulf Stream and NACW and not *in-situ* NASW. The velocity and depths at the sound channel axis, as determined from hydrographic stations through the rings, are plotted in Fig. 1 for cruises CF 156 (June), CF 158 (July), AII 35 (September) and AII 37 (October). The axis velocity and depth at the station furthest from the ring center plot well into the NACW characteristic region for each cruise. Stations taken closer to the ring center fall in a general progression

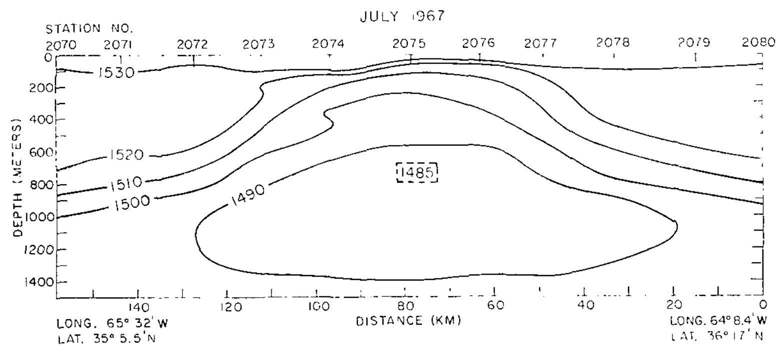

FIG. 3. Sound isovel section (m sec^{-1}) for cruise CF 158.

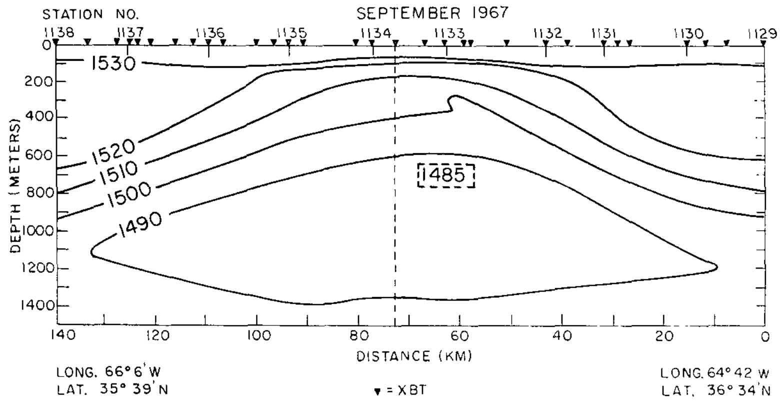

Fig. 4. Sound isovel section (m sec^{-1}) for cruise AII 35.

through the Gulf Stream region to the slope water region.

The sound speed minimum in the ring remained relatively constant in value, with the depth increasing about 100 m during the period of observations. Although individual isovels changed depth slightly from June to October, their overall shape remained steady. These sound velocity sections do not all necessarily bisect a circular ring feature and this could account for the observed variations. However, intersecting lines of hydrographic stations that were meant to bisect the ring were made on CF 156, AII 35 and AII 38 and these stations indicate a circular, symmetric structure.

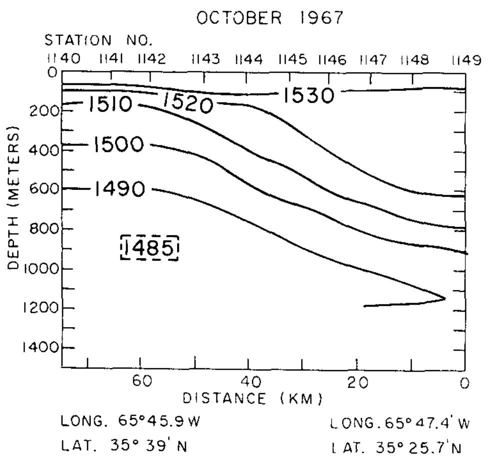

Fig. 5. Sound isovel section (m sec^{-1}) for cruise AII 37.

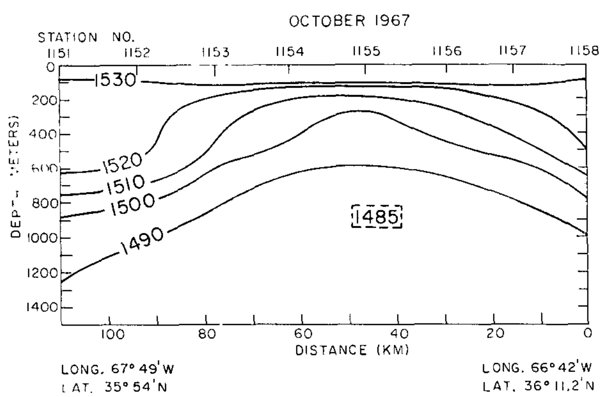

Fig. 6. Sound isovel section (m sec^{-1}) for cruise AII 38.

4. Propagation studies

A numerical study of acoustic propagation in the ring was carried out by computations based on ray theory at the U. S. Navy Fleet Numerical Weather

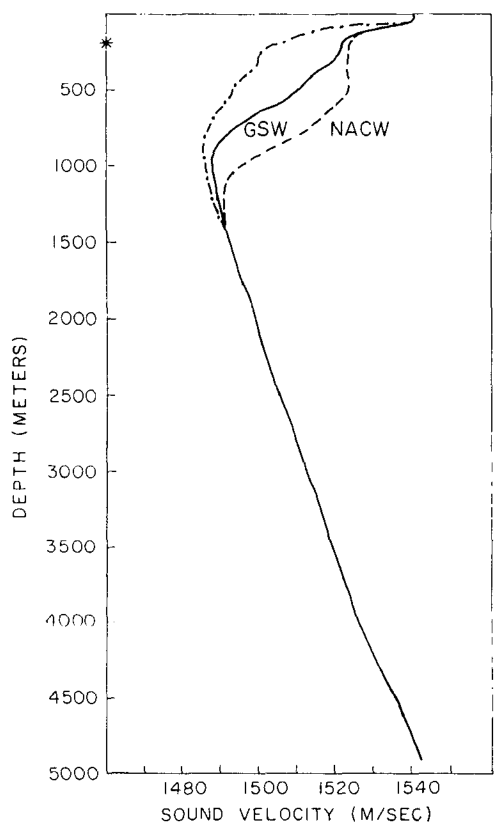

Fig. 7. Sound velocity profiles selected from the isovel section for cruise AII 35.

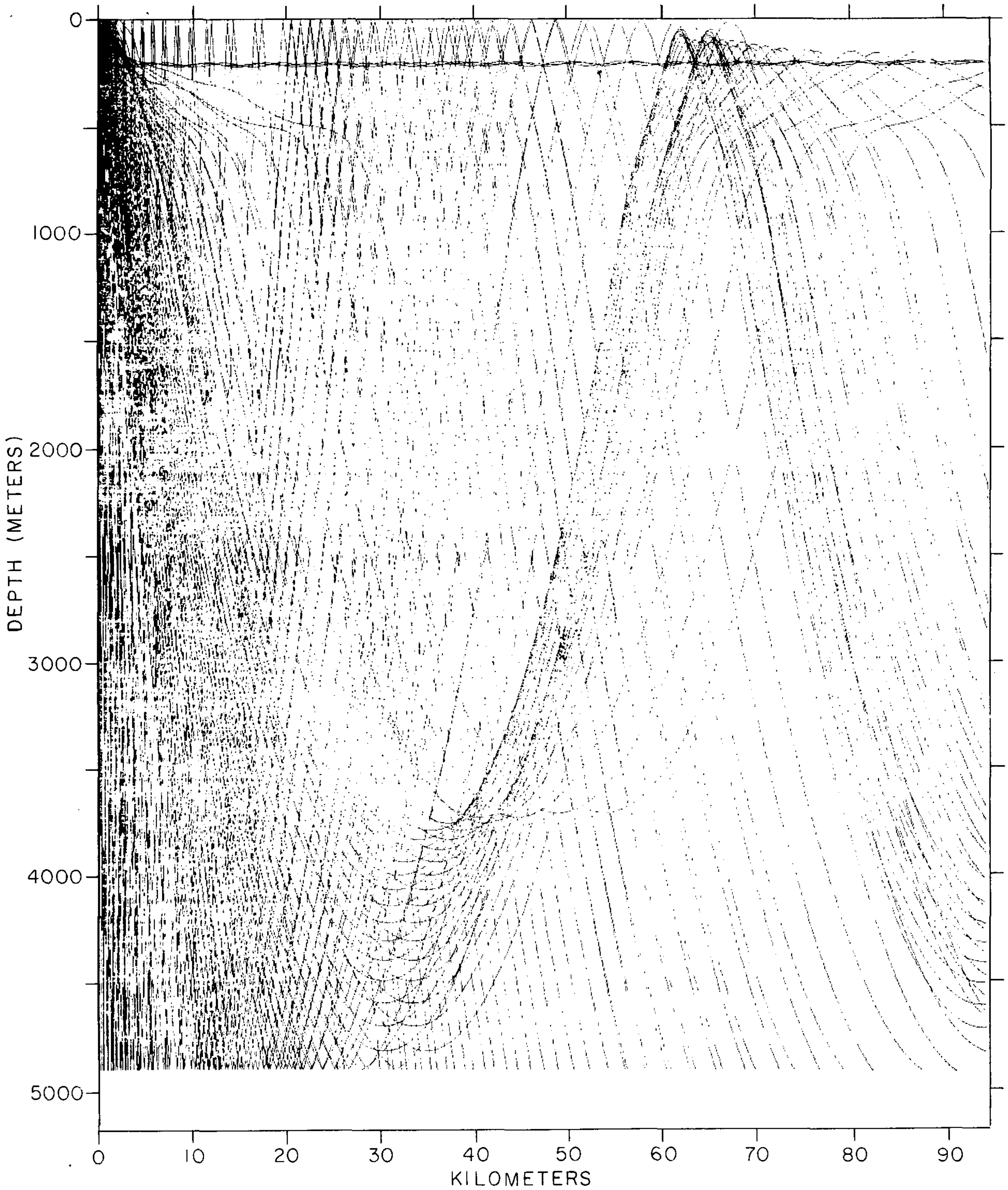

FIG. 8. Ray tracing for the Sargasso Sea sound velocity profile for cruise AII 35.

Central (FNWC) computer facilities, Monterey, Calif. Data collected on cruise AII 35 were selected for the study of sound propagation. The hydrographic stations taken on this cruise were spaced at an average distance of 15 km. The XBT data taken during the section represented in Fig. 4 were used to supplement the temperature field obtained from the stations. An average of two XBT's were taken between stations and one was

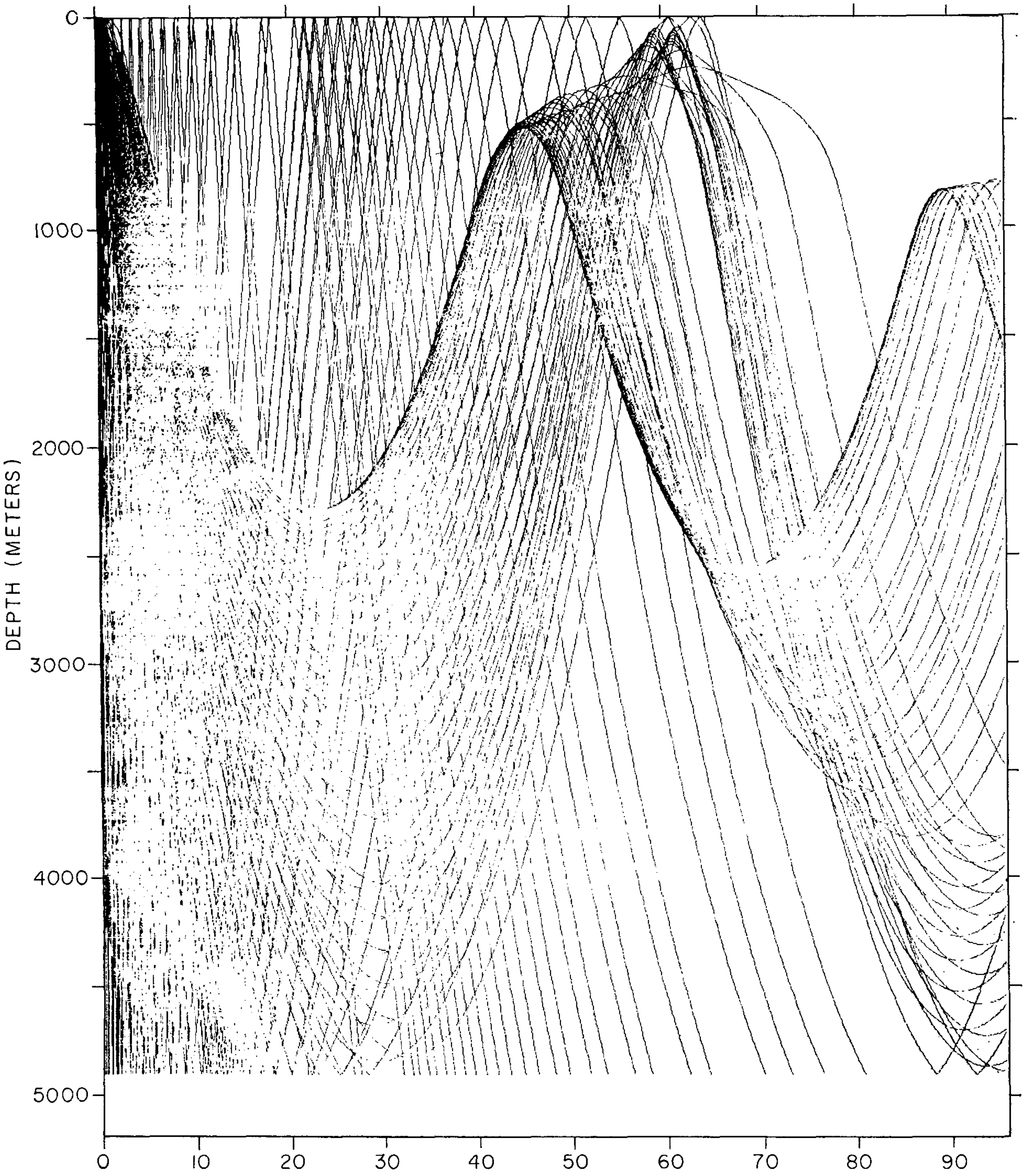

Fig. 9. Ray tracing including the cyclonic ring stations for cruise AII 35. The northernmost half of the ring was used for these calculations.

taken at each station. Although the station and XBT positions did not lie in a straight line, deviations of the positions from a straight line were not large. Therefore, the actual horizontal distances between XBT positions were used for the temperature section. This resulted in a very slight horizontal spreading of the data field. Since the XBT's provided a continuous plot of temperature to a depth of 450 m, these data were used rather than the station data for depths above this level. In several cases, the temperature data from the XBT's did not match the temperature data from the hydrographic stations at the 450 m level primarily because of ship's drift. Smoothing was necessary before the two types of data could be combined at these points. To obtain complete profiles to the bottom, climatological data for the western North Atlantic were provided by FNWC and used for depths between 3000 and 4900 m. At the XBT positions, which are plotted in Fig. 4, temperature and salinity values were interpolated at selected depths from the surface to the bottom. One XBT position was chosen to represent the center of the section and this position is indicated by a dashed line in Fig. 4. The temperature and salinity values obtained from the sections were used to compute a matrix of sound velocity data points which represented a vertical section through the cyclonic ring. This matrix of points was used in the FNWC ray tracing program. The program uses standard ray tracing procedures such as those discussed by Urick (1967).

A sound source at a frequency of 100 Hz was assumed at a depth of 200 m in the center of the ring, and propagation was studied for each half of the vertical section. It was assumed that the sound velocity profile of the XBT position most distant from the center represented (stations 1129 and 1138) Sargasso Sea water; this profile was then repeated until a total range of 200 km from the center was obtained. As a standard for comparison, the calculations were repeated using only the profile from the position of hydrographic station 1129. This profile was repeated to simulate a homogeneous region of the western Sargasso Sea 200 km in length and the comparison carried out for both radii.

The essential acoustic factors are shown in Fig. 7 by three velocity profiles taken from the southeastern side of the ring and the acoustic source which is indicated by an asterisk. The profile marked NACW is from the right edge of the ring and is the profile which was used so simulate the water of the western Sargasso Sea. Profile GSW is midway in the right side of the ring and is characteristic of the remnant of Gulf Stream water encircling the center of the ring. The remaining profile is from the center of the ring and is characteristic of the core. These profiles show the extremes and transition found in the ring during early September 1967. The NACW profile has two sound channels and a surface duct. In profile GSW the mid-depth channel has nearly disappeared and the main sound channel axis has been elevated approximately 300 m. The core profile shows a much more broadened deep sound channel with the axis elevated an additional 100 m.

A ray tracing for 90 km of the standard Sargasso Sea section is shown in Fig. 8. The normal reinforcement zone for long-range propagation appears at a range of 70 km and propagation is evident along the mid-depth sound channel of the NACW velocity profile. The ray tracing in Fig. 9 represents propagation through the northernmost half of the ring section shown in Fig. 4. The progagation is in sharp contrast to the Sargasso Sea standard. In response to the large sound velocity gradient, rays are refracted toward deeper depths in shorter distances than in the standard case. The effect of this bending is an increased propagation to deeper depths within the 50-km range of the cyclonic ring

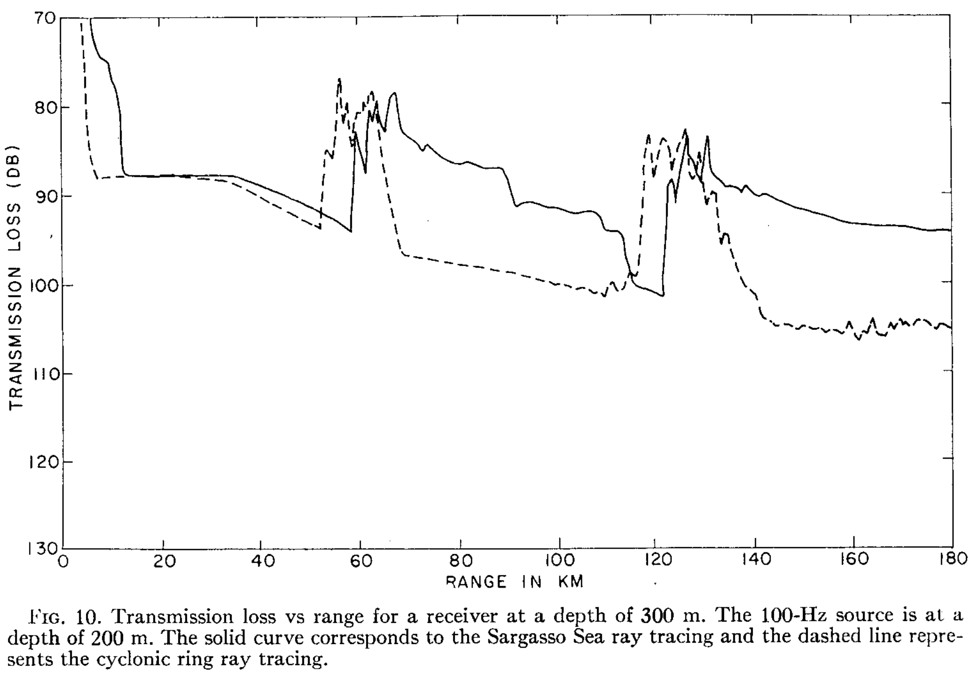

FIG. 10. Transmission loss vs range for a receiver at a depth of 300 m. The 100-Hz source is at a depth of 200 m. The solid curve corresponds to the Sargasso Sea ray tracing and the dashed line represents the cyclonic ring ray tracing.

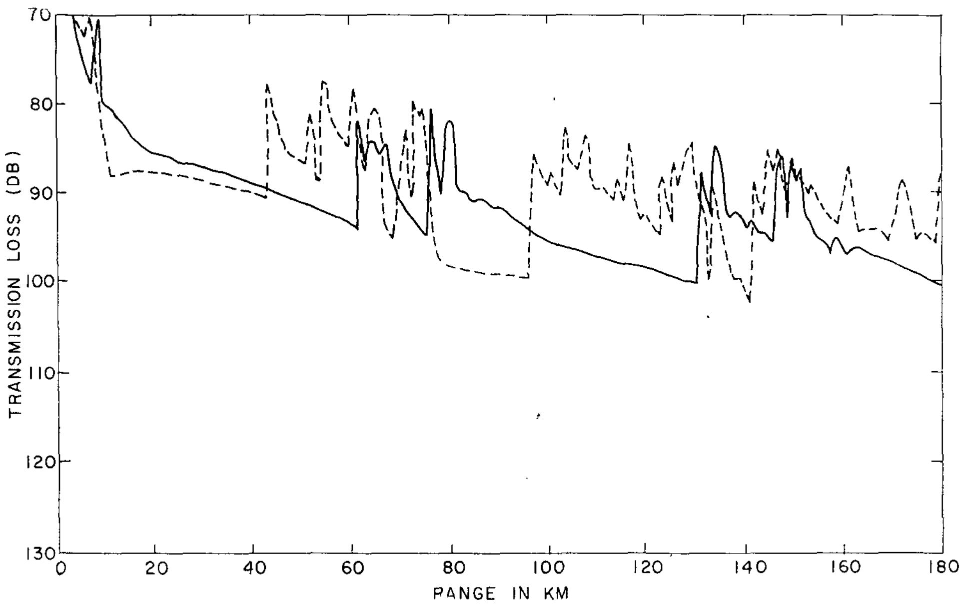

FIG. 11. As in Fig. 10 except for a receiver at a depth of 1000 m.

radius. As a result, the source at a depth of 200 m in the ring center appears as a sofar channel source outside the ring. The increased refraction of the rays also tends to refocus the normal reinforcement regions closer to the source and disrupts the mid-depth propagation present in the Sargasso Sea standard section. The computations for the southern half of the ring yield essentially identical results.

Sound energy levels at two depths are interpreted in terms of transmission loss for the standard and ring sections and are shown in Figs. 10 and 11. The calculation of transmission loss takes into account wave front spreading, volume attenuation, and losses due to boundary interaction (Tatro *et al.*, 1968). The solid loss curve in Fig. 10 represents the standard Sargasso Sea section. The dashed curve for the ring section clearly shows the effective removal of energy from the mid-depth channel by the increased downward refraction of rays within the radius of the cyclonic ring and the refocussing of the reinforcement regions relative to the standard curve. Fig. 11 presents a reversal of the relationship between the transmission loss curves and indicates the increased energy levels to be expected at a sound channel depth of 1000 m due to the acoustic properties of the cyclonic ring.

5. Conclusions

The cyclonic ring acoustic field is a significant perturbation of the relatively uniform acoustic environment of the Sargasso Sea. These ray computations have shown the ability of a cyclonic ring to alter the normal propagation for a near-surface acoustic signal to an effective sofar channel source. An examination of the effect of a variation in the depth of the sound channel (Eliseevnin, 1965) has shown strong dispersion of ray paths in the region where the sound channel changes depth. Considerably more research will be required to examine the effect of source location both within and outside a cyclonic ring, the sound scattering effect of a ring, and the acoustic propagation effects of a distribution of cyclonic rings within the Sargasso Sea.

Acknowledgments This study was supported by the Office of Naval Research under Contract N0014-68-A-0308-002 and by the U. S. Navy Fleet Numerical Weather Central, Monterey, Calif. The authors would like to thank Cmdr. Peter R. Tatro, U. S. Navy, and Dr. A. D. Kirwan, Jr., for their interest and suggestions, and Cmdrs. J. F. Breidenstein and Kenneth Hinman, U. S. Navy, for their assistance in carrying out the ray calculations.

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