NOAA Technical Memorandum NMFS-NE-170

Interaction of Shelf Water with Warm-Core Rings, Focusing on the Kinematics and Statistics of Shelf Water Entrained within Streamers

U. S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole, Massachusetts

March 2003

Recent Issues in This Series:

155. **Food of Northwest Atlantic Fishes and Two Common Species of Squid.** By Ray E. Bowman, Charles E. Stillwell, William L. Michaels, and Marvin D. Grosslein. January 2000. xiv + 138 p., 1 fig., 7 tables, 2 app. NTIS Access. No. PB2000-106735.

156. **Proceedings of the Summer Flounder Aging Workshop, 1-2 February 1999, Woods Hole, Massachusetts.** By George R. Bolz, James Patrick Monaghan, Jr., Kathy L. Lang, Randall W. Gregory, and Jay M. Burnett. May 2000. v + 15 p., 5 figs., 5 tables. NTIS Access. No. PB2000-107403.

157. **Contaminant Levels in Muscle of Four Species of Recreational Fish from the New York Bight Apex.** By Ashok D. Deshpande, Andrew F.J. Draxler, Vincent S. Zdanowicz, Mary E. Schrock, Anthony J. Paulson, Thomas W. Finneran, Beth L. Sharack, Kathy Corbo, Linda Arlen, Elizabeth A. Leimburg, Bruce W. Dockum, Robert A. Pikanowski, Brian May, and Lisa B. Rosman. June 2000. xxii + 99 p., 6 figs., 80 tables, 3 app., glossary. NTIS Access. No. PB2001-107346.

158. **A Framework for Monitoring and Assessing Socioeconomics and Governance of Large Marine Ecosystems.** By Jon G. Sutinen, editor, with contributors (listed alphabetically) Patricia Clay, Christopher L. Dyer, Steven F. Edwards, John Gates, Tom A. Grigalunas, Timothy Hennessey, Lawrence Juda, Andrew W. Kitts, Philip N. Logan, John J. Poggie, Jr., Barbara Pollard Rountree, Scott R. Steinback, Eric M. Thunberg, Harold F. Upton, and John B. Walden. August 2000. v + 32 p., 4 figs., 1 table, glossary. NTIS Access. No. PB2001-106847.

159. **An Overview and History of the Food Web Dynamics Program of the Northeast Fisheries Science Center, Woods Hole, Massachusetts.** By Jason S. Link and Frank P. Almeida. October 2000. iv + 60 p., 20 figs., 18 tables, 1 app. NTIS Access. No. PB2001-103996.

160. **Measuring Technical Efficiency and Capacity in Fisheries by Data Envelopment Analysis Using the General Algebraic Modeling System (GAMS): A Workbook.** By John B. Walden and James E. Kirkley. October 2000. iii + 15 p., 9 figs., 5 tables. NTIS Access. No. PB2001-106502.

161. **Demersal Fish and American Lobster Diets in the Lower Hudson - Raritan Estuary.** By Frank W. Steimle, Robert A. Pikanowski, Donald G. McMillan, Christine A. Zetlin, and Stuart J. Wilk. November 2000. vii + 106 p., 24 figs., 51 tables. NTIS Access. No. PB2002-105456.

162. **U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments – 2000.** Edited by Gordon T. Waring, Janeen M. Quintal, and Steven L. Swartz, with contributions from (listed alphabetically) Neilo B. Barros, Phillip J. Clapham, Timothy V.N. Cole, Carol P. Fairfield, Larry J. Hansen, Keith D. Mullin, Daniel K. Odell, Debra L. Palka, Marjorie C. Rossman, U.S. Fish and Wildlife Service, Randall S. Wells, and Cynthia Yeung. November 2000. ix + 303 p., 43 figs., 55 tables, 3 app. NTIS Access. No. PB2001-104091.

163. **Essential Fish Habitat Source Document: Red Deepsea Crab, *Chaceon (Geryon) quinquedens*, Life History and Habitat Characteristics.** By Frank W. Steimle, Christine A. Zetlin, and Sukwoo Chang. January 2001. v + 27 p., 8 figs., 1 table. NTIS Access. No. PB2001-103542.

164. **An Overview of the Social and Economic Survey Administered during Round II of the Northeast Multispecies Fishery Disaster Assistance Program.** By Julia Olson and Patricia M. Clay. December 2001. v + 69 p., 3 figs., 18 tables, 2 app. NTIS Access. No. PB2002-105406.

165. **A Baseline Socioeconomic Study of Massachusetts' Marine Recreational Fisheries.** By Ronald J. Salz, David K. Loomis, Michael R. Ross, and Scott R. Steinback. December 2001. viii + 129 p., 1 fig., 81 tables, 4 app. NTIS Access. No. PB2002-108348.

166. **Report on the Third Northwest Atlantic Herring Acoustic Workshop, University of Maine Darling Marine Center, Walpole, Maine, March 13-14, 2001.** By William L. Michaels, editor and coconvenor, and Philip Yund, coconvenor. December 2001. iv + 18 p., 14 figs., 2 app. NTIS Access. No. PB2003-101556.

167. **Assessment and Characterization of Salt Marshes in the Arthur Kill (New York and New Jersey) Replanted after a Severe Oil Spill.** By David B. Packer, ed. December 2001. x + 228 p., 54 figs., 58 tables, 6 app. NTIS Access. No. PB2004-106067.

168. **U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments – 2001**. By Gordon T. Waring, Janeen M. Quintal, and Steven L. Swartz, eds., Phillip J. Clapham, Timothy V.N. Cole, Carol P. Fairfield, Aleta Hohn, Debra L. Palka, Marjorie C. Rossman, U.S. Fish and Wildlife Service, and Cynthia Yeung, contribs. December 2001. vii + 310 p., 43 figs., 54 tables, 2 app. NTIS Access. No. PB2002-104350.

169. **U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments – 2002**. By Gordon T. Waring, Janeen M. Quintal, and Carol P. Fairfield, eds., Phillip J. Clapham, Timothy V.N. Cole, Lance P. Garrison, Georgia Department of Natural Resources, Aleta A. Hohn, Blair G. Maise, Wayne E. McFee, Debra L. Palka, Patricia E. Rosel, Marjorie C. Rossman, U.S. Fish and Wildlife Service, Frederick W. Wenzel, and Cynthia Yeung, contribs. September 2002. vii + 318 p., 42 figs., 56 tables, 4 app. NTIS Access. No. PB2003-104167.

NOAA Technical Memorandum NMFS-NE-170

This series represents a secondary level of scientific publishing. All issues employ thorough internal scientific review; some issues employ external scientific review. Reviews are -- by design -- transparent collegial reviews, not anonymous peer reviews. All issues may be cited in formal scientific communications.

Interaction of Shelf Water with Warm-Core Rings, Focusing on the Kinematics and Statistics of Shelf Water Entrained within Streamers

Ronald J. Schlitz

Postal Address: *National Marine Fisheries Serv., Woods Hole Lab., 166 Water St., Woods Hole, MA 02543*
E-Mail Address: *Ron.Schlitz@noaa.gov*

U. S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary
National Oceanic and Atmospheric Administration
Vice Admiral Conrad C. Lautenbacher, Jr., USN (ret.), Administrator
National Marine Fisheries Service
William T. Hogarth, Assistant Administrator for Fisheries
Northeast Fisheries Science Center
Woods Hole, Massachusetts

March 2003

Editorial Notes

Statistical Terms: The NEFSC Editorial Office's policy on the use of statistical terms in all technical communications is generally to follow the International Standards Organization's handbook of statistical methods (*i.e.*, ISO 1981[a]).

Internet Availability: This issue of the *NOAA Technical Memorandum NMFS-NE* series is being copublished, *i.e.*, as both a paper and Web document. The Web document, which will be in HTML (and thus searchable) and PDF formats, can be accessed at: *http://www.nefsc.noaa.gov/nefsc/publications/*.

[a]ISO [International Organization for Standardization]. 1981. ISO standards handbook 3: statistical methods. 2nd ed. Geneva, Switzerland: ISO; 449 p.

Contents

Figures

Tables

Acronyms

AVHRR	=	advanced very-high-resolution radiometer
CTD	=	conductivity-temperature-depth instrument
MOCNESS	=	multiple-opening/closing net and environmental sensing system
NCSE	=	Northeast U.S. Continental Shelf Ecosystem
NMFS	=	National Marine Fisheries Service
NOAA	=	National Oceanic and Atmospheric Administration
OCS	=	outer continental shelf
PSU	=	practical salinity unit
WCR	=	warm-core ring
WCRP	=	Warm Core Rings Program
XBT	=	expendable bathythermograph

ABSTRACT

Three cruises were completed off the northeastern United States during late 1981 and 1982 in cooperation with the National Science Foundation-sponsored Warm Core Rings Program in order to study entrainment of shelf water and associated biota by Gulf Stream warm-core rings (*i.e.*, pinched-off meanders of the Gulf Stream which form clockwise/anticyclonic eddies). Hydrographic data were collected with a conductivity-temperature-depth recorder on board the NOAA R/V *Albatross IV* during 22 September - 6 October 1981, 19 April - 4 May 1982, and 17 June - 2 July 1982. These hydrographic data defined the "streamers" of entrained shelf water which were associated with Rings 81-E, 82-A, and 82-B twice, and formed the basis for the present results and discussion.

The amount of shelf water, delineated by salinity $\leq$ 34 practical salinity units, varied from 58 km^3 in a nearly isolated bowl associated with Ring 82-A, to 290 km^3 associated with the second visit to Ring 82-B. Geostrophically calculated transports across sections of the streamers ranged from 488 x 10^3 m^3 sec^{-1} in the same direction as the azimuthal velocity for Ring 82-B, to 345 x10^3 m^3 sec^{-1} in the opposite direction as the azimuthal velocity for Ring 82-A.

Although each streamer was different in shape and size, a saddle point – a portion of the streamer with a pronounced cross-sectional narrowing – was present within its structure. This saddle point appears to be related to the inshore periphery of a counterclockwise/cyclonic eddy that develops near the head of the streamer.

Analysis of water properties leads to the conclusion that the source of shelf water for streamers is primarily seaward of the cold band, present during the stratified season (*i.e.*, April-September), at water depths approximately 100 m. Therefore, passage of warm-core rings is not likely to have a major direct effect on the biota of the continental shelf, including larvae of commercially important fish species found between Cape Hatteras and Nova Scotia, since their distributions are generally concentrated at shallower depths.

INTRODUCTION

Understanding variation of biological components is a focus of the ecological studies of the Northeast U.S. Continental Shelf Ecosystem (NCSE). For populations of commercially important species in the NCSE, a major source of that variation is recruitment – the number of individuals in the population that annually survive and grow to reach a catchable size. Recruitment in commercial fish populations is highly variable, and the causes of mortality that limit recruitment are not well understood (Hennemuth *et al.* 1980).

Advection of eggs and larvae from a preferred habitat has long been hypothesized as a large source of prerecruit mortality in commercial fish populations (Iles and Sinclair 1982), capable of causing occasional catastrophic losses (Walford 1938). One source for advective loss of shelf water from the NCSE is the interaction of warm-core rings (WCRs) with shelf water at the front separating shelf water and slope water (*i.e.*, the shelf-slope front or shelfbreak front). Several authors describe WCRs and associated processes; see the review of Richardson (1983) and the special series of papers introduced by Joyce (1985). Garfield and Evans (1987) document statistics for the entrainment of shelf water, mainly derived from satellite thermal imagery over the 1979-85 period.

Morgan and Bishop (1977) found a feature with salinity <34‰ (*i.e.*, a conservative, unambiguous indicator of shelf water) at least 90 km from the edge of the continental shelf and to the east of a WCR. However, the precise extent of the shelf water feature was not determined due to the sparse distribution of hydrographic stations. They concluded that a transport of 8.9×10^3 m^3 sec^{-1} was likely for water with salinity <34‰.

Smith (1978) speculated on the interaction between a WCR well south of the Scotian Shelf and fluxes of heat and salt onto the shelf below 50 m. A volume of entrained shelf water on the eastern and western sides of the ring was calculated as 2500 km^3, based on an analysis of an image derived from an advanced very-high-resolution radiometer (AVHRR) on board NOAA's polar-orbiting, environmental-sensing satellites, and on an assumed depth of 50 m for the entrainment. However, shelf water found west of the ring was probably caused by a second ring located farther toward the west.

Fornshell and Criess (1979) provided additional evidence for offshore flow from the continental shelf, finding water with proper temperature and salinity characteristics on the south side of a ring, and patches of similar water on the southeast side of it.

Bisagni (1983) reported on a direct measurement of flow from two satellite-tracked buoys, each equipped with a drogue at 10 m depth and placed at the 106-Mile Dumpsite (39°N, 72°W). The buoys first moved southwest at <25 cm sec^{-1}, then anticyclonically at up to 54 cm sec^{-1} around WCR 80-A. (The nomenclature used in this paper for WCRs follows the scheme of the National Marine Fisheries Service's (NMFS's) Narragansett (Rhode Island) Laboratory: the two-digit year of formation is given first, and the alphabetical sequence of formation in that year is given second.) Interpretation of thermal images from satellites showed that these buoys were within shelf water, but always well seaward of the shelfbreak. Bisagni (1983) estimated the transport of the feature as 1.5×10^5 m^3 sec^{-1}, assuming a mean speed of 25 cm sec^{-1}, depth of 50 m, and width of 12 km.

During the U.S. Department of Energy's Shelf Edge Exchange Processes Experiment, WCR 83-D passed through a linear array of moored instruments across the continental shelf and slope south of Marthas Vineyard (Churchill *et al.* 1986). Based on temperature and salinity data from a mooring located at a 125-m depth, and on an expendable bathythermograph (XBT) section farther to the east that crossed the eastern half of the ring about 2 wk later, Churchill *et al.* (1986) hypothesized that subsurface water from the cold band encircled the WCR at approximately 50 m. The minimum temperatures of the water were <10°C over the shelf and <14°C at the southern end of the ring. Unfortunately, there were no salinity data to distinguish between shelf water and slope water at the southern end. There was slope water with similar temperatures nearby on the contoured section.

These various measurements of "streamers" of shelf water associated with WCRs (*i.e.*, fingers of shelf water located at the trailing edge of WCRs as they move along the edge of the continental shelf towards Cape Hatteras) were mainly fortuitous. However, the National Science Foundation sponsored a specific program – the Warm Core Rings Program (WCRP) – to study WCRs (Warm-Core Rings Executive Committee 1982; Joyce and Wiebe 1983). The WCRP provided a unique opportunity to study cooperatively the interaction of WCRs with shelf water and associated biota. One purpose for NMFS involvement in the WCRP was to determine if the passage of a WCR could lead to loss of early life stages of major commercial fish populations. Such determination would require a description of the physical and biological characteristics, as well as the kinematics, of streamers. A series of interdisciplinary cruises, in conjunction with the WCRP, was completed between September 1981 and September 1982 in order to collect the necessary data.

This paper focuses on a description of the physical characteristics of streamers, as determined primarily from the oceanographic data. These data, even though collected during 1981 and 1982, represent the only extensive collection of in-situ information principally directed toward entrainment of shelf water by WCRs. First, the temperature and salinity characteristics, volume, and spatial structure of streamers of entrained shelf water are described. Then, the kinematics of the streamers are discussed, showing the variability of streamers in time and space. Finally, the primary source for shelf water found in streamers is directly substantiated.

METHODS

DATA COLLECTION

Three cruises on board the NOAA R/V *Albatross IV* extensively sampled shelf water streamers associated with WCRs: 1) 22 September - 6 October 1981, associated with Ring 81-E (initially mislabeled as Ring 81-D (see Fitzgerald and Chamberlin (1984) for an explanation), and appearing as such in Joyce *et al.* (1984)); 2) 19 April - 4 May 1982, associated with Rings 82-A and 82-B; and 3) 17 June - 2 July 1982, associated again with Ring 82-B. The locations of all stations for the three cruises are shown in Figure 1. The station numbers for those stations are shown in Figures 2a-2c. Only a portion of the data collected during the series of cruises is used here.

Sea surface temperatures, derived from the NOAA-6 and NOAA-7 polar-orbiting, environmental-sensing satellites, were used extensively to guide the sampling at sea. Graphical interpretations of the processed, high-resolution images were transmitted from the University of Miami to the research vessel via the Application Technology Satellite III. A compilation of all images for Ring 82-B is found in Evans *et al.* (1984). Colder temperatures and sharp fronts delimited the shelf water. Later analysis of the images ashore aided interpretation of the in-situ measurements presented here.

Temperatures and salinities were sampled with a continuously recording conductivity-temperature-depth instrument (CTD), and with a surface thermosalinograph. Reporting of salinity follows the Practical Salinity Scale, and is expressed as practical salinity units (PSU). At most stations, a CTD cast was completed to 1000 m or near the ocean bottom when the depth was <1000 m. Sometimes, time constraints or special sampling led to shallower casts. On the return of each cast, water samples were collected for salinity analysis to compare with the continuous values. Also, XBTs were used to provide better resolution for the thermal field.

Eulerian currents and temperatures were measured from two arrays of moored current meters along the continental shelf. Positions and schematic views for the two arrays of current meters are presented in Ramp (1989) and Schlitz *et al.* (2001). The two arrays were identical except for their relative position along the continental shelf break. The first array, called WCR1, was deployed from 15 April to 1 July 1982, and was centered at roughly 40°N, 70°W (Ramp 1989). The second array, called WCR2, was deployed during August and September 1982 and was centered at roughly 40°20'N, 67°30'W (Schlitz *et al.* 2001).

Short-term Lagrangian currents were measured by drogues placed within streamers of shelf water. Details about the drifters are found in Schlitz *et al.* (2001).

For sampling plankton, especially ichthyoplankton, either a multiple-opening/closing net and environmental sensing system (MOCNESS) or bongo net haul generally followed the CTD cast at each station.

DATA ANALYSIS

To estimate the volume of shelf water in streamers, a planimetric method was used, based on the isolines shown in Figures 3a-6a. Each isoline in Figures 3a-6a represents the depth of a layer measured from the surface to the deepest level in which the salinity is ≤34 PSU, the value normally at the inshore side of the shelf-slope front. The surface area at each 10-m isoline was determined. Two adjoining levels were averaged, then the value was multiplied by 10 m to obtain a volume. This computation was done for all levels containing shelf water.

To estimate the transport of shelf water along each section across the streamers in this study, geostrophic calculations -- relative to the deepest common depth between adjacent stations (generally about 1000 m) -- were used. Joyce *et al.* (1992) demonstrated that the azimuthal circulation in a streamer is generally geostrophic, based on a combined acoustic Doppler current profiler (ADCP)/"tow-yo" CTD section across the active streamer associated with Ring 82-B during June. Transport was estimated by using an average salinity at each depth level between pairs of hydrographic stations, for those stations which effectively described a section across the streamer. When the shelf water - slope water boundary crossed between paired stations for which a calculation was made, an underestimate was possible due to the increased gradient at the front. A total of 26 sections across the streamers were used for these calculations; three other sections were across the shelfbreak.

Inspection of satellite imagery by Chamberlin (1981), Evans *et al*. (1985), and Garfield and Evans (1987) shows that the surface expression of streamers is a common feature and can be viewed for extended periods. However, the balance of mass for continental shelf water and the direct measurement of shelf water features show that the flow of shelf water into streamers is not continuous. It is not clear how long shelf water might remain identifiable within slope water. Occasionally, shelf water can spiral into the center of a ring (Evans *et al.* 1985) and be rapidly mixed. Nevertheless, this is a rare event in the life of a ring. Without this spiraling into the center of the ring or without interaction with the Gulf Stream, the mixing of shelf water with surrounding slope water should be an important process to dissipate the shelf water.

MODELING DISSIPATION OF A STREAMER

To investigate a time scale for dissipation of a streamer by mixing of shelf water within slope water, a two-dimensional diffusion calculation was performed using an idealized model. The model is based on the diffusion of salt across the sides and bottom of a rectangular area. Salinity was chosen to model due to its relatively conservative nature throughout the year (*i.e.*, seasonal variations are relatively small, and a clear contrast between shelf water and slope water can be defined). Correspondence was also good between the surface thermal gradients and salinity gradients sampled on many crossings of the streamer boundary. The diffusion model in two dimensions is

$$\frac{\partial s}{\partial t} = K_h \frac{\partial^2 s}{\partial x^2} + K_z \frac{\partial^2 s}{\partial z^2} \qquad \text{(Eq. 1)}$$

where S is salinity (PSU), K_h is the horizontal diffusivity ($cm^2\ sec^{-1}$), K_z is the vertical diffusivity ($cm^2\ sec^{-1}$), x is the distance across the region (cm), z is the depth (cm), and t is the time (sec). In this model, the third spatial dimension is assumed as infinite (∞). With boundary conditions of $S = 0$ at each boundary for simplicity, no diffusion through the upper boundary, and a constant initial value ($S = S_o$) within the regime, the solution for salinity becomes

$$S(x,z,t) = \frac{8S_0}{\pi^2} \sum_{\substack{m=1 \\ m,n\ odd}}^{\infty} \sum_{n=1}^{\infty} (A)(B)(C)(D)(E) \qquad \text{(Eq. 2)}$$

where $A = \frac{cos(m\pi) - 1}{m}$; $B = \frac{cos(\frac{n\pi}{2}) - 1}{n}$; $C = sin(\frac{m\pi x}{l})$; $D = sin(\frac{n\pi z}{2h})$; $E = e^{-\pi^2(\frac{m^2 k_h}{l^2} + \frac{n^2 k_z}{4h^2})t}$; l is width of the streamer, and h is depth of the streamer. Five parameters are needed for the calculation: S_o, l, h, K_h, and K_z. The initial salinity deficit within the streamer, S_o, was estimated as 2 PSU based on differences in the average salinity within the streamer and surrounding slope water. The width and depth of the streamer, l and h, were set at 40 km and 60 m, respectively. Horizontal diffusivity, K_h, was estimated from the diffusion diagrams presented by Okubo (1971); for a length of 40 km, it was calculated as $4 \times 10^5\ cm^2\ sec^{-1}$. Vertical diffusivity, K_z, was varied as 0.1, 1, 5, and 10 $cm^2\ sec^{-1}$, following the vertical diffusivity parameterizations by Schmitt and Olson (1985). Calculations used a grid having horizontal resolution of 2 km and vertical resolution of 3 m, and covered a 20-day period.

RESULTS AND DISCUSSION

Each ring was at a different stage of maturity and geographic location, and showed various types and intensities of interactions. The following descriptions of shelf water associated with each ring are named by the nearby ring.

STRUCTURE, HYDROGRAPHY, AND VOLUME OF ENTRAINED SHELF WATER IN STREAMERS

Structure and Hydrography

Ring 81-E

Ring 81-E formed about 16 July 1981 (day 197) near 39°N, 63°W, and moved near 40°N, 64°W during mid-September, approximately 120 nm (220 km) southeast of the Northeast Channel (Fitzgerald and Chamberlin 1984). During 16-24 September, Ring 81-E vigorously interacted with a Gulf Stream meander, causing major changes in the ring's structure (Joyce *et al.* 1984). After the transformation of the ring, a survey of most of the streamer was completed between 23 September and 4 October (69-80 days after formation). The position of Ring 81-E during this study's series of stations is in the same area as the ring described by Smith (1978).

The general structure of the streamer is seen in Figure 3a. The thickness of this streamer ranged from >40 m at the northern end, to 12 m at a saddle point at the southern end. At the southern end, the shelf water bifurcated, with one portion with maximum depth of 29 m moving southeastward, and the other portion with maximum depth of 17 m moving westward along the periphery of the ring. Extension of the western portion was defined at the surface by data from the thermosalinograph, and below the surface by XBTs, as the ship moved toward the northwest after Station 68 (Figure 3a). Positions of the boundary were guided by surface temperatures derived from AVHRR images (Figure 3b).

The streamer associated with Ring 81-E was well away from the continental shelf. The surface expression of the shelfbreak front along the continental shelf north of Cape Hatteras generally separates from close association with the underlying topography near the southeast corner of Georges Bank.

Water with Gulf Stream characteristics (*i.e.*, salinity >36 PSU) was measured underneath the shelf water at the southern end. Those measurements confirmed the satellite imagery that showed shelf water moving along the northern side of the Gulf Stream after interaction between the ring and Gulf Stream (Figure 3b).

Typical temperature (T) and salinity (S) values for Station 35 at the northern side and for Station 68 at the southern side, in proximity to the Gulf Stream, showed differences in water characteristics (Figure 3a). The values changed from S = 32.23 PSU and T = 16.8°C on the northern side, to S = 33.86 PSU and T = 18.4°C on the southern side. Also, the subsurface temperature minimum in the shelf water was no longer in the water column on the southern side. The reason for the change in characteristics is not clear, although different sources for the water in the streamer seem likely rather than mixing, if the events develop over approximately 3-5 days.

Ring 82-A

Ring 82-A formed around 15 January 1982 (day 15) about 110 nm (210 km) southeast of Corsair Canyon (Celone and Price 1985). During April, the ring interacted with a meander of the Gulf Stream, was transformed, and moved eastward (Celone and Price 1985). A new ring, Ring 82-D, formed to the south of Ring 82-A during the last half of April, and exchanged water with Ring 82-A, finally destroying Ring 82-A on 2 May 1982 (day 122). At the time of the survey of the streamer, during 22-27 April (97-102 days after formation), the ring was centered near 39°30'N, 66°30'W, off the southern side of Georges Bank.

The prominent feature of the streamer associated with Ring 82-A was a bowl of shelf water, >75 m thick at the deepest point, nearly separated from the shelf water source (Figure 4a). The series of satellite images during the survey period (Figure 4b) showed slope water moving counter-clockwise/cyclonically around the northern side of the streamer. It finally surrounded shelf water at the surface, agreeing with the station and surface thermosalinograph data collected earlier during the process of separation.

The temperature and salinity values for a station within the center of the entrained shelf water, Station 8, and at the shelf end of the connecting neck, Station 27 (Figure 4a), both showed a subsurface temperature minimum in shelf water, which was cooled during winter and then became isolated by vernal warming. Temperature and salinity within the streamer, T = 5.51°C and S = 32.89 PSU, were in the range of nearby shelf water.

Ring 82-B – First Visit

Ring 82-B was formed on 14 February 1982 (day 45) near 40°N, 68°25W, to the west of the New England Seamount Chain and farther west than most rings previously monitored (Celone and Price 1985), including Ring 82-A. Movement was westward until the end of March when the motion stalled between Block Canyon and Hudson Canyon where the orientation of the continental shelf changes from east-west to northeast-southwest. During this period no interaction occurred with other rings or the Gulf Stream.

The streamer was surveyed between 28 April and 3 May 1982 (73-78 days after formation). During this time, the shelf water within the streamer was generally in a layer <30 m thick over slope water, except for a layer >50 m thick in the northeast corner (Figure 5a). Although the entire streamer was not sampled due to time constraints, indications from satellite imagery were that the shallow layer extended further to the west along the southern side of the ring (Figure 5b).

Temperatures and salinities for one station in the northeast corner of the streamer, Station 39, and at the southern end of the area sampled, Station 59 (Figure 5a), both showed salinity near the transition between shelf water and slope water (S = 33.73 PSU for Station 39 and S = 33.99 PSU for Station 59). The surface temperature at the southern station was about 0.5°C higher.

Again, there was no way to resolve from these data the different sources for the streamer and the local diffusion of salt and heat into the streamer causing property changes. The lack of a subsurface temperature minimum and the salinities near 34 PSU indicate a relatively quiescent period without significant interaction with the nearby shelf. Also, current vectors were alongshelf on 29 April, potentially blocking the source of shelf water (see Ramp (1986), Figure 20).

The greater depth of water with salinity ≤34 PSU at Stations 34 and 39 (Figure 5a) can be interpreted as a new active outbreak of shelf water into slope water. This interpretation is supported by the thermal imagery on 30 April and 1 May (Figure 5b), and also by the daily current vectors with offshore directions (see Ramp (1986), Figure 21).

Ring 82-B – Second Visit

Between early May and the last half of June, Ring 82-B moved along the continental slope to a position southeast of Delaware Bay. An extensive survey of the streamer (including a closely sampled section in cooperation with other vessels) and adjoining waters over the continental shelf was carried out between 21 and 29 June (127-135 days after formation).

The greatest horizontal extent at the surface (approximately 90 nm, 145 km), depth of a layer with salinity ≤34 PSU (>80 m at Stations 65, 20, and 21), and volume of entrained shelf water were found in this streamer (Figures 2c and 6a). A prominent saddle point was observed where the layer of shelf water was only 20 m thick, as in Ring 81-E, and previously in Ring 81-B.

At Station 28 at the southern end of the streamer (Figure 6a), the surface temperature was slightly warmer (T = 17.04 vs. 16.64°C), and the surface salinity was slightly higher (S = 32.87 vs. 32.67 PSU) than at Station 65 at the 200-m isobath near the center of the streamer. An AVHRR image for a time during the CTD stations is shown in Figure 6b. At the subsurface temperature minimum, the water at Station 28 was both slightly cooler and slightly fresher than that at Station 65. Surface temperature and salinity values for Stations 65, 20, and 21 (Figures 2c and 6a) were T = 16.64, 16.27, and 15.87°C, and S = 32.67, 32.73, and 32.83 PSU, respectively. The temperatures at the transition from shelf water at those three stations were T = 9.10, 9.42, and 9.50°C, respectively. These data suggest rapid movement from the continental shelf without significant mixing.

Volume of Entrained Shelf Water

The estimated volume for each streamer is presented in Table 1. The values were between 58 km^3 for the nearly detached streamer associated with Ring 82-A, and 290 km^3 for the streamer associated with Ring 82-B during June.

Each estimate, except for Ring 82-A, was a minimum since there was an area at the southern end containing shelf water that was not sampled. By comparing the shelf water determined from hydrography with the available satellite images for the same time, an underestimate of volume by 10-15% seems likely, but caution must be used since the subsurface structure of a streamer, which is highly variable in these four cases, must be extrapolated from the surveyed region.

Variability in Streamer Structure and Volume of Entrainment

Description of the hydrographic properties of shelf-water streamers provides one view of the variability in the structure and volume of entrained water in these streamers (Figures 3a-6a). Each streamer had a region where the depth of shelf water was at least 40 m, and for the streamer associated with Ring 82-B during June, the depth reached >80 m both near the shelfbreak and at the southern end.

In each streamer, there was a saddle point where the layer of shelf water reached a minimum thickness within the streamer. This saddle point can be striking as in Ring 82-B during June, or relatively subtle as in Ring 82-B during April, but each such saddle point indicates variations in the flow of shelf water associated with WCRs.

The encircling of shelf water by slope water (*i.e.*, thinning of the depth at the saddle point to zero) as seen in the streamer associated with Ring 82-A is the first known report of the isolation of a relatively large mass (30 nm (55 km) in diameter, 60 km^3 in volume) of largely unaltered shelf water within slope water, based on data collected in-situ. There have been other indications of streamers and eddies at the shelf-slope front causing losses of shelf water, but at smaller scales (Houghton *et al.* 1986; Garvine *et al.* 1988).

TRANSPORT OF SHELF WATER BY STREAMERS AND DISSIPATION IN SLOPE WATER

Transport

The overall mean transport of shelf water away from the continental shelf (*i.e.*, for those 21 sections with transport in the same direction as the near-surface circulation of the associated WCR) was 165 x 10^3 m^3 sec^{-1}, with a standard deviation of 149 x 10^3 m^3 sec^{-1}. The overall mean transport for the 19 sections with transport of shelf water in the opposite direction as the near-surface circulation of an associated WCR was 62 x 10^3 m^3 sec^{-1}, with a standard deviation of 90 x 10^3 m^3 sec^{-1}. Table 2 shows offshore transport across sections ranging from 0 to 488 x 10^3 m^3 sec^{-1}. Onshore transports ranged from 0 to 344 x 10^3 m^3 sec^{-1}. The streamer associated with Ring 82-B during June was the most active in removing shelf water.

Dissipation

Based on the two-dimensional model for salt diffusion, the average salinity within the streamer for K_z = 1 cm^2 sec^{-1} was halved, but did not quite reach the S_o/e value (0.74), at 14 days (Figure 7). The average salinity for K_z = 5 cm^2 sec^{-1} was halved just before 8 days, and reached the S_o/e value at 12 days. Note that for a streamer with a given width and depth, these time scales are valid for any initial salinity value within the boundaries, since the decay depends only on the values of K_h and K_z (Equation 2).

Cross sections of the salinity differences are shown at 10 and 20 days in Figure 8. Several points become clear by using a salinity deficit of 1 PSU as a conservative indicator of the recognizable streamer. At 10 days, there was water with shelf characteristics clearly seen at the surface for all values of K_z from 0.1 to 10 cm^2 sec^{-1}. The width of shelf water at the surface was at least one-half of the original dimension for all values of K_z. The depth of shelf water was at least two-thirds of the original dimension for K_z = 5 cm^2 sec^{-1}, and was one-half of the original dimension for K_z = 10 cm^2 sec^{-1}. At 20 days, this streamer was still recognizable at the surface for values up to K_z = 5 cm^2 sec^{-1}. Calculations for both K_z = 0.1 and 1 cm^2 sec^{-1} showed a substantial section of shelf water that was 24 km in width and at least 44 m in depth, little changed in 20 days from the initial condition.

The calculation for diffusion of salt indicates that a streamer of shelf water relatively isolated within slope water would remain cohesive for 2-3 wk in the absence of advective shearing processes or strong air-sea interaction with mixing. Moreover, this streamer could be viewed from satellites even when the original cross section of the streamer has been eroded to a large extent, thereby complicating interpretations based solely or primarily on thermal imagery.

Geostrophic Considerations

It was assumed that the balance of geostrophic forces was the cause for movement, and thus the basis for calculating the velocity and transport, of streamers. Any high-frequency vertical variations of the density field could not be detected based on the sampling scheme, and are an unknown source of error.

One comparison between calculated geostrophic velocities and directly measured velocities was possible. The section sampled by Joyce *et al.* (1992) was concurrent and nearly parallel with Stations 17-25 sampled on 23 June 1982 in this study (Figures 2c (inset) and 9). Calculated velocities for this study were plotted for the 20- and 100-m levels to the same scale as the measured velocities in the Joyce *et al.* (1992) study. (Shallow CTD casts were required in the Joyce *et al.* (1992) study in order to keep up with the second ship as it crossed the streamer.) Vertical shear compares well, changing signs at Station 21 from a subsurface maximum west of the station to a surface maximum east. The lower velocities and occasional reversals in the geostrophic calculation can be at least partially explained by the shallow level of no motion (300 m) for this section, by the inherent averaging in the geostrophic calculations, by the orientation of stations that are not perpendicular to the measured current, and by the spatial variations within the streamer.

Transport by salinity classes estimated by these geostrophic calculations (Table 3) can also be compared with those direct measurements obtained by Joyce *et al.* (1992). The transport of shelf water ($S \leq 34$ PSU) calculated geostrophically for Stations 17-25, 408 x 10^3 m^3 sec^{-1}, is 32 x 10^3 m^3 sec^{-1} higher than that obtained by direct measurement. This difference could be partially caused by low salinity water not being sampled at the western end of the Joyce *et al.* (1992) section. The difference of 9% between these methods, in spite of the shallow reference level and slightly different sections, gives confidence that other transport calculations are reasonable for an overall characterization. The deficit in geostrophic transport for salinities between 34 and 35 PSU appears to be caused by the greater measured velocities at 100 m and the greater intrusion of water with salinity >34 PSU at the western end of the Joyce *et al.* (1992) section. In spite of the range of potential errors, the differences between geostrophic calculations and direct measurements are considered reasonable, and geostrophic calculations are considered acceptable for estimating velocity and transport of entrained shelf water.

SOURCE OF ENTRAINED WATER IN STREAMERS

Various modeling and observational studies using current meters (*e.g.*, Beardsley *et al.* 1985; Ramp 1986; Wang 1992) indicate that the waters of the continental shelf are generally buffered from the passage of WCRs. Yet significant amounts of shelf water (Table 1) were found to be entrained within the streamers associated with this study's rings. The hydrographic data collected during this study's series of cruises provided sufficient spatial resolution to examine the proximate source of water for the streamers.

The most prominent characteristic of the Middle Atlantic Bight during the stratified season (*i.e.*, April-September) is the continuous subsurface band of cold water found along the outer continental shelf (OCS), with its core found along the bottom between 50 and 80 m (Houghton *et al.* 1982). The low temperature and associated low salinity of cold band water are distinct, permitting the unambiguous identification of cold band water if present within a streamer. Alternatively, the absence of cold band characteristics in a streamer requires a source seaward of the cold band for active streamers.

The data collected for the streamer associated with Ring 82-B during June were examined for the presence or absence of cold band characteristics in order to determine the sources of shelf water within the streamer. The temperature and salinity structure on the shelf adjacent to the streamer associated with Ring 82-B during June is shown for three sections which were nearly perpendicular to the local bathymetry (Figures 2c, 6a, and 10-12). The cold band is prominent, with temperatures below 7°C and salinities generally between 32.75 and 33.00 PSU. Note that in the surface layer, salinities below 33.00 PSU extended further seaward only with temperatures above 8°C. A section across the streamer (Figure 13b) showed that only two stations off the continental shelf, Stations 48 and 50 (Figures 2c and 6a), had water with a subsurface salinity minimum below 33.00 PSU. At Station 48, there were two occurrences of water, each more than 3 m thick, separated from each other by about 5 m, and located about 23 and 35 m of depth. Temperatures of 9.0-9.5°C were associated with the upper occurrence, and 8.0-8.5°C with the lower occurrence. At Station 50, there was an occurrence of water about 2 m thick, located between about 28 and 30 m of depth, with a temperature of 7°C. The outcome is that the source of shelf water for the streamer is above the OCS, generally seaward of the cold band. The plume-like structure of the cold band detached from the bottom may occasionally contribute, but in small volume, according to these data. This inference contrasts with the inference of Churchill *et al.* (1986).

Other data also support this present inference. For the streamer associated with Ring 82-B during April, the salinity was entirely above 33.00 PSU except for a surface layer at Station 34 (Figures 2b and 5a) that was 7 m thick. For the nearly-isolated bowl of shelf water associated with Ring 82-A, there was considerable water with temperature below 6°C and salinity below 33.00 PSU (Figures 2b, 4a, and 14). However the source of the water was still from the OCS, as shown in Figure 15 for Stations 24-28 in Figure 2b, since stratification from vernal warming formed a cold band having minimum temperatures below 4.5°C and salinities below 32.75 PSU. For the streamer associated with Ring 81-E, the data are consistent with a source above the OCS and generally seaward of the cold band, but the interpretation is equivocal because both the ring and interacting shelf water are well seaward of the continental shelf.

DYNAMIC BEHAVIOR OF STREAMERS

Each survey of streamers associated with WCRs seemed to give a unique result except for the observation of a saddle point at some distance along the streamer. The presence of a nearby continental shelfbreak was not required. For example, the streamer associated with Ring 81-E during September 1981 was well away from the continental slope, yet entrained at least 131 km^3 of shelf water. The strength of interaction, defined by the amount of shelf water within slope water, did not depend on the age, and therefore energy, of the ring. For example, the most intense observed streamer was during late June 1982 associated with Ring 82-B after this ring had traversed along the continental slope from its formation south of Nantucket to southeast of Delaware Bay, about 130 days after formation. Also as an example, significant interaction occurred with a small ring, Ring 82-A, within a week of its demise.

The idealized results of Wang (1992) were used to merge the seemingly disparate descriptions of this study's streamers. In Wang (1992), a series of models generate results with which to examine the interaction of an eddy with topography resembling a continental slope. The first model is based on a step in topography (*i.e.*, small escarpment) and point vortex under quasigeostrophic conditions, which is then expanded to a finite step and vortex. The fluid in the model is assumed to be barotropic and frictionless in a rotating coordinate system with a rigid lid. Contour dynamics are used in the solutions to the model, giving similar principal results in both cases: 1) ageostrophic nonlinear advection of fluid across the escarpment, 2) formation of a cyclonic eddy containing shelf water offshore, and 3) excitation of waves trapped against the escarpment. The second model, which incorporates a semispectral primitive equation model developed by Haidvogel *et al.* (1991), uses the same basic equations, including bottom friction, but with three different cross-shelf exponential topographies, in order to generate results on the f and ß-planes. Wang (1992) concluded that there were "no fundamental differences in shelf/slope responses and cross-slope exchanges between the results of these two models." The initial tongue of entrained shelf water with high potential vorticity evolves into a narrow streamer and eddy (Wang 1992). The eddy at the head of the streamer is formed from fluid with cyclonic vorticity continually entering after being compressed between the vortex and the anticyclonic field north of the tongue. The saddle point between the eddy and the rest of the streamer is formed at the point of greatest compression just inshore of the eddy. For example, Ring 82-B during June has a deep pool of low-salinity water at the southern end, and a narrowing toward the continental shelf (Figure 6). The cyclonic circulation of the eddy then continues constricting the streamer, eventually detaching as in Ring 82-A (Figure 4).

Cyclonic eddies located within entrained shelf water have been interpreted from satellite imagery (*e.g.*, Evans *et al.* 1985; Ramp 1986), and those located northeast of WCRs have been interpreted from ADCP data (Kennelly *et al.* 1985). This study's data and the modeling by Wang (1992) provide evidence that not only were curvilinear streamers and cyclonic eddies dynamically linked with entrainment, but also those eddies northeast of the ring. For example, the second lobe of shelf water to the northeast of Ring 82-B during April (Figure 5a) corresponds to the evolution of a cyclonic eddy.

The extent to which the assumption of a barotropic fluid by Wang (1992) describes the observed entrainment could be problematic, depending on the vertical scale chosen for the comparison. To illustrate, consider Ring 82-B; it was distinguishable at a depth of 2000 m during June after moving along the continental slope for about 4 mo (*e.g.*, Kennelly *et al.* 1985). Figure 16a shows the geostrophic velocity for the 0-300 m depth range, relative to approximately 1000 m, for Stations 6-11 (Figures 2c and 6a) across the streamer associated with Ring 82-B during June. Within the depth range corresponding to shelf water, 65 m (Figure 16b), the ring could be considered radially barotropic (*i.e.*, little vertical shear at a given distance from the center). Although the velocity is somewhat intensified near the surface for the region with shelf water, below 100 m, all velocities are <10 cm sec^{-1}, and vertical shear in the velocity field above 1000 m is small. Therefore, by choosing a vertical scale of approximately 300 m, qualitative comparisons for the interaction between a barotropic vortex and shelf water seems reasonable, if not complete, for the level of comparison presented here.

CONCLUSIONS

Data have been analyzed to describe the interaction between WCRs (*i.e.*, 81-E, 82-A, and 82-B during April and June) and shelf water, leading to entrainment of shelf water along the trailing edge of WCRs as they move generally southwest in slope water. In-situ data of this resolution have not been described before.

The short-term estimated volumes of entrained shelf water (*i.e.*, salinities ≤ 34 PSU) were 58-290 km^3. An underestimate of 10-15% was likely for all but the nearly enclosed bowl of shelf water associated with Ring 82-A, since the entrainment was not circumscriptively sampled in other cases.

Geostrophically calculated transports of shelf water in the direction of the anticyclonic circulation of an associated WCR were 0-488 x 10^3 m^3 sec^{-1} (mean = 165 x 10^3 m^3 sec^{-1}; standard deviation = 149 x 10^3 m^3 sec^{-1}). Transports in the opposite direction were 0-345 x 10^3 m^3 sec^{-1} (mean = 62 x 10^3 m^3 sec^{-1}; standard deviation = 90 x 10^3 m^3 sec^{-1}). These transport estimates are thought to be reasonable, based on a comparison between geostrophic calculations and ADCP/"tow-yo" CTD measurements taken concurrently during a two-ship crossing of an active streamer during June 1982 associated with Ring 82-B. Changes in the direction of flow are probably a consequence of cyclonic eddies that develop within entrained water.

Analysis of temperature and salinity sections indicates that the shelf water supplying streamers comes primarily from the outer edge of the continental shelf, seaward of the cold band. Since the source of shelf water for streamers is distributed along the shelfbreak for considerable distances rather than being limited to an area nearby, the majority of the continental shelf is, therefore, isolated from direct influence by passage of rings. This finding confirms results of prior studies which measured in detail the temperature and salinity structure and currents across the shelf as WCRs passed.

If the mean seaward extent of the cold band is the 100-m contour (Houghton *et al.* 1982), and if the mean position of the shelf-slope front is anchored at the 100-m contour and intersects the surface 40 km seaward (Beardsley *et al.* 1985), then the ratio of the volume (km^3) of shelf water in a streamer to the length (km) of shelfbreak supplying water to the streamer is 2:1. This ratio results in a range of 29-145 km along the shelfbreak for supplying shelf water to the streamers in this study. It therefore seems plausible to use calculated volumes of streamers to determine the lengths of shelfbreak affected by entrainment.

Being able to consistently and generally interpret the data with modeling is an encouraging, but problematic, accomplishment, given the ideal assumptions of the model -- particularly a barotropic ocean -- and the variability of the strictly nonsynoptic hydrographic data. One puzzling aspect, at least, remains: the streamer associated with Ring 81-E during September 1981 (Figure 3a). Since the presence of an adjacent continental shelf was apparently not required to initiate this streamer, the model by Wang (1992) cannot directly apply in this case. Therefore, other processes should be important in explaining the initiation of entrainment by WCRs at different stages in the history of those rings.

One possible explanation for this “continental-shelf-free” initiation of entrainment are growing frontal waves which are due to horizontal-shear instability on the northern periphery of a WCR, and which then “break” to subsequently become entrained by that ring (Ramp *et al.* 1983). Such frontal waves were observed for a number of days on the periphery of Ring 82-B based on AVHRR images, but the final fate of those waves was not observed due to clouds. The position of the horizontal-shear instability was close to the anticyclonic advection of an eddy on the periphery of Ring 82-B, as interpreted from sequential satellite images (Kennelly *et al.* 1985, Figure 8b). Also, the AVHRR image for Ring 82-B on 30 April 1982 (Figure 5b) supports those observations.

Conceptually, a combination of curvilinear streamers on the periphery, and cyclonic eddies which may remain coherent for 2-3 wk, can describe the observed structure for entrainment by WCRs. Evidence from this study’s data and from the modeling supports this concept. Clearly, further investigation is needed to understand the initiation and evolution of these streamers.

A major goal of this study was to examine the possibility that passage of WCRs could affect recruitment of commercially important fish species during the larval stage. Distributions of larval fish have been portrayed by many authors for the continental shelf between Cape Hatteras and Nova Scotia (*e.g.*, Grosslein and Azarovitz 1982; Morse *et al.* 1987). These portrayals show that the maxima in the general distributions of larvae are well inshore of the 200-m isobath, although bias may occur due to limited sampling near the offshore boundaries. Since the direct measurements and analyses of water masses in this study indicate that the onshore influence of WCRs is about the 100-m isobath, then the potential for significant mortality caused by entrainment of shelf water, as a single process, seems unlikely. Earlier modeling by Flierl and Wroblewski (1985) and statistical analysis by Myers and Drinkwater (1989) had linked WCRs with reduced recruitment of fish. Flierl and Wroblewski (1985) recognized, however, that the results of their model, averaged across the shelf and also vertically, would not be applicable if entrainment were limited near the shelf break.

Detailed analysis of the biological samples collected concurrently during this study’s series of cruises was not possible except for the analysis by Le Blanc (1986). Le Blanc (1986) reported that larvae of fish species normally spawned on the continental shelf were sampled in the entrained shelf water associated with Ring 82-B during June. A quantitative assessment of the impact upon those species’ populations was not attempted, though. Unfortunately, other biological samples for the series of cruises were lost.

ACKNOWLEDGMENTS

These data were originally collected as part of the Warm-Core Experiment in 1981 and 1982. Thanks go to all who participated during the series of cruises, particularly the officers and crew of the *Albatross IV*. Their dedication to the success of data collection made these analyses possible.

REFERENCES CITED

Bisagni, J.J. 1983. Lagrangian current measurements within the eastern margin of a warm-core Gulf Stream ring. *J. Phys. Oceanogr.* 13:709-715.

Beardsley, R.C.; Chapman, D.C.; Brink, K.H.; Ramp, S.R.; Schlitz, R. 1985. The Nantucket Shoals Flux Experiment (NSFE79). Part I: a basic description of the current and temperature variability. *J. Phys. Oceanogr.* 15:713-748.

Celone, P.J.; Price, C.A. 1985. Anticyclonic warm-core Gulf Stream rings off the northeastern United States during 1982. *Ann. Biol.* 39:19-23.

Chamberlin, J.L. 1981. Application of satellite infrared data to analysis of ocean frontal movements and water mass interactions off the Northeast coast. *NAFO* [Northwest Atl. Fish. Org.] *SCR* [Sci. Counc. Res.] *Doc.* 81/IX/123; 15 p.

Churchill, J.H.; Cornillon, P.C.; Milkowski, G.W. 1986. A cyclonic eddy and shelf-slope water exchange associated with a Gulf Stream warm-core ring. *J. Geophys. Res.* 91:9615-9623.

Evans, R.; Baker, K.; Brown, O.; Smith, R.; Hooker, S.; Olson, D.; Warm Core Rings Program Service Office. 1984. Satellite images of warm core ring 82-B sea surface temperature and a chronological record of major physical events affecting ring structure. Unpublished document. Available *from*: R.J. Schlitz, National Marine Fisheries Serv., Woods Hole, MA.

Evans, R.H.; Baker, K.S.; Brown, O.B.; Smith, R.C. 1985. Chronology of warm-core ring 82B. *J. Geophys. Res.* 90:8803-8811.

Fitzgerald, J.L.; Chamberlin, J.L. 1984. Anticyclonic warm-core Gulf Stream rings off the northeastern United States in 1981. *Ann. Biol.* 38:29-33.

Flierl, G.R.; Wroblewski, J.S. 1985. The possible influence of warm core Gulf Stream rings upon shelf water larval fish distribution. *Fish. Bull. (Wash., D.C.)* 83:313-330.

Fornshell, J.A.; Criess, W.A. 1979. Anticyclonic eddy observations in the slope water aboard CGC *Evergreen*. *J. Phys. Oceanogr.* 9:992-1000.

Garfield, N., III; Evans, D.L. 1987. Shelf water entrainment by Gulf Stream warm-core rings. *J. Geophys. Res.* 92:13003-13012.

Garvine, R.W.; Wong, K.-C.; Gawarkiewicz, G.G.; McCarthy, R.K. 1988. The morphology of shelfbreak eddies. *J. Geophys. Res.* 93:15593-15607.

Grosslein, M.D.; Azarovitz, T.R. 1982. Fish distribution. *MESA (Mar. Ecosyst. Anal.) N.Y. Bight Atlas Monogr.* 15; 182 p.

Haidvogel, D.B.; Wilkin, J.L.; Young, R.E. 1991. A semi-spectral primitive equation ocean circulation model using vertical sigma and orthogonal curvilinear horizontal coordinates. *J. Comput. Phys.* 94:151-185.

Houghton, R.W.; Olson, D.B.; Celone, P.J. 1986. Observations of an anticyclonic eddy near the continental shelf break south of New England. *J. Phys. Oceanogr.* 16:60-71.

Houghton, R.W.; Schlitz, R.; Beardsley, R.C.; Butman, B.; Chamberlin, J.L. 1982. The Middle Atlantic Bight cold pool: evolution of the temperature structure during summer 1979. *J. Phys. Oceanogr.* 12:1019-1029.

Iles, T.D.; Sinclair, M. 1982. Atlantic herring: stock discreteness and abundance. *Science* 215:627-633.

Joyce, T.M. 1985. Gulf Stream warm-core ring collection: an introduction. *J. Geophys. Res.* 90:8801-8802.

Joyce, T.; Backus, R.; Baker, K.; Blackwelder, P.; Brown, O.; Cowles, T.; Evans, R.; Fryxell, G.; Mountain, D.; Olson, D.; Schlitz, R.; Schmitt, R.; Smith, P.; Smith, R.; Wiebe, P. 1984. Rapid evolution of a Gulf Stream warm-core ring. *Nature* 308:837-840.

Joyce, T.M.; Bishop, J.K.B.; Brown, O.B. 1992. Observations of off-shore shelf-water transport induced by a warm-core ring. *Deep-Sea Res.* 39(suppl.):S97-S113.

Joyce, T.; Wiebe, P. 1983. Warm-core rings of the Gulf Stream. *Oceanus* 26:34-44.

Kennelly, M.A.; Evans, R.H.; Joyce, T.M. 1985. Small-scale cyclones on the periphery of a Gulf Stream warm-core ring. *J. Geophys. Res.* 90:8845-8857.

Le Blanc, P.R. 1986. The distribution and abundance of larval and juvenile fishes in shelf water entrained by warm-core ring 82-B and contiguous water masses. [M.S. thesis.] Dartmouth, MA: Southeastern Massachusetts Univ.; 143 p.

Morgan, C.W.; Bishop, J.M. 1977. An example of Gulf Stream eddy-induced water exchange in the Mid-Atlantic Bight. *J. Phys. Oceanogr.* 7:472-479.

Morse, W.W.; Fahay, M.P.; Smith, W.G. 1987. MARMAP surveys of the continental shelf from Cape Hatteras, North Carolina, to Cape Sable, Nova Scotia (1977-1984). Atlas No. 2. Annual distribution patterns of fish larvae. *NOAA* [Natl. Ocean. Atmos. Admin.] *Tech. Memo. NMFS* [Natl. Mar. Fish. Serv.]-*F/NEC*-47; 215 p.

Myers, R.A.; Drinkwater, K. 1989. The influence of Gulf Stream warm core rings on recruitment of fish in the Northwest Atlantic. *J. Mar. Res.* 47:635-656.

Okubo, A. 1986. Oceanic diffusion diagrams. *Deep-Sea Res.* 18:789-802.

Ramp, S.R.. 1986. The interaction of warm core rings with the shelf water and shelf/slope front south of New England. [Ph.D. thesis.] Narragansett, RI: Univ. of Rhode Island; 137 p.

Ramp, S.R. 1989. Moored observations of current and temperature on the shelf and upper slope near ring 82B. *J. Geophys. Res.* 94:18071-18087.

Ramp, S.R.; Beardsley, R.C.; Legekis, R. 1983. An observation of frontal wave development on a shelf-slope/warm core ring front near the shelf break south of New England. *J. Phys. Oceanogr.* 13:907-912.

Richardson, P.L. 1983. Gulf Stream rings. *In:* Robinson, A.R., ed. Eddies in marine science. New York, NY: Springer-Verlag; p. 19-64.

Schlitz, R.J.; Manning, J.P.; Smith, K.W. 2001. Structure and transport of alongshelf currents across the southern flank of Georges Bank during late summer, 1982. *Deep-Sea Res. II* 48:341-372.

Schmitt, R.W.; Olson, D.B. 1985. Wintertime convection in warm-core rings: thermocline ventilation and the formation of mesoscale lenses. *J. Geophys. Res.* 90:8823-8837.

Smith, P.C. 1978. Low-frequency fluxes of momentum, heat, salt, and nutrients at the edge of the Scotian Shelf. *J. Geophys. Res.* 83:4079-4096.

Walford, L.A. 1938. Effects of currents on distribution and survival of the eggs and larvae of the haddock (*Melanogrammus aeglefinus*) on Georges Bank. *Bull. U.S. Bur. Fish.* 49; 73 p.

Wang, X. 1992. Interaction of an eddy with a continental slope. [Ph.D. thesis.] Woods Hole, MA: MIT/WHOI [Mass. Inst. Technol./Woods Hole Oceanogr. Inst.] Joint Program in Oceanography; 216 p.

Warm-Core Rings Executive Committee. 1982. Multidisciplinary program to study warm core rings. *Eos* 63:834-835.

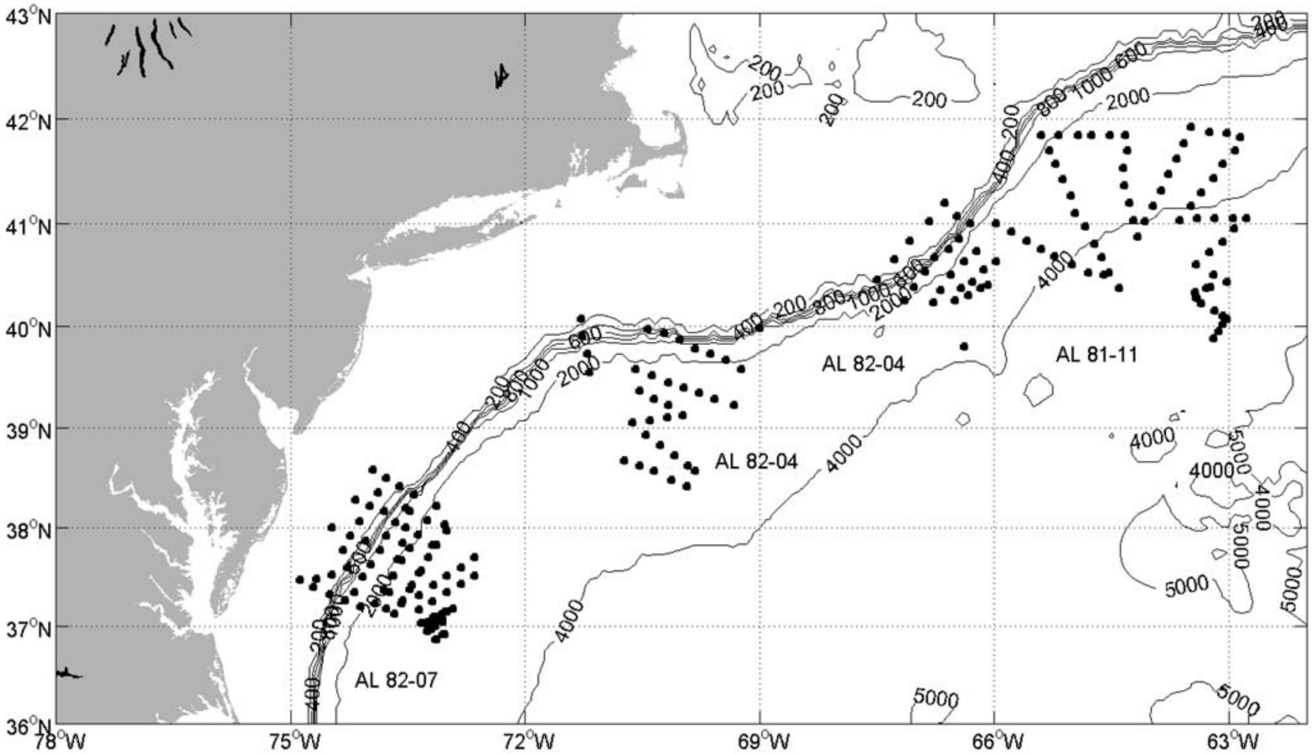

Figure 1. Positions of all stations during the major cruises of the Warm Core Rings Program. (Cruise numbers are proximate to the stations of the respective cruises. Squares represent positions at which CTD casts were completed. Depth contours are in meters.)

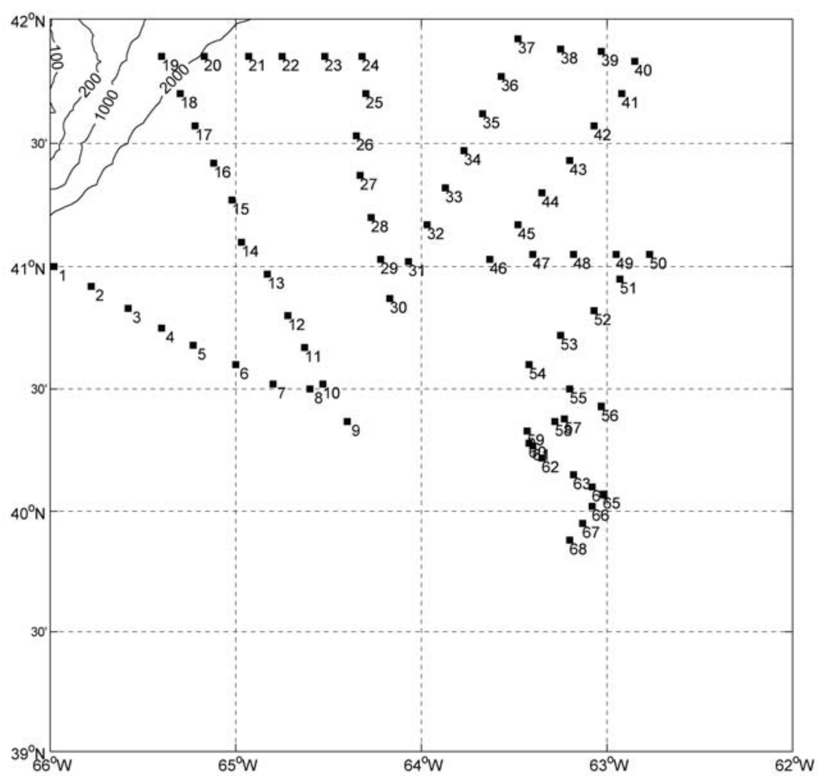

Figure 2a. Positions of stations at which CTD casts were completed on *Albatross IV* Cruise No. AL 81-11 during 22 September - 6 October 1981. (Depth contours are in meters.)

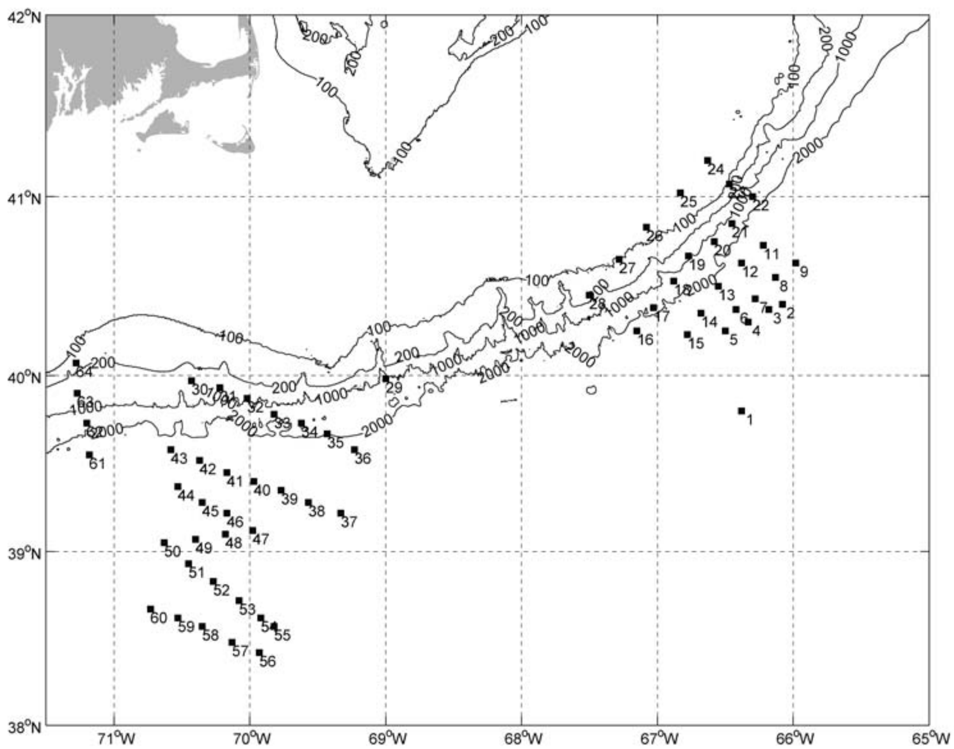

Figure 2b. Positions of stations at which CTD casts were completed on *Albatross IV* Cruise No. AL 82-04 during 19 April - 4 May 1982. (Depth contours are in meters.)

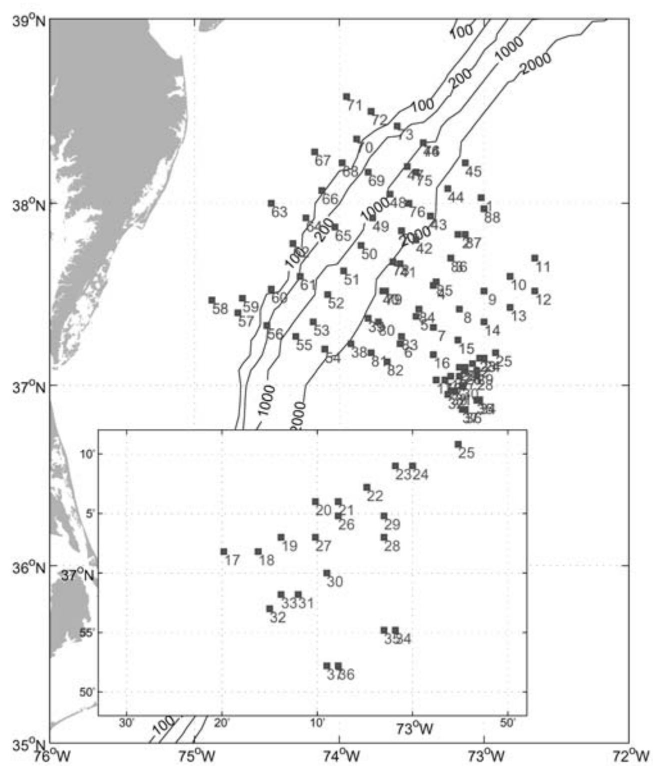

Figure 2c. Positions of stations at which CTD casts were completed on *Albatross IV* Cruise No. AL 82-07 during 17 June - 2 July 1982. (Inset shows closeup view of Stations 17-37. Depth contours are in meters.)

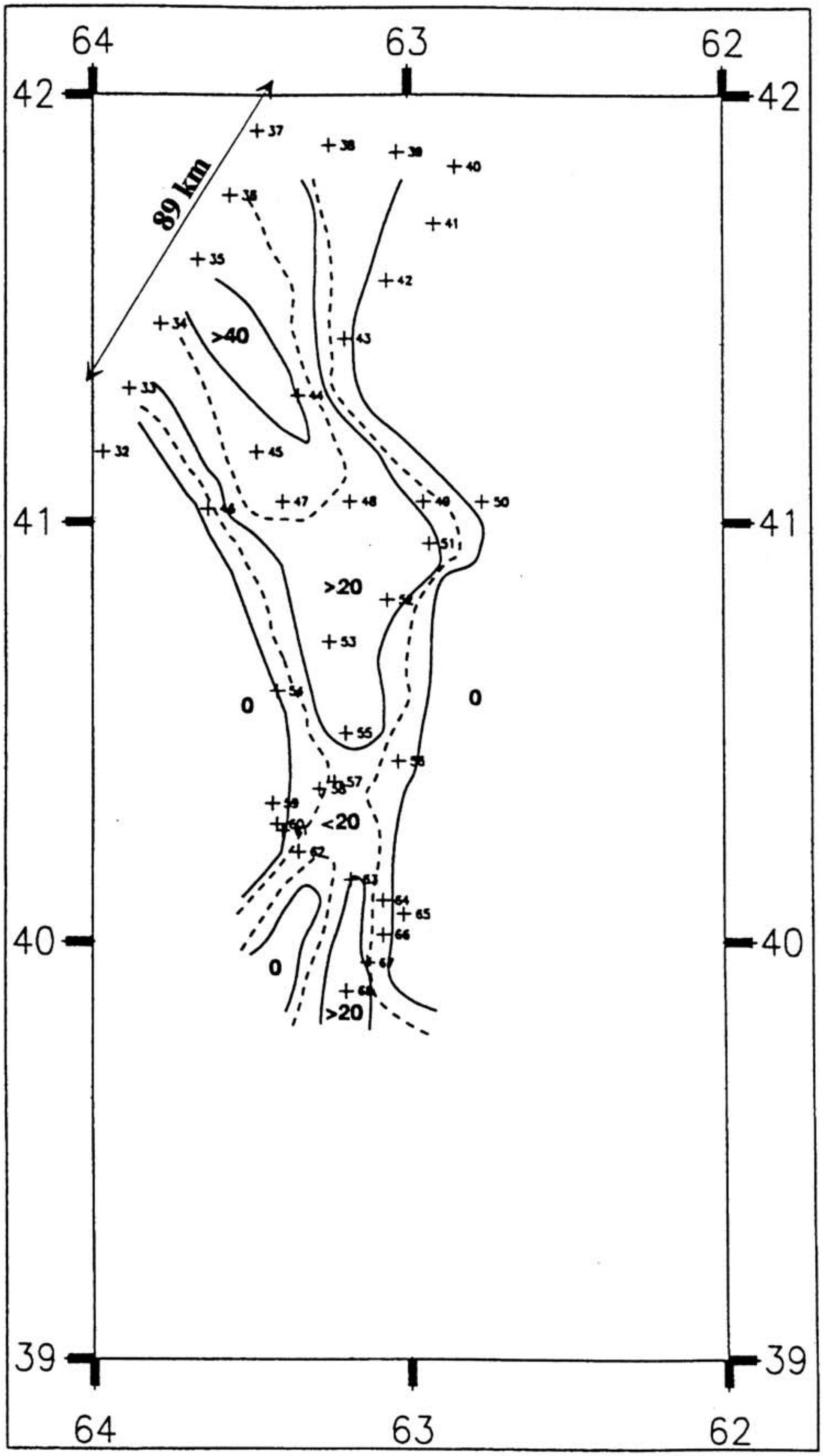

Figure 3a. Depth of a layer from the surface (portrayed with 10-m contours) containing shelf water (salinity ≤34 PSU) entrained by Ring 81-E. (Data were collected on *Albatross IV* Cruise No. AL 81-11 during 23 September - 4 October 1981.)

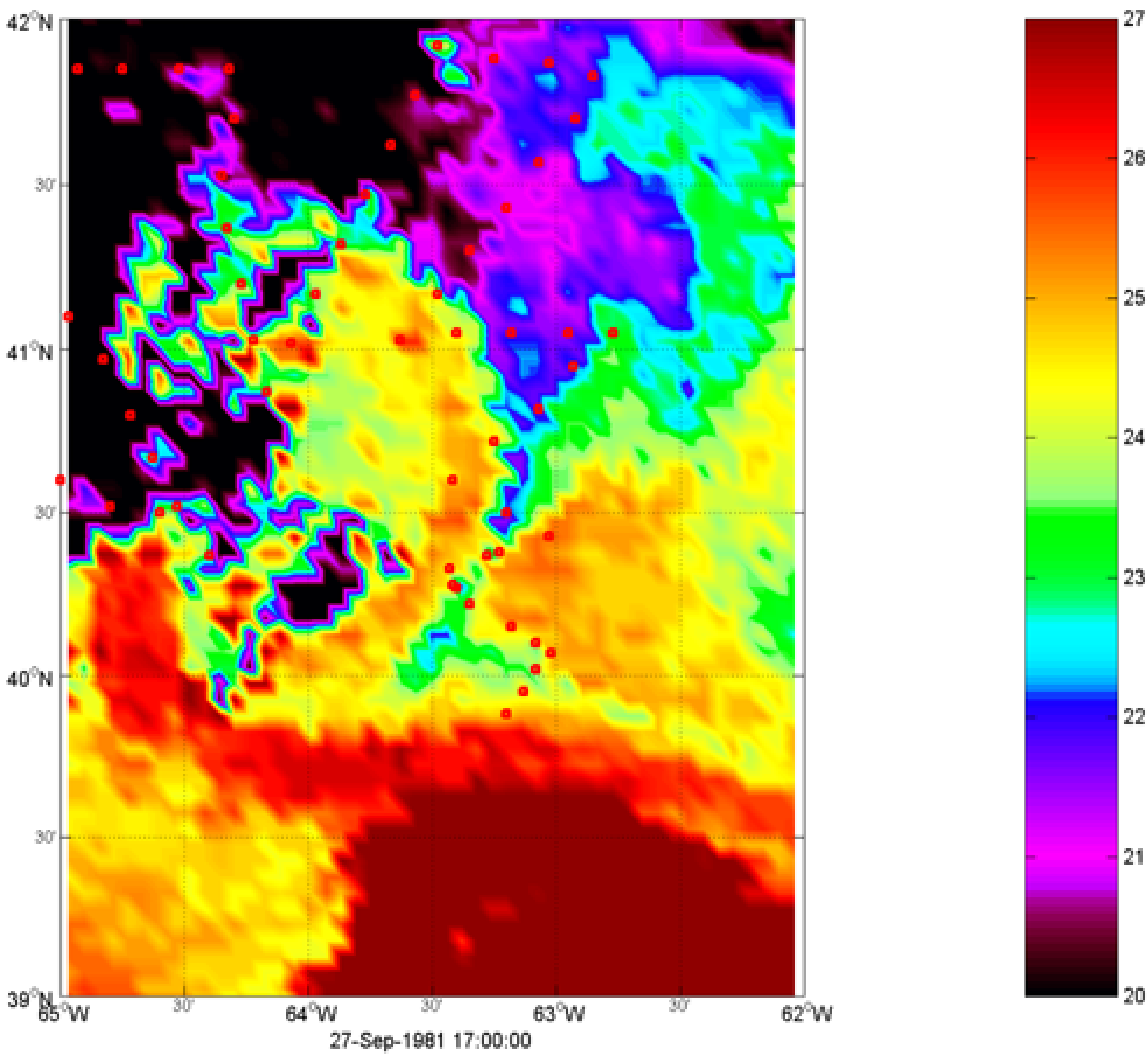

Figure 3b. An AVHRR image for 27 September 1981 showing temperature expression at the surface for shelf water entrained by Ring 81-E. (Clouds are present over the western half of the ring.)

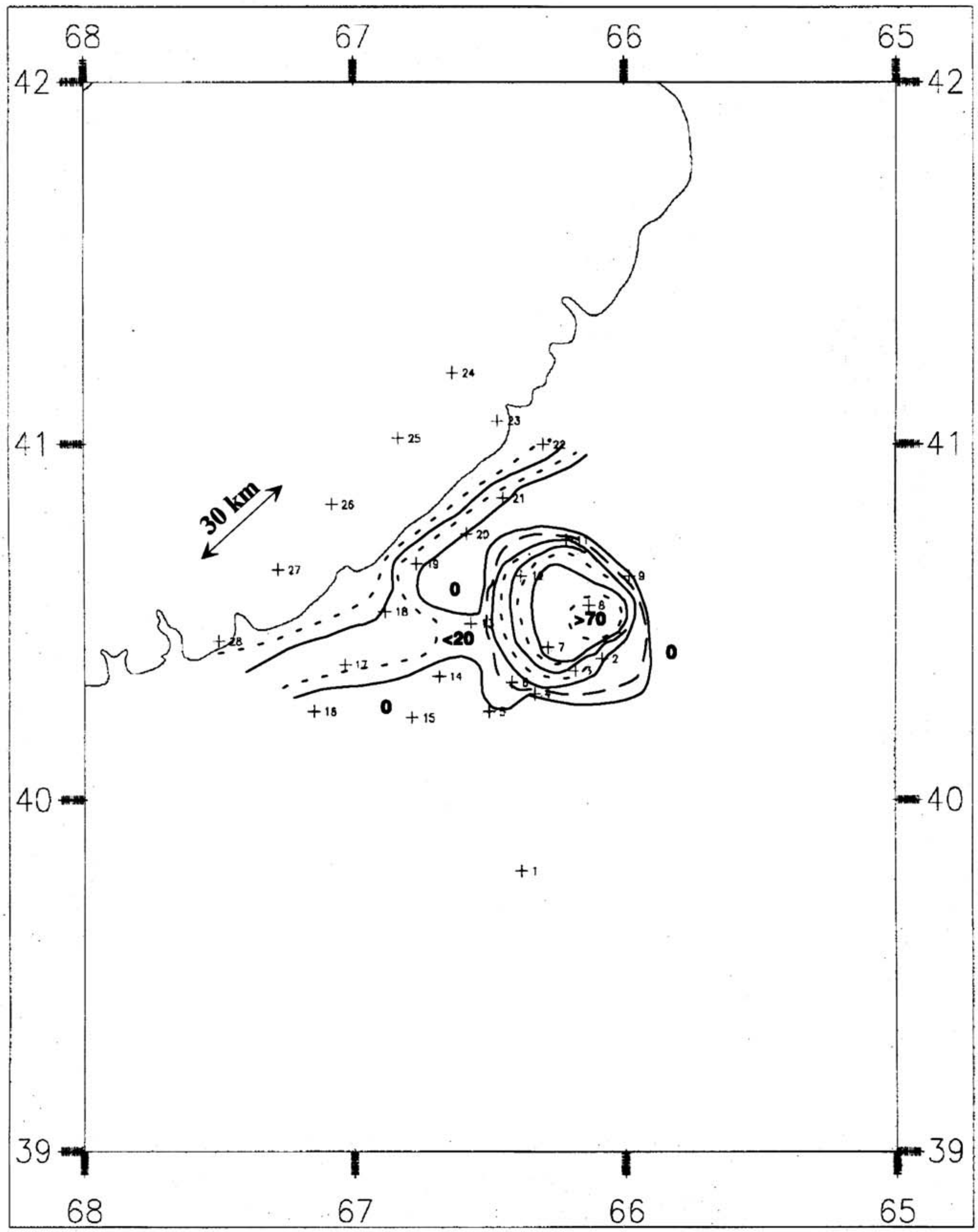

Figure 4a. Depth of a layer from the surface (portrayed with 10-m contours) containing shelf water (salinity ≤34 PSU) entrained by Ring 82-A. (Data were collected on *Albatross IV* Cruise No. AL 82-04 during 22-27 April 1982.)

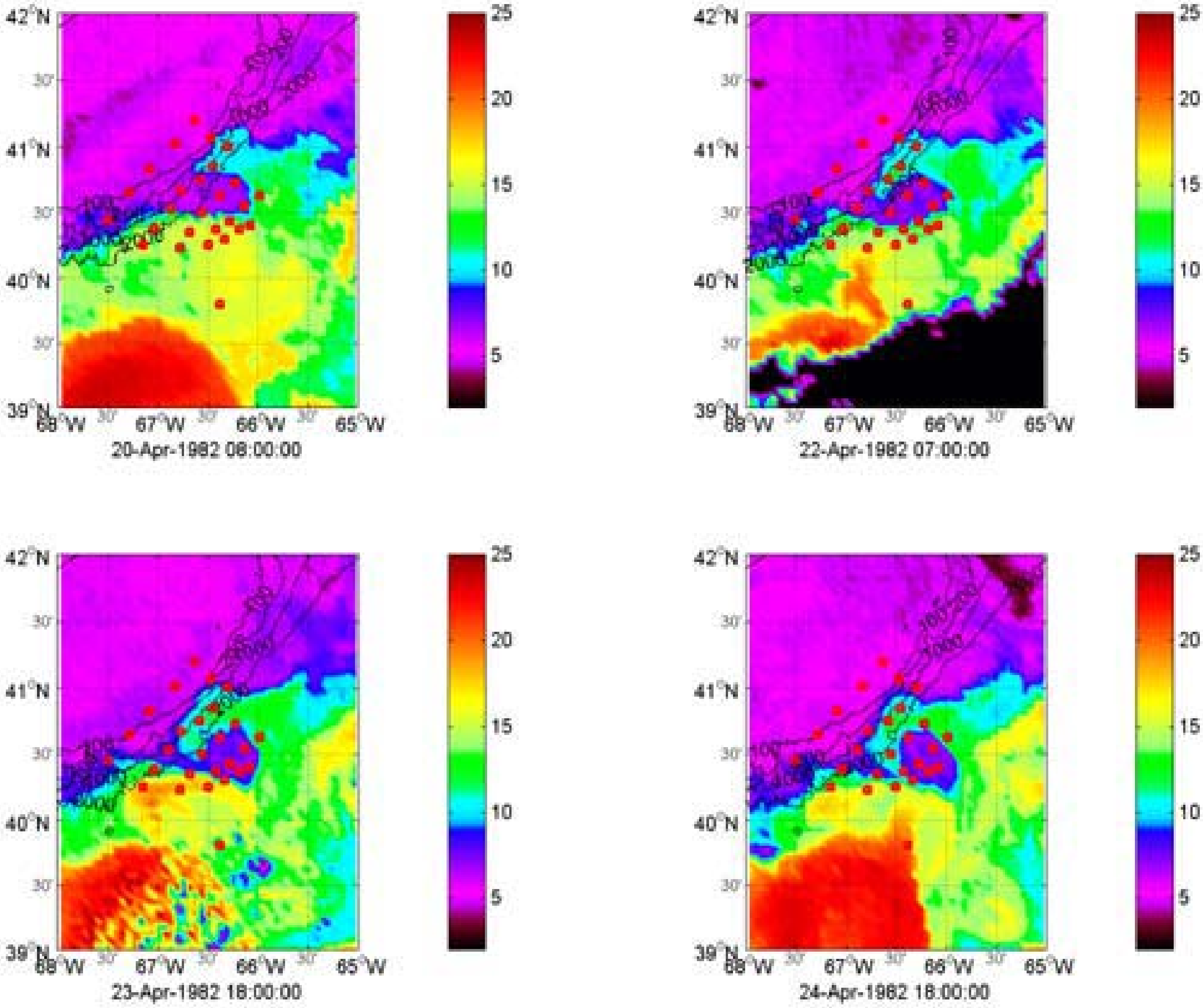

Figure 4b. A series of AVHRR images for 20-24 April 1982 showing temperature expression at the surface as slope water cyclonically encircles the shelf water entrained by Ring 82-A. (The warm water at the southwest corner was caused by a large meander of the Gulf Stream which destroyed Ring 81-E and formed Ring 82-D.)

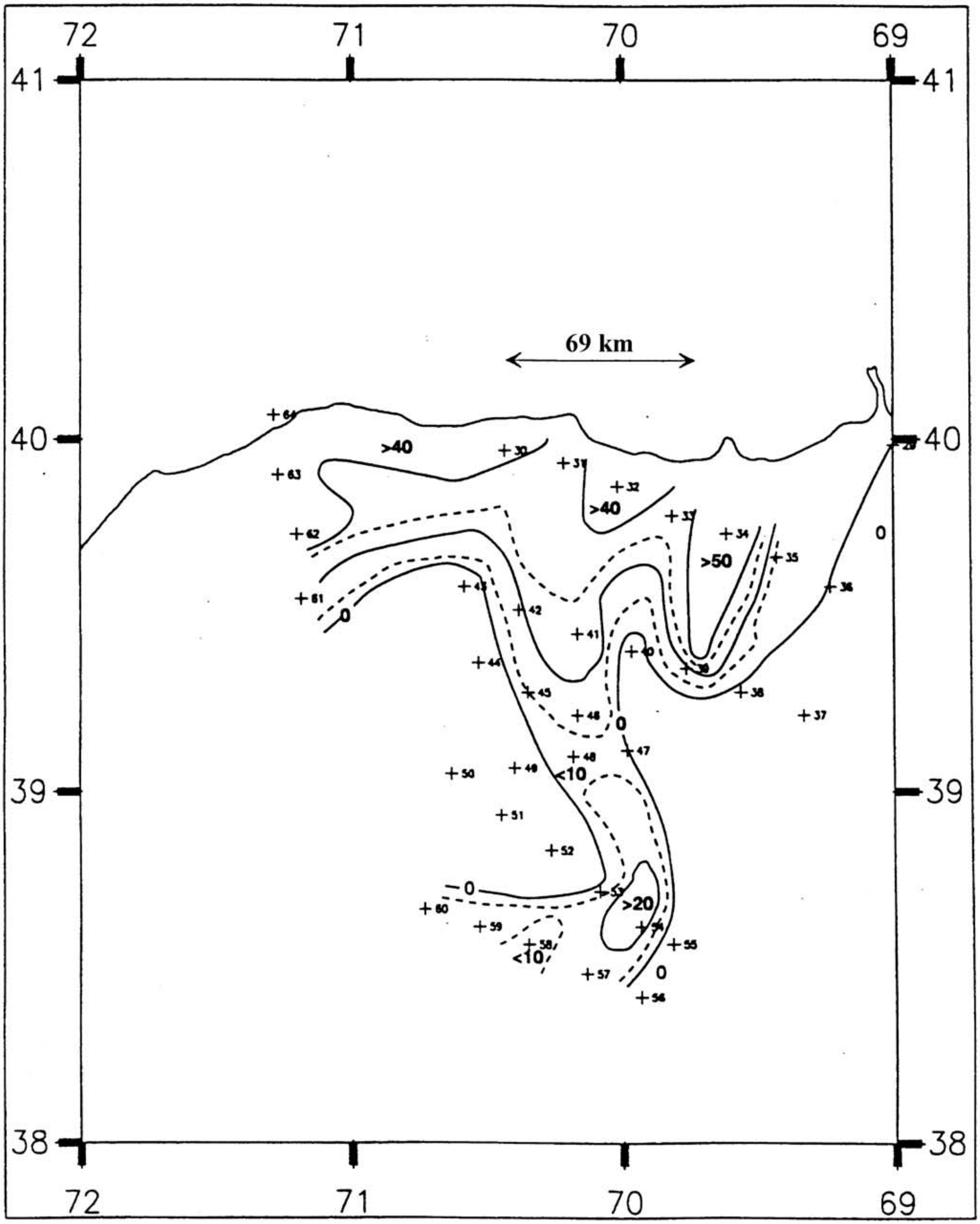

Figure 5a. Depth of a layer from the surface (portrayed with 10-m contours) containing shelf water (salinity ≤34 PSU) entrained by Ring 82-B. (Data were collected on *Albatross IV* Cruise No. AL 82-04 during 28 April - 3 May 1982.)

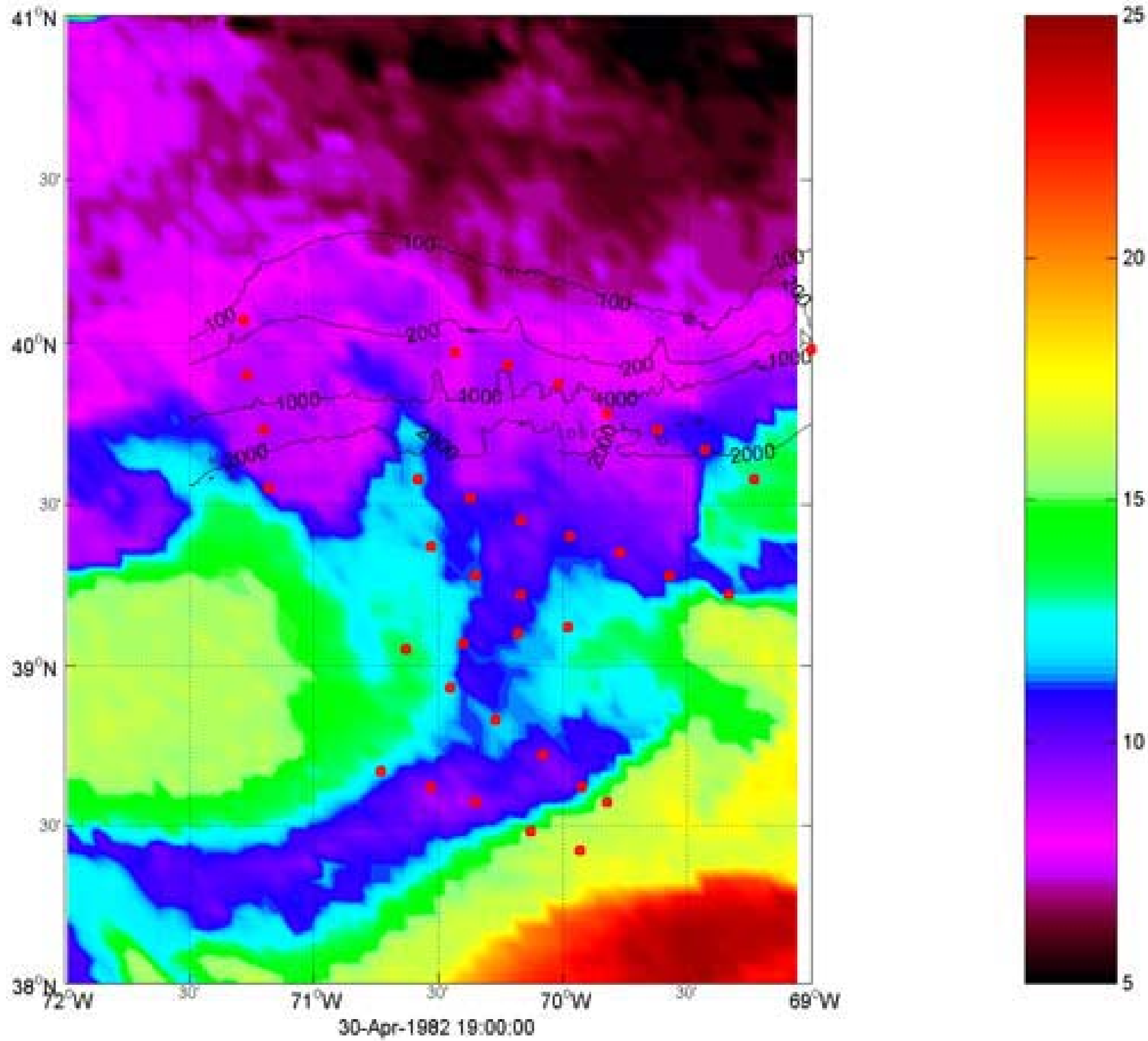

Figure 5b. An AVHRR image for 30 April 1982 showing temperature expression at the surface for shelf water entrained by Ring 82-B. (Note that the undulations at the boundary between shelf water and Ring 82-B show some characteristics of frontal waves.)

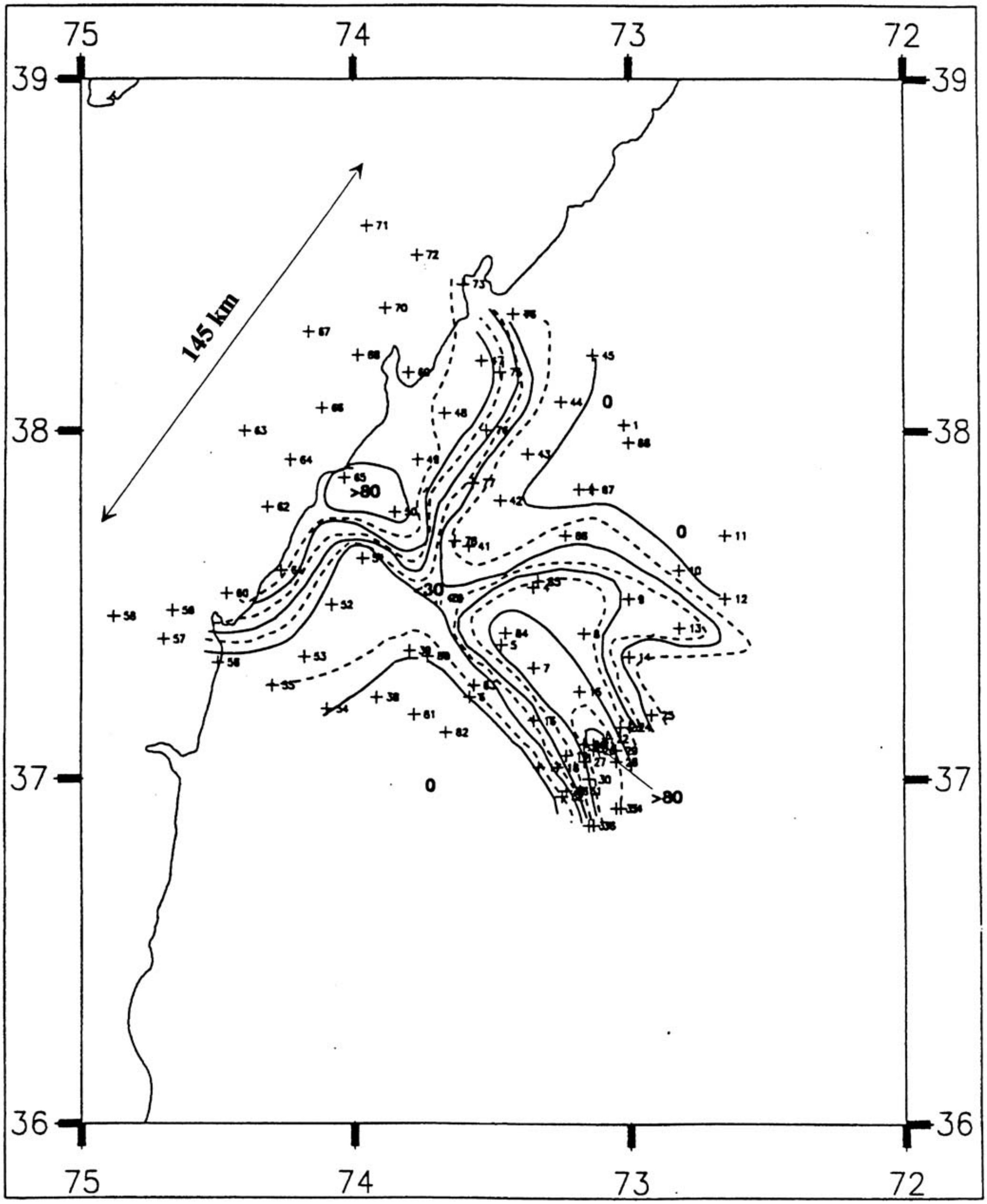

Figure 6a. Depth of a layer from the surface (portrayed with 10-m contours) containing shelf water (salinity ≤34 PSU) entrained by Ring 82-B. (Data were collected on *Albatross IV* Cruise No. AL 82-04 during 21-29 June 1982.)

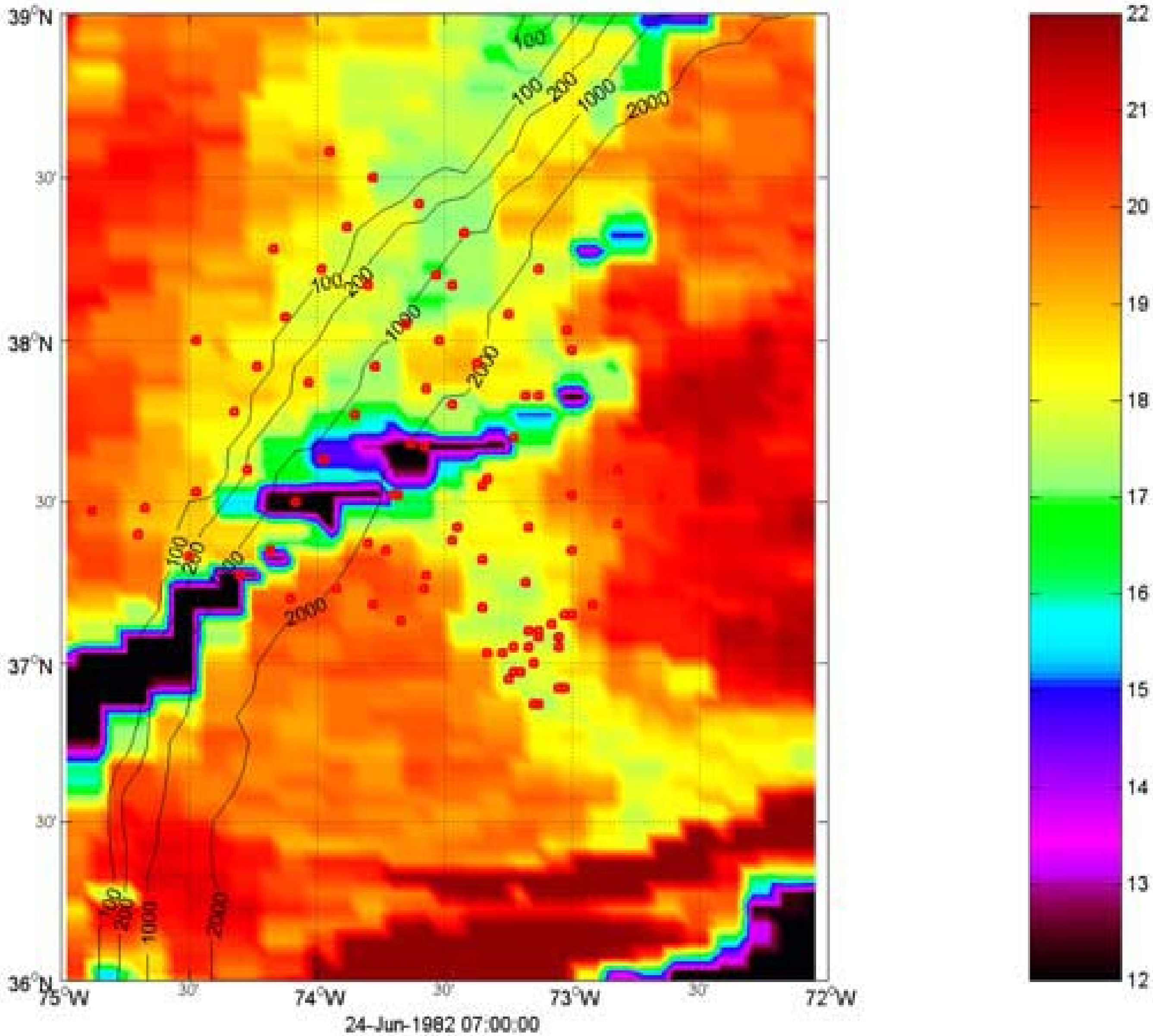

Figure 6b. An AVHRR image for 24 June 1982 showing temperature expression at the surface for shelf water entrained by Ring 82-B. (The northern part of the entrainment is partially obscured by clouds and overall contrast of temperatures at the surface is decreased from earlier in the year due to vernal warming.)

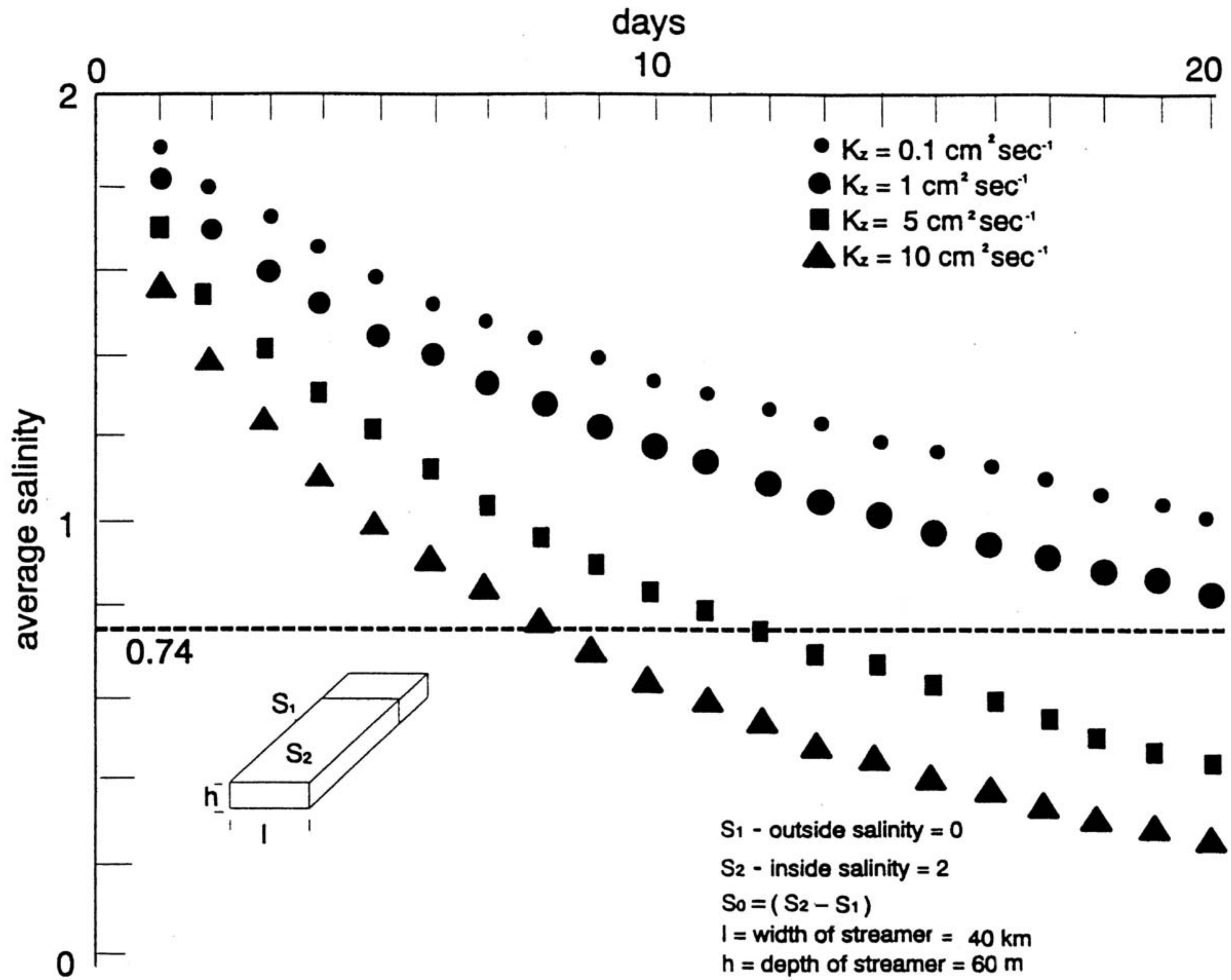

Figure 7. The average salinity decrease for a cross section within a homogeneous rectangular streamer for daily time steps calculated using a two-dimensional diffusion model. (Vertical diffusivity, K_z, was varied as 0.1, 1, 5, and 10 cm^2 sec^{-1}, and horizontal diffusivity, K_h, was maintained at 4 x 10^5 cm^2 sec^{-1}. The line at average salinity was 0.74 (2 x e^{-1}).)

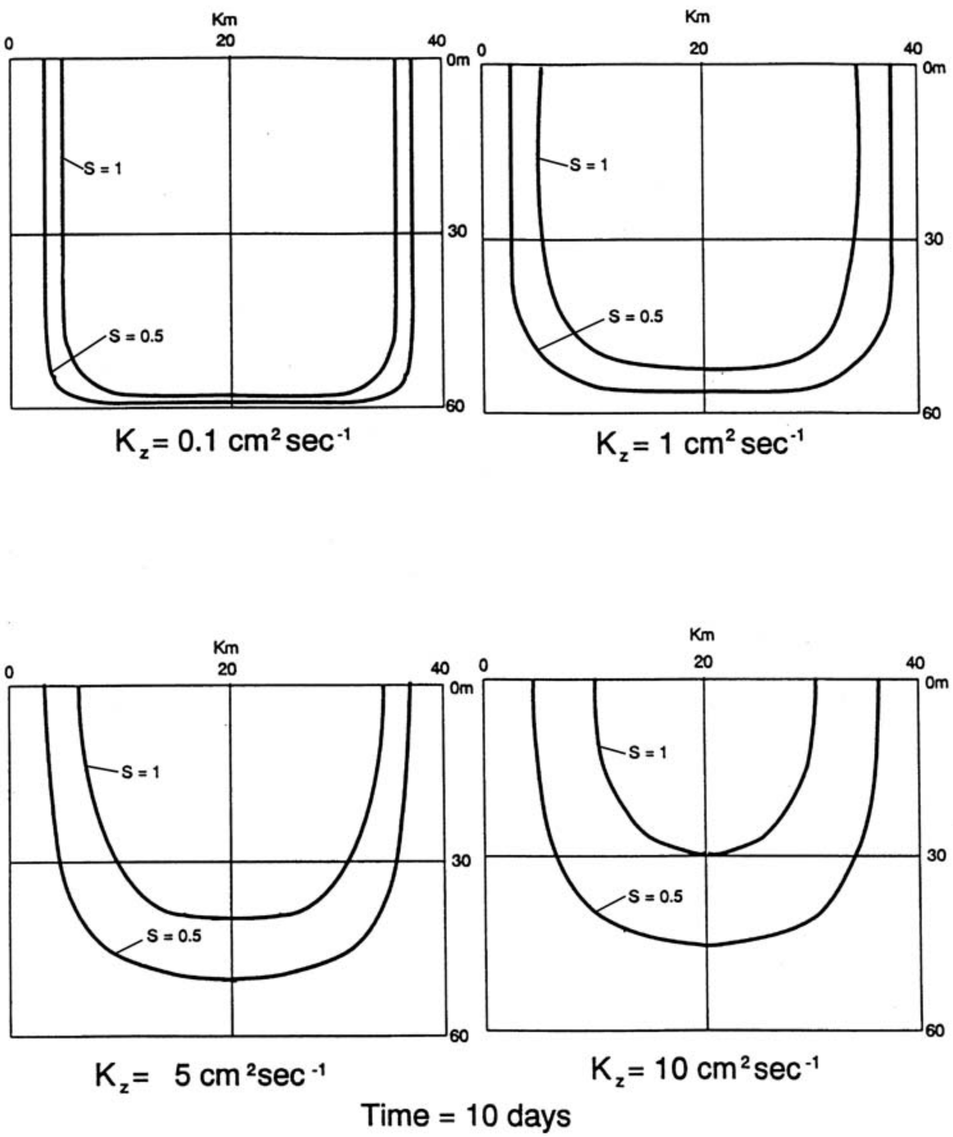

Figure 8a. Cross sections of salinity for an initial layer 60 m thick and 40 km wide after diffusion for 10 days at four different rates (0.1, 1, 5, and 10 cm^2 sec^{-1}) for horizontal diffusivity, calculated using a two-dimensional diffusion model.

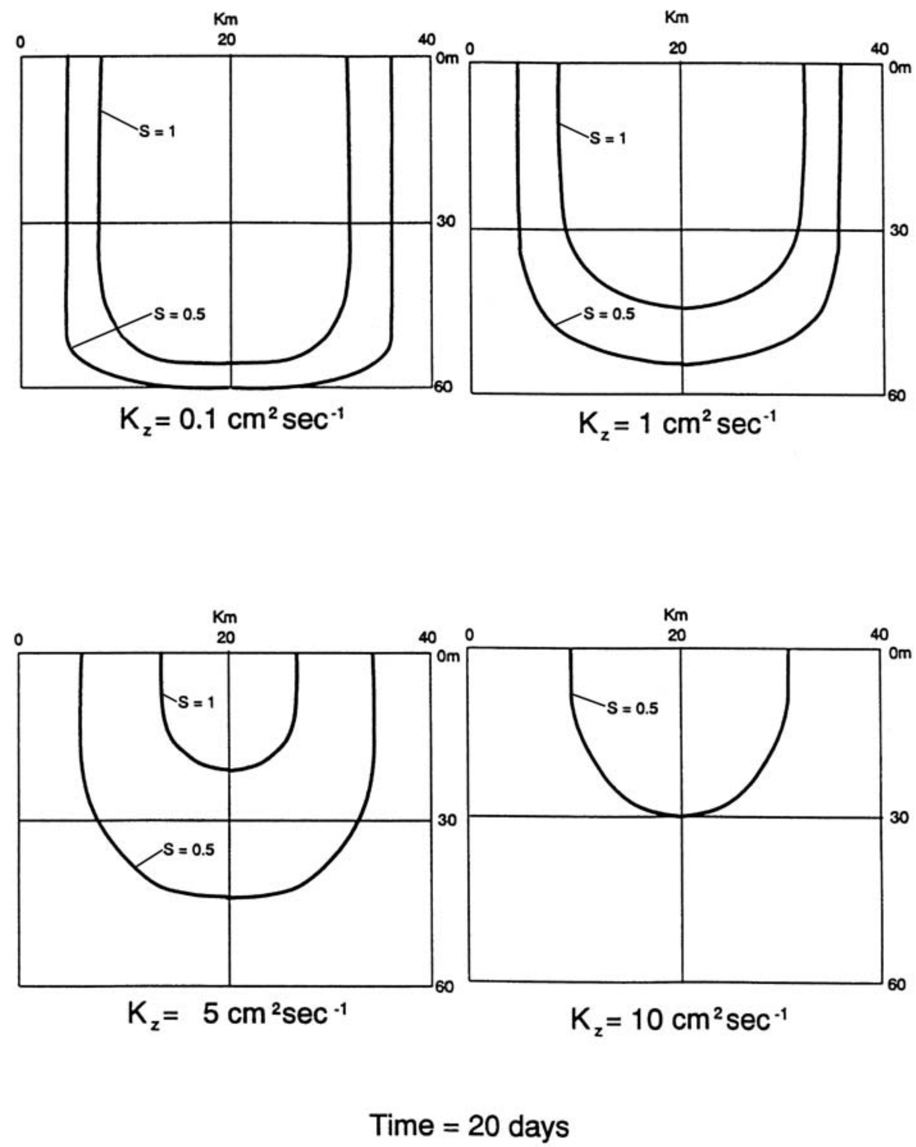

Figure 8b. Cross sections of salinity for an initial layer 60 m thick and 40 km wide after diffusion for 20 days at four different rates (0.1, 1, 5, and 10 cm^2 sec^{-1}) for horizontal diffusivity, calculated using a two-dimensional diffusion model.

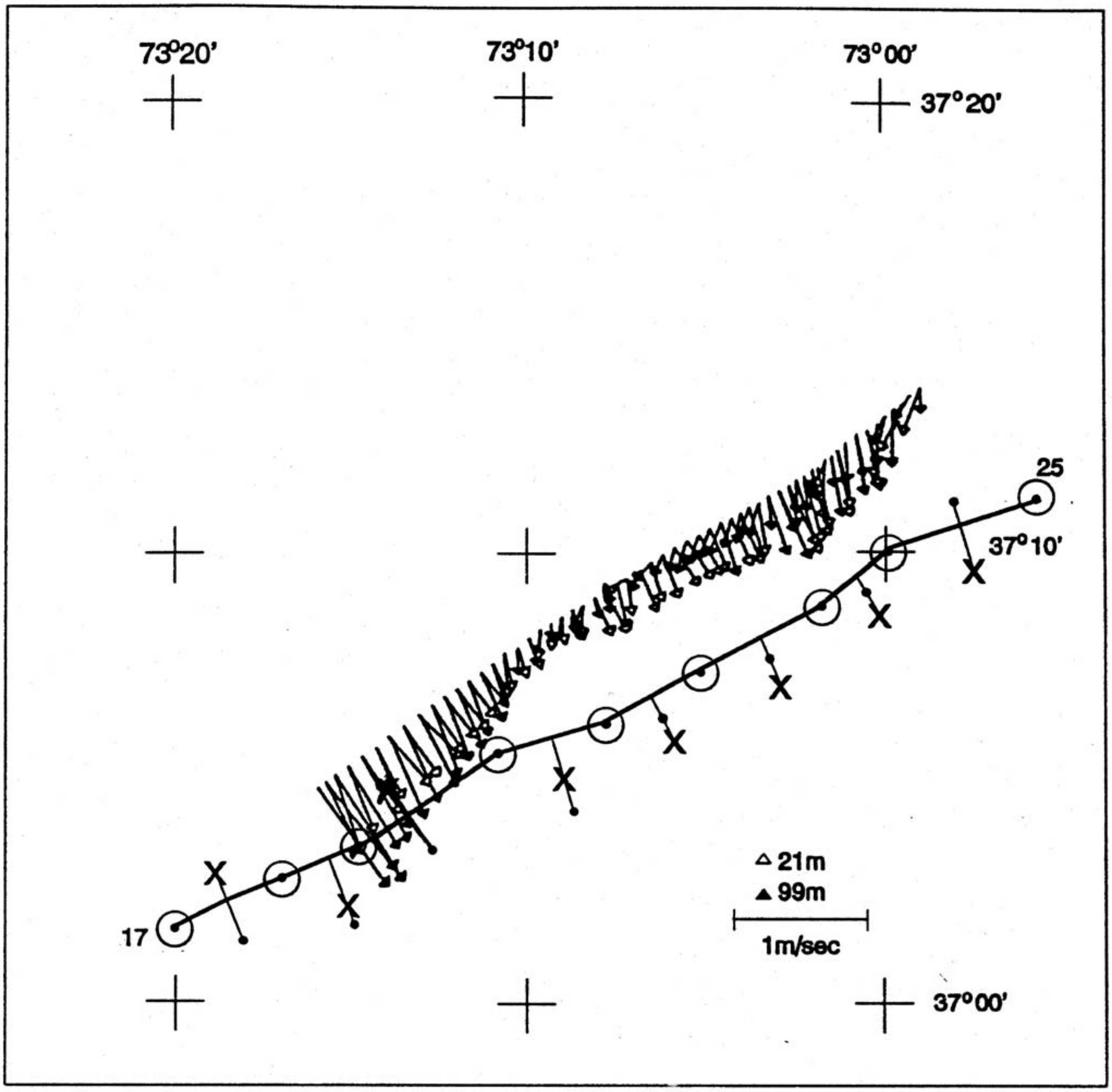

Figure 9. Comparison of velocities (m sec^{-1}) at depths of 21 and 99 m (represented by Δ and ▲, respectively) determined from ADCP measurements, and at depths of 20 and 100 m (represented by x and •, respectively) relative to 300 m determined from geostrophic calculations, on concurrent nearly parallel tracks across shelf water entrained by Ring 82-B on 23 June 1982. (Positions of CTD casts are shown as dotted circles. Modified from Joyce *et al.* 1992)

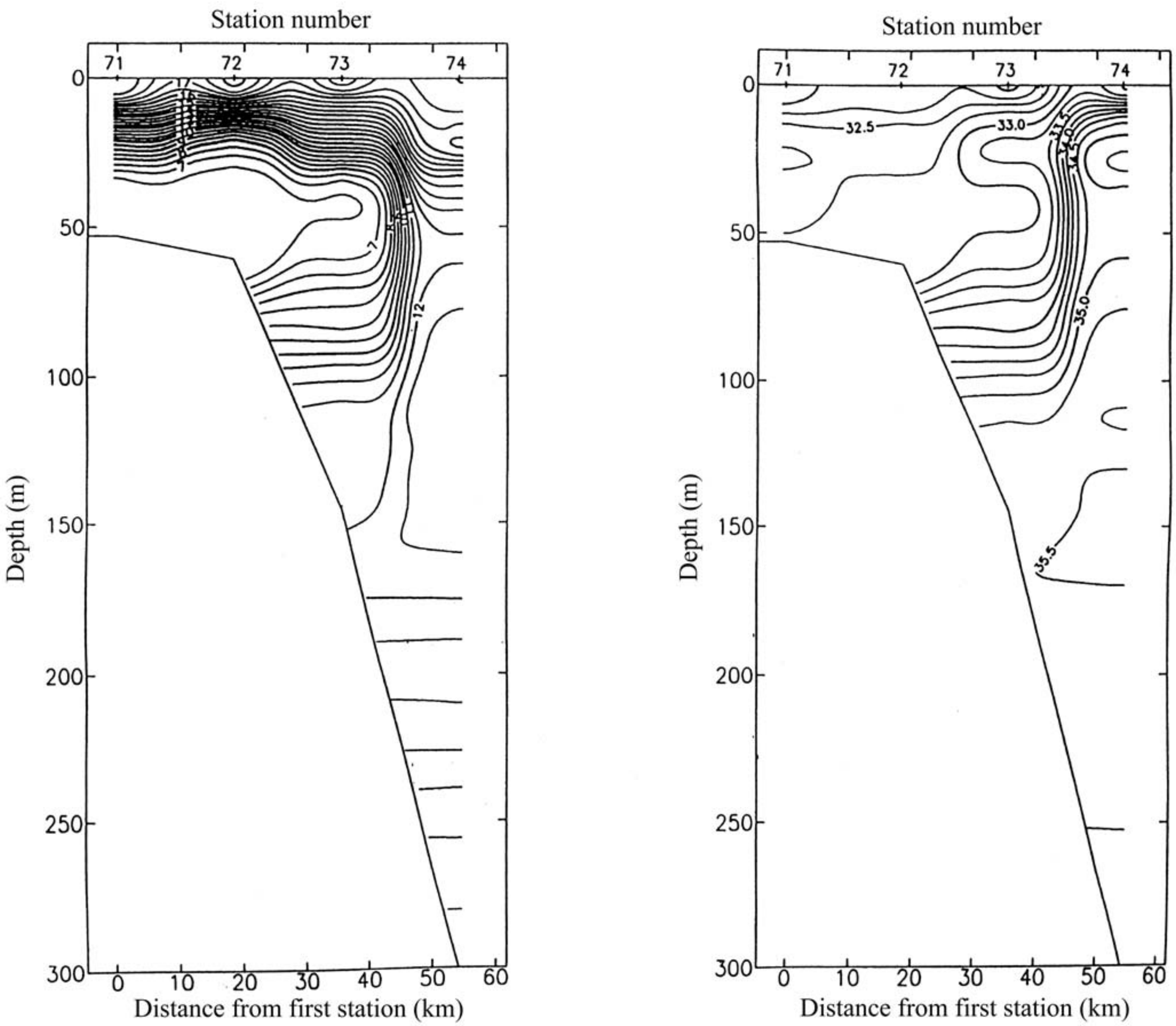

Figure 10. Temperature (°C) and salinity (PSU) sections from CTD data at Stations 71-74 obtained on *Albatross IV* Cruise No. AL 82-07 during 17 June - 2 July 1982. (Depths are in meters and distance along the section is in kilometers. The positions of the stations are found in Figure 2c.)

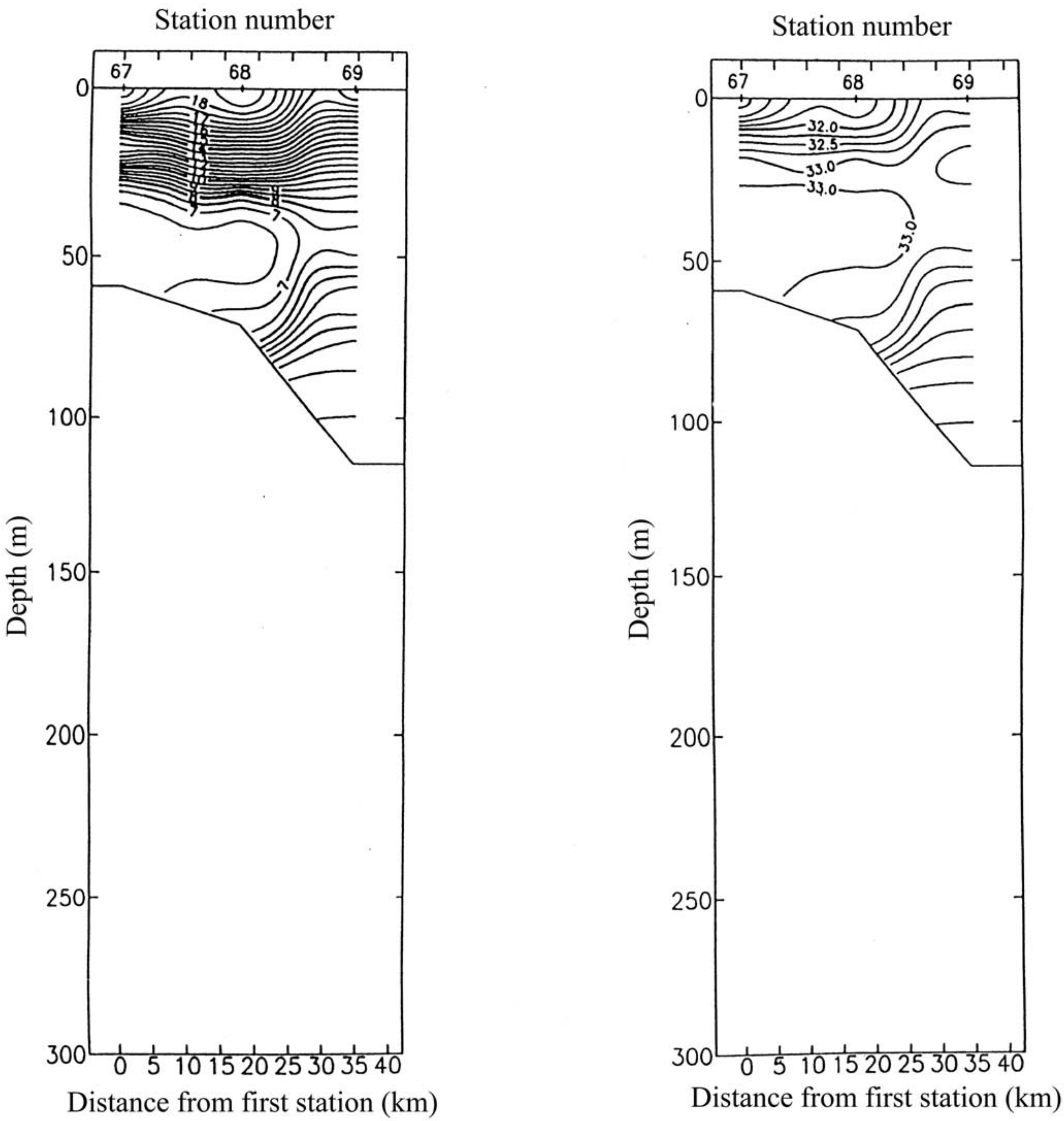

Figure 11. Temperature (°C) and salinity (PSU) sections from CTD data at Stations 67-69 obtained on *Albatross IV* Cruise No. AL 82-07 during 17 June - 2 July 1982. (Depths are in meters and distance along the section is in kilometers. The positions of the stations are found in Figure 2c.)

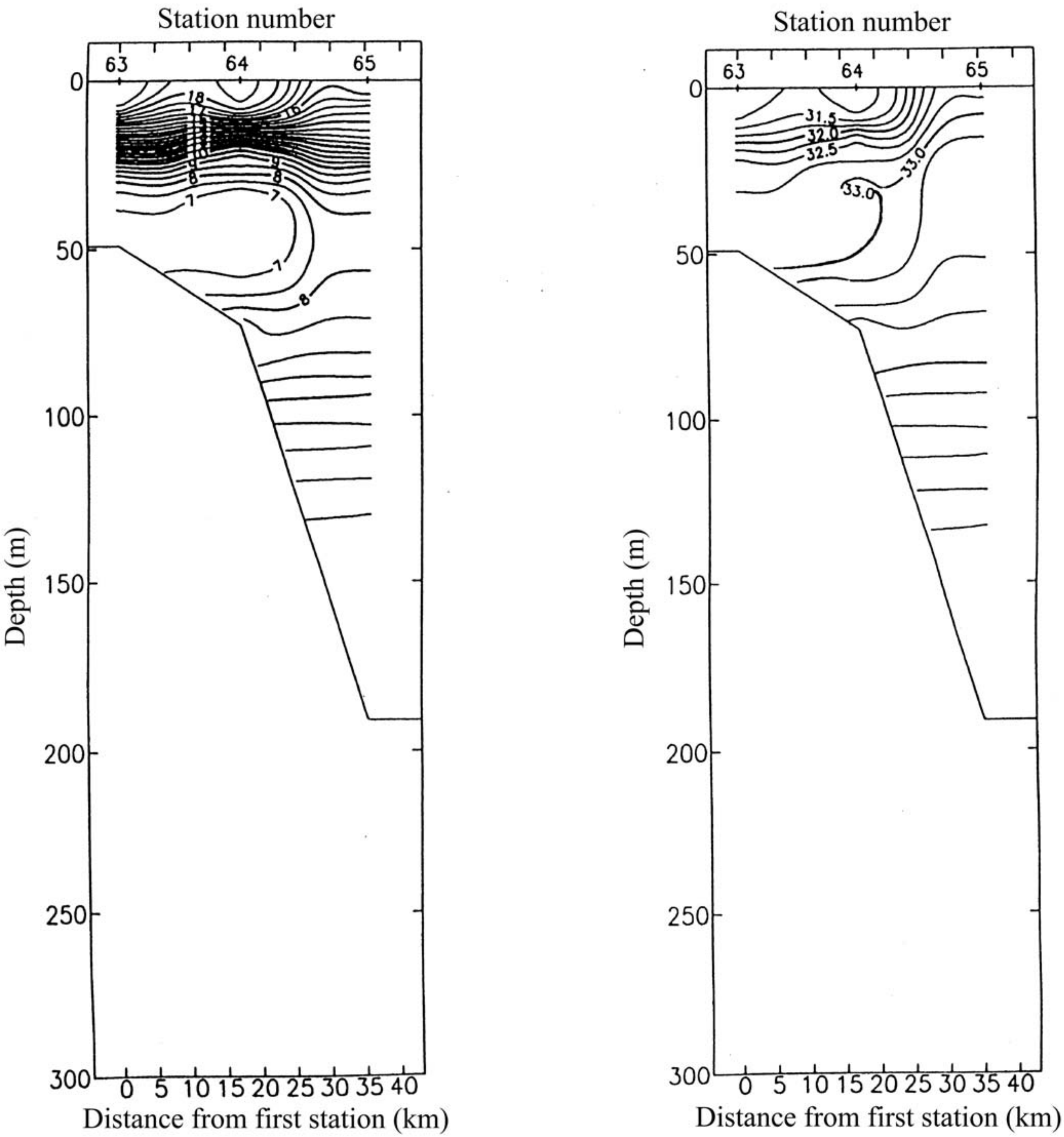

Figure 12. Temperature (°C) and salinity (PSU) sections from CTD data at Stations 63-65 obtained on *Albatross IV* Cruise No. AL 82-07 during 17 June - 2 July 1982. (Depths are in meters and distance along the section is in kilometers. The positions of the stations are found in Figure 2c.)

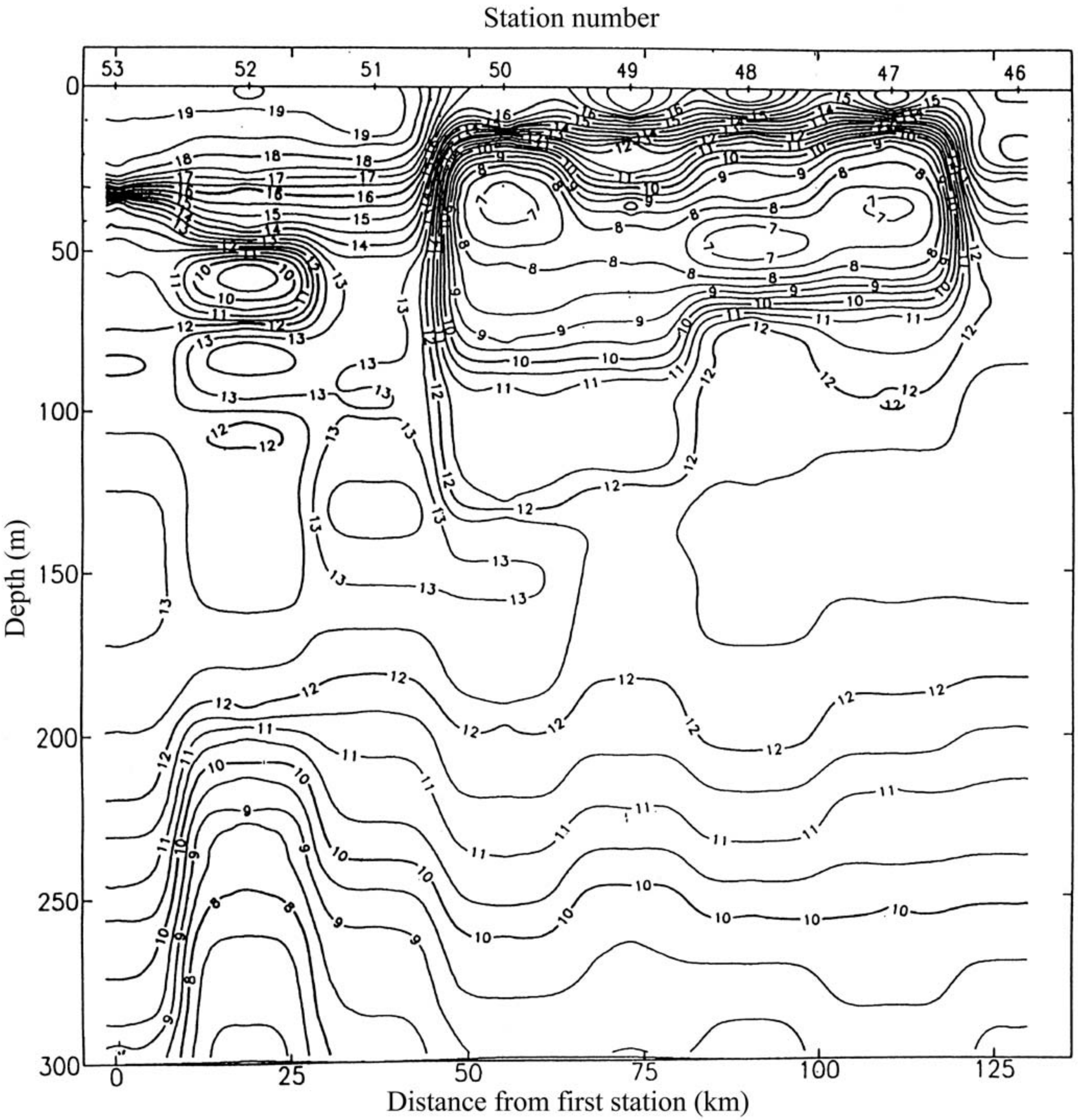

Figure 13a. Temperature (°C) section from CTD data at Stations 53-46 obtained on *Albatross IV* Cruise No. AL 82-07 during 17 June - 2 July 1982. (Depths are in meters and distance along the section is in kilometers. The positions of the stations are found in Figure 2c.)

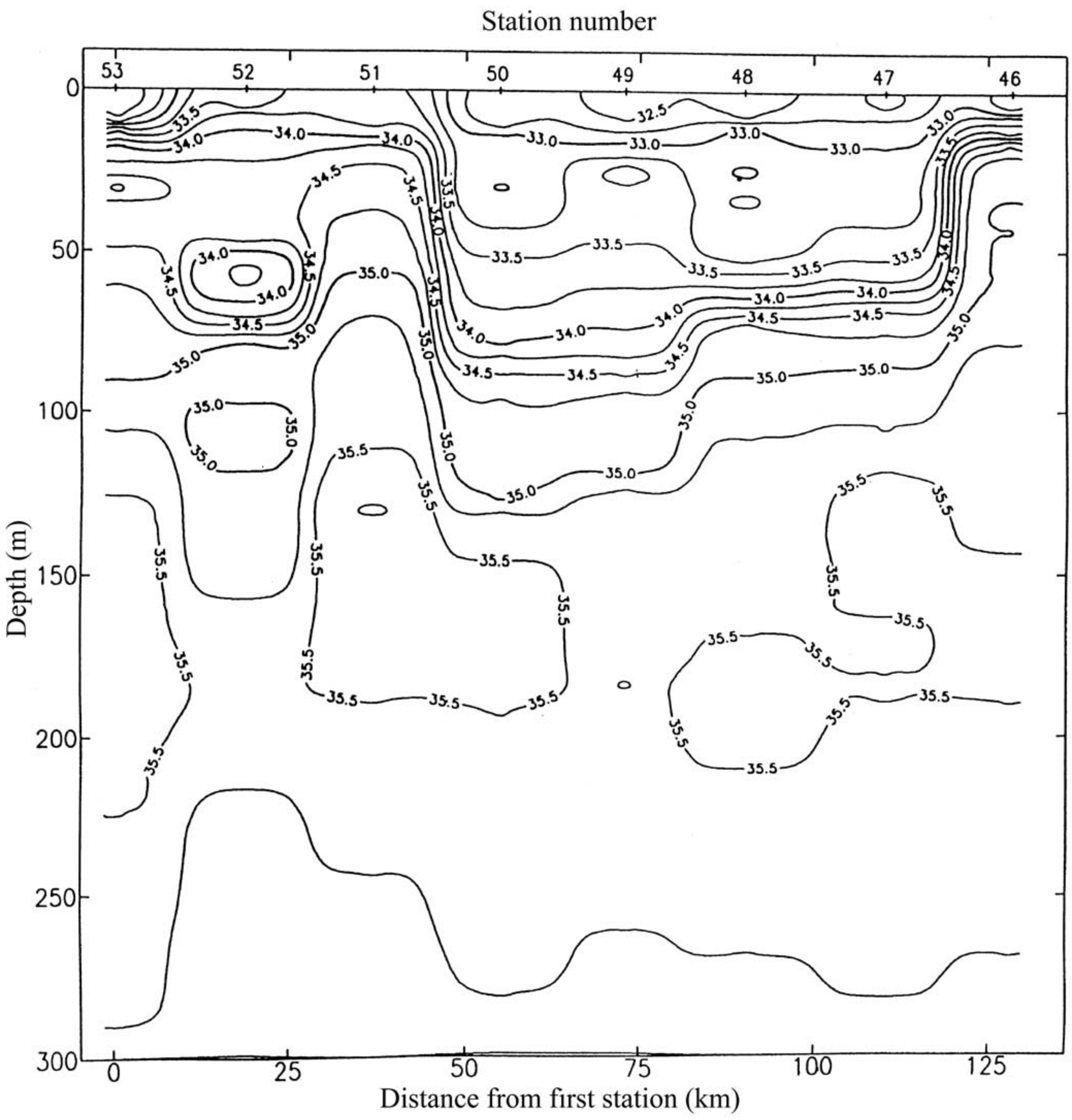

Figure 13b. Salinity (PSU) section from CTD data at Stations 53-46 obtained on *Albatross IV* Cruise No. AL 82-07 during 17 June - 2 July 1982. (Depths are in meters and distance along the section is in kilometers. The positions of the stations are found in Figure 2c.)

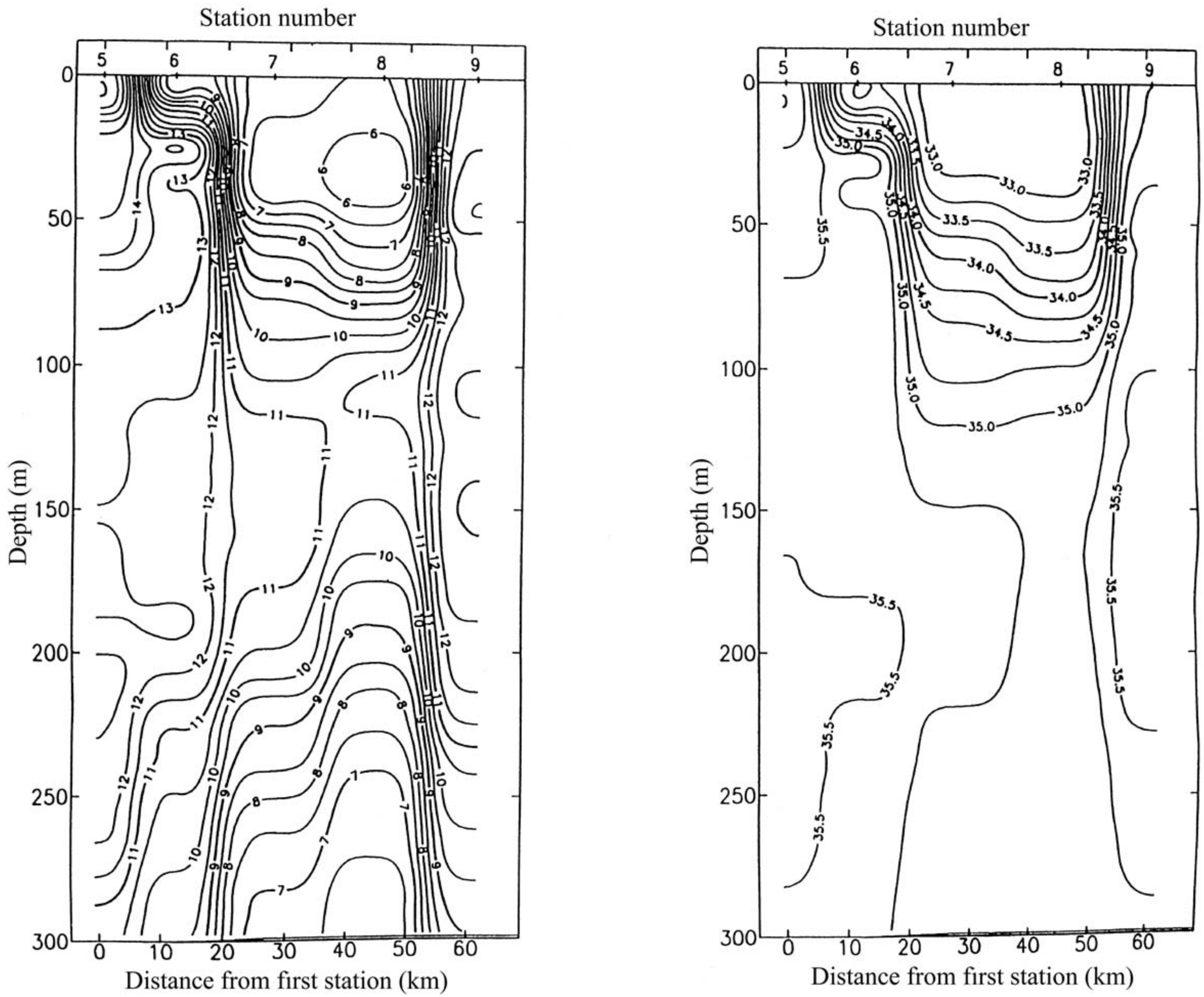

Figure 14. Temperature (°C) and salinity (PSU) sections from CTD data at Stations 5-9 obtained on *Albatross IV* Cruise No. AL 82-04 during 19 April - 4 May 1982. (Depths are in meters and distance along the section is in kilometers. The positions of the stations are found in Figure 2b.)

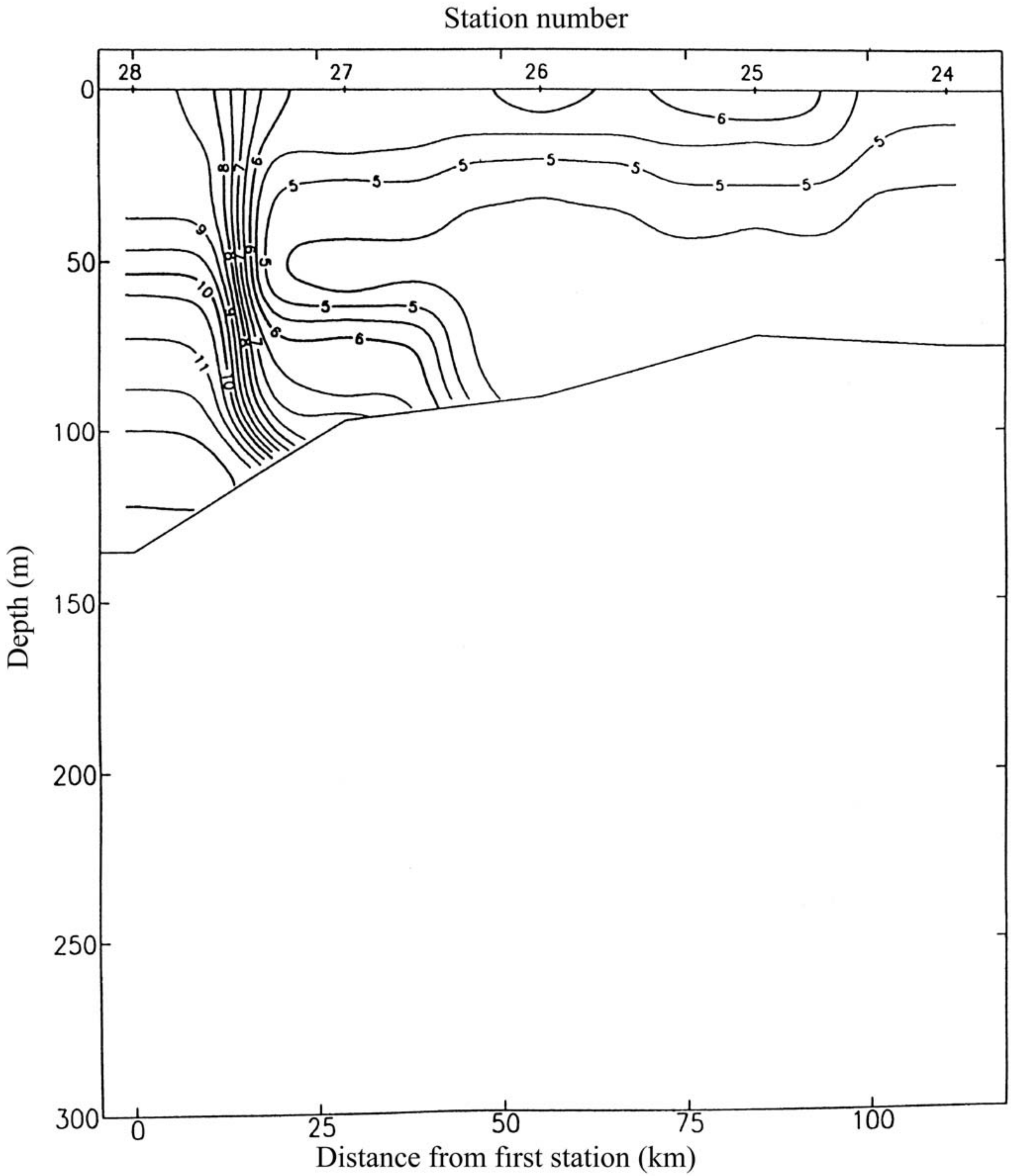

Figure 15a. Temperature (°C) section from CTD data at Stations 28-24 obtained on *Albatross IV* Cruise No. AL 82-04 during 19 April - 4 May 1982. (Depths are in meters and distance along the section is in kilometers. The positions of the stations are found in Figure 2b.)

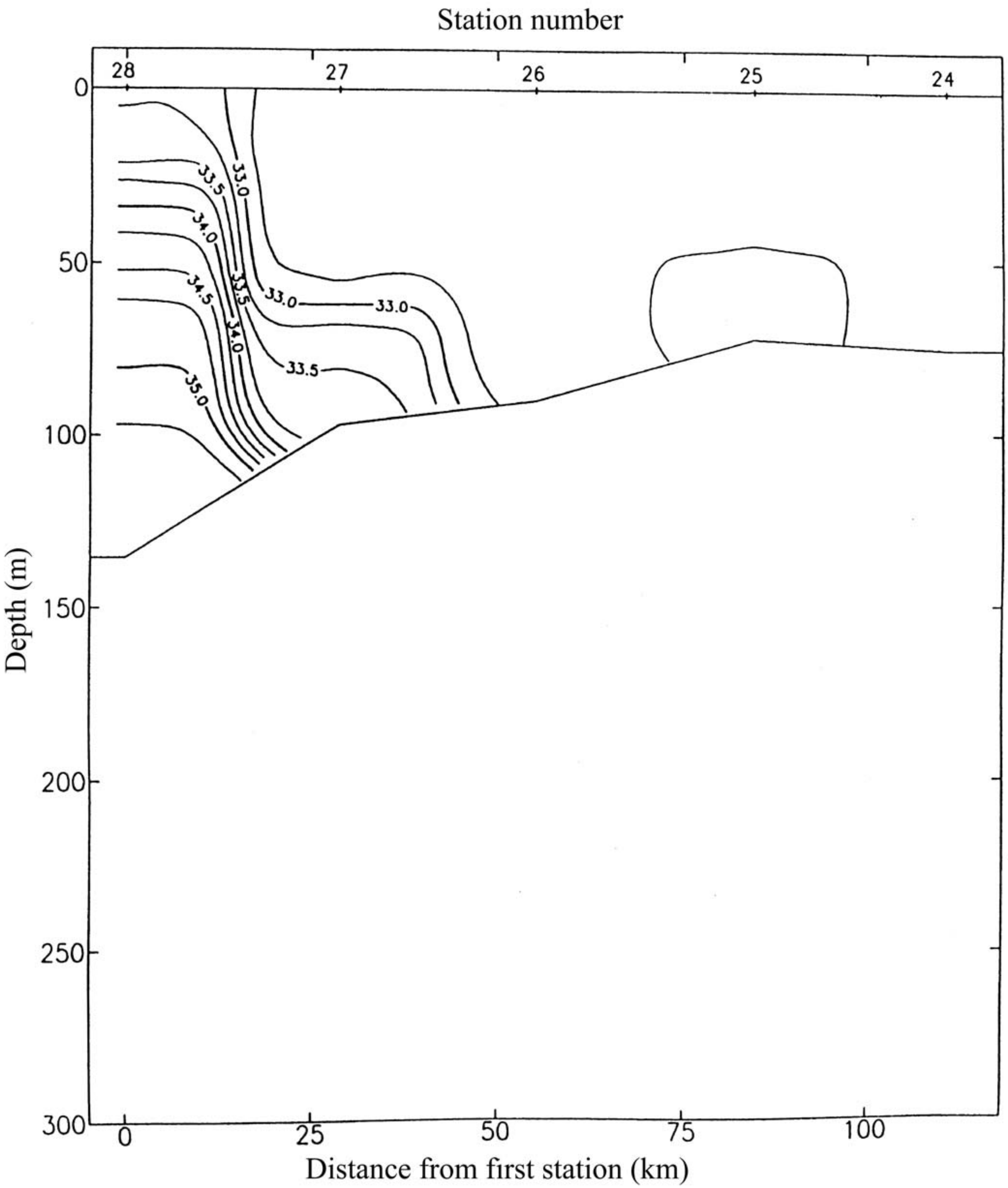

Figure 15b. Salinity (PSU) section from CTD data at Stations 28-24 obtained on *Albatross IV* Cruise No. AL 82-04 during 19 April - 4 May 1982. (Depths are in meters and distance along the section is in kilometers. The positions of the stations are found in Figure 2b.)

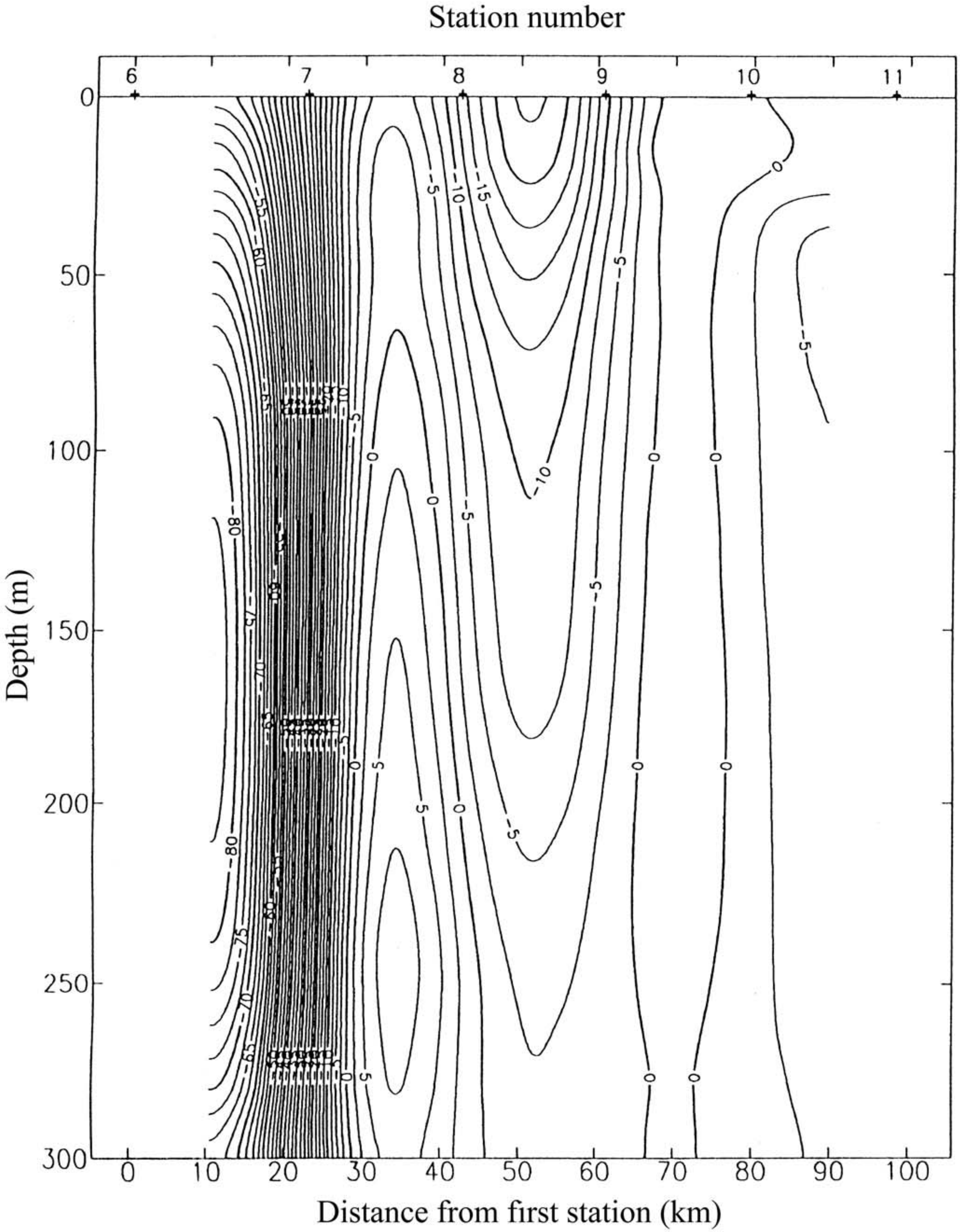

Figure 16a. Velocity (cm sec^{-1}) section from CTD data at Stations 6-11 obtained on *Albatross IV* Cruise No. AL 82-07 during 17 June - 2 July 1982. (Depths are in meters and distance along the section is in kilometers. The positions of the stations are found in Figure 2c. Geostrophic velocity is calculated relative to a level of no motion at approximately 1000 m, and shown for the top 300 m. Illustrated is the extent to which the distribution of velocity can be considered barotropic for comparison with a model including a barotropic vortex.)

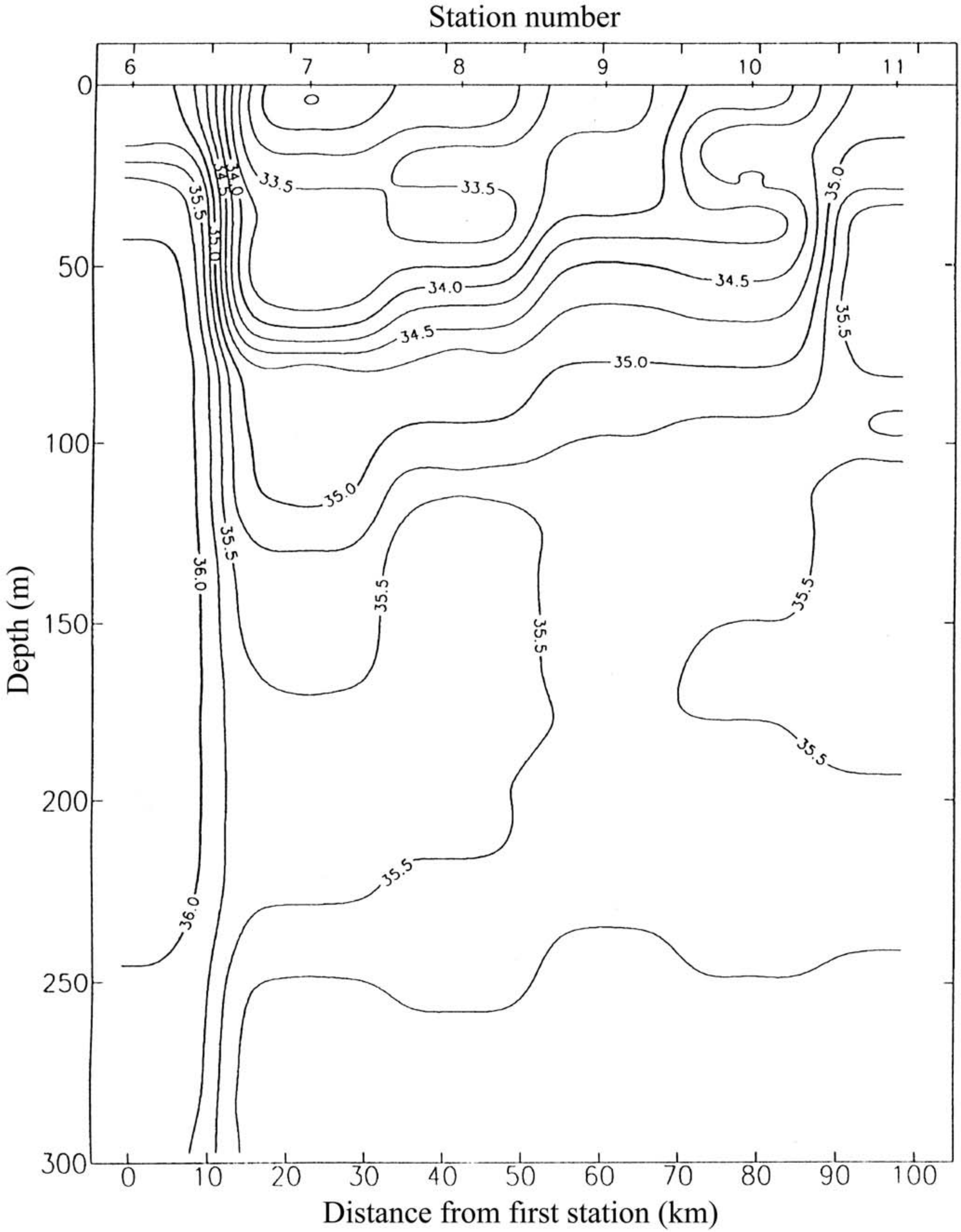

Figure 16b. Salinity section from CTD data at Stations 6-11 obtained on *Albatross IV* Cruise No. AL 82-07 during 17 June - 2 July 1982. (Depths are in meters and distance along the section is in kilometers. The positions of the stations are found in Figure 2c.)

Table 1. Estimated volume (km^3) of shelf water ($\leq$34 PSU) by 10-m depth layer within streamers entrained by Rings 81-E, 82-A, and 82-B twice. (Volumes were calculated using a planimetric method.)

Depth (m)	**Ring**							
	81-E		**82-A**		**82-B (May-June)**		**82-B (June-July)**	
	Layer	**∑**	**Layer**	**∑**	**Layer**	**∑**	**Layer**	**∑**
0		0		0		0		0
	80		19		49		71	
10		80		19		49		71
	54		13		38		54	
20		134		32		87		125
	30		10		27		43	
30		164		42		114		168
	13		8		17		38	
40		177		50		131		206
	3		5		8		34	
50		180		55		**139**		240
	<1		2				27	
60		**181**		57				267
			1				16	
70				**58**				283
							6	
80								289
							1	
90								**290**

Table 2. Geostrophically estimated transport (10^3 m^3 sec^{-1} in both the same and opposite direction as the ring's swirl) of shelf water (≤34 PSU) by station transect within streamers entrained by Rings 81-E, 82-A, and 82-B twice.

Ring	Stations	Transport (10^3 m^3 sec^{-1}) Relative to Ring Swirl Direction		Lowest Average Salinity Class (PSU)
		Same	Opposite	
81-E	65-68	3.5	0	33.75-34.00
	60-65	10.9	0.8	33.75-34.00
	59-56	0	11.5	33.50-33.75
	54-56	0	0	-
	54-50	38.6	0	33.50-33.75
	46-50	22.6	80.8	33.50-33.75
	46-40	163.7	0	33.50-33.75
	30-37	277.4	223.2	32.50-32.75
82-A	5-2	61.7	27.0	32.75-33.00
	5-9	263.5	14.4	32.75-33.00
	15-11	88.2	344.6	33.25-33.50
	16-22	33.4	51.1	33.25-33.50
82-B (April-May)	60-56	38.8	0	33.50-33.75
	50-55	0	0	-
	50-47	0	0	-
	44-47	0	54.0	33.75-34.00
	43-37	32.7	42.5	33.50-33.75
	30-36	45.6	18.2	32.75-33.00
	[61-64]	52.6	73.8	32.75-33.00
82-B (June-July)	6-1	399.8	1.7	33.00-33.25
	6-11	305.5	5.0	32.75-33.00
	16-12	487.9	9.2	33.00-33.25
	17-25	407.6	46.6	32.50-32.75
	38-45	109.2	12.8	33.25-33.50
	53-46	212.3	175.6	32.25-32.50
	81-74	239.7	37.5	32.25-32.50
	82-88	214.4	17.2	32.50-32.75
	[54-58]	47.0	35.2	31.50-31.75
	[71-74]	0	141.8	31.75-32.00
Mean		164.6	61.8	
Std. Dev.		148.5	90.2	

Table 3. Comparison of geostrophic and measured transport estimates (10^3 m^3 sec^{-1}) by salinity class of shelf water entrained by Ring 82-B in June 1982. (Comparisons were based on geostrophic calculations for Stations 17-25 and on a nearby section directly measured (ADCP/"tow-yo" CTD) by Joyce *et al.* (1992).)

Estimation Method	**Transport (10^3 m^3 sec^{-1}) by Salinity Class (PSU)**		
	<33	**33-34**	**34-35**
CTD/Geostrophy	41	367	230
ADCP/CTD	22	354	481
Difference	19	13	-251

Publishing in *NOAA Technical Memorandum NMFS-NE*

Manuscript Qualification

This series represents a secondary level of scientific publishing in the National Marine Fisheries Service (NMFS). For all issues, the series employs thorough internal scientific review, but not necessarily external scientific review. For most issues, the series employs rigorous technical and copy editing. Manuscripts that may warrant a primary level of scientific publishing should be initially submitted to one of NMFS's primary series (*i.e., Fishery Bulletin, NOAA Technical Report NMFS,* or *Marine Fisheries Review*).

Identical, or fundamentally identical, manuscripts should not be concurrently submitted to this and any other publication series. Manuscripts which have been rejected by any primary series strictly because of geographic or temporal limitations may be submitted to this series.

Manuscripts by Northeast Fisheries Science Center (NEFSC) authors will be published in this series upon approval by the NEFSC's Deputy Science & Research Director. Manuscripts by non-NEFSC authors may be published in this series if: 1) the manuscript serves the NEFSC's mission; 2) the manuscript meets the Deputy Science & Research Director's approval; and 3) the author arranges for the printing and binding funds to be transferred to the NEFSC's Research Communications Unit account from another federal account. For all manuscripts submitted by non-NEFSC authors and published in this series, the NEFSC will disavow all responsibility for the manuscripts' contents; authors must accept such responsibility.

The ethics of scientific research and scientific publishing are a serious matter. All manuscripts submitted to this series are expected to adhere -- at a minimum -- to the ethical guidelines contained in Chapter 1 ("Ethical Conduct in Authorship and Publication") of the *CBE Style Manual*, fifth edition (Chicago, IL: Council of Biology Editors). Copies of the manual are available at virtually all scientific libraries.

Manuscript Preparation

Organization: Manuscripts must have an abstract, table of contents, and -- if applicable -- lists of tables, figures, and acronyms. As much as possible, use traditional scientific manuscript organization for sections: "Introduction," "Study Area," "Methods & Materials," "Results," "Discussion" and/or "Conclusions," "Acknowledgments," and "References Cited."

Style: All NEFSC publication and report series are obligated to conform to the style contained in the most recent edition of the *United States Government Printing Office Style Manual*. That style manual is silent on many aspects of scientific manuscripts. NEFSC publication and report series rely more on the *CBE Style Manual,* fifth edition.

For in-text citations, use the name-date system. A special effort should be made to ensure that the list of cited works contains all necessary bibliographic information. For abbreviating serial titles in such lists, use the guidance of the International Standards Organization; such guidance is easily accessed through the various Cambridge Scientific Abstracts' serials source lists (see *http://www.public.iastate.edu/~CYBERSTACKS/JAS.htm*). Personal communications must include date of contact and full name and mailing address of source.

For spelling of scientific and common names of fishes, mollusks, and decapod crustaceans from the United States and Canada, use *Special Publications* No. 20 (fishes), 26 (mollusks), and 17 (decapod crustaceans) of the American Fisheries Society (Bethesda, MD). For spelling of scientific and common names of marine mammals, use *Special Publication* No. 4 of the Society for Marine Mammalogy (Lawrence, KS). For spelling in general, use the most recent edition of *Webster's Third New International Dictionary of the English Language Unabridged* (Springfield, MA: G.&C. Merriam).

Typing text, tables, and figure captions: Text, tables, and figure captions should be converted to WordPerfect. In general, keep text simple (*e.g.*, don't switch fonts and type sizes, don't use hard returns within paragraphs, don't indent except to begin paragraphs). Also, don't use an automatic footnoting function; all notes should be indicated in the text by simple numerical superscripts, and listed together in an "Endnotes" section prior to the "References Cited" section. Especially, don't use a graphics function for embedding tables and figures in text.

Tables should be prepared with a table formatting function. Each figure should be supplied both on paper and on disk, unless there is no digital file of a given figure. Except under extraordinary circumstances, color will not be used in illustrations.

Manuscript Submission

Authors must submit one paper copy of the double-spaced manuscript, one disk copy, and original figures (if applicable). NEFSC authors must include a completely signed-off "NEFSC Manuscript/Abstract/Webpage Review Form." Non-NEFSC authors who are not federal employees will be required to sign a "Release of Copyright" form.

Send all materials and address all correspondence to: Jon A. Gibson (Biological Sciences Editor), NMFS Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA 02543-1026.

Northeast Fisheries Science Center
Operations, Management & Information Services Staff
Research Communications Unit
Editorial Office

National Marine Fisheries Service
166 Water Street
Woods Hole, MA 02543-1026

**Media
Mail**

Publications and Reports of the Northeast Fisheries Science Center

The mission of NOAA's National Marine Fisheries Service (NMFS) is "stewardship of living marine resources for the benefit of the nation through their science-based conservation and management and promotion of the health of their environment." As the research arm of the NMFS's Northeast Region, the Northeast Fisheries Science Center (NEFSC) supports the NMFS mission by "planning, developing, and managing multidisciplinary programs of basic and applied research to: 1) better understand the living marine resources (including marine mammals) of the Northwest Atlantic, and the environmental quality essential for their existence and continued productivity; and 2) describe and provide to management, industry, and the public, options for the utilization and conservation of living marine resources and maintenance of environmental quality which are consistent with national and regional goals and needs, and with international commitments." Results of NEFSC research are largely reported in primary scientific media (*e.g.*, anonymously-peer-reviewed scientific journals). However, to assist itself in providing data, information, and advice to its constituents, the NEFSC occasionally releases its results in its own media. Currently, there are three such media:

NOAA Technical Memorandum NMFS-NE -- This series is issued irregularly. The series typically includes: data reports of long-term field or lab studies of important species or habitats; synthesis reports for important species or habitats; annual reports of overall assessment or monitoring programs; manuals describing program-wide surveying or experimental techniques; literature surveys of important species or habitat topics; proceedings and collected papers of scientific meetings; and indexed and/or annotated bibliographies. All issues receive internal scientific review and most issues receive technical and copy editing.

Northeast Fisheries Science Center Reference Document -- This series is issued irregularly. The series typically includes: data reports on field and lab studies; progress reports on experiments, monitoring, and assessments; background papers for, collected abstracts of, and/or summary reports of scientific meetings; and simple bibliographies. Issues receive internal scientific review, but no technical or copy editing.

Resource Survey Report (formerly *Fishermen's Report*) -- This information report is a quick-turnaround report on the distribution and relative abundance of selected living marine resources as derived from each of the NEFSC's periodic research vessel surveys of the Northeast's continental shelf. There is no scientific review, nor any technical or copy editing, of this report.

OBTAINING A COPY: To obtain a copy of a *NOAA Technical Memorandum NMFS-NE* or a *Northeast Fisheries Science Center Reference Document*, or to subscribe to the *Resource Survey Report*, either contact the NEFSC Editorial Office (166 Water St., Woods Hole, MA 02543-1026; 508-495-2228) or consult the NEFSC webpage on "Reports and Publications" (*http://www.nefsc.noaa.gov/nefsc/publications/*).