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Anticyclonic Warm-Core Gulf Stream Rings off the Northeastern United States during 1988

by

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Abstract

This annual report, the fifteenth in a series, summarizes formations, movements and life histories of warm-core rings in the slope water off the northeastern United States. In 1988, fifteen rings were present in the slope water, 12 of which formed in 1988; the remaining 3 rings were formed in 1987 and survived into 1988. This number of rings is higher than any of the previous fourteen reporting years. Life spans of individual rings ranged from 17 to greater than 170 days, with four rings having life spans of 30 days or less. All the rings which developed in 1988 formed east of 68° W longitude. Four survived into 1989.

This report summarizes for the fifteenth year, 1988, the movements of anticyclonic warm core Gulf Stream rings in the slope water region off the coast of the northeastern United States, primarily from Georges Bank and south of Nova Scotia to Cape Hatteras, North Carolina. Similar yearly analyses have been prepared for each of the preceding fourteen years, beginning with and generally following the methods described by Bisagni (1976).

Information Sources and Analysis Methods

This analysis is based primarily on data collected by the Advanced Very High Resolution Radiometer (AVHRR), a sensor aboard NOAA-9 and NOAA-11, two of the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. Two to three satellite passes covering the study area are potentially available each day, depending on the extent of cloud cover present. Using the processing facilities of the Oceanographic Remote Sensing Laboratory, University of Rhode Island, the high resolution (1 km) digital data are atmospherically and geometrically corrected and are en-

hanced to clearly identify thermal features. Oceanographic Analysis Charts prepared jointly by the NOAA National Weather Service and the National Environmental Satellite Data and Information Service (NESDIS) are used to help intepret the relative positions of thermal features. Opportunistic shipboard data received from scientists and fishermen are also integrated when available.

A base map showing locations of submarine canyons as well as zones used in the zonal analysis is provided in Figure 1. Ring center positions and tracklines are plotted in Figures 2-7, 9-13, and 15-18. Formation and destruction locations and other periodic positions are dated. At any time of the year, and especially in the summer, rings may not be visible in satellite imagery, because of lack of thermal contrast at the surface. When rings in close proximity to one another are not visible or are hidden by clouds for a number of weeks there may be uncertainty in distinguishing between the rings when they reappear. In such cases, the simplest interpretation of movements has been accepted.

Surface boundaries of rings are shown for the estimated date of formation and at representative stages in the life of the ring. The location of these boundaries involves errors of unknown magnitude, though every effort has been made to use various enhancement techniques to reduce these errors.

Only rings which occurred west of 60° W longitude during some portion of their lifetime are considered in this analysis. Rings are labelled with the year in which they formed or crossed 60° W, and alphabetically in the order of formation. This report includes only warm core rings formed when the Gulf Stream meanders to the north, then closes back on itself, trapping warm Sargasso Sea water in its core, and then breaks away from the Stream. Additional warm patches of water with apparent circulation appear periodically in the slope water region; however, since their formation is not in the above described manner, these are not labelled as warm core rings. These warm eddies are, therefore, not included in this report.

Ring Histories

A total of fifteen warm core Gulf Stream rings occurred in the slope water region between Cape Hatteras, North Carolina and 60° W longitude during 1988. Three of these rings formed in 1987 and the remainder formed in 1988. Four of the rings that formed in 1988 persisted into 1989. Estimated formation and destruction dates as well as lifespans for each ring are listed in Table 1.

Ring 87-H (Fig. 2) was generated from a Gulf Stream meander on about 4 October 1987 and crossed 60° W on about 20 October, centered at 41.5° N, 61.6° W. Throughout the rest of 1987, ring 87-H did not progress very far in the normal southwestward direction due to the presence of a large meander just to the west of the ring.

Because of persistent cloud cover over the area of this ring, all positions shown in Figure 2 were derived from the charts and not digital imagery. The positions shown on the charts were verified by digital imagery only twice during the period from January to March. Therefore, the locations, movements and size of ring 87-H as described below must be considered estimates.

In mid-January ring 87-H began interacting with a Gulf Stream meander. This process continued for several weeks, during which time the ring's location remained essentially unchanged. On 9 February, the ring broke away from the Gulf Stream once again and moved westward. At the beginning of March, the ring began interacting with the northwest extension of another large Gulf Stream meander which was forming ring 88-A. On 25 March, ring 87-H, located at approximately 40.9° N, 62.5° W, was resorbed by ring 88-A.

Ring 87-I (Fig. 3) formed on about 24 November near 39.8° N, 64.3° W from the same Gulf Stream meander that resorbed 87-G. By mid-December, the westward moving ring began interacting with a Gulf Stream meander. Clouds obscured the ocean surface until mid-January, when ring 87-I was observed entraining shelf water. Persistent cloud cover again obscured the area until mid-February. By this time, the ring had moved northeastward under the influence of the meander which was interacting with it. Its surface area was greatly reduced and its original surface diameter of 220 km decreased to 108 km in mid-February. The interaction with the Gulf Stream continued into early March, and by 9 March, only a small remnant of the ring remained, centered near 40.4° N, 64.9° W.

Ring 87-J (Fig. 4) formed from a Gulf Stream meander on 30 December 1987, centered at 38.5° N, 67.5° W. Cloud cover obscured the ocean during the majority of this ring's short lifespan. In mid-January, the ring was observed interacting with the Gulf Stream meander to its east, from which it formed, and entrainment of shelf water was evident. By 17 January, this interaction with the meander as well as the entrainment had subsided. During late January, ring 87-J began to interact with a Gulf Stream meander to its southwest, and its resorbtion by the Gulf Stream began. An estimated position on 9 February was centered at 38.8° N, 67.6° W. There was no evidence of this ring the next time this area was cloud-free in mid-February, and thus its resorbtion is estimated to have been around 11 February 1988.

Ring 88-A (Fig. 5) formed from the northwest extension of a large Gulf Stream meander on about 12 March (centered at 39.7° N, 62.3° W on 15 March). As ring 88-A formed, it resorbed ring 87-H before breaking away from the Gulf Stream in late March. When the ring formed it had a large surface diameter of 220 km, which later decreased in size.

Ring 88-A began progressing westward in early April. By mid-April, it was interacting with a Gulf Stream meander and on 19 April had a surface diameter of 160 km. The ring moved northward as it separated from the meander, then began moving southwestward in early May. The ring's progression was halted by a large Gulf Stream meander to the west of the ring, which later formed ring 88-E.

Throughout the rest of May, ring 88-A remained almost stationary, bounded by a Gulf Stream meander to the south and rings 88-E and 88-F to the west and east, respectively. Persistent cloud cover obscured the area from late May to early June, however it appears that ring 88-A was resorbed by a Gulf Stream meander on or about 1 June. The last known center position of the ring was reported on 25 May at 40.5° N, 62.9° W.

Ring 88-B (Fig. 6) was a very short-lived ring which formed from a Gulf Stream meander on 21 March, centered at 40.5° N, 63.5° W. Chart positions were again the primary source of data because of cloud cover. As the ring moved westward, it remained in close proximity to the meander. In early April, Ring 88-B began interacting with the same meander. Due to persistent cloud cover in the area, it was impossible to determine the exact location of the ring in mid-April. The last known location of 88-B was on 5 April at 39.5° N, 64.1° W. The ring was apparently resorbed on or about 14 April 1988 by a Gulf Stream meander and was not visible in clear imagery on 16 April.

Ring 88-C (Fig. 7) formed from a Gulf Stream meander on 31 March, centered at 38.8° N, 66.3° W. The ring broke away from the Gulf Stream almost immediately and was pushed to the northwest by the meander. At the end of April the ring began moving westward. Throughout this time the ring's size remained fairly constant at approximately 120 km diameter.

As ring 88-C moved westward, the surface expression elongated and gradually increased in size as it entrained cool slope water and shelf water, wrapping the cooler water along its eastern and southern borders. On 23 May, its surface diameter was 160 km. The ring remained relatively stationary for a couple of weeks in late May and began moving again in mid-June, this time in a southwesterly direction. By the end of June, the ring's surface expression was more rounded again.

In early July, a large mass of warm water was located along the northern border of ring 88-C. This warm pocket of water was not actually part of the ring, but it appeared to be pushed up from the Gulf Stream. Over a period of about two weeks the warm pocket decreased in size, eventually broke away and dissipated in the surrounding warm slope water. Meanwhile, the ring continued progressing southwestward throughout July and August.

The M/V Oleander crossed through ring 88-C on 7 July during an XBT survey. The vertical temperatue section (Fig. 8) from that transect confirmed the presence of

the ring. Within the ring, the 15° C isotherm deepened to a depth of 200 meters and the surface salinity reached a maximum of 35.6°/$_{oo}$ which indicates the influence of Gulf Stream waters through the center of the ring. During the 19 August Oleander cruise, ring 88-C had moved south of the ship's trackline and therefore was not detectable on the vertical section.

Persistent cloudiness obscured the area from late August through mid September, therefore it is impossible to determine the ring's exact movements and locations during this time. Based on chart locations and available imagery, ring 88-C apparently continued moving southwestward until early September. Then the ring began interacting with a meander of the Gulf Stream and was absorbed on or about 13 September at approximately 38.1° N, 73.4° W. Remnants of ring 88-C were visible in the slope water for two to three weeks after it was resorbed.

Ring 88-D (Fig. 9) was formed by a Gulf Stream meander on or about 12 April. Due to extensive cloud cover in the area during the period, the exact formation date and location are unknown, however it appears that ring 88-B was resorbed by ring 88-D as the latter was forming. On 19 April 88-D was centered at approximately 39.2° N, 64.0° W and had a large surface expression (240 km diameter). The ring was very short-lived. It never broke away completely from the Gulf Stream and travelled only a short distance. Ring 88-D, centered at approximately 38.9° N, 64.3° W, was resorbed by a large Gulf Stream meander on about 28 April.

Ring 88-E (Fig. 10) was formed from a meander of the Gulf Stream on about 11 May 1988. It was first centered at 40.0° N, 65.0° W, with a large surface expression of approximately 195 km. The ring started moving slowly southwestward, entraining shelf water along its border.

Throughout May, June and July, ring 88-E continued moving southwestward, remaining fairly constant in size but becoming more elongated in shape. The ring apparently continued entraining shelf water and slope water throughout this time.

In late August, the surface area of ring 88-E started decreasing in size. By mid September it slowed considerably in its southwest progression. At the end of September, the ring began interacting with a meander of the Gulf Stream and was pushed slightly northward by the meander. On or about 13 October, ring 88-E, centered at 39.3° N, 70.4° W, was resorbed by this meander.

Ring 88-F (Fig. 11) was a very short-lived ring which formed on about 28 April 1988, centered at 41.8° N, 56.7° W. The ring crossed 60° W on about 10 May and was subsequently designated as 88-F. The last known center position of the ring was on 15 May at 41.3° N, 61.1° W. Due to extensive cloud cover in the area, it is difficult to determine the exact destruction date or location, however, 88-F was apparently resorbed

by a Gulf Stream meander on about 22 May. Imagery from 23-25 May shows ring remnants in the area of 88-F.

Ring 88-G (Fig. 12) formed from a large meander on 5 June. On 7 June, it was centered at 40.3° N, 63.0° W, and had a surface diameter of approximately 200 km. The ring separated from the Gulf Stream almost immediately and was pushed northeastward by the northwest extension of a meander which was just west of the ring. The ring began interacting with the meander by 16 June.

Ring 88-G maintained its relative position with respect to the meander throughout June as it continued moving slightly northward. By early July, a very large Gulf Stream meander started forming another ring (88-H). Meanwhile, as 88-G interacted with this meander, the ring's surface diameter decreased to 125 km. On 14 July, ring 88-G, centered at 41.2° N, 63.5° W, was resorbed into the meander.

Ring 88-H (Fig. 13) formed from a large Gulf Stream meander on 15 July centered near 40.6° N, 63.0° W, resorbing ring 88-G as it formed. Ring 88-H was a comparatively large ring, with a surface diameter of approximately 266 km on 21 July. This ring moved westward just north of the Gulf Stream, having limited interactions with the Gulf Stream. By 3 September the surface diameter of the ring had decreased to approximately 192 km. In mid-September, ring 88-H began interacting with a large Gulf Stream meander to its south, entraining Gulf Stream water around the ring for several days. By 20 September, the ring had moved west of the meander and its interactions with the Stream subsided. In early October, ring 88-H was bounded by a northward building meander to its east and by ring 88-E interacting with another Gulf Stream meander to the west, thereby confining 88-H's movement. By mid-October, these meanders had propagated eastward, and ring 88-H began moving westward, entraining Gulf Stream water from a meander to its east. From late October to mid-November, ring 88-H entrained shelf water and wrapped it around most of the surface boundary of the ring. By early December, the surface expression of the ring had diminished to approximately 48 km diameter, and the shelf water entrainment was no longer evident.

On 2 December, the M/V Oleander crossed through ring 88-H during an XBT transect. The vertical temperature section from that transect (Fig. 14) shows a deepening of the isotherms and an increase in surface salinity throughout the area of the ring. The 15° C isotherm extended to below 280 meters and the surface salinity in the ring was more than 36‰, indicating the influence of Gulf Stream/Sargasso Sea water in the ring.

On 31 December, the ring, centered at 38.2° N, 73.0° W, had become very elongated in an east-west direction and was exhibiting strong slope water entrainment. This ring continued moving southwestward and persisted into 1989.

Ring 88-I (Fig. 15), formed from a large Gulf Stream meander on about 1 Septem-

ber centered near 40,5° N, 62.0° W. During its formation, ring 88-I partially absorbed an unnamed ring northeast of it. Throughout its short lifespan, ring 88-I continued to interact strongly with the Gulf Stream, though its own circulation was evidenced by the entrainment of shelf water and slope water wrapped around its northeastern boundary. Ring 88-I continued interacting with this meander, moving to the east with the meander throughout the majority of the ring's life. By late September, the interaction with the Gulf Stream had weakened this ring considerably so that only a small patch of warm water exhibiting some entrainment of slope water was seen on 28 September. Ring 88-I was resorbed by the Gulf Stream meander on about 30 September near 41.0° N, 59.4° W.

Ring 88-J (Fig. 16) formed from a Gulf Stream meander on 8 November, centered at 39.7° N, 61.1° W. At the time of its formation, the surface diameter of this ring was approximately 278 km. Clouds obscured the area until late November, and when the ring was seen on 26 November, its surface diameter had been reduced to approximately 76 km. Apparently, ring 88-J had broken off from the main body of the meander from which it formed, and continued to move to the southwest as a much smaller ring. Interactions with this meander occurred throughout December, as the ring increased in size. By 30 December, the ring, centered near 39.1° N, 67.1° W, ceased interacting with the Gulf Stream. The ring continued progressing southwestward and persisted into 1989.

Ring 88-K (Fig. 17) formed from a Gulf Stream meander on 14 November, centered near 39.8° N, 66.0° W. The rotational strength of this ring was demonstrated through the surface expression of entrainment of shelf water wrapped around most of the perimeter of the ring throughout November and December, as the ring moved in a westward direction. Shortly after formation, the major axis of this elliptical ring was directed in a northwest-southeast direction. By early December, its orientation became northeast-southwest, and by mid-December, the original orientation was observed. Ring 88-K continued into 1989, and was centered near 39.4° N, 70.0° W on 31 December 1988.

Ring 88-L (Fig. 18) formed from a large Gulf Stream meander on about 14 December, though the exact date of formation is estimated due to cloud cover. On 20 December, the ring was centered at 40.4° N, 63.1° W. The same meander which formed 88-L also spawned Ring 88-J a month earlier. Ring 88-L continued to interact with this meander throughout December thereby inhibiting its movement. This ring, which continued into 1989, was centered near 40.1° N, 63.7° W on 30 December.

Zonal Analysis

A generalized summary of the movements of rings during 1988 is presented in Table 2. This summary shows mid-month positions of the rings with respect to the zones diagrammed in Fig. 1. There were 35 total zone-month occurrences. During the years 1975-1986, the total zone-month occurrences ranged from a low of 24 in 1974 to a high

of 51 in 1982 and 1983, with a mean of 38. Two rings occupied the same zone at mid-month only once in 1988. This is the fourth consecutive year that no rings have occupied Zone 8.

Composite Tracklines of Ring Center Positions and Envelope of Surface Boundaries

A composite of tracklines of all ring center positions, and an envelope of ring surface boundaries appear in Fig. 19. The envelope was developed from boundary positions digitized from satellite data and from weekly analysis charts. Of the twelve rings which formed in 1988, six rings formed east of 63° W (88-A, 88-F, 88-G, 88-H, 88-I, 88-J); four formed between 63° W and 65° W (88-B, 88-D, 88-E, 88-L); and the remaining two formed west of 65° W. Of the total fifteen rings which occurred in 1988, eight rings never moved west of 65° W; four others never moved west of 70° W; and only three (88-C, 88-E, 88-H) travelled west of 70° W.

Number of Rings, Times of Formation, and Longevity

Twelve warm core Gulf Stream rings formed during 1988 off the northeast coast of North America. During 1974-1987, ring formation averaged nine per year, ranging from a minimum of five in 1974 to a maximum of eleven in 1979 and 1982. Three rings that formed in 1987 survived into 1988. Of the twelve rings that formed in 1988, four had formed and crossed 60° W by the end of April, one ring (88-F) formed in April and crossed 60° W in May, four formed from May through September, and three formed after early November. Longevity of the rings formed in 1988 ranged from 17 days to greater than 170 days with four rings having life spans of 30 days or less. Four rings persisted into 1989.

Acknowledgements

We would like to thank Glenn Strout of the Marine Climatology Investigation (MCI), NMFS/NOAA for his extensive work in digitizing the ring boundaries. Also, We would like to thank Glenn and Robert Benway also of MCI, for providing the hydrographic vertical sections from the XBT surveys.

REFERENCE

Bisagni, J. J. 1976. *Passage of anticyclonic Gulf Stream eddies through Deepwater* Dumpsite 106 during 1974 and 1975. NOAA Dumpsite Evaluation Report 76-1, 39 pp.

Table 1. Ring Formation and Destruction Dates, and Life Spans.

Ring	Dates	Life Span (days)
87-H	(10/4/87) - 3/25/88	194
87-I	11/24/87 - (3/10/88)	106
87-J	12/30/87 - (2/11/88)	44
88-A	3/12/88 - (6/1/88)	82
88-B	3/21/88 - (4/14/88)	25
88-C	3/31/88 - 9/13/88	167
88-D	(4/12/88) - (4/28/88)	17
88-E	(5/11/88) - (10/13/88	156
88-F	(4/28/88) - (5/22/88)	25
88-G	6/5/88 - 7/14/88	40
88-H	7/15/88 - Continued into 1989	>170
88-I	9/1/88 - 9/30/88	30
88-J	11/8/88 - continued into 1989	>55
88-K	11/14/88 - continued into 1989	>48
88-L	(12/14/88) - continued into 1989	>18

Dates not in parentheses are accurate to within two days.
Dates in parentheses could be off by greater than one week, as clouds obscured the sea surface.

Table 2. Ring positions at mid-month with respect to zone during 1988.

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	87-H		87-H						88-I			
2		87-H	88-A 88-B	88-A	88-A	88-G	88-G				88-J	88-L
3	87-I	87-I		88-D	88-E			88-H			88-K	88-J
4	87-J			88-C		88-E	88-E		88-H			
5					88-C	88-C		88-E	88-E	88-H		88-K
6							88-C	88-C			88-H	88-H
7									88-C			
8												

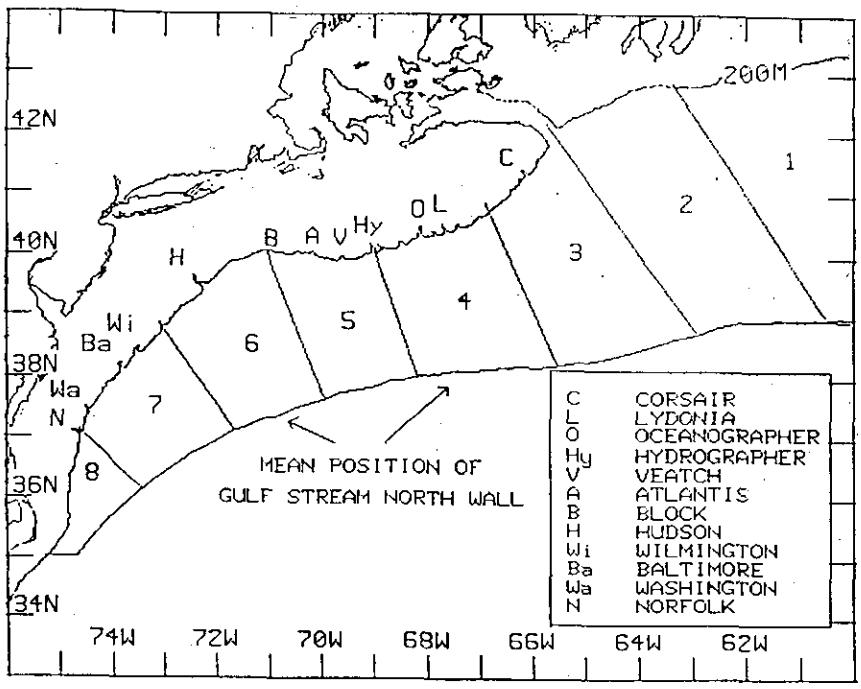

Figure 1. Base map for ring tracklines, showing canyon names and zones used in Table 2.

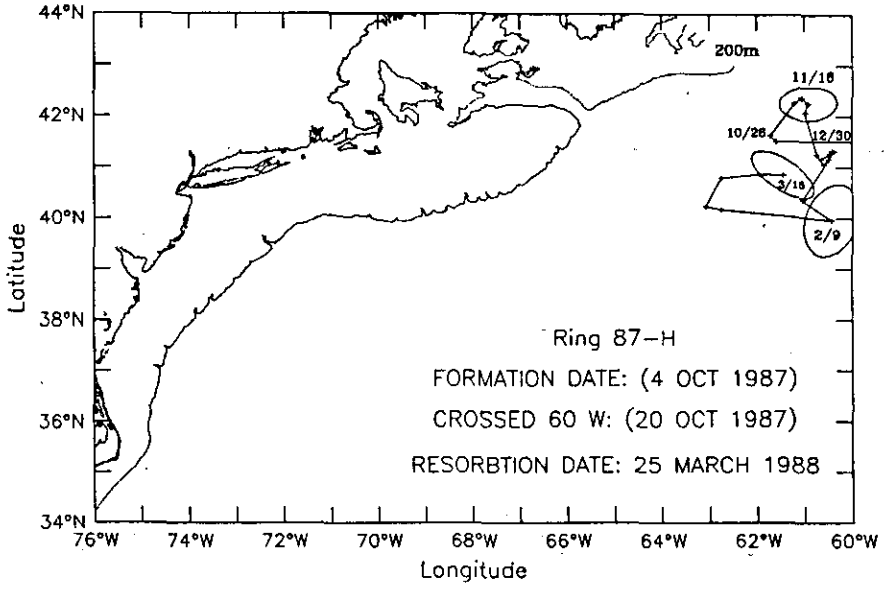

Figure 2. Trackline of Ring 87-H.

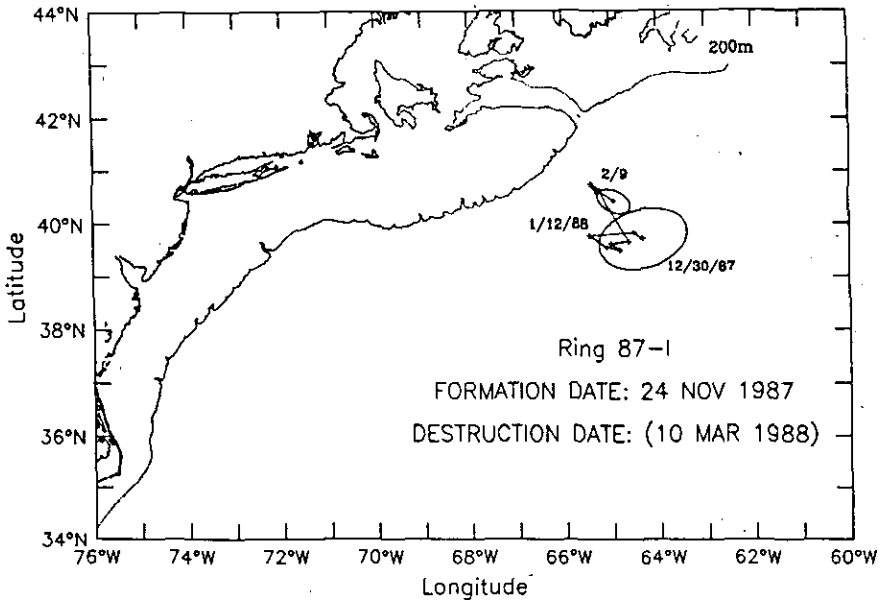

Figure 3. Trackline of Ring 87-I.

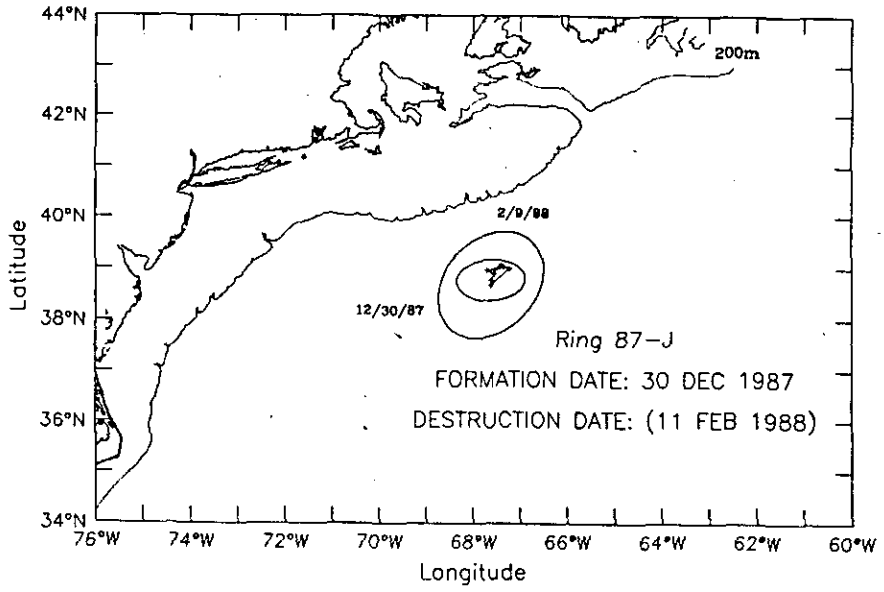

Figure 4. Trackline of Ring 87-J.

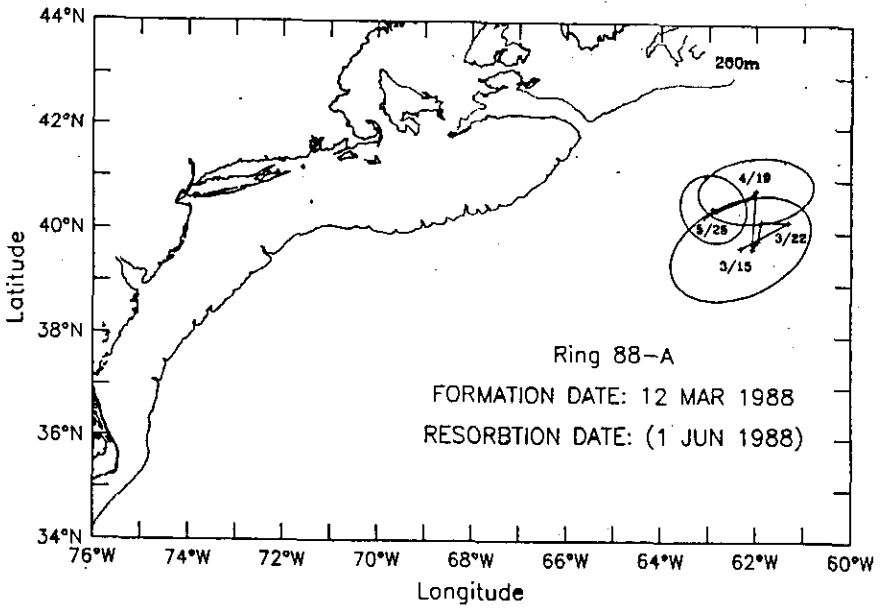

Figure 5. Trackline of Ring 88-A.

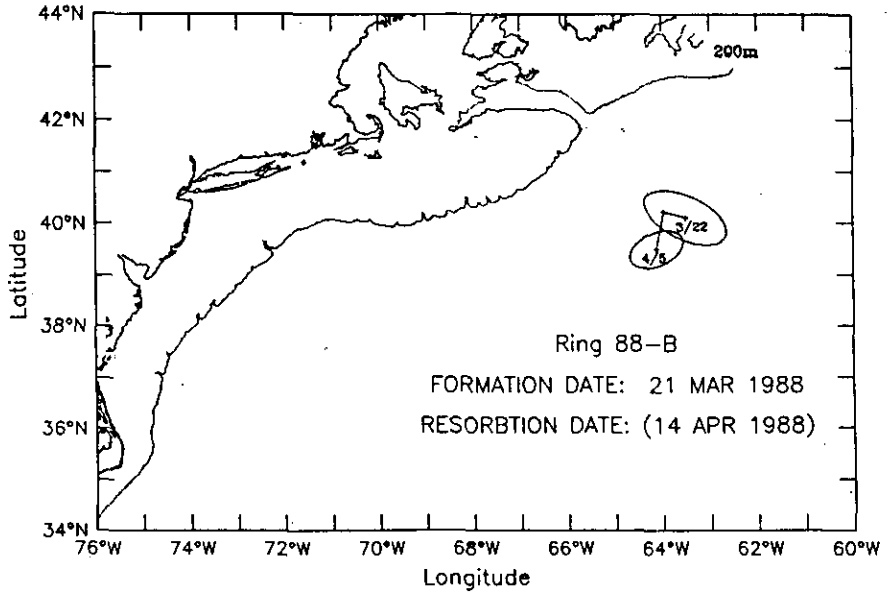

Figure 6. Trackline of Ring 88-B.

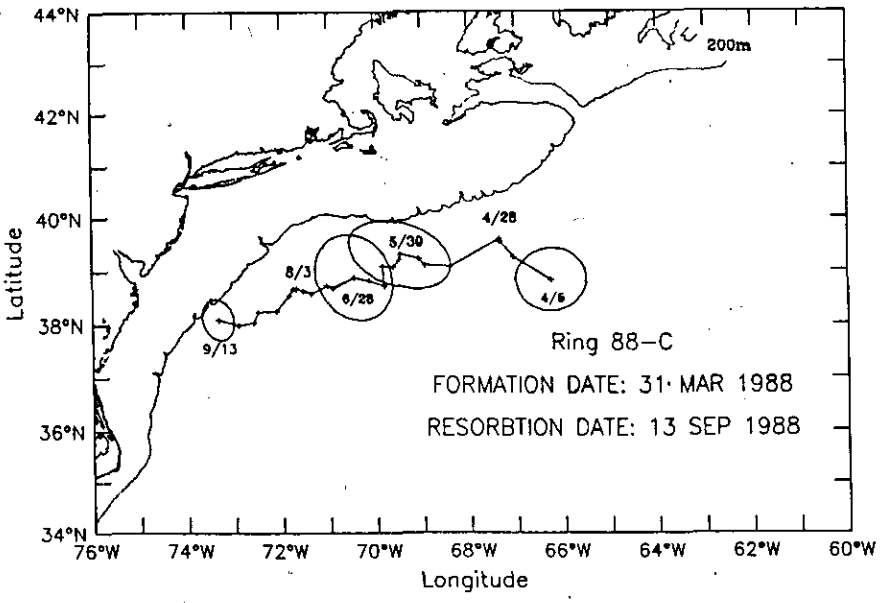

Figure 7. Trackline of Ring 88-C.

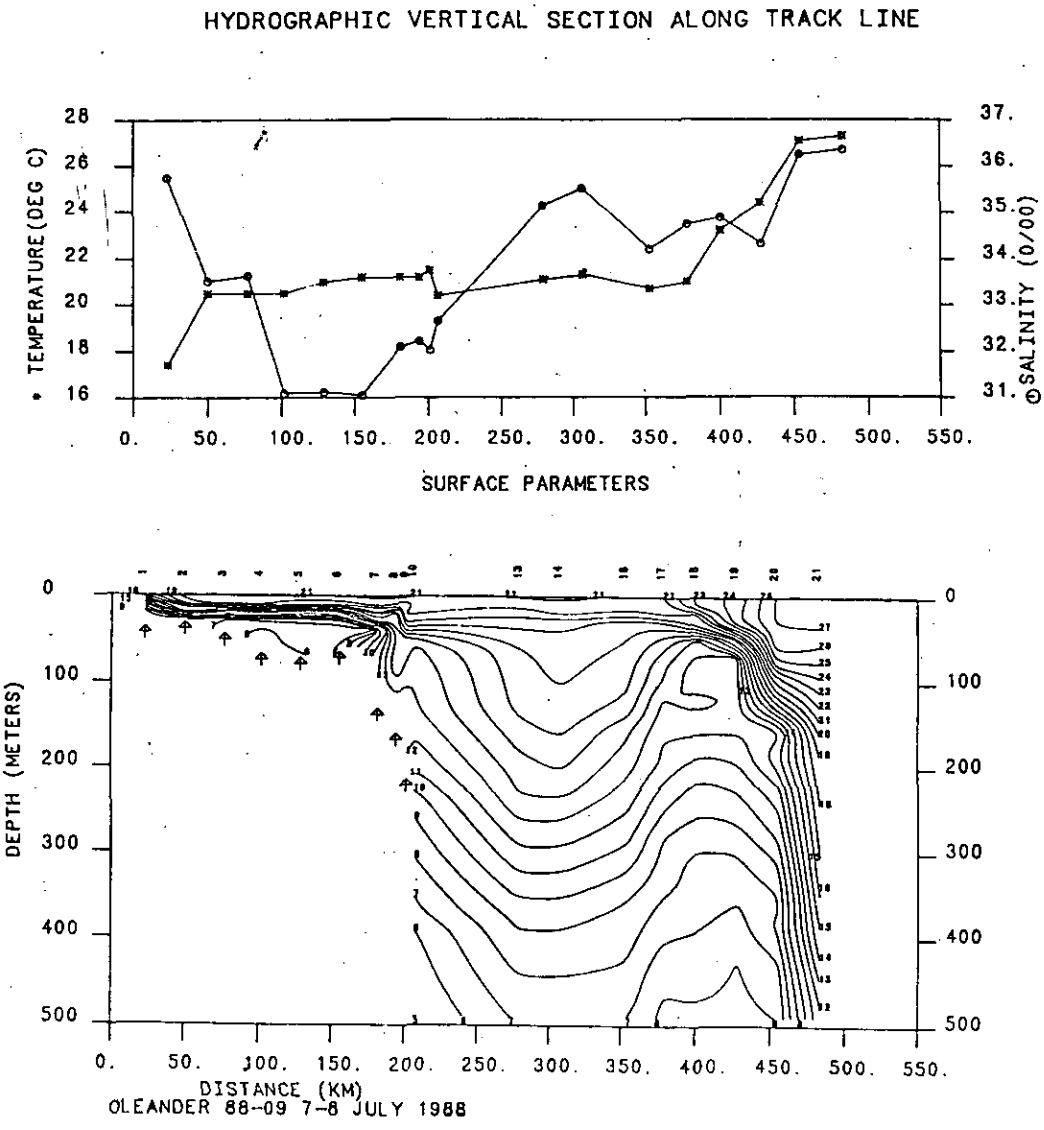

Figure 8. Hydrographic data from M/V Oleander XBT Survey 7/7/88.

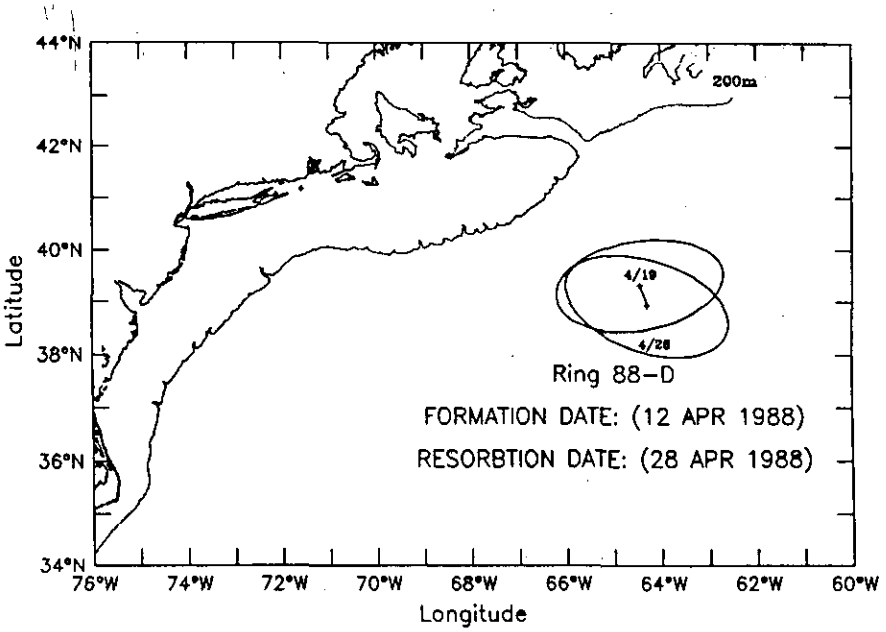

Figure 9. Trackline of Ring 88-D.

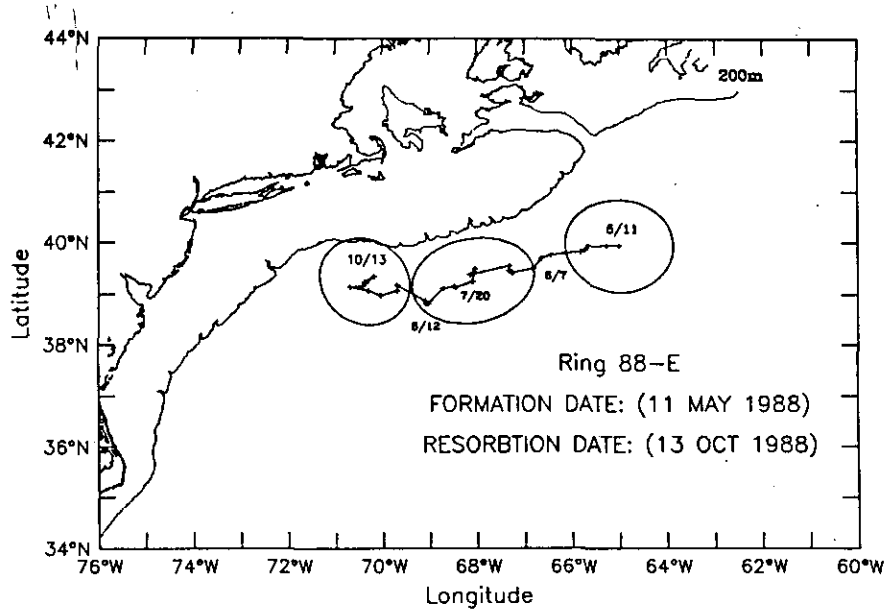

Figure 10. Trackline of Ring 88-E.

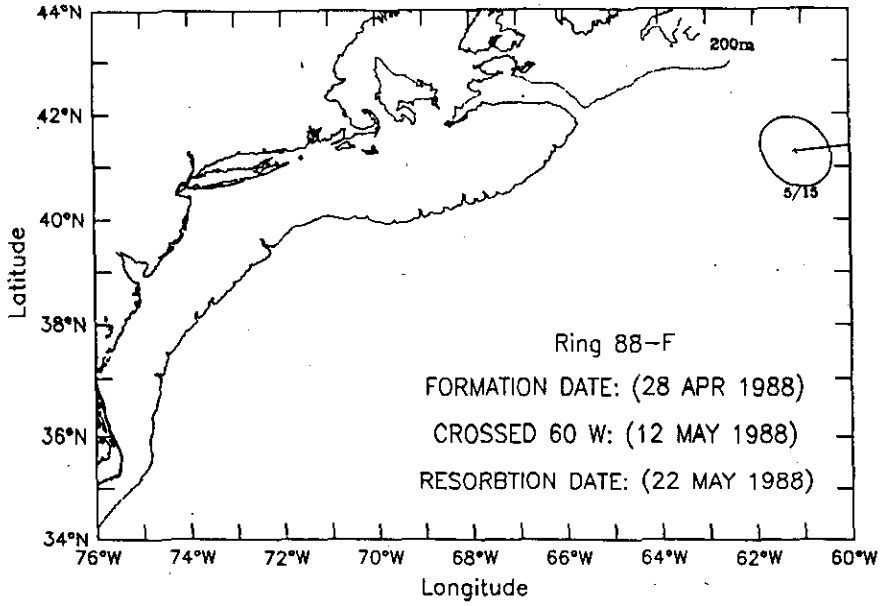

Figure 11. Trackline of Ring 88-F.

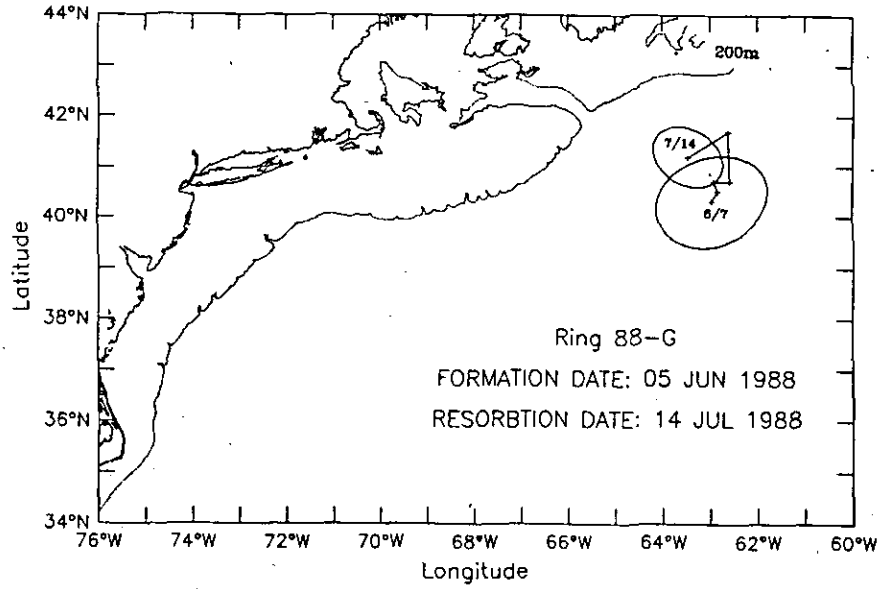

Figure 12. Trackline of Ring 88-G.

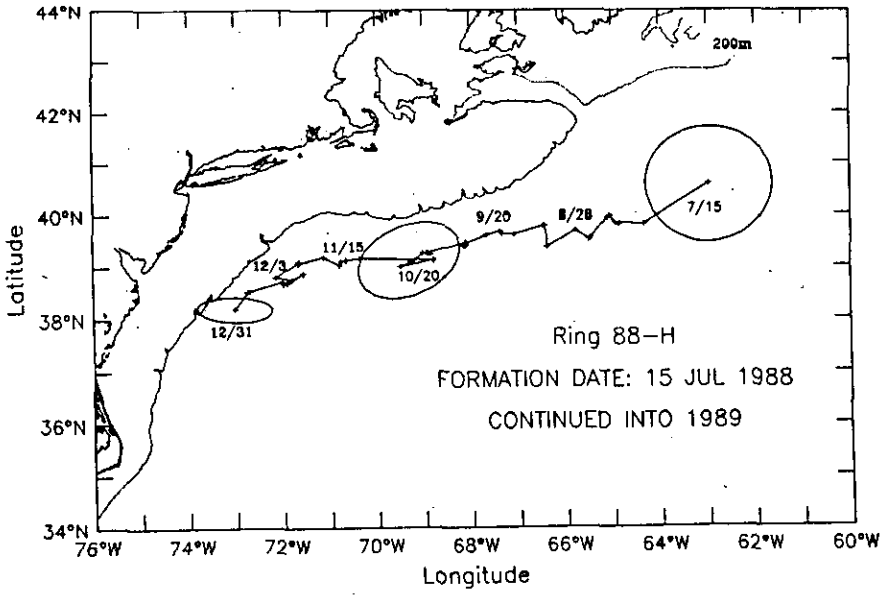

Figure 13. Trackline of Ring 88-H.

HYDROGRAPHIC VERTICAL SECTION ALONG TRACK LINE

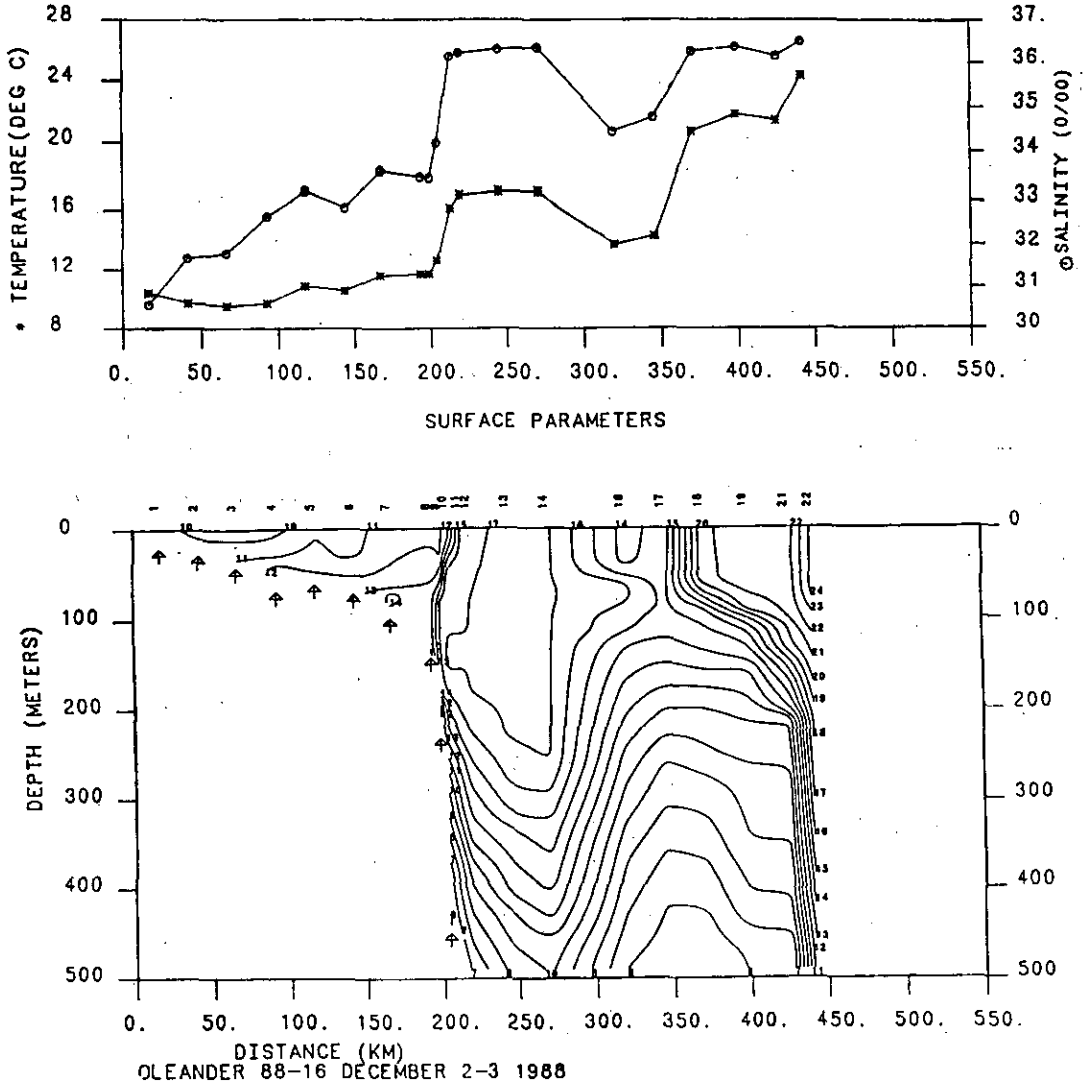

Figure 14. Hydrographic data from M/V Oleander XBT Survey 12/2/88.

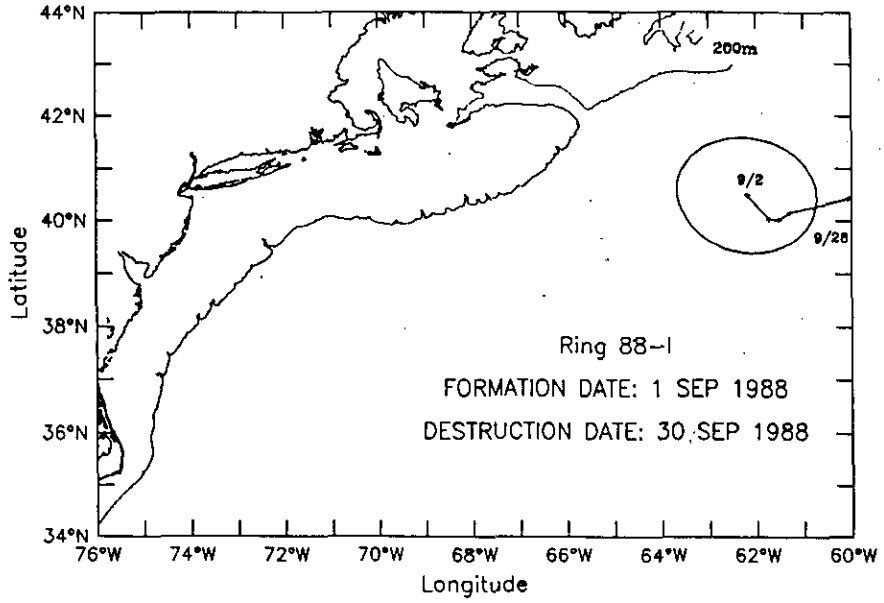

Figure 15. Trackline of Ring 88-I.

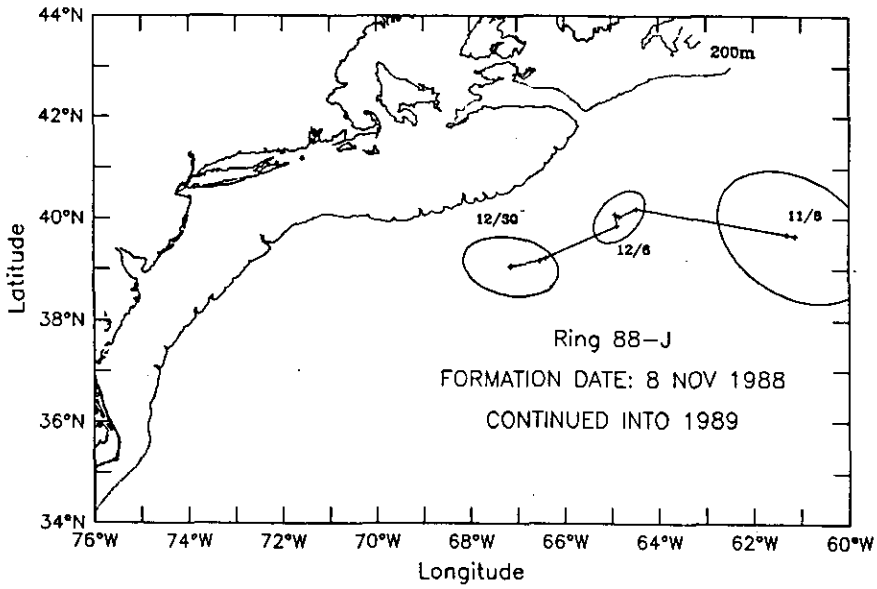

Figure 16. Trackline of Ring 88-J.

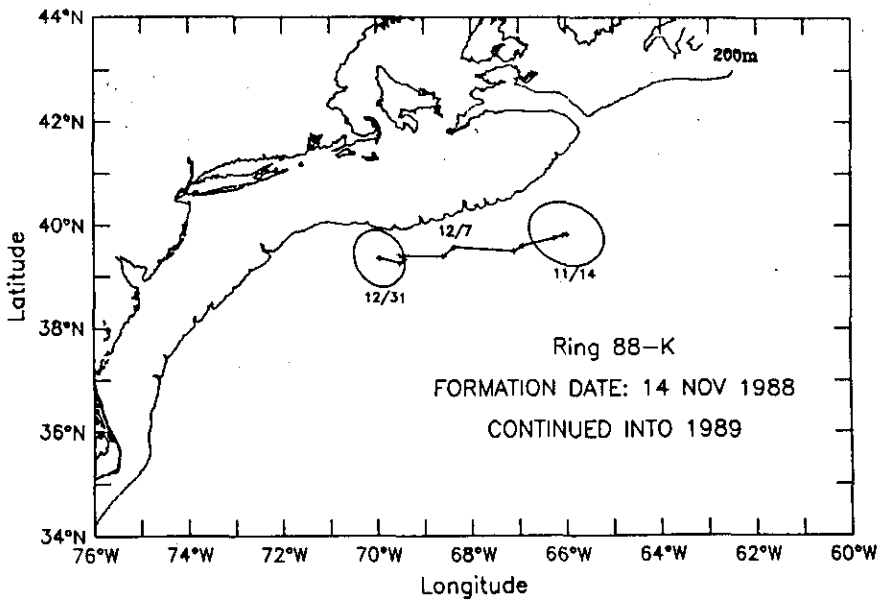

Figure 17. Trackline of Ring 88–K.

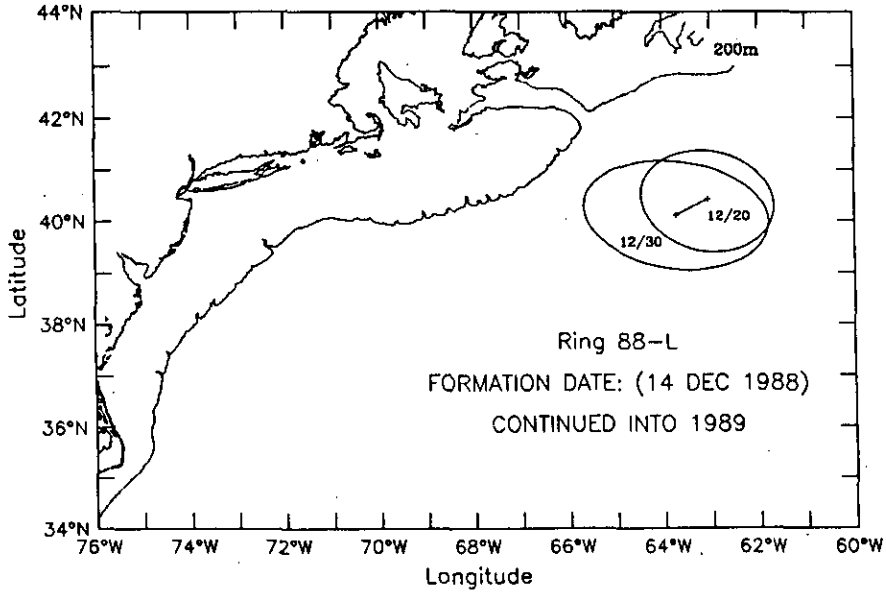

Figure 18. Trackline of Ring 88–L.

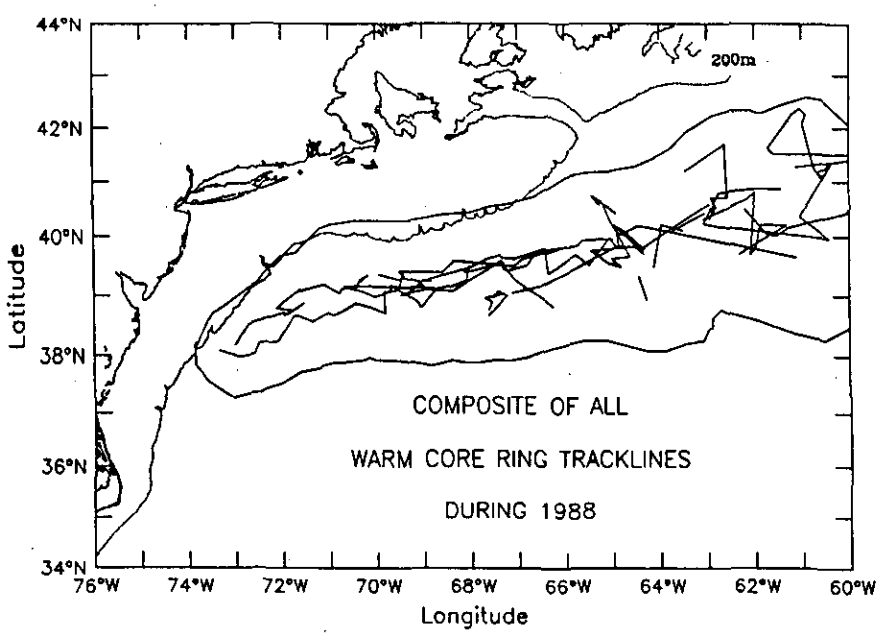

Figure 19. Composite of all Tracklines and Envelope of Ring Positions.