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Anticyclonic Warm-Core Gulf Stream Rings off the Northeastern United States during 1989

by

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Abstract

This annual report, the sixteenth in a series, summarizes formations, movements and life histories of warm-core rings in the slope water off the northeastern United States. In 1989, fourteen rings were present in the slope water, ten of which formed in 1989; the remaining four rings were formed in 1988 and survived into 1989. Life spans of individual rings ranged from 18 to 186 days, with four rings having life spans of 30 days or less. All the rings which developed in 1989 formed east of 69°W longitude. Only one ring survived into 1990.

This report summarizes for the sixteenth year, 1989, 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 fifteen 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-11, one 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 enhanced to identify thermal features. Oceanographic Analysis Charts prepared by the NOAA National Ocean Service are utilized to help interpret the relative positions of thermal features. Opportunistic shipboard data received from scientists and fishermen also are integrated when available.

A base map showing submarine canyon locations and zones used in the zonal analysis is provided in Figure 1. Ring center positions and tracklines are plotted in Figures 2-4,6,8-17. 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 fourteen warm core Gulf Stream rings occurred in the slope water region between Cape Hatteras, North Carolina and 60° W longitude during 1989. Four of these rings formed in 1988 and the remainder formed in 1989. One of the rings that formed in 1989 persisted into 1990. Estimated formation and destruction dates as well as lifespans for the rings are listed in Table 1.

Ring 88-H (Fig. 2) formed from a large Gulf Stream meander on 15 July 1988 centered near 40.6° N, 63.0° W. Ring 88-H was a comparatively large ring, with a surface diameter of approximately 266 km on 21 July. On 31 December, the ring, centered at 38.2° N, 73.0° W, had become very elongated in an east-west direction and was exhibit-

ing strong slope water entrainment. This ring continued moving southwestward in early January and was resorbed by the Gulf Stream on 16 January 1989. Its last known position was centered at 36.7° N, 74.4° W on 14 January.

Ring 88-J (Fig. 3) formed from a Gulf Stream meander on 8 November 1988, centered at 39.7° N, 61.1° W. At the time of its formation, the surface diameter of this ring was approximately 278 km. By 30 December, the ring, centered near 39.1° N, 67.1° W, ceased interacting with the Gulf Stream. Clouds obscured the area for several days, but apparently the ring was resorbed in early January. An exact destruction date or location could not be determined because of extensive cloud cover. The last known position was centered at 38.4° N, 67.4° W on 7 January, but by 14 January only warm remnants of the ring remained.

Ring 88-K (Fig. 4) formed from a Gulf Stream meander on 14 November 1988, centered near 39.8° N, 66.0° W. The ring moved westward in the slope region for the rest of the year and was centered near 39.4° N, 70.0° W on 31 December 1988.

On 3 January 1989, ring 89-K was centered at 39.3° N, 70.3° W, with a surface diameter of 114 km. The ring continued to exhibit strong circulation, entraining large amounts of shelf and slope water. In late January and early February, warm Gulf Stream water spilled out of the north wall as the Stream meandered southward. This warm water moved westward under the influence of the ring. Meanwhile, excess shelf water from the entrainment formed a pool southwest of the ring.

The M/V Oleander passed through ring 88-k during an XBT survey on 3 February. Data from the Oleander (Fig. 5) show a surface salinity maximum of 35.9 ppt in the central area of the ring (reference distance 210 km on figure 5), indicating the influence of higher salinity Sargasso sea water. Further along the trackline (ref. dist. 300 km) the salinity dropped to 32.5 ppt, indicating the presence of shelf water entrained in the ring's northern half and carried along the ring's southern border. The vertical temperature profile also confirms the ring's location as evidenced by depression of the isotherms within the ring (ref. dist. 200-300 km).

Although cloud cover obscurred the area throughout much of February, ring 88-K apparently moved southward in the slope region. The ring's size continued to decrease until it was finally resorbed on about 7 March. The last known center position for ring 88-K was on 2 March at 37.2° N, 74.0° W.

Ring 88-L (Fig. 6) formed from a large Gulf Stream meander on about 14 December 1988, though the exact date of formation is estimated because of 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.

Ring 88-L was centered at 41.3° N, 64.9° W on 14 January. After remaining in the same general area for nearly a month, with a compact circular surface expression, the ring began a fairly rapid southwest movement, with translation between the 21 February and 2 March positions averaging nearly 13 km per day. This was accompanied by warming of slope waters to the east of the ring and an absence of meanders in the Gulf Stream. In mid-March, the ring was centered at about 40° N, 68° W and was interacting with a streamer of warm water which had broken out of the north wall of the Gulf Stream to the west of the ring. These warm steamers, known as shingles, occur periodically along the Gulf Stream's north wall.

From mid-March through May, the ring entrained large amounts of shelf and slope water, circulated around as much as three-fourths of the ring's boundary, and frequently interacted with warm shingles from the west. The diameter of the ring after passing 66° W, averaged about 86 km and nearly always was in contact with the shelf edge and the north wall of the Gulf Stream. Though surface evidence of ring circulation continued, thermal contrast between the ring center and the surrounding water was sometimes less than 1° C.

On 11 June, the ring was centered at 38.7° N, 72.4° W, and was about two-thirds surrounded by a warm shingle. An XBT transect through the northeast edge of the ring, by M/V Oleander on 10 June (Fig. 7), confirmed the extremely weak surface contrast of the ring seen in the satellite imagery. The ring was resorbed fully by the next clear scene on 17 June.

Ring 89-A (Fig. 8) formed from a Gulf Stream meander on 15 January and was centered at 40.6° N, 59.4° W. The ring crossed 60° W longitude on 2 February. It was very difficult to follow the progression of this ring because its location was so far to the east where cloud cover persisted for long periods of time. The area of the ring was only clear of clouds approximately once per three to four weeks on average. Therefore, the description and positions given here are estimates only.

Ring 89-A was a very large ring (224 km surface diameter) when it formed. It remained large for a few weeks as it began moving slowly westward. It continued interacting with the Gulf Stream during this time. The ring gradually decreased in surface diameter throughout February and March. A meander formed to its south in mid-March which prevented the ring from moving westward. Also, the ring was interacting with a portion of the Gulf Stream to the east which also restricted its westward progress.

In early April it became difficult to distinguish Ring 89-A's outer boundary from the surrounding slope water. The ring apparently moved a short distance to the west although it remained under the influence of the Gulf Stream meanders to either side of the ring. The ring was resorbed by a meander on 27 April. Its last known center position was 40.2° N, 64.6° W on 26 April with a surface diameter of 80 km.

Ring 89-B (Fig. 9) was a short-lived ring which formed along the western edge of a Gulf Stream meander on 3 June. The ring was first centered at 40.3° N, 64.8° W with a surface diameter of 100 km. Although the ring had detached from the Gulf Stream, it continued to be influenced by the meander. The ring moved slightly eastward and then traversed southward down the face of the meander. Meanwhile another meander formed to the west, trapping the ring between the two meanders. Ring 89-B was resorbed in the trough between the meanders on 21 June.

Ring 89-C (Fig. 10) was formed from a Gulf Stream meander on 24 June, centered at 39.2° N, 67.7° W. The ring began traversing westward, entraining shelf water along its eastern and southern borders. During this period 89-C was flanked to the west by a warm circulation feature and to the east by ring 89-D which had just formed.

89-C continued its westward movement in early July. In mid July a large meander located east of the ring moved northwestward pushing the ring with it. The meander continued building toward the ring and eventually resorbed ring 89-C. The exact resorption date could not be determined due to cloud cover, but, by 22 July the ring was no longer visible in the surrounding slope water. Its last known position was on 15 July centered at 39.7° N, 69.4° W.

Ring 89-D (Fig. 11) was another very short-lived ring. It formed from a meander on 28 June, and was centered at 39.7° N, 66.5° W. The ring detached from the Gulf Stream and began moving westward by early July. The meander from which 89-D formed moved northwestward, stopping the westward movement of the ring. Clouds obscured the area throughout much of the month, but apparently the meander resorbed 89-D in mid-July. By 11 July the ring had weakened considerably and was difficult to distinguish from the surrounding warm slope water. Imagery from 15 July showed only remnants of the ring.

Ring 89-E (Fig. 12) formed on about 22 July. Clouds obscured the area for the previous 10 days so the actual formation date could not be determined. The ring was centered at 41.6° N, 63.5° W after forming along the northeast edge of a northwest trending meander.

Ring 89-E continued interacting with the meander as the meander began pinching off to form a new ring. The ring appeared to split in early August and the main portion moved westward while the smaller portion was resorbed by the meander. By 10 August, the ring exhibited a stronger surface expression and better defined outer boundaries.

It was difficult to track the path of 89-E throughout much of mid- to late August because of cloud cover and poor thermal contrast with the surrounding waters. However, 89-E continued interacting with the large newly formed ring (89-H) to its south. Ring 89-H eventually absorbed much of 89-E and the remaining portion lost energy and dissi-

pated in the slope water. The last known position for 89-E was on 27 August, centered at 41.7° N, 64.8° W.

Ring 89-F (Fig. 13) formed along the northwestern edge of the same meander which generated ring 89-E. 89-F was first located at 40.3° N, 66.1° W on 24 July. The ring quickly broke away from the Gulf Stream and began moving westward. By the end of July the ring had a strong surface expression and a surface diameter of 114 km as it began entraining shelf water and circulating it along its eastern boundary.

Ring 89-F was pushed slightly northward by the large meander to the east and then the ring continued its westward movement. By mid-August 89-F was interacting with the meander. The meander pinched off to form 89-H which also interacted with ring 89-F. Ring 89-F was bounded to the west by ring 89-G and stopped moving westward. The ring decreased in size, and became elongated as it interacted with 89-H. Ring 89-F was absorbed by 89-H on 29 August at 39.8° N, 67.3° W. At the time its surface diameter was only 57 km.

Ring 89-G (Fig. 14) was a very large ring which formed from a Gulf Stream meander on 27 July, centered at 39.1° N, 68.7° W. The ring began moving northwestward, however its southeastern edge remained in contact with the meander. The ring's surface shape elongated to the west while continuing to interact with the meander to its east.

On 9 August the ring appeared to separate from the meander and began entraining shelf water along its eastern edge. Cloudy weather obscured the area for a few days, but apparently the ring started interacting with the meander again. During this time 89-G remained very large (178 km diameter) with a strong surface expression.

Clouds continued to obscure the area throughout much August, however it was possible to follow generally the ring's interaction with the meander. The meander was also very large and trended far to the west of its base connection with the Gulf Stream. Because of the ring's continued interaction with the meander it did not progress very far westward during August.

In early September Ring 89-G increased in size to 218 km surface diameter. Also, a long streamer of warm water was trending westward from the northern edge of the ring. This streamer had a sea surface temperature similar to the ring's SST. As the ring traversed westward the streamer dissipated and was no longer visible by the end of October.

The ring continued interacting with the meander which also remained large. By mid-September a new ring began forming from the meander. This new ring (89-I) also absorbed some of 89-G so that when the rings finally separated from the Gulf Stream in late September, the surface expression of 89-G had decreased to 140 km diameter.

Clouds obscured the area for several days in early October and the ring was not vis-

ible again until 13 October. As the ring moved through the slope water it entrained shelf water and carried the shelf water along its eastern and southern borders. Ring 89-G moved in a southwesterly direction during November. Clouds obscured the area from 14 November through 26 November, during which time the ring moved rapidly through the slope water. It was seen much further to the southwest on 27 November. The ring continued moving southward in December and its size continued to decrease. Clouds again obscured the area at the end of December, but 89-G apparently continued into 1990 (visible in early January, 1990). Its last known center position of 1989 was 37.8° N, 73.4° W on 15 December with a surface diameter of 63 km.

Ring 89-H (Fig. 15) formed as an extremely large ring on 12 August. It was first centered at 39.6° N, 64.6° W and had a surface diameter of 224 km. The ring immediately began interacting with 89-E to the north and 89-F to the east. By the end of August it had absorbed both 89-E and 89-F. On 31 August the ring began moving westward. Its surface expression had decreased to 175 diameter and its major axis had shifted to a more east-west orientation.

In early September ring 89-H continued to diminish in size. The ring was interacting with the eastern edge of the large meander which was also interacting with 89-G. The ring appeared to lose strength rapidly during this period and remained nearly stationary. The area was obscured by clouds in late September and early October, but apparently the ring was resorbed by the Gulf Stream on about 8 October. Clear imagery on 10 October showed that the ring was completely dissipated. The last known location of 89-H was on 2 October centered at 40.6° N, 65.9° W.

Ring 89-I (Fig. 16) formed from a large Gulf Stream meander which also was interacting with ring 89-G. 89-I was first centered at 39.3° N, 67.2° W on 22 September. Although the ring was initially quite large (surface diameter of 184 km), its surface expression decreased quickly and by 10 October it had a surface diameter of 89 km.

Ring 89-I moved slowly westward in September and October. It remained influenced by the Gulf Stream and by Ring 89-G to the west. The ring continued losing energy as evidenced by its decreasing surface expression throughout October. On or shortly after 24 October, the ring was resorbed by the Gulf Stream. The ring's last center position was 39.5° N, 68.6° W at which time its surface diameter was only 40 km.

Ring 89-J (Fig. 17) formed along the western edge of a meander on 17 October. It was first centered at 39.9° N, 64.0° W. The ring began to move westward, however it immediately lost strength as it continued interacting with the meander. The ring had a weak surface expression on imagery from 11 November through 15 November and was resorbed sometime after 15 November. Unfortunately, clouds obscured the area for the rest of the year so the resorption date is only an estimate.

Zonal Analysis

A generalized summary of the movements of rings during 1989 is presented in Table 2. This summary shows the rings' mid-month positions with respect to the zones diagrammed in Fig. 1. There were 24 total zone-month occurrences in 1989, the lowest total (along with 1974) in the sixteen years that these statistics have been calculated. The low zone-month total was because several rings were very short-lived. During 1974-1988, the total zone-month occurrences averaged 37 with a high of 51 occurrences in 1982 and 1983. No zone was occupied by more than one ring at mid-month in 1989. This is the fifth 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. 18. The envelope was developed from boundary positions digitized from satellite data. Of the ten rings which formed in 1989, only one formed east of 63° W (89-A); four formed between 63° W and 65° W (89-B,89-E,89-H,89-J); and the remaining five formed west of 65° W. Of the total fourteen rings which occurred in 1989, three rings never moved west of 65° W; seven others never moved west of 70° W; and four travelled west of 70° W.

Number of Rings, Times of Formation, and Longevity

Ten warm core Gulf Stream rings formed during 1989 off the northeast coast of North America. During 1974-1988, ring formation averaged nine per year, ranging from a minimum of four in 1974 to a maximum of fifteen in 1988. Four rings that formed in 1988 survived into 1989. Of the ten rings that formed in 1989, one had formed and crossed 60° W by the end of April, seven formed from June through September, and one formed in mid October. Longevity of the rings formed in 1989 ranged from 18 days to greater than 158 days with four rings having life spans of 30 days or less. Only one ring persisted into 1990.

Acknowledgements

We would like to thank Robert Benway and Glenn Strout of the Marine Climatology Investigation, NMFS/NOAA for providing the hydrographic vertical sections from the XBT surveys. Satellite image processing was performed at the Oceanographic Remote Sensing Laboratory, URI using software developed and maintained by O. Brown, R. Evans, J. Brown and A. Li at the University of Miami, FL.

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)
88-H	07/15/88 - 01/16/89	186
88-J	11/08/88 - (01/07/89)	62
88-K	11/14/88 - (03/07/89)	114
88-L	12/14/88 - 06/12/89	181
89-A	01/15/89 - 04/27/89	103
89-B	06/03/89 - 06/21/89	19
89-C	06/24/89 - (07/22/89)	29
89-D	06/28/89 - 07/15/89	18
89-E	07/22/89 - 08/29/89	38
89-F	07/24/89 - 08/29/89	36
89-G	07/27/89 - Continued into 1990	>158
89-H	08/12/89 - (10/09/89)	59
89-I	09/22/89 - 10/24/89	33
89-J	10/17/89 - (11/15/89)	30

Table 2. Ring Positions at Mid-Month with respect to Zone during 1989.

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1			89-A									
2				89-A				89-E			89-J	
3	88-L	88-L			89-B		89-H	89-H				
4			88-L				89-D	89-F		89-I		
5				88-L			89-C	89-G	89-G	89-G		
6	88-K	88-K			88-L	88-L					89-G	
7												89-G
8												

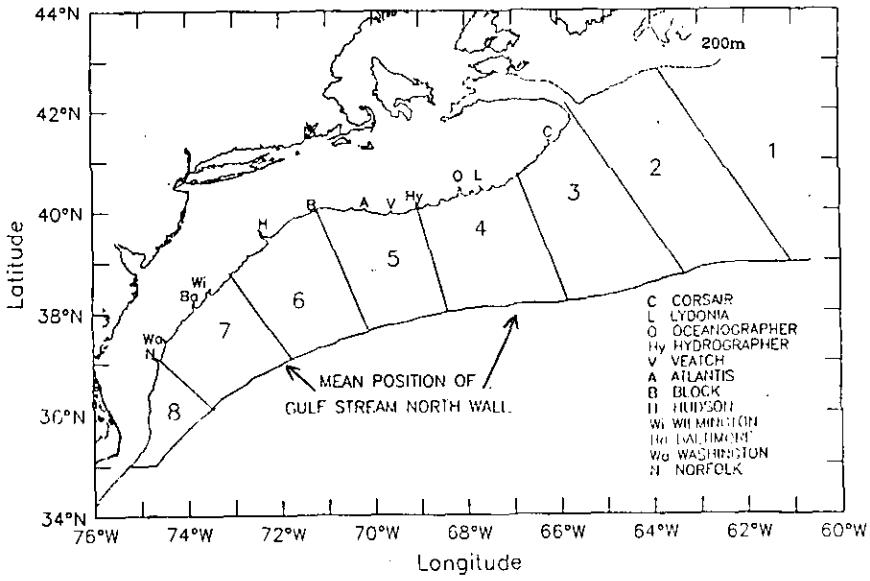

Figure 1. Base Map for ring tracklines, showing canyon names and zones used in Table 2.

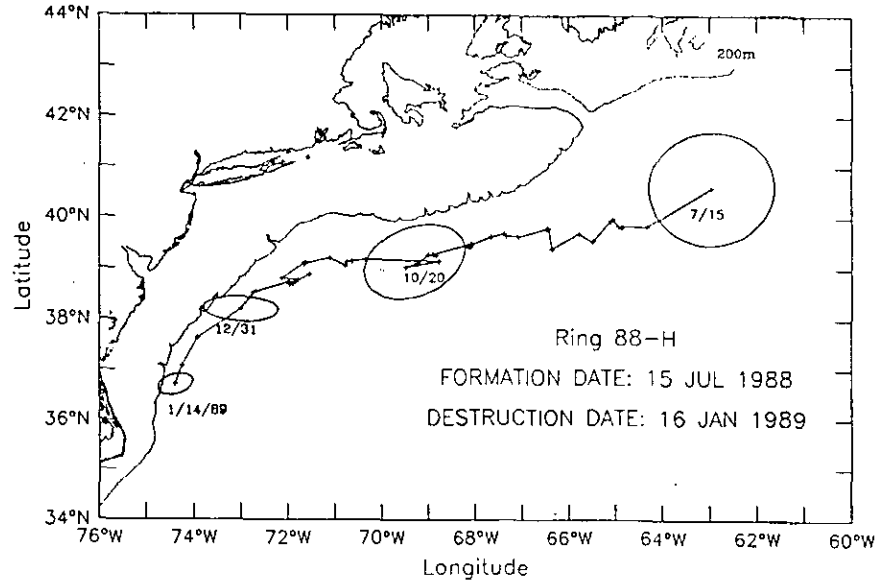

Figure 2. Trackline of Ring 88-H.

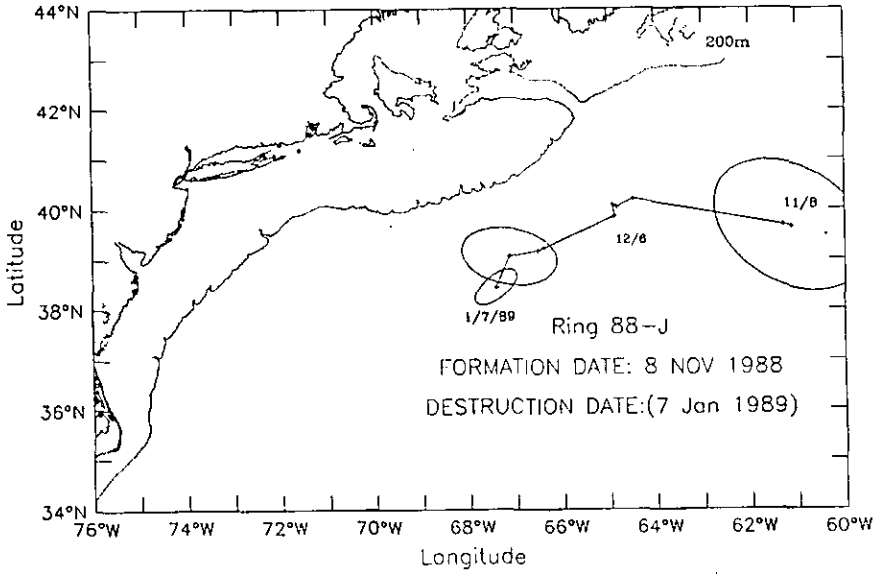

Figure 3. Trackline of Ring 88-J.

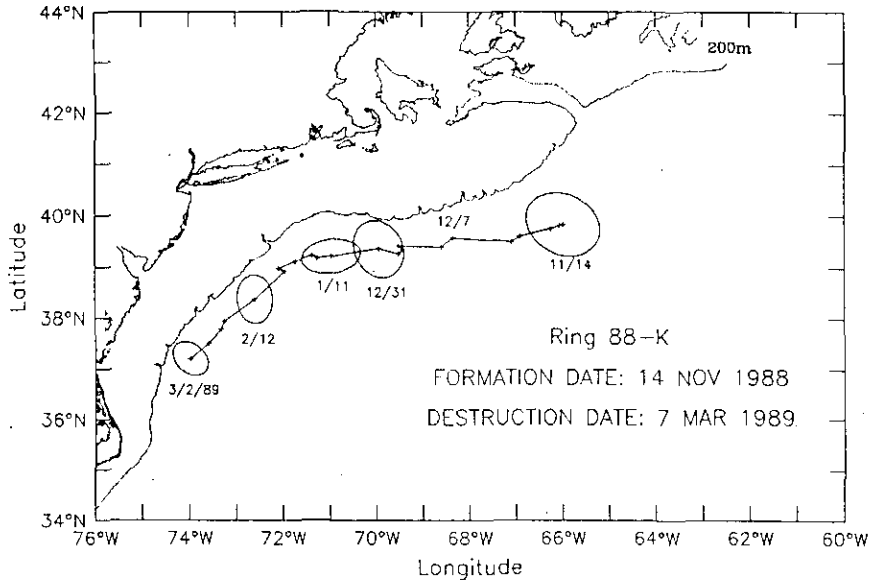

Figure 4. Trackline of Ring 88-K.

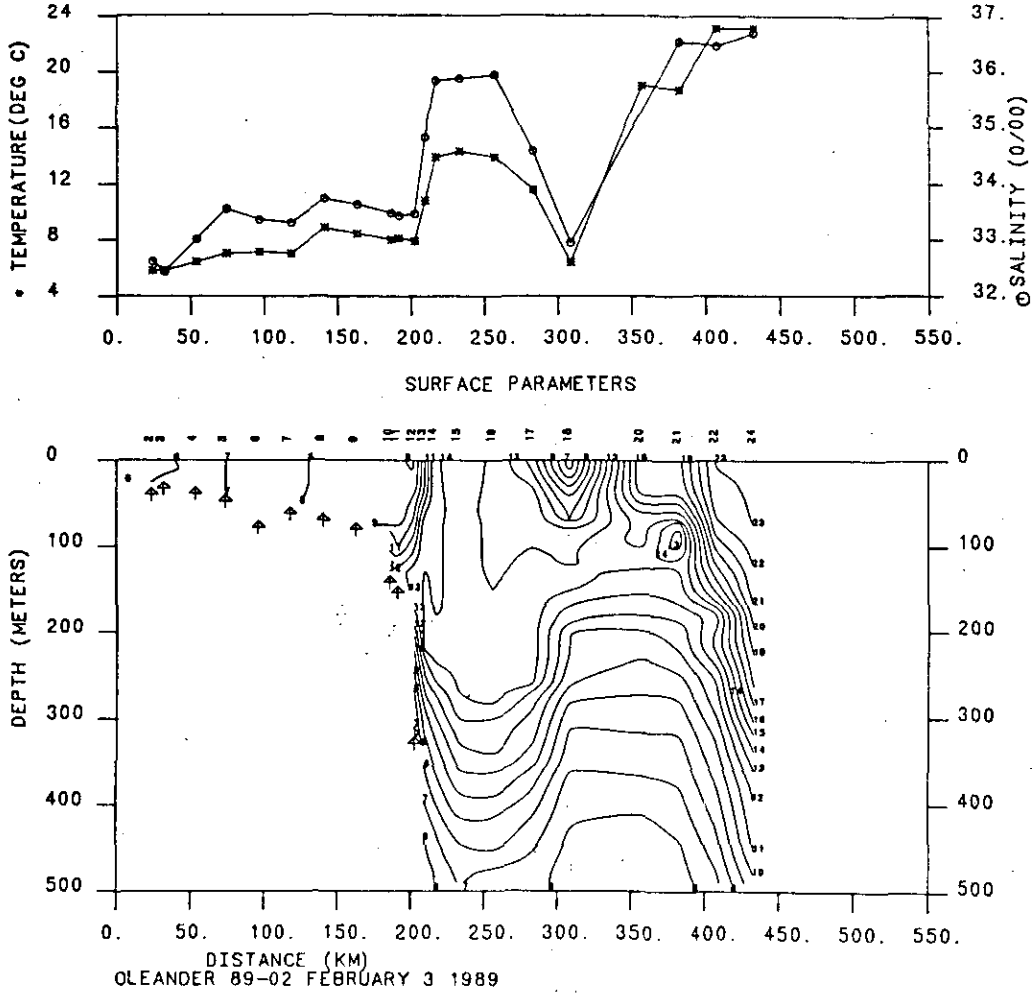

Figure 5. Surface and water-column conditions (temperature in $^{\circ}C$, salinity in parts per thousand) detected by M/V Oleander XBT survey on 3 February 1989.

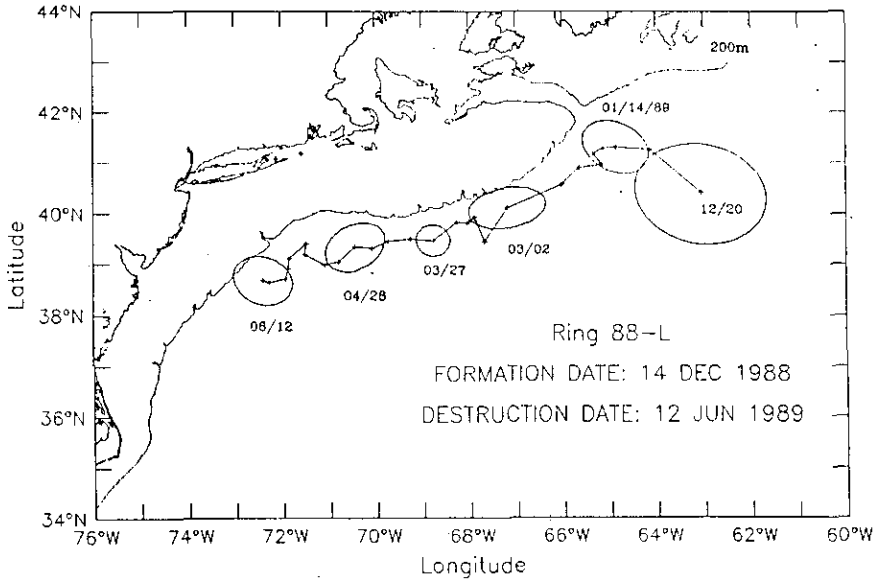

Figure 6. Trackline of Ring 88-L.

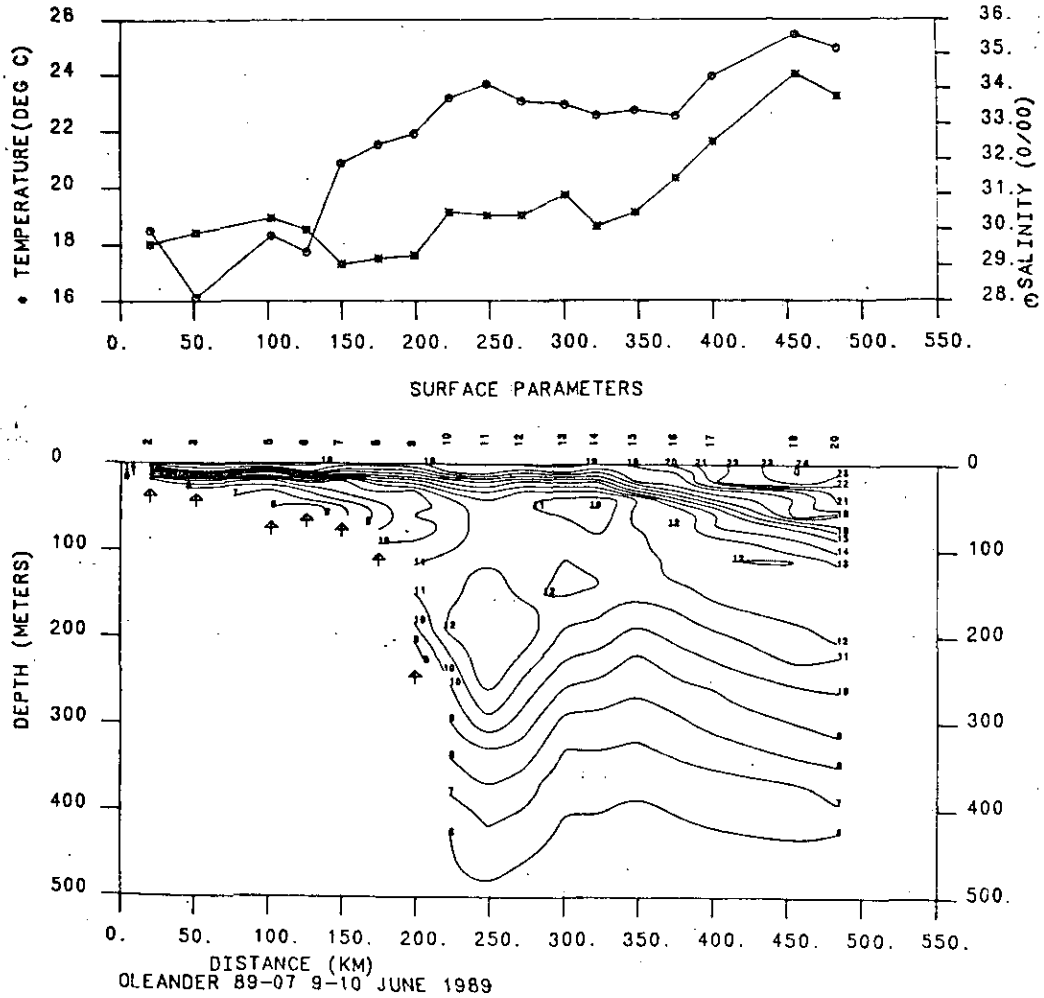

Figure 7. Surface and water-column conditions (temperature in $^{\circ}C$, salinity in parts per thousand) detected by M/V Oleander XBT survey on 9-10 June 1989.

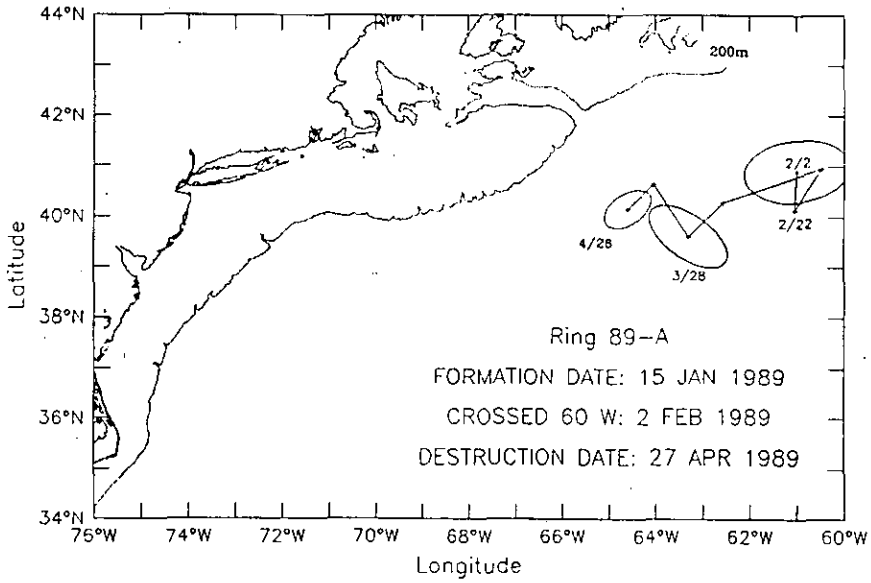

Figure 8. Trackline of Ring 89-A.

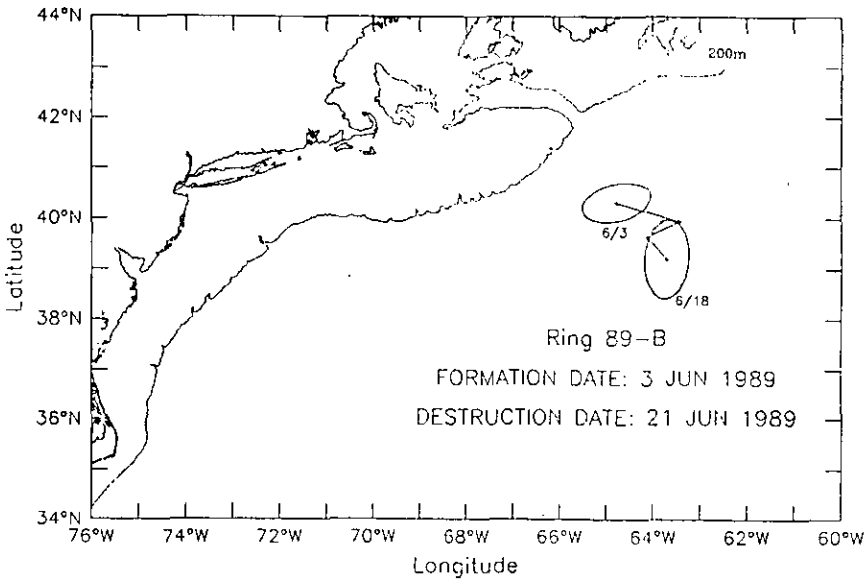

Figure 9. Trackline of Ring 89-B.

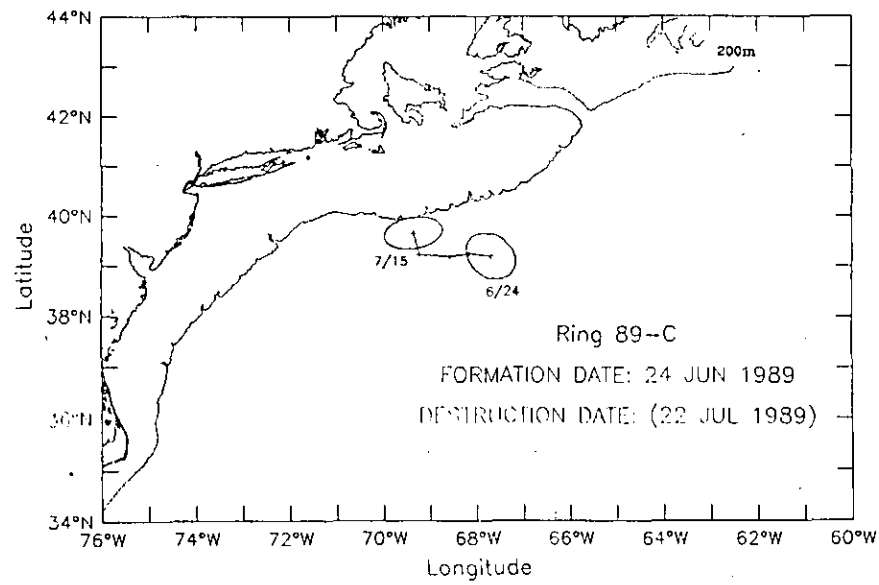

Figure 10. Trackline of Ring 89-C.

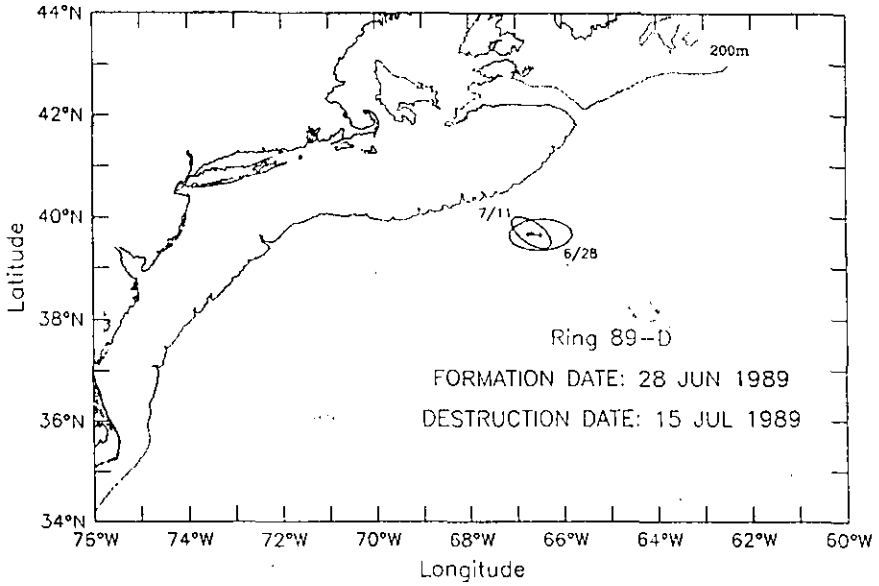

Figure 11. Trackline of Ring 89-D.

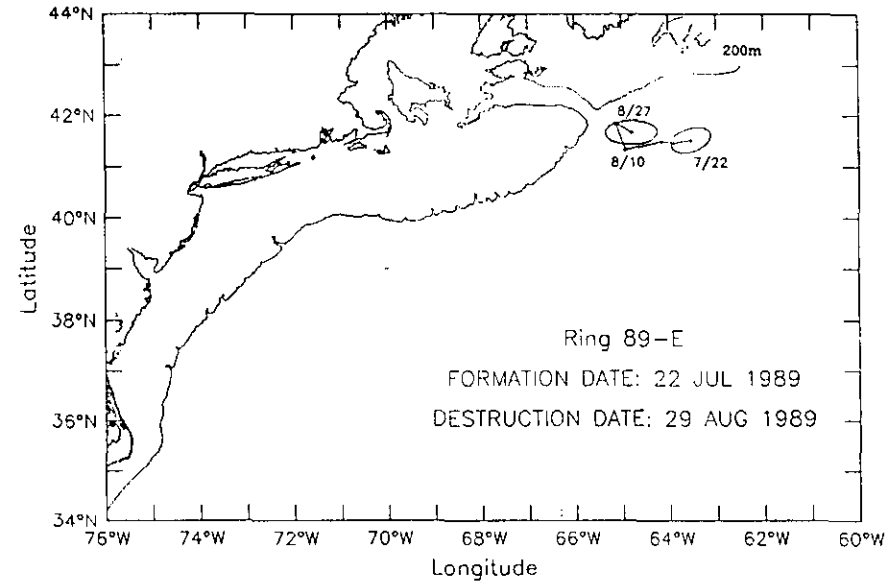

Figure 12. Trackline of Ring 89-E.

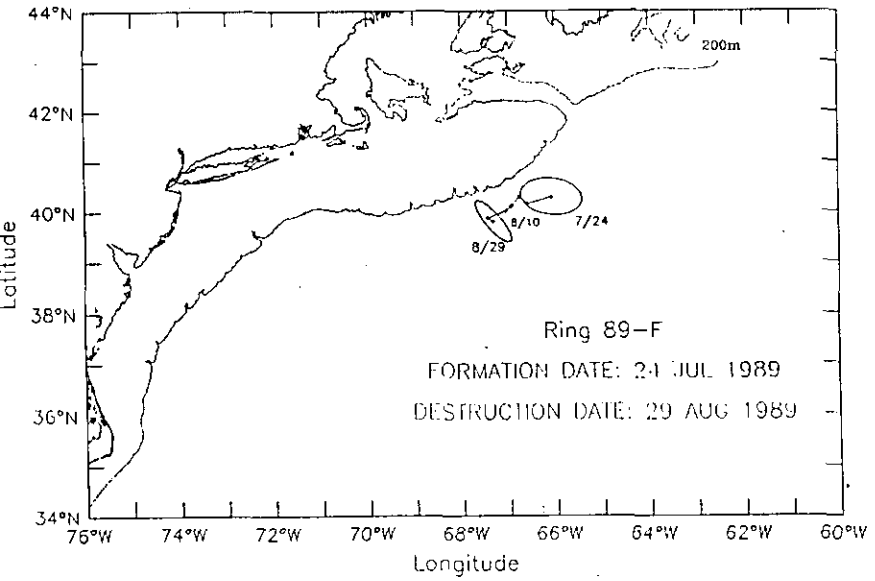

Figure 13. Trackline of Ring 89-F.

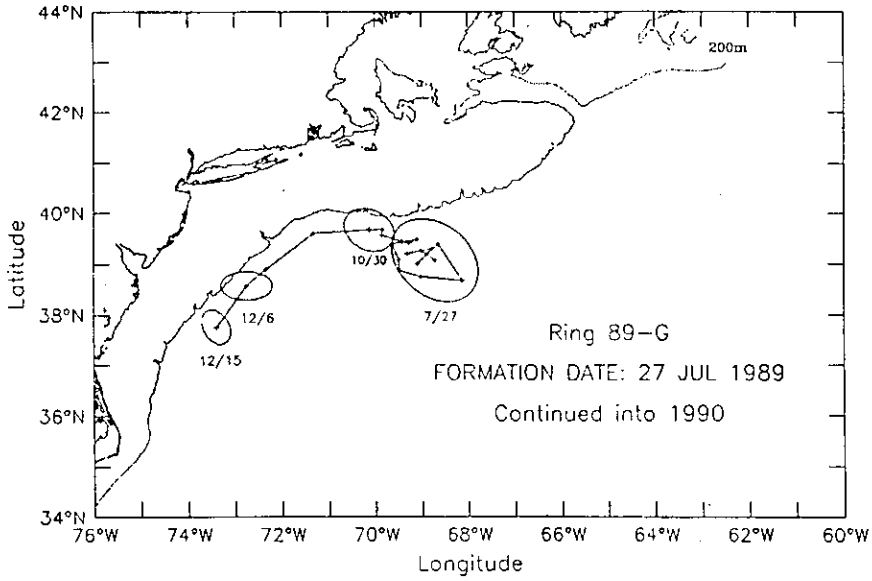

Figure 14. Trackline of Ring 89-G.

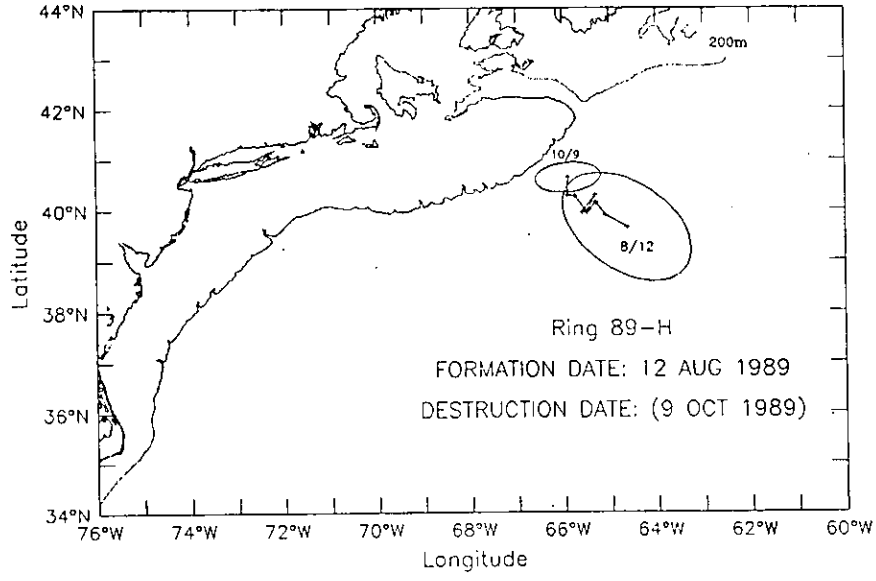

Figure 15. Trackline of Ring 89-H.

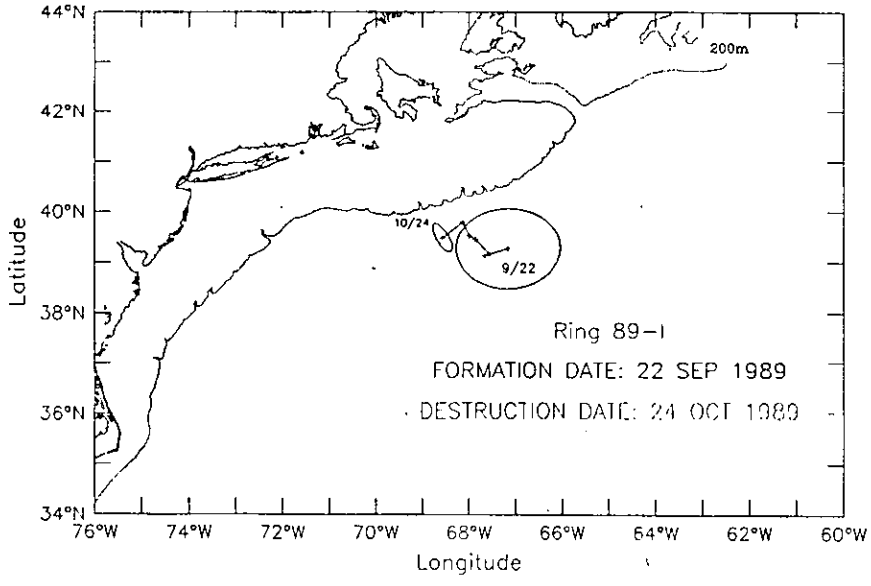

Figure 16. Trackline of Ring 89-I.

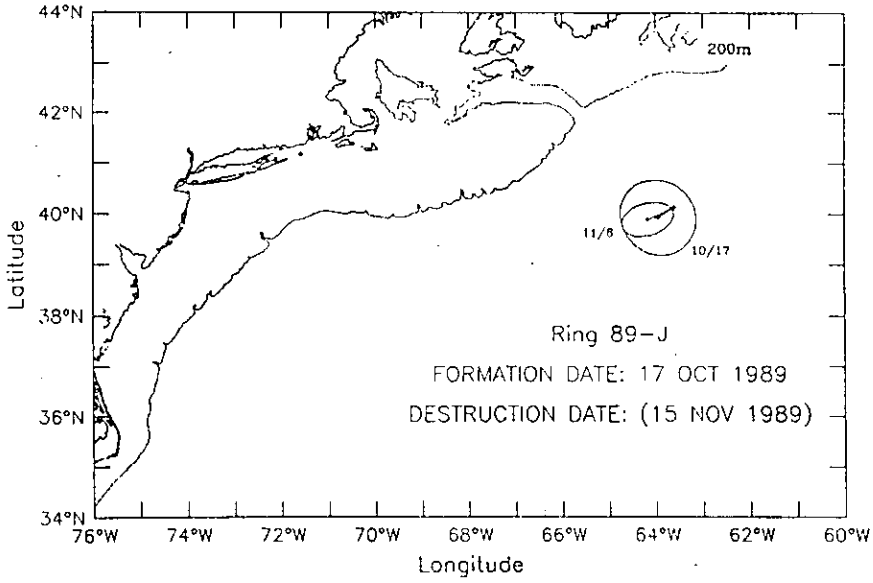

Figure 17. Trackline of Ring 89-J.

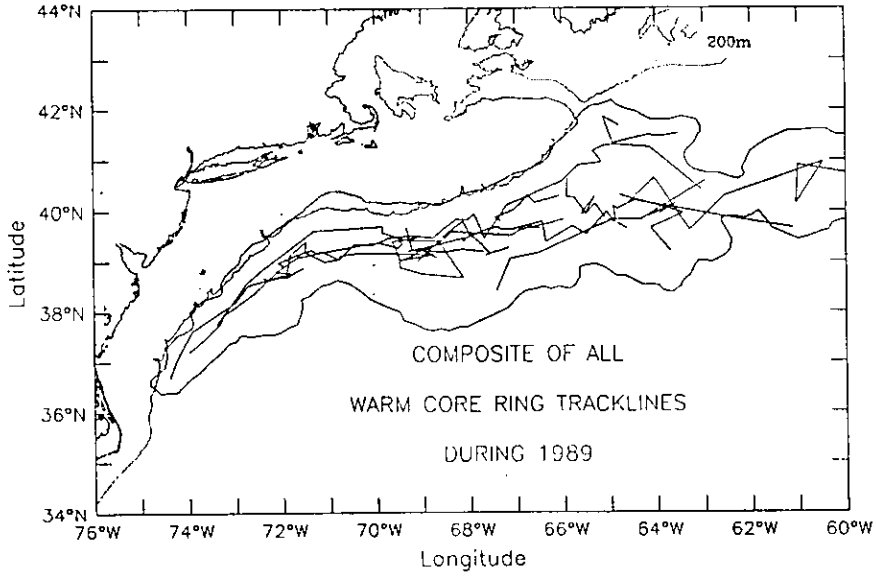

Figure 18. Composite of all Tracklines and Envelope of Rings Positions.