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Recent Changes in the Hydrography of the Scotian Shelf and Gulf of Maine - A Return to Conditions of the 1960s?

by

K.F. Drinkwater[1], D.B. Mountain[2] and A. Herman[1]

[1]Department of Fisheries and Oceans, Bedford Institute of Oceanography
Box 1006, Dartmouth, N.S., Canada B2Y 4A2

[2]National Marine Fisheries Service, Northeast Fisheries Center
Wood's Hole, Massachusetts, USA 02543

Abstract

Temperature and salinity measurements reveal the replacement of Warm Slope Waters adjacent to the continental break along the Scotian Shelf and Gulf of Maine by colder, fresher Labrador Slope Water during the autumn of 1997 and winter of 1998. Temperatures dropped by 2-4ºC along the slope depending upon location and depth. This cold water was first observed off Banquereau Bank in September and reached offshore of Emerald Bank by October. By January it was beginning to enter the Gulf of Maine, appearing on the northern side of the Northeast Channel. By February, it was located on the southern flank of Georges Bank and by March had reached the southern entrance to the Great South Channel. These cold slope waters began to penetrate into Emerald Basin on the Scotian Shelf by December. By mid-February, the entire Basin was flushed, with bottom temperatures decreasing by over 2ºC and salinity by 0.5 from conditions during mid-December. By April in the Basin, temperatures decreased by an additional 1ºC and 0.25 psu in salinity. The recent T,S properties in lower layers of Emerald Basin are similar to those observed during the 1960s and the coldest in approximately 30 years. The cause of the appearance of Labrador Slope Water so far south is thought to be due to an increase in the transport of the Labrador Current associated with atmospheric changes, in particular the reduction in the strength of the Icelandic Low associated with the recent low North Atlantic Oscillation (NAO) index.

Introduction

Petrie and Drinkwater (1993) described the ocean climate variability on the Scotian Shelf and in the Gulf of Maine between the late 1940s to 1990. They found high coherence in the decadal scale fluctuations from Cabot Strait in the north to the Gulf of Maine in the south. The dominant feature included a decline in temperature during the 1950s to a very cold period with minimum-recorded temperatures in the mid-1960s. In the late 1960s, temperatures rose rapidly, and remained relatively steady and above the long-term mean through the 1970s and the 1980s. While the amplitude and precise timing of the fluctuations varied spatially, this pattern was coherent both vertically and throughout the region. Temperature and salinity were coupled, such that during the cold periods, the salinity tended to be relatively low while during warm periods it was relatively high. Following the lead of Lauzier (1960), Petrie and Drinkwater (1993) suggested the cause of these observed hydrographic fluctuations on the shelf was due to changes in the offshore Slope Waters. These Slope Water changes in turn penetrate onto the Shelf in the deeper layers through gullies and channels, forced by meteorological events, Gulf Stream rings, or gravitational flows generated by differences in the density of the water onshore and offshore. The similarity in interannual variability on the shelf throughout the water column was believed to arise in large part through vertical mixing. Consistent with the hypothesis of offshore forcing of the shelf ocean climate, Petrie and Drinkwater (1993) found the largest amplitude change in Emerald Basin on the Scotian Shelf was at depths of 150-200 m, which is the approximate depth of the sill separating the basin from the offshore waters. They also reported the maximum amplitude of the decadal scale variability in the offshore Slope Waters. Further support for the hypothesis came from the studies by Umoh (1995) and Battisti et al. (1996) who showed that atmospheric heat fluxes could not account for the observed interannual ocean temperature variability in the region and suggested that they were caused by advection.

The Slope Waters are a combination of colder, fresher deep Labrador Current water and warmer, saltier North Atlantic Central Water. Gatien (1976) identified two types of slope waters off the Scotian Shelf, Labrador Slope Water with temperatures <8ºC and Warm Slope Water with temperatures generally >8ºC. The water type depended upon whether the North Atlantic Central or Labrador Current water mass component was dominant. Petrie and Drinkwater (1993) discussed the causes of the interannual variability in the slope water characteristics along the shelf break off the Scotian Shelf and the Gulf of Maine. They found a strong dependence upon the strength of the deep (100-300 m) Labrador Current that flows around the Tail of the Grand Banks and proceeds southward along the continental shelf off Nova Scotia and the Gulf of Maine. In years of higher than average transport, the colder Labrador Slope Water was found further southward. During the cold 1960s, the transport of the deep Labrador Current reached a maximum and Labrador Slope Water was found as far south as the Middle Atlantic Bight. In the warmer period of the 1950s and again in the 1970s and 1980s, the Labrador Slope Water was primarily restricted to the region of the Laurentian Channel and north. During this time, Warm Slope Water typically lay along the shelf edge off the Gulf of Maine and the Scotian Shelf.

Through the 1990s temperatures along the shelf break and in the deep basins remained very warm. Indeed, the warmest extended period in the last 50 years within the deep basins of the Scotian Shelf and the Gulf of Maine was during the 1990s (Fig. 1). In this paper we present observations taken during the autumn of 1997 to the spring of 1998. Extremely cold water, reminiscent of the 1960s has again been observed at the edge of the Scotian Shelf and southward. We document the movement of this water southward along the shelf, onto the Scotian Shelf and into the Gulf of Maine.

Data and Methods

Scientists from the Bedford Institute collected temperature and salinity data during August, October and December 1997, and again in April 1998. A single station in Emerald Basin was obtained in February 1998. Additional summer data were taken during a sentinel fisheries survey by the Fisherman's and Scientist's Research Society under contract to the Canadian Department of Fisheries and Oceans. Data in October and April were collected using a BATFISH, an undulating, tow body with a conductivity-temperature-depth (CTD) attached. In December they were taken with a moving vessel profile (MVP), a newly developed instrument at BIO that is similar to a CTD but one that can be deployed and retrieved continually, while the ship is underway (Herman et al., 1998). The horizontal resolution from both the BATFISH and the MPV varies from about 400 m to 2 km depending on the bottom depth. All other data were collected with a traditional CTD.

Scientists from the National Marine Fisheries Service at Wood's Hole collected data in the Gulf of Maine and Middle Atlantic Bight using a traditional CTD. The data obtained over Georges Bank and vicinity were part of the GLOBEC field studies. Additional temperature and salinity measurements from the Gulf, the Scotian Shelf and locations to the north were obtained from the historical hydrographic database held at the Bedford Institute of Oceanography which are updated regularly by the Marine Environmental Data Service in Ottawa.

Results

Scotian Shelf

In October 1997 a cruise out of the Bedford Institute undertook three BATFISH transects and a number of CTD stations on the Scotian Shelf. The transects included one across Cabot Strait, one along the Banquereau Line and another along the Halifax Line (Fig. 2). Most noticeably was very cold, relatively fresh water off the continental shelf on both the Banquereau and Halifax Lines (Fig. 3, 4). CTD measurements suggested that this cold water had not made it much further westward than the Halifax Line by October. Minimum temperatures at the shelf edge were <1°C around 75 m off Halifax and near 100 m off Banquereau. Below depths of approximately 50 m, temperatures were colder than 7°C, characteristic of the Labrador Slope Water. Later examination of data obtained in September revealed that water of these characteristics were present off Banquereau in September. These cold waters are in contrast to the Warm Slope Waters observed during most of the past 25 years. Over the shelf, temperature and salinity characteristics remained typical of recent years. These included strongly stratified waters with temperatures <3°C in the deep waters over the Banquereau Line and the presence of a colder layer at intermediate depths over the inshore half of the Halifax Line. In the deepest regions of Emerald Basin, waters were >9°C. Temperatures in Cabot

Strait also show a strong cold intermediate layer (CIL) with salinities <33. We shall return to the Cabot Strait waters later in the paper.

During test trials of the MVP in December, temperature and salinity measurements were made along the Halifax Line to Emerald Bank, but not as far as the shelf break. Of particular note was the cold water (<3°C) observed at the inshore edge of Emerald Bank (approximately the 20-km mark on Fig. 5). This suggested that the cold water observed offshore of the Bank in October had circulated around the Bank. Such a flow is consistent with the known mean circulation. In addition, during December, colder, lower salinity water appeared to be penetrating into Emerald Basin below 100 m. This penetration was restricted to an area adjacent to the inshore edge of Emerald Bank as the temperature, salinity properties of the water in the deepest part of Emerald Basin remained unchanged from October.

By February, the warm water in the deep basin were flushed out and replaced by cold, fresher water. Temperatures throughout the water column at a station in the center of Emerald Basin decreased relative to December (Fig. 6). In the upper 100 m or so this was most likely due to winter cooling. However, below 100 m, where there is no measurable seasonal cycle, temperatures dropped by about 2C° and salinity by 0.5. Densities below 200 m essentially remained unchanged (temperature and salinity are compensating), but from 100 to 200 m they decreased from December to February.

By April, temperatures in Emerald Basin had fallen by an additional 1C° and 0.25 in salinity in the deeper layers of the Basin suggesting further flushing of the basin (Fig. 6). Again the density of the deepest waters (> 200 m) was similar to earlier occupations while between 100 and 200 m, the densities had increased slightly over those observed in February.

The T,S diagram of the waters at 250 m in Emerald Basin were subdivided into three periods; 1960-68, 1969-1997 and 1998 (Fig. 7). The first represents the cold period when the water generally fell within Labrador Slope Water properties or colder. During the warm period of the past 30 years the water characteristics were similar to that of Warm Slope Water. During 1998, the February and April data points have returned to more Labrador type properties reminiscent of the 1960s. However, for the same temperature, the 1998 conditions tend to be slightly lower in salinity than those from the 1960s.

Gulf of Maine

The cold water observed along the edge of the Scotian Shelf began to penetrate into the Gulf of Maine through the Northeast Channel by at least January 1998. The T,S characteristics of the water from 100 m to near bottom (approximately 200 m) at a standard station in the Channel on the northern (Browns Bank) side shows the waters generally below 8°C during January in contrast to the warm waters the previous October (Fig. 8). No data were available between October 1997 and January 1998. Conditions consistent with Labrador Slope Water have continued in the Northeast Channel through into May 1998, although with some variability (Fig. 9).

Along the continental slope off southwestern and southeastern Georges Bank, the Labrador Slope Water did not appear until February, a month later than in the Northeast Channel (Fig. 9). Temperatures continued to decrease, producing minimum values in March in the Channel and at the southwestern flank of the Bank. Surprising, the station intermediate between these two showed evidence of Warm Slope Waters. However, satellite imagery revealed the presence of a Gulf Stream eddy in the vicinity, which could account for this warming. The cold Labrador Slope Waters extended westward to a station near the southern entrance to the Great South Channel (not plotted). By April, the southeastern flank of the Bank was again surrounded with the cold Labrador Slope Water while the southwestern flank warmed. This is consistent with the eddy moving further to the southwest. By May the southwestern flank was beginning to cool although it remained much warmer than the southeastern flank or in Northeast Channel. No data were available in April or May along the shelf break west of the southwestern flank of the Bank but we expect that these cold Labrador Slope Waters likely now have reached the Middle Atlantic Bight.

Possible Mechanism

What has caused the recent predominance of the colder Labrador Slope Water along the edge of the Scotian Shelf and the Gulf of Maine? Based on the work of Petrie and Drinkwater (1993) it is most likely an increase in the transport of the deeper Labrador Current. But why now? Myers et al. (1978) found a relationship between the geostrophic transport in the top 100 m of the Labrador Current and the North Atlantic Oscillation (NAO) index. This is an index of the large-scale atmospheric circulation and is a measurement of the pressure difference in winter between the Azores and Iceland. In years when the index is high, the Icelandic Low intensifies, causing an increase in the northwest winds over the Labrador Sea, resulting in colder air temperatures, more ice and an increase in the heat loss to the atmosphere from the ocean, i.e. a cooling of the ocean (Drinkwater 1996). The opposite occurs during low index years, that is a weakening of the Low, decreased winds, less ice and warmer sea temperatures. More importantly from the perspective of this paper, Myers et al. (1989) noted that in the low NAO years the southward transport of the Labrador Current was higher. This is consistent with the findings of Petrie and Drinkwater (1993) who found that in the 1960s (when the NAO was low) the geostrophic transport of the deep (100-300 m) Labrador Current was high and in the 1970s (when the NAO increased) the transport decreased.

In the winter of 1996 the largest annual decrease in the NAO index in the 100-year record was observed. The index has remained relatively low in 1997 and again in 1998. The increase in the amount of Labrador Slope Water along the shelf may be related to these changes in the large-scale atmospheric circulation. The cause of the apparent long delay between the change in the NAO and the appearance of the Labrador Slope Water on the Scotian Shelf as well as the details of the linkages between the atmospheric circulation and the transport in the Labrador Current are unknown. If indeed this is the mechanism, then one might expect that the event might be somewhat long-lived. The longest such event on record was in the 1960s but other shorter-term events have been observed. Worthington (1964) documented one such event that occurred in 1959. During that year large amounts of cold Labrador Current water were observed off the Scotian Shelf. Although not noted in his paper, this cold water also penetrated into Emerald Basin. Interestingly enough Worthington (1964) suggests that the large influx of cold water that year was related to a decrease in the strength of the Icelandic Low, i.e. a low NAO year, during the winter of 1959. If true, the delay between the atmospheric forcing and the oceanographic response was less than a year.

The Gulf of St. Lawrence waters flow seaward through Cabot Strait and out onto the Scotian Shelf, some directly onto the Shelf and some flowing along the Laurentian Channel, around the outer edge of Banquereau Bank and down the shelf. This pathway could account for some of the cold water observed on the outer edge of the Scotian Shelf in the autumn of 1997. However, analysis of the T,S properties of the waters from Cabot Strait in September and the outer Halifax Line in October suggest that the waters off the Scotian Shelf are slightly higher in salinity that the Gulf waters. In addition, T,S properties of waters along the southern edge of the Grand Banks in summer (August) match more closely those found off the Scotian Shelf in autumn than do the Gulf waters. From this analysis, we believe that most of the water along the Scotian Shelf in the autumn of 1997 came from the Newfoundland shelves rather than the Gulf of St. Lawrence.

Brief Discussion and Summary

During the autumn of 1997 through to the spring of 1998, Labrador Slope Water replaced Warm Slope Water adjacent to the shelf break along the Scotian Shelf and the Gulf of Maine for the first time in almost 30 years. The timing of the progression of this water type begins off Banquereau Bank in September, to the Halifax Line by October, is into the Northeast Channel by January, along the southern flank of Georges Bank in February and to Great South Channel by March (Fig. 10). Based upon distances traveled and the timing of these events the advection speed is between 4 and 10 km per day. Because of the infrequency of the measurements, these represent minimum speeds, for example measurements in the Northeast Channel were only available in October and then not again until January. The presence of Gulf Stream eddies near the shelf edge can temporally modify the water properties as observed on the southern flank of Georges Bank in late winter of 1998. The penetration of this cold water onto the Shelf, at least in the case of Emerald Basin on the Scotian Shelf, proceeded relatively slowly. Present at the shelf edge in October, this water did not begin to appear in the Basin until December and not until sometime in January or February were the deepest waters of the basin flushed.

Cause of the appearance of the cold Labrador Slope Water south to the Gulf of Maine (and possibly to the Middle Atlantic Bight) is thought to be due to an increase in the strength of the Labrador Current, although direct evidence is lacking. It is also suggested that such an increase may be associated with the decline in the NAO index based on a past relationship that indicated high Labrador Current transport during years when the NAO index is low.

Acknowledgments

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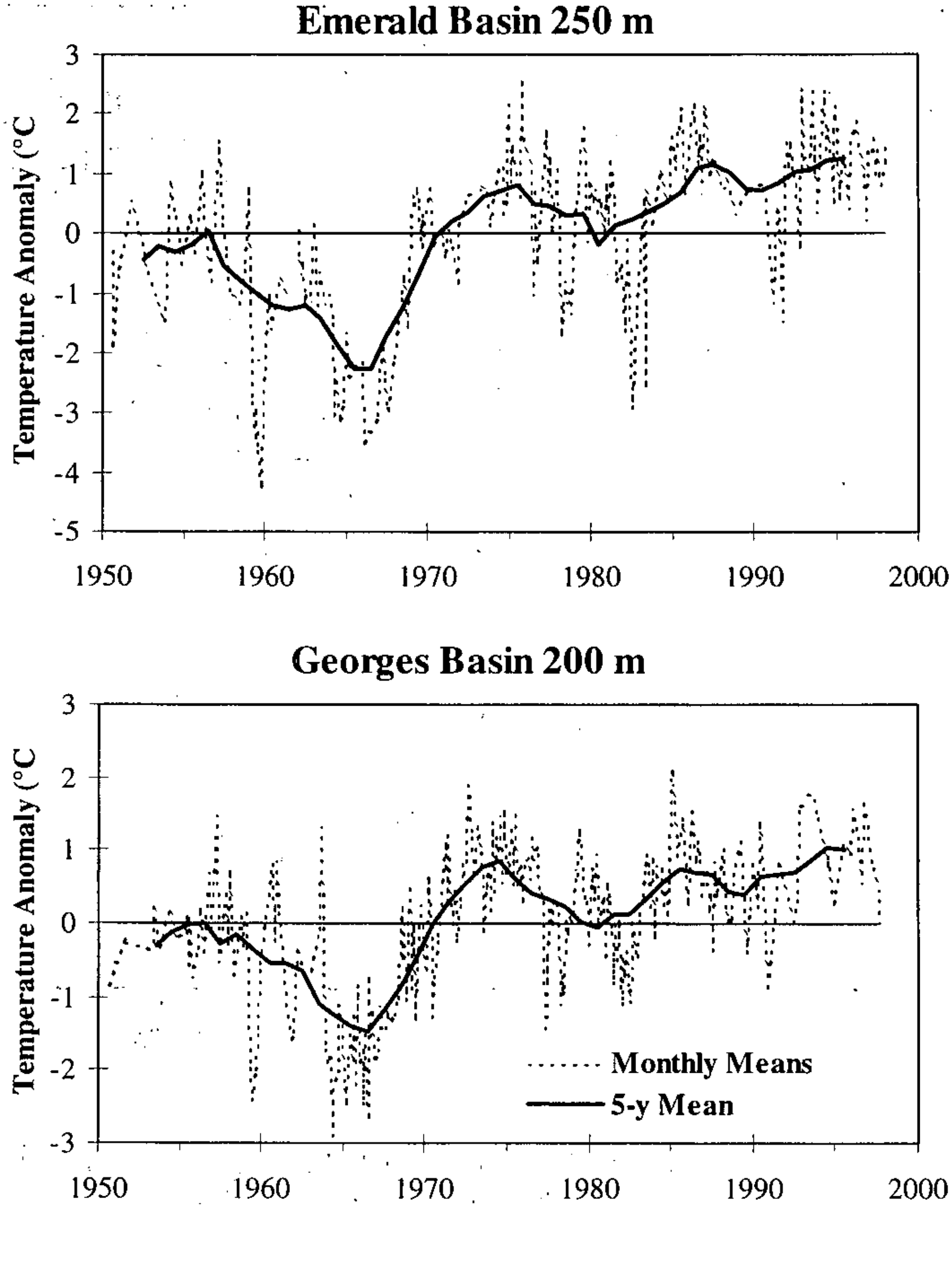


Fig. 1. The monthly (dashed lines) and the 5 year running means of the temperature anomalies at 250 m in Emerald Basin on the Scotian Shelf (top panel) and at 200 m in Georges Basin in the Gulf of Maine.

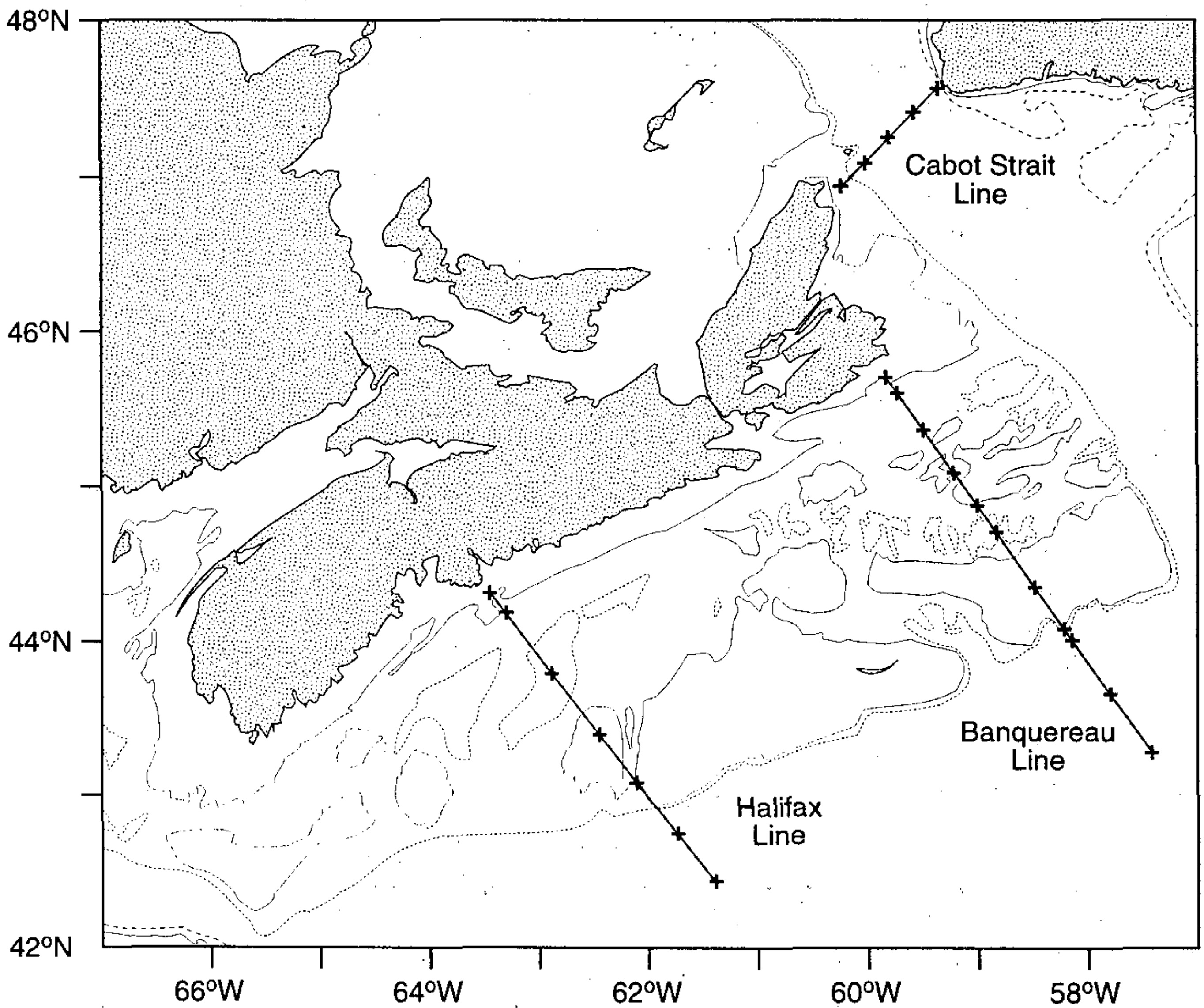


Fig. 2. The Scotian Shelf showing the location of the BATFISH transects during October 1997. They were conducted across Cabot Strait and along both the Banquereau and Halifax Lines.

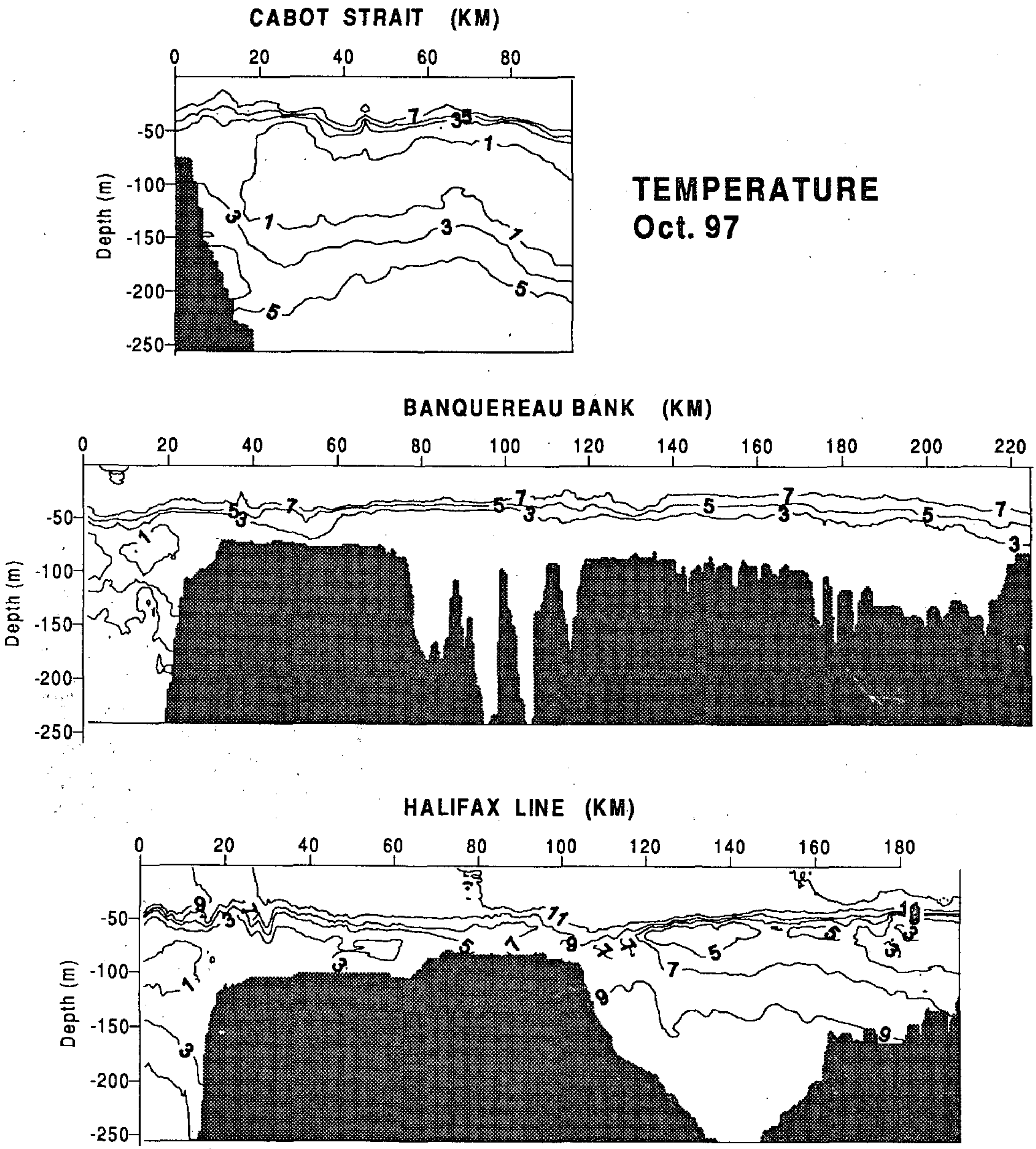


Fig. 3. The temperature transects taken using the BATFISH during October 1997. The Nova Scotia coast is on the right for the Halifax and Banquereau Lines and on the left for the Cabot Strait Line. The deep region at around 140 km on the Halifax Line is Emerald Basin.

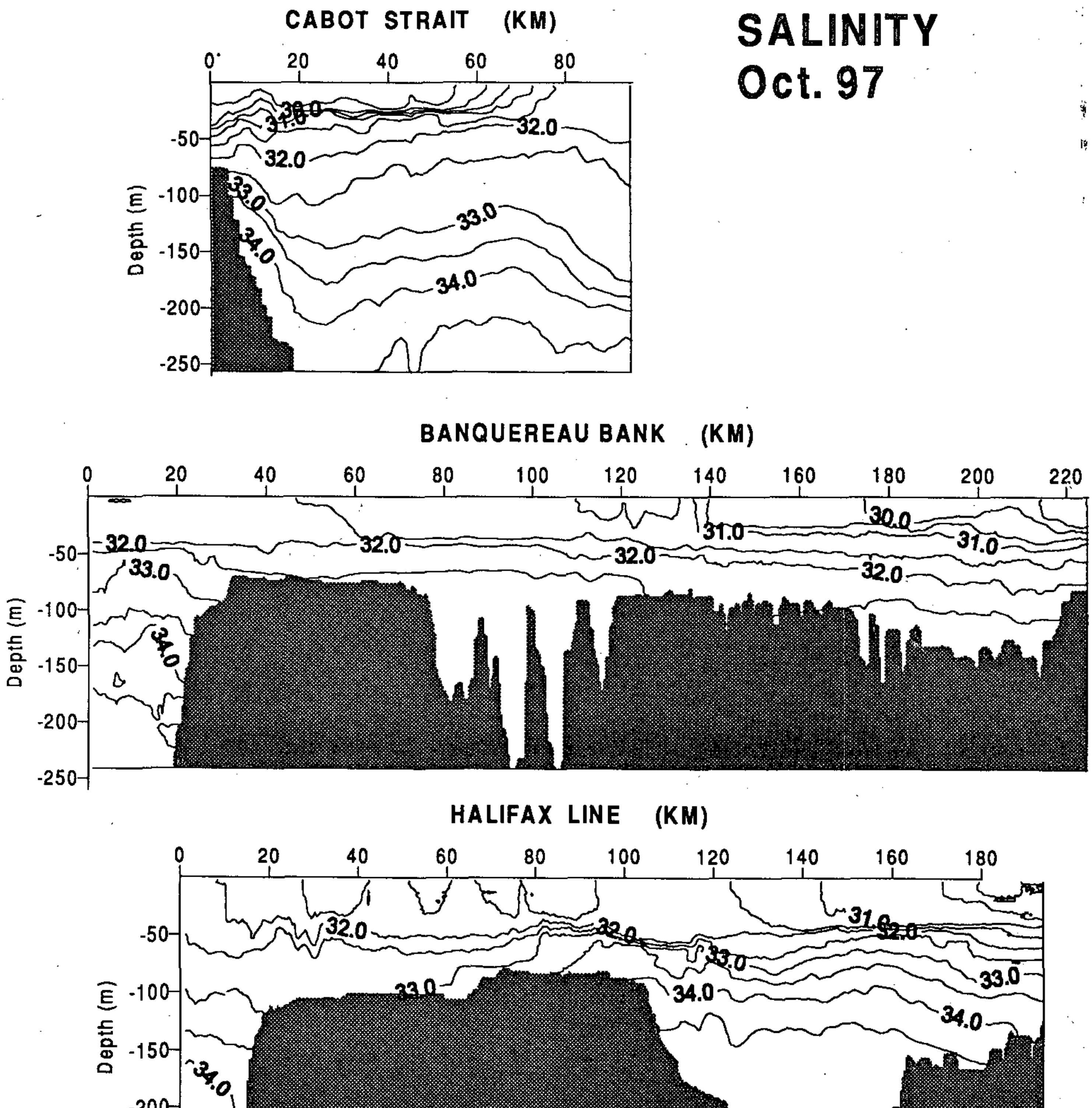
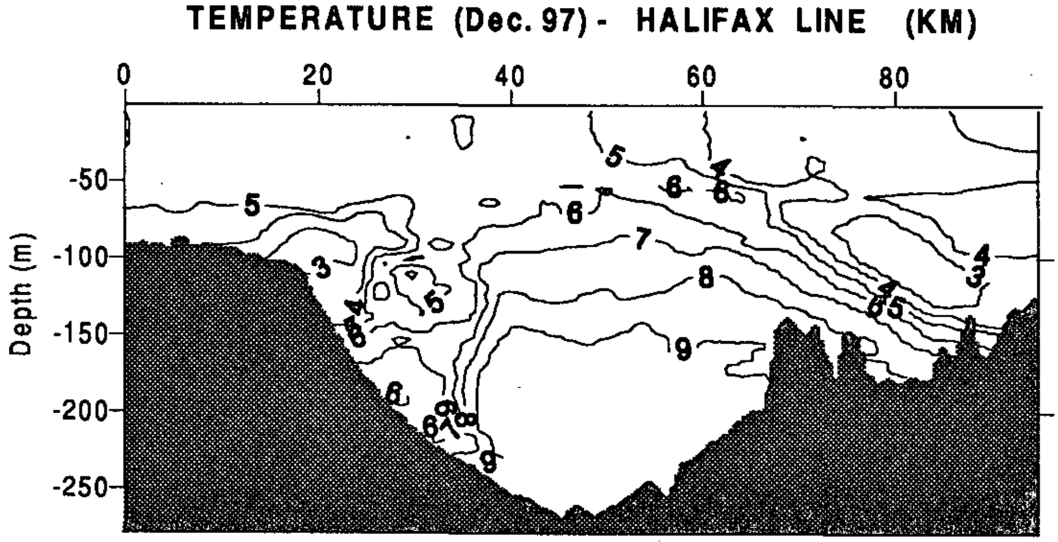


Fig. 4. The salinity transects from the BATFISH during October 1997.



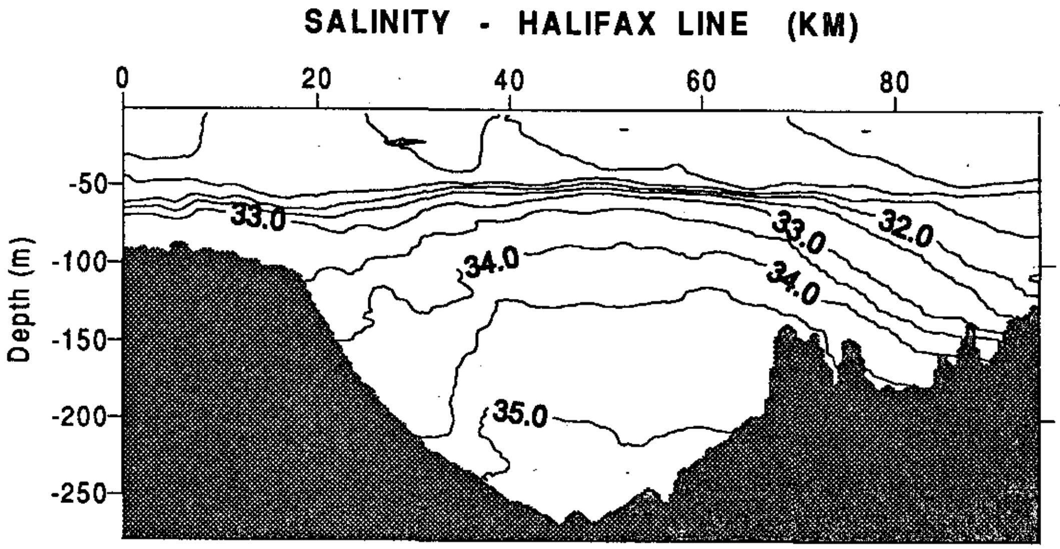


Fig. 5. The temperature and salinity transect along the Halifax Line taken with the MVP during December 1997. The distance is measured from the furthest offshore location and hence the coast of Nova Scotia is to the right. The deep region in the center is Emerald Basin.

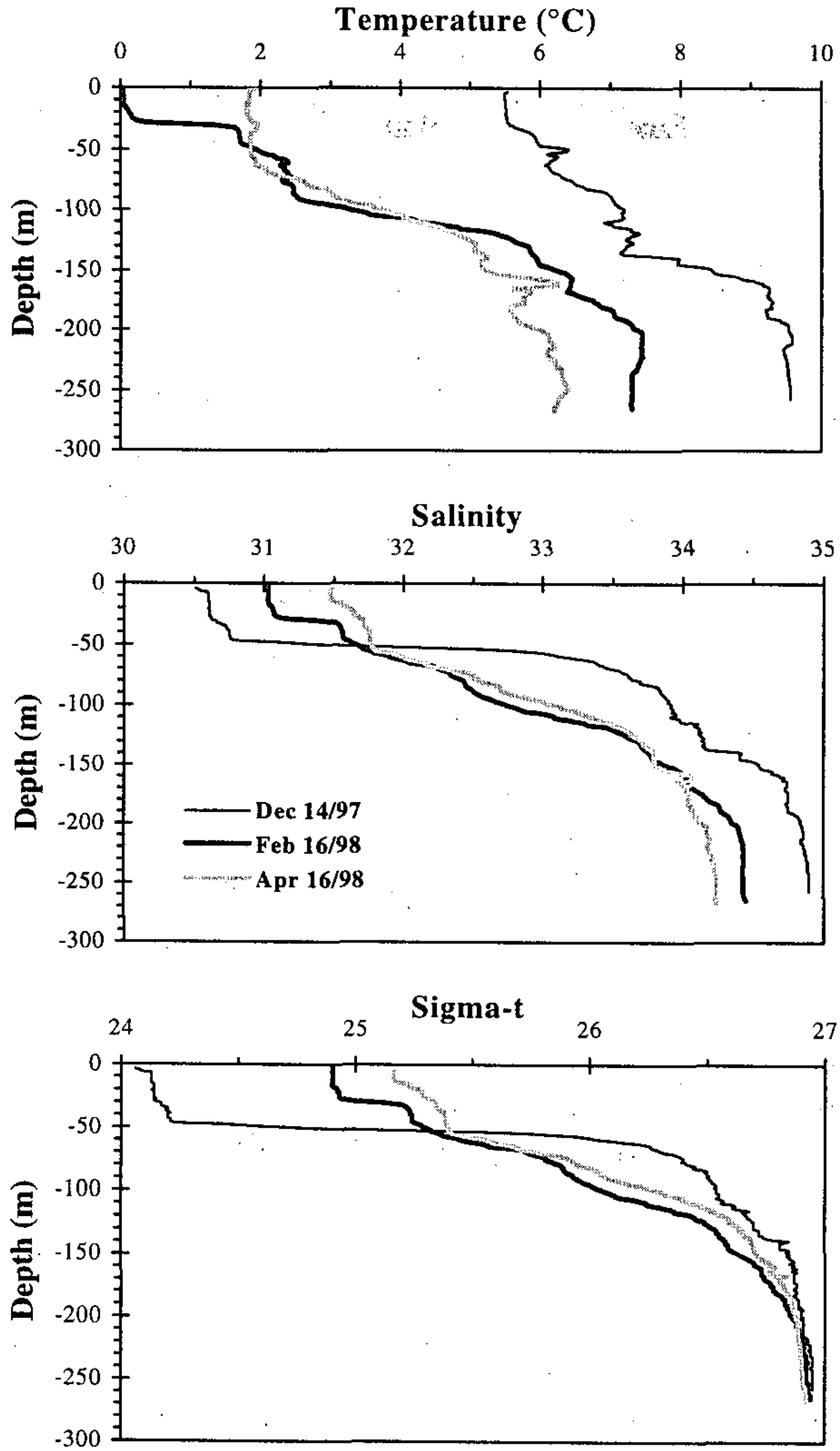


Fig. 6. The temperature, salinity and density (sigma-t) profiles from a station in the center of Emerald Basin taken during December 1997 and February and April 1998.

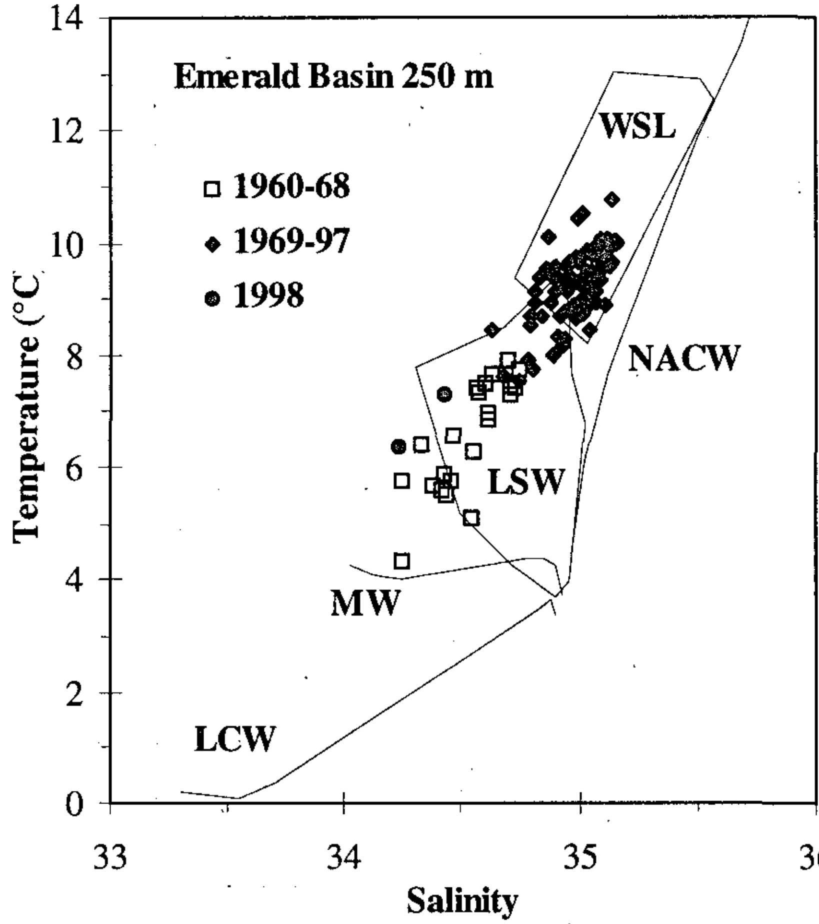


Fig. 7. The temperature, salinity diagram showing characteristics for waters at 250 m in Emerald Basin broken down by the periods 1960-68, 1969-1997 and 1998. The solid lines define the characteristics of the Warm Slope Waters (WSL) and Labrador Slope Waters (LSW) as given by *Gatien (1978)* as well as the North Atlantic Central Waters (NACW), the Labrador Current (LCW) waters and the Mixed Waters (MW) as presented by Morgan (1969).

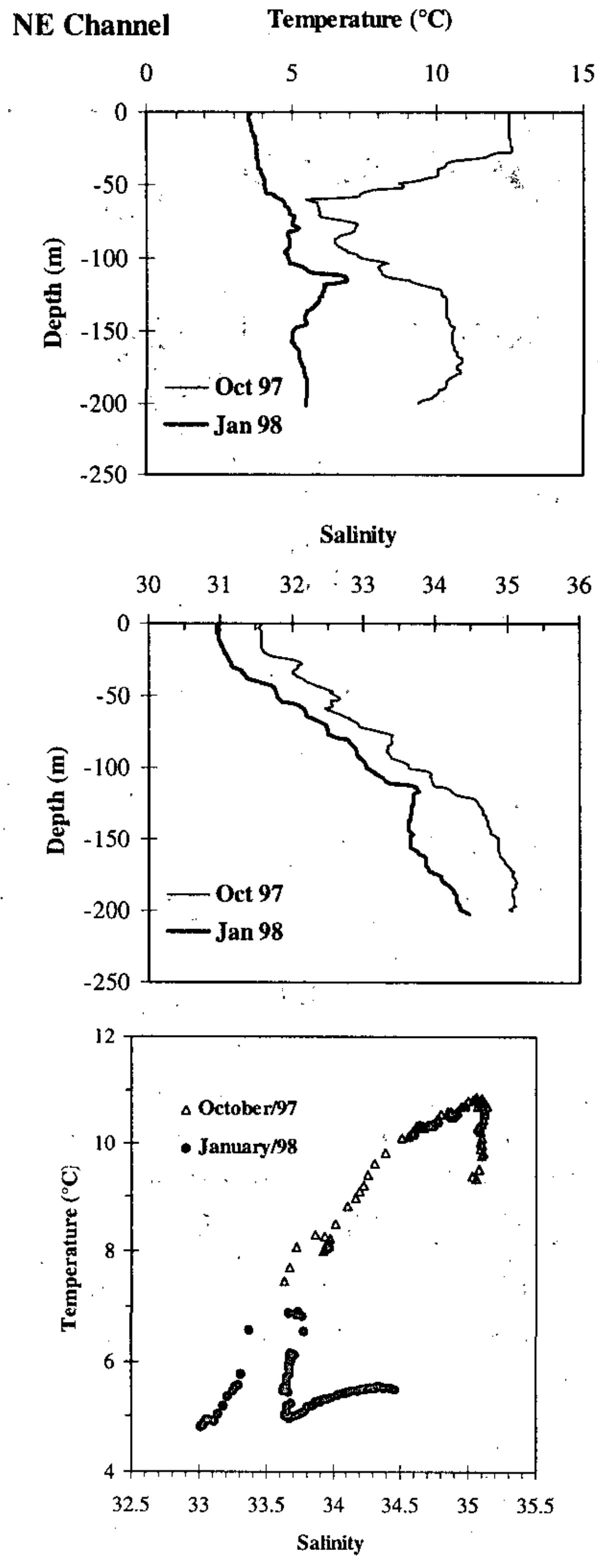


Fig. 8. The temperature and salinity profiles from a site just inside the Northeast Channel (GLOBEC standard station 25) and the T,S diagram (>100 m) from data collected during October 1997 and January 1998.

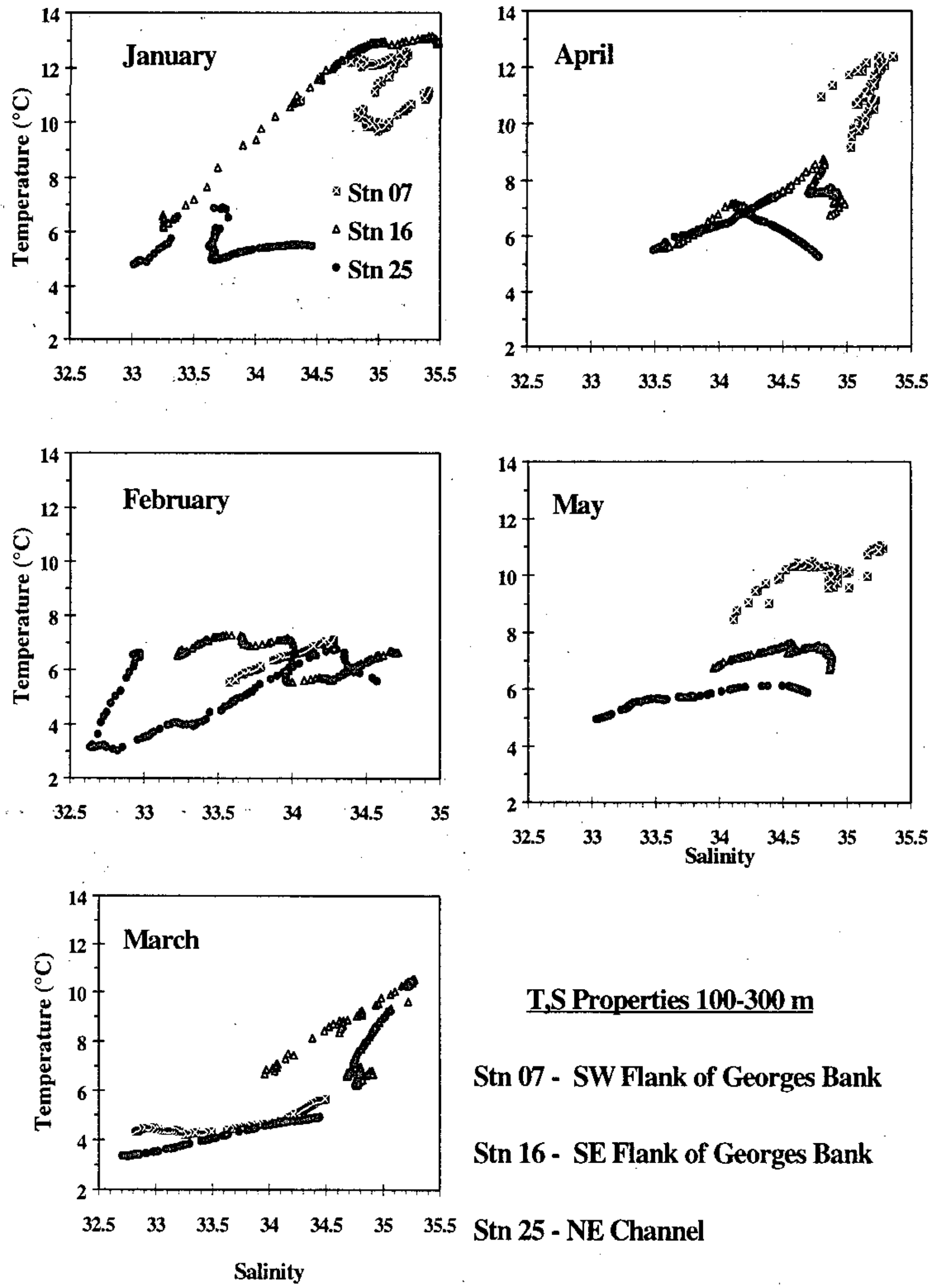


Fig. 9. The monthly T,S diagrams (100-300 m) for January to May for stations in Northeast Channel, on the southeastern flank of Georges Bank and the southwestern flank of the Bank.

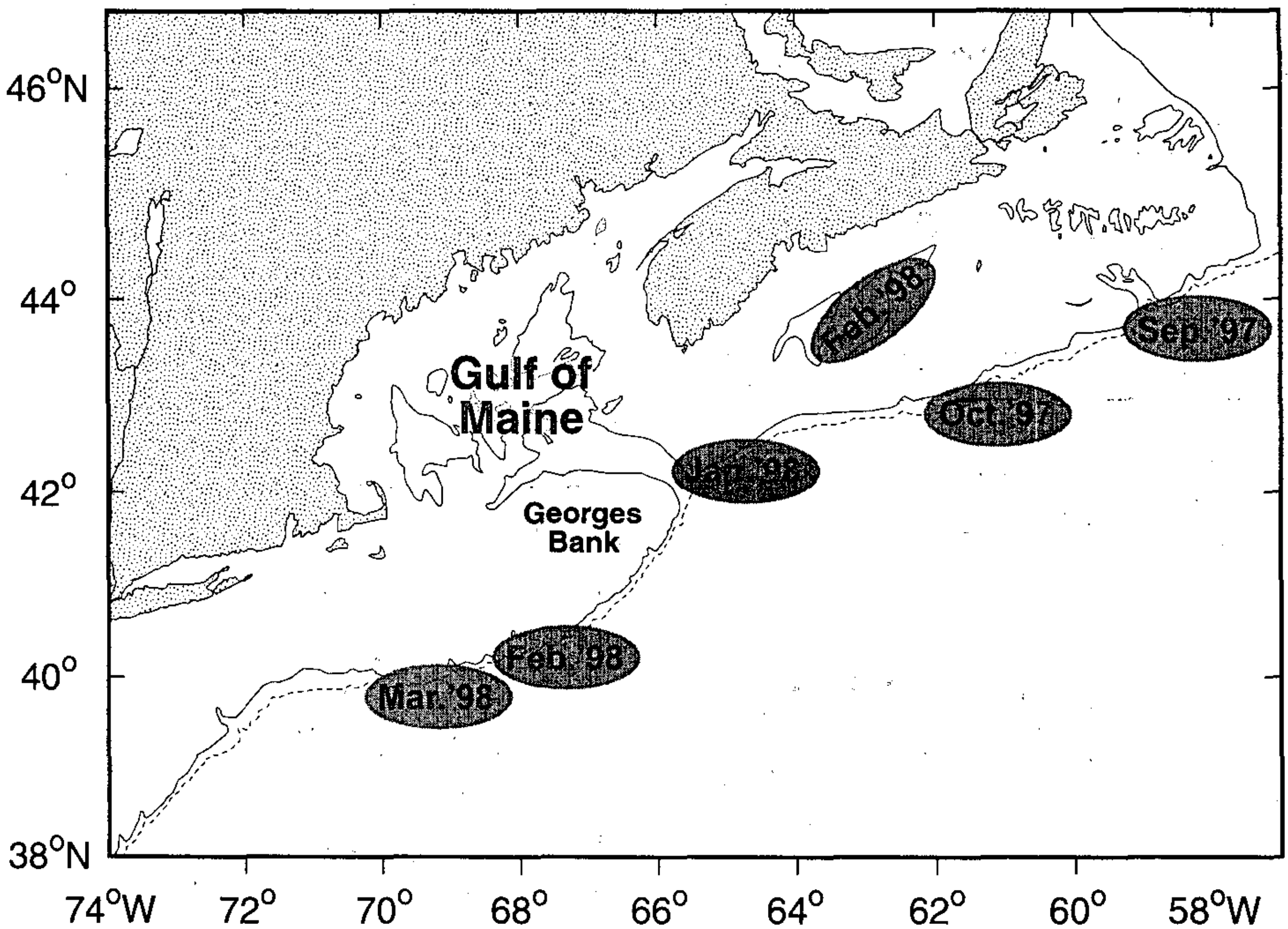


Fig. 10. Chart of the Scotian Shelf and Gulf of Maine showing the progression of the Labrador Slope Water with time.