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Interannual variations in the stratification and transport of the Labrador Current on the Newfoundland Shelf

by

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Abstract

During the past several decades' climate conditions in the northwest Atlantic have been characterised by several extremes, from the warm 1960s and late 1990s to cold conditions of the early 1970s, mid-1980s and early 1990s. The magnitude of these variations is proportional to the strength of the winter atmospheric pressure fields in the north Atlantic represented by the NAO index. Variations in stratification and the baroclinic component of the volume transport of the Labrador Current on the Newfoundland Shelf during these events are presented. The historical (1950-1999) summer temperature and salinity data along standard transects on the Newfoundland Shelf were used to compute geostrophic currents and to construct time series of baroclinic transports. The results generally show large interannual variations, but the trend indicates higher-than-average transport during the warm 1960s (low NAO index) and lower than average values during the cold early 1970s and the mid-1980s (high NAO index). During the late 1980s the transport increased to above average values that continued into the mid-1990s, a period of high NAO index anomalies. The results are consistent with earlier work based on data up to the mid-1980s and with the hypothesis that increased transport of Labrador Current Water around the southeast Grand Bank during the warm 1960s on the Newfoundland Shelf resulted in colder ocean conditions further south on the Scotian Shelf. However, the higher-than-average transport during the high NAO index period of the early 1990s is not consistent with that observed during similar high NAO conditions of the early 1970s and mid-1980s.

Introduction

The Labrador Current, which transports sub-polar water to lower latitudes along the continental shelf of eastern Canada, has been investigated many times since the pioneering work of Smith et al. (1937). The results of the studies show a strong western boundary current following the shelf break with relatively low current variability compared to the mean flow, and a considerably weaker branch over the banks and inshore regions, where the variability often exceeds the mean flow. Mean flows in the offshore regions typically range from 30-50 cm/s, while over the banks and inshore currents are generally much less, averaging between 5-15 cm/s (Smith et al. 1937; Fissel and Lemon 1991; Lazier and Wright 1993; Colboume et al. 1997). For the most part, the inshore branch is not well defined but appears as a broad weak flow pattern. Only in specific locations such as the Labrador Marginal Trough, the Bonavista Saddle and the Avalon Channel, where bathymetric effects intensify the currents, is a distinct inshore coastal jet obvious.

The sub-surface water mass characteristics of the inshore branch are typical of sub-polar waters with a temperature range of -1 to 2°C and salinities of 31 to 33.5. The offshore branch, on the other hand, is generally warmer and saltier than the sub-polar shelf waters with a temperature range of 3 - 4°C and salinities in the range of 34 to 35 (Lazier 1982). Throughout most of the year, the cold relatively fresh water overlying the continental shelf is separated from the warmer higher density water of the continental slope region by a frontal region characterized by strong horizontal temperature and salinity gradients. This front is a dominant oceanographic feature but undergoes significant spatial and temporal oscillations throughout the year (Narayanan et al. 1991). The strong horizontal density gradients, indicated by the tilt in the isopycnal surfaces along cross-shelf transects represent a highly baroclinic component to the offshore current jet. Previous investigations indicate that the baroclinic component of the currents represents between 30-40 % of the overall transport of 11-12 Sv. (1 Sv = 10^6 m^3/s) shoreward of the 1500-m isobath.

During the past several decades oceanic conditions in the northwest Atlantic have been characterized by several extremes, from the warm 1960s and late 1990s to cold conditions of the early 1970s, mid-1980s and early 1990s (Colboume et al. 1994; Drinkwater 1996; Drinkwater et al. 1999). During these periods of extremes, the shelf stratification has also undergone significant changes implying potential variations in the strength of the Labrador Current. Myers et al. 1989 presented seasonal and interannual variability in the baroclinic transport for the period of the early 1950s up to the mid-1980s. The primary purpose of this study is to examine shelf stratification during the periods of climate extremes and to update and present interannual variations in the offshore shelf-slope branch of the Labrador Current transport.

Data and Methods

Ocean temperature and salinity have been measured regularly at a standard hydrographic monitoring station (Station 27) located in the inshore branch of the Labrador Current on the Newfoundland Continental Shelf since 1946 (Colboume and Fitzpatrick 1994). It is located about 8 km off St. John's harbor, Newfoundland in a water depth of 176-m (Fig. 1). This position is ideal for monitoring variations in the water properties of the Newfoundland inner shelf region. In recent years the station has been occupied on a regular basis, about 2-4 times per month, making it one of the most frequently monitored hydrographic stations in the northwest Atlantic. This regular sampling permits a detailed analysis of the seasonal and interannual variability in water properties at temporal scales from months to decades. Following standard methods, the seasonal salinity cycle was determined by fitting a least-squares regressions of the form $\cos(\omega t-\phi)$ to the annual data for the years 1961-1990. Monthly salinity anomalies, which were computed by subtracting the least squares fitted values from each observation, were then averaged to produce an annual value. These data are then used to identify anomalous periods or trends in the shelf stratification.

In 1976 the International Commission for the Northwest Atlantic Fisheries (ICNAF) adopted a suite of standard oceanographic stations along transects in the Northwest Atlantic Ocean from Cape Cod (USA) to Egedesminde (West Greenland) (Anon. 1978). Three of these transects are occupied annually during a mid-summer oceanographic survey conducted by the Canadian Department of Fisheries and Oceans. They include the Seal Island transect (Colboume et. al. 1995) on the Southern Labrador Shelf and Hamilton Bank; the Bonavista transect (Colboume and Senciall 1993) off the eastern Newfoundland Shelf; and the Flemish Cap transect (Colboume and Senciall 1996) which crosses the Grand Bank at 47°N and continues eastward across the Flemish Cap (Fig. 1). Temperature and salinity data from these surveys were used to compute density using the UNESCO equation of state for seawater. The density profiles were first smoothed and then extrapolated to the surface. All historical data that were not part of the synoptic transect observations were excluded from the analysis. The density data were then used to compute geostrophic currents from the horizontal gradient of the steric height using the standard geostrophic balance relationship according to Gill (1982).

Results

Variations in Salinity

The strength of the cyclonic atmospheric circulation over the north Atlantic during the winter months (NAO) (Rogers 1984) to a large degree determines ocean climate variations throughout most of the year influencing ice extent and duration, ocean temperatures and shelf stratification. Historically, the upper layer salinity on the Newfoundland Shelf reaches it's minimum during late September, corresponding to the arrival of spring ice-melt water from the Labrador Shelf (Myers et al. 1990). The increased ice production associated with high NAO index and subsequent melting have opposing effects on the salinity cycle, creating either positive anomalies due to salt rejection or negative anomalies from fresh melt-water. In addition, spatial variations in the location of ice formation and melt together with advection determine the magnitude of local salinity anomalies. For example, increase ice formation further south on the eastern Newfoundland Shelf could produce positive salinity anomalies locally, since the melting will most likely occur further south due to advection. Recently, ice production on the Newfoundland Shelf has been below normal and with warmer than normal air temperatures ice melt occurred on the Labrador Shelf earlier in the year. This has resulted in a phase shift in the salinity cycle causing fresher than normal salinities further south, by mid-spring for example during 1999 on the Newfoundland Shelf (Colboume 2000a).

The vertically averaged (O-50 m) summer (July-September) salinity anomalies exhibit large amplitude variations with fresher-than-normal periods occurring since the early 1970s at near decadal time scales (Fig. 2). Salinity anomalies during these periods are correlated with the NAO anomalies, however, the combined influences of advection and the temporal and spatial variability in ice formation and melting probably accounts for some of the phase shifting in the two signals. The magnitude of negative salinity anomaly on the inner Newfoundland Shelf during the early 1990s is comparable to that experienced there during the 'Great Salinity Anomaly' of the early 1970s (Dickson et al. 1988). The salinity anomaly of the mid-1980s is the weakest of the three anomalous periods on the inner Newfoundland Shelf. These periods of negative salinity anomalies are significantly correlated with increased shelf ice cover as expected and with larger than normal volumes of cold intermediate water (CIL) on the shelf.

The cross-shelf vertical temperature structure on the Newfoundland Continental Shelf during the summer is dominated by a layer of cold sub-zero °C water trapped between the seasonally heated upper layer and warmer slope water near the bottom. This water mass is commonly referred to as the cold intermediate layer or CIL (Petrie et al. 1988). The cold, relatively fresh, shelf water is separated from the warmer saltier water of the continental slope by an intense temperature and salinity front near the edge of the continental shelf. At the low temperatures typically encountered on the Newfoundland Shelf the density stratification is primarily determined by the salinity field.

The summer salinity structure on the shelf representative of four different climate regimes (warm 1960s and the cold periods of the early 1970s, mid-1980s and early 1990s) is displayed in Figs. 3 and 4. These data all show a strong horizontal gradient indicated by the net upward displacement of the isohalines towards the offshore near the edge of the shelf. In general, salinities range from less than 32.5 in the surface layers to about 33 near bottom over the shelf. During the cold periods of the early 1970s and mid-1980s the density front at the shelf break was considerably weaker than that present during the mid 1960s and early 1990s. The salinities over the inner shelf during the early 1990s however were comparable to those observed during the early 1970s and mid 1980s, the main difference being the offshore extent of the fresh water during the latter time period. It appears that the most intense fresh anomaly during the early 1990s was restricted to the continental shelf, whereas during the great salinity anomaly of the early 1970s for example, fresh water was much more extensive. Upper layer salinities during 1972 (Fig. 3) for example were less than 32.5 across the entire slope region where the core of the Labrador Current is normally located. As a result the strength of the horizontal density gradient in this region was much weaker during the early 1970s and the mid-1980s compared to other time periods. With the limited spatial extent of the fresh anomaly during the 1990s the strength of the horizontal density gradient across the shelf during this time period was comparable to that observed during the warm 1960s (Fig. 4).

Geostrophic Circulation

The geostrophic currents relative to 300-m depth along the Seal Island transect show distinct inshore and offshore branches of the Labrador Current (Fig. 5a). The inshore branch is located within about 100 km from the shore and the offshore branch, which is typically less than 100 km wide, is centered at about 225 km offshore over the 500-m isobath. In the offshore branch, current speeds range from 0.05 m/s at 200-m depth to greater than 0.25 m/s in the upper water column. In the inshore branch, current speeds are generally less than 0.15 m/s. Currents over the shoreward portion of Hamilton Bank are very weak and on the outer bank they are generally southward at speeds of less than 0.08 m/s.

Along the Bonavista transect the flow generally reveals an inshore and offshore branch, however for some years (1999 for example) the baroclinic current appears broad with no distinct separation between the inshore and offshore components (Fig. 5). Current speeds in the upper 200-m of the water column generally range from 0.05-0.15 m/s. During 1998 (not shown) the offshore feature was more prominent at about 125 km wide with speeds ranging from 0.05 m/s at 200-m depth to greater than 0.20 m/s in the upper 50-m of the water column (Colboume 2000a). The broader flow patterns generally observed along this transect are consistent with the significant cross-shelf component as indicated by tracks from the drifting buoys, current meter data and modeled results (Narayanan et al. 1996; Sheng and Thompson 1996). This is a region where the inshore branch bifurcates with a component flowing towards the offshore through the Bonavista Saddle and combining with the offshore branch and a weaker component continuing to flow southward through the Avalon Channel.

The flow patterns perpendicular to the Flemish Cap transect show the well-known features of the circulation. The strong baroclinic component of the offshore branch as a bathymetrically trapped jet near the edge of the Grand Bank, the general anticyclonic circulation around the Cap and the northward flowing water of the North Atlantic Current east of the Cap are evident (Fig. 5c). The inshore branch of the Labrador Current is weak with speeds typically less than 0.05 m/s and is restricted to the Avalon Channel region within 50 km of the coast. Currents over most of the Grand Bank are near 0 m/s. Peak current speeds in the surface layer of the offshore jet on the slope of the Grand Bank are over 0.3 m/s. In this region the current is about 100-km wide and extends to below 100-m depth. Typical geostrophic speeds range from 0.05-0.10 m/s in the gyre over the Cap and near 0.20 m/s to the east of the Cap in the North Atlantic Current.

A comparison of geostrophic currents to the total current measured by an acoustic Doppler current profiler (ADCP) is displayed in Fig. 6 along the Grand Bank portion of the Flemish Cap transect where ADCP bottom referencing was possible. The ADCP data presented shows the total current field, which includes high frequency components such as wind driven flows, inertial currents and tides. Even so both the directly measured currents and the geostrophic estimates show similar features, however the magnitude of the direct measurements is much larger with peak currents reaching 0.4 m/s, compared to only 0.15 m/s for the geostrophic estimates. This is consistent with previous studies, which show geostrophic components at about 30-40% of the total transport, thus indicating the importance of barotropic flows on the Newfoundland Shelf.

Variations in Geostrophic Transport

The volume transport for all transects was calculated by integrating the speed both vertically through the water column and horizontally in the offshore direction across the shelf. A reference level of 130-m was chosen for all three transects since this was the deepest level common to all three transects that did not intersect the bottom, thus eliminating potential problems associated with a bottom reference level. Also, the main interest was to examine variations in stratification and volume transport during recent ocean climate changes on the continental shelf. Changes in shelf stratification are mainly confined to the upper layers and are mainly due to salinity changes resulting from increased ice formation and melt. The magnitude of the resulting horizontal density gradient will then determine the strength of the geostrophic component of the Labrador Current.

The time series of volume transport of the offshore branch of the Labrador Current for the three transects show large interannual variations with an average transport of between 0.4-0.5 Sv. to the south relative to 130-m (Fig. 7). In general, the trends highlighted by the 5-year running means indicate higher than average transport during the late 1950s and into the 1960s, lower than average values during the cold period of the early 1970s and to a lesser extent during the cold period of the mid-1980s. During the late 1980s the transport increased to above average values, which for the most part, although not without exceptions, continued into the mid-to-late 1990s. Some of the annual variations are probably due to eddies or possibly high frequency internal wave propagation, which contaminates the density profiles and thus introduces noise and sometimes reversals in the horizontal pressure gradient force.

The results show some similarity with those obtained by Myers et al. (1989) during the same time period (1950-1986). That is, they show a significant, albeit weak, negative correlation between the upper layer geostrophic transport and the NAO index, especially along the Bonavista and Flemish Cap transects, indicating reduced transport during cold periods. Both studies support the suggestion by Petrie and Drinkwater (1993) that increased transport of Labrador Current Water around the southeast Grand Bank during warm periods (mid 1960s) on the Northeast Newfoundland Shelf resulted in colder conditions on the S.cotian Shelf. In addition, the increased transport of Labrador Current Water may have contributed to the colder than normal conditions observed on the northern Scotian Shelf and southern Newfoundland Banks during the 1990s (Drinkwater et al. 1999). Also an increase in Labrador Slope Water was traced as far south as the southern Scotian Shelf during 1998.

Discussion and Summary

Variations in the baroclinic component of the volume transport of the Labrador Current on the Newfoundland Shelf during recent climate changes in the Northwest Atlantic were examined. During the past several decades climatic conditions in the Northwest Atlantic have been characterized by several extremes, from the warm 1960s and late 1990s to cold conditions of the early 1970s, mid-1980s and early 1990s. The magnitude of climate variations in the north Atlantic is often measured by the strength of the winter atmospheric pressure fields or NAO index. The ocean generally responded to these climate variations through changes in the shelf stratification due mainly to temperature and salinity changes resulting from variations in ice formation and subsequent melting and through variations in wind forcing. These variations may cause changes in the transport of major current systems. For example, strong winter northwesterly winds generally associated with high NAO index in the northwest Atlantic would be expected to erode shelf-slope density fronts and hence reduce the strength of the density driven currents at the shelf break. The results presented here generally show large interannual variations, but the trend indicates higher-than-average transport during the warm 1960s (low NAO index) and lower than average values during the cold early 1970s and the mid-1980s (high NAO index). During the late 1980s the transport increased to above average values that continued into the mid-1990s, a period of high NAO index anomalies and fresher than normal salinities. The results are consistent with earlier work based on data up to the mid-1980s and with the hypothesis that increased transport of Labrador Current Water around the southeast Grand Bank during the warm 1960s on the Newfoundland Shelf resulted in colder ocean conditions further south on the Scotian Shelf. Furthermore, colder-than-normal conditions were experienced over most of the northern Scotian Shelf during the early 1990s and increased Labrador Slope water was detected as far south as the Gulf of Maine during 1998 (Drinkwater et al. 1999). The higher-than-average transport, at least over the shelf-break regions during the high NAO index period of the early 1990s, is not however consistent with that observed during similar high NAO conditions of the early 1970s and mid-1980s.

The increase in the geostrophic flow over the shelf slope during the 1990s requires further comment, especially since during similar climatic conditions in the 1970s and 1980s this flow was apparently reduced. During these two time periods is was hypothesized that strong mid-latitude winter westerly winds resulting from high NAO conditions eroded the shelf-slope density fronts and with reduced horizontal density gradients in the location of the main offshore branch the result was a reduced baroclinic transport (Myers et al. 1989). Although the magnitude of the salinity anomaly on the inner Newfoundland Shelf during the early 1990s is comparable to that observed there during the Great Salinity of the early 1970s (Fig. 2), it was in general weaker than that of both the early 1970s and mid-1980s over much of the outer shelf regions (Figs. 3 and 4). This difference in the large-scale stratification resulted in different trends in the geostrophic transport during the 1990s compared to the earlier cold periods. It appears that while the temperature anomaly of the early 1990s extended over much of the Northwest Atlantic, the most intense anomalies in salinity and hence stratification were restricted to the inner shelf regions. As a result the shelf-slope density front remained strong thus maintaining strong geostrophic flows in the offshore branch of the Labrador Current. An examination of the salinity anomalies offshore of the shelf-slope branch on the Flemish Cap (Colboume 2000b) confirm that the salinity anomaly of the early 1970s extended far beyond the slope regions whereas during the early 1990s it was considerably weaker in the offshore regions.

The strength of the horizontal pressure gradient and hence the baroclinic flow along the shelf-slope regions is directly proportional to the strength of the horizontal density gradient of the front separating the warmer slope water from the cold fresher shelf waters. The integrity or strength of this front appears to depend on the amount of spring ice melt over the shelf-slope regions, which most likely depends on local wind forcing. For example, even though the early 1990s was one of the longest periods in the past 4 decades with above normal ice coverage on the shelf, it did not appear to extend out over the slope regions as it did during the early 1970s and mid-1980s (Fig. 8). The ice extent however was considerably above normal during mid-February for all three years shown with sea-ice reaching the southernmost area of Newfoundland. As a result, significant negative salinity anomalies existed over the shelf, however, the front remained strong except for 1993 on the southern Labrador Shelf. Increased ice melt shoreward of the slope increases the stratification over the shelf regions and depending on local wind forcing this may strengthen the shelf-slope front density gradients, thereby increasing the baroclinic flow. This seems to have been the case during most of the 1990s, however a more detailed examination of the shelf stratification, spatial variations in sea-ice extent and the local and large scale wind forcing is required to quantify these effects.

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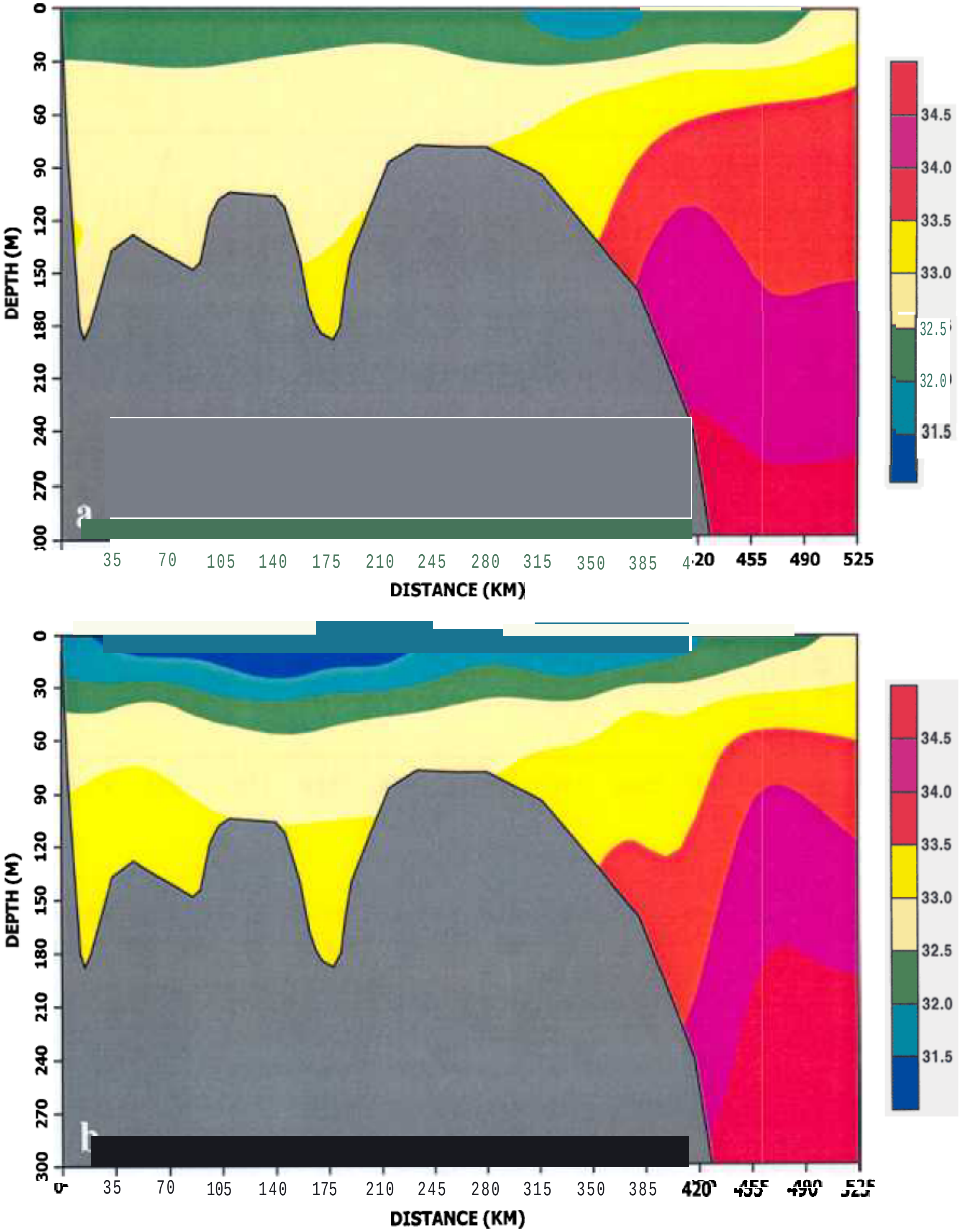


Fig. 3 Vertical cross-sections of salinity on the eastern Newfoundland Shelf along the Flemish Cap transect representative of the cold periods of (a) early 1970s and (b) the mid-1980s.

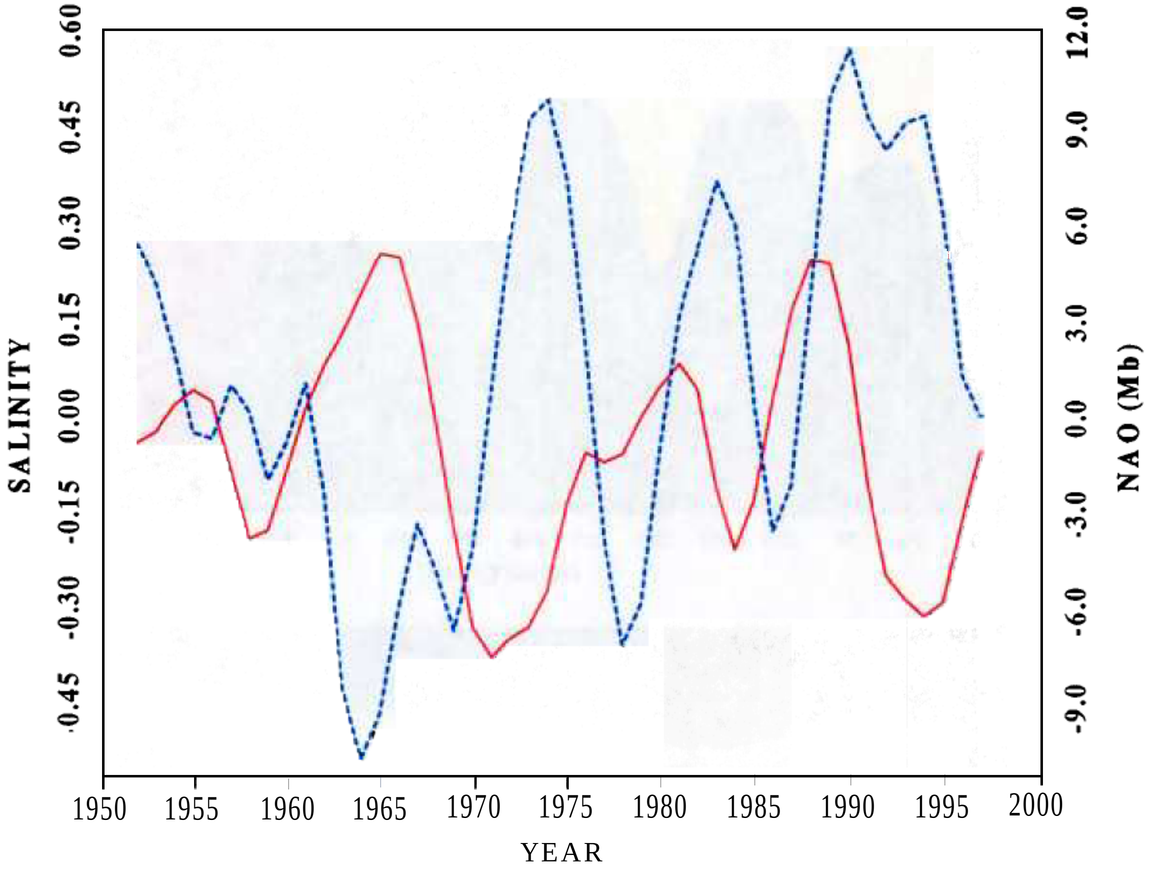


Fig. 2. The 5-year running means of the annual vertically averaged (O-50 m) Station 27 summer (July-Sept.) salinity anomalies (solid line) and the NAO index anomalies (dashed line).

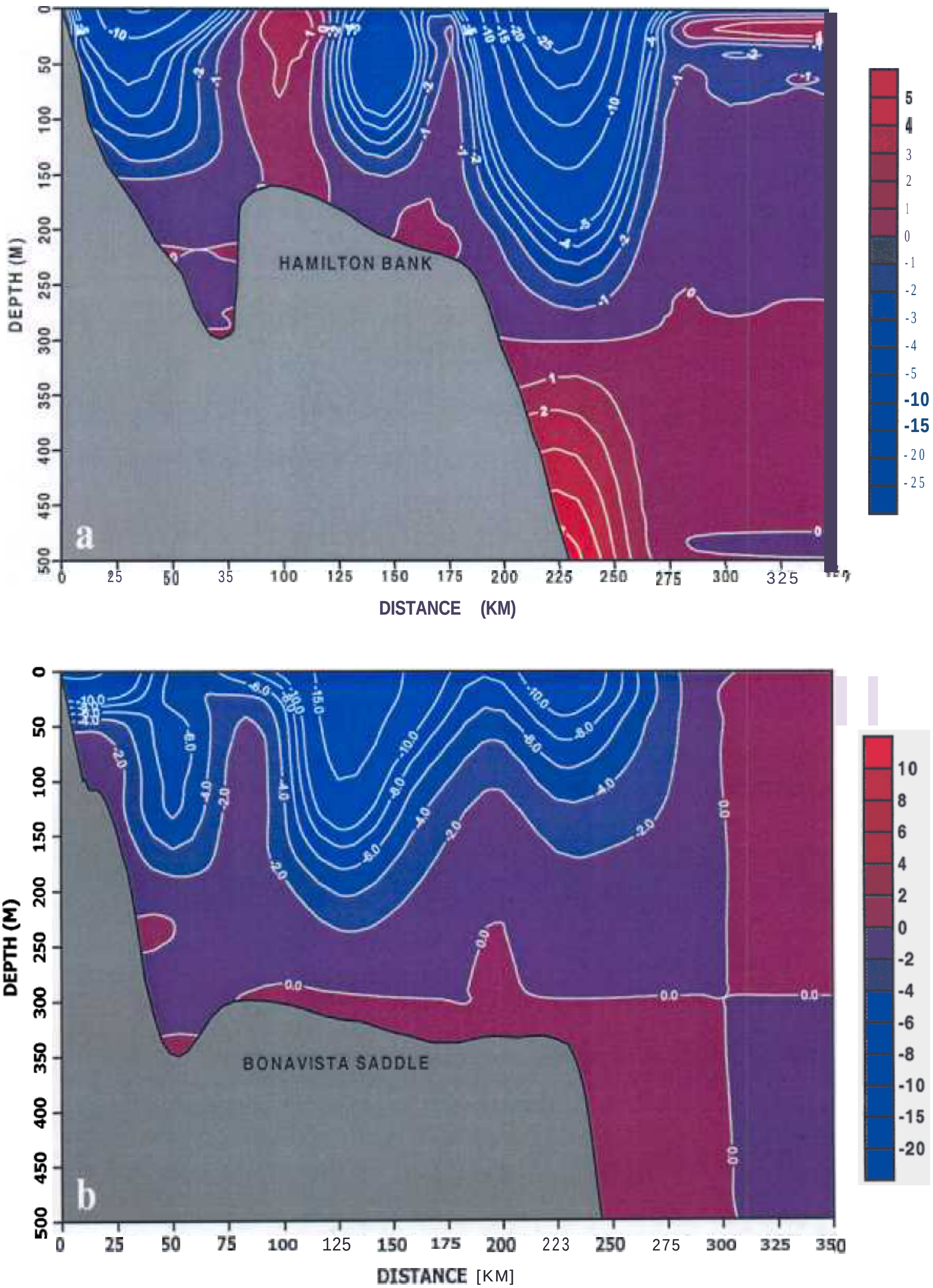


Fig. 5. Vertical cross-sections of summer geostrophic currents (cm/s) along (a) the Seal Island transect (b) the Bonavista transect and (c) the Flemish Cap transect. Negative values are southward.

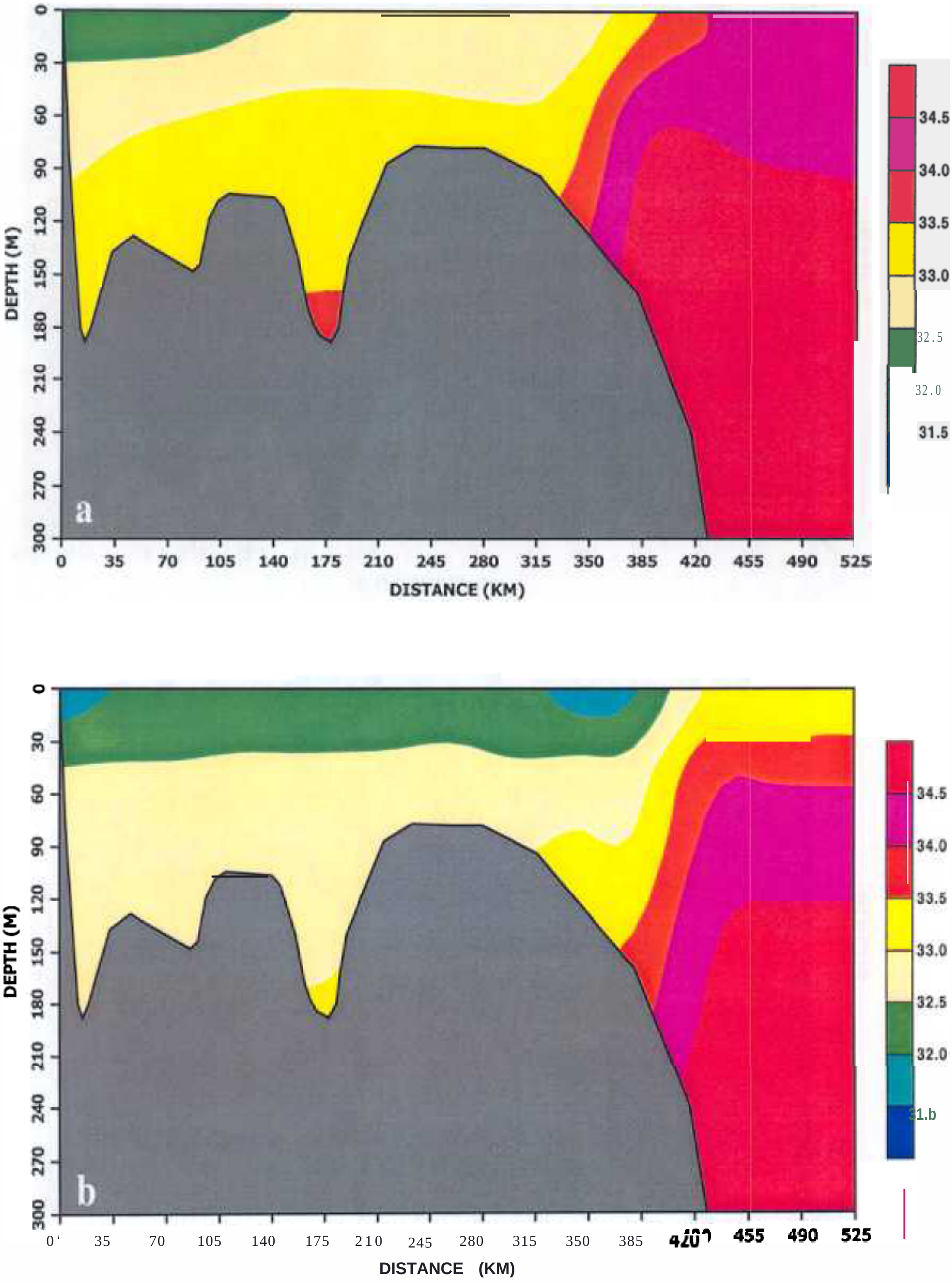


Fig. 4 Vertical cross-sections of salinity on the eastern Newfoundland Shelf along the Flemish Cap transect representative of the warm period of (a) the mid-1960s and (b) the cold period of the early 1990s.

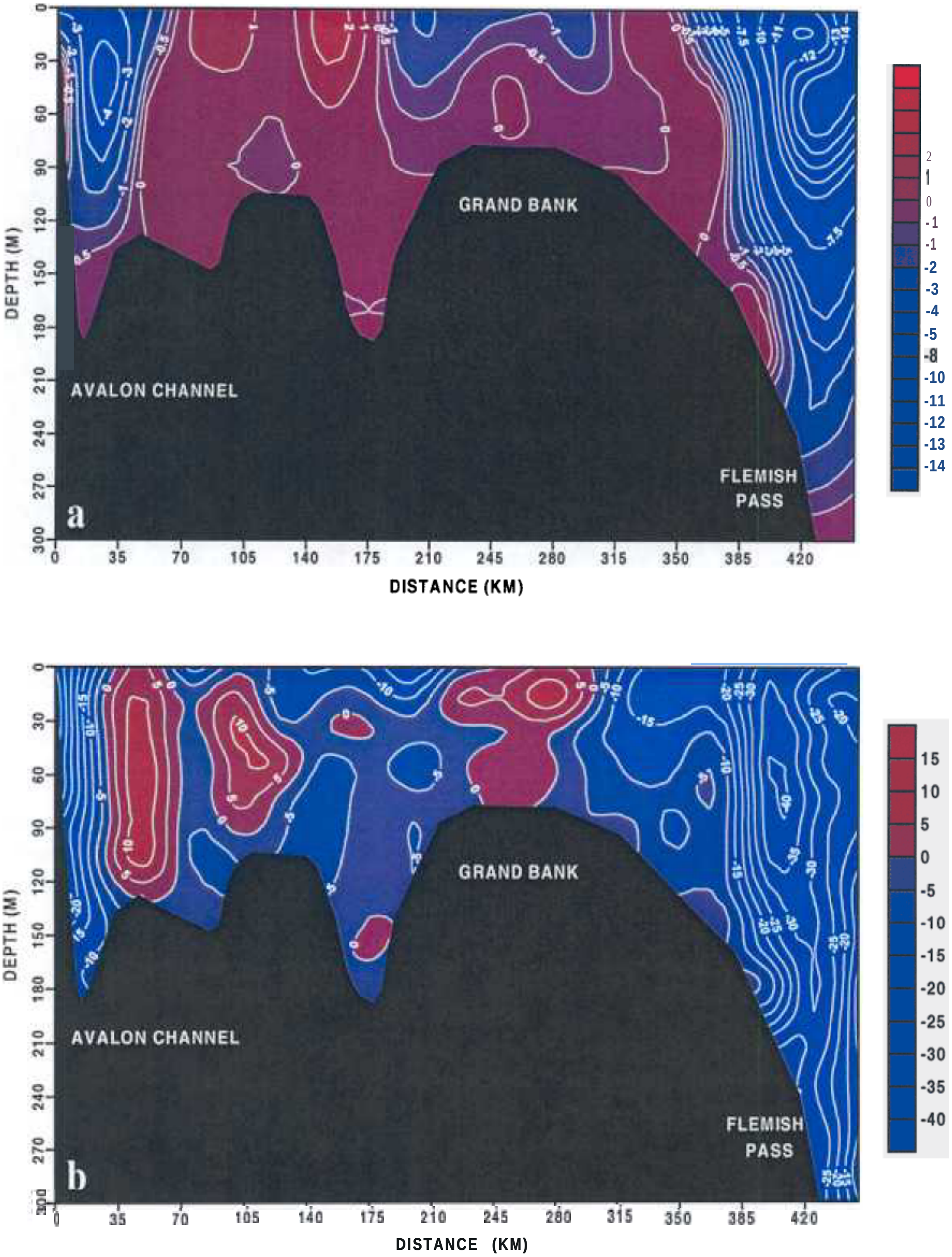


Fig. 6. Vertical cross-sections of (a) summer 1995 geostrophic currents (cm/s) and (b) summer 1995 ADCP measured currents (cm/s) along the Grand Bank portion of the Flemish Cap transect. Negative values are southward.

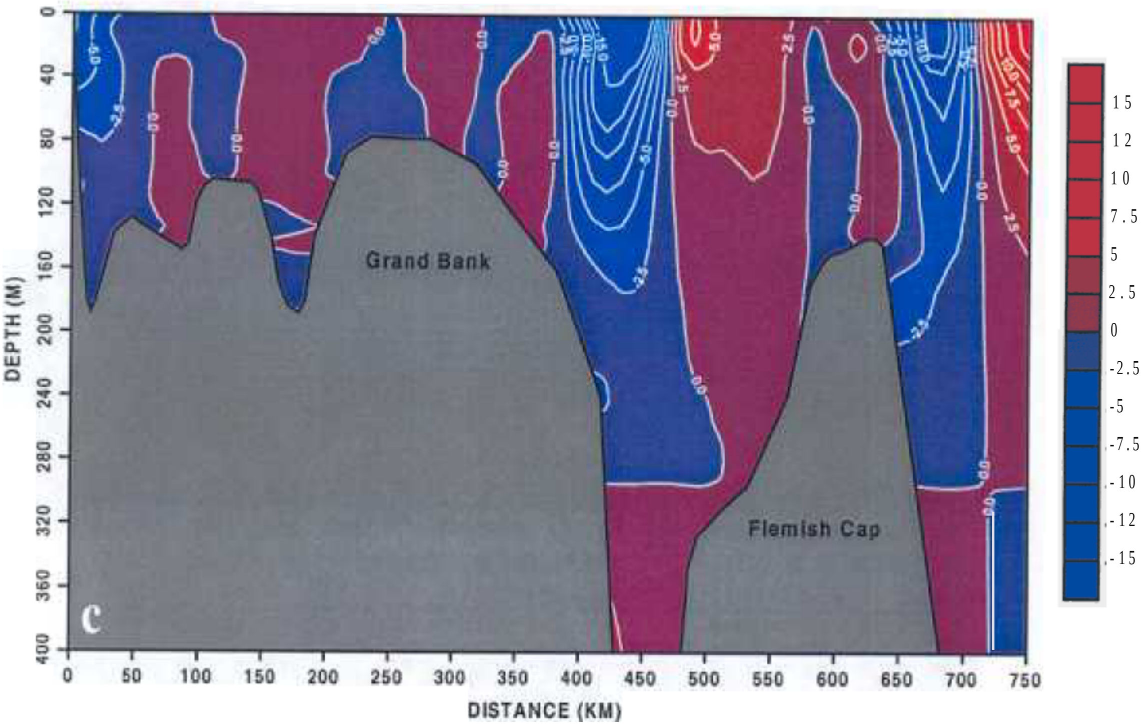
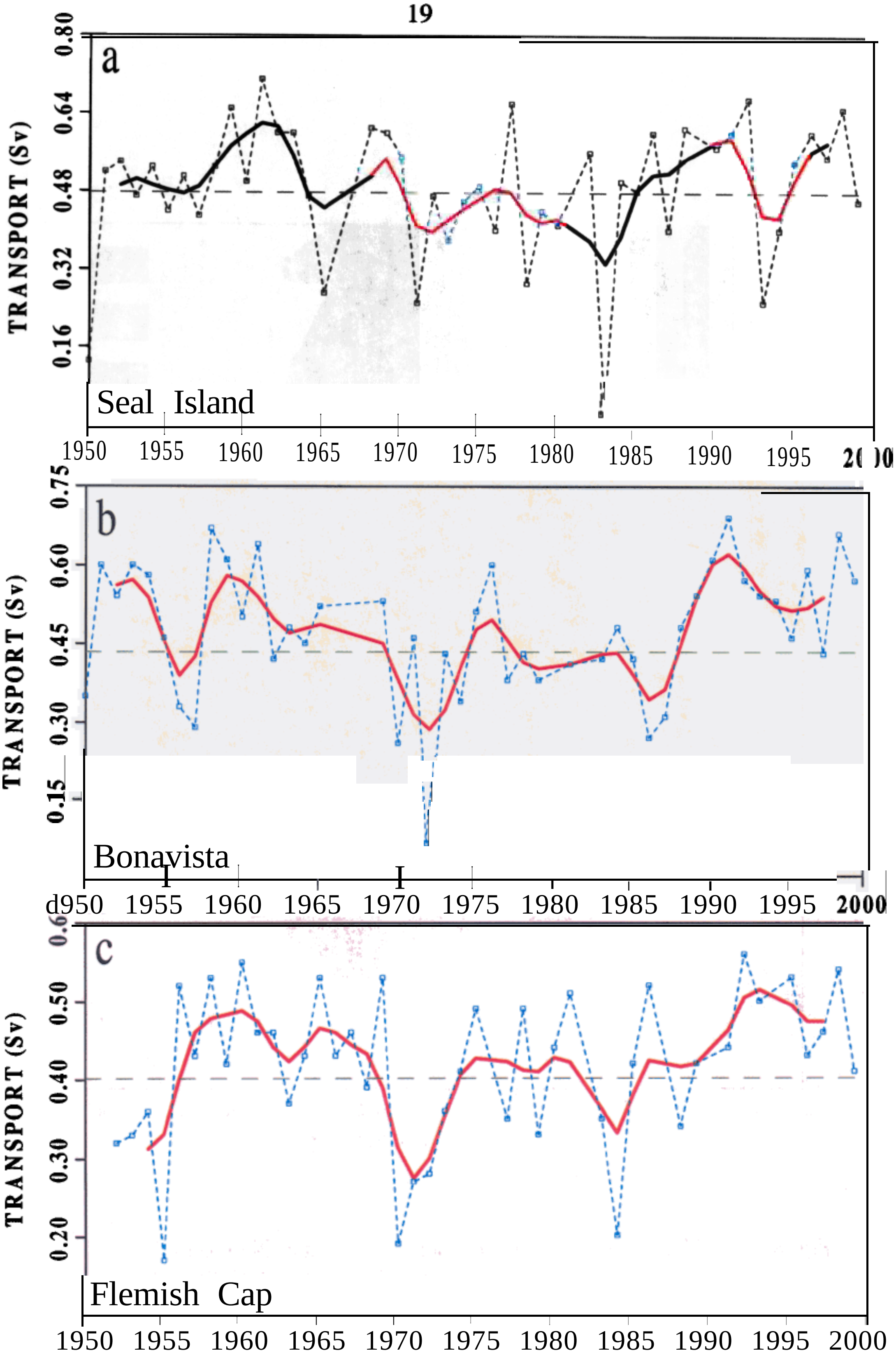


Fig. 5 **(cont).** Vertical cross-sections of summer geostrophic currents (cm/s) along (a) the **Seal** Island transect (b) the Bonavista transect and (c) the **Flemish** Cap transect. Negative values are southward.



ig. 7 Time series of geostrophic transport (Sv=10^6 m^3/s) relative to 130-m depth of the offshore branch of the Labrador Current through (a) the Seal Island, (b) Bonavista and (c) the Flemish Cap transects. The horizontal dashed lines represent the 1961-90 average. The heavy line represents the 5-year running average.

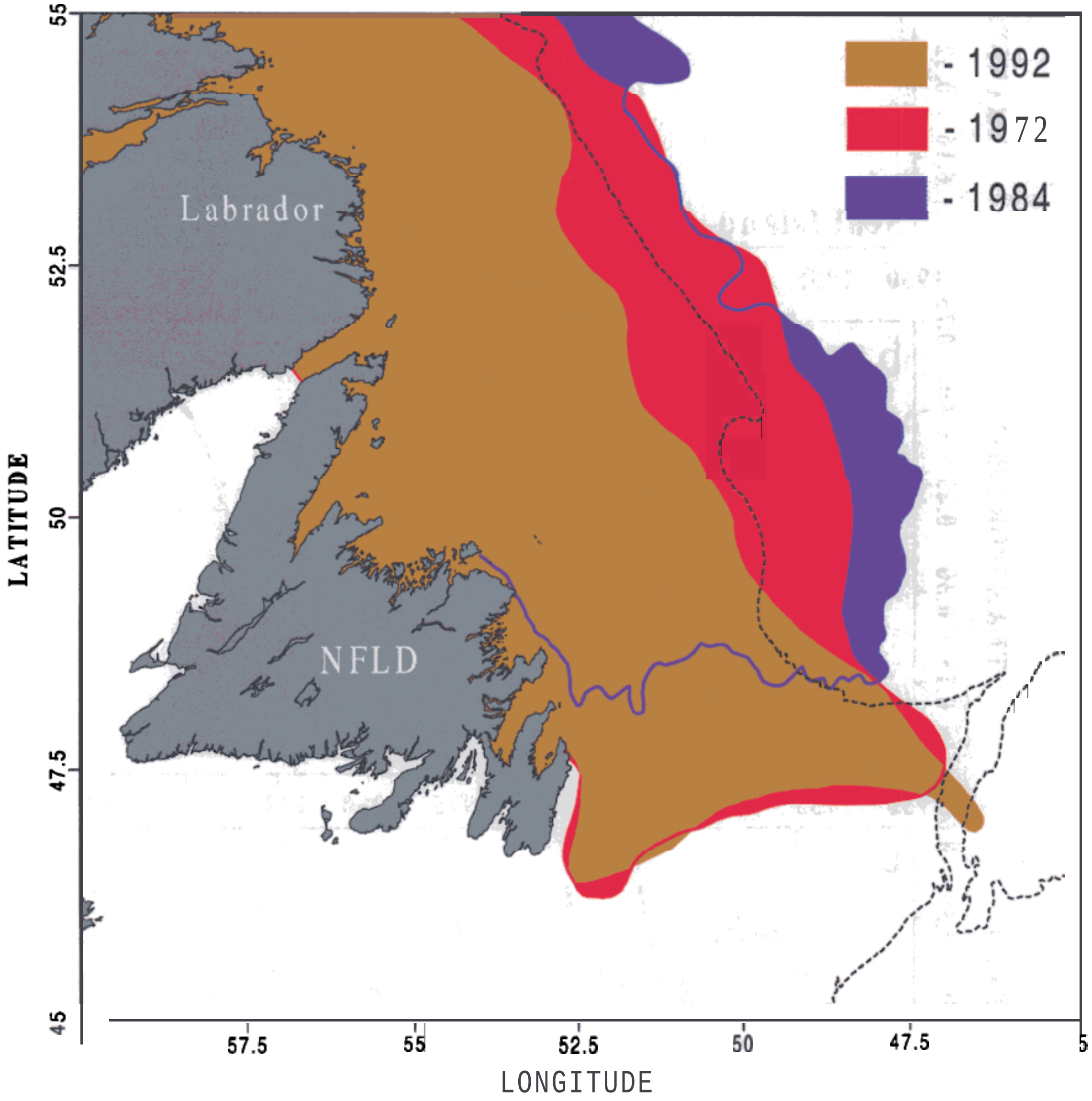


Fig. 8 The spatial extent of sea-ice on the Newfoundland and southern Labrador Shelves during mid-February of 1972, 1984 and 1992. The bathymetry contour is 1000 m.