Northwest Atlantic Fisheries Organization

Serial No. N2225 NAFO SCR Doc. 93/44

SCIENTIFIC COUNCIL MEETING - JUNE 1993

The Influence of the Labrador Current on the Ocean Climate of the Scotian Shelf and the Gulf of Maine

by

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ABSTRACT

Examination of temperature and salinity data from the Scotian Shelf, Gulf of Maine, Gulf of St. Lawrence and the adjacent continental slope has shown that the dominant low frequency event over the last 45 years was a cooling and subsurface freshening of the water masses from 1952-67 followed by a rapid reversal of these trends. The largest temperature and salinity changes (1952-67) were 4.6°C and 0.7, respectively, and occurred at about 100 m over the slope. Exchanges with shelf waters and vertical mixing gave rise to the surface manifestation of this variability. The westward transport of the Labrador Current was found to have similar variability, increasing from about $1x10^6 m^3 s^{-1}$ in the early 1950s to about $4x10^6 m^3 s^{-1}$ in the mid-1960s. A simple model, that accounts for this variation of transport and has a constant entrainment of North Atlantic Water, indicates that changes of the westward flow of the Labrador Current could contribute significantly to the T-S fluctuations.

INTRODUCTION

The region from the Middle Atlantic Bight to the Grand Banks exhibits the highest interannual variability of sea surface temperature (SST) anywhere in the North Atlantic Ocean (Weare 1977, Cayan 1986). Between 1949 and 1969, the dominant low frequency, SST feature in the Atlantic Ocean north of 30°S was a major cooling trend (Weare, 1977). Its maximum amplitude was centered over the continental slope (42°N, 54°W) south of the Grand Banks of Newfoundland and decreased gradually westward over the Scotian Shelf, the Gulf of Maine and the Middle Atlantic Bight. Hachey and McLellan (1948) were among the first to note in-phase variations of SST from the Gulf of St. Lawrence to the Middle Atlantic Bight. Prior to the cooling trend, there was a broad scale warming from about 1940 to the early 1950s. Stearns (1965) indicated that the peak of this warming trend in the early 1950s along the U. S. east coast was strongest in the Gulf of Maine but was apparent as far south as South Carolina.

Thompson et al. (1988) applied an empirical orthogonal function (EOF) analysis to SST data (1946-80) averaged over irregular polygons from the Labrador Sea to Cape Hatteras. Their first mode, accounting for 28% of the variance and in-phase over the entire area, had a maximum on the Scotian Shelf and was dominated by the long period of decreasing amplitude from 1951 to the mid-sixties similar to Weare (1977). They hypothesized that variations of offshore winter (Nov.-Feb.) winds over the Scotian Shelf and Gulf of Maine would cause variations in cold water production and lead to anomalies of SST. A correlation of 0.65 between offshore, winter geostrophic wind and the February mode 1 amplitude supported this hypothesis. However, we note that since their modes 1 and 2 accounted for 57% of the SST variability on the Scotian Shelf (their Table 1, they did not consider the modes separately), then the wind accounted for at most 24% (0.65^2x0.57) of the SST variability.

Umoh (1992) developed a 1-dimensional model of the upper 75 m of the ocean forced by the surface heat fluxes. The model accounted for only 1% of the interannual SST variability when it was applied to the Scotian Shelf. Thus, it is unlikely that the hypothesis of Thompson et al. (1988) is correct.

Fewer studies have examined subsurface temperature changes. In a particularly insightful paper, Lauzier (1965) noted that bottom temperature trends during the 1950s and early 1960s in the Bay of Fundy and at several locations on the Scotian Shelf paralleled those observed near surface. He attributed the short term temperature fluctuations to variations in local weather and speculated that the longer term trends were due to changes in the "mix" of water masses in the region - e. g. more Labrador Water in some years. In addition, he speculated that the properties of constituent water masses might vary. Colton (1968) found similar temperature trends for the deep waters (200 m) in the Gulf of Maine in the mid-1960s. Deep water (>200 m) temperature changes in the Laurentian Channel in the Gulf of St. Lawrence have been similar to SST variations (Lauzier and Trites 1958; Bugden 1991) and have been associated with temperature changes of the water at the mouth of the Channel (Bugden 1991).

Petrie et al. (1991) examined temperature variability in Emerald Basin on the Scotian Shelf. They found large amplitude fluctuations at periods of 10-20 y that were highly coherent throughout the water column with maximum values between 100-150 m. Similar temperature variability was observed from the Laurentian Channel to the Gulf of Maine indicative of a broad-scale ocean climate response. Moreover, the variations appeared to be strongest in those water masses originating over the Slope suggesting a largely oceanic orgin of the low-frequency anomalies.

In this paper we examine additional temperature time series from the Scotian Shelf and Gulf of Maine and investigate the origin of the dominant long-period trend of SST, the decline from the warm period of the 1950s to the temperature minimum in the mid-1960s.

DATA AND METHODS

The primary data sets, their time span and sampling frequency are listed in Table 1 and their locations are shown in Fig. 1. Data included sea surface temperatures (SSTs) from several coastal sites and SST and bottom temperatures from Lurcher and Sambro Lightship vessels. Other temperature and salinity data were supplied by the Marine Environmental Data Service (MEDS) in Ottawa. They were examined for duplicates, density inversions, extreme values, impossible depths and a number of other quality control checks first by MEDS and subsequently by ourselves. These data include bottle, CTD, BT and XBT temperatures from oceanographic and other vessels. An overall guideline for the accuracy of these data would be 0.1°C for temperature and 0.1 for salinity.

Where possible, time series of temperature and salinity were created at standard depths of 0, 10, 20, 30, 50, 75, 100, 125, 150, 175, 200, 250 and 300 m for selected areas. All data within 5 m of the standard depths from 0-75 m were considered to be at the standard depth. For the range 100-200 m, and for the depths 250 and 300 m, all data within 10, 20 and 25 m, respectively, were considered to be at the standard depth.

RESULTS

As noted by Petrie et al. (1991), the temperatures at Emerald Basin rose during the late 1940s and early 1950s to a maximum of about 1°C above the long-term (1946-88) mean in 1952-53 (Fig. 2). Temperature declined for approximately the next 16 y to a minimum of about 3°C below normal in the mid to late 1960s. A rapid temperature rise occurred over 2 y in the late 1960s, followed by a slower increase to maximum values of about 2°C above normal in the late 1970s. A slow decline into the 1980s brought temperatures near normal by 1990. The same pattern was seen at all depths. The surface pattern is less distinct, in part, because it is more affected by the rapidly varying weather systems. It is also apparent that the long-period temperature trends have larger amplitudes at depth than near the surface (Fig. 2). For example, the magnitude of the cooling from 1952 to 1967 was greatest (least) at 150 m (0 m), a decline of 3.9°C (1.6°C) and decreased slowly with increasing depth.

The depth of the maximum amplitude of the cooling trend (150 m) is close to the depth range (140-160 m) of the saddle connecting the slope region to the inner basins. Moreover, this measure of climate variability changes little as depth increases. This indicates that the long-period temperature fluctuations on the shelf are at least partially driven by deep intrusions of slope water.

The salinity time series for depths $\geq$ 100 m feature long term variability similar to that of temperature though far fewer observations are available. There was a decline of salinity from the early 1950s to the mid-1960s, followed by a subsequent rise to above average values. The mean salinity decrease (1952-67) for depths ≥ 100 m was 0.53 (with a typical standard error of 0.15). At shallower depths, the change was not significantly different from 0. The joint occurrence of high (low) temperatures and salinities in the deeper waters of the Basin is further illustrated in the temperature-salinity (T-S) diagram for observations from depths ≥100 m (Fig. 3). The shift of T and S from the early fifties to lower values in the sixties is evident. The water properties in the fifties correspond most closely to the high temperature end of Labrador Slope Water as defined by Gatien (1976); on the other hand, in the sixties, the properties lay between Labrador Slope Water and Mixed Water (Morgan, 1969).

Similar long-term temperature variability to that observed in Emerald Basin has been found in deep waters (200-300 m) of the Gulf of St. Lawrence (Bugden, 1991) and in the deep basins of the Gulf of Maine (Colton, 1968). A temperature minimum of about 4.5°C (S = 34.4), similar to that found in Emerald Basin, occurred at the mouth of the Gulf of St. Lawrence in about 1966. The minimum occurred progressively later farther into the Gulf, indicating an oceanic origin of the anomalies. Over the next decade, the deep temperatures (salinities) in the Gulf rose by 1.5°C (0.3). In the Gulf of Maine, Colton (1968) observed cold conditions in the deep basins during the mid-sixties and attributed them to changes in the volume and composition of slope water flowing into the Gulf. True and Wiitala (1990) noted that these cold conditions extended upwards into the top 30 m.

We have examined the temperature and salinity data from 5 other areas of the shelf and slope (Fig. 1). The temperature time series and the cooling trend from 1952 to 1967 for Emerald Bank, the continental slope and Georges Basin exhibit variability similar to that seen in Emerald Basin (Fig. 4, Table 2). The largest cooling trend occurred in the Slope Water between 30 and 125 m where it exceeded 4°C. In Georges Basin, the cooling trend was about 2.5°C averaged from 0 m to 250 m. On the other hand, the variability and the cooling trend were only weakly reflected in the Sydney Bight time series (Fig. 4). The temperature change from 1952-67 was greater for Banquereau Bank (Table 2), which lies offshore of Sydney Bight. The occurrence of the largest changes over the continental slope again indicates a subsurface, oceanic origin. The reduced response at the eastern end of the Scotian Shelf implies that the outflow from the Gulf of St. Lawrence was not a primary cause.

Salinity decreased by as much as 0.7 from 1952 to 1967 at all standard depths (0-300 m) in the slope waters and Georges Basin for depths≥100 m (Table 2). However, for the upper 50 m in Sydney Bight, salinity increased by as much as 1 during the same period (Fig. 5, Table 2). A similar trend was seen in the observations from Banquereau Bank, and to a lesser extent in the shallow waters of Emerald and Georges Basins. This variability is likely the result of the decrease of freshwater runoff into the Gulf of St. Lawrence from a high of about 16,000 m^3s^{-1} in the early 1950s to a low of 12,600 m^3s^{-1} in the mid 1960s (Koutitonsky and Bugden, 1991). The Nova Scotia Current would carry the influence of this freshwater input variability along the Scotian Shelf and into the Gulf of Maine. Taking the transport of the Nova Scotia Current in the upper 30 m as half the estimated average flow of $0.35 \times 10^6 m^3 s^{-1}$ (Drinkwater et al., 1979), and mixing it with the high value of freshwater inflow from the early fifties and the low inflow of the mid-sixties, produces salinity differences of about 0.55. This is the same order of magnitude as the observed changes. Increased (decreased) freshwater runoff is likely to result in a shallower (deeper) mixed layer, thereby leading to a larger salinity difference than was estimated using a constant depth of 30 m.

Lightship Observations

Temperature observations were made twice a day at 0 and 90 m from the Sambro and Lurcher Lightships from 1950 to the late 1960s (Fig. 1). The time series are quite similar to the ones previously discussed (Fig. 6). The trends for 1952-67 for Lurcher and Sambro, 0 and 90 m, are -2.24, -2.56, -4.21 and -2.37°C, respectively. These results generally are consistent with the observations from Emerald Basin and indicate that aliasing is not a problem for the areas that we have selected. However, the trend for the surface at Sambro is considerably larger than found elsewhere except for the subsurface slope areas. Coastal upwelling may have enhanced the surface temperature trend at Sambro as Thompson and Hazen (1983) show that during early fifties the along-shore wind stress anomaly favoured downwelling and hence higher SST; whereas, in the mid-sixties the anomalies favoured upwelling leading to lower SST.

The vertical and horizontal lagged correlations calculated from the two data sets lend some support to the idea of subsurface origin of the cooling trend. At both sites the largest vertical correlations were for zero lag, but they were asymmetric for non-zero lags, having larger values for the bottom series leading the surface. The horizontal correlation function was also asymmetric and was higher for Sambro 90 m leading Lurcher 90 m. The largest correlation was for a lead of 3 months, though at 0.69 it was not significantly different from the zero lag value of 0.67. However, the drift velocity of 0.04 ms^{-1}, derived from the 3 month lead, is consistent with measured alongshore mean flows in the region (Smith, 1983). Though not conclusive, the evidence is consistent with a westward and upward movement of the temperature anomalies.

Coastal SST Stations

Sea surface temperature data have been collected at three sites in the region from as early as 1906. Anomaly time series, created using 1951-1980 to establish the monthly means, were filtered using a 12 month running mean (Fig. 7). The trends from 1952-67 were -1.23, -1.84 and -3.23°C for Halifax, St. Andrews and Boothbay Harbor, respectively. The first two are consistent with the other observations, but the trend at Boothbay, like Sambro, is somewhat larger than expected - we do not think that the anomaly should grow as it progresses downstream.

In addition to the three coastal stations, the time series from Prince 5, near the mouth of the Bay of Fundy (Fig. 1), at 0 and 90 m appear to be highly correlated (Fig. 7). The trends from 1952 to 1967 were -2.12 and -2.37°C, slightly higher than those found at St. Andrews. However, the salinities measured at Prince 5 do not show any significant trend, perhaps the result of the large variability introduced by the nearby rivers and strong, vertical mixing caused by tides.

These coastal time series also indicate that significant low frequency variability occurred prior to 1945. During this period generally lower temperatures prevailed; between the late 1930s and early 1950s, there was a strong warming trend especially evident in the Boothbay Harbour record.

Sea surface temperature data from Entry Island and surface and subsurface temperature and salinity observations from Sta. 27 (Fig. 1) were examined and did not have trends similar to those discussed above. This indicates that the anomalies did not originate in the Gulf of St. Lawrence nor from the inshore region of the Newfoundland shelf.

To summarize, the temperature and salinity data have shown that there was large-scale, coherent low frequency variability over the continental slope and shelf from the deep Gulf of St. Lawrence to the Gulf of Maine. The major feature was a cooling and subsurface freshening from 1952-67 with the largest changes occurring over the slope at about 100 m.

THE LAUZIER HYPOTHESIS

Lauzier (1965) suggested two processes that may contribute to these very low frequency (longer than 1 y) fluctuations. The proportions of constituent water masses that make up the slope water off the shelf may change and/or the T-S properties of these basic water types may vary temporally. We shall investigate these hypotheses by examining the variability of the temperature, salinity and transport of the Labrador Current, a fundamental component of the offshore waters in the region (McLellan, 1957).

Between 1934 and 1967, the International Ice Patrol (IIP) compiled the average T-S properties (Morgan, 1969) of the Labrador Current from hydrographic sections off Newfoundland (Fig. 1, insert). The time series of average temperature and salinity at 100, 200, 300 and 400 m for the eastern continental slope show that between 1934 and 1941, both T and S were increasing (Fig. 8). Furthermore, when the transects started again in the late 1940s, generally positive trends for the water properties were observed into the mid-1960s when the IIP discontinued this form of T-S analysis. The correlations between these average T-S values are generally high and indicate that warm-salty or cold-fresh conditions occurred together (Fig. 9). The temporal variability of subsurface temperature and salinity in the Labrador Current were opposed to the trends shown in the data from the Scotian Shelf and the Gulf of Maine. Thus, although systematic changes of the water mass properties of the Labrador Current have been found, they were in the opposite sense that Lauzier hypothesized. However, even when its temperature and salinity are greatest, the subsurface Labrador Current water is still cold and fresh relative to other source waters on the Scotian Shelf. Thus, a large westward flow of this water along the shelf break could lead to reduced temperatures and salinities on the Scotian Shelf.

The geostrophic transports of the Labrador Current relative to 1000 dbar (Fig. 10) have been calculated by the IIP (see Kollmeyer et al., 1966 for a discussion of method and compilation of some of the transports) for sections A3 and A4 (Fig. 1) up to the time of cancellation of their intensive hydrographic surveys in the late 1970s. A greater number of estimates is available for the more frequently sampled A3 section. Low frequency variability is evident in both time series with increasing transport from the mid-1930s (about $1\text{-}2\times10^6 m^3 s^{-1}$ at A4) to the early 1940s (approximately $6\times10^6 m^3 s^{-1}$ at A4). From the early 1950s to the mid 1960s, the westward transport at A4 increased from about $1\times10^6 m^3 s^{-1}$ to $4\times10^6 m^3 s^{-1}$. The variability was similar at A3 but the values were generally higher indicating that some of the flow may have turned eastward before reaching A4 at the Tail of the Bank. From the late 1960s until the surveys ended in the late 1970s, the geostrophic transport generally decreased in both sections to about $1\text{-}2\times10^6 m^3 s^{-1}$. The geostrophic transports at A3 from 1948 to 1976 are negatively correlated (-0.35, 41 estimates) with Emerald Basin 100 m temperatures taken in the same month. Thus, the period 1952-1967 was one of generally declining temperatures and salinities in the Scotian Shelf area, and increasing subsurface temperatures and salinities, and transport of the Labrador Current. Note as well that the period of high, increasing transport (1936-41) was also a time of below normal temperatures at Boothbay Harbor, St. Andrews and Prince 5 (Fig. 7). In addition, the apparent decrease of transport beginning in the mid-1960s corresponded to the period of rapid warming of Scotian Shelf waters.

Greenberg and Petrie (1988) estimated the westward transport of Labrador water along the shelf break at 63° 30'W as $0.9\times10^6 m^3 s^{-1}$ from 2 y of current meter data collected in 1976-77. Most of the transport was for depths ≥ 300 m. This estimate agrees with the geostrophic computations for the same period and the weak westward flow in the depth range 100-300 m is consistent with the relatively warm-salty conditions on the Shelf.

We propose that the increased westward transport of the Labrador Current could contribute significantly to the observed property changes on the Scotian Shelf. Consider the following simple model of circulation and mixing in the continental slope region (Fig. 11). Near the Tail of the Bank (section A4) there is a westward moving Labrador Current with transport U_o. In order to avoid the annual cycles of T and S, we have limited our model to the depth range 100-300 m, where we have vertically averaged the observations. From individual sections, we estimate that about 40% of the transport is accounted for by the 100-300 m layer, i.e. the transport in this layer would vary from about $0.4\times10^6 m^3 s^{-1}$ in the early 1950s to $1.6\times10^6 m^3 s^{-1}$ in the mid-1960s. As the Labrador Current water moves westward, it entrains and mixes with North Atlantic Central Water at the rate of E $m^3 s^{-1} km^{-1}$. From Smith (1978), we estimate an E of $0.06\times10^6 m^3 s^{-1}$ per 100 km due solely to the entrainment of upper 50 m waters by Gulf Stream eddies and their subsequent subsurface replacement. From McLellan (1957), who developed a water mass budget for the slope region, we calculate an E of $0.15\times10^6 m^3 s^{-1}$ per 100 km after reducing his westward transport of the Labrador Current from $3.3\times10^6 m^3 s^{-1}$ (too high for the warm period he was considering) to $1\times10^6 m^3 s^{-1}$ and further reducing the entrainment rate by 0.4 to account for the depth range of our model.

Then for any initial value of T or S, designated P_o, and for North Atlantic water (P_a), at X km along its path, the property value, P, of the slope water is given as:

$$P = P_o\ (U_o/(U_o + E^*X)) + P_a\ (1 - U_o/(U_o + E^*X))$$

The entrainment, E ($0.1\times10^6 m^3 s^{-1}$/100 km), and the T (13°C) and S (35.6) of the North Atlantic Central Water are assumed constant. For a cold (warm) period on the Scotian Shelf, the transport and the initial temperature and salinity of the Labrador Current are estimated from the data to be $1.6\times10^6 m^3 s^{-1}$ ($0.4\times10^6 m^3 s^{-1}$), 2.66°C (1.73°C) and 34.36 (34.24) respectively (Fig. 11). The water properties are based on averages in the 100-300 m depth range in the region. Recall that relative to the Scotian Shelf water masses, both of these are cool and fresh.

The simple model gives reasonable agreement with the observations from the Scotian Shelf and south of Georges Bank (Fig. 12). However, temperature and salinity are overestimated for the Gulf of St. Lawrence even though Bugden (1988) has noted that a substantial fraction of Labrador Water is required to produce the deep T-S characteristics , 58% in cold years versus 37% in warm. The data we have used for the Gulf are from about 400 km inshore of the continental slope, the area where the model estimates apply. Bugden (1991) has shown that vertical diffusion of heat and salt is an important process along the axis of the Laurentian Channel, and causes cooling and freshening of inflowing waters. Using his estimate of vertical diffusivity ($2.2 \times 10^{-4} m^2 s^{-1}$), along-channel inflow velocity ($0.04\ ms^{-1}$) and vertical gradients for warm and cold years (Bugden, 1988, 1991; El-Sabh, 1975) near Sydney Bight, we find that the temperature and salinity points (Fig. 12) should be increased by 0.4°C (0.2°C) and 0.2 (0.1) for cold (warm) period. This gives better agreement for the cold period comparison but still leaves a substantial underestimate for the warm period. There are several factors that could contribute to this discrepancy. The correction to the above calculation is sensitive to the values of current and vertical T and S gradient. In particular, during warm periods the gradients at the mouth of the Laurentian Channel (44°N) are larger, leading to corrections of as much as 0.8°C and 0.3 for T and S respectively. Though this improves the salinity fit significantly, the temperature is still too low. The inshore branch of the Labrador Current may affect the observations at the entrance to the Gulf of St. Lawrence (Petrie and Anderson, 1983). Lastly, the model is quite simple and is intended only to demonstrate whether or not the variation of the Labrador Current could contribute significantly to the low frequency variability of water properties on the Scotian Shelf. Its assumption of a spatially constant entrainment, in particular, is dubious given that the number of Gulf Stream rings varies significantly with longitude. Trites and Drinkwater (1990), Drinkwater and Trites (1991) and Trites (pers. comm.) indicated that, for 1988-1990, the average number of rings during an individual year per 5° longitude between 50° and 70°W was 15 (60° to 65°W) and 8 (50° to 55°W). Moreover, the rings appeared to last longer in the western end of the region. Thus, entrainment could be weaker in the Grand Banks area and stronger offshore of the Scotian Shelf.

DISCUSSION AND CONCLUSIONS

Our analysis of oceanographic data for the area from the Grand Banks to the Gulf of Maine indicates that, over the last 45 y, the dominant feature in the low frequency temperature and subsurface salinity variability was a cooling and freshening trend from the early 1950s to the mid-1960s, followed by a rapid warming and increase of salinity to 1970. This was a broad scale, coherent ocean climate fluctuation that affected different water masses. The largest changes were subsurface and appeared to originate in the waters over the continental slope. Exchanges with shelf waters and vertical processes gave rise to the surface manifestation of the variability noted by Weare (1977) and Thompson et al. (1988). The enhanced trends observed at Boothbay Harbor and Sambro Lightship at the surface are exceptional and may have been augmented by coastal upwelling. In particular at Boothbay Harbor and, in fact, for the entire Gulf of Maine, a modelling effort similar to the one by Umoh (1992) for the Scotian Shelf would be required before the role of the air-sea fluxes relative to subsurface processes could be established. Higher frequency variability may have been forced predominantly by atmosphere-ocean interactions.

An opposing salinity trend (1952-67) was found for the near-surface, shelf areas and was strongest in Sydney Bight which is dominated by outflow from the Gulf of St. Lawrence. This observation appears connected to the reduction of freshwater runoff into the Gulf.

The low frequency variability of temperature and salinity of the Labrador Current was opposite to that of the Scotian Shelf water properties. However, the transport of Labrador Current water increased between 1952 and 1967 leading to the hypothesis that it is the increased westward flow of this water that leads to the cooling and freshening trend seen over the Scotian Shelf. The first result is opposed to one hypothesis of Lauzier (1965) while the latter is in agreement with his second proposal.

A simple model indicates that variations of the westward transport of the Labrador Current could significantly contribute to the observed temperature and salinity fluctuations of waters from the Gulf of St. Lawrence to the Gulf of Maine. However, a steady westward transport of $1 \times 10^6 m^3 s^{-1}$ and a variable entrainment rate of $0.063 \times 10^6 m^3 s^{-1}$ or $0.25 \times 10^6 m^3 s^{-1}$ per 100 km could give the same result. We do have measures of the variability of the Labrador Current, we do not presently have an indicator of a fluctuating entrainment rate.

The question of what causes the variations of the Labrador Current naturally arises. At present we do not know. Examination of atmospheric time series, such as the sea level pressure difference between Greenland and Newfoundland, has thus far proved unsuccessful. However, there appear to be connections to variability in more northern waters. Narayanan et al. (1992) show that the cross-sectional area of the cold intermediate layer ($T \leq 0^{\circ}C$) measured on a standard oceanographic transect over the northeast Newfoundland shelf decreased in a linear fashion from about 35 km^2 in the early 1950s to 20 km^2 in the mid-1960s. This is consistent with our observation (Fig. 13) of increasing Labrador Current temperatures during the same period. In addition, we have found some interesting but statistical unreliable relationships between the strength of the current off the Labrador Shelf, West Greenland and section A3. These issues are being pursued.

ACKNOWLEDGEMENTS

We thank Dr. Don Murphy in particular for his assistance inunderstanding and verifying the methods that his predecessors at IIP, U. S. Coast Guard had used to analyze the Newfoundland data they had collected. We thank G. Bugden and S. Narayanan for comments that clarified parts of the manuscript and the former for suggesting corrections that improved the fit of the Laurentian Channel data.

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TABLE 1

Summary of oceanographic data sets covering the period 1945-1990 unless noted otherwise.

Data Set	Sampling Frequency
Sea surface temperature	
Boothbay Harbor	2/day
St. Andrews	"
Halifax Harbour	"
Entry Island (1945-77)	"
Light vessels, surface and bottom temperature	
Lurcher (1950-69)	2/day
Sambro (1950-66)	"
Oceanographic monitoring stations	
Prince 5	1/month
Station 27 (1951-1990)	2/month on average
Oceanographic stations of opportunity	
Sydney Bight	irregular
Banquereau Bank	
Emerald Basin	
Emerald Bank	
Slope Water	
Georges Basin	

TABLE 2

Temperature (°C) and salinity changes for the period 1952-67 from the monthly anomaly time series.

DEPTH (m)	SYDNEY BIGHT	BANQUEREAU BANK	EMERALD BASIN	EMERALD BANK	SLOPE WATER	GEORGES BASIN
			TEMPERATURE			
0	-0.63	-1.02	-1.64	-2.01	-3.36	-2.26
10	-0.55	-0.80	-2.36	-2.30	-3.47	-2.51
20	-0.39	-1.38	-2.46	-2.78	-3.89	-2.81
30	-1.54	-1.73	-2.62	-2.11	-4.27	-2.50
50	-0.94	-1.27	-2.09	-2.41	-4.64	-2.65
75	-0.91	-2.22	-2.61	-3.03	-4.54	-2.55
100	-1.20	-2.14	-3.45	-2.54	-4.55	-2.82
125	-1.01	-1.78	-3.66		-4.57	-2.54
150	-1.82	-1.50	-3.89		-3.45	-2.78
175	0.32	-1.81	-3.67		-2.83	-2.31
200	-0.33	-1.24	-3.61		-3.03	-2.37
250			-3.49		-3.12	-2.23
300					-1.81	-1.77
			SALINITY			
0	0.92	0.58	0.11	0.21	-0.25	-0.10
10	1.05	0.59	0.09	-0.03	-0.15	0.09
20	0.70	0.33	-0.10	0.21	-0.29	0.10
30	0.67	0.29	0.14	0.12	-0.32	0.24
50	0.18	0.19	0.06	-0.18	-0.53	0.21
75	-0.08	0.02	-0.19	-0.10	-0.69	0.24
100	-0.27	-0.35	-0.42	0.02	-0.57	-0.33
125			-0.59		-0.62	
150	-0.05	0.33	-0.58		-0.65	-0.74
175		-0.31	-0.48		-0.19	
200			-0.59		-0.40	-0.66
250			-0.52		-0.44	-0.23
300					-0.24	-0.29

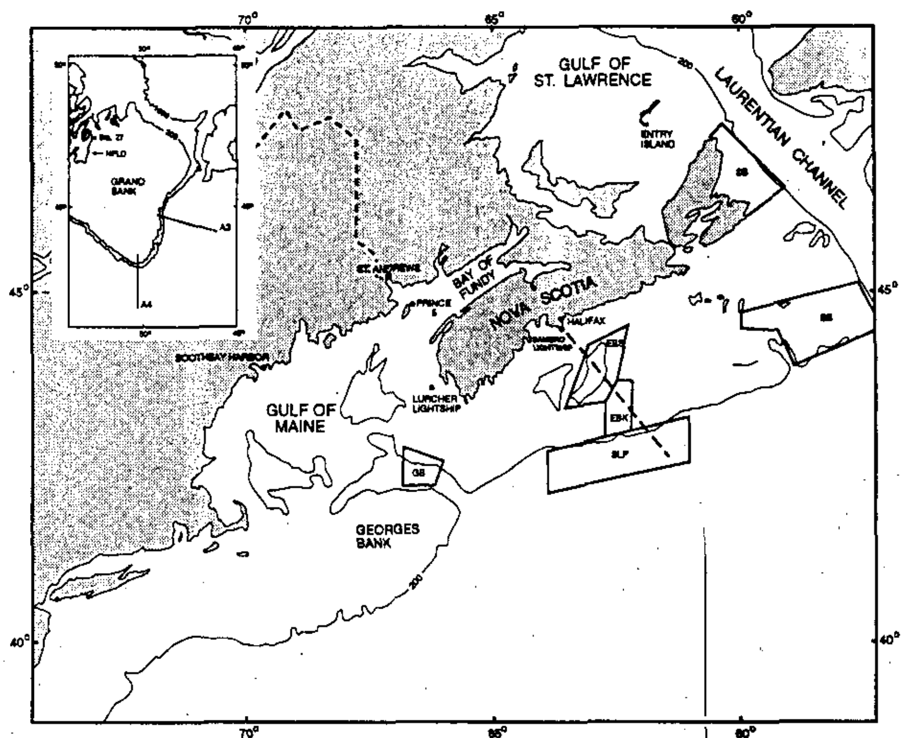


Fig. 1. The Scotian Shelf and Gulf of Maine coastal sea surface temperature and lightship locations are indicated. The polygons from which data were extracted are labelled SB (Sydney Bight), BB (Banquereau Bank), EBS (Emerald Basin), EBK (Emerald Bank), SLP (Slope Water region), and GB (Georges Basin). The Halifax Section is shown as a broken line. Station 27 and the U.S. Coast Guard hydrographic sections (A3 and A4) are shown on the insert.

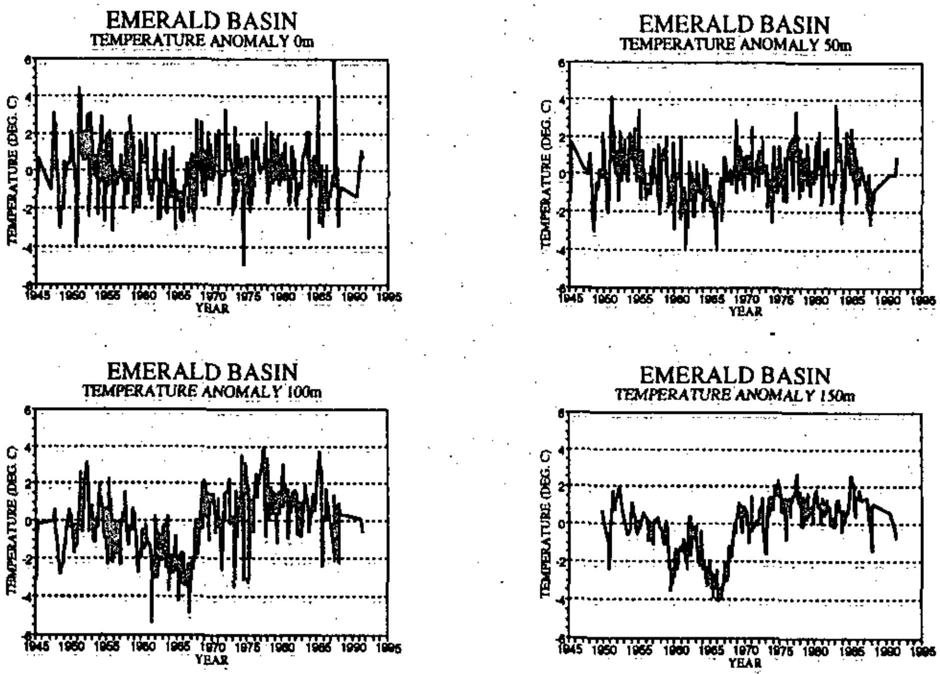


Fig. 2. Monthly temperature anomalies for Emerald Basin at 0, 50, 100 and 150 m for the period 1945-92.

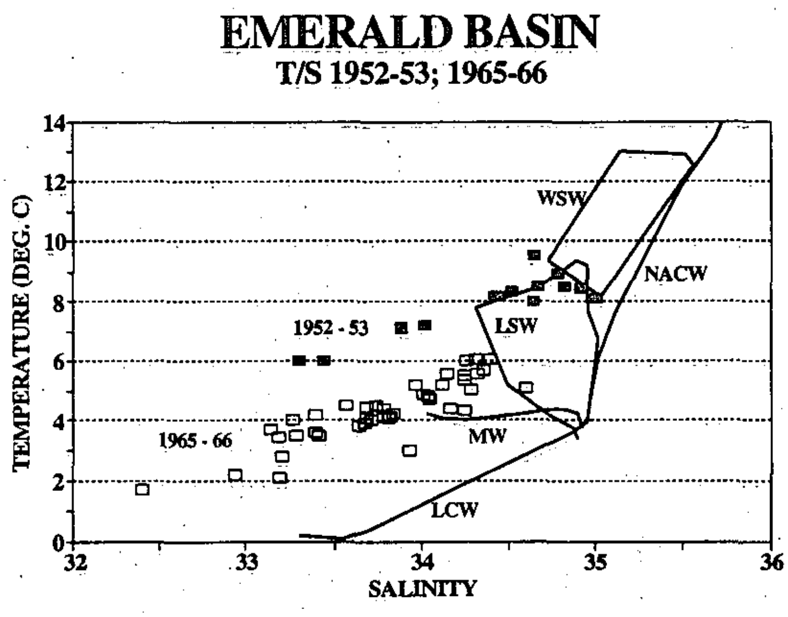


Fig. 3. Temperature-salinity diagram of observations from depths≥100 m for a warm (1952-53, solid box) and cold (1965-66, open box) period. The envelopes of T-S characteristics for Warm Slope Water (WSW) and Labrador Slope Water (LSW) (from Gatien, 1976), and the average curves (Morgan, 1969) for North Atlantic Central (NACW), Mixed (MW) and Labrador Current Water (LCW) are also shown.

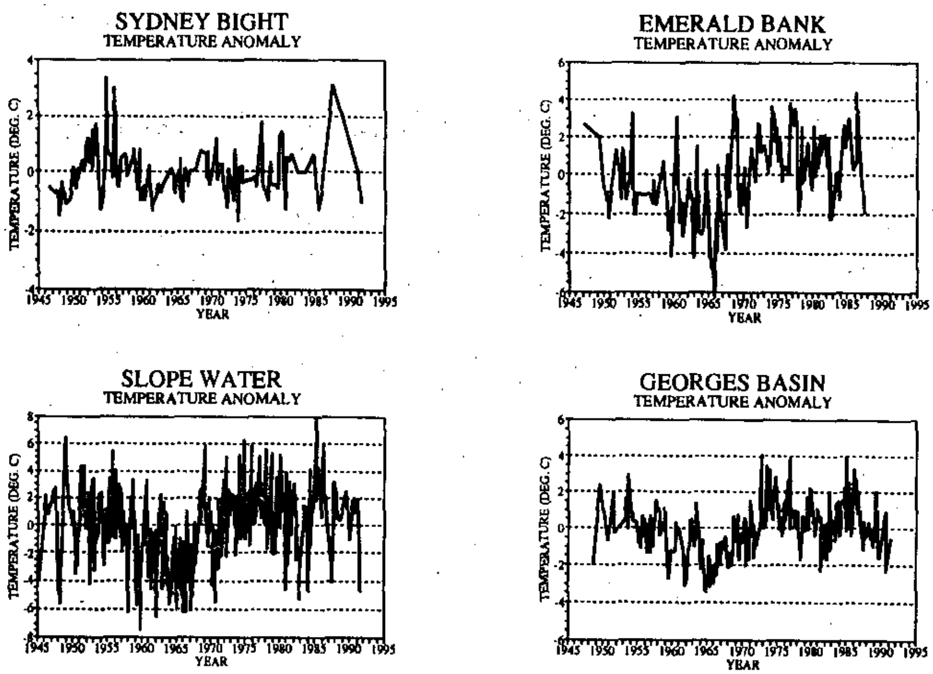


Fig. 4. Monthly temperature anomalies at 100 m for Sydney Bight, Emerald Bank, the Slope Water and Georges Basin.

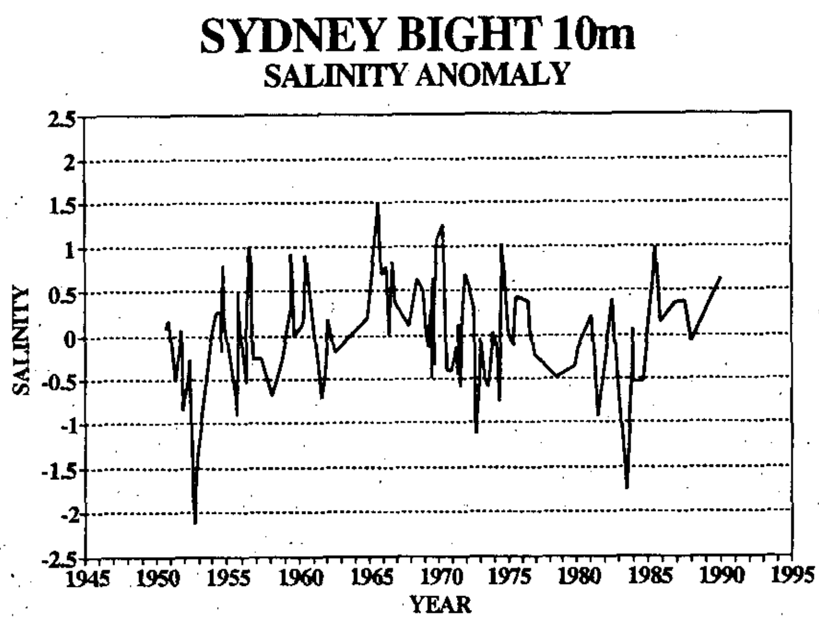


Fig. 5. Time series of monthly salinity anomalies from the Sydney Bight, 10 m.

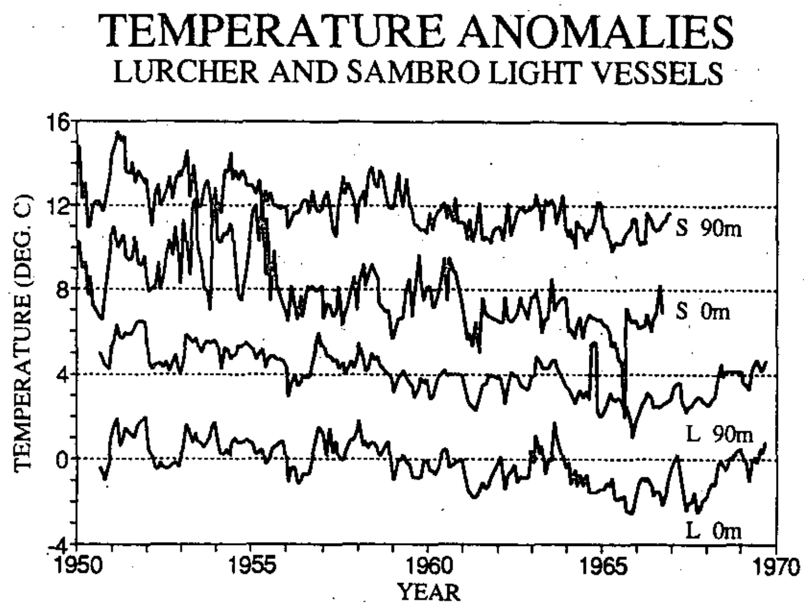


Fig. 6. Time series of the monthly, 0 and 90 m temperature anomalies from the Lurcher (L) and Sambro (S) Lightships. The upper series have been offset by 4°C from the one directly below.

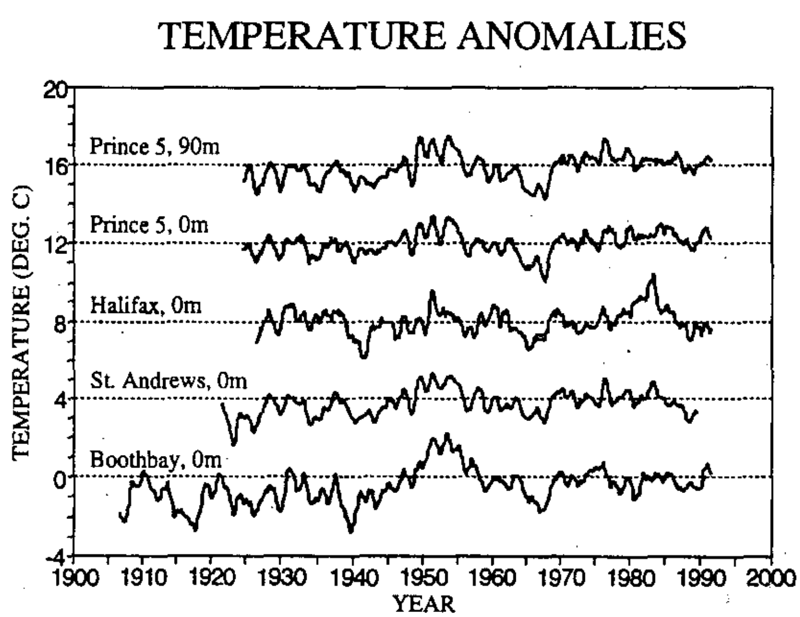


Fig. 7. Monthly sea surface temperature anomalies from three coastal sites and surface and bottom temperatures from the Prince 5 oceanographic station. The data have been smoothed with a 12 month running mean filter and the series have been offset by 4°C.

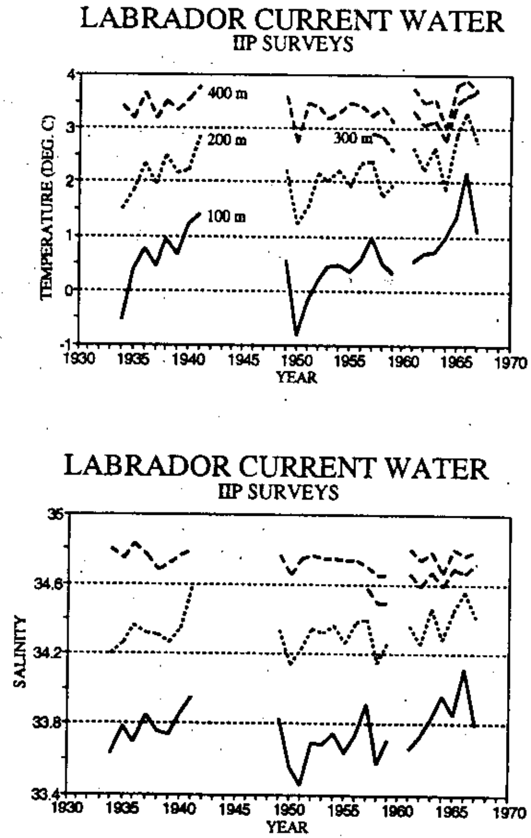


Fig. 8. Average temperature and salinity of the Labrador Current waters at 100, 200, 300 and 400 m from U.S. Coast Guard surveys (see Morgan, 1969, for example).

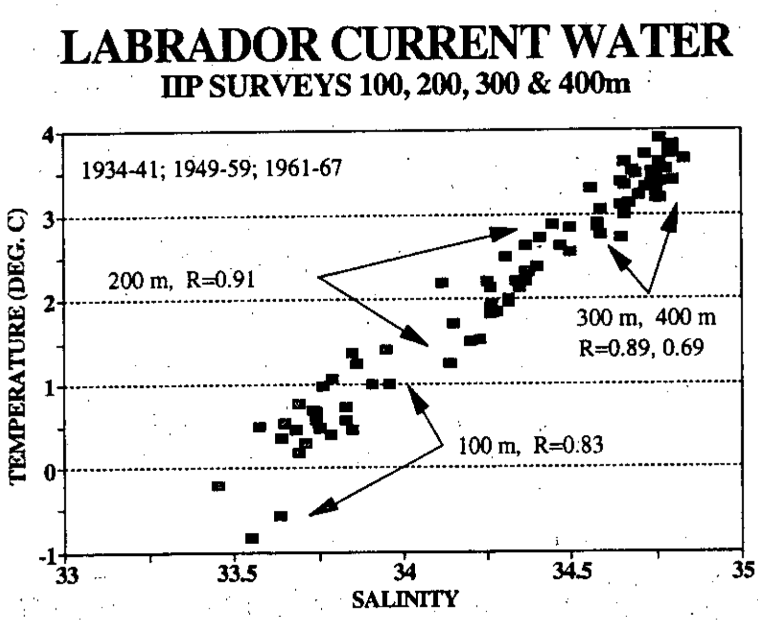


Fig. 9. Average temperature and salinity of the Labrador Current Water at 4 depths (100, 200, 300 and 400 m) from the period 1934-67. The years that data were collected and the T-S correlations (R) are shown.

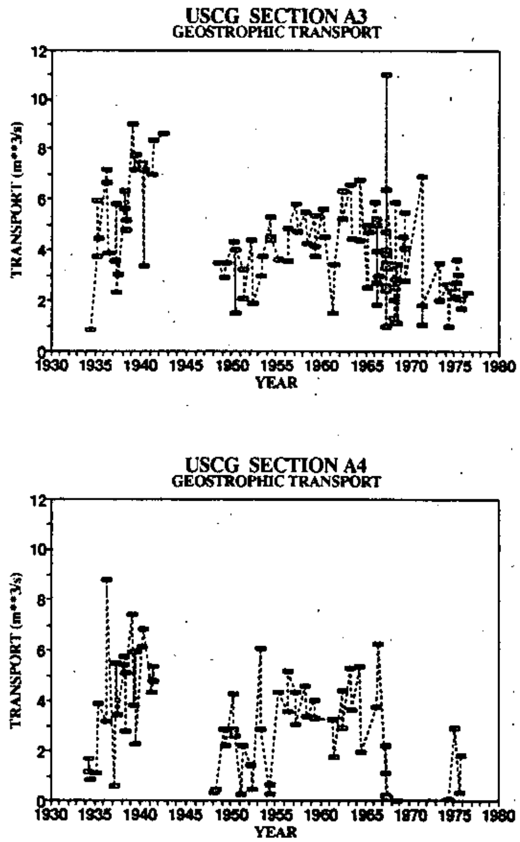


Fig. 10. Geostrophic transport of the Labrador Current relative to 1000 dbar, 1934-77 (see Kollmeyer et al., 1966, for example).

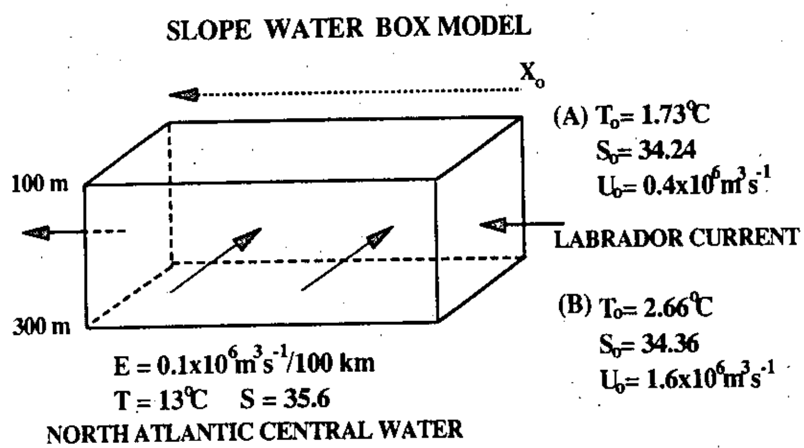
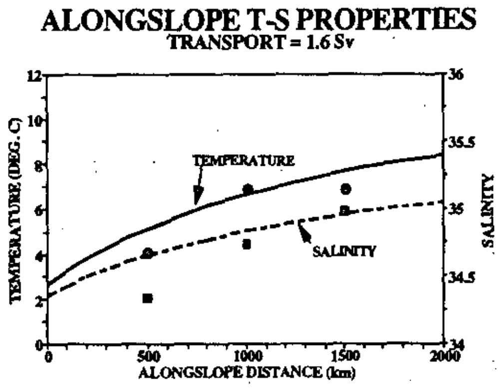


Fig. 11. Box model of slope water where X_o is located at Section A4 (Fig. 1). The Labrador Current water properties and transport are given as (A) and (B) and correspond to a warm and cold year respectively, on the Scotian Shelf. The entrainment rate, E, temperature and salinity of North Atlantic Central Water are taken as constant.



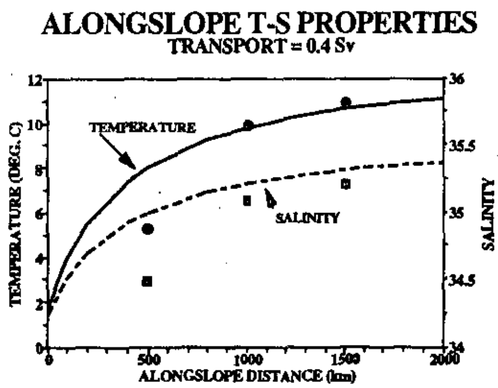


Fig. 12. The predicted alongslope temperature and salinity variation for the 100-300 layer is shown for conditions of high ($1.6 \times 10^6 m^3 s^{-1}$) and low ($0.4 \times 10^6 m^3 s^{-1}$) westward transport of the Labrador Current. The observed average properties at the Laurentian Channel (at 500 km, Bugden, 1991), Emerald Basin and south of Georges Bank (Colton, 1968) are indicated for T (circles) and S (squares). Note 1 Sv = 10^6 $m^3 s^{-1}$.