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Ocean Climate variations for the Canadian East Coast: A Simple Model with an Update for 1993

by

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Abstract

We present a simple model of the heat balance for the Canadian East Coast shelf waters to a depth of 100 m. The overall balance in the model is between the advection into the system in the north and the heat flux from the atmosphere. A variation of the inflow from 1.1 to $2.0 \times 10^6 m^3/s$ can account for the observed interannual variations of shelf water temperatures. Other processes such as cross-shelf and cross-frontal heat exchange contribute to the overall heat balance, particularly in the slope water region south of the Scotian and Newfoundland shelves. The interannual variability of percent saturation of oxygen varies with the changing water masses, where periods of increased Labrador (North Atlantic Central) Water correspond to higher (lower) saturation levels. Data collected in 1993 are added to the long times series to indicate the recent tendencies of ocean climate fluctuations.

Résumé

Nous présentons un modèle simple de l'équilibre thermique des eaux qui recouvrent la plate-forme de la côte est du Canada à une profondeur de 100 m. Dans le modèle, l'équilibre global se situe entre l'advection dans le système au nord et le flux thermique provenant de l'atmosphère. On peut imputer à la variation de l'afflux d'eau, de 1,1 à 2,0 x $10^6 m^3/s$, les écarts interannuels observés dans les températures de l'eau sur la plate-forme. D'autres phénomènes comme l'échange de chaleur sur l'ensemble de la plate-forme et du front contribuent à l'équilibre thermique global, en particulier dans le secteur d'eau de pente situé au sud des plates-formes néo-écossaise et terre-neuvienne. La variabilité interannuelle du pourcentage de saturation de l'oxygène est relié aux changements de masses d'eau, les périodes de plus grand apport d'eau du Labrador (centre de l'Atlantique nord) correspondant à des niveaux de saturation plus forts (faibles). Les données recueillies en 1993 sont ajoutées à la série chronologique de longue haleine pour illustrer les tendances récentes des fluctuations climatiques de l'océan.

Introduction

The intention of this article is to present a simple, non-comprehensive model of the overall heat balance for shelf waters from the northern Grand Bank to the Gulf of Maine under the assumption that the major balance is between the atmospheric heat input and ocean currents. We also briefly review the variability of the temperature and salinity of east coast waters over the last 50 years or so and update these time series with 1993 data where possible. A recent paper of Petrie and Drinkwater (1993) covers much of this ground in greater detail and discusses further issues.

Overall Heat Budget for the East Coast Shelf Waters

The transfer of heat between the atmosphere and the ocean and the heat supplied by warm and cold ocean currents are the major factors determining shelf water temperatures (Figure 1). If the atmospheric heat flux (Q) and the heat from warm currents exceed the heat deficit from cold water currents, then the temperature of Atlantic shelf waters will increase and vice-versa. In this region over an average year, the atmosphere supplies more heat to the ocean in the spring, summer and fall than it extracts in winter. For the Grand Banks, the Gulf of St. Lawrence and the Scotian Shelf the net monthly heat fluxes are 61, 28 and 47 W/m^2 respectively (Bugden, 1981; Umoh, 1992; Umoh et al., 1994; Figure 2). The overall area-weighted average Q is 46 W/m^2. Over the period of 1 year, this could cause water temperatures for a 100 m deep shelf to rise by 3.4°C over and above the typical annual cycle. Now this does not happen in general, so to maintain average conditions the heat loss due to cold water current inflow must exceed the contribution of warm currents.

The major inflow in this shelf region is the Labrador Current amounting to about 5 million cubic meters per second (Figure 3, where the small boxes on the figure indicate estimates of the flow in millions of cubic meters per second). Part of the Labrador Current flows over the Grand Banks mainly through Avalon Channel, part enters the Gulf of St. Lawrence through Belle Isle Strait, while the major portion flows along the edge of the Grand Banks where it exchanges heat and salt with the shelf waters. A portion of this shelf edge flow is entrained in the North Atlantic Current and moves eastward. On the other hand, some of the flow moves westward past the Tail of the Grand Bank, subsequently entering the Gulf of St. Lawrence, the Scotian Shelf and the Gulf of Maine. Petrie and Drinkwater (1993) note that the influence of this Current has been felt as far south as Cape Hatteras.

Another major process that contributes to the overall heat balance occurs at the boundary (front) between the shelf and slope waters. The mean position of this front lies 100-200 km off the shelf break (Figure 3). Here eddies and meanders generated by the Gulf Stream remove water from the shelf and generally replace it with warmer, saltier North Atlantic waters.

The Gulf of St. Lawrence circulation features the strong, well-defined jet of the Gaspé Current and the outflow onto the Scotian Shelf that wends its way to the Gulf of Maine. Petrie and Drinkwater (1993) were able to trace the influence of the freshwater discharge in the Gulf of St. Lawrence to Gulf of Maine.

One is left with the impression of a region with inflowing cold waters to the northeast and outflowing warmer waters in the southwest. It is this simple model that we want to pursue further.

Consider then the box model where all the region's waters from 0 to 100 m have been mixed together, with inflowing cold water from the north at an average temperature, T_{in}, and warm water, at an average temperature T_{out}, flowing out in the south (Figure 4). For T_{in}, we have used the annual mean temperature from the Northeast Newfoundland Shelf, while for T_{out} we have used the annual mean temperature for waters in southwest Nova Scotia. The temperature difference between these water masses was about

5.8°C. To attain a heat balance, the cold water inflow must amount to 1.3 million cubic meters per second, a value that is the same order as the flow attributed to the Labrador Current.

There have been periods of lower and higher water temperatures in the region over the last 50 years. In the early 1950s, the temperature difference between the waters of the Northeast Newfoundland Shelf and southwest Nova Scotia was near its maximum at about 6.8°C. We would expect a reduced cold water flow and, indeed, that is the case with the model giving about 1.1 million cubic meters per second. In the mid-60s when the contrast of temperatures was the least at 3.8°C, the flow in this model would have to have been the greatest at 2.0 million cubic meters per second. The range of 1-2 million cubic meters per second is certainly within the variability that could be attributed to the Labrador Current. It is also an indication of how accurately one must measure the flow in order to evaluate its contribution to changes in the region's climate.

This simple model has been useful, indicating that the inflow of Labrador Current water is an extremely important process, that variations of this flow within reasonable values of its mean strength can produce significant climate variations, and that in order to understand how the region's oceanography varies, we must discover the causes of Labrador Current transport variability. In addition to this overall picture, there are processes within the region that lead to temperature and salinity variability. For example, from the work of Petrie and Drinkwater it is necessary to understand why on some occasions lasting many years, the Labrador Current makes it around the Tail of the Bank, whereas, in other periods it does not.

The net atmospheric input of heat amounts to 3.2×10^{13}W (Figure 5). The exchange of heat across the shelf-slope front adds an additional 1.7×10^{13}W to the shelf water budget. This was not considered above and would require additional inflow of cold water to maintain a balance. Loss of heat from the shelf region occurs at the boundary between the Labrador Current and waters over the Grand Bank. In addition, cold water inflow through the Strait of Belle Isle would tend to lower temperatures. However, neither of these processes is large compared with the atmospheric or shelf-slope exchange inputs.

Observations

Scotian Shelf

The temperature at 0, 50, 100 and 150 m depths in Emerald Basin has shown considerable variability over the past 50 years (Figure 6). The major features include:

1) A period of temperature decline from the early 1950s to the mid 1960s at all depths but in particular at 150 m. This temperature change was also accompanied by a change of salinity with higher temperatures associated with higher salinities. Petrie and Drinkwater (1993) have shown that this long-term decline was the result of an increased westward flow of Labrador Current water. This Labrador Current water made up the bulk of the waters over the continental slope and flowed onto the shelf mainly through the deep channel between Emerald and Lahave Banks. The colder waters of the mid 1960s had an increased content from the Labrador Current. This is illustrated in Figure 7 where these waters are characterized as roughly 75% Labrador in composition, whereas, waters from the warm 1950s or mid 1980s have a 25 to 50% Labrador component. The cold minimum of the mid 1960s was followed by a rapid warming as more North Atlantic waters flowed onto the shelf at depth. A longer, more gradual warming period followed.

2) Higher frequency temperature changes are greater near the surface and decline rapidly with increasing depth indicating a surface origin, probably caused by atmospheric variations; on the other hand, low frequency variations have a maximum at 100 to 150 m indicating a subsurface oceanic origin (Figure 8).

3) Short-lived cold and warm events are found in the records, such as the cold year of 1959, reported by Worthington (1964) for the Sargasso Sea but also evident in Emerald Basin.

4) For the past 10 y or so, the upper layers appear to have been cooling, such that in 1993 temperatures at 0, 50 and 100 m are generally below normal. However, although some cooling is evident at 150 m, water temperature is still above normal by about 0.5°C. At 200 and 250 m, temperatures remain about 1°C

above normal.

The magnitude of the changes is perhaps best illustrated by the two April sections of Figure 9, one from the cold period of the mid 60s and the second from a warm period in the mid 70s. The section runs from off Halifax, through Emerald Basin onto Emerald Bank and out over the slope. Temperatures in the deep Basin changed from 4-4.5°C to about 10°C over this period. Salinities increased by about 1 psu.

These changes occurred over large areas and were not confined to Emerald Basin. Similar variability was found at the adjacent Emerald Bank and westward in the Gulf of Maine at Georges Basin just north of Georges Bank; the largest changes occurred in the slope water (Figure 10). Petrie and Drinkwater show that these variations, in particular the decline from 1950 to 1965, were observed in the western Gulf of Maine and in the Bay of Fundy. However, on the northeastern Scotian Shelf the trends are not as evident especially in Sydney Bight (Figure 11). There is some indication of a temperature decline in the sparsely sampled Banquereau region. However, in the deeper waters of Cabot Strait there is a strong indication of the variability seen in Emerald Basin. These deeper waters are directly linked to the slope waters by the Laurentian Channel. After about 6 years of decreasing temperatures, the deep waters of the Gulf of St. Lawrence reached a minimum in 1991. The past 2 years has seen a rapid rise of temperature such that by November of 1993, T was near its long-term high.

The water mass composition also affects other variables (Figure 12). The dissolved oxygen time series from Emerald Basin varies in the opposite sense of temperature. The mid 60s feature high percent saturation during periods of lowered T, while subsequently , when T increased, oxygen saturation fell. The tight, linear relationship between dissolved oxygen and temperature is illustrated in Figure 13 where high oxygen content, 70-75% saturation, occurs when temperatures are low, corresponding to a high content of Labrador Current waters. When water temperatures are high, saturations are low, 45 to 50%, corresponding to low Labrador water content.

The influence of fresh water discharge from the St. Lawrence can be seen in the salinity in Sydney Bight where, during periods of high runoff, below average salinities are observed and vice-versa (Figure 14). The effects are still visible at the surface in Emerald Basin, though they are considerably diminished. In the deep waters of the Basin, the opposite trends occur.

Grand Banks

Standard sections are sampled across the Newfoundland shelf at several locations during the year. One of these sections begins outside Bonavista Bay and extends over 300 km offshore into deep water. Several cross sections of this transect show that from year to year the amount of water with T≤0°C (called the cold intermediate layer or CIL) varies considerably (Figure 15). These cross sections have been compiled for the Hamilton Bank, Bonavista and Flemish Cap Sections, each group averaged separately, each individual section divided by the appropriate average, the three series averaged (all three sections varied in the same way) and plotted (Figure 16). A considerable amount of variability is seen with areas generally decreasing from the 1950s to the mid 1960s, reminiscent of the temperature in Emerald Basin but in the opposite sense, i.e., smaller amounts of cold water over the Grand Banks corresponds to cold T in Emerald Basin. Three periods of above average cold water areas are evident, in the early 1970s, the early 1980s, and for the last 6 years. During 1993, the CIL area was about 30% above normal.

The temperatures at Sta. 27, located outside of St. John's Harbour, have varied much like the CIL area. This is especially evident for the cold periods of the early 1970s, 1980s and during the past several years for the average temperature over the entire, 0-175 m, water depth (Figure 17). The variations of temperature are similar at all depths for these cold periods, however at other times, there may be above average values in one depth range but below average values in another. Unlike the Scotian Shelf, the both the high and low frequency variability decreases with increasing water depth (Figure 18).

A more dramatic way to illustrate the persistence of the cold and warm periods is to sum the temperature by degree months beginning with the first data point as the arbitrary origin, i.e., in 1946 at 0 (note that in this figure a positive slope, slanting upward to the right indicates above normal temperatures; a negative slope, slanting upward to the left, below normal temperatures; the straight line shows what 120 months at 0.33°C below normal would look like if the summation were started in 1980, Figure 19). For example, a one month period with temperatures 2°C above normal gives 2 degree months, a 5 month period of 1°C below normal temperatures gives -5 degree months. In this figure, the first 20 years of the record show no strong trends; however, we can see the above average period of 1965-1972, followed by below average temperatures from 1972-75. The last 10 years has been one of generally below average values by about 0.4°C, with the coldest conditions from 1984-86 and 1991-1993. It is worthwhile to note that similar cold conditions could have occurred in the past, most likely in the 1920s (R. Myers, pers. comm.).

The temperature at Sta. 27 and the CIL area are plotted along with the ice area anomaly (in units of 10,000 km^2 for convenience) and the wind stress in the northwest (positive) to southeast (negative) directions over the Labrador Shelf (Figure 20). We might expect that periods of stronger wind stress to the SE would bring colder water, more ice and result in a greater CIL area. This figure illustrates that this is generally observed. The wind stress can account for 40% of the variability of the water temperature, 35% of the CIL area changes and 51% of the ice area variations. This indicates that the atmosphere and ocean are strongly coupled and lends support to directing statistical and mathematical modelling efforts to this problem.

Does the Labrador Current vary? The data strongly indicate that it does over long periods of time (Figure 21). Most notably there is an increase of transport of the Current from 1950 to 1965-66, when the change from warm to cold conditions on the Scotian Shelf occurred. This makes sense, more Labrador water to the west, colder temperatures. Petrie and Drinkwater (1993) used this variation to force a simple model of slope water (and consequently shelf water) properties from the Tail of the Bank to the Gulf of Maine. It worked.

Closing Points

The heat flux over the Newfoundland and Scotian Shelves has interannual variations of up to 20 and 30 W/m^2 respectively. These heat fluxes last for several years and could produce significant water temperature changes. However, a model developed by Umoh and Thompson at Dalhousie (Umoh, 1992) and applied by Umoh and Thompson for the Scotian Shelf and by Umoh, Loder and Petrie (1994) for the Newfoundland Shelf cannot account for the interannual variability of ocean temperature. This indicates that, given the heat flux estimates are valid, ocean currents play a fundamental role in the heat balance.

Little has been presented for the Gulf of St. Lawrence. That is because the data analysis is not as far along there as it is for the rest of the region. A proposal has been made at IML to begin examining the archived data.

Acknowledgements

We thank all those who have assisted us in the updating of the various datasets, in particular, Gary bugden, Eugene Colbourne and Savi Narayanan.

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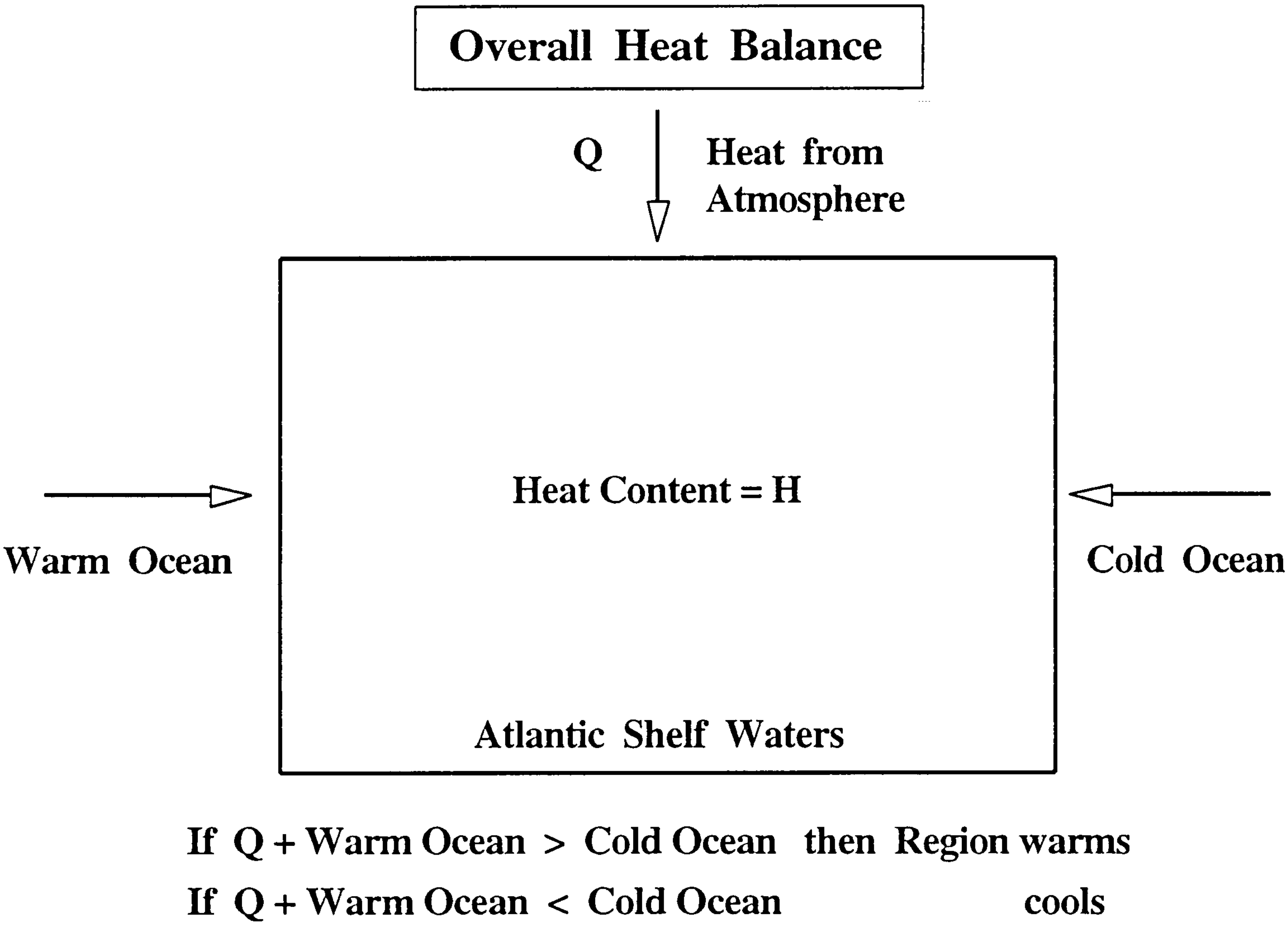

Figure 1. Schematic diagram of the overall heat balance of Atlantic shelf waters.

MONTHLY AVERAGE HEAT FLUX

+ = more heat from atmosphere to ocean

AREA	$Q(W/m^2)$	$RANGE(W/m^2)$
Nfld. Grand Banks 6(2^ox2^o) squares	61	54-68
Gulf St. Lawrence 4 polygons	28	13-52
Nova Scotian Shelf 6 polygons	47	25-57
Nova Scotian Slope 1 polygon	-53	-

For a 100m deep shelf over 1 year, using an area-weighted, average Q of 46 W/m^2

$$\Delta T = Q*dt/(\rho*C_p*Z)$$

$$\Delta T = (46*365*86400)/(1025*4200*100)$$

$$\Delta T = 3.4^oC$$

In general, require an excess of cold water over warm to maintain annual balance.

Figure 2. Monthly average heat fluxes for Atlantic Canadian shelf waters (from Umoh and Thompson, 1994; Vowinkel and Orvig, 1977; Bugden, 1981; Umoh et al., 1994).

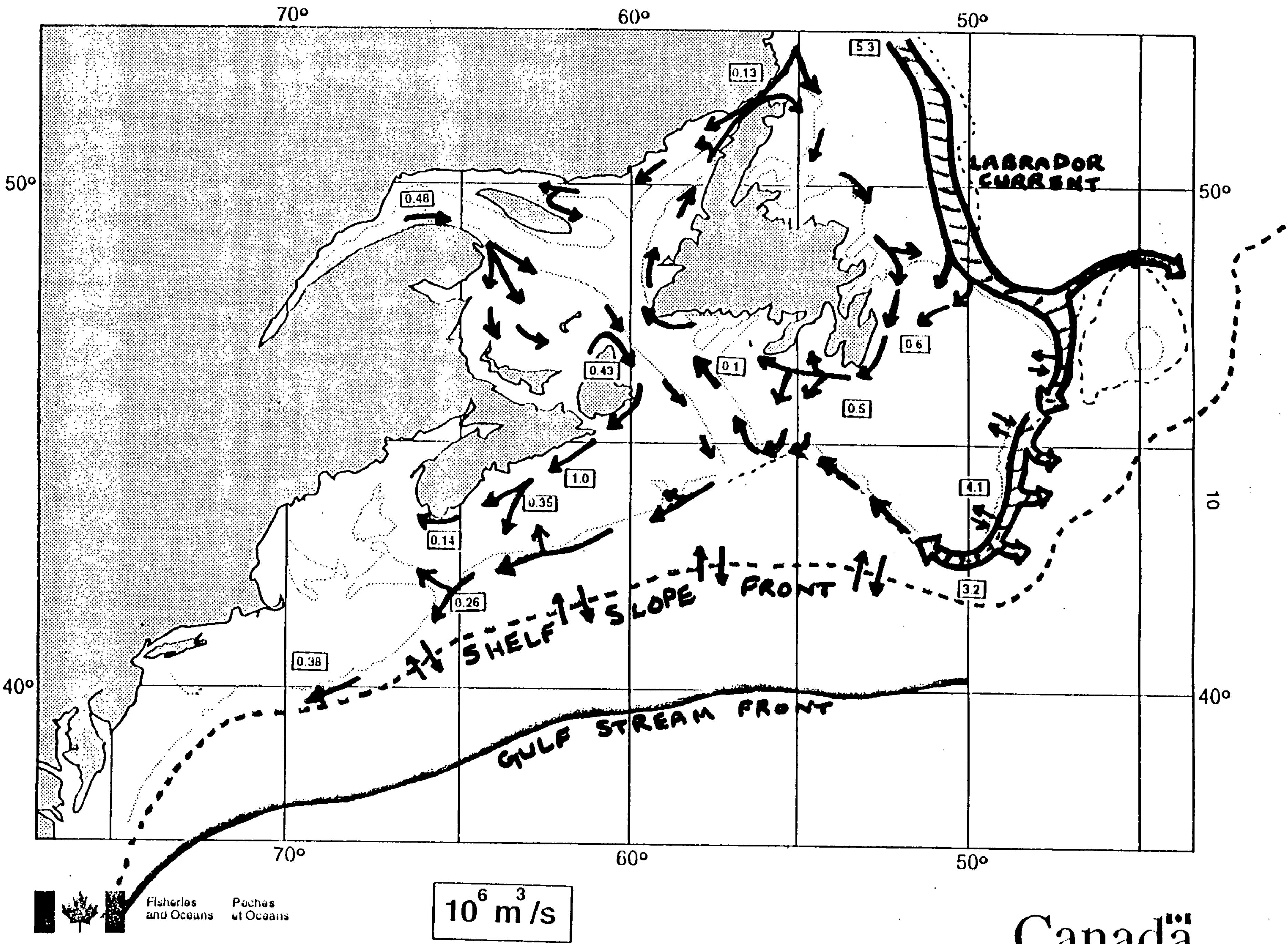

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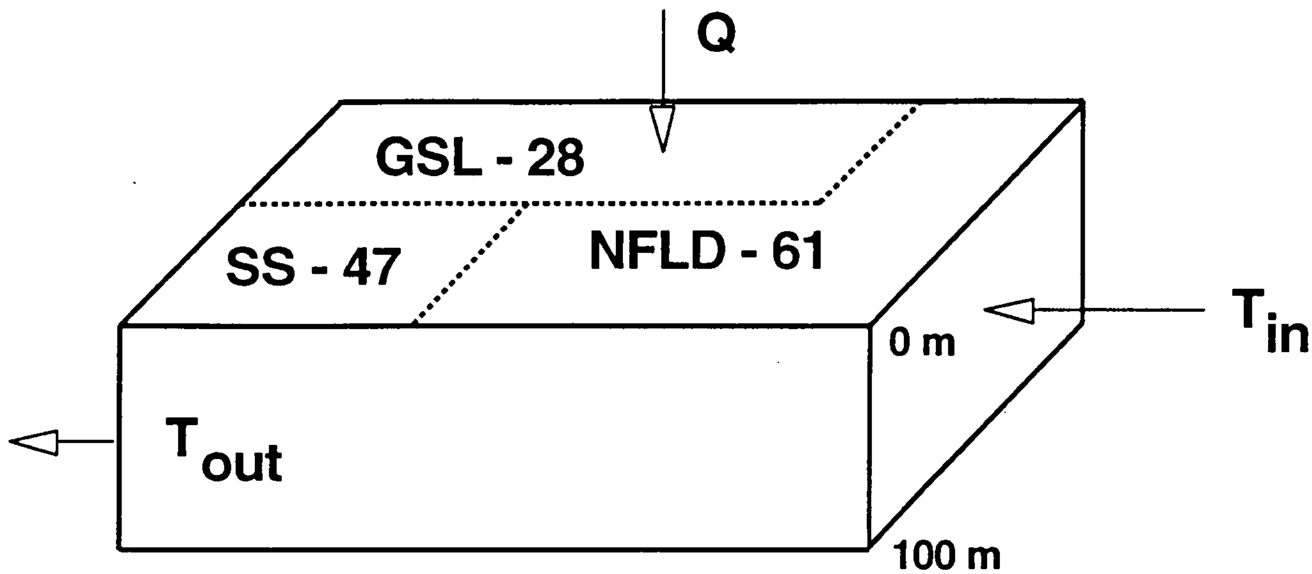
Figure 3. Idealized circulation for part of the east coast of Canada. Numbers in squares indicate estimates or observations of the currents from various sources in millions of cubic meters per second.

FLOW THROUGH MODEL



$$Q*AREA = \rho*C_p*V*(T_{out}-T_{in})$$

where, T_{in}=0.7°C, T_{out}=6.5°C, Q=46W/m^2, AREA=7*$10^{11}$$m^2$

$$V = 1.3*10^6\ m^3/s$$

Early 50s, ΔT=6.8°C $\rightarrow$ V = 1.1*10^6 m^3/s

Mid 60s, ΔT=3.8°C $\rightarrow$ V = 2.0*10^6 m^3/s

Figure 4. Simplified model of the heat balance for the east coast waters to 100 m. The average, regional, monthly flux is balance by an inflow of cold water with the temperature characteristics of the Northeast Newfoundland shelf waters. The outflow has the temperature characteristics of the southwest Scotian shelf waters. The average and extreme (greatest and least temperature differences between inflowing and outflowing waters) conditions are presented.

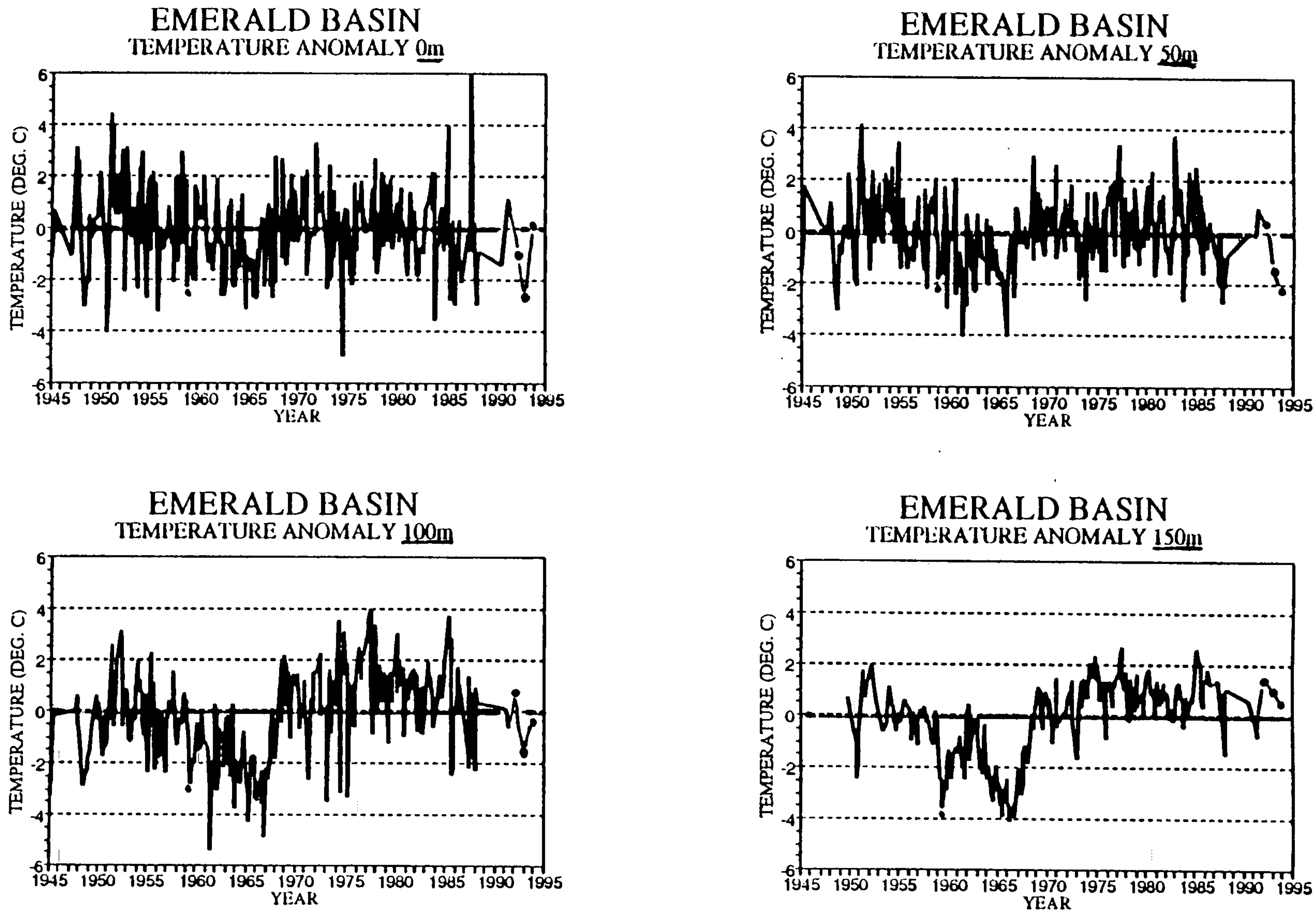
Other Processes Contributing Heat

ATMOSPHERE	$+3.2*10^{13}$ W
SHELF-SLOPE EXCHANGE[1]	$+1.7*10^{13}$ W
EASTERN GRAND BANK[2]	$-0.07*10^{13}$ W
BELLE ISLE STRAIT[3]	$-0.16*10^{13}$ W

[1]Tail of GB to NE Chn
[2]Labrador Current-Shelf Exchange
[3]part year, may be high

Figure 5. Evaluation of other processes adding or taking away heat from the shelf waters.

Monthly Temperature Anomalies



1993

z(m)	May	Jul	Oct
200	1.52	1.41	1.19
250	1.16	1.30	1.01

Figure 6. Monthly temperature anomalies at four depths in Emerald Basin, Scotian Shelf. Observations from 1993 have been added to the figure.

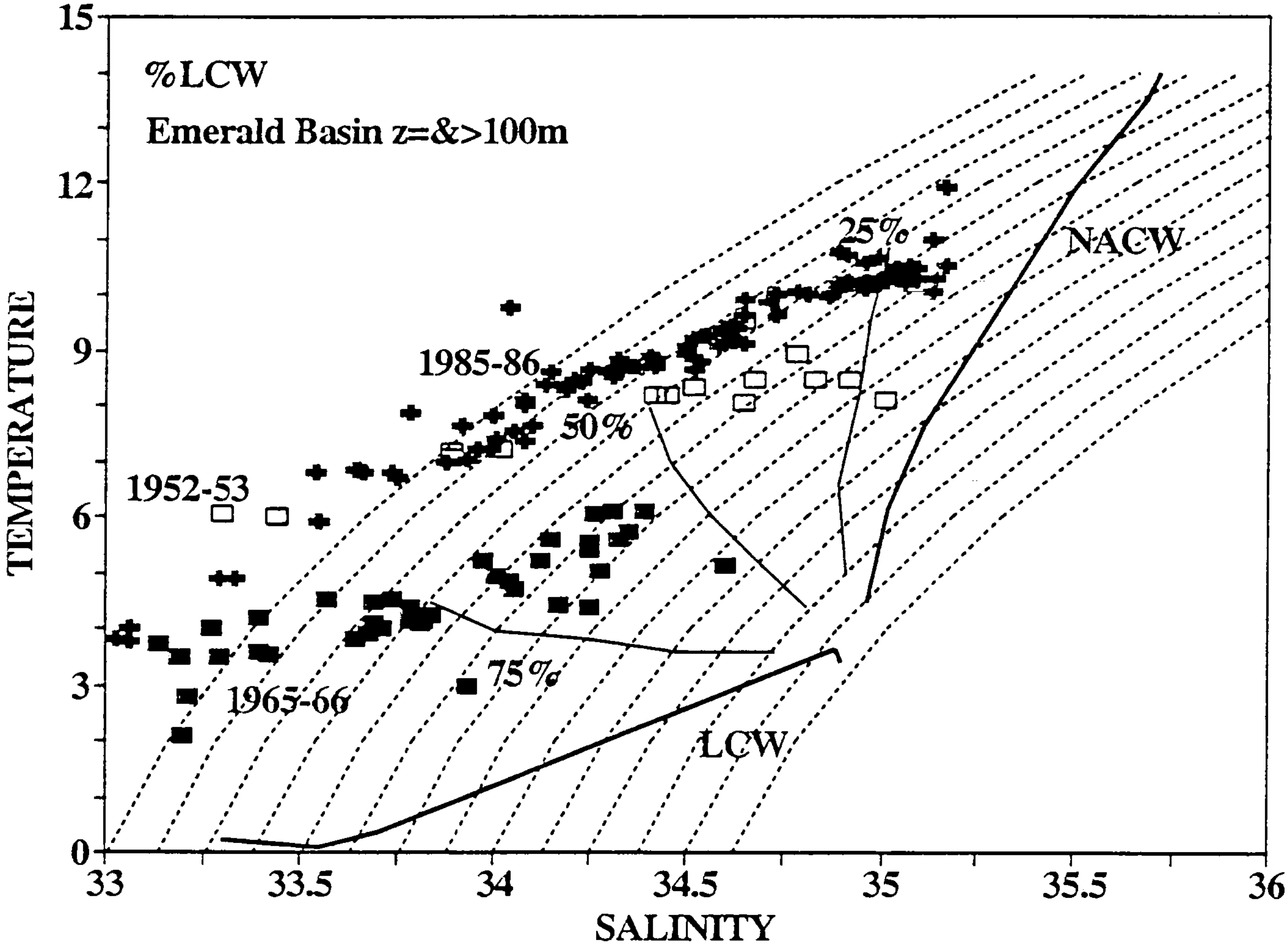


Figure 7. Temperature and salinity diagram for Emerald Basin waters at depths of 100 m and greater for a cold period (1965-66) and two warm periods (1952-53, 1985-86). Also shown are the T-S relationships for North Atlantic Central Water and Labrador Water. The contours of 25, 50 and 75% represent the amount of Labrador Water required to mix with NACW to give the T-S curve depicted by the 3 lines.

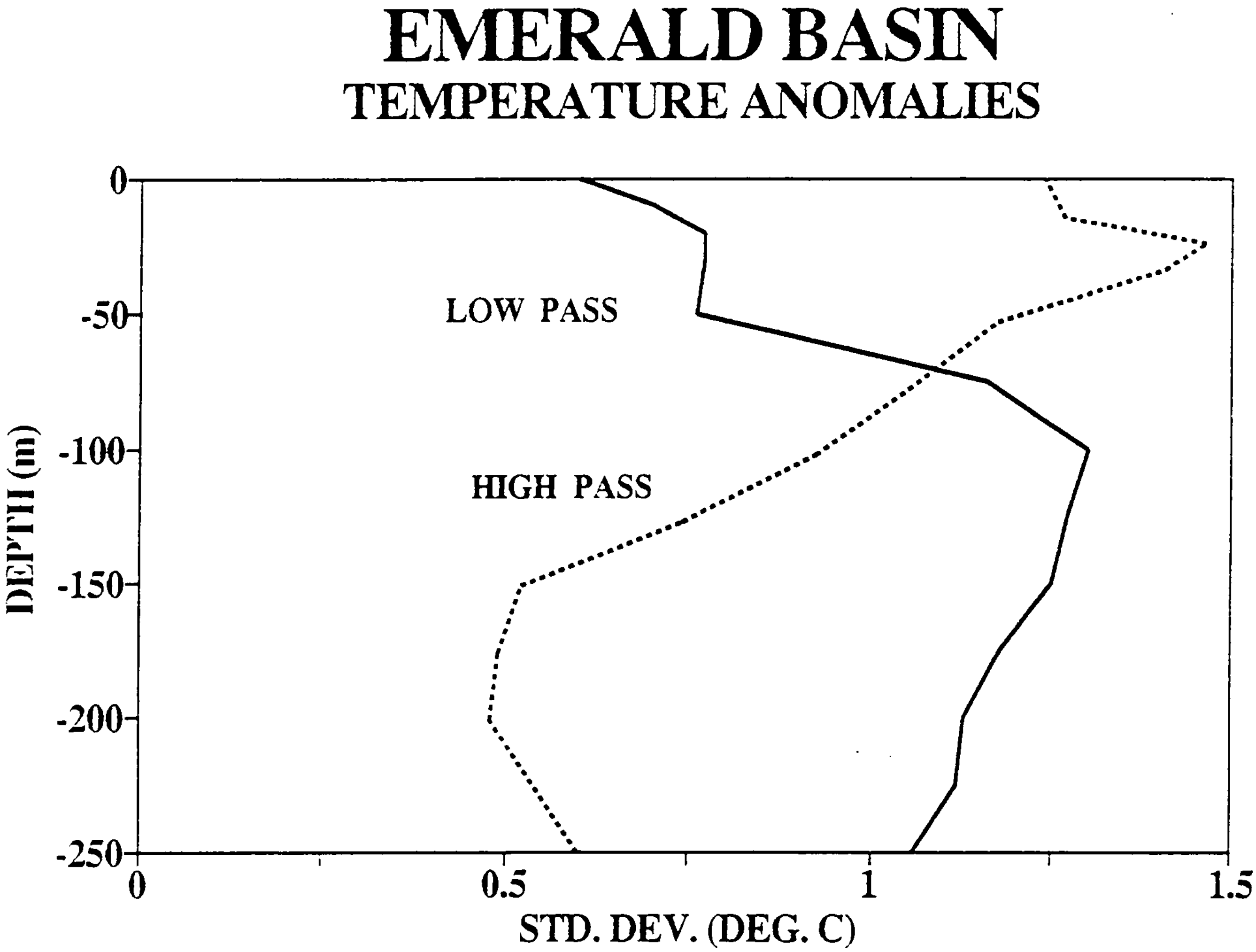


Figure 8. The distribution of temperature variance with depth for Emerald Basin. High (low) pass represents variability with periods shorter (longer) than 2 years.

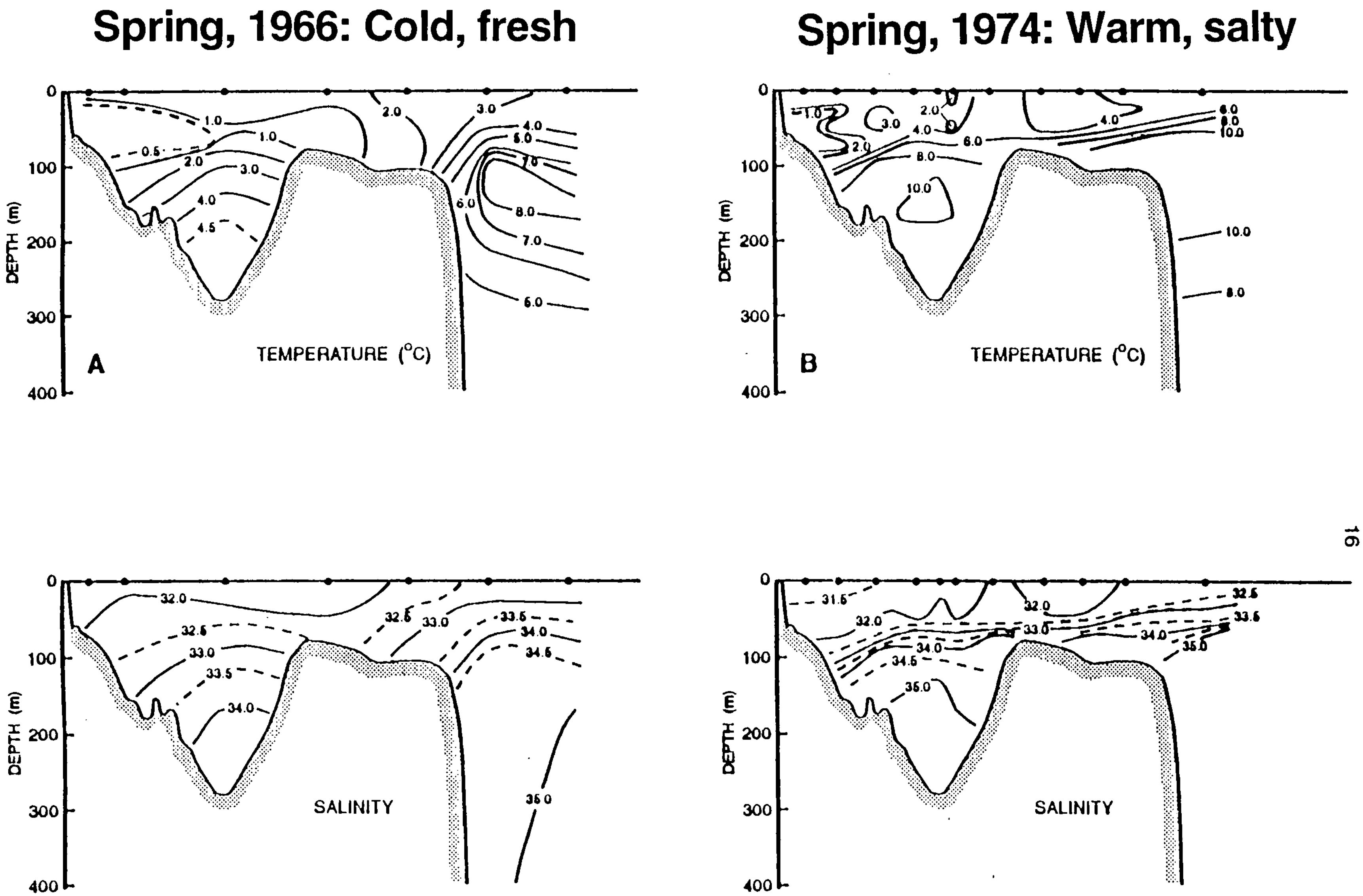


Figure 9. Two T-S sections across Emerald Basin and into the slope water during a cold fresh period (1966) and a warm salty period (1974).

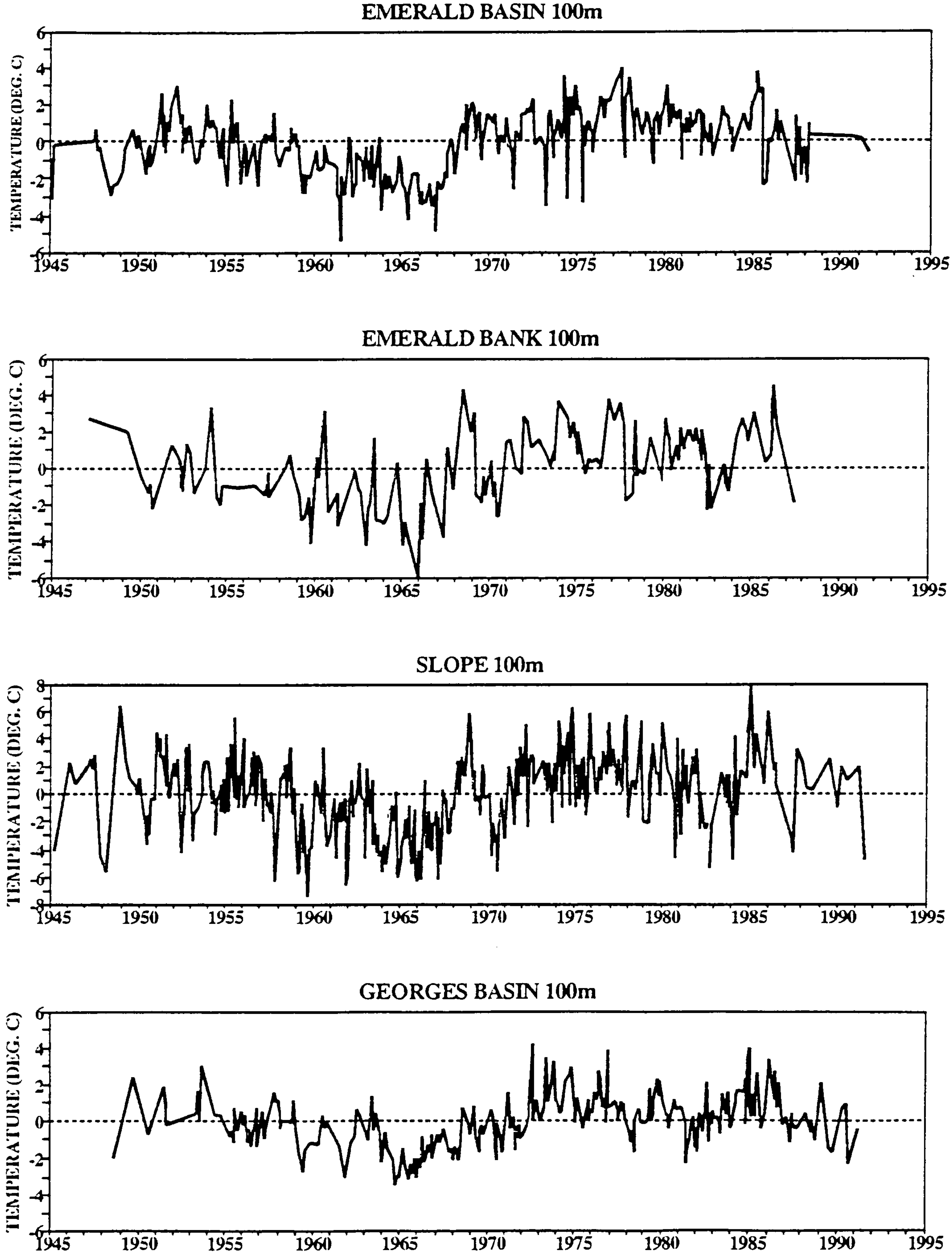


Figure 10. Monthly temperature anomalies from 100 m for Emerald Basin, Bank, the continental slope off Emerald Bank and Georges Basin in the Gulf of Maine.

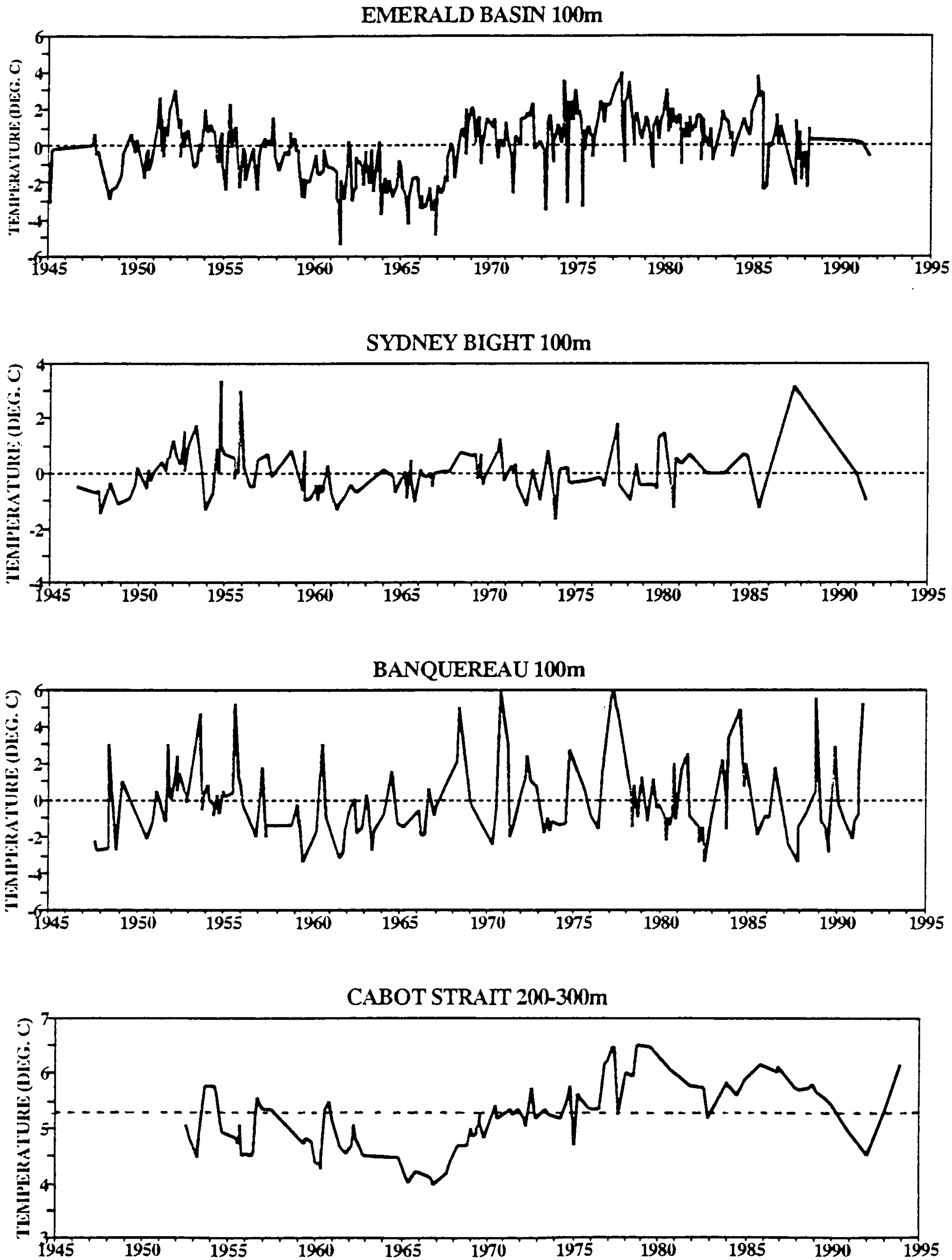


Figure 11. Monthly temperature anomalies from 100 m for Emerald Basin, Sydney Bight, Banquereau Bank and Cabot Strait, located at the mouth of the Gulf of St. Lawrence.

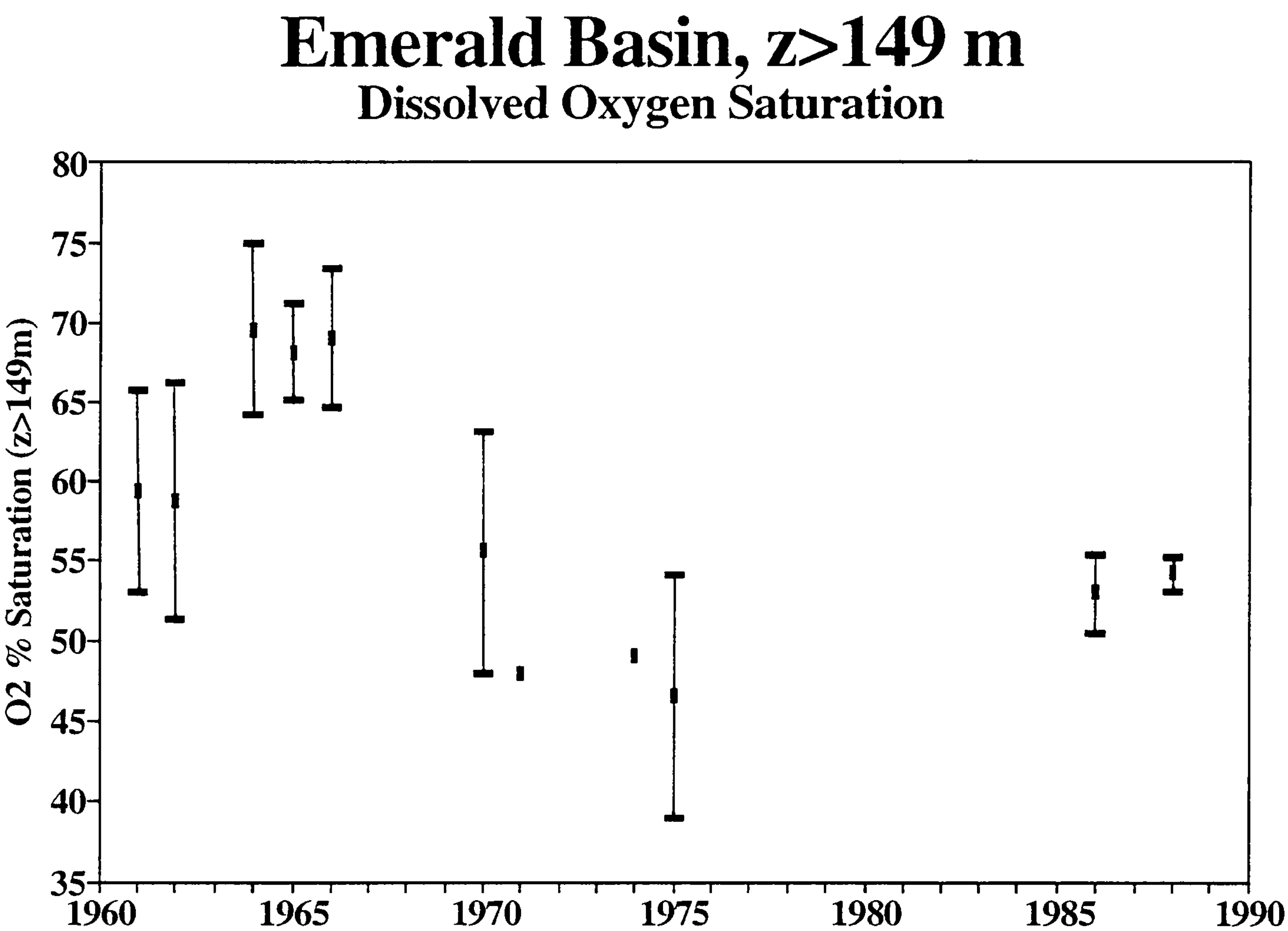


Figure 12. Time series of dissolved oxygen percent saturation for Emerald Basin for all data from depths greater than 149 m. The mean and standard deviation (when possible) are shown.

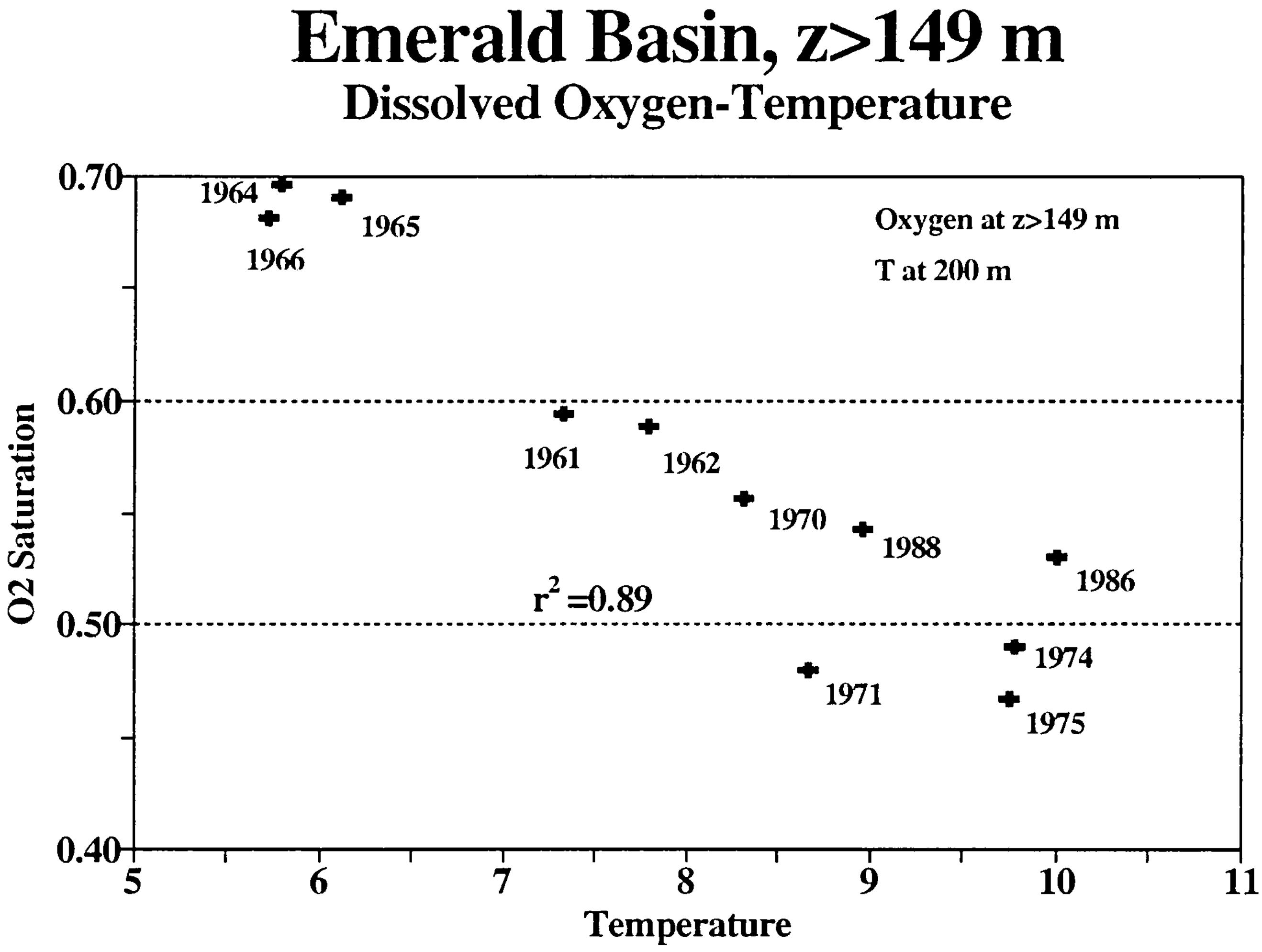


Figure 13. The relationship between dissolved oxygen saturation (multiply by 100 to get % saturation) and T at 200 m for Emerald Basin.

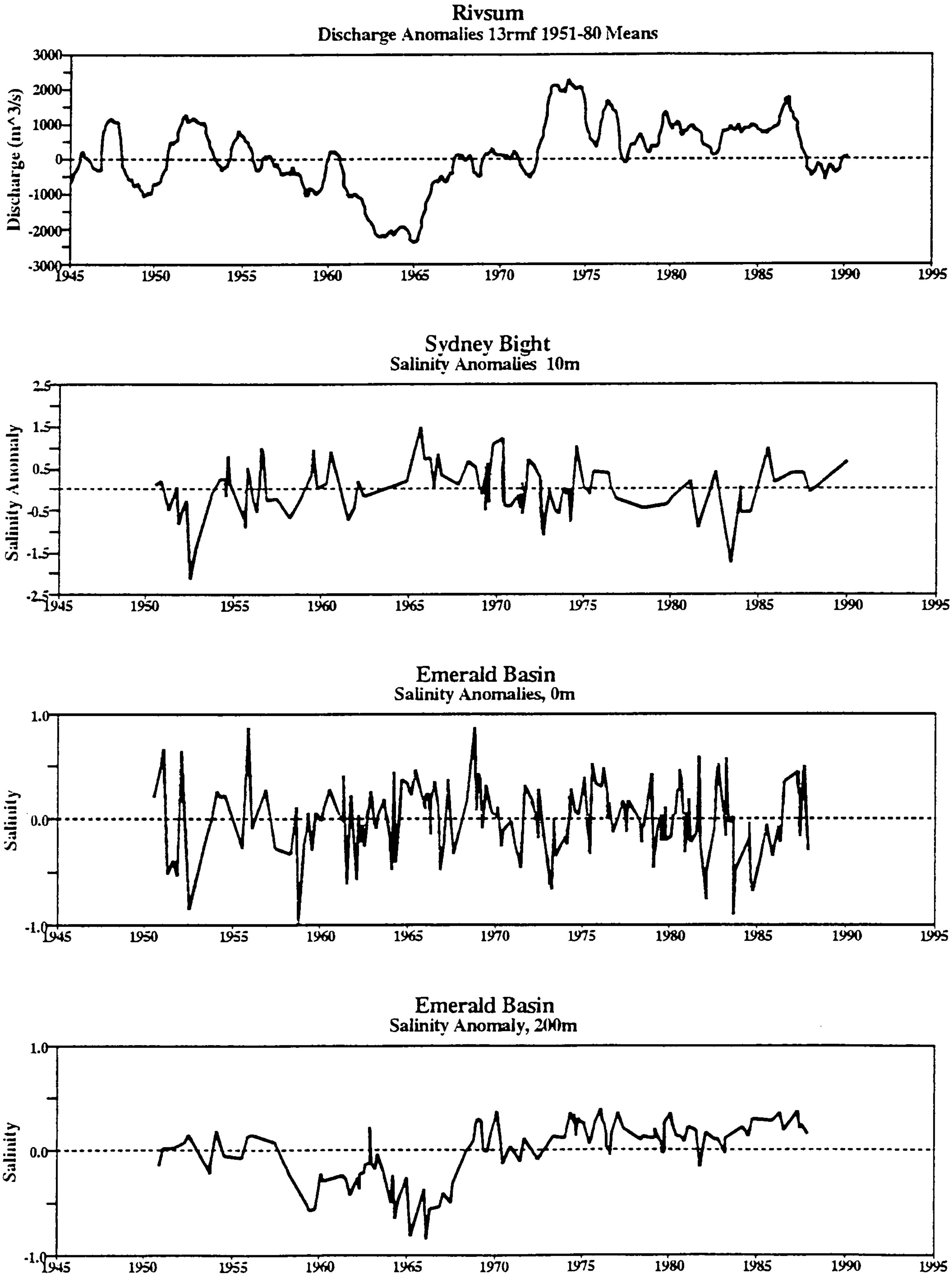


Figure 14. Time series of the anomalies of RIVSUM, Sydney Bight salinity at 10 m, and Emerald Basin salinity at 0 and 200 m.

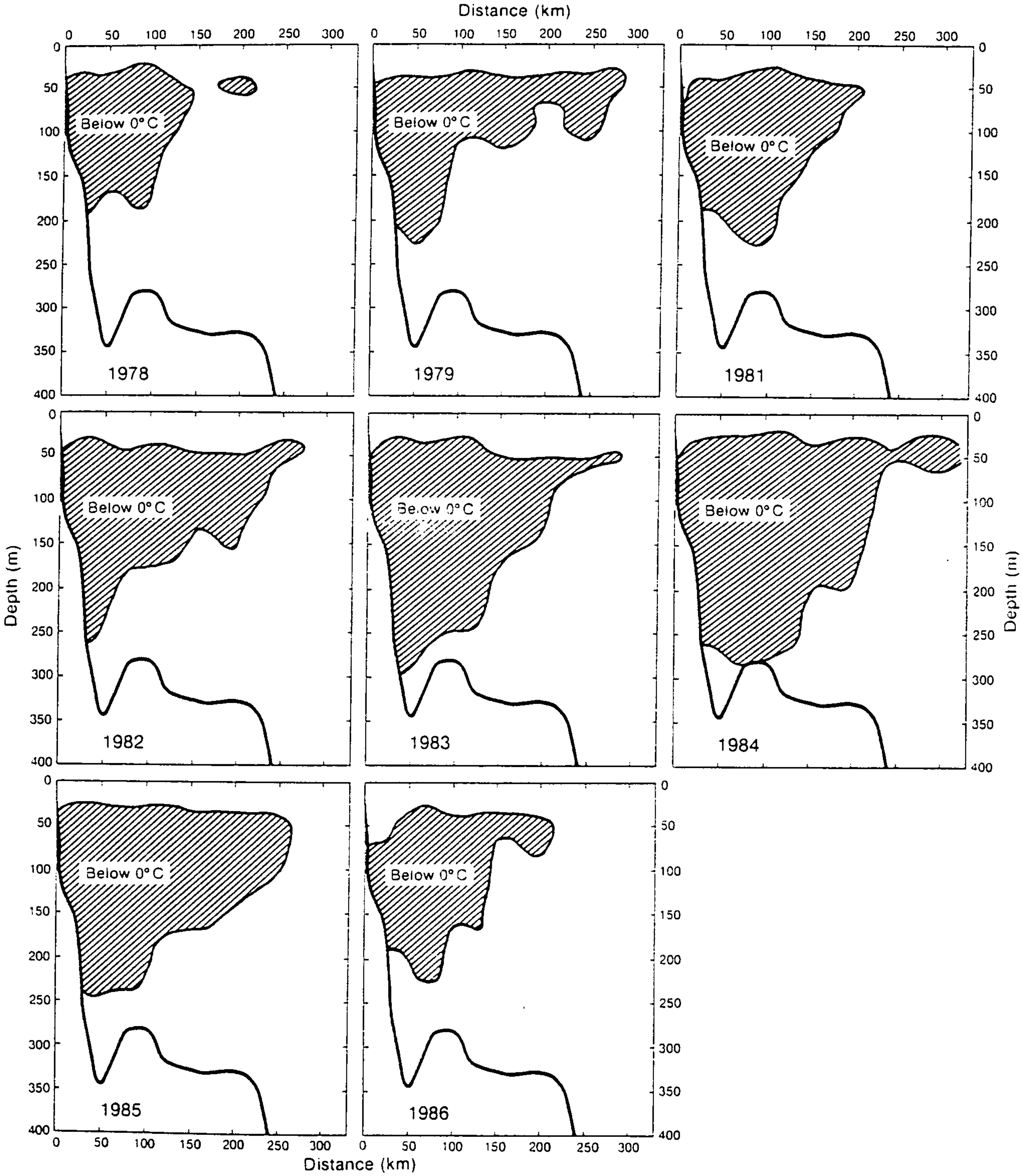


Figure 15. Cross sections of the water with T less than or equal to 0°C for the August Bonavista Sections on the Northeast Newfoundland shelf from 1978-86 (from Petrie et al. 1988).

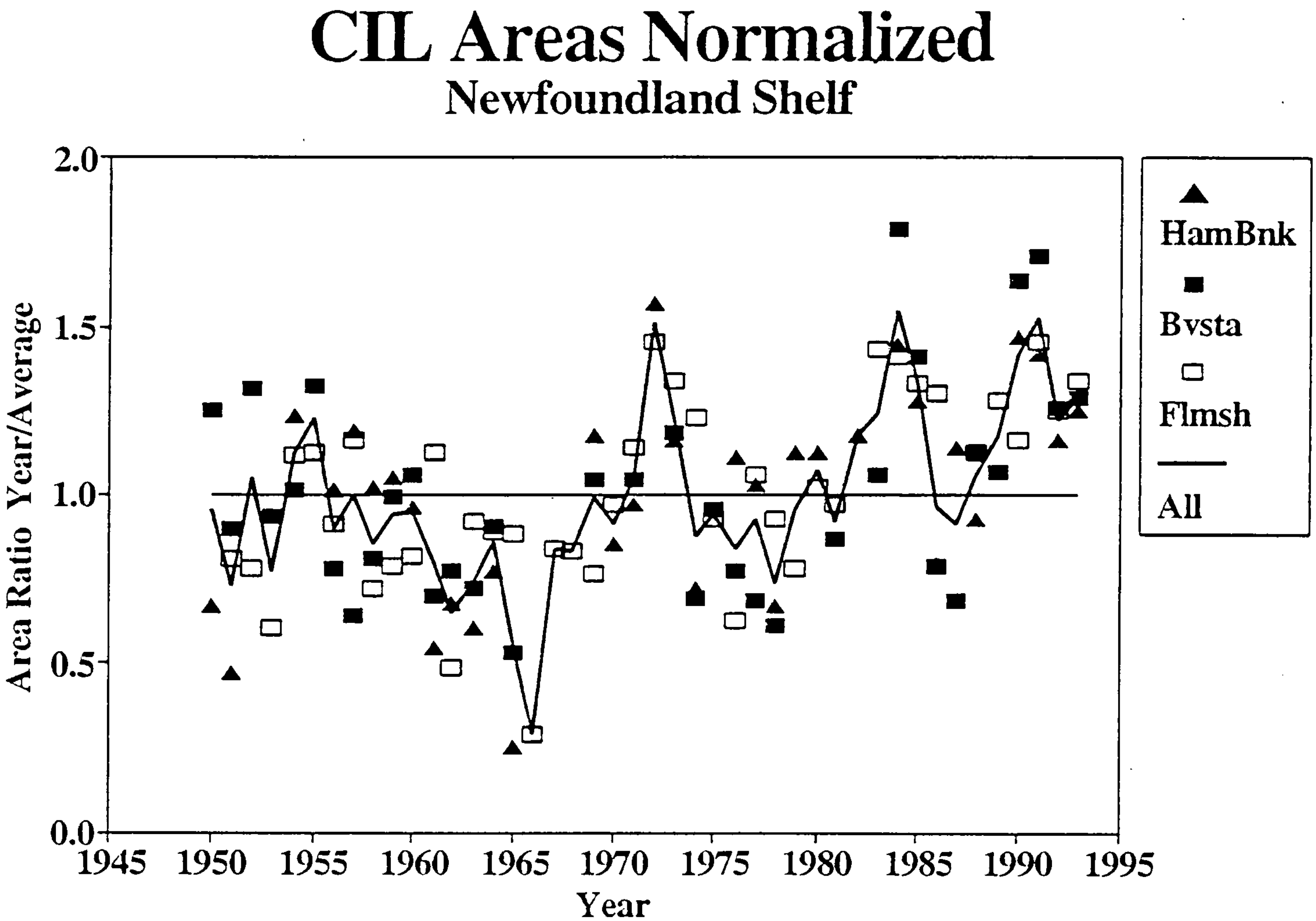


Figure 16. Normalized CIL areas for three sections across the Newfoundland Shelf at Hamilton Bank, Bonavista and Flemish Cap. Each value has been divided by its average value. All three normalized values have been averaged to produce the composite curve.

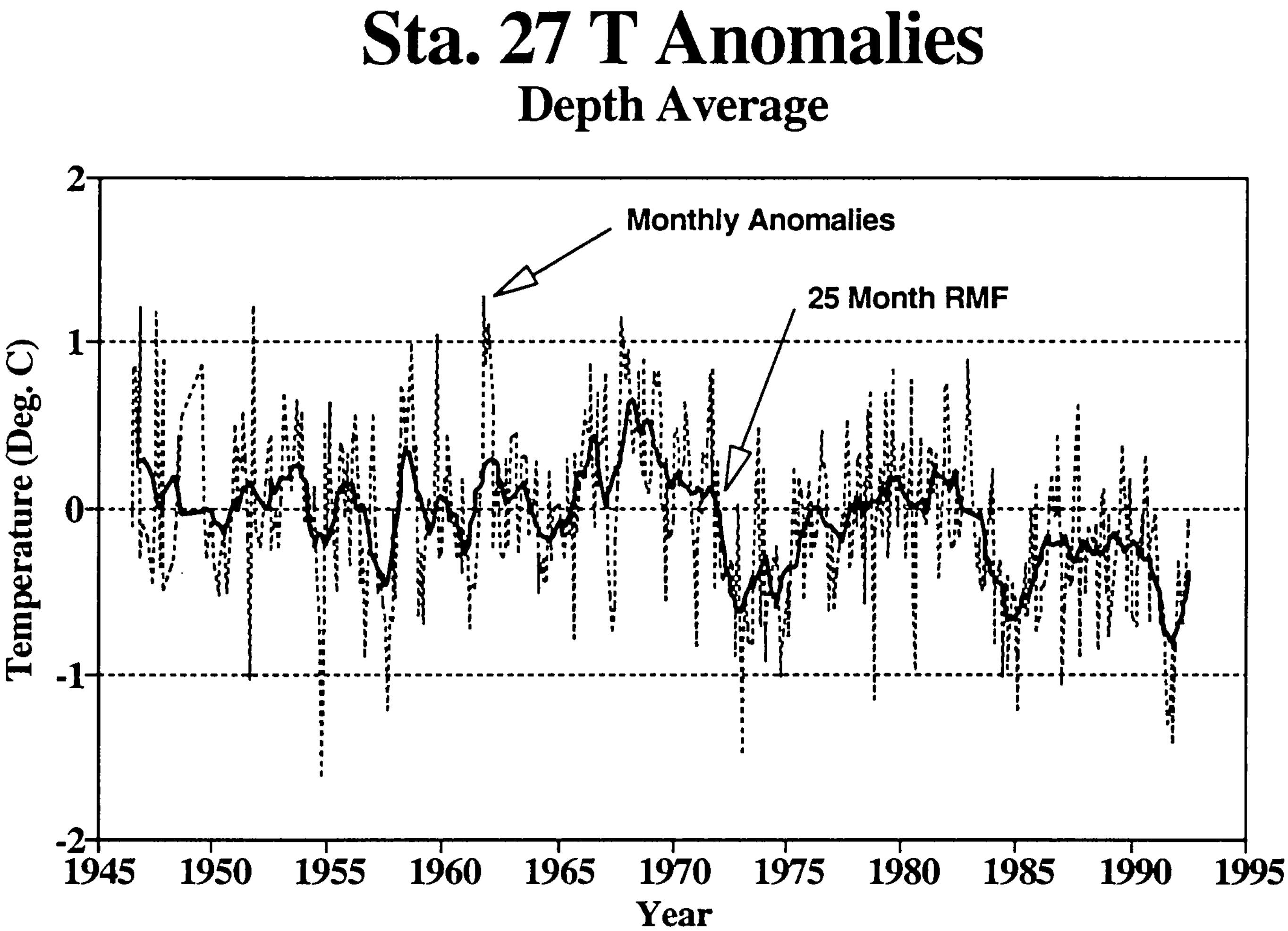


Figure 17. Depth averaged temperature anomalies from Sta. 27.

Standard Deviation of Temperature at Sta. 27

Depth (m)	High Freq	Low Freq.
0	1.01	0.38
50	1.00	0.34
100	0.45	0.21
150	0.29	0.20

High Freq.<2y
Low Freq.>2y

Figure 18. Standard deviations of the high (periods shorter than 2 years) and low frequency (longer than 2 years) temperatures for Sta. 27 with depth.

Sta. 27 Integrated Temperature Anomaly
Sum of Delta T, 1951-80 Mean

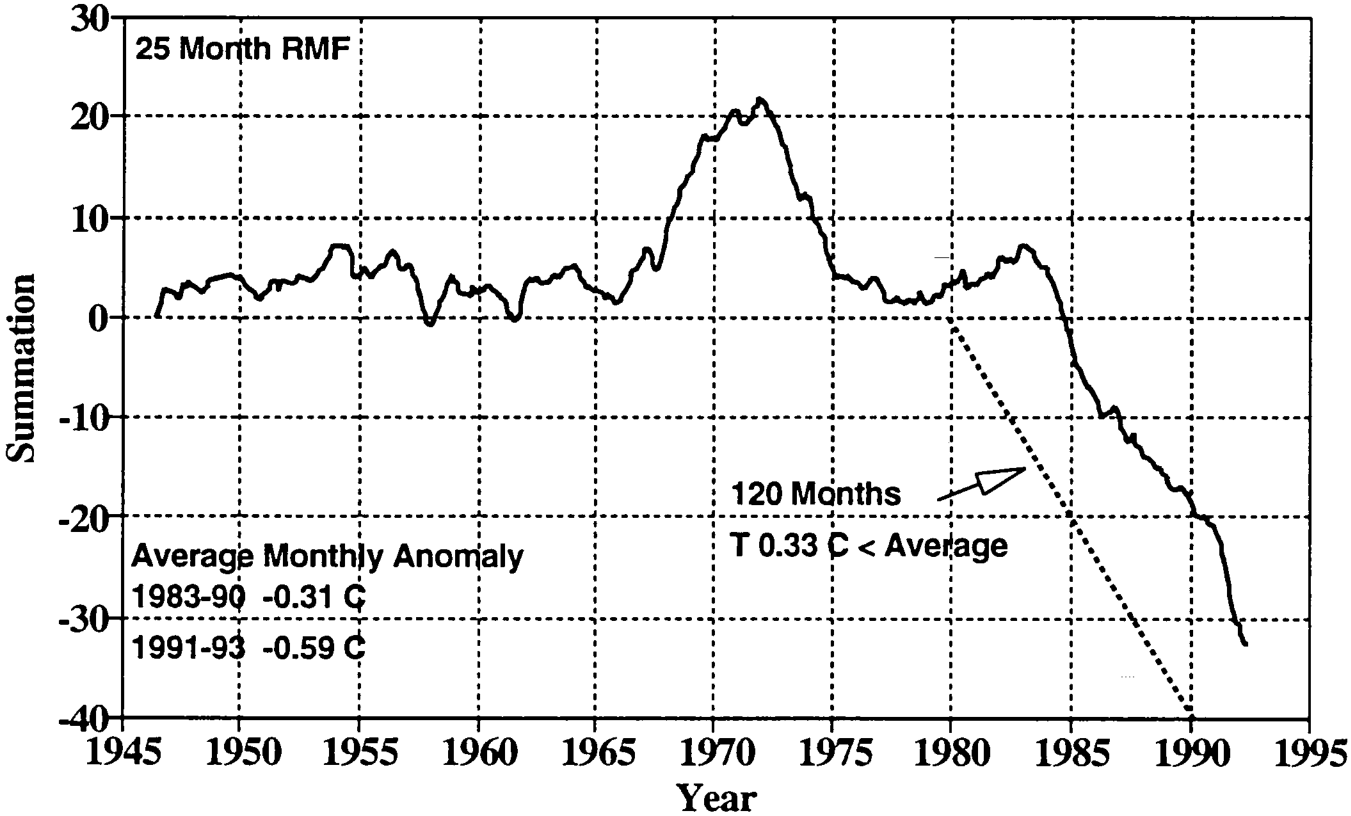


Figure 19. Degree months for the 0-175 m temperature anomalies beginning in 1946. An upward slope means above average T, a downward slope means below average T.

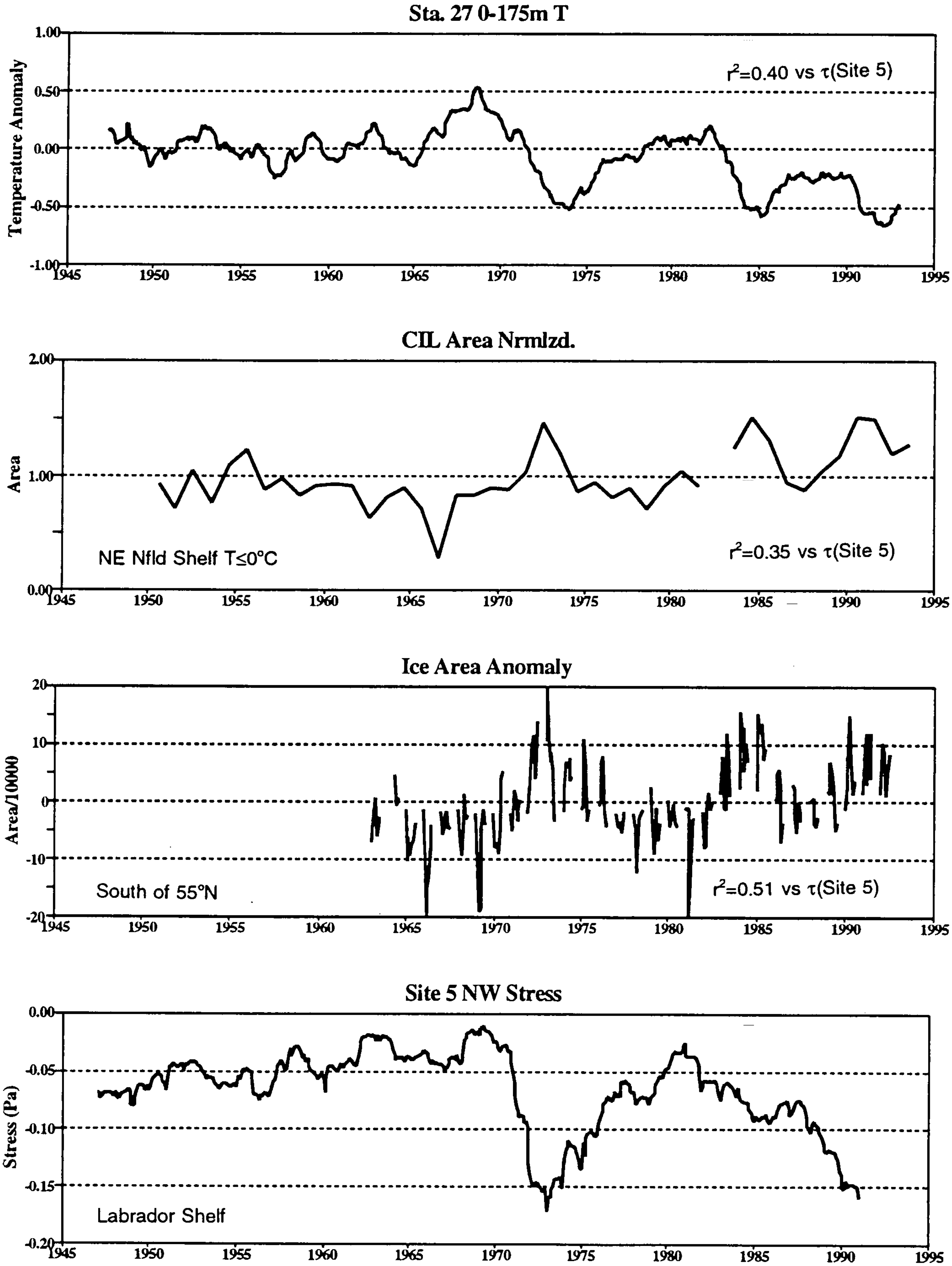
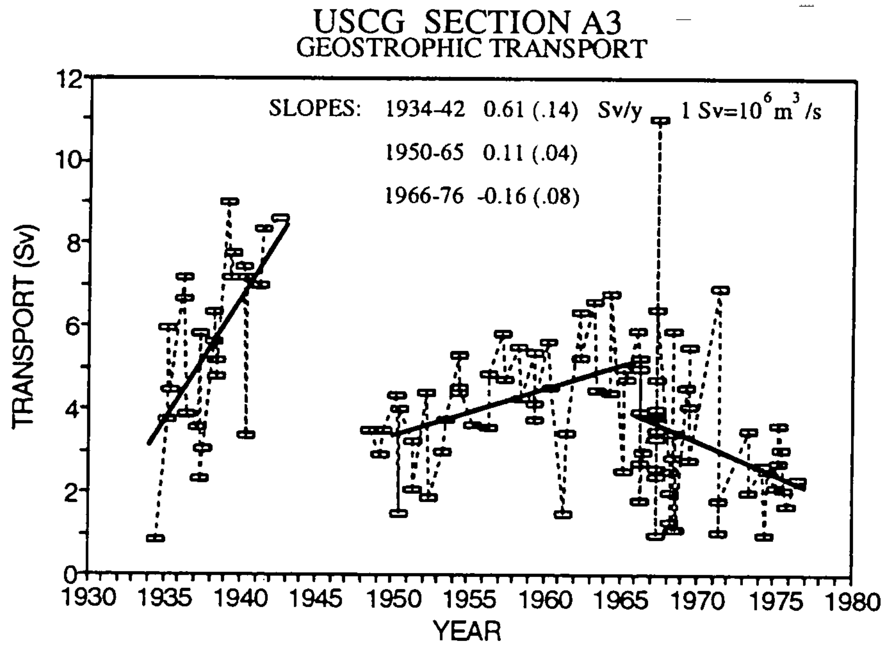


Figure 20. Time series of anomalies of T(0-175 m) at Sta. 27, CIL areas for August, ice area south of 55°N and northwest wind stress off the Labrador Shelf.



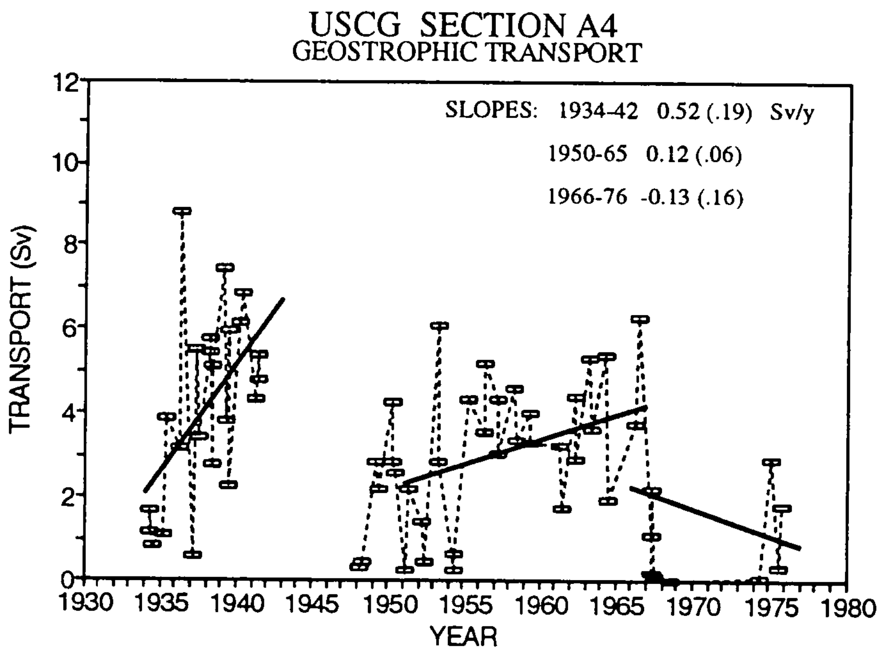


Figure 21. Time series of geostrophic currents relative to the 1000 dbar for the IIP sections A3 off the eastern slope of the Grand Bank and A4 off the Tail of the Bank.