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Spatial and Temporal Variability in the CIL on the Newfoundland and Labrador Shelves

by

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ABSTRACT

Oceanographic data from the Grand Bank, northeast Newfoundland Shelf and the Labrador Shelf are used to determine variability in the CIL during the summer and fall periods in relation to the long-term average. The summer area of the CIL across the northeast Newfoundland Shelf has returned to near normal during 1994 at Bonavista but remained above normal on Hamilton Bank and on the Grand Bank. CIL volume estimates are highly correlated with the cross-sectional areas measured along widely spaced transects, with the volume of subzero °C water on the shelf slowly decreasing since 1991. A significant south-north positive temperature gradient at CIL depths of approximately 1/4 °C per 100 km was observed from the northeast Newfoundland and southern Labrador Shelves to the northern Labrador Shelf, probably the result of the insulating effect of the winter ice cover.

INTRODUCTION

The vertical temperature structure (Fig 2a) on the Newfoundland and Labrador continental shelves is dominated by a cold layer of water in the range of -1.7 °C to 0.0 °C trapped between the seasonally heated upper layer and warmer slope water which floods the deep cross shelf trenches near the bottom. This layer of water has been called the cold intermediate layer (CIL) and on the Newfoundland and Labrador Shelf has been defined as the volume of water below 0.0 °C (Petrie et al., 1988). Other definitions may equally apply, for example, in the Gulf of St. Lawrence the 3.0 °C isotherm best represents the interannual and annual variability in the CIL (Gilbert and Pettigrew, 1995).

The CIL is most apparent in summer when spring ice melt and seasonal heating increases the stratification in the upper layers to a point where heat transfer to the lower layers is inhibited. In the winter months the intermediate layer effectively disappears as the upper layers cool down to between -1.0 and 0.0 °C from January to March due to winter cooling and mixing of surface water into the CIL. By late April and early May the warming of the surface layer commences and the cross-sectional area of ≤ 0.0 °C water decreases from the winter maximum to a minimum in the fall due to summer heating.

The summer cross-sectional area from the Flemish Cap transect on the Grand Bank to the Seal Island transect on Hamilton Bank (Fig. 1) are highly correlated (Petrie et al., 1992), however, a detailed analysis shows unexpected north-south variations (Colbourne and Foote, 1994). The purpose of this paper is to further examine the spatial and temporal variations in the extent of the CIL on the Newfoundland and Labrador shelves during different climatic conditions.

SUMMER CIL

Oceanographic measurements have been made along transects mainly during the summer on the Newfoundland and southern Labrador Shelf since the late 1940s and even earlier on the Labrador Shelf (Colbourne, Senciall and Foote, 1995). The areal extent of the CIL along the Seal Island transect bounded by the 0.0 °C isotherm for the years 1991-1994, which were cold years, together with the July-August (1929-1994) average are shown in Fig. 2b. Since 1990 the CIL has been above normal in total area with 1991 showing the greatest extent. In general, subzero °C water covers most of the southern Labrador Shelf during the summer reaching more than 200 km offshore with a strong thermal front near bottom at the edge of the continental shelf, unlike the Bonavista transect where the bottom temperature gradient is very weak near bottom in the offshore region (Colbourne and Senciall, 1993).

The offshore extent of the CIL along the Seal Island transect during 1994 was about 218 km compared to an average of 214 ± 26 km and the maximum thickness was 263 m compared to an average of 227 ± 53 m, this corresponds to a cross-sectional area of 34 km^2, compared to an average of 28 ± 7 km^2 for the time period 1929-1994.

Along the Bonavista transect during 1994 the cold layer extended offshore to about 240 km, with a maximum thickness of about 200 m corresponding to a cross-sectional area of approximately 28 km^2. The average offshore extent of the CIL along this transect is about 220 ± 44 km with an average thickness of about 200 ± 35 m, corresponding to an average cross-sectional area of 26 ± 9 km^2 for the time period 1946-1994.

AUTUMN CIL

During the annual fall groundfish assessment surveys, which started in the late 1970s, temperature measurements were made over a large area on the shelf (Fig. 2a, inset) which enables a calculation of the cross-sectional areas of the water mass anywhere from approximately 44 to 55 °N latitude. The fall CIL area along the Bonavista transect calculated from this data set for the period 1980 to 1994 shows similar trends as in the summer, however, the average area has decreased from 33 ± 9 km^2 during the summer to 24 ± 6 km^2 in the fall as a result of summer heating and vertical mixing over the water column. The CIL area during the fall of 1994 was about 26 km^2 compared to about 30 km^2 in 1993, 27 km^2 in 1992 and about 22 km^2 in 1991.

The Seal Island CIL area is more variable and smaller in average magnitude than the more southerly Bonavista transect, with some years when 0.0 °C water was completely eroded by fall convection. The average CIL area for the period 1980 to 1994 during the fall along this transect was about 13 ± 10 km^2. The CIL area during the fall of 1994 was about 14 km^2 compared to 16 km^2 in 1993, 26 km^2 in 1992 and 11 km^2 in 1991.

CIL VOLUME

The total volume of water on the Newfoundland and southern Labrador shelves shoreward of the 1000 m isobath and within NAFO divisions 2J3KL is approximately 1.85×10^{14} m^3. The calculation of the volume of CIL overlying the continental shelf is determined by defining Z_1 as the upper boundary of the CIL and Z_2 as the lower boundary for each temperature profile. The thickness of the water mass is then calculated as Z_2-Z_1 (Fig. 2a). The thickness of the CIL for each temperature profile measured during the summer (July-Sept.) and fall (Oct.-Dec.) time periods were then calculated and gridded onto a square projection of 0.25° latitude by 0.38° longitude (7.96×10^8 m^2) by a finite difference interpolation scheme. The total volume was then calculated by summing the volumes for each grid element of known area. Variations in the thickness over one grid element were generally small and ignored. In cases where the CIL intersected the bottom the total water depth was taken as Z_2. Due to limited data sets the volume estimates were not calculated prior to 1980.

The spatial variation in the amount of subzero water on the shelf in different years is determined by contouring the thickness of the layer of water less than 0.0 °C on the Northeast Newfoundland Shelf in NAFO Divisions 2J and 3KL during the summer and fall periods for 1984, a cold year and 1986, a warm year and for 1994 (Figs. 3 and 4). The isolines of CIL thickness show large variations from summer to fall of the same year and from cold years to warmer years. The thickness of the CIL is maximum (> 150 m) along the east coast of Newfoundland within 100 km of the shore and decreases to 0.0 m near the edge of the shelf, on the southern Grand Bank and on Hamilton Bank during warm years in the fall. Of particular interest is the reduction, particularly in 1986, in the amount of subzero °C water off southern Labrador and its almost complete disappearance in the fall of 1986.

Figure 5a shows time series of the CIL cross-sectional area for the Seal Island, Bonavista and Flemish Cap transects from 1980 to 1994 for the summer (July-August) period. In 1994 the CIL area off Bonavista was about 7

% above normal compared to 28 % in 1993 and up to 68 % in 1991. The CIL area along the Seal Island and Flemish Cap transects remained above normal during the summer of 1994 at about 36 % and 12 % respectively compared to 61 % and 48 % during 1991.

The time series of total volume of subzero water over the 2J3KL area together with the average (Seal Island, Bonavista and Flemish Cap) CIL cross sectional area are shown in Figure 5b for the summer period and Figure 5c for the fall period. These time series exhibit some differences but as expected are highly correlated with correlation coefficients of 0.85 and 0.76 for the summer and fall periods respectively. These plots shows large variations from the warm years of the early and late 1980s to the cold periods of the mid 1980s and early 1990s. For example, the total volume of subzero water on the shelf increased from approximately 3.28×10^4 km^3 during the summer of 1989 to 5.61×10^4 km^3 in 1990 a 70 % increase.

Since the summer of 1991 the volume of subzero °C water has been slowly decreasing, however it is still significantly above the values of the early 1980s and from 1986 to 1989. The average volume of subzero °C water on *the shelf during the summer is approximately* $4.06\times10^{13} \pm 0.94$ m^3 (40,000 km^3) roughly one-quarter of the total volume of water on the shelf. The time series during the fall shows similar trends but the total volume has reduced to $2.38\times10^{13} \pm 0.79$ m^3 about one-half the summer values.

SPATIAL VARIATIONS

The horizontal temperature structure on the Newfoundland and Labrador shelves at 75 m depth for the July and October (1930-1994) average and for the summer of 1980 and 1993 is shown in Figures 6 and 7. The large decrease of the subzero °C water from summer to fall is clearly evident at 75 m depth. Also of interest is the significant north-south temperature gradient with warmer temperatures on the northern Labrador Shelf compared to the Hamilton Bank and the northeast Newfoundland Shelf areas. For example, during the summer of 1980 the temperature at 75 m depth increased from -1.0 °C on the northeast Newfoundland and southern Labrador shelves to 0.5 to 1.0 °C on the northern Labrador Shelf, a gradient of approximately 0.25 °C/degree latitude (1/4 °C per 100 km). Even during cold periods (summer 1993) the horizontal extent of subzero °C water showed a significant contraction towards the north. The latitudinal variations in the cross-sectional area of subzero °C water along 14 cross-shelf transects from the summer of 1993 from 47 °N (central Grand Bank) to 57.2 °N (Nain Bank) (Fig. 8) show the maximum volume of cold water occurs on the northeast Newfoundland Shelf and decreases towards the northern Labrador Shelf. The large spike corresponding to the White Bay transect is associated with the broad (450 km), relatively deep (200-400 m), northeast Newfoundland Shelf.

DISCUSSION

Our results accord with those of Lazier (1982) who found evidence (see his Figure 5) that, for the July August period, Labrador Shelf waters in the depth range from 50 to 150 m were cooler on the southern Labrador Shelf (52 to 55 °N) than they were on the northern shelf (56 to 60 °N). Lazier further found indications of an along shelf temperature gradient in autumn at 150 m depth, with the temperature in the north being about 1.0 °C warmer than that for the southern shelf. In addition, Dunbar (1951) also showed a general warming trend towards the north along the Labrador coast to Hudson Strait for the August-September period at 100 m depth.

Lazier noted the possible influence of tidal mixing in Hudson Strait. It was proposed by Lazier that the autumn deepening of the thermocline provided the right configuration of water masses to allow isopycnal mixing of warm water into the intermediate depth zone of the Labrador Shelf, and that this new mass was then advected south, thus explaining the autumn along shelf temperature gradient. Our data suggests that the north-south temperature gradient is already quite pronounced in summer, indicating that a seasonally generated warm anomaly, drifting south, must first appear well before summer, if it is to influence the mid-Labrador Shelf by July.

It is conceivable that a steady, rather than seasonal, input of heat from Hudson Strait could be responsible for erosion of the CIL on the northern Labrador Shelf. Sutcliffe et al. (1983) proposed that freshwater and three oceanic water masses were mixed in Hudson Strait, accounting for the distinctive properties of Labrador Shelf water (including apparent high nitrate concentration). However, a warm mass influencing the northern Labrador Shelf will also affect the southern Labrador Shelf in a time period of 1 to 3 months, given a southward drift of the Labrador current at about 15 to 50 cm/s, and thus it is not clear that a steady input of heat could account for the decline of CIL area toward the north.

Finally, we note the possibility that heavier ice formation in the north insulates the northerly shelf waters, relative to those in the south, thus accounting for the unexpected warmth of the CIL on the northern half of the Labrador Shelf. Normally, by December most of the Arctic including Hudson Bay and the Labrador coast as far south as Harrison Bank is covered by solid ice. According to calculations by Symonds (1986), one meter of ice can reduce the heat loss of the ocean to the atmosphere by over 90%. We envision that the low heat content of the northerly waters permits the upper layer to reach -1.8 °C (the freezing point of seawater) before these extremely chilled waters have been mixed to appreciable depths. Once ice formation commences in the fall it limits further cooling since heat extracted by the atmosphere contributes to ice formation, rather than solely to chilling the mixed layer. As the ice thickens, it insulates, and further limits the heat loss of the mixed layer. Thus, the preferential ice formation in the north may limit the penetration depth of the very coldest waters, implying a thicker cold layer for the more southerly waters.

ACKNOWLEDGEMENTS

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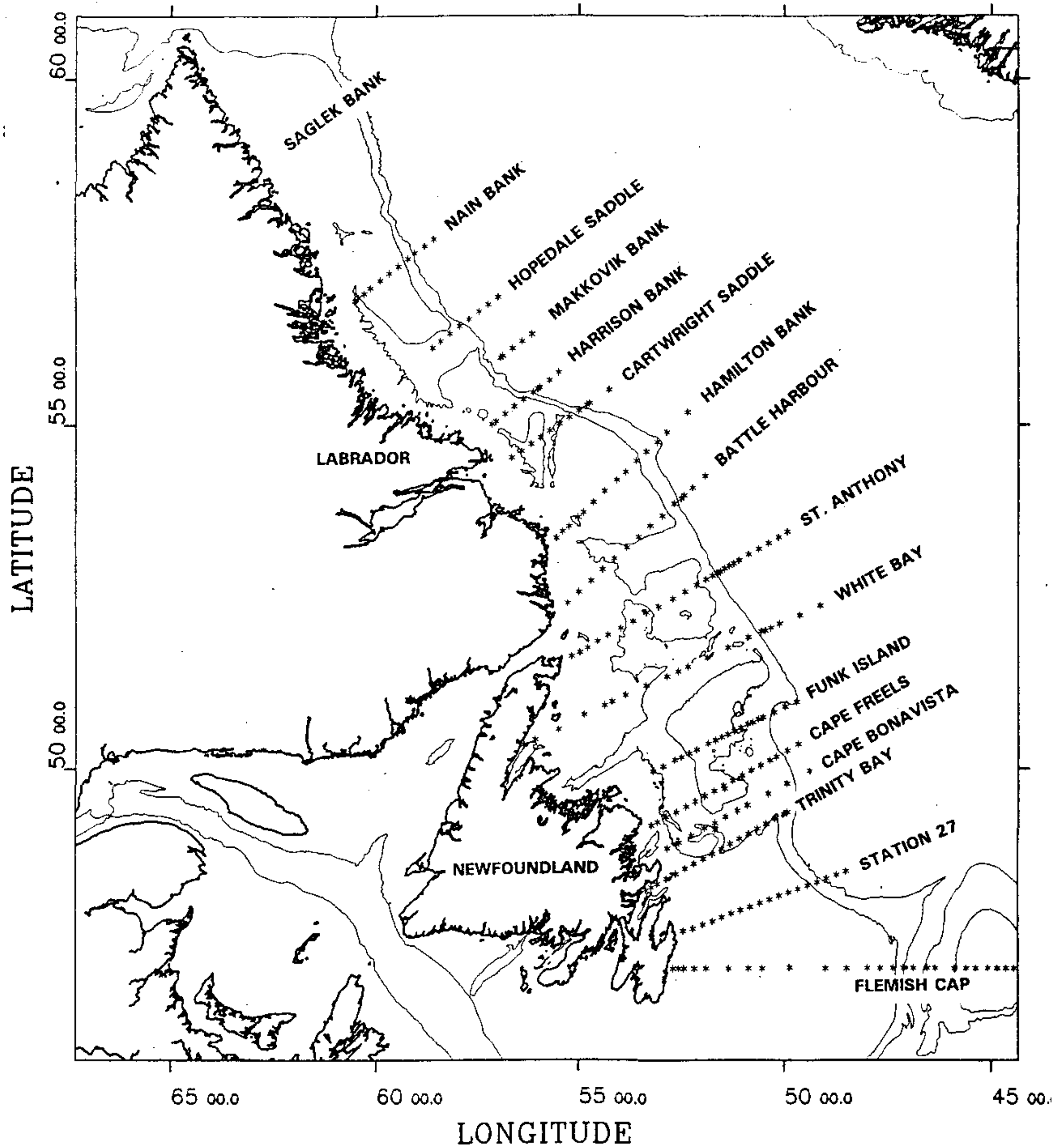

Fig. 1. Location map showing positions of transects occupied during the summer of 1993.

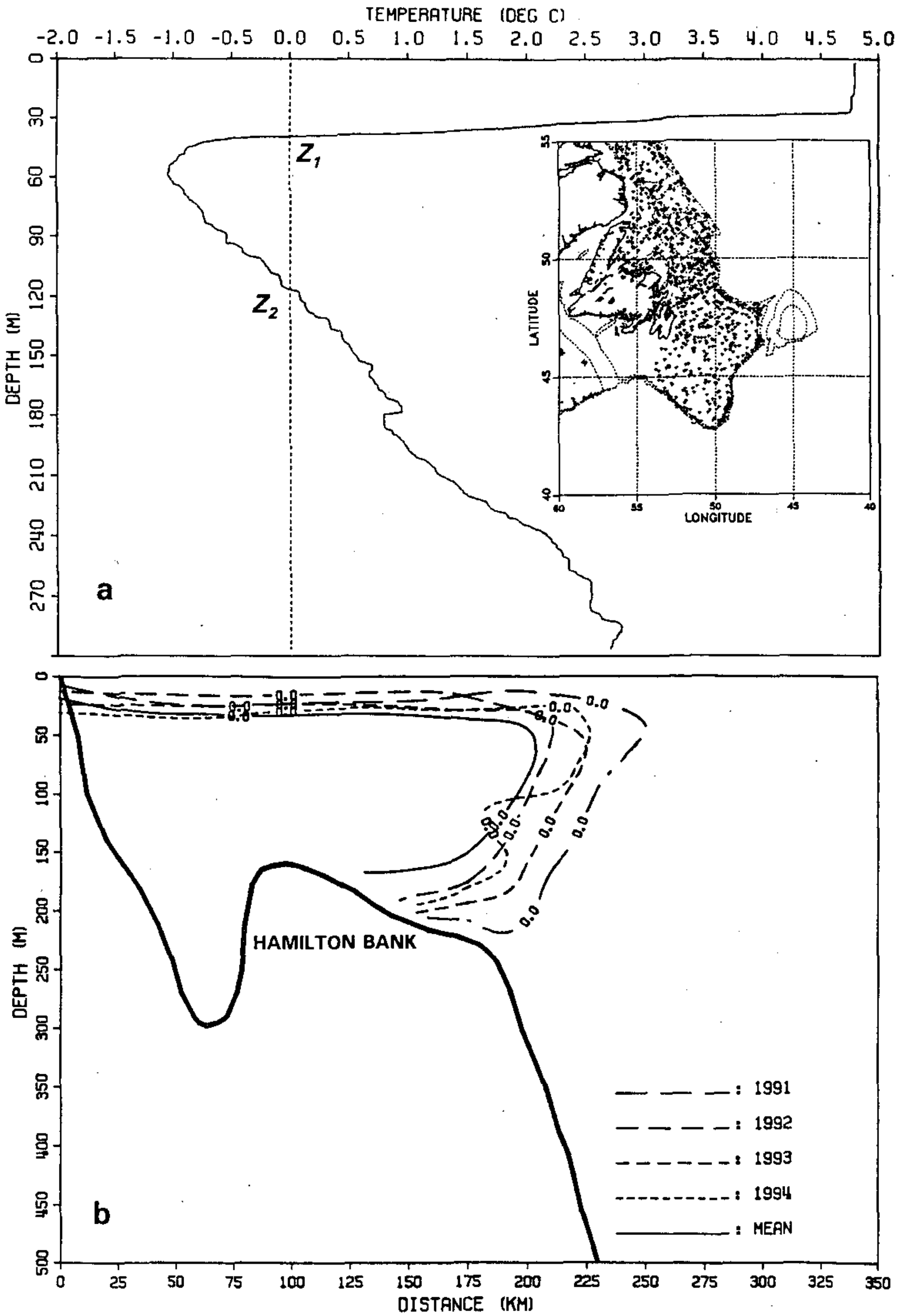

Fig. 2. (a) A typical temperature profile through the CIL along the Bonavista transect, inset shows locations of temperature profiles during the annual groundfish survey. The levels Z_1 and Z_2 are the depths of the 0.0 °C crossing. (b) The summer CIL along the Seal Island transect.

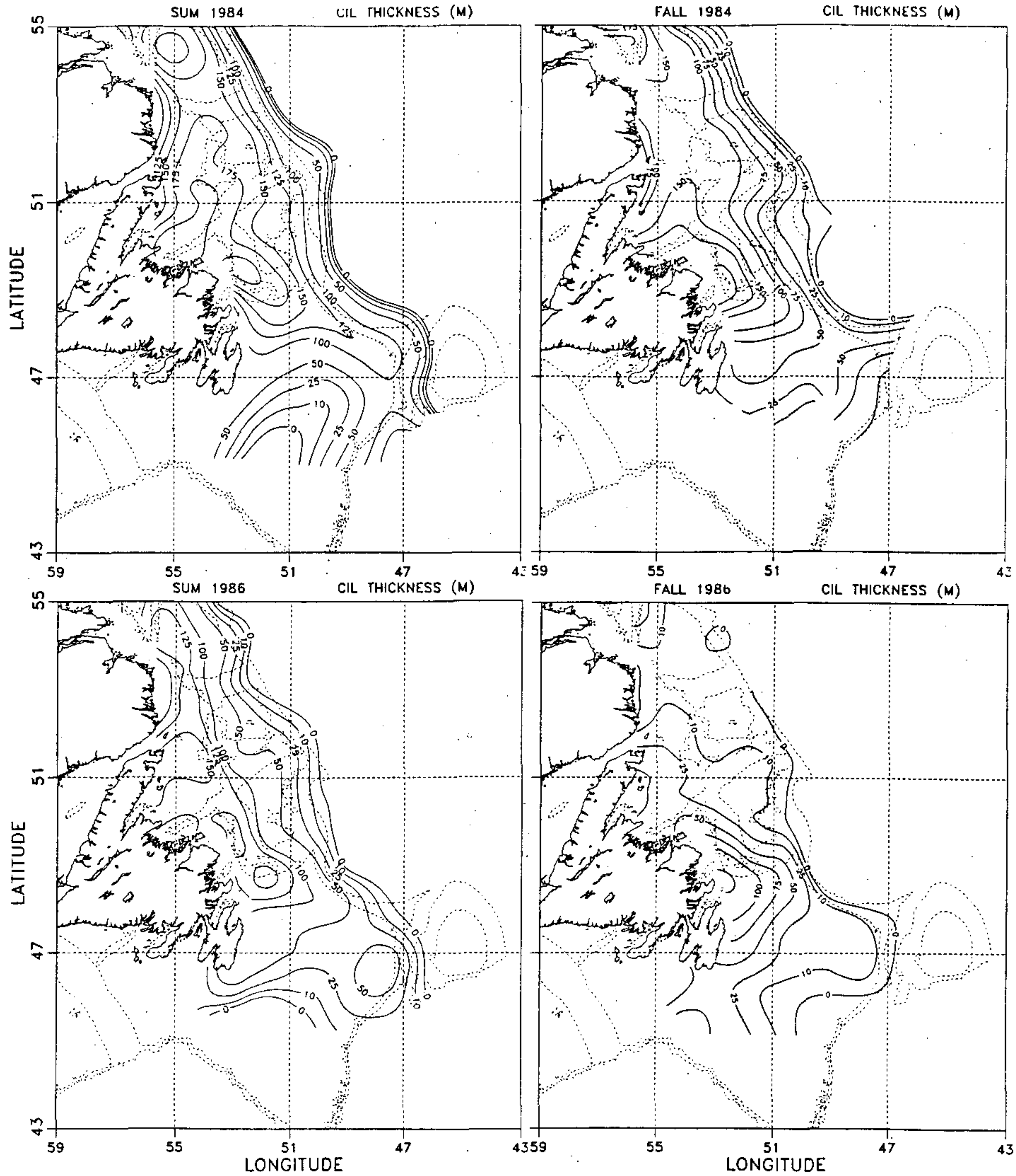

Fig. 3. Horizontal maps of the summer and fall CIL thickness (m) over the 2J3KL areas for 1984 and 1986.

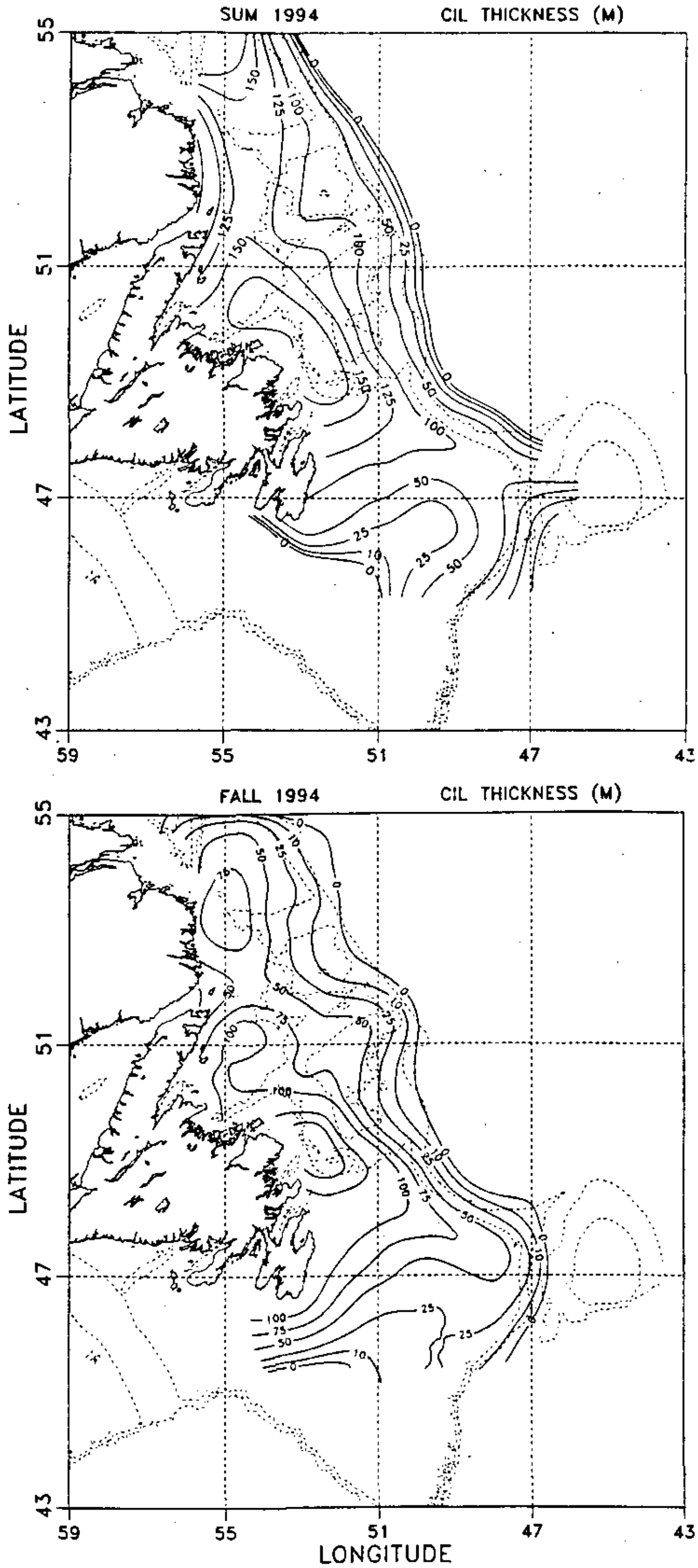

Fig. 4. Horizontal maps of the summer and fall CIL thickness (m) over the 2J3KL areas for 1994.

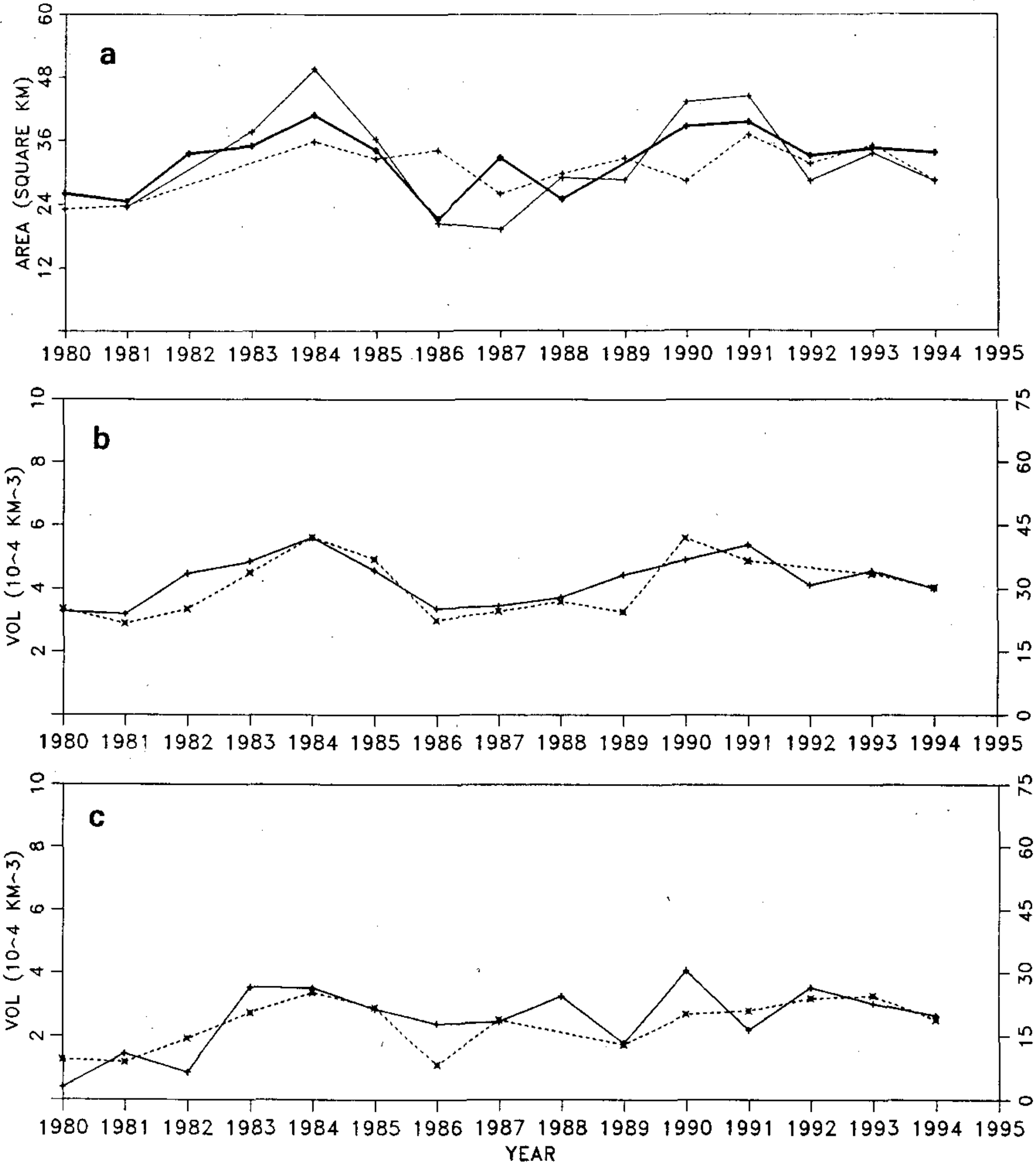

Fig. 5. (a) Time series of summer CIL area along the Seal Island (heavy solid line), Bonavista (light solid line) and Flemish Cap (dashed line) transects. (b) Time series of the summer average of the Seal Island, Bonavista and Flemish Cap CIL areas (solid line) and the summer CIL volume (km^3) (dashed line) over the 2J3KL areas. (c) Time series of the fall average of the Seal Island and Bonavista CIL areas (solid line) and the fall CIL volume (km^3) (dashed line) over the 2J3KL areas.

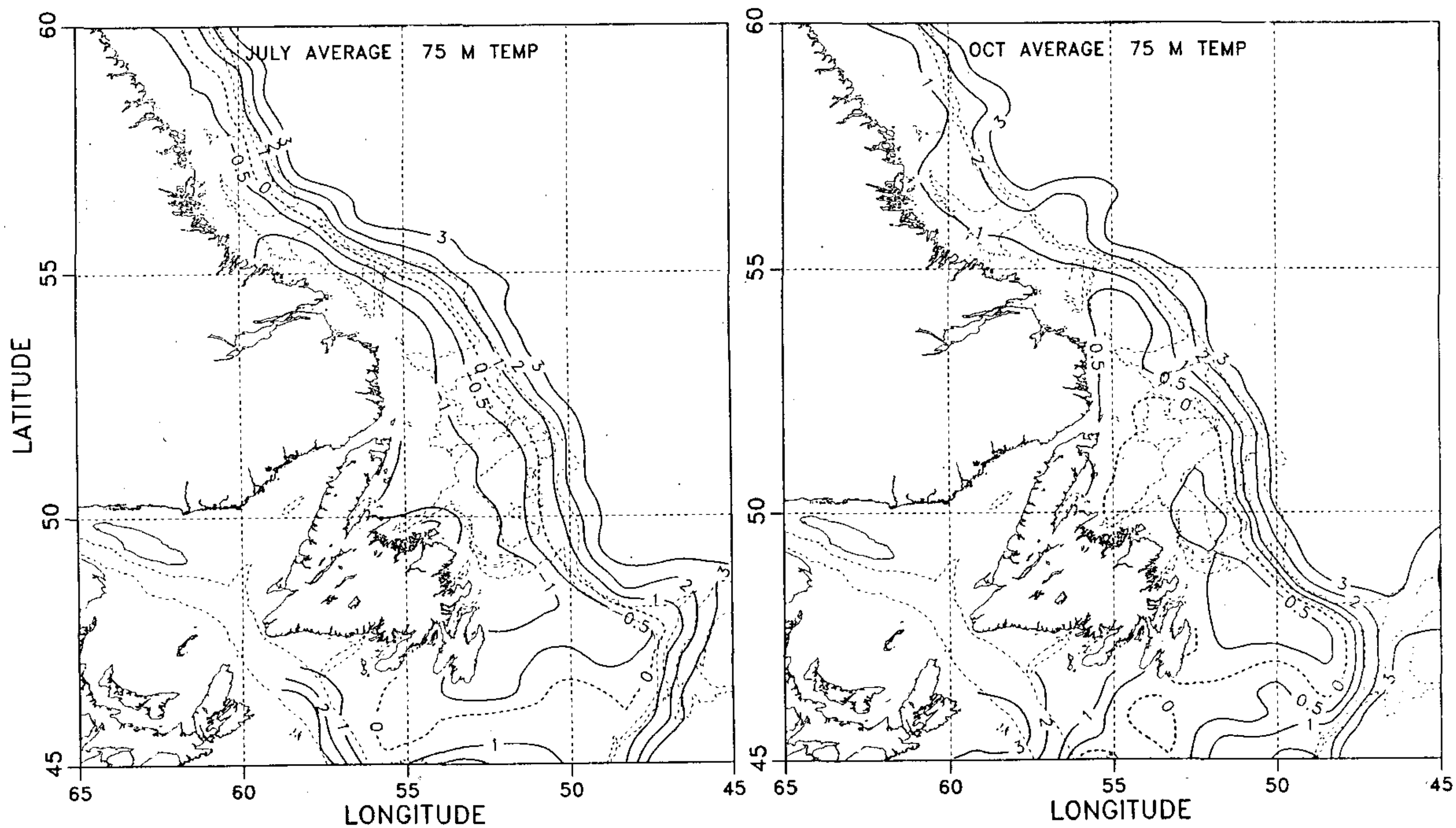

Fig. 6. The July and October average temperature at 75 m depth. Based on all available data from 1930-1994.

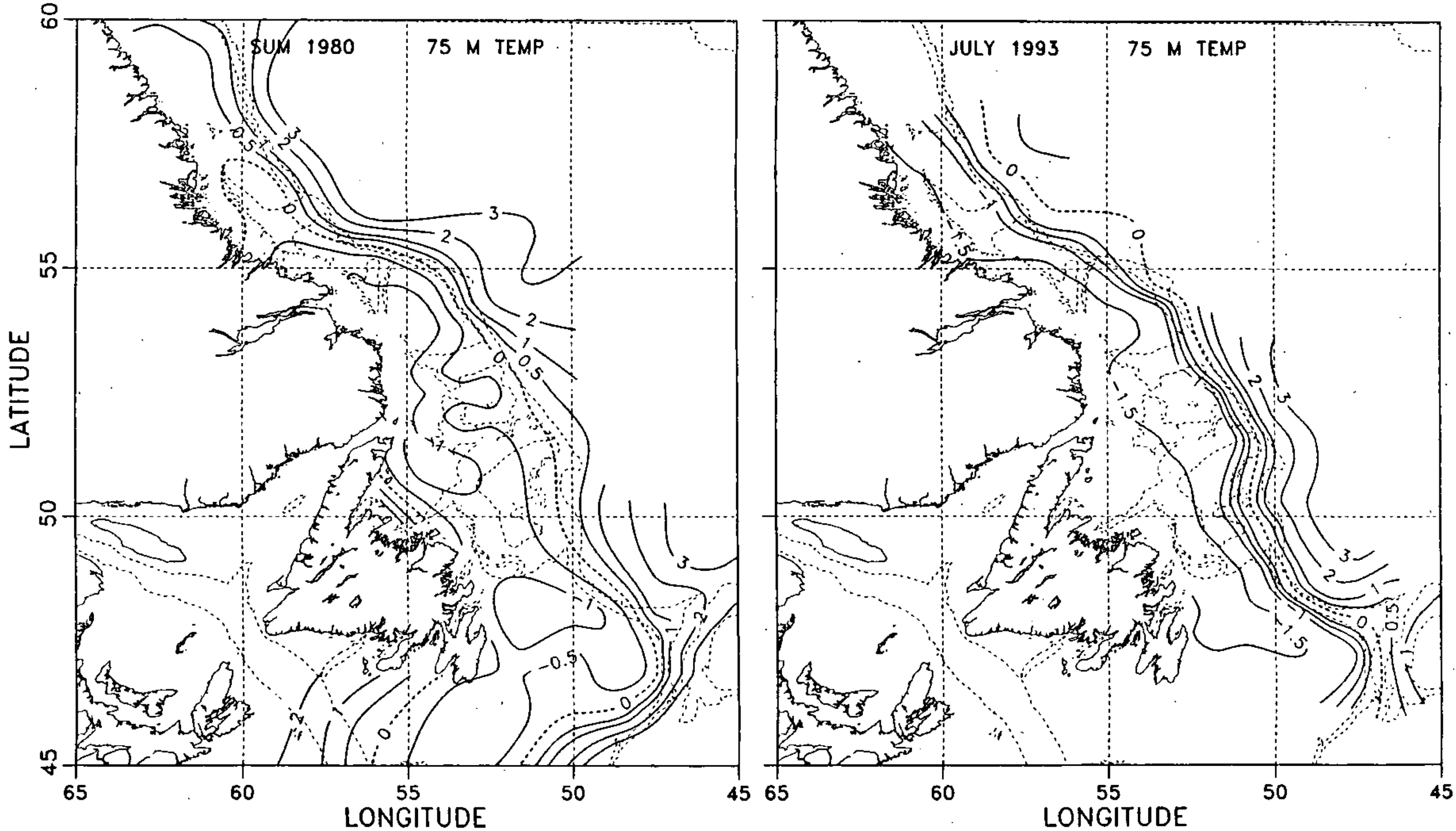

Fig. 7. The summer (July-August) 1980 and the July 1993 temperature at 75 m depth.

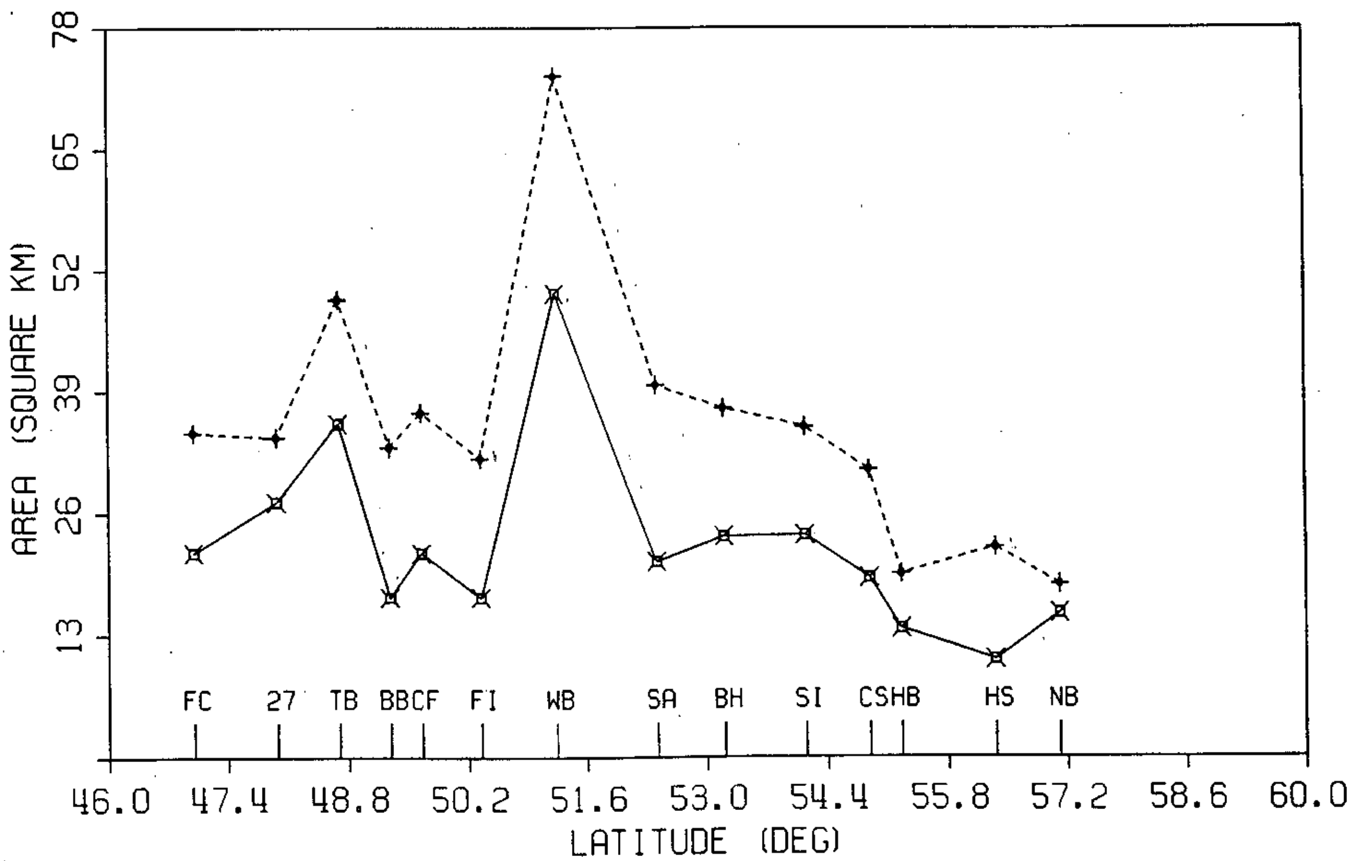

Fig. 8. The south-north variation in the CIL area for 0.0 °C (dashed line) and for the -1.0 °C (solid line) from all transects shown in Fig. 1.