Ocean Climate Variability on the Scotian Shelf and in the Gulf of Maine

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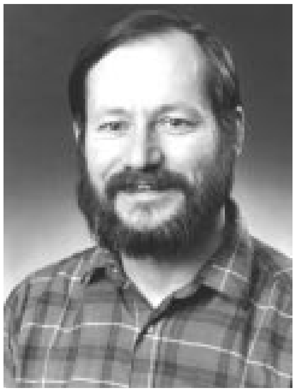

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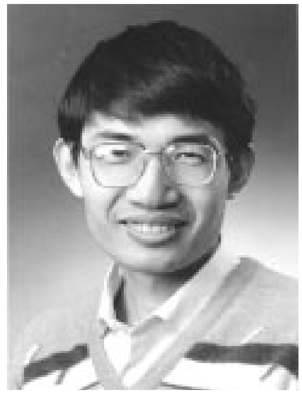

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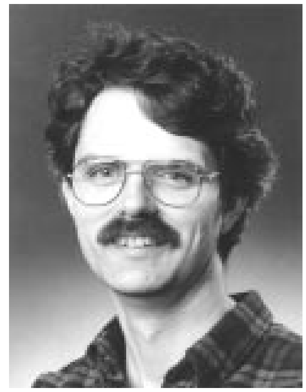

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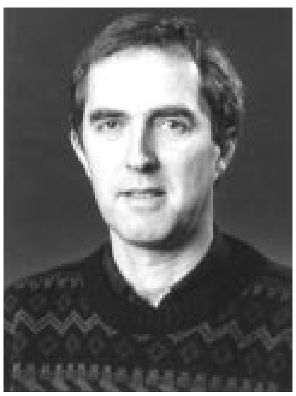

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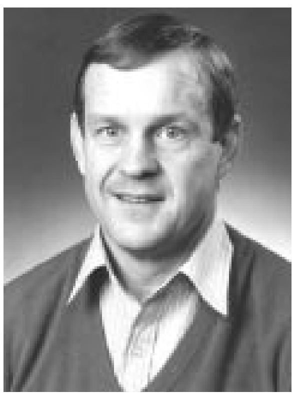

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Introduction

Thirty-two years ago in Rome at the International Commission for the Northwest Atlantic Fisheries (ICNAF) Environmental Symposium, Louis Lauzier of the St. Andrews Biological Station reported on the long-term water and air temperature variations in the Scotian Shelf-Gulf of Maine area (Lauzier 1964, see Figure 1 for locations mentioned in text). Using sea surface temperature time series from coastal sites and lightship vessels, and deeper data from a small number of offshore banks and channels, he was able to describe the year-to-year fluctuations and the longer-term trends of the ocean climate from Cabot Strait to the central Gulf of Maine. In his closing discussion Lauzier stated: "We cannot explain the long-term variations of temperatures described previously. ...More information on the circulation, water mass production and heat budget is essential. Little is known about the first two and less about the last one."

Since Lauzier's presentation, the ocean climate of the Scotian Shelf-Gulf of Maine area has continued to experience short and long-term variations. There also has been a dramatic increase in the amount of temperature and salinity data collected in the region. Extensive databases of oceanographic observations along with tools for rapid recovery and analysis of these data have allowed us to describe the climate fluctuations in more detail than in the past. Meteorological and sea surface temperature data have been combined to permit calculations of the transfer of heat between the atmosphere and ocean. Moreover, models have been developed that can examine the effects of climate changes on ocean currents on the continental shelf. All of these factors have contributed to the progress that has been made in addressing the issues raised by Lauzier.

Average Conditions

Before discussing the climate variations that occur in Scotian Shelf-Gulf of Maine waters, we shall briefly describe the average conditions. As an example, the wintertime surface temperature and salinity for the northwestern Atlantic shelf are shown in Figure 2. The Scotian Shelf-Gulf of Maine region features surface water temperatures from about -1 to 6°C and surface salinities of 32-33. The region is part of a larger oceanographic area that includes the Gulf of St. Lawrence, Newfoundland and Labrador Shelves. The shelf waters tend to move through the region in an overall southwesterly direction, from the Labrador Shelf to the Newfoundland Shelf and the Gulf of St. Lawrence, and finally onto the Scotian Shelf and into the Gulf of Maine. The northern component of the region's waters contributes to their lower temperatures and salinities relative to the offshore oceanic waters. River discharge and land runoff also tend to reduce salinity. Over the continental slope offshore of the Scotian

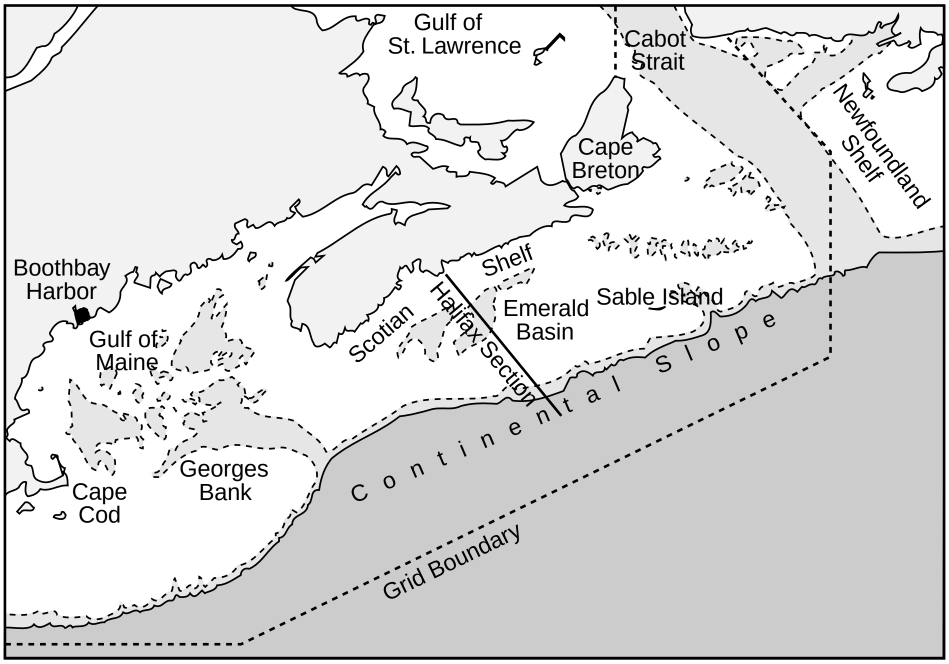

Figure 1: Area map with place names used in the text.

Shelf, the temperature and salinity increase to values characteristic of the Gulf Stream and the Sargasso Sea. We are left with the impression of a distinct shelf regime adjacent to the deep ocean. A similar general picture holds throughout the year.

The temperature and salinity also change with depth and season. During winter on the Halifax Section (see Figure 1 for location), the ocean has a two-layer structure with cooler, fresher waters near the surface overlaying warmer, saltier waters (Figure 3). In summer, the temperature of the near-surface waters increases substantially giving rise to a three layer structure with a warm surface layer, a cold intermediate-depth layer and a warm bottom layer. The bottom layer in Emerald Basin, the deep shelf basin in Figure 3, is caused by relatively dense water from the continental slope moving onto the shelf and flooding the inner basins. Through mixing, these waters gradually influence the shallower waters over the shelf. The deep inner basin waters generally remain there until they are displaced by another onshelf flow of slope water.

The water over the upper continental slope is typically made up of two types: Labrador Slope Water, derived principally from the Labrador Current, with temperatures of 4-8°C and salinities of 34-35; and Warm Slope Water, with a major component from the Gulf Stream, with higher temperatures and salinities of 8-13°C of 34.5-35.5 respectively. The changing proportions of these two types of slope water, one time the cooler, fresher Labrador Slope Water dominant, another time the warmer, saltier Warm Slope Water, causes variations in the temperature and salinity of the shelf waters.

Temperature and Salinity Variability

Temporal Changes

One of the data series Lauzier used to illustrate ocean climate variability was the sea surface temperature record from Boothbay Harbor, Maine. Started in 1906, this record is one of the longest for the east coast of North America. The annual mean temperatures show that large fluctuations can occur from year to year (Fig. 4); in addition, there have been extended periods when temperatures were well above normal, particularly from the late 1940s to the late 1950s, and well below normal, for several years centred around 1915, 1940 and 1965. To determine if these temperature variations also occurred offshore, we examined data collected from oceanographic ships. However, in this instance, we are restricted to the last 50 years because there were only a limited number of surveys prior to 1950. Even since 1950, there are areas of the shelf that have substantially more data than others.

One such area is Emerald Basin where observations were taken frequently for three decades as part of the standard oceanographic Halifax Section. In addition, as we saw above, data from the Basin cover essentially the full range of temperature and salinity properties on the shelf, including offshore waters from the upper continental slope.

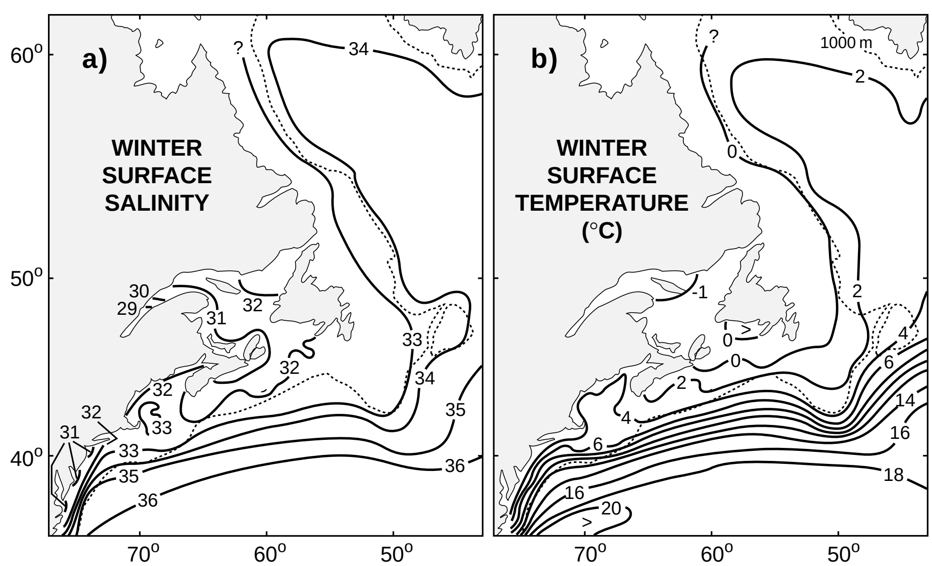

Figure 2: Winter surface temperature and salinity for the northwestern Atlantic shelf region.

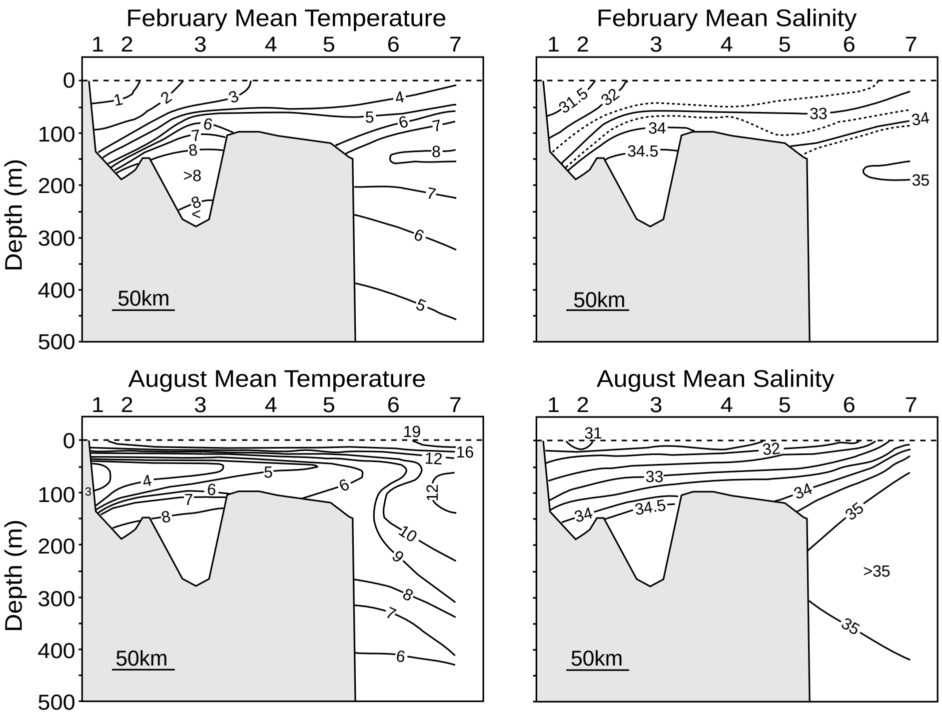

Figure 3: Average February and August temperature and salinity on the Halifax Section across the Scotian Shelf.

The variability of the annual temperature anomaly (the difference of the average temperature for any given year from the mean value calculated for all years combined) is quite similar to the temperature at Boothbay Harbor for the same period (Fig. 5). From the early 1950s to the mid 1960s, the temperatures in Emerald Basin decreased steadily from about 1°C above normal (positive anomalies) to about 3°C below normal (negative anomalies) in the 0-200 m layer. Over this period the decrease was greater for the deeper 100-200 m layer than for the shallower 0-100 m layer. In the late 1960s there was a rapid change to above normal temperatures, so that by the mid 1970s the values were as high as the earlier maximum. Above or near normal conditions have prevailed to the present time. Occasionally, in the late 1980s for example, the 0-100 m layer had below normal temperatures. On the other hand, temperatures in 1994-95 were among the highest recorded. Over the entire period, the lower layer generally had greater anomalies than the shallower one. The larger magnitude of the anomalies in the deeper layer was one of the factors that led Petrie and Drinkwater (1993) to conclude that the long-term changes were caused by subsurface waters from the upper continental slope moving onto the shelf and flooding the deep inner basins. These waters would then spread into the upper layers with their influence diminishing as they mixed with the shallower waters.

The variations of salinity are not as systematic as those for temperature. However, the periods of below normal temperatures generally have below normal salinities and vice versa. This is consistent with Labrador Slope Water dominating during times of negative anomalies, and Warm Slope Water having the greatest influence during periods of positive anomalies.

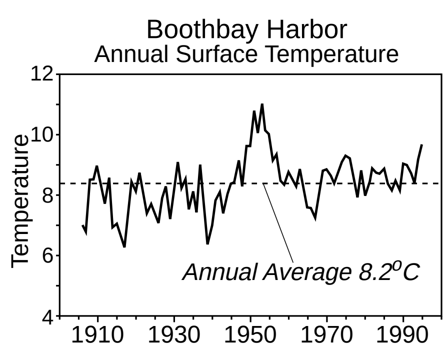

Figure 4: Time series of the annual surface temperature for Boothbay Harbor, Maine from 1906-1995.

Spatial Changes

How widespread are the temperature and salinity variations seen in Figures 4 and 5? For example, did water temperatures over the entire Scotian Shelf and Gulf of Maine change as dramatically from the mid 60s to the early 70s as they did in Emerald Basin? Since there are not enough data to map the year-to-year variations of temperature and salinity for the entire region, we have combined data from 1959-67 to represent a cold period (henceforth the cold 60s) and observations from 1972-81 to represent a warm period (the warm 70s) based on the Emerald Basin record (Fig. 5). We expect that, because we averaged data from many years, the temperature and salinity differences between these two periods will be smaller than the maximum differences of nearly 5°C and 1 seen in Figure 5.

For each of the two combined datasets, we calculated the temperature and salinities for each season for the shelf area from Cabot Strait to Cape Cod as well as for a limited region over the continental slope (indicated by the grid boundary in Figure 1). The differences between the warm and cold years for the summer for the sea surface and the bottom (or 300 m, whichever is shallower) are shown in Figures 6 and 7. Positive values mean that the temperatures in the warm 70s were greater than in the cold 60s, whereas, negative values mean the opposite.

At the surface the differences range from about -1°C to about 3°C (Fig. 6). Negative values are found on the eastern Scotian Shelf, particularly east of Cape Breton, and in an area over most of Emerald Basin and extending southward to the continental slope. Over most of the region, differences of 1-2°C prevail. In the Gulf of Maine, there is a small patch with temperature differences of about 3°C.

At the bottom the temperature differences range from just below zero to about 3°C and are generally greater than at the surface (Fig. 7). Negative differences are limited to the eastern Scotian Shelf and around Sable Island; otherwise, the differences are positive. In particular, the region over and west of Emerald Basin has a value of 3°C. Temperature differences in the Gulf of Maine and Georges Bank are 1-2°C.

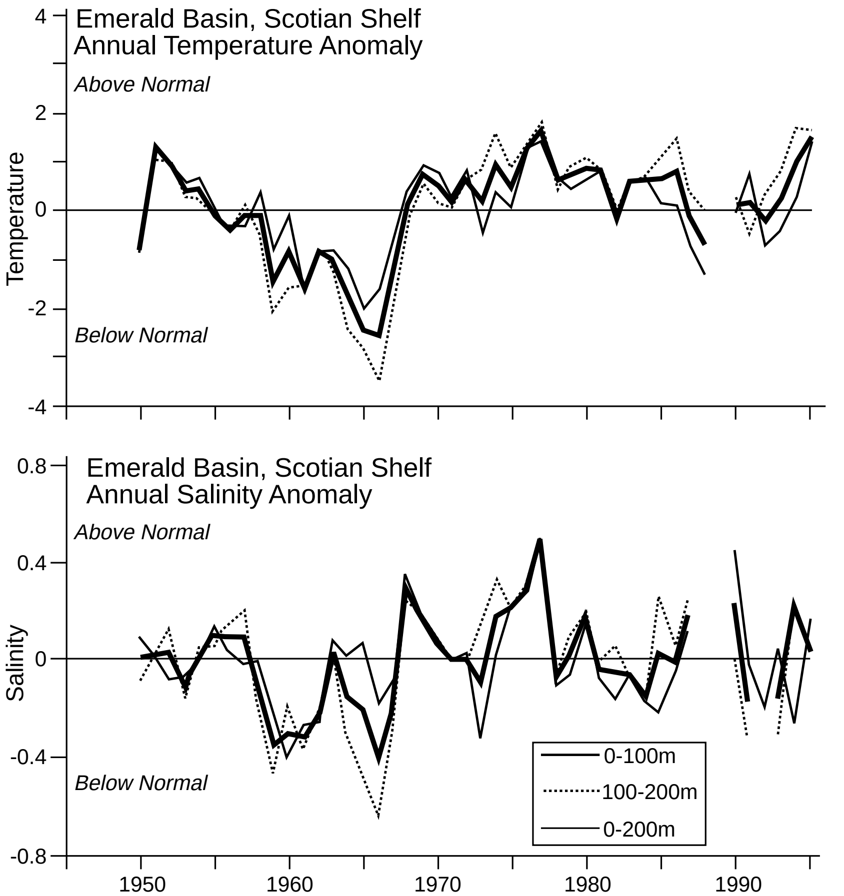

Figure 5: Time series of the annual temperature and salinity anomalies for Emerald Basin for the 0-200, 0-100 and 100-200 m layers. Gaps in the record indicate years when data were not collected.

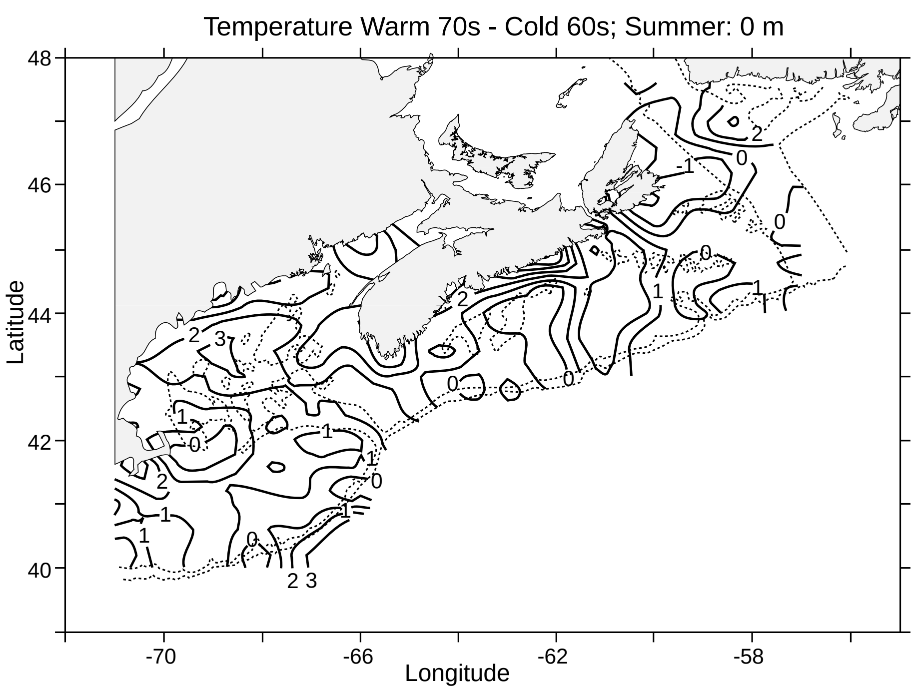

Figure 6: The summer, surface temperature differences (Warm 70s-Cold 60s). A positive difference means that the temperature in the warm 70s was higher than during the cold 60s and vice versa.

Similar analyses show that there were higher salinities during the 1970s associated with higher temperatures over most of the Scotian Shelf and the Gulf of Maine. The eastern Scotian Shelf was the exception with lower surface salinities in the 1970s corresponding to the lower temperatures found there.

We conclude that the shift to higher temperatures and salinities between the 1960s and 1970s was widespread across the Scotian Shelf and the Gulf of Maine but the magnitude varied with location. Thus the time series of Emerald Basin temperatures and salinities (Fig. 5) capture the general flavour of the climate variations in the region but the exact nature of the changes depends on the site.

Circulation Variability

We have seen how temperature and salinity changed over a wide area in the last section. Did these changes affect the currents as well? Or, on the other hand, did changes to the currents cause the variations of temperature and salinity? To address these questions, we have examined the vertical temperature, salinity and density structure for the cold 60s and the warm 70s for the Halifax Section. The winter values are shown in Figure 8 where the temperature, salinity and along-shelf current (derived from the density structure) for the cold 60s are shown in the left hand panels; the differences between the warm 70s and the cold 60s are shown on the right. The deep temperatures and salinities were higher over the continental shelf and slope during the warm 70s, consistent with a greater contribution of Warm Slope Water. On the other hand, salinities and (to a lesser extent) temperatures were lower at shallower depths, particularly over the continental slope, apparently related to increased St. Lawrence River runoff during the warm 70s. A key result is the indication of significant changes in the current structure especially evident as reduced southwestward flow over the slope during the warm 70s, which is consistent with a reduced Labrador Slope Water influence on slope water properties. The sense of this picture for the currents over the slope does not change from season to season and demonstrates that important long-term circulation changes on the Scotian Shelf are associated with variations

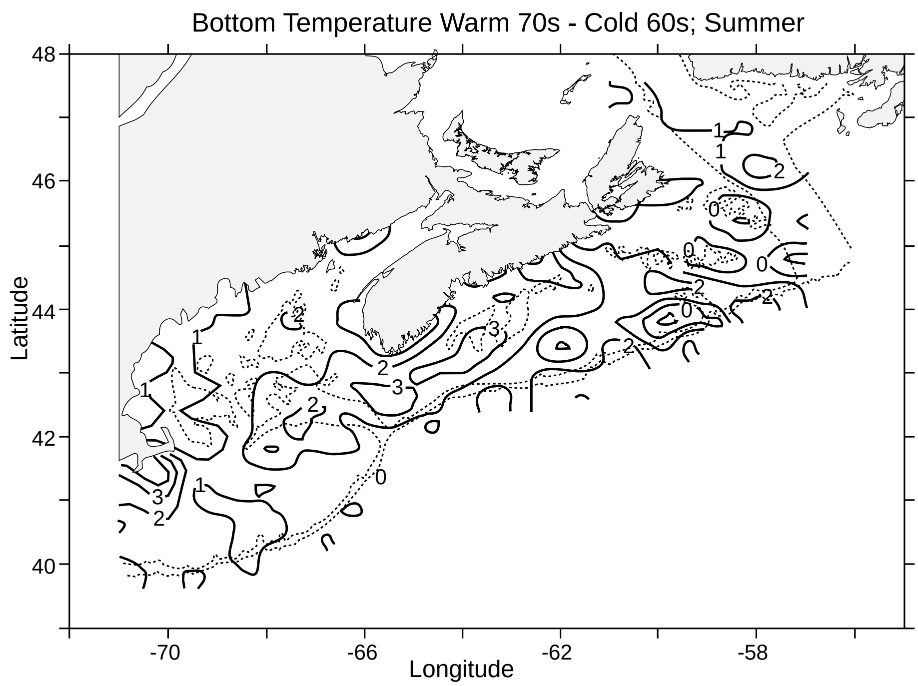

Figure 7. The summer, bottom (or 300 m, whichever is shallower) temperature differences (Warm 70s-Cold 60s). A positive difference means that the temperature in the warm 70s was greater than during the cold 60s and vice versa. Note that the bottom depths vary from about 10 to over 1000 m in the region.

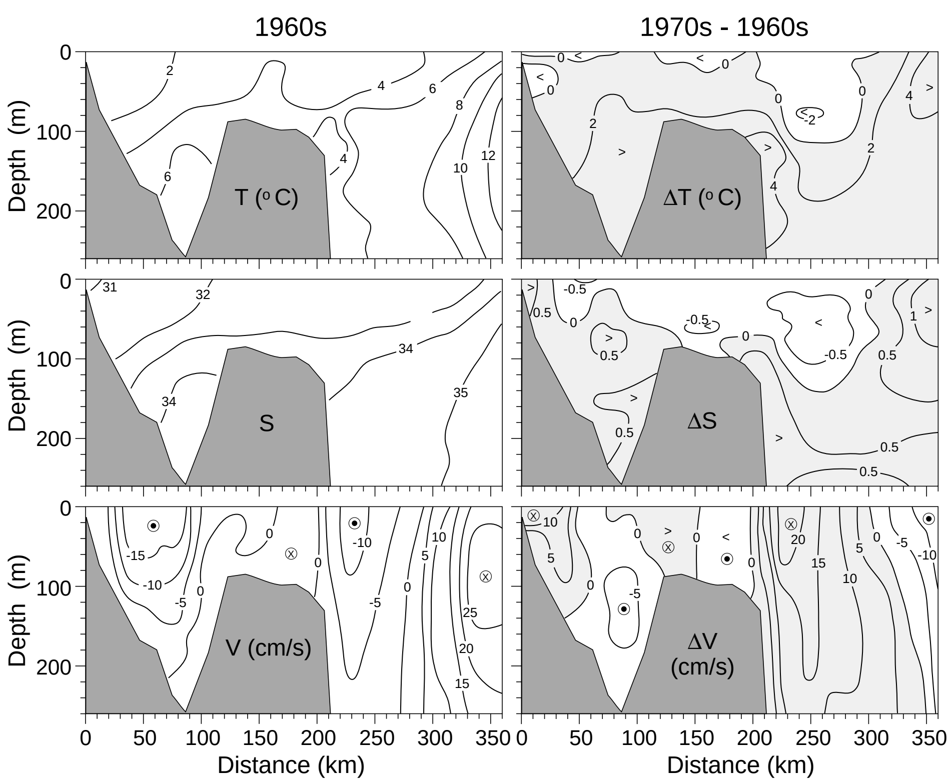

Figure 8. Wintertime estimates of temperature, salinity and along-shelf current (positive northeastward) for the Halifax Section. The left panels are the values for the cold 60s, the right hand panels are the differences between the warm 70s and the cold 60s.

in the temperature and salinity fields that in turn are strongly influenced by the upstream supply of both shelf (from the Gulf of St. Lawrence) and slope (Labrador Current) waters.

Causes of the Temperature and Salinity Variations

Thompson *et al*. (1988) suggested that year-to-year variations in the magnitude of the local heat exchange between the atmosphere and the ocean might account for the longer-term variability characterized by the temperature in Figure 5. However, a quantitative investigation by Umoh (1992) indicated that this was not true for the central Scotian Shelf. In addition, estimates of the atmosphere-ocean heat exchange indicate that there was slightly more heat transferred to the ocean during the cold 60s than during the warm 70s, contrary to expectations. Thus it is unlikely that local atmosphere-ocean exchange was the cause of the long-term temperature variability.

On the other hand, Petrie and Drinkwater (1993) found that during the cold 60s the westward flow of the Labrador Current along the upper slope from the Newfoundland to the Scotian Shelf was about four times greater than during the warm 70s. They used this observation in a simple model to predict successfully the temperature and salinity properties of the slope water from the Grand Banks to Georges Bank. This offered strong evidence that the westward transport of the Labrador Current contributes fundamentally to the observed temperature and salinity fluctuations from the Gulf of St. Lawrence to the Gulf of Maine.

The question of what causes the variations of the Labrador Current naturally arises. At present we must respond, as Lauzier did, that we cannot explain these long-term variations of the Current. On the other hand, significant progress has been made addressing the issues he raised: characterizing the changes in water mass structure, determining their effects on the circulation over the continental shelf and slope, evaluating the heat exchange between the atmosphere and ocean, and defining the role of the Labrador Current in the production of slope water.

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