NAFO Sci. Coun. Studies, 5: 51-78

Overview of Oceanographic Conditions in NAFO Subareas 2, 3 and 4 During the 1970-79 Decade

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Abstract

An overview of oceanographic conditions in NAFO Subareas 2, 3 and 4 of the Northwest Atlantic during 1970-79 is developed by reviewing available reports and publications together with selected analyses of long time-series of data held at the Bedford Institute of Oceanography, the Marine Environmental Data Service and the World Climate Center. In addition to summarizing decadal conditions relative to the longer term mean, an attempt is made, through use of correlation matrices, to look for possible interrelationships, temporally and spatially, between variables such as temperature, salinity, fresh-water discharge, and wind speed and direction. A summary of impressions is presented at the end of the paper.

Instroduction

Responding to a request to prepare an oceanographic overview of conditions in NAFO Subareas 2, 3 and 4 for the 1970-79 decade infers that one should consider all time scales from one month to 10 years and longer and space scales from a few kilometers to 2,000 and more. Within these space and time frames, the reader might reasonably expect to learn how conditions in the 1970's were, in comparison with those in the 1960's and with the longer term. Were they average or colder or warmer than "normal"? Did the winters get warmer and the summers colder, or *vice versa*? Was the water saltier or fresher? Did the whole area respond similarly, or did each subarea behave differently? In other words, the task is to provide a summary of climate based on the oceanographic "weather" observed during the decade. Additionally, one would be expected to go beyond this statistical type of presentation and attempt to provide plausible explanations of what physical processes may have been mainly responsible for producing the observed conditions.

In developing a picture of oceanographic conditions over the continental shelf and slope regions between Hudson Strait and Georges Bank (Fig. 1), one should keep in mind the various physical processes and driving forces important in determining conditions in any given area. Fresh-water input from rivers, precipitation and melting ice markedly lowers the salinity of the surface layer and affects stratification, transport and mixing processes throughout most of the area under consideration. Local heating and cooling and other meterological driving forces result in an easily recognizable seasonal cycle in the upper layers throughout most of the region but often produce wide variation within an area and on a time scale of days rather than months. The invasion of warmer, more saline water onto the continental shelf and the extraction of coastal water through offshore forcing from the Gulf Stream system produce significant effects on a time scale of days to weeks. Vertical and lateral mixing, brought about by tidal currents and wave motion, is a dominant oceanographic feature in some areas. It is not intended to focus on all of these factors but rather to ensure that they are not overlooked when considering the physical ocenaography of the subareas within the region.

To develop a systematic overview of conditions in such a large and complex area, with the specific objective of describing the 1970's in relation to "normal" or to the previous decade or a longer period, requires extensive data bases. The accuracy of such descriptions is dependent on the temporal and spatial density of the data. Invariably, the oceanographic data are sporadic in space and time and are often inadequate for describing conditions in detail.

This paper attempts to develop an overview through two approaches. Firstly, following a brief description of general features of the region, a sumary of oceanographic conditions, based on published information, is presented on a subarea basis. Sufficient time was not available to digest all available documentation, and hence some important and relevant papers have undoubtedly been overlooked. Secondly, an attempt is made to present analyses of some of the available data bases containing information that was judged sufficient to provide useful descriptions of, and some insights into, a few of the possible teleconnections that may be operative within the NAFO area.

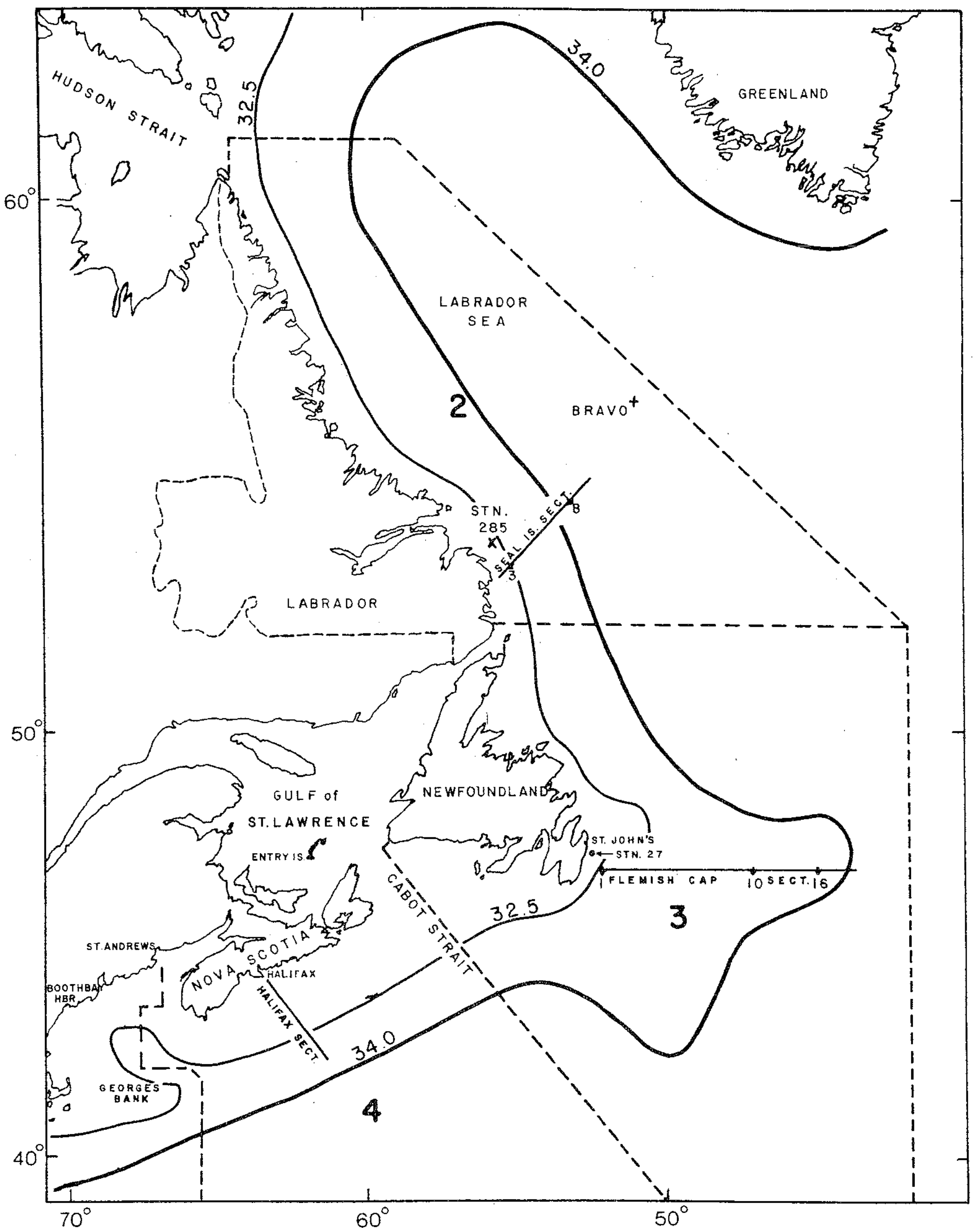

Fig. 1. Map showing boundaries of NAFO Subareas 2, 3 and 4, place names and locations of stations and sections discussed in the text. Additionally, the approximate mean locations of the 32.5 and 34.0 ‰ salinity isopleths at 30 m are shown. (From Worthington, 1976.)

General Features of the Area

In describing general features, the mean circulation is commonly considered to be of major importance in many applications. Despite this, there is a paucity of direct measurements, and, for most areas, patterns have been inferred from temperature and salinity measurements and computed geostrophic currents. In the literature, one can find a number of maps showing the mean surface currents in the Northwest Atlantic, e.g. Sverdrup *et al.* (1942), Hachey (1961), Leim and Scott (1966), Sutcliffe *et al.* (1976), and Kudlo *et al.* (1980). Most of these composite maps show similarities in the major features although often differing in some of the details. The general features of the surface currents in the NAFO area are shown in Fig. 2, compiled by R. Reiniger and C. R. Mann of the Bedford Institute of Oceanography. However, an important point to remember is that currents at any given time are seldom "average", a much more noteworthy feature

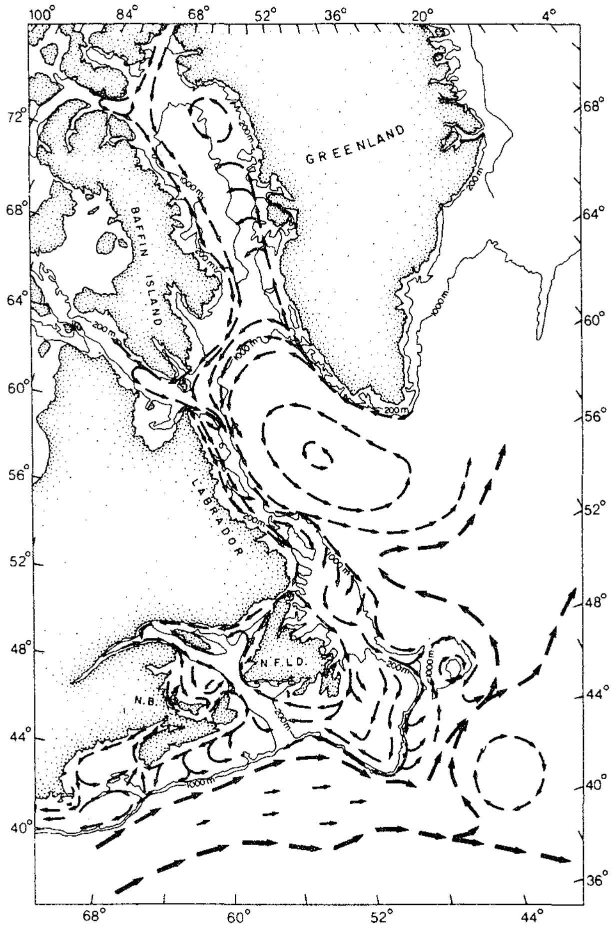

Fig. 2. Map depicting general features of the surface currents within the NAFO area. (Compiled by R. Reiniger and C. R. Mann, Bedford Institute of Oceanography, Dartmouth, Nova Scotia.)

being their variability. For example, surface currents over parts of the Scotian Shelf may be southwestward at 2-5 miles per day when averaged over a year but may be northeastward at 5-10 miles per day for a given month or southeastward at 10-15 miles per day for a given week. Current maps expressed in probabilistic terms would provide a more realistic picture of conditions.

Subareas 2, 3 and 4 all display marked surface layer dilution from fresh-water inflow. The input enters the area primarily from the Gulf of St. Lawrence, Hudson Strait and Davis Strait. Proportionally, most of the input is in the form of ice in the northern areas. Recent calculations of a world water balance (Baumgartner and Reichel, 1975) provide some useful comparative estimates for the Atlantic coast of North America. They estimated that, of the total river inflow between 30° and 90° N, 53% occurs between 45° and 55° N. Sutcliffe *et al.* (1976) noted that the annual fresh-water discharge of the St. Lawrence River system alone is greater than the sum of the fresh-water discharge along the Atlantic coast of the United States between Canada and southern Florida. The scale and pattern of the influence of fresh-water input is illustrated in Fig. 1, which shows the mean location of the 32.5 ‰ and 34 ‰ salinity isopleths at a depth of 30 m (from Worthington, 1976).

The annual cycle of heating and cooling and the fresh-water input produce a broadly similar structure and pattern of temperature and salinity at any given point in the area. The general characteristics can be illustrated with data from Station 27, located 5 miles off St. John's, Newfoundland (Fig. 1), which was usually occupied 20-30 times per year over the past 30 years. These data have been summarized by Keeley (1981a), and the average temperature and salinity patterns by depth and time are shown in Fig. 3. The annual cycle of heating and cooling is a dominant feature, with a distinct surface layer about 30-40 m in thickness developing in May. As heating continues, the mixed surface layer decreases in thickness and by August, when the maximum temperature for the year is attained, the surface layer is only about 10 m thick. Thereafter, the surface layer deepens as cooling progresses, becoming nearly isothermal by late January, with the temperature decreasing below 0° C throughout most of the water column. Maximum temperature occurs progressively later with depth, varying from August at the surface to late January at 190 m. Salinity also exhaibits an annual cycle, which is not congruent with the temperature pattern, the principal difference being the time of occurrence of the minimum. Salinity at the surface varies from a minimum in September-October to a maximum in March-April. The time of occurrence of both the minimum and maximum salinity becomes progressively later with depth, being about 5-6 months out of phase at 180 m.

Examination of oceanographic data over the continental shelf in the region of 40°-50° N latitude and 50°-70° W longitude reveals a generally similar pattern to that at Station 27, although the absolute values and times of occurrence of maxima and minima may vary appreciably (El-Sabh, 1979; Sutcliffe *et al.*, 1976). This is particularly true for the salinity minimum which arises from spring melting of ice and from river freshets. The timing of this minimum thus varies widely, depending on location of the fresh-water source.

Of interest as well is the year-to-year variability in temperature and salinity at any given site. An indication of the magnitude and character of this variability can be seen by comparing the pattern in a particular year to the long-term mean, again using temperature and salinity data for Station 27 (Fig. 4). In 1966, the maximum temperature of the surface layer was about 1° C lower than the long-term mean (Fig. 3) and

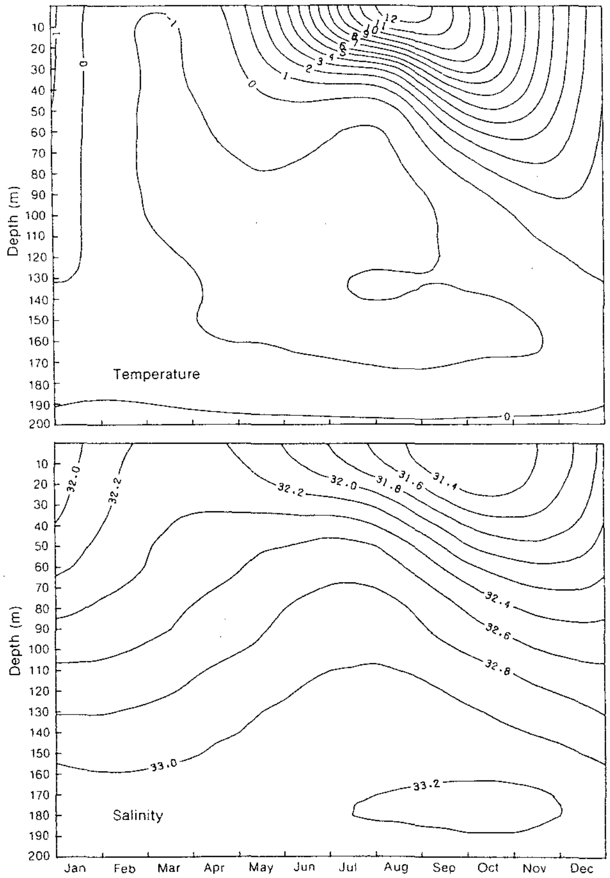

Fig. 3. Average yearly temperature and salinity by depth and time at Station 27 for the 1946-77 period. (From Keeley, 1981a.)

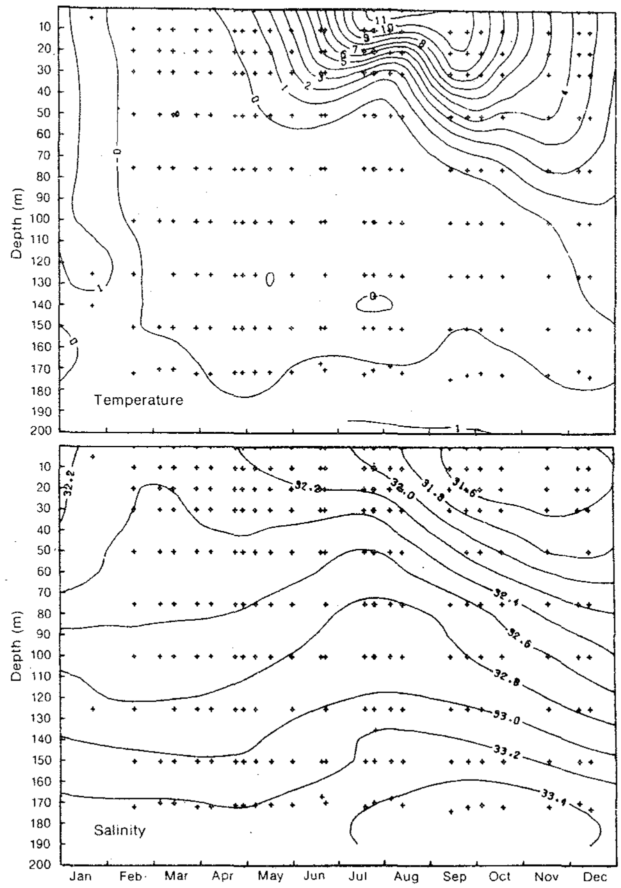

Fig. 4. Temperature and salinity distribution by depth and time for 1966. (From Keeley, 1981a.)

occurred about a month earlier. While temperatures less than -1°C are normally present at depth from February to November, they were not present at all in 1966. Salinity in 1966 was above the mean at all depths in all months except December. The timing of the surface layer minimum salinity in 1966 also occurred about a month later than the long-term mean.

Another way of viewing the year-to-year variability in tempeature and salinity is shown in Fig. 5, which is a plot of Station 27 temperature and salinity anomalies at the surface and 150 m for the years 1960-78 relative to the 1946-78 period. From visual examination, a number of points are evident: the records show considerable variability; there are periods (1-3 years duration) when temperature is consistently above or below the mean, and the same applies to salinity; for periods less than a year, there is little correlation between anomalies at the surface and 150 m for both temperature and salinity; and there is little correlation between anomalies of temperature and salinity at corresponding depths. Smoothing the data by averaging over 3 or more years to reveal longer-term trends would probably show some general similarities.

Review by Regions

Labrador Shelf and Sea

Lazier (1982) has analyzed existing data in the Marine Environmental Data Service (MEDS) files for both the Labrador Shelf and Sea. He found that the T-S (temperature-salinity) analyses for the entire shelf area between 52° and 60°N were very similar. By grouping all of the available data for the 1928-78 period, he developed a picture of the annual cycle of temperature and salinity in the upper 200 m of the water column (Fig. 6). The general pattern is similar to that at Station 27 although the timing and ranges are significantly different. The maximum mean surface temperature is less than 7°C in contrast to a value greater than 12°C at Station 27. Salinity, on the other hand, shows greater variability, ranging both lower and higher than at Sation 27. The time of minimum salinity at the surface occurs in July-August, about 2 months earlier than at Station 27.

To examine year-to-year variation for the 1950-79 period, Lazier (Bedford Institute of Oceanograhy,

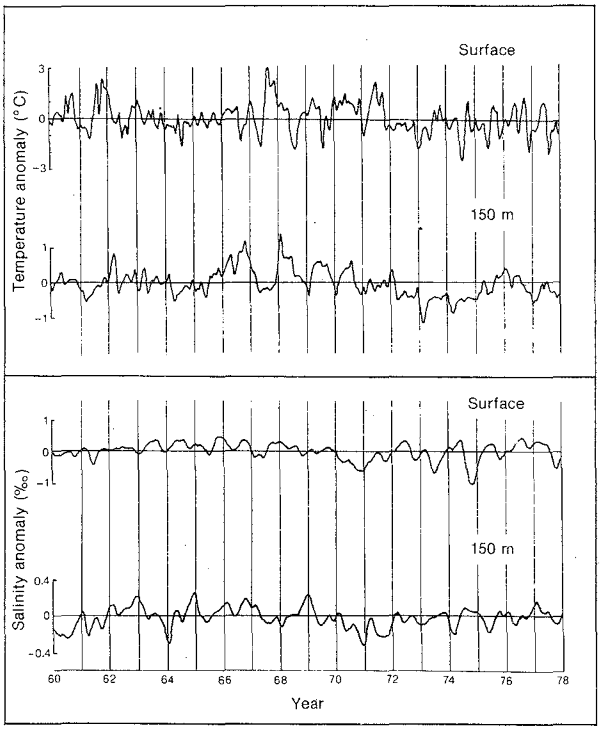

Fig. 5. Temperature and salinity anomalies at the surface and 150 m for Station 27 for the 1960–77 period, relative to the 1946–77 period (Redrawn from Keeley, 1981a.)

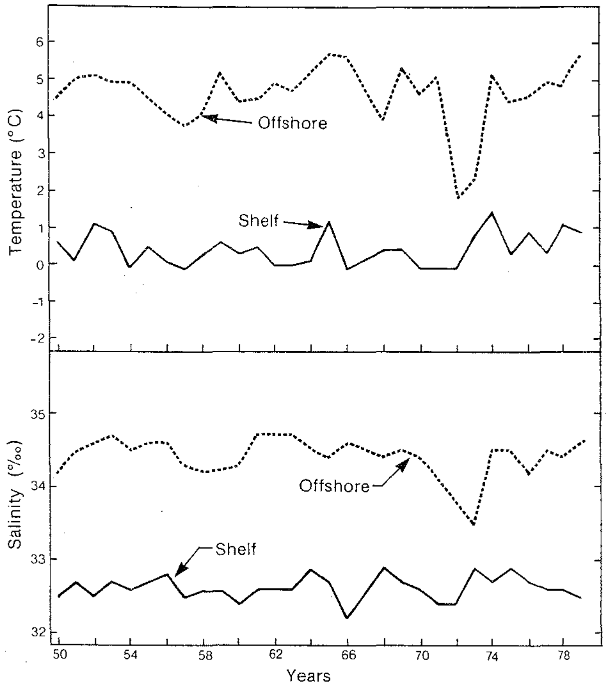

Fig. 7. July temperature and salinity for the Labrador Shelf and the offshore area for the 1950–79 period. Values have been averaged for the top 100 m of the water column. (From Lazier, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, pers. comm.)

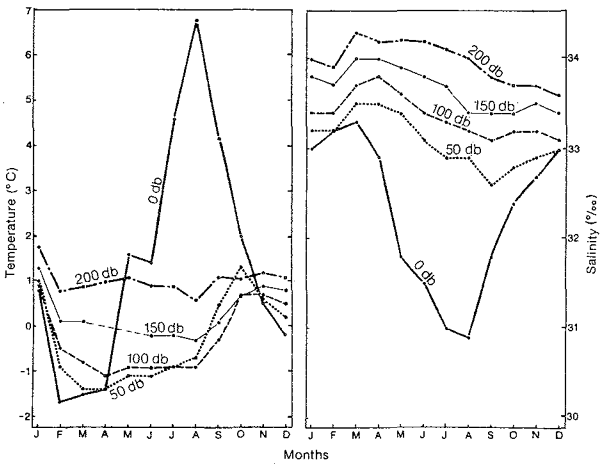

Fig. 6. The average yearly cycle of temperature and salinity at selected depths for the Labrador Shelf, using available data for the 1928–78 period from the Marine Environment Data Service. (From Lazier, 1982.)

Dartmouth, Nova Scotia, pers. comm.) analyzed the July temperature and salinity data for the Labrador shelf and offshore areas, and computed averages for the upper 100 m of the water column (Fig. 7). There is no obvious relationship in the year-to-year variation between the shelf and offshore areas, but some correspondence between temperature and salinity in the offshore region is evident. The declining trend in temperature during 1966–72 corresponds to declining salinities. These trends also show very strikingly at Ocean Weather Station *Bravo* (Fig. 1) for salinity (Lazier, 1980) in the upper 100 m for the 1967–72 period (Fig. 8). Temperatures at 200 m (Lazier, 1980, fig. 4) (and presumably shallower as well) show a declining trend in the 1967–72 period. Lazier noted that the presence of lower salinity water in the 1967–71 period coincided with relatively mild winters which tended to limit winter convective overturn to about 200 m. He concluded that one of the more probable causes of the changes observed in the Labrador Sea was related to the meteorological conditions over the North Atlantic and Arctic oceans during the 1960's. It was suggested that an anomalously high pessure cell which existed over Greenland between the early 1950's and late 1960's (Dickson *et al.*, 1975; Dickson and Lamb, 1972) increased the cold fresh-water component of the East Greenland Current which in turn increased the salinity stratification and hence the stability in the Labrador Sea.

Borovkov (1982) and Stein (1982) have discussed autumn oceanographic conditions along or near the Seal Island Section (Anon., 1978) across Hamilton Bank. Borovkov found that maximum negative anomalies in temperatures (-2.48°C) and salinity (-0.87‰) occurred in 1972 in the surface layer over and seaward of the shelf edge and slope. Maximum

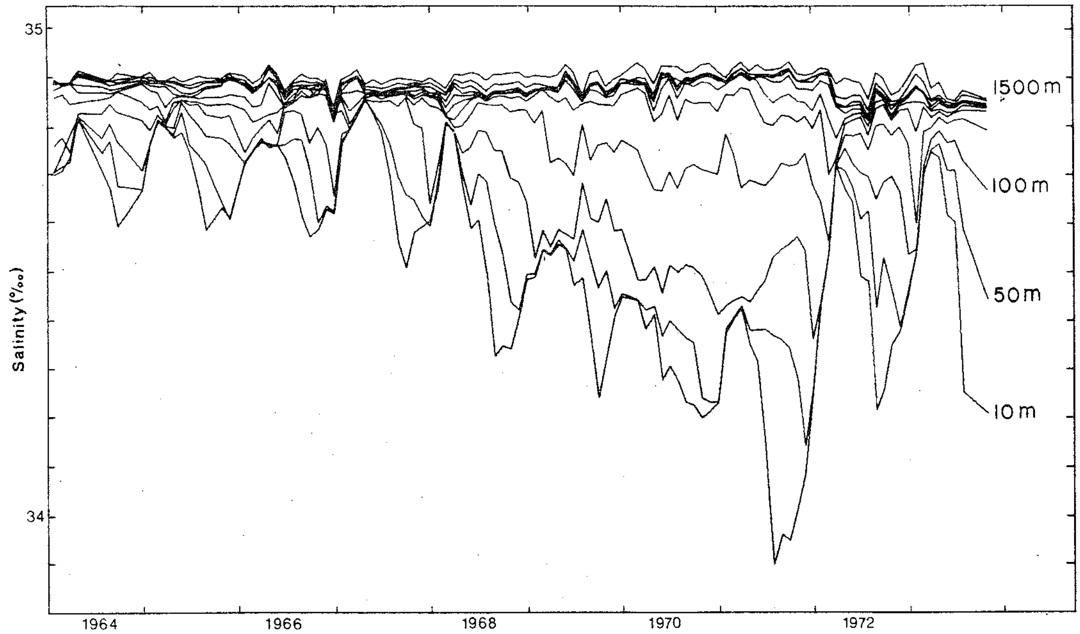

Fig. 8. Monthly averages of salinity at 11 depths at station *Bravo* from 1964 to 1973. (From Lazier, 1980.)

positive anomalies in temperature (3.08°C) and salinity (1.08 ‰) occurred in 1977 inshore near the bottom. Temperature anomalies for the upper 200 m along USSR Section 8A (near the Seal Island Section) for the 1970-79 period were tabulated by Burmakin (MS 1980). These are shown in Fig. 9 for comparison with temperature anomalies averaged over the upper 50 m for each station along the Seal Island Section (Stein, 1982). There is generally good agreement between the two sets of data, which show temperatures declining to a low for the decade in 1972-73 and a high in 1977-78. These results are consistent with those reported by Lazier (1982) for mean July temperatures, averaged over the upper 100 m, for the offshore area (Fig. 7). Interestingly, Lazier's data do not show the same results for the shelf area. It appears that the phenomenon may have been more widespread in autumn than in summer, because Stein's (1982) data show both the shelf and offshore areas behaving in broadly similar ways. Temperature and salinity anomalies for 1970-79 relative to the long term for Station 3 and 8 on the Seal Island Section are shown in Fig. 10 and 11 respectively. These diagrams show the anomalously low temperatures and salinities in the offshore area (Station 8) in the 1971-73 period, as discussed previously (Borovkov, 1982; Stein, 1982). The inshore area, represented by Station 3, shows below normal temperatures for 1972 only, with salinities near normal. In general, the inshore and offshore anomaly patterns do not bear much similarity to each other. This may in part be real, but the rather scanty data (only about one sample per year) places severe limitation on the degree of reliability in the patterns.

In recent years, as part of investigations by the Bedford Institute of Oceanography in the Labrador

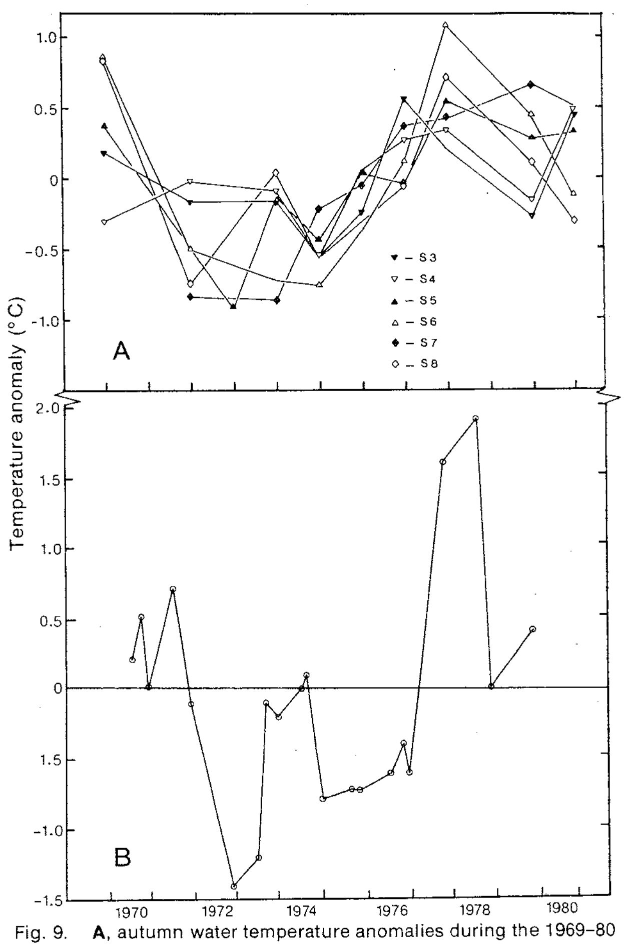

Fig. 9. **A**, autumn water temperature anomalies during the 1969-80 period for upper 50 m of the water column at six stations on Seal Island Section (from Stein, 1982). **B**, water temperature anomalies for the 0-200 m layer of USSR Section 8A (near Seal island Section) for the 1970-79 period. (Data from Burmakin, MS 1980.)

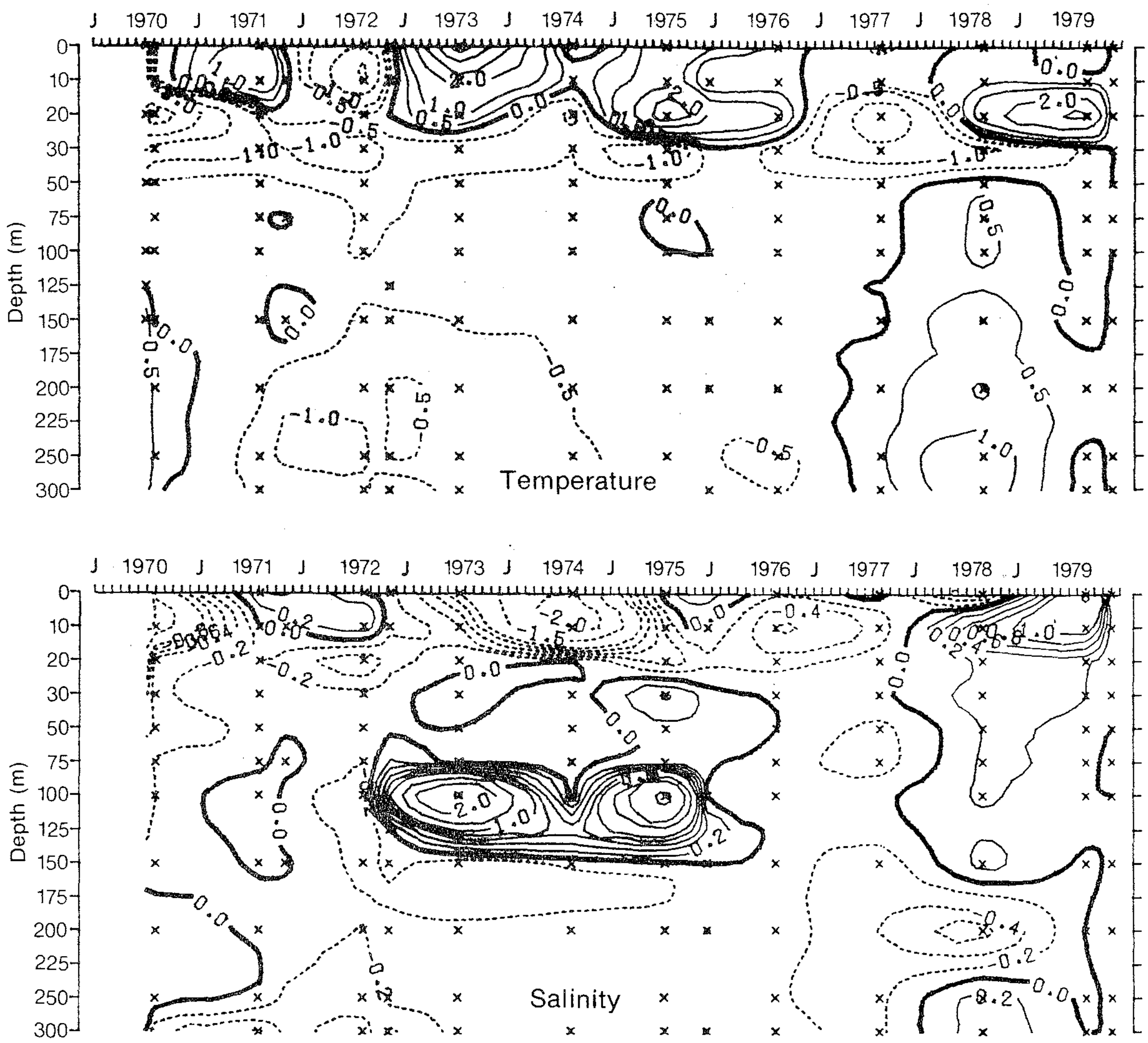

Fig. 10. Potential temperasture (upper) and salinity (lower) anomalies at Station 3 of the Seal Island Section for the 1970–79 period. (Dashed lines are negative anomalies.)

Shelf and Sea areas, current meters were moored at a number of lcoations (Lazier, 1979, 1982). One of the longest records available is from Station 285 (Fig. 1) at 200 m in the trough separating Hamilton Bank from the inshore area. Except for a short gap in August 1979, a continuous 2-year record, commencing in October 1978, of current, salinity and temperature was obtained (Fig. 12). In general, the patterns were similar for both years. Maximum temperature occurred in late December and early January, followed by near-minimum values in mid-February. The period of declining temperature was accompanied by a major drop in salinity and an increase in current velocity. Lazier (1982) noted that the rise in temperature in December cannot be produced by local convective cooling but must be due to advection of water, probably from the north. Although the general patterns are repeated each year, the full annual variation in properties typically occurs in about 1 rather than 6 months. Examination of shorter time series along the slope (Lazier, 1979), where horizontal gradients are higher, show even higher frequency fluctuations, greater than 5°C temperature and 1 °/oo salinity changes occurring in periods less than 1 day at 100 m depth. Caution must therefore be exercised when attempting to infer warm or cold years based on infrequent sampling. Borovkov (1982) also pointed out the aliasing problem, particularly in the slope area where horizontal gradients are large. During a 24-hr period in October 1980, the variability roughly equalled the year-to-year variability.

Grand Bank and Flemish Cap

Although there is a paucity of data for the Grand Bank as a whole, the frequent occupation of Station 27 and the Flemish Cap Section (Fig. 1) provides relatively

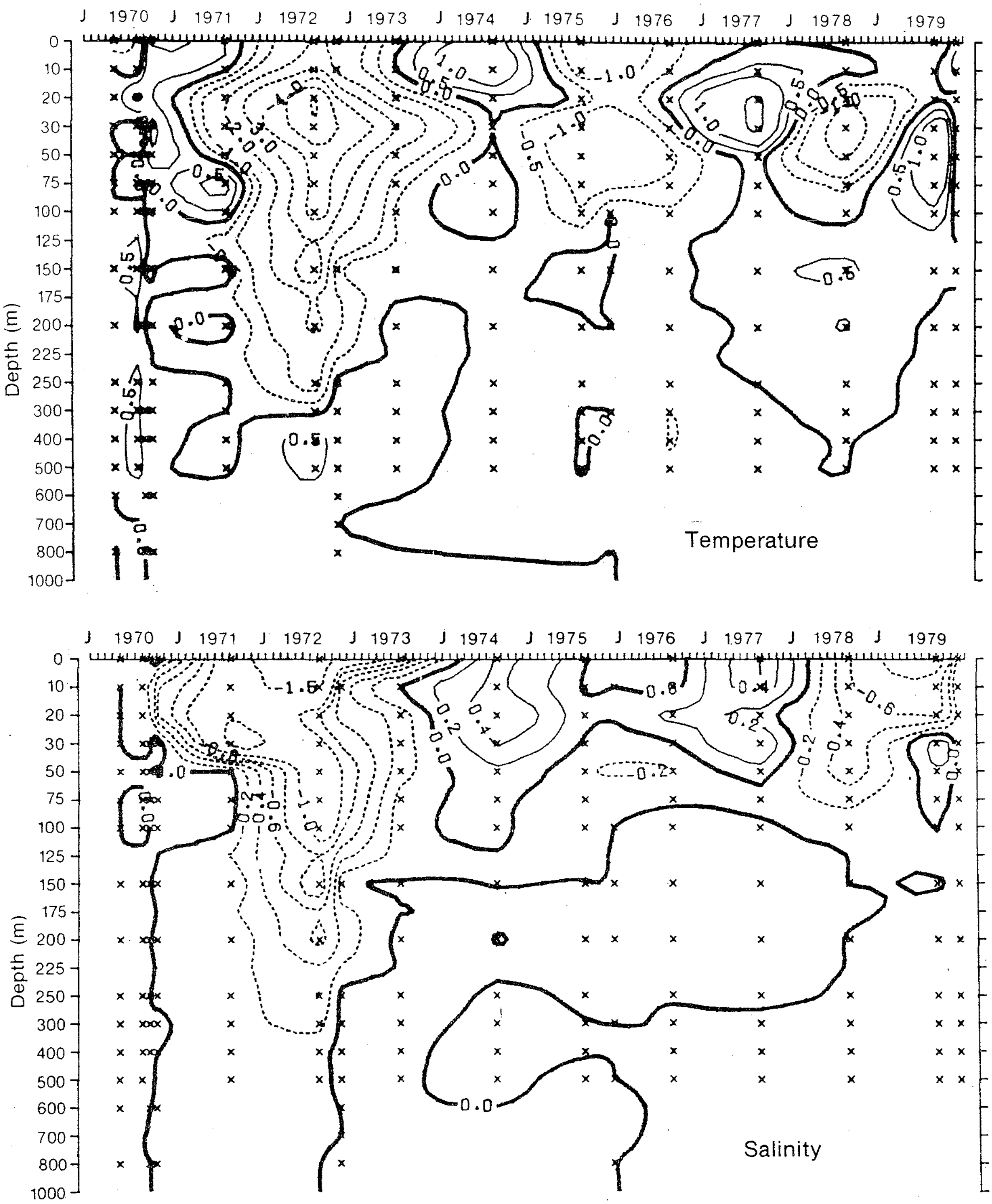

Fig. 11. Potential temperature (upper) and salinity (lower) anomalies at Station 8 of the Seal Island Section for the 1970–79 period. (Dashed lines are negative anomalies.)

good coverage of temperature and salinity for at least the northern part of the bank. Much less data are available for the southern and southwestern parts of the bank, which may at times show markedly different features, because offshore forcing from warm-core eddies may produce onshore and offshore excursions.

Keeley (1981b, 1982) has analyzed available data in the MEDS data files for the Flemish Cap Section, there being a total of 43 years in which stations along the section were sampled. The earliest was in 1910 and the record is continuous from 1948 to 1980, although data are sparse in winter and from stations east of

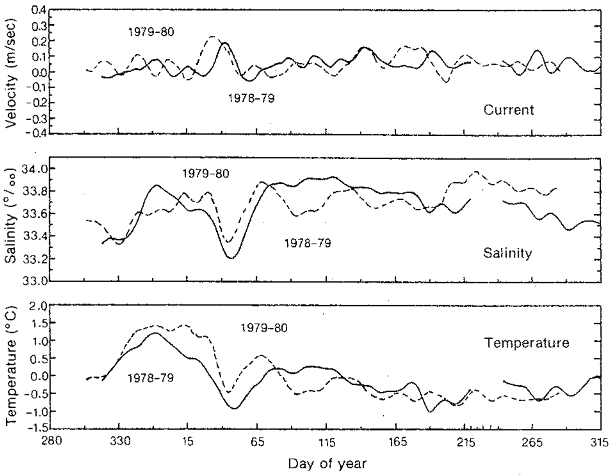

Fig. 12. Current, salinity and temperature variation at 200 m for Station 285 on the Labrador Shelf from October 1978 to October 1980. Current is the component parallel to local bathymetry, 150°T (from Lazier, 1982).

Flemish Cap. Keeley plotted mean monthly cross-sections of potential temperature, salinity and density anomalies and presented a volumetric analysis of θ–S (potential temperature-salinity) characteristics. Plots of potential temperature and salinity anomalies for the 1970–79 period relative to the long-term means at Stations 1, 10 and 16 along the section are shown in Fig. 13, 14 and 15 respectively. Station 1 is taken to be indicative of conditions in the Avalon Channel, Station 10 for the western side of Flemish Cap Pass and Staiton 16 for the Flemish Cap.

Looking first at Station 1 data (Fig. 13), the most striking feature is the negative temperature anomalies in the upper 50 m during 1974–77. However, since observations during this period were made only in summer, it should not be concluded that this was true for all months of the year. Similarly, there is the suggestion that summer temperatures in 1970–73 were

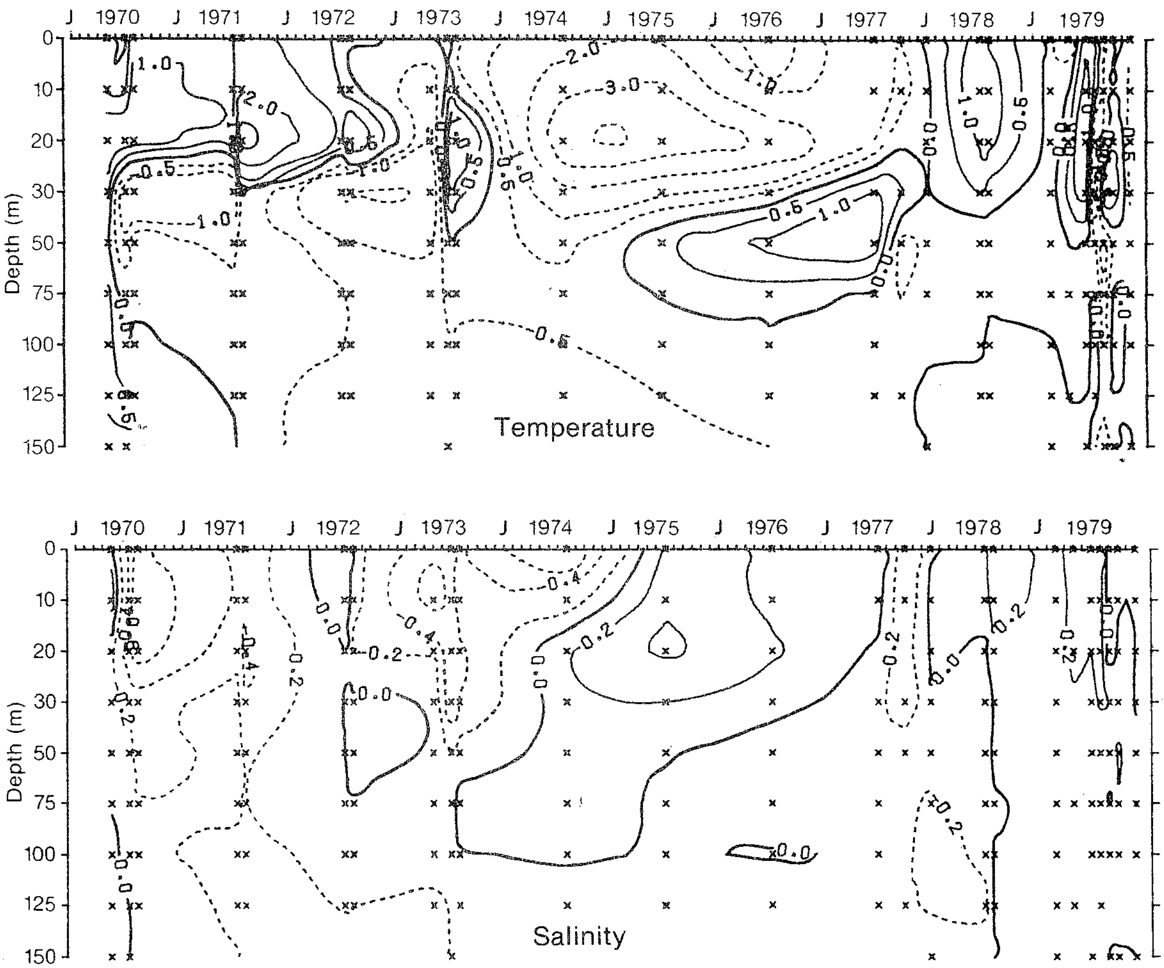

Fig. 13. Potential temperature (upper) and salinity (lower) anomalies at Station 1 of the Flemish Cap Section for the 1970–79 period. (Dashed lines are negative anomalies.)

generally above normal in the upper 20 m. In 1979, this station was occupied 6 times during the year, and a much ore complex pattern is displayed. Therefore, the reliability of the pattern shown for the 1970–77 period must be questioned, and one should not conclude that the picture gives more than year-to-year summer anomalies.

Figure 14 shows temperature and salinity anomalies at Station 10, which is located near the core of the Labrador Current. This station was occupied more frequently than Station 1, and this undoubtedly played a significant role in producing a more complex pattern. In the surface layer, temperatures were below normal for about 5 periods in the decade and above normal for

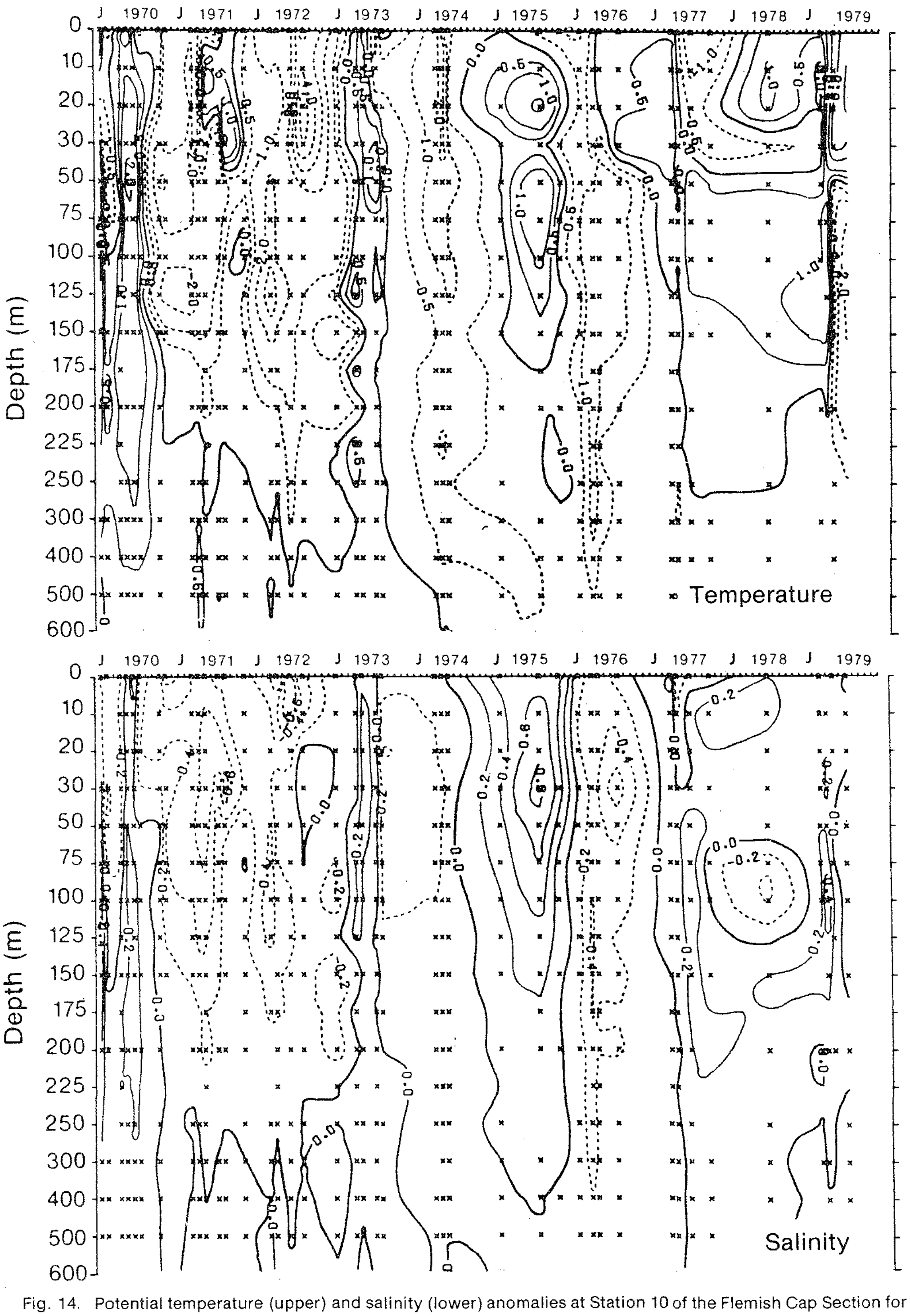

Fig. 14. Potential temperature (upper) and salinity (lower) anomalies at Station 10 of the Flemish Cap Section for the 1970–79 period. (Dashed lines are negative anomalies.)

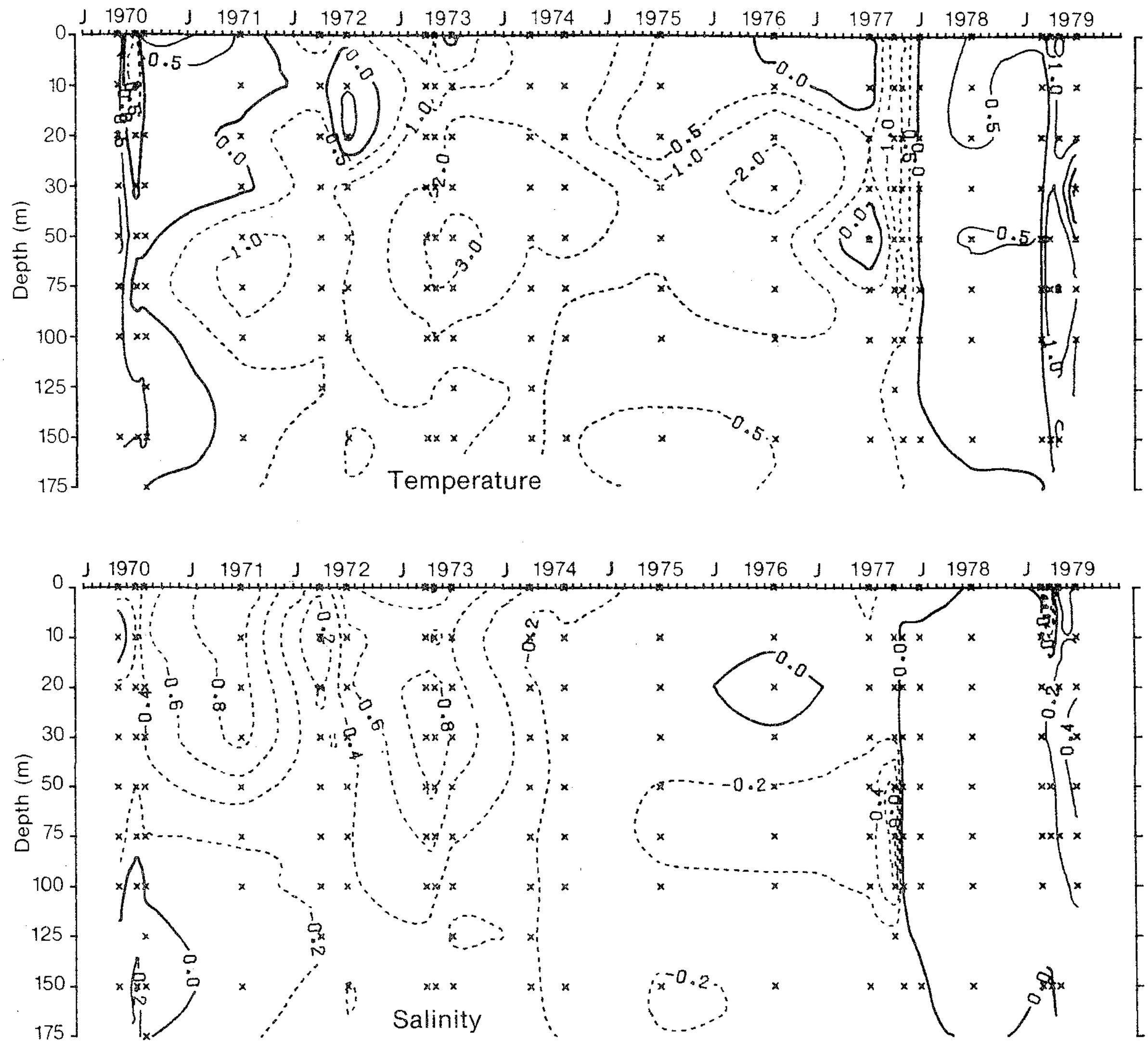

Fig. 15. Potential temperature (upper) and salinity (lower) anomalies at Station 16 of the Flemish Cap Section for the 1970–79 period. (Dashed lines are negative anomalies.)

5 periods. The character of the signal takes on more of that displayed at Station 27 (Fig. 5).

The pattern displayed at Station 16 (Fig. 15) on Flemish Cap is also oversimplified because the data for 1970–76 were mainly obtained during the warmer months. It does, however, indicate that summer temperatures were generally below normal, with near or slightly below-normal salinities.

Examination of data for various stations along the Flemish Cap Section reveals the extent of spatial *versus* temporal variability. For example, the positive anomalies in the upper 50 m at Station 10 in 1975 (Fig. 14) correspond to negative anomalies at Stations 1 and 16 (Fig. 13 and 15). Since Station 10 is located in an area of relatively strong currents and gradients, a small lateral shift in the position of the Labrador Current may have produced this anomaly.

Gulf of St. Lawrence

The general features of the Gulf of St. Lawrence have been presented by several researchers (e.g. Hachey, 1961; Trites, 1972; Trites and Walton, 1975; Dickie and Trites, 1982). It is convenient to consider the Gulf as a large complex estuary with physical oceanographic features determined by a spectrum of parameters, such as fresh-water discharge, winds, tides, topogaphy, and air-sea heat exchange. Primary connection with the open ocean is through Cabot Strait which has, on the average, an annual seaward transport on the Cape Breton side of about 0.5 Sverdrups (1 Sverdrup = 10^6 m^3/sec), ranging from a low in June of 0.2 Sverdrups to a maximum in August of more than 0.7 Sverdrups (El-Sabh, 1977). Seaward transport through Cabot Strait is about 30 times the fresh-water discharge into the Gulf.

The role that fresh-water plays in determining the oceanographic features both in the Gulf of St. Lawrence and beyond is yet to be fully clarified. As fresh-water enters an estuary, it drives an estuarine circulation, with outflow of fresh-water in the surface layer and inflow of salt-water in a deeper layer. In a large complex estuary like the Gulf of St. Lawrence, the circulation and distribution of properties depends not only on the fresh-water discharge and the influx of salt-water through Cabot Strait and Strait of Belle Isle but also on tidal mixing, bathymetry, and air-sea interactions and exchanges. Neu (1975, 1976) drew attention to the changes in seasonal discharge of fresh-water into the Gulf as a result of major hydro-electric and river-regulation projects and pointed out the need for understanding how and to what degree the marine environment is being altered through man-made changes.

The year-to-year monthly variation in fresh-water discharge into the Gulf from three major rivers (St. Lawrence, Ottawa and Saguenay combined) is shown in Fig. 16. Long-term changes in discharge are evident for all months with a downward trend in the early 1950's to the early 1960's and an upward trend in the subsequent 10-year period, but the most striking changes occurred in the spring months (May–June) during 1964–74. The discharge in May 1974 was 70% higher than in May 1964.

Sutcliffe *et al.* (1976) extended earlier correlative work and found a high correlation between fresh-water discharge of the St. Lawrence River and appropriately time-lagged sea-surface temperatures at several coastal sites in the Gulf of St. Lawrence, Nova Scotia and Gulf of Maine areas. They point out that the role played by the St. Lawrence River discharge must be viewed cautiously. It cannot be considered as uniquely determining the fluctuations or indeed of being a major contributor. However, correlation analysis does suggest that fresh-water inflow is in part influential in determining these sea-surface temperature changes. Trends in sea-surface temperature for the Gulf of St. Lawrence, as measured at Entry Island, are reviewed in a subsequent section along with data from other coastal monitoring stations (see Fig. 22).

Scotian Shelf and Slope

Canadian oceanographic effort in this region during the 1950's and early 1960's was focussed in large measure on monitoring and obtaining synoptic kinds of measurements. The development and availability of self-recording current, temperature and conductivity sensors, together with improved mooring technology, resulted in a major shift in program emphasis, with increased attention being given to process-oriented studies.

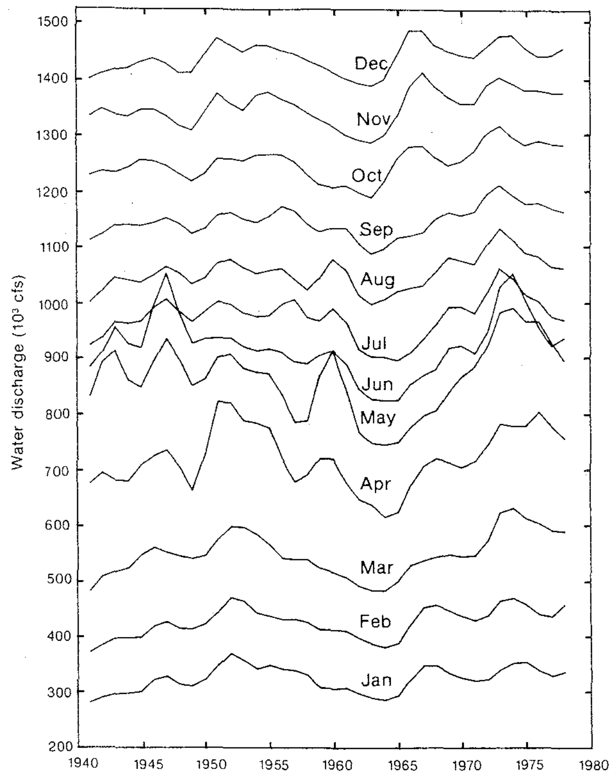

Fig. 16. Monthly average discharge of the St. Lawrence River system for the 1941–78 period. (Each month is successively offset 10^5 cfs for visual convenience; 3-year normally weighted smoothing has been applied.)

Sigaev (1978), using temperature and salinity data from USSR investigations during 1963–73, computed geostrophic current patterns over the Scotian Shelf on a seasonal basis. Although he found considerable within-year variation in the patterns, particularly in regions of cyclonic and anticyclonic gyres which covered most of the shelf, a southwestward flow near the coast was indicated for all seasons. Likewise, a southwestward flow was generally evident along the edge of the shelf.

Examination of data from the Halifax Section (Mann and Needler, 1967; Drinkwater *et al.*, 1979) identifies some of the limitations of the data set in terms of determining year-to-year variability. Drinkwater *et al.* (1979) computed mean monthly transports through the section and found variations from 0.15 Sverdrups in summer to a maximum of 0.6 Sverdrups in winter. Flow over the inshore one-third of the shelf accounted for 75% of the calculated net annual transport. B. Petrie (Bedford Institute of Oceanography, Dartmouth, Nova Scotia, pers. comm.) pointed out that up to 80% of the year-to-year variation in transport can occur within a 1-week period. Similarly, up to 90% of the year-to-year variation in mean temperature can occur within about a week. At a sampling rate of 4–6 times per year, the data are badly aliased because of high-frequency variability. Therefore, taken by itself, quarterly sampling of the Halifax Section shows little promise of reliably identifying warm *versus* cold or fresh *versus* salty years.

Major programs of mooring instruments on the slope of the Scotian Shelf and in the Northeast Channel are helping to identify some of the more important processes (Petrie, 1975; Petrie and Smith, 1977; Smith, 1978, 1979; Smith *et al.*, 1978; Ramp and Vermersch, MS 1978; Ramp and Wright, MS 1979) and to shed additional light on the role played by internal tides, shelf waves, Gulf Stream warm-core eddies, Slope Water, meteorological forcing, etc., in determining the oceanographic features of the continental shelf and slope.

The importance of cross-shelf mixing in determining the water-mass characteristics and biological productivity of the Scotian Shelf was demonstrated by Houghton *et al.* (1978). They found, through water-mass analysis, that the water at the northeastern end of the shelf was diluted with Slope Water by 40%, as a result of cross-shelf mixing, by the time the water reached the Halifax Section. The observed along-shelf gradients of temperature, salinity, and nitrate concentrations were consistent with the productivity requirements and the measured low-frequency eddy fluxes at the edge of the Scotian Shelf (Smith, 1978).

At any given time, the Slope Water area commonly contains a number of anticyclonic warm-core eddies embedded in it. These have been shed by the Gulf Stream between 50° and 70° W longitude. While many of these eddies are reabsorbed by the Gulf Stream within a week or two, others may exist for periods up to a year, moving westward to Cape Hatteras before disappearing. An indication of the eddy field and general complexity of the Gulf Stream-Slope Water area is shown in Fig. 17. This map, prepared by the U. S. National Environmental Satellite Service, is based on satellite infrared data and sea-surface temperature observations from ships of opportunity. At least four warm-core eddies are evident in the diagram. The westernmost eddy (F-80) was formed in early August 1980 at about 62° W and was finally reabsorbed by the Gulf Stream east of Cape Hatteras during late July 1981 (Fitzgerlad and Chamberlin, MS 1982), having a life span of almost exactly 1 year.

The role played by warm-core eddies in extracting surface water from the continental shelf is clearly indicated in Fig. 18. Eddy G-79 developed in mid-September 1979 and Eddy H-79 a week or so later. These eddies entrained large quantities of water from the southwestern Scotian Shelf (Fig. 18B). Surface currents, determined by satellite-tracked drifting buoys, confirm the accuracy of interpretation of the surface thermal maps (Trites, 1981). Similarly, Eddy

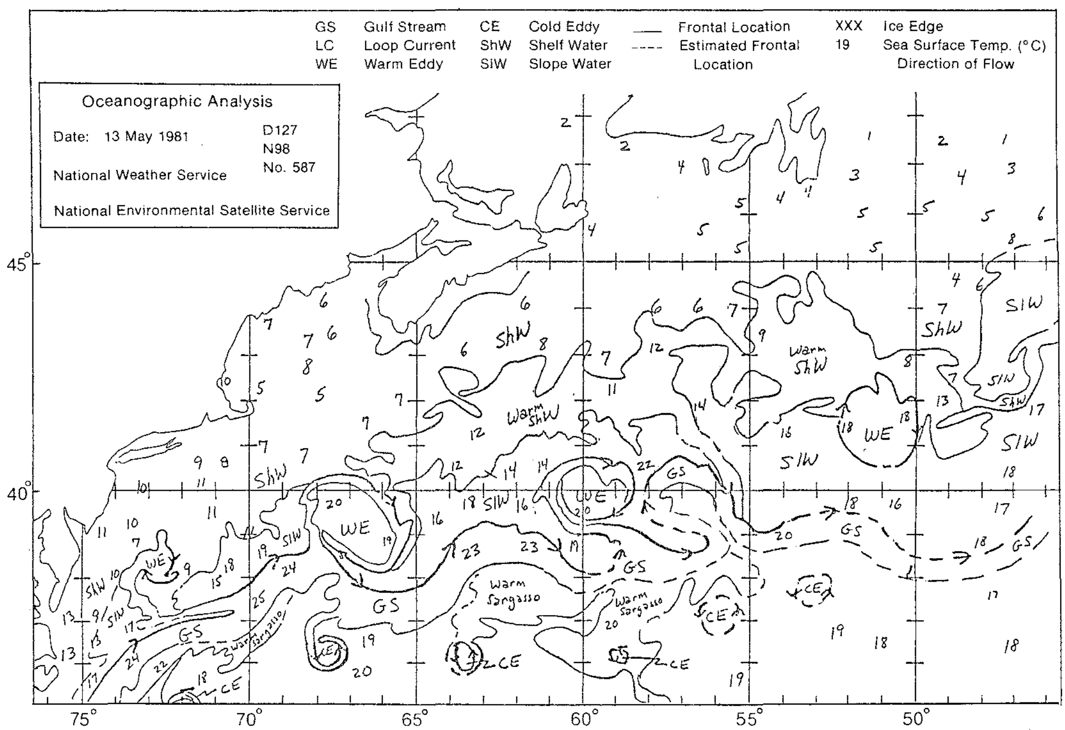

Fig. 17. Map showing sea-surface temperatures and frontal features for 13 May 1981, based on satellite infrared imagery and sea-surface temperatures provided by ships of opportunity. (Prepared by the National Environmental Satellite Service of the U. S. National Weather Service.)

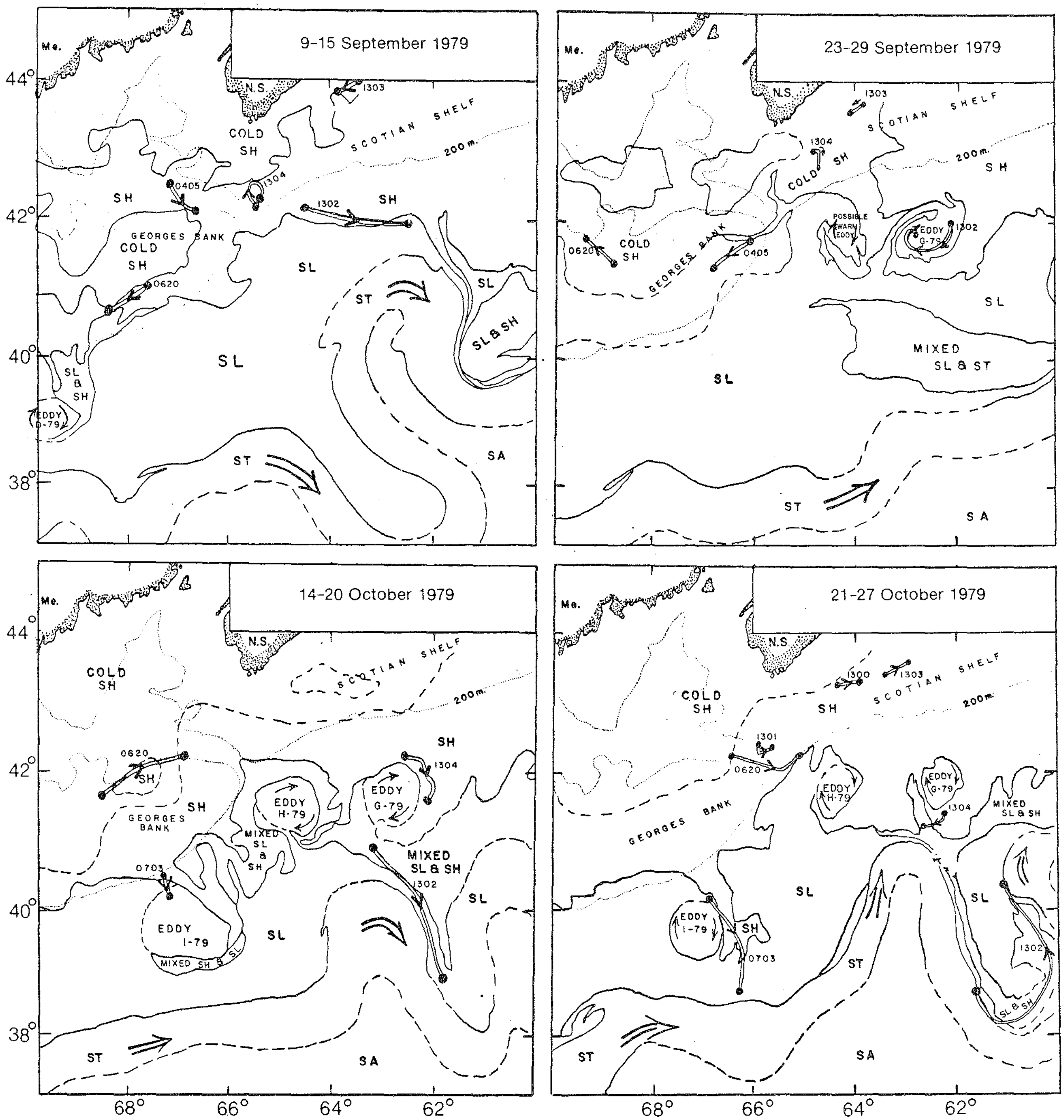

Fig. 18. Maps, extracted from the U. S. Naval Oceanographic Experimental Ocean Frontal Analyis Charts, showing surface thermal features for 4 weekly periods during September and October 1979. (Key for water types: SA = Sargasso, ST = Gulf Stream, SL = Slope Water, SH = Shelf Water, and COLDSH = Cold Shelf Water. Approximate trajectories of several satellite tracked buoys for each 7-day period are also shown.)

I-79 produced a large-scale excursion from Georges Bank in late October 1979 (Fig. 18D). Other examples of offshore forcing and removal of shelf water have been reported by Smith (1979). Current meters, moored near the edge of the shelf off southwestern Nova Scotia in 1977, clearly showed the impact of Eddy Q which formed and moved through the slope-water area in the July-September period. Associated with this movement was an influx of Slope Water through the Northeast Channel and onto Browns Bank.

Such large and rapid off-shelf excursions of surface water will undoubtedly transport the bulk of any plankton and ichthyoplankton organisms contained in it. Synoptic measurements have yet to be taken to determine the proportions of fish eggs and larvae that may be lost from an area through this process. Clearly, however, it is potentially of major importance in the southwestern Scotian Shelf and Georges Bank areas in any studies of factors responsible for good and poor year-classes in the commercial fisheries.

Bay of Fundy-Gulf of Maine

The strong tidal currents in the eastern Gulf of Maine, Georges Bank and Bay of Fundy areas distinguish this region from all others in the Northwest Atlantic. Not only do the tidal currents create intense mixing which virtually prevents vertical stratification in some areas (Garrett *et al.*, 1978), but they may be responsible for major upwelling in the area west and southwest of Nova Scotia (Garrett and Loucks, 1976). Interaction of strong tidal currents with the bathymetry of the region may also result in generation of significant mean circulation around areas such as Georges Bank and Browns Bank (Loder, 1980). In terms of the impact on ocean climate, variation in oceanographic properties might be expected over long time-periods, due to variation in strength of tidal currents and hence in vertical mixing. For example, Loder and Garrett (1978) inidicated that the semi-diurnal and diurnal tidal forces are modulated by a few percent over the 18.6-year tidal cycle and should accordingly produce in some areas a significant cycle in sea-surface temperature.

The intense vertical and lateral mixing in the area should produce large areas of nearly homogeneous water, and it might be expected that monitoring of climatic conditions could be achieved with widely-spaced sampling sites. The longest series of oceanographic data for the Canadian Atlantic coast are sea-surface temperatures at St. Andrews, New Brunswick, where readings have been taken twice daily since 1921. In addition to the mean monthly temperatures (Fig. 19), the extremes and the years in which they occurred are shown. It is interesting to note that 18 of the 24 extremes occurred in 3 years (1923, 1951 and 1976). For the period from November 1922 to September 1923, 9 of the 11 months were record cold ones. Conversely, the period from December 1950 to March 1951 experienced record high temperatures as did also the May-September 1976 period, although the months of July-September 1951 were nearly as warm.

The long-term trends in annual mean temperature during 1921-80, derived from averaging the monthly mean values, are shown in Fig. 20. Relative to the average for the entire period (7.0°C), temperatures from the early 1920's to the mid 1940's were generally below normal whereas those from 1945 to about 1960 were above normal. Subsequently, the trend is less clear

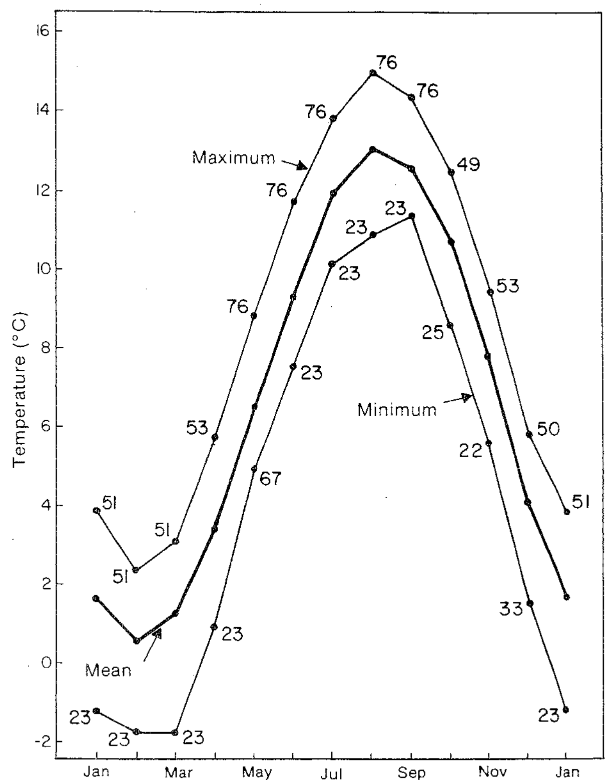

Fig. 19. Mean monthly sea-surface temperatures, St. Andrews, New Brunswick, 1921-80, including monthly maxima and minima and the year of occurrence (23 = 1923, etc.).

although the mean for the 1960-69 decade is clearly below average and that for the 1970-79 decade above average. The records indicate rather large year-to-year variation in temperature (up to 1.8°C) which is a sizeable portion of the maximum change (3.1°C) between the coldest (1923) and the warmest year (1951).

Rodewald (1972), in his study of temperature conditions in the Northwest Atlantic during the 1960-69 decade, examined sea-surface temperature records for Boothbay Harbor, Maine, just beyond the western extremity of Subarea 4. His illustration has been updated by adding the mean monthly trend for the 1970's (Fig. 21). Relative to the long-term average for the 1906-45 period, mean temperature in all three decades (1950-59, 1960-69 and 1970-79) were above normal, the positive anomalies being 1.83°, 0.40° and 0.96° respectively. During these decades, the deviation from normal had a pronounced seasonal variation ranging from a maximum positive anomaly in winter to a maximum negative anomaly in summer. Overall, the 1970's could be described as being intermediate between the 1950's and 1960's, although the anomalies for the first half of the year were closer to those for the 1960's. In summary, surface temperatures at Boothbay Harbor during the past 30 years were higher in winter and lower in summer than those in the 1906-45 period,

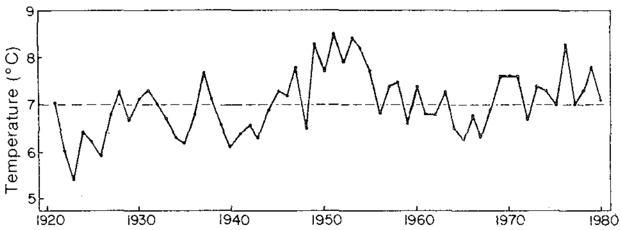

Fig. 20. Mean annual sea-surface temperatures, St. Andrews, New Brunswick, for the 1921–80 period.

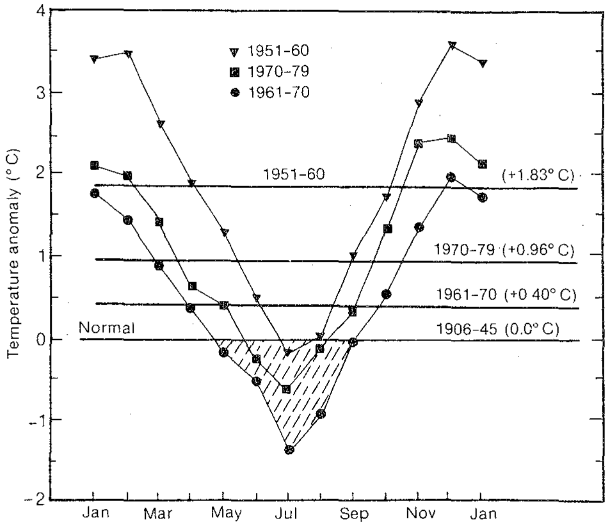

Fig. 21. Deviation of 1951-60, 1961-70, and 1970-79 decadal monthly and annual means of sea-surface temperature from normal for Boothbay Harbor, Maine, USA. (Data for 1951-60 and 1961-70 from Rodewald 1972.)

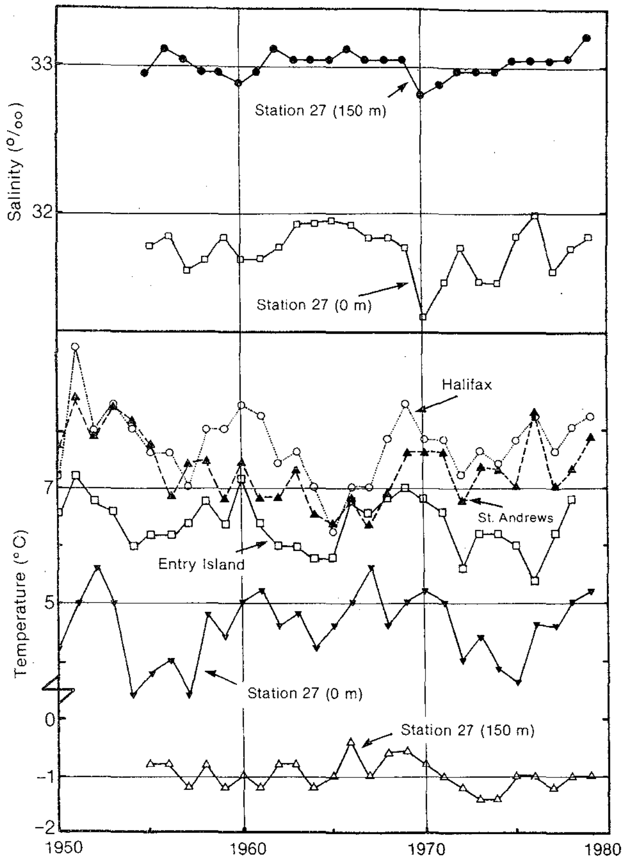

Fig. 22. Mean annual sea-surface temperatures at St. Andrews, Halifax, and Entry island for the 1950–79 period, and mean temperatures and salinities at 0 and 150 m at Station 27 for the 1955–79 period.

suggesting that the climate was more under maritime influences in the recent period than in the first half of the century.

To gain an impression of the geographic scale of these long-term temperature changes, it is useful to look at air temperatures because the records are available for a longer time and for more sites than are water temperatures. Sutcliffe *et al.* (1976) showed that there was a good correlation between 3-year running means of average annual air temperature for Ottawa, Fredericton, Eastport and Sable Island. Similarly, Lauzier (1972) showed that there was good correlation between sea temperatures at St. Andrews and air temperatures at Sable Island, when running means over several years are used.

To examine further the geographic scale of these year-to-year changes, average annual sea-surface temperatures are shown in Fig. 22 for St. Andrews, Halifax, and Station 27 (surface and 150 m). Salinities at the surface and 150 m for Station 27 are also shown. The long-term temperature trends for St. Andrews and Halifax are very similar and the trend for Entry Island is generally similar to the two. However, temperature and salinity variations at Station 27 appear to bear little relationship to the trends for the other sites. On the other hand, Rodewald (1972), in his study of decadal changes, found coherent changes over the entire region, but he used mainly offshore data.

Akenhead *et al.* (1981), in their examination of ocean climate variability, pointed out that, although sea-surface temperatures recorded at Halifax and Sambro Lightship (located just outside the entrance to Halifax Harbor) show long-term features similar to the St. Andrews data, there are differences in detail. For example, 1953 was a very warm year at St. Andrews and Sambro but only just above the mean at Halifax, and 1939 was a cool year at Halifax and St. Andrews but a warm one at Sambro. Thus, for periods of a year or less, coastal stations may be representative of a very small geographic area, as Halifax and Sambro are less than 35 km apart.

Akenhead *et al.* (1981) further explored spatial scales of temperature variability by computing the correlation function between 1° × 1° rectangles of monthly mean values on the Scotian Shelf from 4 years of data published in *Gulfstream*. They found that the correlation was low between neighboring 1° rectangles, suggesitng that each fishing bank has its own local climate. They concluded that there appears to be a large-scale, slowly-varying climate signal with local, higher-frequency variations superimposed. The variance in both signals seemed comparable.

Analysis of Some Available Data Bases

Data and methods of analysis

In view of the apparent serious limitations in the extent to which coastal monitoring stations can be used to infer within-year conditions on spatial scales of more than a few kilometers, it was considered that a better view of year-to-year ocean climate within the NAFO area might be developed by analyses of sea-surface temperature (SST) data held at the World Climate Center, Asheville, North Carolina. This data base, consisting of data reported by ships of opportunity as part of a World Meteorological Organization program, covers the World's oceans and contains observations dating from the 1850's. By incorporating other data sets, such as discharge from the St. Lawrence River system, sea level observations, air temperatures, anemometer records, and other atmospheric and oceanographic parameters at specific sites, and using correlation techniques, it was thought that some new insights into possible mechanisms producing environmental variability might be revealed. Accordingly, data tapes were obtained for Marsden Squares 150 and 151 (area contained within 40°-50°N and 50°-70°W). To augment the SST file, data from the bathythermograph files of MEDS were incorporated. Other data in the form of monthly averages were also utilized (Table 1).

The SST data base was arranged into 12 files by month of observation and contained a total of 1.18 million records, ranging from a minimum of 73,000 for February to a maximum of 116,000 for May. Data in each monthly file were sorted by year and by 1° × 1° rectangles. Averages and sums of squared deviations from the averages were computed for each year and rectangle, as well as the means over all years and the within-year and between-year variances for each rectangle. Monthly anomalies for the 1970-79 decade relative to the 1960-69 decade and to the long-term were computed and tabulated. Since oceanographic data records are typically variable, the data were also grouped into larger segments (Grand Bank, Gulf of Maine, Bay of Fundy, etc.), and monthly averages were computed for each year of the 1970-79 period as well as average annual temperatures for the 1950-79 period. Correlations between variables were computed and correlation matrices tabulated similar to those described by Sutcliffe *et al.* (1976).

Some results of these analyses are presented in the following sections. Although attempts were made to screen out bad data in the SST tapes, some errors are still present. These probably do not have a significant effect on the averages and anomalies when a large number of data points are available (e.g. mean temperature for a year), but the number of data points available for a particular area and month is often undesirably small.

Sea-surface temperature anomalies by 1° grid

Monthly SST anomalies relative to the long-term and to the 1960-69 decade were computed for each 1° rectangle. Two examples of such calculations are illustrated in Fig. 23 and 24, which show the SST anomalies for January and February of the 1970-79 decade rela-

TABLE 1. Data bases used in analyses of ocean climate changes.

Parameter	Location	Data Source
SST - vessel reports	40°-50°N, 50°-70°W	World Climate Center
- bathythermograph records	" "	Marine Environmental Data Service
- coastal stations	Halifax, St. Andrews	Bedford Institute of Oceanography
	Entry Island	Marine Environmental Data Service
Sea temperatures	Station 27, Prince 5	Bedford Institute of Oceanography
Salinity	Station 27, Prince 5	Bedford Institute of Oceanography
Sea level	Halifax, Yarmouth	Bedford Institute of Oceanography
	St. John's	Environment Canada, Water Levels
River discharge	St. Lawrence River	Bedford Institute of Oceanography
Atmospheric pressure	Halifax	Bedford Institute of Oceanography
	North Atlantic	Dalhousie University
Air temperature	Ottawa, Eastport	Bedford Institute of Oceanography
Wind speed and direction	Sable Island	Atmospheric Environment Service

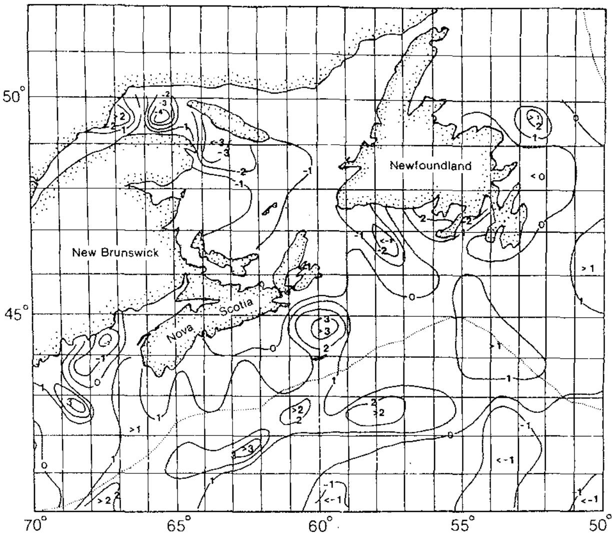

Fig. 23. Sea-surface temperature anomalies for January in the 1970–79 period relative to January in the 1960–69 period. (Data from World Climate Center, Asheville, North Carolina, and Marine Environmental Data Service, Ottawa, Ontario, analysed by 1° quadrangles.)

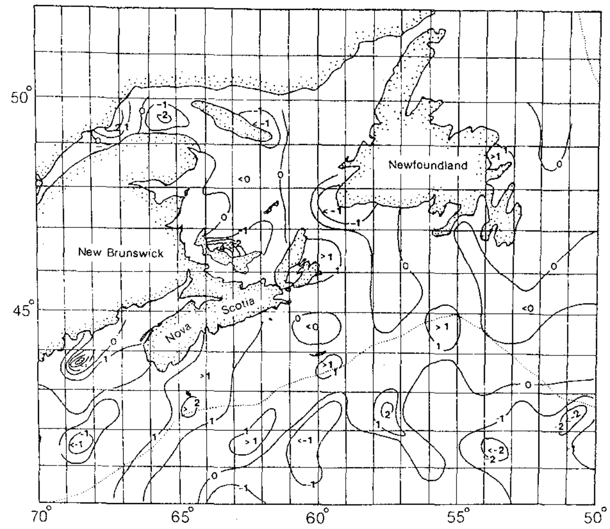

Fig. 24. Sea-surface temperature anomalies for February in the 1970–79 period relative to February in the 1960–69 period. (Data from World Climate Center, Asheville, North Carolina and Marine Environmental Data Service, Ottawa, Ontario, analyzed by 1° quadrangles.)

tive to those of 1960–69. For January, a maximum negative anomaly (>4° C) was located in the St. Lawrence estuary off the Gaspé coast and maximum positive anomalies (>3° C) south of Nova Scotia. The area of positive anomaly extended in a wide band in an east-northeast direction from Georges Bank to the Grand Bank, including some of the Slope Water area. Negative anomalies were evident throughout much of the Gulf of St. Lawrence and in the southeastern part of the area analyzed. In February, the anomaly pattern had changed significantly with generally lower values present. The large area of positive anomalies had diminished in intensity and size. By March (not shown), it disappeared entirely and no large-scale anomalies were evident.

Anomaly maps of this type are very interesting to look at, but they do not seem to lead to an improved understanding of what in fact may have been happening. There may be several reasons for this. Firstly, the period of 10 years has been arbitrarily chosen, and, consequently, the thermal processes may be masked by the pooling of data for years when extraordinary heating and cooling occurred. Perhaps a period based on some theoretical grounds or on observations of cycles of trends in the data itself should be chosen. Secondly, if real seasonal changes were occurring, a better view would probably emerge by combining the data for 2 or 3 months. Thirdly, the numbers of observations for some of the rectangles are small and the means have large variances, making some of the values not very reliable.

Grouping of data by geographic area

Within Marsden Squares 150 and 151, nine subsets of SST data were selected and grouped along boundary lines of latitude and longitude (Fig. 25) rather than on a bathymetric or other oceanographic basis. Nevertheless, they are sufficient to broadly characterize areas like the Bay of Fundy, Browns Bank, Georges Bank, etc. Mean annual seasurface temperatures for the 1942–79 period are shown in Fig. 26 for seven of the selected areas. The long-term trend in temperature is similar for all areas, declining from a high in the early 1950's to a low in the mid-1960's and rising to some intermediate level in the 1970's. On a decadal basis, the patterns are generally comparable to that at Boothbay Harbor (Fig. 21), namely, highest temperatures in 1950–59, lowest in 1960–69, and intermediate levels in 1970–79. There does appear, however, to be some significant differences in some of the detail between the different regions (Fig. 26). For example, the pre-1950 character of the Slope Water temperatures departs from that of the other areas. Also, during the early 1970's, temperatures for the Grand Bank, Eastern Scotian Shelf and to a lesser extent the Western Scotian Shelf and Gulf of Maine show a downward trend, whereas temperatures for the remaining areas were relatively steady or increased.

Lockwood (1979) reported that sea-surface temperatures in both the North Pacific and the North Atlantic during 1971-75 were significantly lower, with the snow-cover area significantly larger and average air temperatures in the low and middle latitudes significantly lower than in the previous 5-year period. He also reported that data for the southern hemisphere show cooling until the mid-1960's and then a slight warming. However, it appears that the cooling trend during 1971-75, which may have taken place in the North Atlantic as a whole, did not occur in all coastal areas along the eastern seaboard of North America.

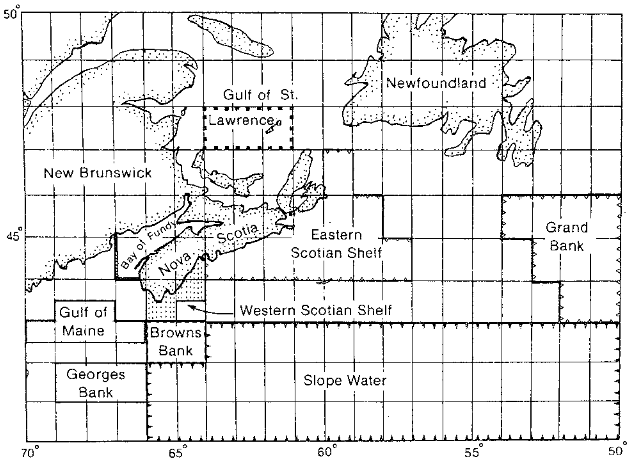

Fig. 25. Map showing nine areas where sea-surface temperature data were grouped together.

An analysis of mean temperatures for the 1950–59, 1960–69 and 1970–79 decades in the seven areas for which the SST data were grouped (Table 2) indicates that the changes were much larger for the Gulf of Maine, Georges Bank, Browns Bank and Slope Water areas than for the Eastern Scotian Shelf and Grand Bank areas. This could be partially due to the time periods chosen for averaging, because the two major regions appear to differ in some aspects of their long-term trends.

Interannual variability

The year-to-year trends in sea-surface temperature for the Browns Bank area are shown in Fig. 27 for both the monthly means and their 3-year normally weighted means. The most notable aspects of these high values of the early 1950's which were most pronounced in winter, the downward trend during 1955–65 which was present in all months, and an upward trend to a high in the mid-1970's which appeared to be mainly but not entirely a winter phenomenon. Similar plots for the Slope Water are shown in Fig. 28. This area displays essentially the same features as Browns Bank, except that the monthly upward trends in the late 1960's and early 1970's are spread over all months from January to August.

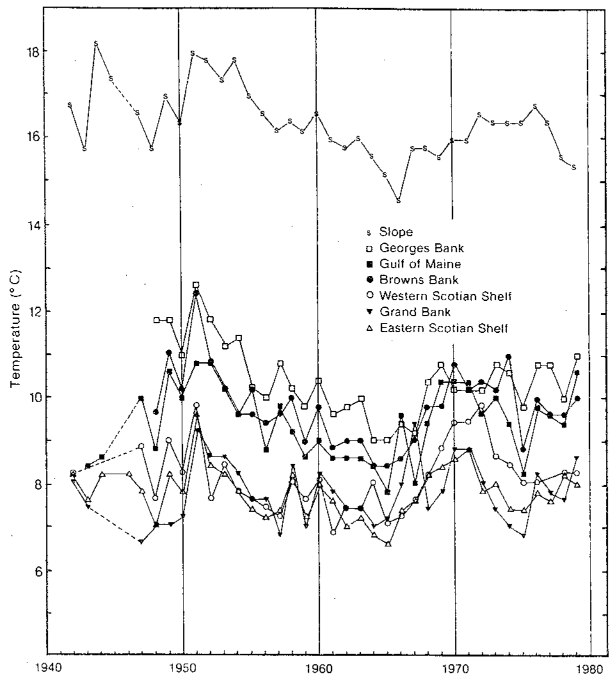

Fig. 26. Mean annual sea-surface temperatures for the 1942–79 period in seven of the areas identified in Fig. 25. (Raw data from World Climate Center, Asheville, North Carolina.)

The monthly year-to-year trends in sea-surface temperature for the Grand Bank region (Fig. 29) display different attributes from those in Fig. 27 and 28. Above-normal annual mean temperatures occurred in the early 1950's, but the peaks were produced mainly by abnormally high summer rather than high winter temperatures. Monthly summer trends, which were downward during 1955–65 for the Browns Bank and Slope Water areas, were upward for the Grand Bank area. Also dominant in the Grand Bank records are the below-normal temperatures which occurred in 1973–75 and were noticeable in most months except autumn.

These patterns indicate that, while the long-term trends in annual mean temperature have qualitative similarities over much of the area being considered, they are created through a different combination of seasonal conditions in each area, i.e. above-normal

TABLE 2. Mean sea-surface temperatures for 1950–59, 1960–69 and 1970–79 and between-decade changes for 7 areas in NAFO Subareas 3 to 5.

Area	Mean temperature (°C)			Difference	
	1950–59	1960–69	1970–79	60s–50s	70s–60s
Gulf of Maine	9.80	8.42	9.23	–1.38	+0.81
Georges Bank	10.90	9.59	10.39	–1.31	+0.80
Browns Bank	10.01	8.90	9.58	–1.11	+0.68
Slope Water	16.97	15.69	16.21	–1.28	+0.52
W. Scotian Shelf	7.94	7.44	8.21	–0.50	+0.77
E. Scotian Shelf	7.92	7.41	7.82	–0.51	+0.41
Grand Bank	7.86	7.70	7.64	–0.16	–0.06

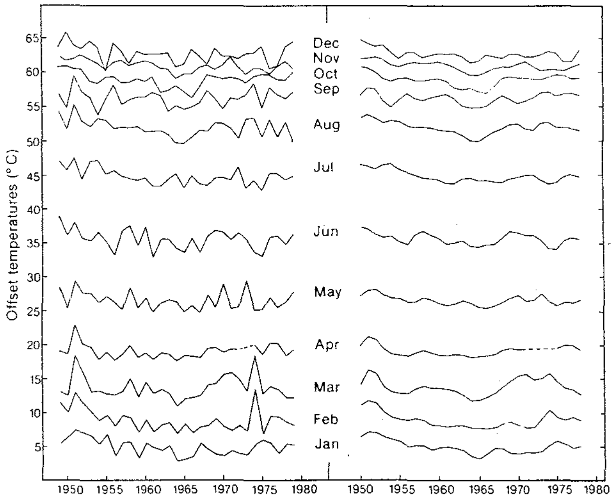

Fig. 27. Plots of monthly sea-surface temperatures for the Browns Bank area during 1949-79. (Each month is successively offset 5° C for visual convenience; left hand diagram is unsmoothed; right hand diagram is smoothed using 3-year normally weighted means.)

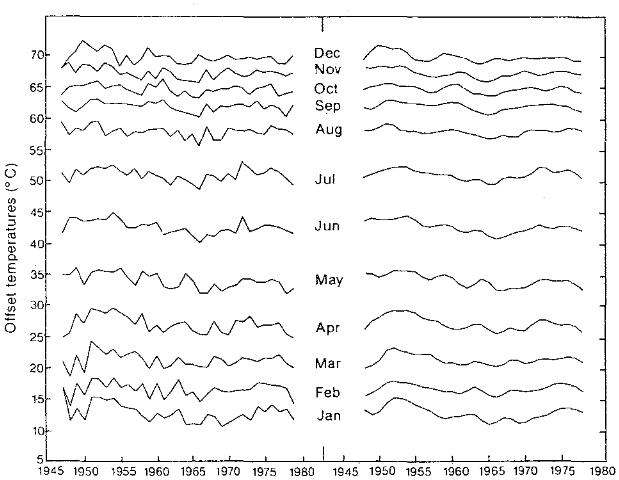

Fig. 28. Plots of monthly sea-surface temperatures for the Slope Water area during 1949-79. (Each month is successfully offset 5° C for visual convenience, left hand diagram is smoothed; right hand diagram is smoothed using 3-year normally weighted means.)

yearly average temperatures may be produced by above-normal winter temperatures in one area, above-normal summer temperatures in another, and by above-normal temperatures in all seasons in yet another area.

Within-year variability

Looking specifically at the 1970-79 period and comparing average monthly sea-surface temperatures on a year-by-year basis with those for the 1960-69 period gives yet another view of what the 1970's were like. As was noted earlier, the Brown's Bank area showed higher temperatures in late winter during the

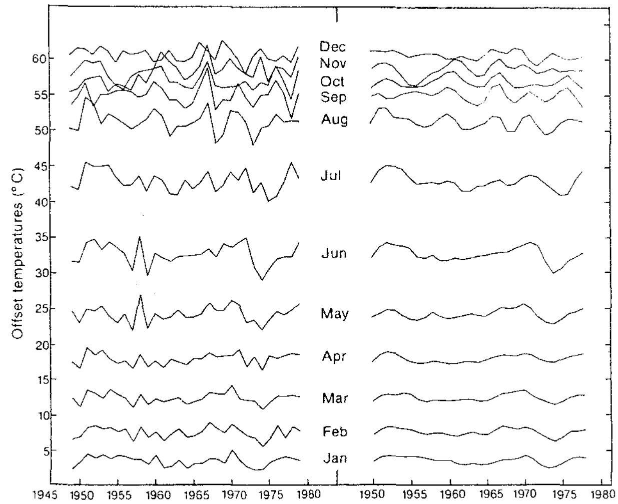

Fig. 29. Plots of monthly sea-surface temperatures for the Grand Bank area during 1949-79. (Each month is successfully offset 5° C for visual convenience; left hand diagram is unsmoothed; right hand diagram is smoothed using 3-year normally weighted means.)

early 1970's than in the 1960's. This is clearly evident for the winters of 1970-74 but not for 1975 in Fig. 30, which illustrates the phenomenon more markedly than Fig. 27.

To gain an impression of the spatial scale of the monthly temperature anomalies, plots for the seven areas are shown in Fig. 31 and 32 for 1973 and 1976 respectively relative to the averages for the 1960-69 period. For 1973, the Gulf of Maine, Georges Bank and Browns Bank areas all displayed roughly similar features with mainly positive anomalies. By contrast, those for the Grand Bank were consistently negative except for two months (Fig. 31). It was noted earlier that record high sea-surface temperatures occurred at St. Andrews during May-September 1976 (Fig. 19), and it is interesting to see the spatial extent of this anomaly (Fig. 32). In all areas, temperatures in 1976 were above those for the 1960-69 period during most months of the year, with moderately close similarity in the trends for Gulf of Maine, Georges Bank and Browns Bank.

Many pelagic fishes are known to be associated with particular temperatures and thermal fronts. For example, the northeastward spring migration of Atlantic mackerel, *Scomber scombrus*, along the Scotian Shelf and into the Gulf of St. Lawrence roughly coincides with the progression of the 7° C surface isotherm. Analysis of the 1960-79 surface temperatures on a semi-monthly basis for April-June indicates maked year-to-year variation, with differences up to a month in terms of "arrival" time of the 7° C isotherm at a given point. In 1970 (an "early" year), the 7° C isotherm moved more or less uniformly from offshore towards the coast (Fig. 33A), whereas in 1974 (a "late" year) the isotherm remained mainly seaward of the Scotian

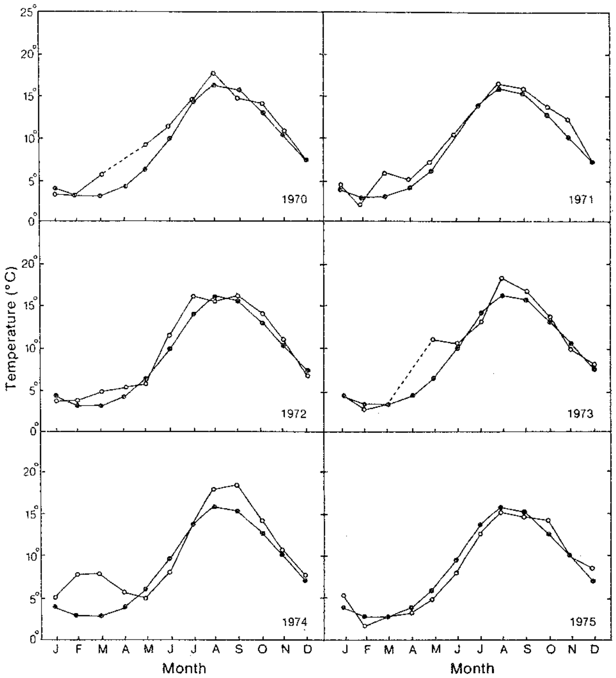

Fig. 30. Mean monthly sea-surface temperatures in the Browns Bank area for each year in the 1970–75 period. (Curves with solid dots represent the mean monthly temperatures for the 1960–69 period.)

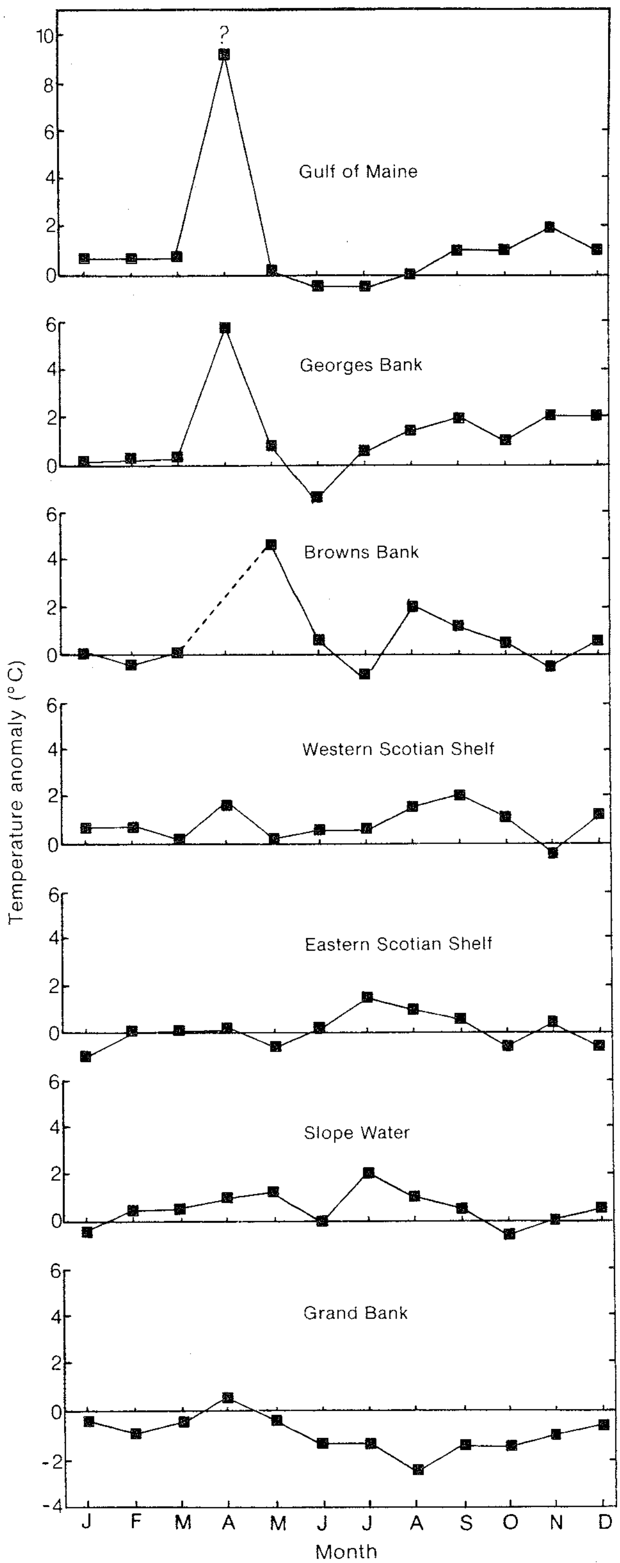

Fig. 31. Monthly sea-surface temperature anomalies for 1973, relative to the mean for the 1960–69 decade, for seven of the grouped areas.

Shelf until June when it advanced rapidly to the coast (Fig. 33B). R. H. Loucks (Loucks Oceanology Ltd., Halifax, Nova Scotia, pers. comm.) has classified each year of the 1960–79 period (no data were available for 1972) into one of three categories — early, intermediate and late. The early years were noted as 1960, 1969, 1970, 1976 and 1979, the intermediate years as 1963, 1966, 1968, 1971, 1973, 1977 and 1978, and the late years as 1961, 1962, 1964, 1965, 1967, 1974 and 1975.

Correlation analysis

General comments and methods of analysis. The foregoing analyses give the impression that oceanographic changes may be induced by large-scale variation in weather patterns. Basically, these large-scale systems must control wind patterns, air temperatures, heat budgets and precipitation. Thus, for any given location, one would expect the variation to be determined by both direct and indirect factors. Sutcliffe *et al.* (1976) examined this problem in some detail and found some interesting interrelationships. Although Cayan (1980) reported a very close relationship between surface temperature and air temperature for Marsden Square 150 as a whole, Sutcliffe *et al.* (1976) found that the correlation coefficients were generally less than 0.7 for selected stations within the square, indicating that air temperatures alone cannot account

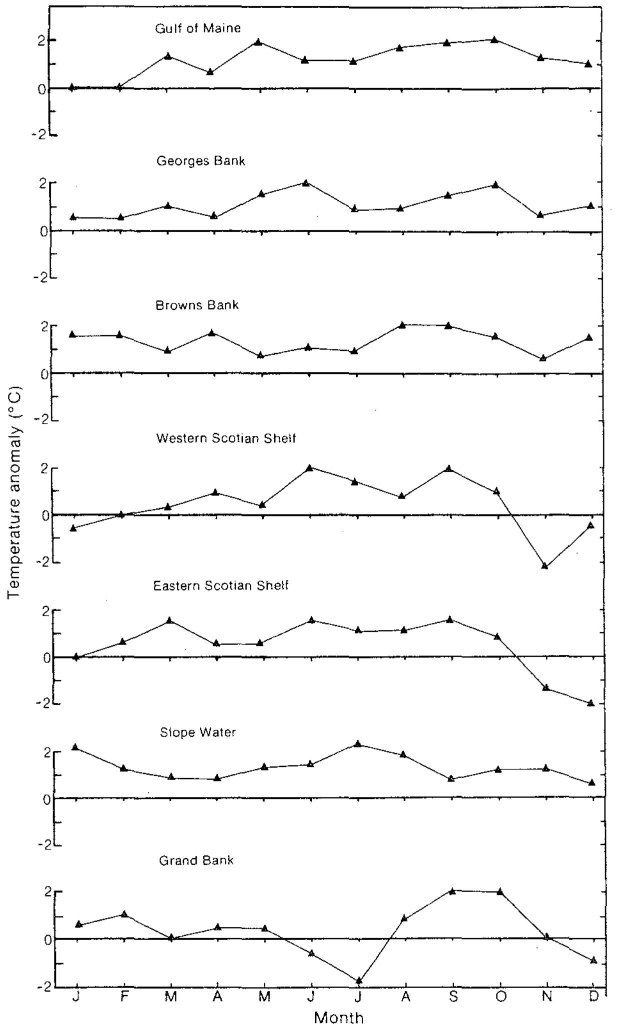

Fig. 32. Monthly sea-surface temperature anomalies for 1976, relative to the mean for the 1960-69 period, for seven of the grouped areas.

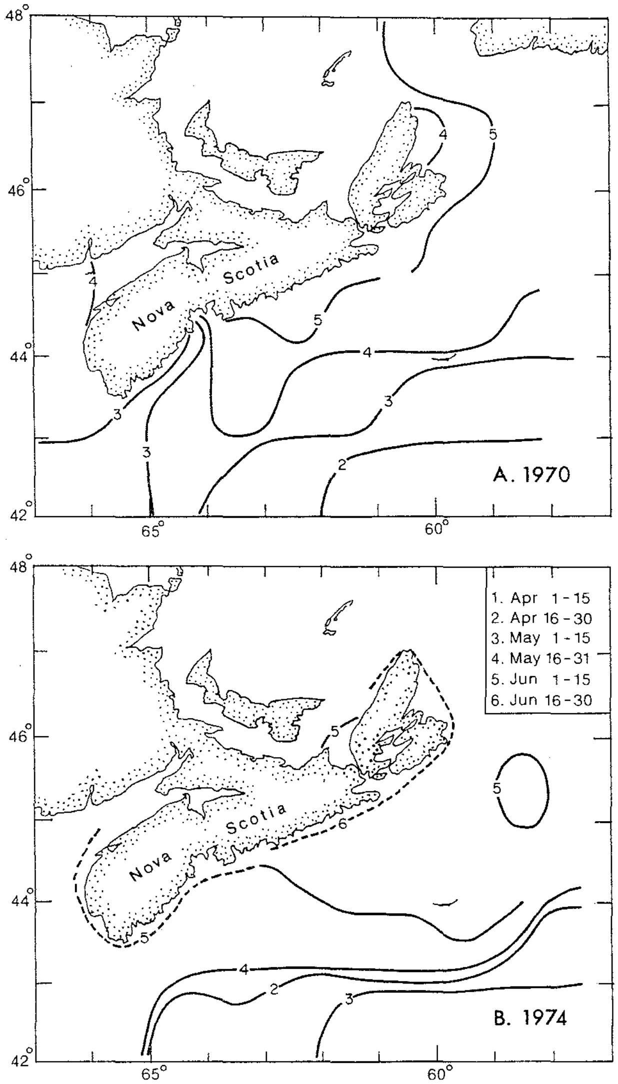

Fig. 33. Progression of the 7°C surface isotherm across the Scotian Shelf during April to June in (**A**) a relatively warm year (1970) and (**B**) a relatively cool year (1974). (Location of isotherm is coded for each twice-monthly period.)

for the variability in surface temperature. The entire Northwest Atlantic region can be connected by the surface circulation pattern (Fig. 2), and the character of this pattern must reflect, to an important extent, the fresh-water discharged from rivers. Sutcliffe *et al.* (1976) demonstrated that the effects of the St. Lawrence River discharge can be traced by correlation analysis with sea temperatures and found to propagate from the Gulf of St. Lawrence onto the Scotian Shelf and through the Gulf of Maine at known ocean-drift speeds.

Although high correlation coefficients by themselves do not permit one to discern direct or indirect relationships, they do usefully focus attention on particular features. The procedure used here to develop correlation coefficient matrices was similar to that used by Sutcliffe *et al.* (1976). For example, to investigate the relation between surface salinity at Station 27 off St. John's and surface temperature on the Eastern Scotian Shelf, correlation coefficients were calculated using monthly values of these parameters. After averaging by 3-year equally-weighted running means, the monthly salinities were progressively lagged behind the monthly temperature signals one month at a time (e.g. December salinity *versus* January temperature), beginning with no lag and proceeding to a 12-month lag.

Correlation coefficients were calculated for each lag and each temperature month (see Table 3). This resulted in a 12 × 13 matrix of coefficients, where each of the horizontal rows represents correlations at a particular lag-time of salinity for each month of temperature. A vertical column represents correlations between one temperature month and lags of salinity from 0 to 12 months, and a diagonal running downward from left to right represents correlations between one set of monthly salinity data and each of the 12 months of temperature data.

Since one can readily think of 20 or more variables that might have significant correlations between or among them, it was necessary to exercise some priorities in carrying out the computations. It has been suggested that Station 27 salinities represent an important data set for indexing purposes. Accordingly, particular emphasis was placed on correlating this data set with others such as temperature in various areas. Although other data sets such as St. Lawrence River discharge *versus* temperature have been used and surface temperature persistence through autocorrelations have been examined, many other matrices remain to be computed and scanned.

Station 27 salinities and Eastern Scotian Shelf temperatures. Correlation coefficients were computed for a matrix of monthly surface temperature and salinity data. In the first instance, salinity at Station 27 was progressively lagged from 1 to 12 months for each month of Eastern Scotian Shelf temperatures (Table 3). This matrix shows an area in the temperature months of August-October with correlation coefficients of -0.7 to -0.8, indicating highly significant correlation of August-October temperatures on the Eastern Scotian Shelf with Station 27 salinities in the previous March-May period. November-December temperatures also show high correlations for 0 and 1 month lag in salinity. Additionally, the March-May tempeatures appear to be highly correlated with salinity in the preceding October.

To examine the complementary situation where events on the Scotian Shelf precede those at Station 27, a correlation matrix for Station 27 surface salinities and Eastern Scotian Shelf surface temperatures was computed as shown in Table 4, i.e. salinity for each month was correlated with progressively lagged temperatures. The areas of high correlation coefficients indicate that salinities at Station 27 in July-September are highly correlated with Eastern Scotian Shelf temperatures in the preceding April-June, and that the November-December salinities are highly correlated with temperatures for 0 and 1 month lag.

To show that these high correlation coefficients are not spurious or artificial, the actual salinity and temperature data for the 1955-78 period, used to compute the high (bracketed) coefficients in Tables 3 and 4, are plotted in Fig. 34. These plots show reasonably convincingly the inverse relationship between the variables, namely, September-November temperatures and previous April-June salinities (Fig. 34A) and September-November salinities and previous June-August temperatures (Fig. 34B).

As pointed out earlier, there is no way of readily discerning whether the cause-effect relationship is direct or merely associative or some combination of both. The high correlation between late winter-spring salinities at Station 27 and the following summer-autumn temperatures on the Scotian Shelf is consistent with a cause-effect relationship invoking an advection-stability hypothesis. From the mean surface circulation pattern of Fig. 2, Station 27 is seen to be "upstream" from the Eastern Scotian Shelf area. Applying a mean speed of 5 miles per day to water movement over a route of 600-800 miles (traversing part of the Gulf of St. Lawrence) would produce a time lag of 4-6 months. The negative correlation is consistent with the fact that low salinities would increase the vertical stability of the water column, thereby inhibiting vertical mixing, and hence result in higher-than-normal temperature of the surface layer during the heating season.

TABLE 3. Correlation matrix for Eastern Scotian Shelf sea-surface temperature and Station 27 surface salinity, based on data averaged over 3 months. (**Bold** values represent the highest correlations.)

Salinity months lagged	Months for temperature											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	-0.6	-0.4	0.0	0.1	0.0	-0.4	-0.5	-0.3	-0.4	-0.5	**-0.8**	**-0.9**
1	-0.6	-0.6	-0.4	0.0	0.0	-0.2	-0.2	-0.5	-0.3	-0.3	**-0.7**	**-0.8**
2	-0.4	-0.5	-0.5	-0.3	-0.1	-0.2	-0.3	-0.3	-0.3	-0.2	-0.5	**-0.7**
3	-0.6	-0.4	-0.5	-0.4	-0.3	-0.3	-0.5	-0.5	-0.3	-0.2	-0.3	-0.5
4	-0.3	-0.6	-0.5	-0.5	-0.4	-0.4	-0.6	**-0.7**	**-0.7**	-0.2	-0.3	-0.4
5	-0.3	-0.5	**-0.7**	-0.5	-0.6	-0.4	-0.5	**-0.7**	**(-0.8)**	-0.6	-0.3	-0.4
6	-0.4	-0.5	-0.6	**-0.7**	-0.5	-0.6	-0.4	-0.5	**-0.7**	**-0.7**	-0.6	-0.3
7	-0.6	-0.4	-0.5	-0.5	**-0.7**	-0.5	-0.5	-0.2	-0.3	-0.5	-0.4	-0.4
8	-0.5	-0.6	-0.4	-0.4	-0.5	-0.6	-0.4	-0.3	0.0	-0.2	-0.3	-0.2
9	0.0	-0.5	-0.6	-0.4	-0.3	-0.4	-0.4	-0.2	0.0	0.1	0.0	0.0
10	0.3	0.0	-0.5	-0.5	-0.4	-0.3	-0.4	-0.2	0.0	0.1	0.2	0.2
11	0.6	0.4	0.1	-0.5	-0.6	-0.4	-0.4	-0.4	0.1	0.1	0.1	0.3
12	0.5	0.6	0.4	0.0	-0.5	-0.6	-0.6	-0.4	-0.1	0.3	0.1	0.2

TABLE 4. Correlation matrix for Station 27 salinity and Eastern Scotian Shelf sea-surface temperature, based on data averaged over 3 months. (**Bold** values represent the highest correlations.)

Salinity months lagged	Months for salinity											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	-0.6	-0.4	0.0	0.1	0.0	-0.4	-0.5	-0.5	-0.4	-0.5	**-0.8**	**-0.9**
1	-0.6	-0.5	0.0	0.2	0.0	-0.3	**-0.7**	-0.5	-0.5	-0.4	-0.6	**-0.8**
2	-0.3	-0.5	-0.2	0.2	0.2	-0.4	**-0.7**	**-0.7**	-0.6	-0.5	-0.5	**-0.7**
3	-0.2	-0.2	-0.2	0.1	0.3	-0.2	**-0.7**	**-0.7**	**(-0.8)**	-0.5	-0.5	-0.5
4	-0.1	-0.1	-0.2	-0.1	0.1	0.0	-0.5	**-0.7**	**-0.7**	-0.5	-0.5	-0.4
5	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.4	-0.6	-0.4	-0.5	-0.2
6	0.1	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.4	-0.3	-0.3	-0.1
7	0.2	-0.1	-0.5	-0.2	-0.3	-0.4	-0.3	-0.1	-0.2	0.0	-0.2	0.1
8	0.4	-0.1	-0.4	-0.5	-0.4	-0.4	-0.5	-0.3	-0.2	0.1	0.1	0.2
9	0.4	0.1	-0.4	-0.5	-0.5	-0.4	-0.5	-0.5	-0.5	0.0	0.2	0.5
10	0.4	0.1	-0.2	-0.4	-0.4	-0.3	-0.5	-0.5	-0.6	-0.4	0.1	0.6
11	0.5	0.1	-0.2	-0.2	-0.2	-0.2	-0.3	-0.4	-0.6	-0.5	-0.3	0.6
12	0.4	0.3	-0.1	-0.2	-0.2	0.0	-0.3	-0.2	-0.5	-0.6	-0.4	0.3

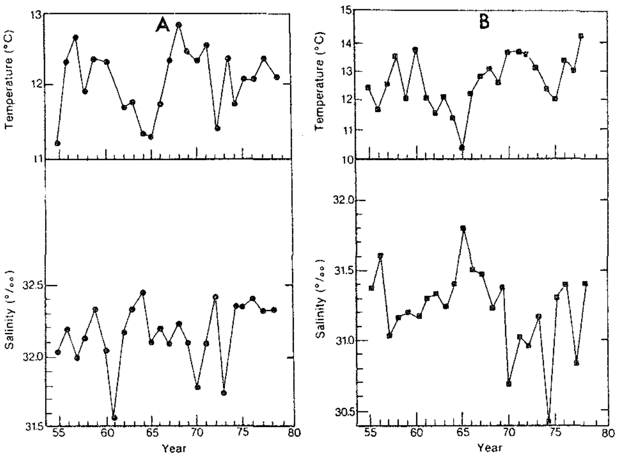

Fig. 34. **A**. Plots of sea-surface temperature (upper) for the Eastern Scotian Shelf during September-November and sea-surface salinity (lower) for Station 27 for the previous months of April-June in the 1955-78 period. (Same data as used to compute correlation coefficient bracketed in Table 3, r = -0.8.). **B**. Plots of sea-surface temperature (upper) for the Eastern Scotian Shelf during June-August and sea-surface salinity (lower) for Station 27 for the following months of Sep-temperature-November in the 1955-78 period. (Same data as used to compute correction coefficient bracketed in Table 4, r = -0.8.)

Referring again to Table 3, the high correlation coefficients in November-December with little or no lag is likely to be associated with meteorolgical conditions, although it is not obvious why the phenomenon is confined to only 2 months of the year. The correlation between March-May temperatures and the previous October salinities is probably a reflection of the March-May salinity correlation with the subsequent August-October temperatures. In other words, they are both part of the same phenomenon.

Although mean surface circulation maps show Station 27 to be "upstream" from the Eastern Scotian Shelf, there is evidence that the surface circulation may be significantly altered and partly reversed during some seasons so that Station 27 is "downstream" from the Eastern Scotian Shelf. Analyses of drift-bottle data (Bumpus and Lauzier, 1965; Trites, 1979) and the drift of satellite-tracked buoys (Trites *et al*, 1982) indicate a northeast movement from the Eastern Scotian Shelf in spring towards the south coast of Newfoundland, reaching as far east as Cape Race in 2-3 months.

Suitable data sets do not exist to enable examination of the relationship between surface temperatures and salinities for the Eastern Scotian Shelf, but there is adequate basis for believing that, during the heating season, the two variables would be negatively correlated with near-zero time lag. Correlation with phased lags between temperature in one area and salinity in another may well be the result of a third factor — advection. Thus, the key physical factor responsible for producing the high correlations between spring surface temperatures on the Eastern Scotian Shelf and the summer surface salinities at Station 27 (as shown in Table 4) may be wind-driven surface currents. Certainly, the available Lagrangian surface current measurements and wind records lend support to this suggestion.

Eastern Scotian Shelf surface temperatures and Sable Island winds. A correlation matrix was computed to investigate the possible relationship between surface temperatures on the Eastern Scotian Shelf and the southeast wind component at Sable Island (Table 5). Interestingly, February winds are highly correlated with surface temperatures during February-July. Plots of the wind component for February-April and surface temperature for the following June-August of the 1953-78 period (Fig. 35) give rather convincing evidence of the similarity between the two parameters. It is surprising that wind is not highly correlated with

TABLE 5. Correlation matrix for Eastern Scotian Shelf sea-surface temperature and southeast wind component at Sable Island, based on data averaged over 3 months. (**Bold** values represent the highest correlations.)

Wind months lagged	Months for temperature											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0.5	**0.7**	0.5	0.5	0.4	-0.3	-0.3	-0.1	0.5	0.4	0.4	**0.7**
1	**0.8**	0.6	**0.8**	0.5	0.5	0.4	-0.5	-0.4	0.2	0.6	0.5	0.5
2	**0.7**	**0.7**	0.6	**0.8**	0.4	0.5	0.2	-0.5	-0.2	0.4	0.5	0.5
3	**0.7**	0.6	0.5	0.6	**0.8**	0.5	0.5	0.0	-0.2	0.1	0.3	0.4
4	0.3	0.6	0.5	0.5	**0.7**	**(0.8)**	0.6	0.4	0.1	0.1	0.2	0.3
5	0.2	0.3	0.6	0.5	0.5	0.6	**0.7**	0.4	0.3	0.3	0.4	0.3
6	0.1	0.2	0.3	0.6	0.5	0.4	0.4	0.5	0.2	0.3	0.4	0.5
7	0.5	0.0	0.1	0.4	0.5	0.4	0.2	0.1	0.2	0.2	0.3	0.4
8	0.2	0.5	-0.1	0.1	0.3	0.4	0.1	-0.1	0.1	0.1	0.1	0.2
9	0.0	0.1	0.5	-0.2	0.0	0.2	0.1	-0.2	0.0	0.2	0.2	0.1
10	-0.2	0.0	0.1	0.3	-0.2	-0.1	-0.1	-0.2	-0.1	0.1	0.3	0.2
11	0.1	-0.1	0.1	-0.1	0.3	-0.3	-0.4	-0.2	-0.2	0.1	0.1	0.2
12	0.2	0.1	0.0	0.2	-0.2	0.2	-0.5	-0.6	-0.3	-0.2	0.1	0.0

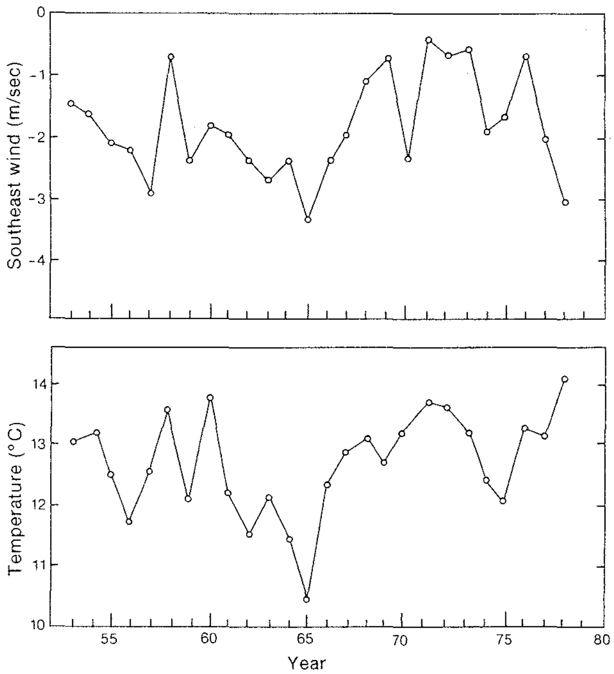

Fig. 35. Plots of southeast component of wind speed (upper) for Sable island during February-April and sea-surface temperature (lower) for the Eastern Scotian Shelf for the following months of June-August in the 1953-78 period. (Same data as used to compute correlation coefficient bracketed in Table 5, r = 0.8.)

temperature in any other month than February and likewise that the February "event" persisted in the surface temperature pattern for the following 5 months. It should be noted that the correlation coefficients would have been negative if the northwest wind component had been used. Typically in February, higher air temperatures are associated with southeast winds and the inverse for northwest winds.

Other correlations. The correlation of St. Lawrence River discharge with surface temperatures at shore stations and lightships (Sutcliffe *et al.* (1976) suggested a pathway of influence from the Gulf of St. Lawrence southwestward along the continental shelf. Extension of the correlation analysis, using the sea-surface temperature data grouped by geographical area (Fig. 24), produced results that were consistent with the analysis of Sutcliffe *et al.* (1976), with peak correlations of 0.7 and 0.8 between spring river discharge and surface temperatures in successively later months along the hypothesized drift path; for example, the peak correlation occurred in August for the Eastern Scotian Shelf, September for the Western Scotian Shelf and September to December for the Gulf of Maine.

Autocorrelations of sea-surface temperature for both the Eastern and Western Scotian Shelf areas were computed. In general, the two areas displayed rather different features. For the Eastern Scotian Shelf, persistence was evident on a time scale of 1 or 2 months except in autumn. For the Western Scotian Shelf, there was strong month-to-month persistence in January-May and very little persistence from May to June and from June to July. Autocorrelations were at intermediate values for other months. Further analysis of these data sets and cross correlations between other selected data sets are required before any interpretations can be offered.

Atmosphere-Ocean Coupling and Response

In the foregoing section on correlations, it was evident that ocean-atmosphere interactions can occur on a scale of at least a few hundred kilometers. In an earlier section, it was noted that the declining salinities observed during 1967-71 at Ocean Weather Station *Bravo* were probably related to meteorological conditions over the Northwest Atlantic and Arctic oceans during the 1960's. One explanation offered by Lazier (1980) was that an increased supply of cold, fresh polar water, resulting from an anomalously high atmospheric pressure cell over Greenland, lowered both the temperature and salinity of the East Greenland Current. This current flows southward along the east coast of Greenland, turns westward around Cape Farewell and northward into the Labrador Sea. An ocean-pathway delay time of 12–18 months between Denmark Strait and Station *Bravo* was estimated, indicating an oceanographic response scale of at least 2,000 km.

Namias (1966) noted the contemporaneous occurrence of drought in the northeastern United States with the presence of colder-than-normal sea-surface temperatures along the Atlantic coast in the 1962–65 period. He speculated that an interlocking feedback mechanism was operative; the greater prevalence of northerly winds increased the Labrador Current transport which lowered sea-surface temperatures and in turn air temperatures along the Atlantic coast, resulting in increased atmospheric baroclinicity, and thereby completing a positive feedback loop.

Cayan (1980) has shown that large-scale features of sea-surface temperature and surface air temperature are closely related on monthly, seasonal and annual time scales over both the North Pacific and North Atlantic oceans. He found, however, that the correlation varied seasonally, being higher in summer at mid-latitudes, and that spatial scales varied seasonally with different patterns in the Atlantic and the Pacific. Although Namias (1973) showed a good correlation between sea-surface temperature and the thickness of the 1,000–700 mb surfaces in the North Pacific, Cayan (1980) pointed out that a strong relationship between sea-surface and surface air temperatures does not necessarily imply a strong coupling between the lower troposphere and the sea surface.

Namias and Born (1970) indicated that large sea surface temperature anomalies may develop over a large area of the North Pacific and persist for many months. Namias (1972, 1976, 1980) discussed teleconnections between these anomalies and subsequent extreme weather conditions over the North American Continent (e.g. anomalous winters of 1971/72 and 1978). However, the 1978/79 pattern appeared to have been influenced by a vast area of Arctic blocking, because the statistically-derived teleconnection predicted a warm winter along the Atlantic coast. Although there is convincing envidence that events in one area produce responses in subsequent months over distances of several thousand kilometers, the 1978–79 pattern emphasizes the unsatisfactory state of understanding that exists in much of the short-term climate variability.

Summary Impressions

1. There is evidence that long-term changes (several years) in sea-surface temperatures are coherent over space scales of a few thousand kilometers, comparable to the size of NAFO Subareas 2, 3 and 4. However, from the data available, there is an indication that the area does not fit into a single "regime". The Bay of Fundy, Gulf of Maine, Georges Bank and part of the Scotian Shelf appear generally to behave similarly and may be part of a larger "southern regime". Although data are insufficient for the northern region on a year-round basis, the Labrador, Grand Bank and Eastern Scotian Shelf areas appear to display similar tendencies in terms of long-term trends and may be part of a larger "northern regime".
2. Using Boothbay Harbor, Maine, sea-surface temperature data as an index of conditions in the southern part of Subarea 4, it appears that the 1970–79 decade was intermediate between the 1950's when temperatures were high and the 1960's when they were low. Relative to the 1906–45 period, the area seems to have been under increased maritime influence during the past 30 years, experiencing warmer winters and cooler summers.
3. Using the grouped sea-surface temperature data for the Grand Bank as an index of conditions in Subareas 2 and 3 and the northern part of Subarea 4, it appears that the 1970–79 decade was slightly cooler than the 1960–69 and 1950–59 periods. The decadal fluctuations in temperature appear to be much smaller than those for the southern part of Subarea 4. This might be partially due to the time series of data chosen for averaging, as the two regions appear to have differences in some aspects of their long-term trends.
4. For much of Subareas 2 and 3, the 1970–72 period was one of generally declining surface temperatures and salinities. Lowest temperatures in the more northerly divisions appear to have been reached in 1972, whereas the cooling trend seems to have persisted at least until 1975 in the southern divisions. By 1978, surface temperatures appear to have returned to near-normal levels.
5. Significant regional differences are evident in the compositions of the annual temperature signal. For example, although all parts of Subareas 3 and 4 may have experienced a downward trend in average annual sea-surface temperature from

mid-1950's to the mid-1960's, temperatures during April–July in the Grand Bank area tended to increase during the 1970–79 decade, whereas those in the southern part of Subarea 4 exhibited a downward trend over all months.

6. Little can be said about space and time variations of conditions at subsurface depths throughout the NAFO area due to the paucity of subsurface oceanographic data. From Station 27 data, there is no basis for believing that the long-term trends in temperature and salinity below the depth of convective overturn bear close similarity to the properties of the overlying surface layer.

7. Recurring conditions over periods of several years are an important feature of sea-surface temperature data. For example, recurrence in the late 1960's at Ocean Weather Station *Bravo* occurred over a 5-year period and appeared to be a response to a large-scale atmospheric phenomenon linked through the surface layer circulation regime and occurring on a space scale of at leat 2,000 km.

8. The significantly different character of temperature anomalies of the Gulf of Maine, Browns Bank and Georges Bank areas from the more northerly areas may in part be due to offshore forcing, because Gulf Stream eddies are capable of producing major changes in shelf conditions over a period of weeks or months. However, the data base (satellite imagery) is still too short to determine year-to-year variation in eddy numbers and their location on a decadal time scale.

9. The high positive correlation of fresh-water discharge from the St. Lawrence River system with sea-surface temperatures through the Gulf of St. Lawrence, over the Scotian Shelf, and into the Gulf of Maine phase-lagged by realistic surface-current drift times, indicates a pathway of river-discharge influence on a space scale up to 2,000 km. It may be that increased discharge increases buoyancy and inhibits vertical mixing, thus confining the incoming radiation to the shallow surface layer. The similarity of trends in river discharge during winter and spring to trends in annual temperature for most of Subarea 4 should also be noted.

10. Changing seasonal wind patterns probably produce pronounced changes in surface circulation on a time scale of several months.

11. The climate signal, as indicated by sea-surface temperatures at different coastal stations does not correlate well on spatial scales of even a few tens of kilometers for time scales of a year or less. There is some indication that spatial coherence at these time scales in the offshore areas is generally much larger.

13. The use of 10-year periods for investigating long-term variations has limited value and may mask significant changes. The data records themselves should be the guide to time-block analyses.

Acknowledgements

The author acknowledges the assistance of many individuals during the preparation of this paper. In particular, thanks are expressed to R. H. Loucks of Loucks Oceanology Ltd., who carried out the amalgamation of data bases, statistical and correlation analyses, and assisted through numerous discussions as the material was being interpreted and assimilated; to W. H. Sutcliffe for helpful discussion of the correlation matrices; to J. R. Keeley of MEDS for analyzing data for several of the NAFO standard oceanographic sections; to J. R. N. Lazier for discussion and provision of material relevant to the Labrador Sea and Shelf areas; and to W. M. Petrie, G. B. Taylor, D. L. Allen and C. A. Simmons for drafting and typing assistance.

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