

12-Year Hydrographic Survey of the Newfoundland Basin: Seasonal Cycle and Interannual Variability of Water Masses

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Abstract

Through the 1980s and early 1990s, Soviet research vessels conducted an extensive survey of the area to the southeast off the Grand Banks known as the Newfoundland Basin. The measurements collected in this survey were evenly distributed in space and repeated seasonally or monthly. A special technique was developed to identify the dominant water masses in the Newfoundland Basin data. This technique was based on statistical T-S analysis with the horizontal gradient added as the third dimension and resulted in distinctive separation of water masses and fronts. Time series of temperature and salinity for the waters on either side of the front were analyzed to estimate the seasonal and interannual variability.

The highest amplitudes of the annual cycle were found at the surface inshore of the Subpolar Front. However, the highest contributions of the cycle to the total variance were observed in the offshore sector. There the annual cycle also penetrates to a greater depth than in the Shelf and Slope areas. Below 20 m the seasonal cycle inshore of the Front has a significant semiannual component, implying that there are two phases of cooling: winter, produced by the local heat loss and summer, caused by advection of the seasonal cycle from the north.

The interannual variability also differs on either side of the Subpolar Front. The interannual signal in the offshore waters is practically uniform with depth, whereas inshore of the front it has some differences above and below 50 m. Time series analyses of the hydrographic data and sea surface temperature revealed a cold event that originated in the Labrador Sea in the winter of 1982-1983 and shortly after that appeared in the inshore waters of the Newfoundland Basin at 100 m. Thereafter, this anomaly progressed south and east from the Labrador Basin and entered the surface layer of the Newfoundland Basin in the winter 1983-1984, where it stayed till the end of 1986.

Introduction

After passing the Southeast Newfoundland Rise the Gulf Stream abruptly changes its direction from southeastward to northward, creating a large cyclonic meander, which is distinctively seen in the climatic distributions (*Yashayaev, 2000*). Somewhere around this point, a part of the flow branches off, contributing to the Gulf Stream recirculation and the Azores Current. However, the major fraction of the Stream continues north to become the North Atlantic Current. The area between the abrupt change of the course of the Gulf Stream to the south of the Grand Banks and the Flemish Cap is commonly referred to as the Newfoundland Basin.

Brief History of Exploration

Heland-Hansen and *Nansen (1920)* were the first who detected and quantified climatic variations of temperature in the northern part of the North Atlantic. They quality controlled and summarized an enormous collection of ship measurements. According to the maps, produced by *Heland-Hansen* and *Nansen (1920)*, at the location of the Southeast Newfoundland Rise the Gulf Stream turns to the northeast and becomes significantly colder, continuing to cool down to the east. What is even more important in regard to the present paper is the fact that *Heland-Hansen* and *Nansen* revealed significant interannual changes of sea surface temperature near the Subpolar Front, and attempted to locate the cause of these change by looking the variation of conditions over a larger area.

Later *Iselin (1940)* pointed out that the Gulf Stream splits into branches to the south of the Grand Banks. This idea was further developed by *Mann (1967)*, who conducted two detailed deep hydrographic surveys in the Basin, mapped the splitting, computed the transport in the branches and to discovered a quasi-permanent anticyclonic circulation in the central part of the area. *Worthington (1976)* opposed the notion that the North Atlantic Current branches from the Gulf Stream by proposing the existence of an isolated gyre-like circulation to the northeast of the Southeast Newfoundland Rise. Later *Clarke et al. (1980)* showed that the suggestion that the North Atlantic Current is separated from the Gulf Stream doesn't have sufficient grounds and contradicts with the existing transport estimates. *Clarke et al.* based their 1980 paper on a large-scale experiment conducted in the spring and summer of 1972. *Clarke et al. (1980)* gave a detailed view on the water mass structure and circulation in the Newfoundland Basin and explained the property change in the transition from the Gulf Stream to the North Atlantic Current as a result of intense exchange and vigorous mixing across the front. This provided a solution to the seeming disagreement in the flow characteristics and re-opposed the *Worthington (1976)*'s separate gyres theory, which was based on the difference in physical and chemical properties of the Gulf Stream and the North Atlantic Current.

A series of works originated from the International Ice Patrol (IIP) survey (*Smith et al., 1937; Voorheis et al., 1973, etc.*) dealt with the issues of the Labrador Current transport and recirculation, fronts, eddies etc. The IIP program emphasized the shelf break and slope regions, the areas of remarkably high variability and dynamic activity. Unfortunately, the IIP surveys didn't extend offshore far enough to have the deeper part of the Basin well sampled.

Major features of Oceanography of the Newfoundland Basin

The North Atlantic plays an exceptional role in the entire climatic system of the Earth, performing the northward heat transport and producing intermediate and deep waters. The

intermediate and deep waters of the north Atlantic form in the northern basins (Labrador, Norwegian and Greenland Seas) and subduct as they advect south. Variations of conditions in the sources of these waters result in changes in the convection scenarios and rates of the water mass formation (*Dickson, 1988; Dickson, Lazier, 1996*). The upper northward and deep southward transports of heat and salt change direction and undergo substantial changes in the Newfoundland Basin. There, the sea water properties change dramatically not only in transition from one water mass to another, but also in direction along the pathways of these waters.

To the south and east of the Grand Banks the Gulf Stream produces several branches, which transport warm and salty water to different parts of the North Atlantic. The mechanism of the splitting is still unclear, as is the merger of the Gulf Stream and the Slope Water Current in the western part of the Basin. To the east of the Southeast Newfoundland Rise the Gulf Stream abruptly changes its direction, forming a large meander. From this point the flow is known as the North Atlantic Current. The dramatic change in the water properties associated with this transition fed the *Worthington*'s theory of co-existence of two separate gyres. Near the Tail of the Grand Banks the Labrador Current splits into two branches. The first branch continues to the west or northwest, the other branch turns back toward the Flemish Cap, forming the Labrador Current recirculation. Anticyclonic (clockwise) circulation in the central Newfoundland Basin was described by *Mann (1967)* and is commonly referred to as the Mann Eddy. This eddy or gyre plays an exceptional role in the circulation, air-sea interaction and climatology of the region. It resides between the Gulf Stream branches, conserves a large amount of heat and salt and rotates a volume of water, heat and salt comparable with the total northward transport by the major currents.

The upper 500 m layer of the Newfoundland Basin can be partitioned to cold, slope, warm and frontal sectors. The cold sector includes the Labrador Current (LC), Shelf Water (ShW) and Subarctic Intermediate Water (SIW) and Labrador Sea Water (LSW). The major residents of the warm sector are the Gulf Stream, North Atlantic Current (NAC), Central North Atlantic (CNAW) and Newfoundland Basin Mode waters (NBMW). The traces of the Slope Water can be found in the western part of the Newfoundland Basin. Since this water mass is not a dominant water mass in the Basin, it's not considered in the present study. Subarctic Intermediate Water (*Arhan, 1990*) is formed to the northeast of the Newfoundland Basin and generally underlies the Subpolar Front. This mass is highly mutable and forms a cloud of scattered points or a veer on θ -S diagram. Labrador Sea Water is a product of the deep convection in the Labrador Sea. The depth of its core ranges in the Newfoundland Basin from 400-700 m near the continental slope to 1400-2000 to the south of the Subpolar Front. Newfoundland Basin Mode water presents is a modification of Central North Atlantic Water. It's characteristic for the Mann Eddy, where it penetrates as deep as 900 m.

Three types of frontal systems can be identified in the distributions of various sea water properties in the Newfoundland Basin: *the Gulf Stream - Slope Water Front*, *the Slope Water - Labrador Current (or Shelf Water)*, *the Gulf Stream - Labrador Current (or Shelf Water)*.

There is a distinct maximum of the surface heat fluxes near the Subpolar front in the Newfoundland Basin. The position and magnitude of this maximum reflects certain oceanographic conditions, such as the sharp thermal contrasts at the fronts, the curvature of the stream pathways, the source of heat accumulated in the Mann Eddy, and atmospheric processes - cold continental air outbreaks and a merger of the most frequent storm-tracks. These factors maintain the air-sea temperature contrast and high winds in the Newfoundland Basin.

The complexity of the water mass structure, circulation and air-sea interaction makes the Newfoundland Basin one of the most challenging areas for marine scientists. An advance in oceanography of the Basin and the studies of water masses, circulation and climatic variability in the entire North Atlantic are closely related.

In the Focus of the Study

The present study had the following goals:

- to describe the state of the major water masses in the upper 500 meter layer of the Newfoundland Basin;
- to quantify the contributions of seasonal and interannual variability to the time variance at different depths on either side of the Subpolar Front,
- to identify the seasonal cycle and its variation with depth,
- to reveal the interannual signal in different water masses and to establish its origin by relating it to anomalous events over a larger area.

The paper presents an extensive compilation of observation collected in a 12-year hydrographic experiment in one of key regions of the North Atlantic. It also demonstrates a new approach to water mass analysis in the vicinity of fronts.

Data

A systematic compilation of hydrographic data from the Newfoundland Basin started with the International Ice Patrol (IIP) survey in the early 1930s. The IIP produced an immense data collection from marginal and frontal areas in the northwest corner of the north Atlantic, which covers more than 4 decades. In 1964, 1966 and 1972 the Bedford Institute of Oceanography conducted precise Newfoundland Basin experiments. *Mann (1967)* and *Clarke et al. (1980)* summarize the results of these surveys.

A new phase of the Newfoundland Basin explorations started in early 1980s with extensive oceanographic and meteorological observations conducted by the Soviet ships in support of the “SECTIONS” program. “SECTIONS” was a multidisciplinary scientific program aimed at areas of intense energetic exchange between ocean and atmosphere. The program lasted for more than a decade, fading in the early 1990s with the collapse of the Soviet Union. In the Newfoundland Basin alone Soviet research vessels conducted 64 surveys and collected more than 6600 stations between 1980 and 1992. The area was visited at least once in a season. The nominal or standard grid of stations consisted of 7 cross-frontal sections spaced at 60 miles. Each of these sections contained 15 stations 30 miles apart. The 105 circles in Fig. 1 represent the standard grid. Measurements of temperature, salinity, oxygen, pH, alkalinity and nutrients were collected between the sea surface and 2000 meters depth. Near fronts the distance between stations was normally reduced to 5-10 miles. There were also experiments dedicated to specific tasks, such as a study of changes on short time scales, involving operation of several ships revisiting the same stations. On at least 16 occasions the survey area was extended to the east and west. Temperature measurements collected in one such extended survey (Atlantex-90; May, 1990) were used to create the field shown in Figure 1.

Creation and Analysis of Time Series

Time series of oceanographic variables are traditionally composed of measurements collected in close proximity of a certain geographic location or averaged over a spatial domain. Local changes near oceanographic fronts can be resulted from evolution in water masses or from changes in position of water masses and fronts. This results in non-stationarity of time series in regions of sharp spatial gradients.

In the presence of high frequency variability, the detection of seasonal and interannual variability requires frequent and continuous sampling. Away from the coastal areas the observations are mostly irregular and sampling is poor, which complicates analysis of local time series.

The present work suggests another approach to the analysis of long-term variability near oceanographic fronts. The main idea of the method is compensation of inadequate temporal sampling by spatial averaging in a water mass and, therefore, benefiting from all measurements available in a domain. Ideally, this approach requires that a sampling (observational) grid remains the same and the data coverage is sufficient to resolve the fronts between the analyzed water masses. If the grid has changed, the analysis can be performed in the intersecting part or the results from different surveys can be corrected to compensate the spatial variation in the properties.

Identification of water masses

T-S analysis is commonly used to identify water masses, quantify their properties and to explore mechanisms of their interaction and transformation. Its principle, development and applications are summarized in (*Mamayev, 1975*).

Statistical, area and volume metric modifications of T-S analysis were earlier used to describe water masses over large areas (*Montgomery, 1958*). The presence of fronts did not have a significant effect on results of such analyses. However, in some regions, particularly in the vicinity of the western boundary currents, the fraction of fronts in the total volume becomes more sensible. This creates a certain ambiguity in identification of water masses residing in a relatively small area and lacking a distinguishable maximum on T-S diagram. A water mass and a front can be also indistinguishable in T-S space. For example, the Slope Water and the front separating the Gulf Stream and the Shelf Water form overlapping T-S clusters (Fig. 2).

The noted difficulties suggest that the first step in identification of water masses in the vicinity of fronts must be their separation from fronts. To perform such separation one can use oxygen, nutrient or other biochemical measurements. Unfortunately, these variables are not conservative, sparse in availability and often have large errors. To identify water masses the present study employs spatial gradient of basic properties. The gradient method described in the paper lets to partition the area of study into three major structures frontal, warm and cold and estimate their characteristic properties.

The major water masses in the Newfoundland were analyzed in the following way.

Temperature (T) and salinity (S) measurements from a survey were interpolated to vertical and horizontal grids. The vertical and horizontal steps of the grid were set to 10 m and 10 km, respectively. The gridded values were then used to compute area or frequency in T-S bins ($1^{\circ}\text{C} \times 0.2 \text{ ppt}$). The Shelf Water, Labrador Current, Central North Atlantic and the other water masses

can be identified as local maxima in T-S space and characteristic properties of these water mass can be computed by averaging T, S, and density in all grid points whose position in T-S space fell within a certain normalized distance from a particular maximum. In many cases the water masses are well defined. However, if a water mass was located near the edge of the survey area, it might not appear as an individual maximum on the T-S diagram, but form an extension of a T-S ridge, associated with a front. To separate a water mass from a front and improve the separation of water masses, the approach was further developed by including spatial gradients (G) of T and S in the same way as T and S and defining three-dimensional (G-T-S) bins for frequency, area or volume computation.

Spatial or horizontal gradient measures local inhomogeneity in a field and can be used to detect fronts and separate water masses. A water mass is defined as a relatively homogeneous and continuous volume of water. Therefore, a value of gradient indicates whether a given point should be attributed to a water mass or a front. Depending on differences in properties of neighboring water masses, the distinction between the water masses and fronts can be based on temperature gradient (G_t), salinity gradient (G_s) or composite gradient (G_c). G_c is a combination of G_t and G_s . To detect both thermal and haline fronts G_c can be designed as $(G_t^2 + (aG_s)^2)^{1/2}$, where a is a constant based on the linear regression of T against S at the depth of analysis. In the case of this study, a is close to 5. The spatial patterns of G_t and G_s in the Newfoundland Basin are similar. Because of that, a choice among G_t , G_s or G_c did not have a significant affect on the results. The gradients were computed from the data on the regular grid and were used as the third dimension in the modified areal analyses. This modification of T-S analysis is, hereafter, called T-S-G analysis, where G is one of G_t , G_s or G_c . Results of T-S-G analysis can be presented in a three-dimensional coordinate system, with T and S axes on the horizontal plane and G as the vertical axis. The high-G part of the diagram represents frontal areas, whereas water masses occupy the low-G part. In the case of two water masses separated by a front, this presentation will show an arch-like structure where the water masses form the bottom supports of the arch and the front occupies the top part of it (Fig. 2).

Errors in spatial gradients increase in transition from a water mass to a front. However, due to the large difference between the gradients in a water mass and a front, their separation is not sensitive to certain variations of the threshold or separation gradient (G^*). This principle was employed to determine the separation value (G^*) by building a relationship between G^* and the area of $G > G^*$ and finding a specific G^* whose variations have the least impact on the area. For example, the corresponding value for temperature gradient at the sea surface was found to be about 4°C/100 km. Note that G^* is a function of spatial and temporal averaging and resolution in the gridded data (*Gulev and Yashayaev, 1991*). G^* also changes seasonally and with depth.

In the case of two adjacent gradient ranges ($G < G^*$ and $G > G^*$) T-S-G analysis produces two separate T-S diagrams representing the waters outside ($G < G^*$) and inside ($G > G^*$) frontal areas. Depending on the depth of analyzed layer, the low-G (water mass) portion of the T-S-G diagram can reveal the Labrador Current, Shelf, Slope, Subarctic Intermediate, Newfoundland Basin Mode and Central North Atlantic waters. In turn, the high-G (frontal) part summarizes properties of the frontal areas at the boundaries of the named waters. The suggested approach solves the mentioned difficulty of separation of the Slope Water and the front. As shown in Figure 2 they entered different G ranges, populating different clusters, and, therefore, can be analyzed separately.

T-S-G area metric analysis was applied to the gridded data to compute temperature, salinity, density and area of the dominant water masses and fronts. The high gradient portion of the T-S-G diagram was used to compute mean temperature and salinity of the front. This point was projected to the low gradient diagram splitting it to warm and cold sectors. The water mass contents of each sector were defined above. Each sector was searched for clusters of high frequency. The resulting clusters were associated with particular water masses. Areas, T and S modal values, medians, means in a certain vicinity of the T-S modes and corresponding deviations were then computed in the detected water mass clusters. These computations were repeated for all standard depths in each survey, and time-depth series of the named characteristics were constructed for the warm, cold and frontal sectors.

Time Series Analysis

The time series were analyzed as a combination of regular seasonal, interannual, irregular seasonal and high frequency variability. Since, eddies and meanders fall in T-S clusters of their source waters, the contribution of high frequency variability to the total variance is significantly less than in the case of a fixed geographical location.

The regular seasonal cycle was defined as

$$\sum_{i=1}^n A_i \cos(\omega_i t + \varphi_i) + A_0 \quad (1),$$

where n is the number of harmonics, ω_i , φ_i , and A_i are the frequencies, amplitudes and phases, consequently, and A_0 is the annual mean. Parameters of the regular seasonal can be obtained by least square fitting of model (1) to monthly means (*Merle (1983), Levitus (1987), Petrie et al. (1991), etc.*).

In the present study the seasonal cycle was approximated by a combination of a mean and the first two harmonics: annual and semiannual, whose joint contribution to the variance of the seasonal cycles exceeded 90%.

Even if the seasonal cycle dominates the variability of the climatic variables, its least square fit is sensitive to outliers (coarse errors) in original data. A data outlier is defined as a point significantly different from estimated typical conditions. The major sources of such outliers are inaccurate or inadequate sampling or some natural phenomena, like an extremely intense mesoscale eddy or an anomalous displacement of a front etc. The low-frequency signal can also affect the estimates of the seasonal cycle, especially when the seasonal distribution of observations (or gaps in such) changed in time. The presence of the gaps in observations can result in uneven distribution of the data through the year and cause aliasing of the low frequency signal in to the seasonal cycle. For these reasons, the estimates of φ_i and A_i can be improved by deleting the outliers and removing the low-frequency variability from the series prior to the final evaluation of the seasonal cycle. To achieve that a special technique was developed to identify the seasonal cycle in the presence of data gaps¹, coarse outliers and the low-frequency variability. This technique is outlined in Appendix A.

¹ Hereafter, a “data gap” refers to a length of time with no data.

Seasonal Cycle

The contribution of the seasonal cycle to the total variability was defined as a fraction of the variance of the seasonal cycle in the variance of original time series. The term “total variability” refers to all variability captured in the time series analyzed in the paper. Assuming statistical independence of the seasonal, low frequency and high frequency components, the sum of the variance of the residuals² and the variance of the seasonal cycle must be close to the variance of the original time series. Some difference between these numbers can arise because of data gaps, insufficient sampling or short duration of time series. The analyzed time series met this requirement within 3% of the original variance. This justified the interpretation of the seasonal-to-original variance ratio as the contribution of the seasonal cycle to the total variability of oceanographic variable.

In the warm sector of the Newfoundland Basin, the seasonal cycle dominates variability of temperature, salinity and density (Fig. 3) in the upper 200 m. The contribution of the seasonal cycle to the variability of temperature decreases monotonically from 94% at 20 m to 17% at 300 m. In the case of salinity, the contribution fluctuates around 50% in the upper 150 m layer, and decrease monotonically with depth at deeper levels.

In the cold sector the contribution of the seasonal cycle to the total variability is generally less than in the warm sector, mostly in a result of the dominance of the low frequency variability associated with large year-to-year variations in temperature and salinity. The contribution of the seasonal cycle to the temperature variability in the upper 30 m layer in the cold sector exceeds 80% and rapidly decreases below 30 m. The contribution of the seasonal cycle to the total variability of salinity is even smaller. It ranges between 40% and 50% above 30 m and drops to 6% at 75 m.

In spite of the relatively low contribution to the total variability in the cold sector, the seasonal cycle of surface temperature and salinity has the highest amplitude there (Fig. 3). The sea surface annual amplitude in the cold sector is almost double that in the warm sector for temperature, and near a factor of four for salinity. However, because of a rapid change with depth, the annual cycle of cold-sector temperature below 20 m is weaker than the corresponding warm-sector cycle. On other hand, the semiannual harmonic in the cold sector becomes more significant at 30 m, reaching 1.2°C at 50 m.

The phase was defined as a time span (in months, positive or negative) between the beginning of the year and the first minimum of the annual harmonic. In both sectors the annual phase increases with depth. In the warm sector the annual phase of temperature at 100 m lags that at the surface by a month. The corresponding lag in the cold sector is about 6 months. The seasonal minimum of surface temperature occur at the same time in the warm and cold sectors, so the seasonal cycle in the cold sector lags the cycle in the warm sector at any depth below the sea surface. The rate of salinity annual phase increase with depth is similar in both sectors and has an order of 5 months per 100 m in the upper 100 m. The differences in the phase distributions of temperature and salinity annual cycle in the warm and cold sectors imply differences in origin of the seasonal variability of these variables.

Seasonal evolution of temperature and salinity is presented in Figure 4. The seasonal cycle here was constructed from annual and semiannual harmonics. In addition to the noted phase delay

² Residuals were computed by subtracting the seasonal cycle from original series.

and decrease of amplitude with depth, the time-depth evolution reveals a subsurface maximum in the salinity in the warm sector. It forms in the early summer at 50 m, deepens through the warm part of the year and disappears by the late winter.

The semiannual oscillations dominate below 50 m in the cold sector. The first temperature and salinity minimum follows the winter cooling and freshening of the surface layer. The second minimum occurs in August-September, half a year later. The first minimum is formed due to local winter convection or surface forcing (resulting in propagation of the annual wave from the surface). The second minimum is associated with the advection of the annual signal with the Labrador Current. This explains the 6 months lag of the annual cycle at 100 m relative to the surface cycle in the cold sector. The annual cycle at the surface is a result of the local heating and cooling, whereas at 100 m the annual cycle is mostly induced by the advection of the seasonal cycle. Assuming that the Labrador Current is the coldest in its origin in February-March, the time required for the cold signal to reach the Newfoundland Basin is about 6 months. This suggests that the speed of the transport of the seasonal signal by the Labrador Current can be anywhere between 6 and 10 cm/sec, depending on the location of the source of the Labrador Current.

Interannual Variability

Interannual temperature and salinity anomalies were obtained by low-pass filtering of the time series with seasonal cycles removed. The results are presented in Fig. 5.

The most remarkable event revealed by this analysis was an intense cold and fresh anomaly in the waters inshore from the Subpolar Front. This anomaly entered the Newfoundland Basin in the summer of 1983 at depths between 75 m and 150 m (Labrador Current and Subarctic Intermediate waters). At the same time the surface conditions were warm (salty) to mild. In the summer of 1984, almost a year later, the anomaly arrived in the surface layer. At the time when the surface waters were in their coldest and freshest state in the winter-spring of 1985, the intermediate waters (between 100 m and 200 m) were already getting warmer and saltier. The total duration of this event in the Newfoundland Basin was between 3 and 4 years. From 1987 to 1991 the inshore waters were generally warmer and saltier than mean conditions.

The time series of warm-sector anomalies reveal a general tendency of increasing temperature and salinity between 1982 and 1991. The anomalies are coherent with depth, resulting in a significant change of integrated heat and fresh water content through the years. The overall average changes of temperature and salinity in the upper 500 m between 1982 and 1991 were estimated as 1°C and 0.2 psu, respectively. This change in salinity corresponds to a loss of 3 m of fresh water from the water column, while the seasonal cycle accounts for only 0.5 m variation in the fresh water content.

Discussion

Interannual variability

The delay in the appearance of cold and fresh anomaly at the sea surface relative to 100 m was explained from analysis of sea surface temperature (SST) extracted from the Comprehensive Ocean-Atmosphere Data set (COADS). The procedure of analysis of the COADS time series was similar to that described in the "Creation and Analysis of Time Series". The anomalies

were averaged over the cold period of the year (November-May) and summarized in the maps presented in Figure 6.

Roughly at the same time when the cold anomaly was found at 100 m in the cold sector of the Newfoundland Basin (1883-1884), the central and western part of the Labrador Sea featured a prominent negative anomaly of SST. Assuming that the advection time from the western Labrador Sea to the Newfoundland Basin is of order of months, the anomaly at 100 m in the cold waters of the Newfoundland Basin is a direct response to the cooling of the Labrador Sea in the early 1980s. This signal was transported by the Labrador Current to the Newfoundland Basin, where it first showed up in the core of the Labrador Current below 50 m.

In 1985-1986 the SST anomaly (Fig. 6) was moving out of the Labrador Sea and progressed south and east. At this stage it entered the Newfoundland Basin in the surface layer and was captured by hydrographic data (Fig. 5) above 60 m. It stayed in the Newfoundland Basin till 1987, as seen in either analysis.

There are several explanations why the propagation of the anomaly is slower above 50 m than below this depth: (i) The advection in the cold layer (50-150 m) is more persistent through the year and less affected by the seasonal variations; (ii) Similarly to the seasonal cycle, the appearance of the interannual anomaly in the cold sector below 50 m can be associated with the advection from the north, whereas the surface anomaly is mostly induced by the change in the local conditions (fluxes, etc); (iii) The water mass structure is different at 0 m and 100 m and due to spatial averaging the estimates presented in the paper represent different water mass contents at these depth.

Acknowledgments

The author is grateful to S. S. Lappo and S. K. Gulev (P.P. Shirshov Institute of Oceanology, Moscow, Russian Federation), who put extensive effort in shaping the Soviet explorations of the Newfoundland Basin. The author also thanks R. A. Clarke and R.M. Hendry (Bedford Institute of Oceanography, Dartmouth, Canada) for their valuable comments and useful suggestions.

Dr. Yashayaev has been supported within the Ocean Sciences Division by climate research funds supplied by the Panel on Energy Research and Development and also through the Ocean Climate Research Program of the Sciences Branch, Department of Fisheries and Oceans. Initially this research was supported by the Russian Ministry of Science and technology as a part of the Federal National Program "World Ocean".

Appendix A

Evaluation of the Seasonal Cycle

The identification of the seasonal cycle was conducted in consecutive iterations of evaluation of the seasonal cycle, removal of the outliers and low-pass filtering (Table 1). Since the seasonal cycle is a major contributor to the total variance (i), is defined by a small number of parameters (ii) and typically there are gaps in time series (iii), a succession of iterations usually started with the evaluation and removal of the seasonal cycle. Another motivation for removing the seasonal cycle before searching for outliers and for using the iterations was the fact that some outliers could be “hidden” within the seasonal range, and after those had been identified and deleted the seasonal cycle was reevaluated on a cleaner data set.

The estimates of A_0 , A_i and ϕ_i in (1) were obtained by least square fitting of a time series with the annual (1 year) and higher order (1/2 year, 1/3 year, etc.) harmonics. After removal of the seasonal cycle, the time series of residuals was examined for outliers. A data point was regarded as an outlier if it differed by more than N median absolute deviations from a median of the data from a moving time window centered in the analyzed data point. The median absolute deviation was computed for the same window as the median. The size of the window was based on the number of available monthly values and varied between 10 years and the whole length of the series. N varied between 5 and 7, depending on assumption about the level of natural noise in the data. This outlier detection was proved to be robust and generally not sensitive to the mentioned variations in N and the size of the median window. Identified outliers were discarded from the series and were not used in the subsequent computations. The time series with the seasonal cycle removed and the outliers excluded was subjected to low-pass filtering³ to establish the low frequency signal. This completed the first round of iterations.

The second round of iterations began with removing the low frequency signal identified in the first round from the original time series with the outliers excluded. The seasonal cycle was then estimated again through harmonic analysis and removed from the time series. This new time series was subjected to the outlier detection procedure again, revealing new points that were thereafter “permanently” excluded from the data used in all subsequent operations. The updated seasonal cycle was then removed from the original series with the outliers excluded and the low frequency signal was reevaluated (by low-pass filtering or polynomial fitting).

All subsequent iterations were similar to the second iteration. Each round of the iterations resulted in updating parameters of the seasonal cycle, revealing new outliers (which had been immediately removed from the original data) and reevaluation of the low frequency component. The results of each round were tested to find out if the seasonal cycle and the low frequency signal didn't change from those estimated in the previous round and if there were no new outliers identified. When both conditions were satisfied, implying that the further iterations wouldn't improve the result, the iterations stopped and the estimates from the last iteration were considered as final. Normally, two or three iterations sufficed.

³ As an alternative way to the low-pass filtering the low frequency signal was also constructed by fitting a polynomial function to the residual time series. The final estimates of the seasonal cycle turn out not sensitive to the choice of the technique of evaluation of the low frequency variability.

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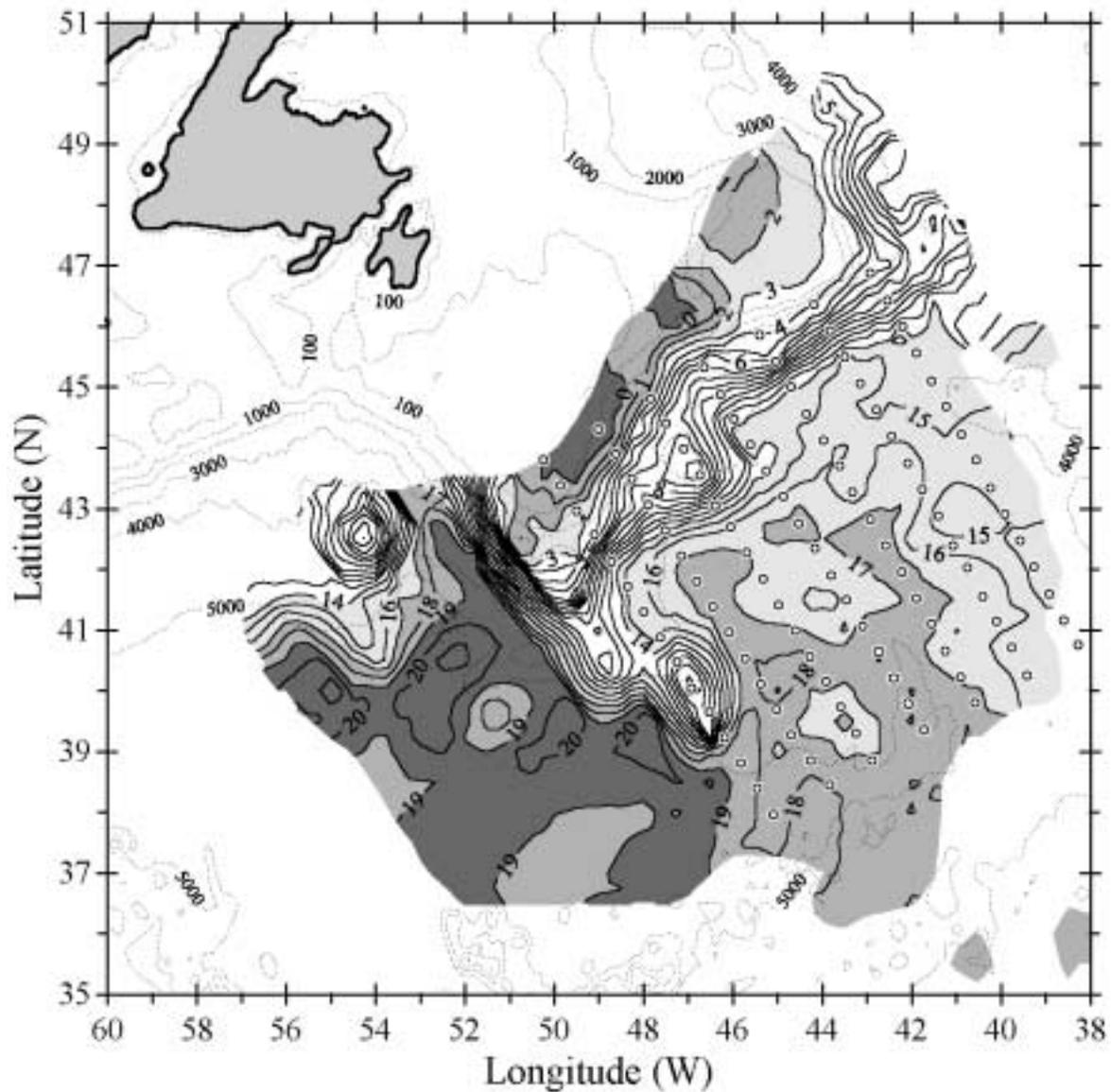


Figure 1. Temperature at 50 db (solid contours) from the May 1990 survey of Newfoundland Basin. Circles show standard station positions, dotted contours - selected bathymetric contours.

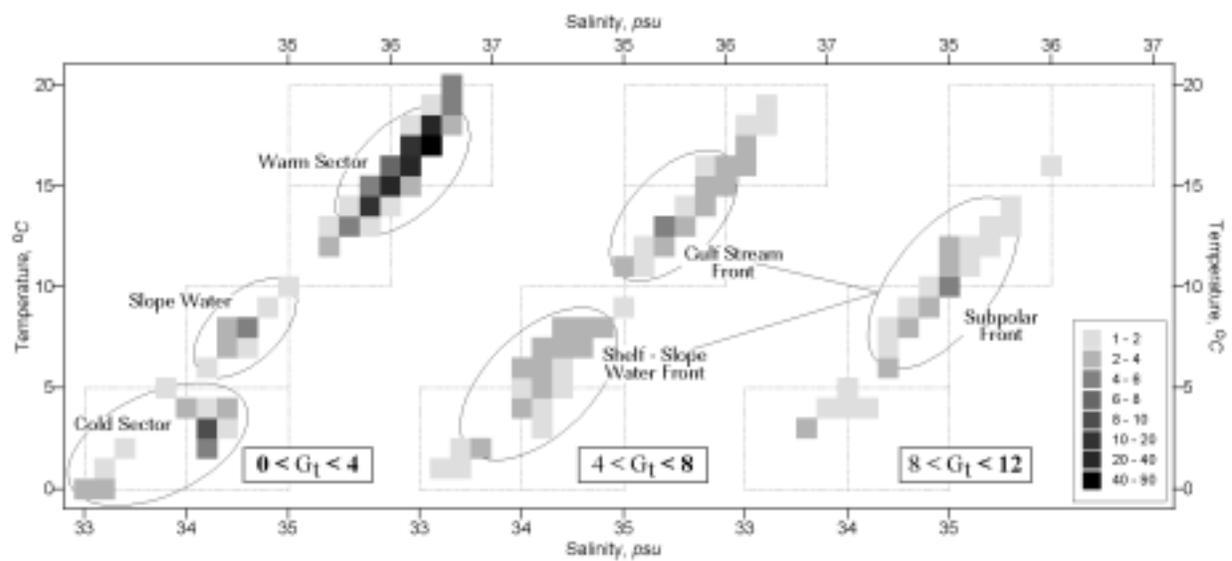


Figure 2. Area occupied by $0.2 \text{ psu} \times 1^\circ\text{C}$ classes in three ranges of temperature gradient (G_t) at 50 db in the May of 1990 (T - S - G_t analysis). The area of analysis was restricted to the standard polygon shown in Fig. 1.

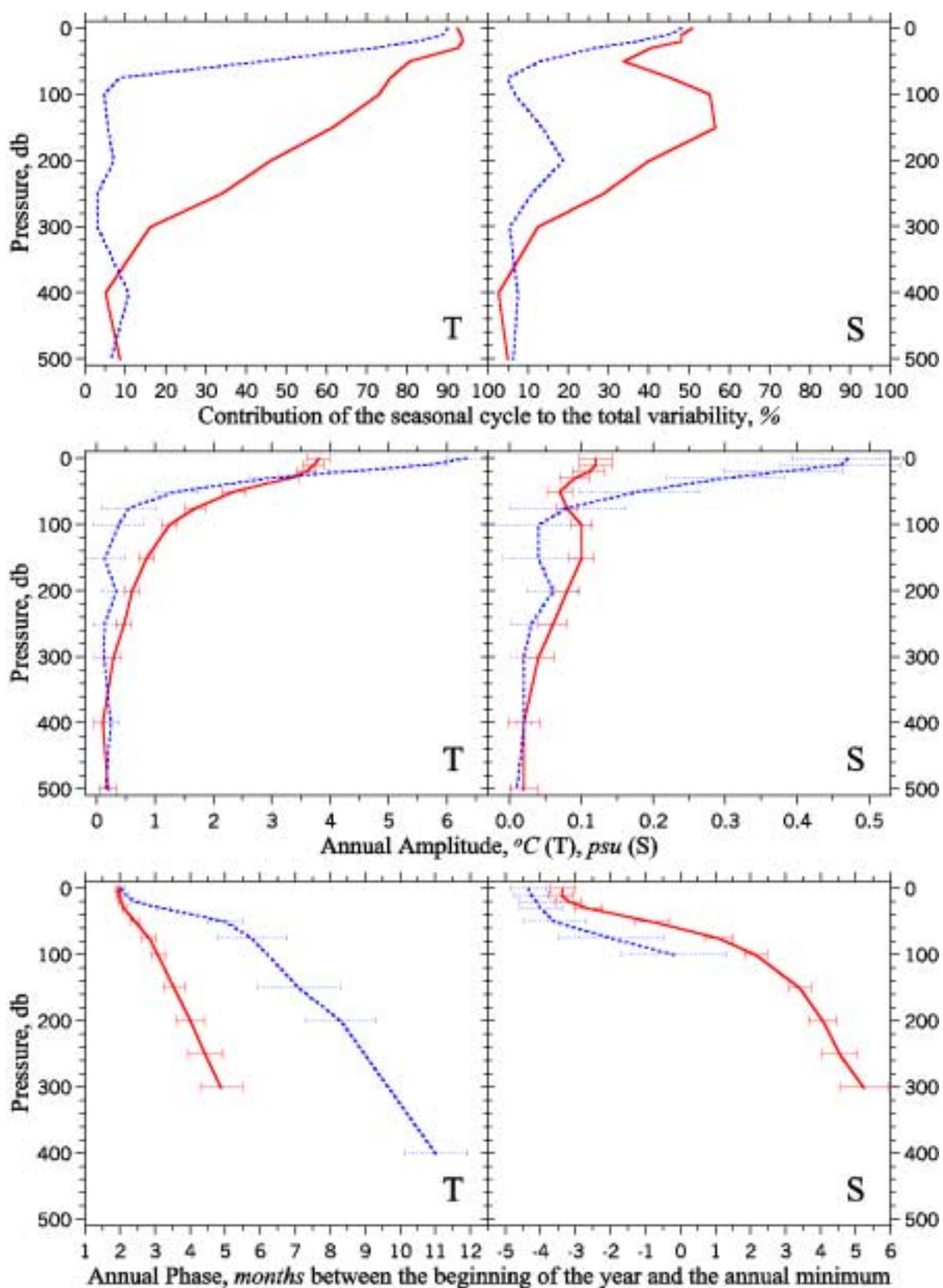


Figure 3. Contributions of the seasonal cycle to the total variability, amplitudes and phases of the annual harmonic of temperature (T) and salinity (S) in the warm and cold (solid and dotted lines, respectively) sectors of the Newfoundland Basin.

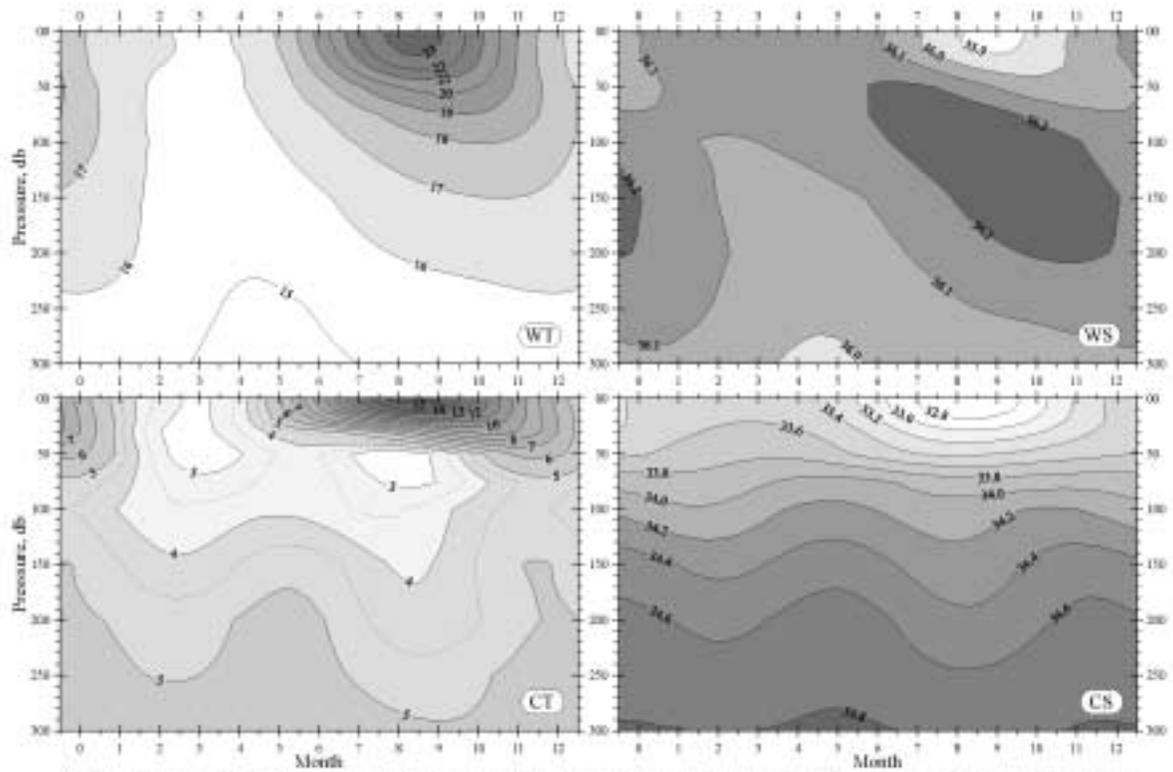


Figure 4. Seasonal evolution of temperature (WT, CT) and salinity (WS, CS) in the warm (WT, WS) and cold (CT, CS) sectors of the Newfoundland Basin

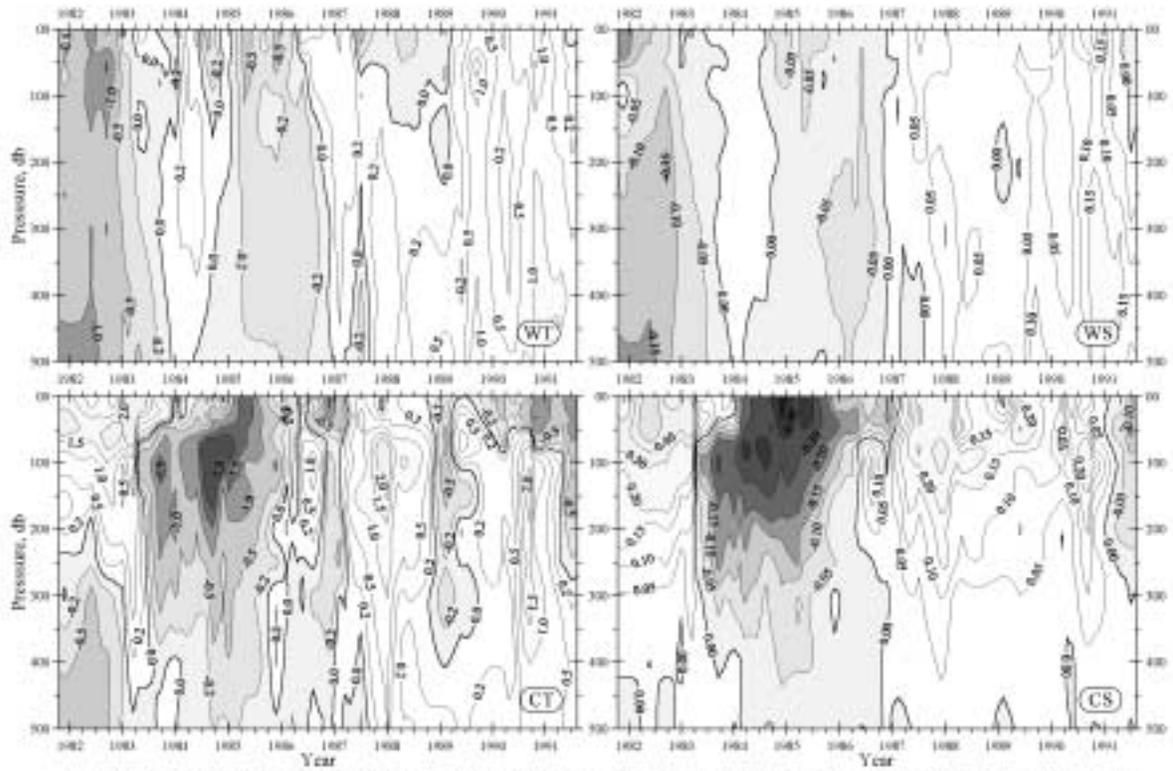


Figure 5. Interannual anomalies of temperature (WT, CT) and salinity (WS, CS) in the warm (WT, WS) and cold (CT, CS) sectors of the Newfoundland Basin

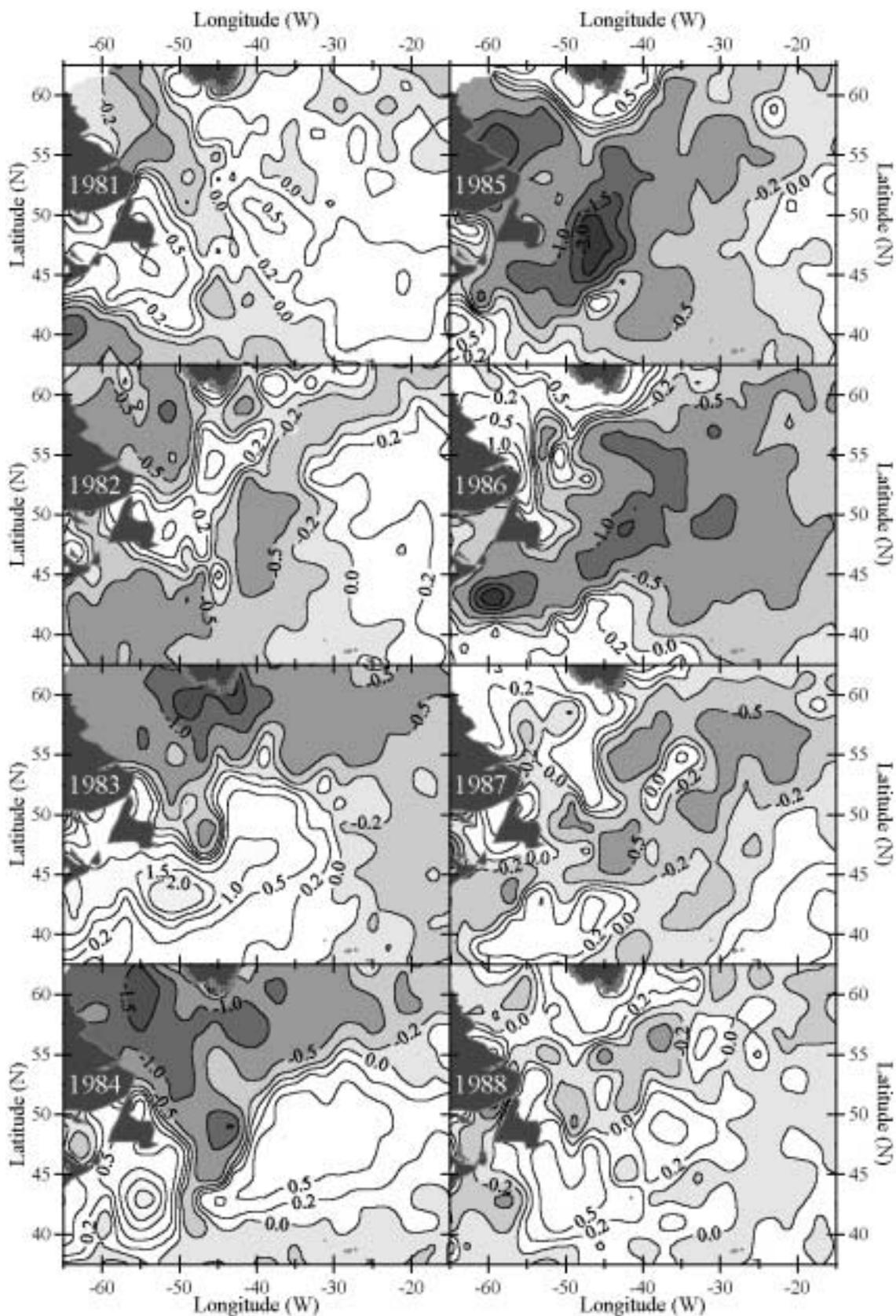


Figure 6. SST anomalies computed from the COADS data and averaged over the cold part of the year (1981 represents November 1980 to May 1981 mean, etc.).