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Development of a Sea Surface Temperature Index for the Canadian East Coast; Nutrient and Dissolved Oxygen Variability on the Scotian Shelf: a Preliminary Report from the Zonal Monitoring Program

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Abstract

We calculate a single ocean climate index from a 17 year time series of satellite-derived, sea surface temperatures for the Canadian east coast from Hamilton Bank to Georges Bank. This index accounts for 59% (49%) of the annual (seasonal) temperature variability. The index is in phase throughout the region, i.e., shows widespread warming or cooling episodes. Comparison with in situ data indicates that the index captures the broad-scale variations of the regional ocean climate, particularly for the Newfoundland Shelf. The annual cycle of nitrate variability for the central Scotian Shelf shows a typical cycle: high nitrate levels at shallow depths during winter, followed by a rapid depletion in spring, low levels throughout the summer and a gradual increase in the late fall. Estimates of the primary production, derived by converting nitrate to carbon, compare favourably with in situ measurements but are substantially smaller than satellite calculations. The nitrate and dissolved oxygen pool on the Scotian Shelf has varied substantially over the past 30 years. Recently, the invasion of the Scotian Shelf by Labrador Slope Water has lead to decreasing nitrate and increasing dissolved oxygen levels, much like what transpired during the mid-60s when a similar event occurred.

Résumé

Nous avons calculé un indice unique du climat océanique à partir d'une série chronologique de données sur la température de la surface de la mer réparties sur une période de 17 ans obtenues par satellite pour la côte est du Canada, du banc Hamilton au banc Georges. L'indice explique 59 % (49 %) de la variabilité annuelle (saisonnière) de la température. Il demeure en phase pour toute la région, indiquant les épisodes généralisés de réchauffement et de refroidissement. La comparaison avec des données obtenues sur place montre que l'indice reflète les variations à grande échelle du climat océanique régional, notamment pour la plate-forme de Terre-Neuve. Le cycle annuel de la variabilité du nitrate dans le centre du plateau néo-écossais est typique : de fortes concentrations de nitrate dans les eaux peu profondes en hiver suivies d'un épuisement rapide au printemps, de faibles valeurs en été et d'une augmentation graduelle à la fin de l'automne. Les estimations de la production primaire, obtenues en convertissant le nitrate en carbone, se comparent favorablement aux valeurs obtenues sur place, mais sont passablement inférieures aux valeurs calculées à partir des données obtenues par satellite. Le bassin de nitrate et d'oxygène dissous du plateau néo-écossais a varié de façon appréciable au cours des 30 dernières années. Récemment, l'arrivée d'eau du talus du Labrador sur le plateau néo-écossais a donné lieu à une baisse du nitrate et à une augmentation des teneurs d'oxygène dissous, comme cela s'est produit au cours du milieu des années 1960 suite à un phénomène semblable.

Introduction

A zonal monitoring program (ZMP) has recently been established for the Canadian east coast (Therriault et al., 1998). The program has a number of goals including the preparation and presentation of annual environmental assessments. The Fisheries Oceanography Committee (FOC) publishes annually an environmental overview that concentrates on physical variables. The ZMP group intends to produce a report that is complementary to the FOC overview. Thus, the ZMP document will have an emphasis on those aspects of ocean climate that get less attention in the FOC summary. Though the ZMP is not fully underway, there are a number of things that the group has initiated in biology, chemistry and physics that warrant at least a preliminary report. At this year's FOC meeting, these reports are presented separately because the structure is not yet in place to present a collated, comprehensive review. We would like the FOC to consider the material and give us an indication of which parts have merit. In addition, the FOC could suggest alternative forms or products that would be useful. The two topics of this paper are quite different: the first presents an analysis and an attempt to find a single, perhaps useful, index of sea surface temperature climate for the east coast; the second reports on the nutrient and dissolved oxygen variability on the Scotian Shelf. The latter topic has also been treated for the Newfoundland region in a companion paper (Pepin and Benoit, 1999).

Sea Surface Temperature

Data

The MCSST (multi-channel, sea surface temperature) dataset provides 18 km by 18 km resolution, weekly temperature estimates for the world's oceans. The dataset begins in October of 1981 and is updated monthly. The boundaries for our east coast region are 35-67^{O}N, 35-77^{o}W. The dataset has 3,931,153 points with 266,193 for 1998, about 17% more return than average. In our region, areas subject to ice cover suffer from a lack of coverage even during months when ice is not present. The Jet Propulsion Laboratory (JPL), who produce the dataset, use particularly severe regional masks for ice that, for example, screen out the Labrador Shelf for most of the year. The dataset for the northwest Atlantic is available on line as a database through the Ocean Sciences Division's website (http://www.mar.dfo-mpo.gc.ca/science/ocean/welcome.html). The monthly SST and SST anomaly images in eps and gif formats are also available at the same site.

Results

Monthly maps of sea surface temperature and temperature anomaly for February, May, August and November 1998 are presented in Figure 1a, b. The monthly temperature maps show the seasonal cycle typical of the region and illustrate the scarcity of data north of 50^{o}N and east of 50^{o}W. This is a quirk of the MCSST dataset and is not a true indication of the availability of data from those areas. We are looking into incorporating the latest JPL SST product, the Pathfinder series which provides finer spatial resolution and better coverage in the North Atlantic, into our database as soon as we have completed intercomparisons with in situ data and verified the Pathfinder's reliability. A complete set of monthly maps for 1981-1996 and the monthly climatologies (based on 1981-1996 observations) were given by Mason et al. (1998). Their report also discussed the accuracy of the MCSST estimates compared to in situ data. In general, monthly (annual) temperatures are accurate to about 1°C (0.6°C), using the in situ data as the standard.

The anomaly maps (1981-1996 base period) show generally near normal temperatures in February for what little data coverage is available (Figure 1b). The May temperatures are above normal over the Grand Banks and into the Gulf of St. Lawrence. In some cases, the 1998 values are as much as 3°C above the average temperatures. The western Scotian Shelf appears to be closer to normal conditions. Generally, above normal conditions appear to persist into summer for the Grand Banks and over the Scotian Shelf, while the Gulf temperatures are within 1°C of normal. By fall, the central and western Scotian Shelf are below normal, whereas the Grand Banks and eastern Scotian Shelf are above normal. Near average conditions prevail in the Gulf of St. Lawrence. Perhaps the most outstanding feature of 1998 was the above normal temperature conditions over the Grand Banks.

A goal of this presentation was to determine if the SST climate for the east coast region can be summarized usefully in a single index. If it can, then an overview of one aspect of ocean temperature can be attained by presenting one, rather than a large number of time series. Of course, some applications will require closer examination of the data from particular areas. Our approach was to compile the MCSST data for 14 regions from Hamilton Bank to Georges Bank, including 4 areas in the Gulf of St. Lawrence (Table 1). The data were extracted by month and year, a monthly climatology created, monthly anomalies calculated, and averaged to seasonal and annual anomalies. Complete datasets were available for 10 of the 14 regions; Hamilton Bank, the Estuary, the NE Gulf of St. Lawrence, and the Bay of Fundy did not have complete time series.

Table 1

Area	Latitude (°N)	Longitude (°W)
Magdalen Shallows	46-48	61-64
NE Gulf of St. Lawrence	49-50	58-61
Estuary	48-49	68-69
NW Gulf of St. Lawrence	49.4-50	65-67
Hamilton Bank	53.5-54.5	54-56
NE Nfld Shelf	48.5-50	51-53
Avalon Channel	46-48	51-53
SE Shoal	44-46	50-52
St. Pierre Bank	45.333-46.333	54-56
Eastern Scotian Shelf	44.2-45.667	58-60
Central Scotian Shelf	43.333-44.333	62-64
Western Scotian Shelf	42.5-43.333	64.5-65.5
Bay of Fundy	44.5-45.5	65-66.333
Georges Bank	41-42	66.5-68

We carried out an empirical orthogonal function (EOF) analysis of the correlation matrix for the 10 areas with complete datasets. The results of that analysis are presented in Table 2 and Figure 2a, b.

The first mode of the EOF analysis of the annual temperature anomalies accounted for 59 % of the variance with nearly equal eigenvector amplitudes with the same sign in each region (Table 2). This indicates that each region contributes approximately the same amount of variance to the first mode. Moreover, the fact that the eigenvector components all have the same sign indicates that the changes for this mode occur in the same sense, i.e., uniform warming or cooling. Mode 2, accounting for only 14 % of the overall variance, features out of phase variability between the Newfoundland Shelf and the rest of the region, similar to the finding of Thompson et al. (1988). The time series of mode 1, along with the annual anomalies for all areas, generally shows above normal conditions in 1983-84, below normal temperature conditions in 1985-86, and near normal conditions in 1987-90; SST conditions were well below normal in 1992, and were followed by an extended period of above normal conditions from 1994 to 1998 (Figure 2a). The limited series from Hamilton Bank (few data), the Estuary, the NW Gulf of St. Lawrence and the Bay of Fundy (these latter 3 series began in 1983) had correlations of 0.41, 0.31, 0.70 and 0.59 with the mode 1 amplitude series. This indicates that these more limited data series would vary in phase with the other 10 regions. Drinkwater et al. (1998) show time series of in situ temperature data throughout the region. Their results, for example, for surface temperatures everywhere, for the 0-175 m vertically averaged temperature anomaly at Sta. 27 off St. John's, for the 200-300 m temperatures in the Gulf of St. Lawrence, are quite similar to the variability displayed for mode 1 (Fig. 2a). The deeper layers on the Scotian Shelf appear to vary the least like mode 1.

Table 2

	Eigenvalue Amplitude Mode 1		**Eigenvalue Amplitude Mode 2**	
Location	**Annual**	**Seasonal**	**Annual**	**Seasonal**
NE Nfld Shelf	0.30	0.31	-0.39	-0.27
Avalon Channel	0.38	0.36	-0.22	-0.37
SE Shoal	0.30	0.32	-0.42	-0.35
St. Pierre Bank	0.38	0.37	-0.20	-0.21
NE GSL	0.34	0.34	0.05	-0.04
MagShlw	0.29	0.32	0.25	0.18
E Scotian Shelf	0.37	0.34	0.01	0.11
C Scotian Shelf	0.31	0.30	0.45	0.40
W Scotian Shelf	0.26	0.27	0.44	0.49
Georges Bank	0.17	0.19	0.36	0.42
Percent Variance	**Annual**	**Seasonal**	**Annual**	**Seasonal**
	59	49	14	14

A similar analysis was carried out for the seasonal data from the 10 regions indicated above. In this case mode 1 captured 49 % of the overall variance; the eigenvector amplitudes show the same behavior for mode 1 and 2 as in the annual case (Table 2). The second mode only accounted for 14% of the overall variance. The time series of the mode 1 eigenvector shows considerable variability at the seasonal time scales (Figure 2b). This is particularly evident for the period from 1987 to 1993.

Conclusions
The analysis has shown that, for a 17 year time series, a single index can capture 59% (49%) of the annual (seasonal) temperature variability in the region. Moreover, this index appears to capture some of these features reported for specific areas and at different depths by Drinkwater et al. (1998a). This indicates that either the annual or seasonal index could be a useful general summary for the ocean sea surface temperature in the region. Additional work is merited to determine if a more general index could be developed.

Nutrient Variability on the Scotian Shelf

Data
The nutrient data are from a database compiled by the Marine Environmental Sciences Division at Bedford Institute. This database was built from observations collected from Fisheries and Oceans surveys as well as missions conducted by universities, consulting groups, private industry and other government institutions.

Results
The annual cycle of nitrate for the central Scotian Shelf, which is comprised of Emerald and Lahave Banks and Basins, was determined from approximately 2,500 observations. It features the highest concentrations at shallow depths in the winter and is followed by a rapid decrease in late winter and early spring (Figure 3). Concentrations remain low throughout the summer before starting to increase in the late fall and early winter. Nitrate levels increase by 40% in the 75-135 m layer from February to August. The increase may reflect the sinking and decomposition of the spring bloom. A similar pattern occurs for the eastern (2,000 points) and western (2,000 points) Scotian Shelf, and for the Gulf of Maine (11,000 points) at shallow depths. The deeper layer increase, also 40%, is observed for the Gulf of Maine from March to October (Figure 3), and there is evidence for the same effect for the eastern Scotian Shelf. The western Scotian Shelf does not have sufficient data to determine the pattern for the deeper layer. Similar variability is seen in the silicate monthly means (there were roughly the same number of silicate observations as nitrate by region).

The Redfield ratio was used to convert the changes in the total nitrate content for depths less than 100 m to carbon and thus provide an estimate of new primary production. A conservative 100 m was chosen to represent a level where primary production would not occur (T. Platt, E. Head, pers. comm.). The procedure was to integrate the monthly nitrate concentrations from the surface to 100 m to get the total nitrate. The difference between months was assumed to have been converted to carbon, i.e., primary production. If the amount of nitrate increased from month to month, then the production was taken as zero. These estimates should be regarded as a lower bound on new production as they neglect production derived from other nitrogen sources in the shallow layer, and any upward vertical flux of nitrate from deeper depths. These production estimates are compared with the in situ estimates for the Scotian Shelf that we could find in the literature (Figure 4). A surprisingly few number of primary production estimates have been made for the Shelf. The Couchlan (1986) and Fournier et al. (1977) measurements are for total production (Figure 4). The *f* ratios from Couchlan are 0.7, 0.3 and 0.3 for March, April and July; these bring the March estimate of new production down slightly from the value of total production, and the April value well below the line. The July estimate moves substantially lower, and into closer agreement with the calculation from nitrate alone. The Fournier et al. estimates are based on incubation periods of daylight to 24 hours; they do not differentiate between new and "regenerated" production. Satellite estimates for the Shelf (Longhurst et al., 1995; G. Harrison, pers. comm.) are also shown in Figure 4. These estimates require knowing the subsurface distribution of chlorophyll, the parameters relating photosynthesis and light, the sun angle and cloudiness. They represent total carbon production. This dataset has considerably higher values, as would be expected, than the nutrient changes predict. Revised estimates of production that incorporate, for example, more chlorophyll profile data are underway from satellite observations for the Scotian Shelf.

The pool of nitrate on the central Scotian Shelf has changed markedly over the years, particularly at depths greater than 100 m (Figure 5). In the mid 1960s, a period when Labrador Slope Water dominated, nitrate levels below 100 m were at or near all time lows with concentrations of about 13 μM. Moreover, dissolved oxygen levels were at or near all time highs with percent saturations of about 70 %. During the early 1980s, a period of intense nutrient sampling, Warm Slope Water dominated and nitrate levels reached 23 μM. Oxygen levels were down to about 40% saturation. The nitrate pool from 0 m to the bottom in the central Scotian Shelf was about 40% greater than during the mid-1960s. Beginning in October, 1997 there was an indication that Labrador Slope Water was exerting a greater influence on the upper portion of the continental slope of the Scotian Shelf (Drinkwater e al. 1998b). By early 1998, this water had penetrated into Emerald Basin, completely flooding it by early spring. This event is reflected in the changes of nitrate and dissolved oxygen concentrations (Figure 5). Thus, for the 1998 season and perhaps extending some time into the future, there is a smaller nutrient pool in the deeper layers of the Scotian Shelf. This could affect the level of primary productivity on the Shelf. It is worthwhile to note however, that it is the flux of nutrients into the upper layer that counts, not necessarily the absolute concentration. This flux would depend on factors such as the strength of the seasonal pycnocline, the wind variability - higher winds promote increased mixing, winds in certain directions produce greater upwelling - the fresh water inflow, the strength of solar radiation, etc. Figure 6 show the density difference between 0 and 50 m and from 50 and 100 m for the central Scotian Shelf (detailed calculations for areas within the Scotian Shelf and Gulf of Maine are given by Drinkwater et al., 1999). Long term variability is evident with perhaps the most outstanding feature of the 0-50 m plot being the 1987-present episode of above normal stratification. On the other hand, from 50-100 m stratification generally increased from the early 1950s to the mid-1980s. In recent years the stratification has decreased. These long term changes in the magnitude of vertical stratification would have had an impact on the vertical mixing and hence on the nutrient fluxes.

Conclusions

We conclude that it would be useful to have a measure of nutrient concentrations in the upper layers for the winter months. This would allow crude estimates of the amount of productivity in the spring bloom. Models that incorporate nutrient recycling, grazing by zooplankton could add additional interpretive power to ongoing nutrient and plankton measurements. It is also evident that the Scotian Shelf undergoes considerable interannual variability in its nutrient pool. Ongoing measurements throughout the year would be able to quantify the changes and help interpret the CPR and fixed station biological datasets that are being collected as part of the ZMP.

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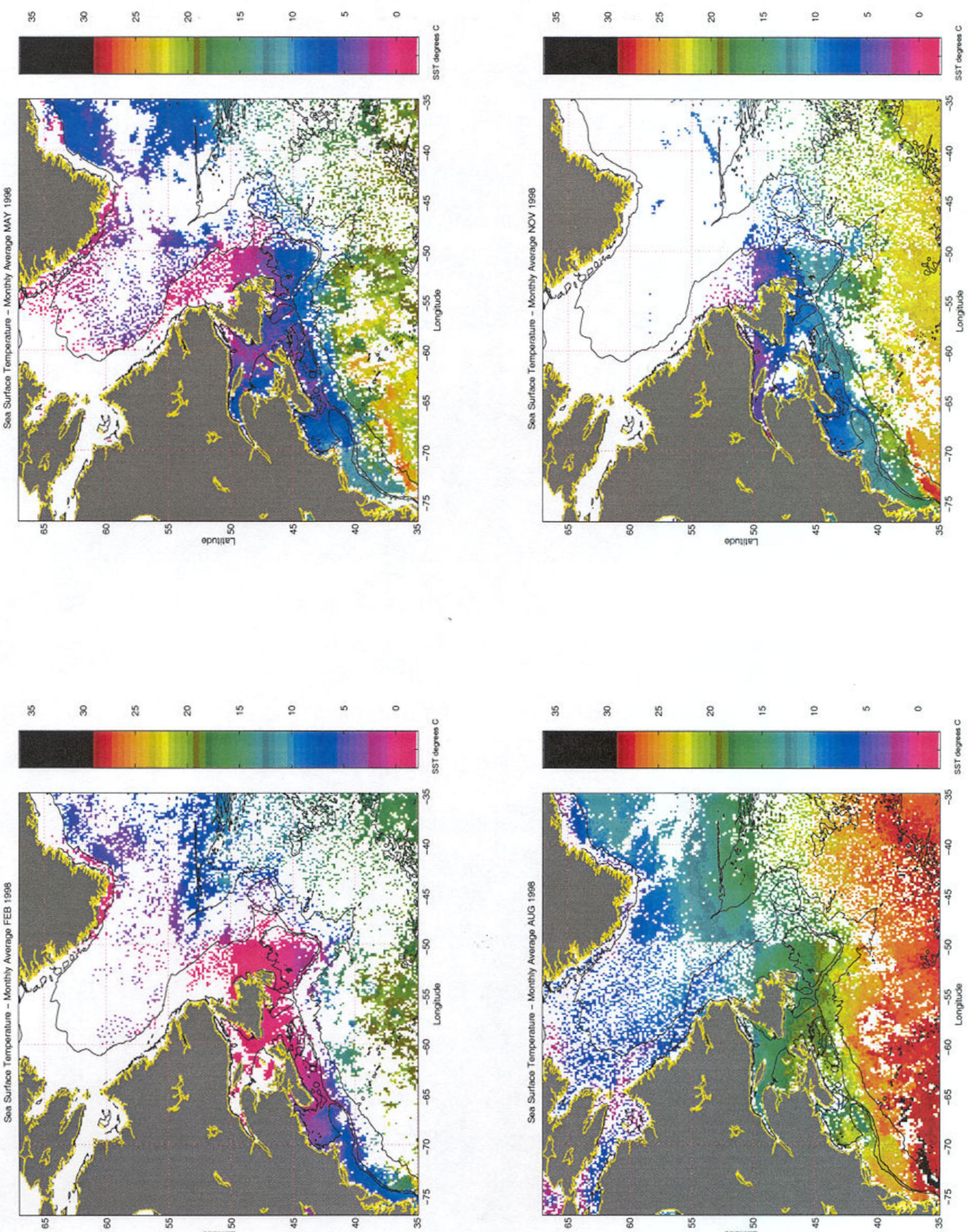


Figure 1a. MCSST for February, May, August and November, 1998.

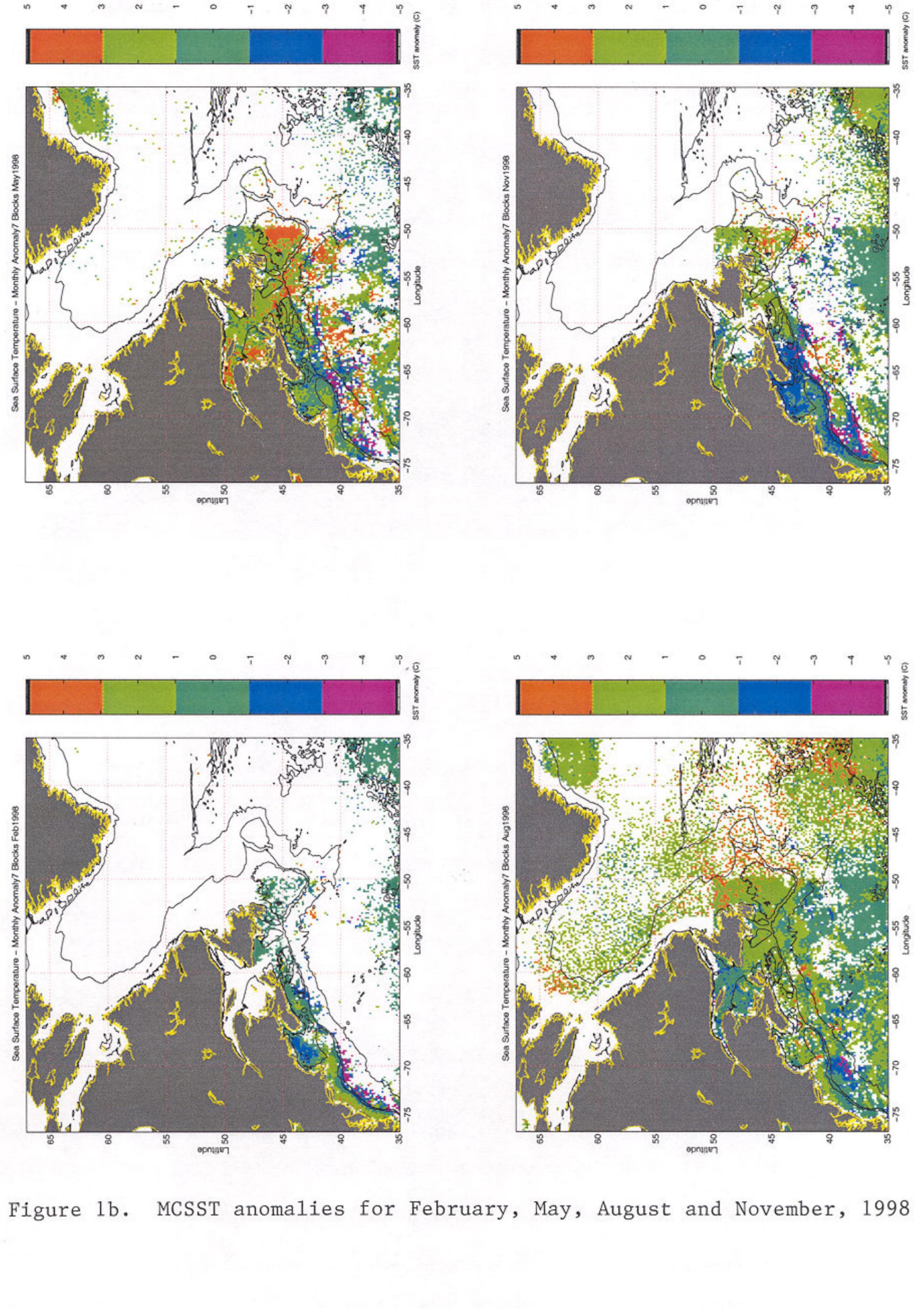


Figure 1b. MCSST anomalies for February, May, August and November, 1998.

Fig. 2a. Annual Sea SurfaceTemperature Anomalies

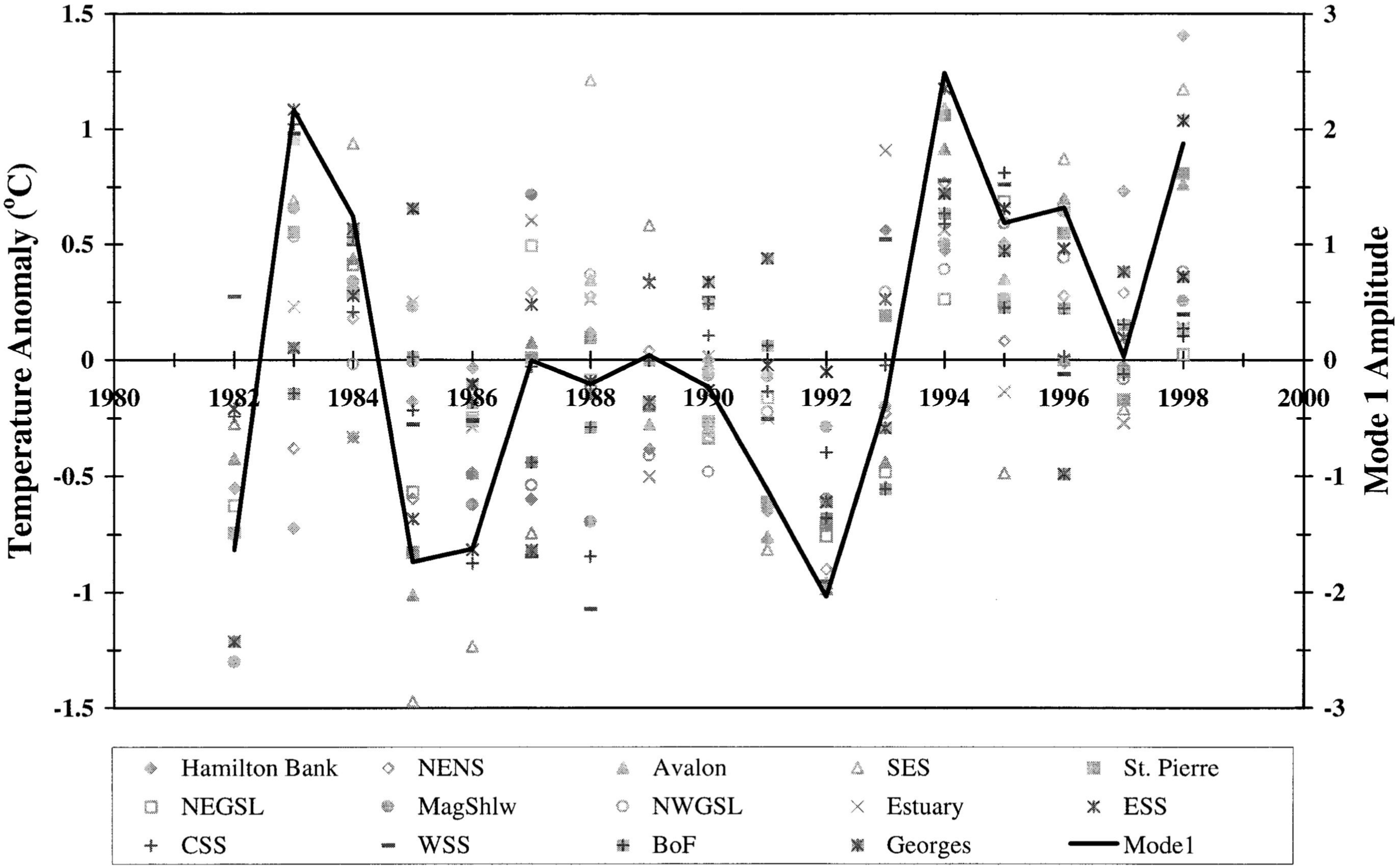
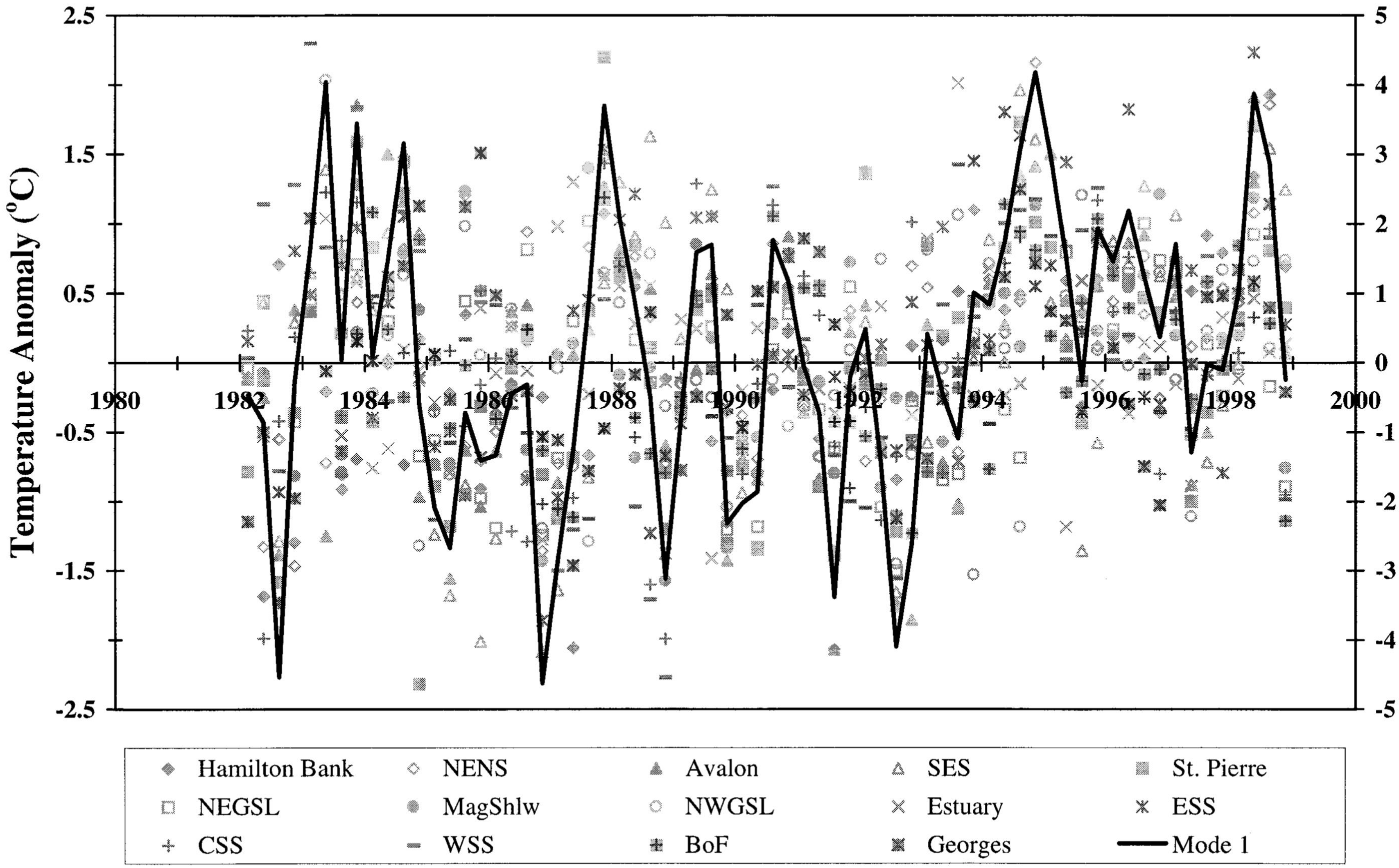


Fig. 2b. Seasonal Sea Surface Temperature Anomalies



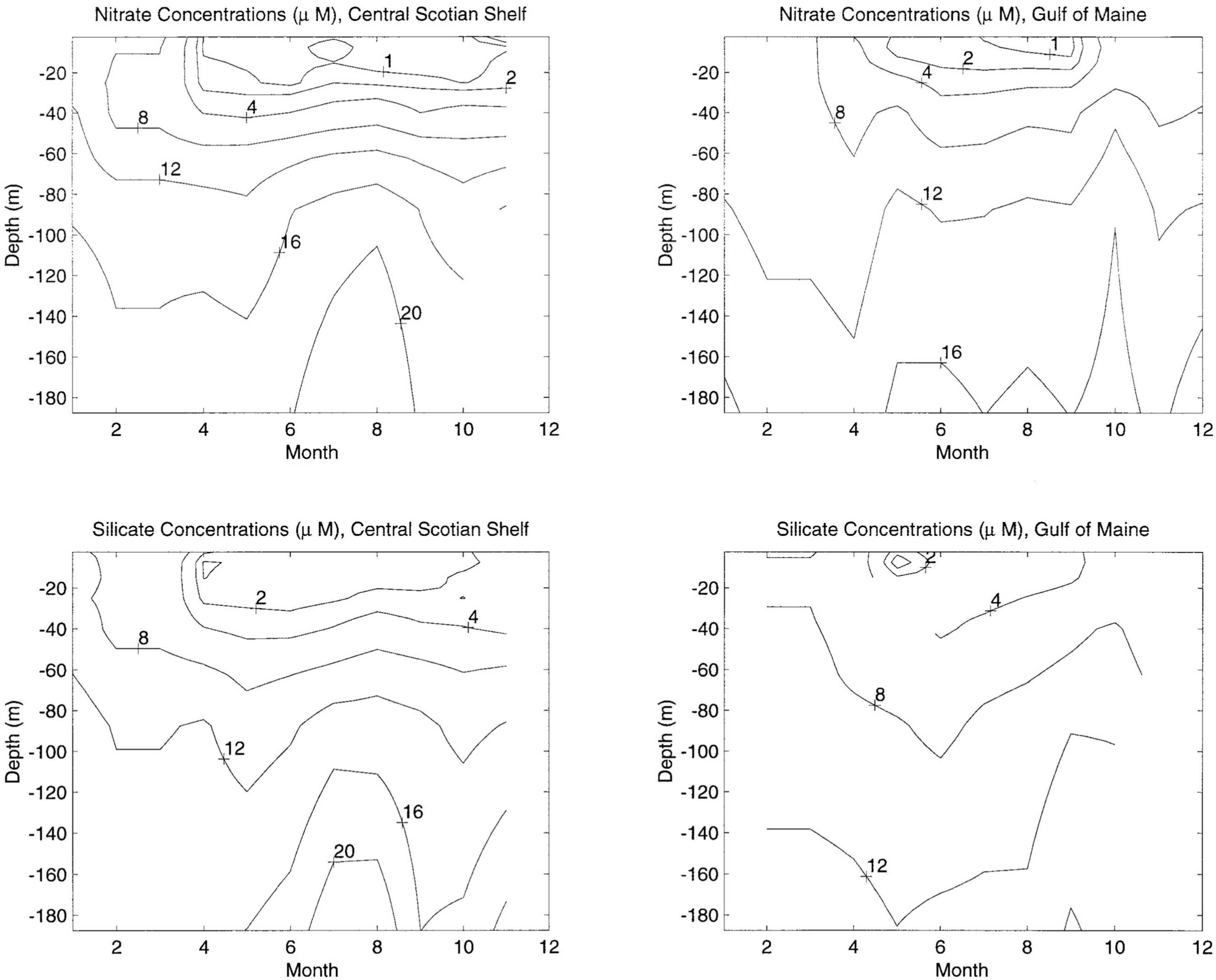
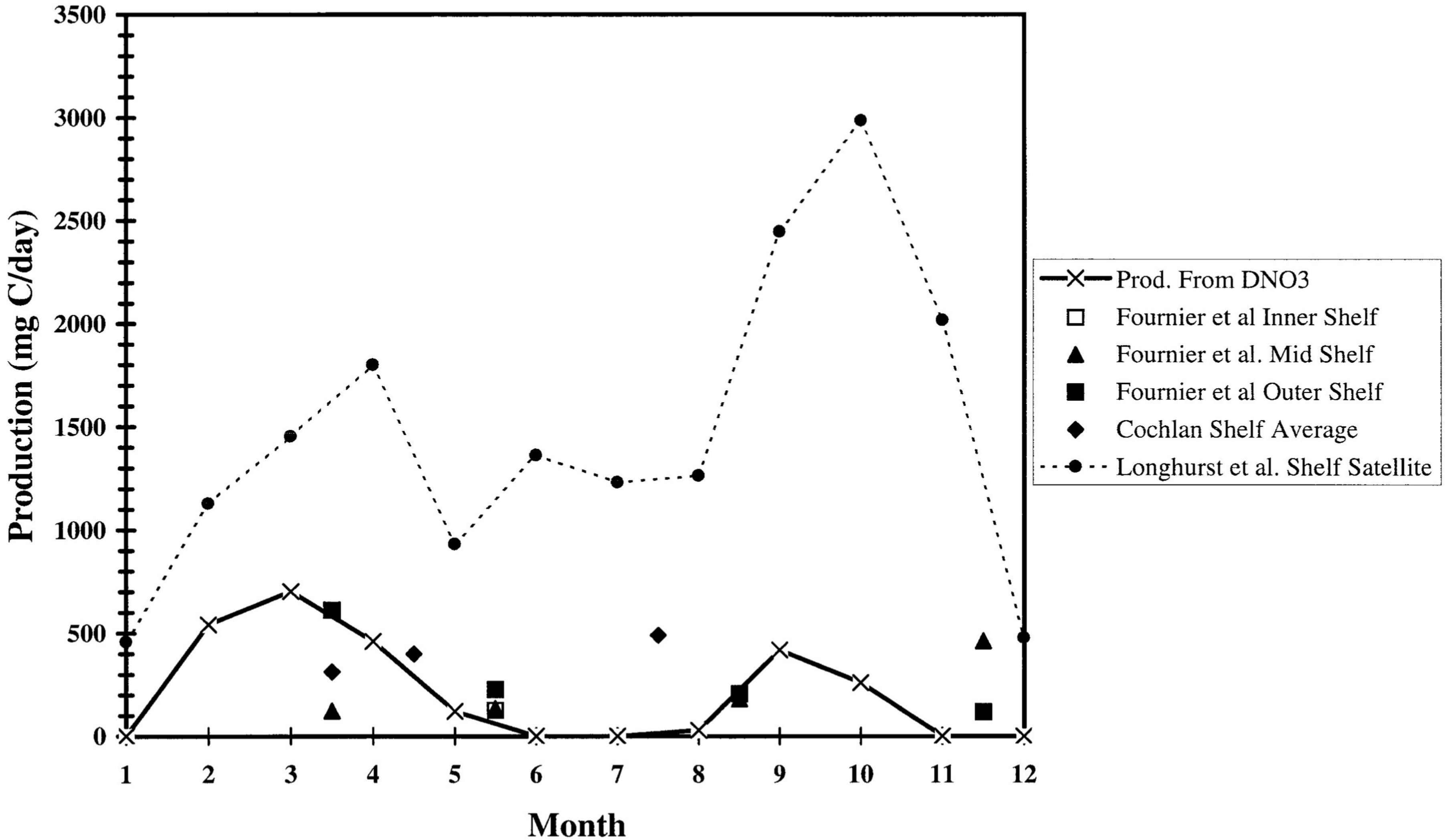
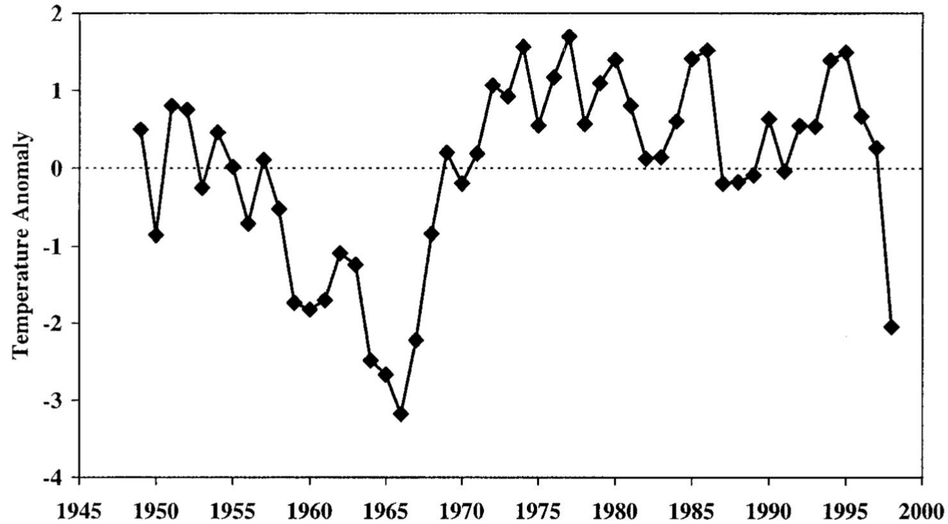


Figure 3. Monthly mean nitrate and silicate concentrations for the central Scotian Shelf and the Gulf of Maine.

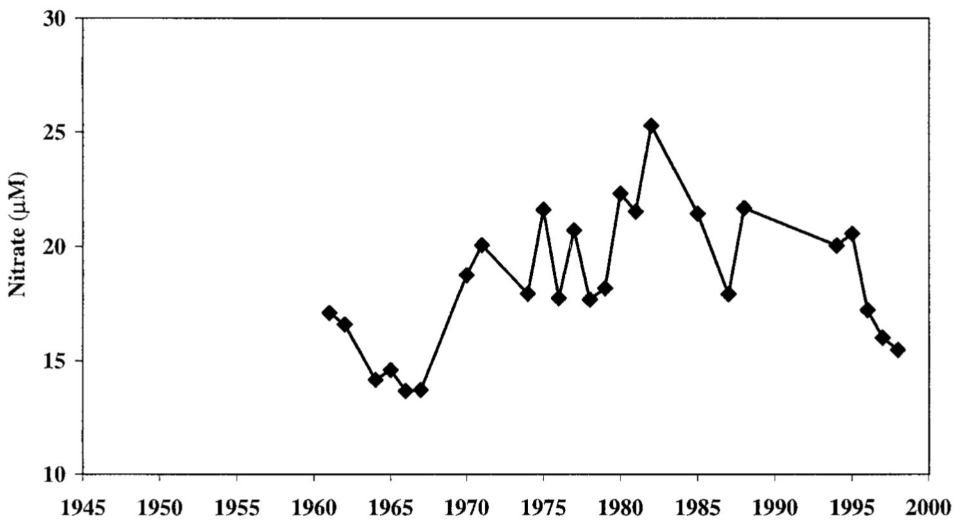
Fig. 4. Production from DNO3 versus in situ Observations



Central Scotian Shelf Temperature Anomaly (100-200m)



Annual Nitrate (μM) Central Scotian Shelf Depth>150m



Dissolved Oxygen (μM) Central Scotian Shelf Z>150m

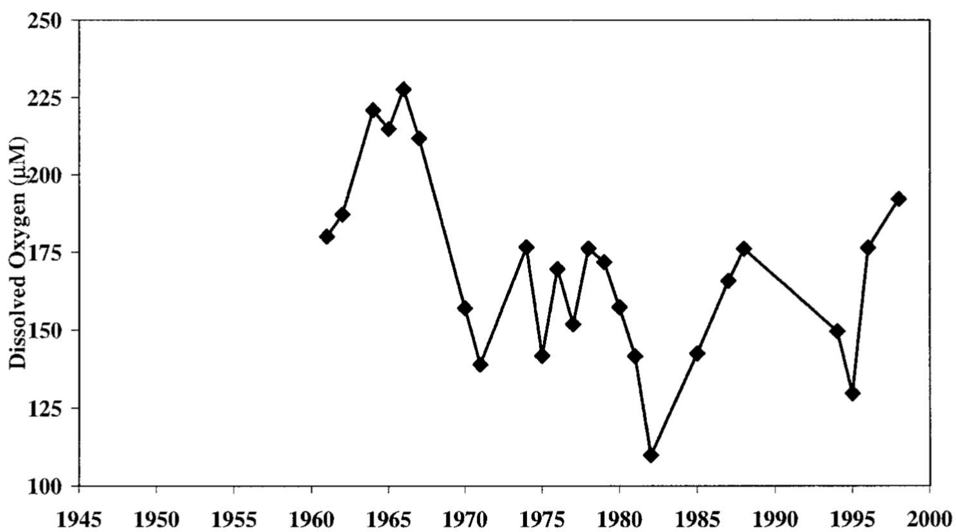


Figure 5. Annual anomalies of temperature 100-200 m, annual average nitrate and dissolved oxygen z>150 m on the central Scotian Shelf.

Fig. 6. Annual Anomaly of Sigma-t Difference 0-50m; 50-100m