Pêches et Océans Canada Sciences
Fisheries and Oceans Canada Science

December / Décembre 2003 No. 3

ATLANTIC ZONE MONITORING PROGRAM

AZMP Bulletin PMZA

PROGRAMME DE MONITORAGE DE LA ZONE ATLANTIQUE

http://www.meds-sdmm.dfo-mpo.gc.ca/zmp/main_zmp_e.html

Content / Table des matières

Edited by / *Édité par*
Jean-Claude Therriault[1], Brian Petrie[2] et Laure Devine[1]
[1]Institut Maurice-Lamontagne
850 route de la Mer, Mont-Joli, QC, G5H 3Z4
[2]Bedford Institute of Oceanography
Box 1006, Dartmouth, NS, B2Y 4A2

therriaultjcsci@dfo-mpo.gc.ca

Le Bulletin du PMZA

Le Bulletin annuel du PMZA publie des articles en anglais, français ou bilingues afin de fournir aux océanographes et aux chercheurs des pêches, aux gestionnaires de l'habitat et de l'environnement, ainsi qu'au public en général les plus récentes informations concernant le Programme de Monitorage de la Zone Atlantique (PMZA). Le bulletin présente une revue annuelle des conditions océanographiques générales pour la région nord-ouest de l'Atlantique, incluant le golfe du Saint-Laurent, ainsi que de l'information reliée au PMZA concernant des événements particuliers, des études ou des activités qui ont eu lieu au cours de l'année précédente.

The AZMP Bulletin

The AZMP annual Bulletin publishes English, French, and bilingual articles to provide oceanographers and fisheries scientists, habitat and environment managers, and the general public with the latest information concerning the Atlantic Zone Monitoring Program (AZMP). The Bulletin presents an annual review of the general oceanographic conditions in the Northwest Atlantic region, including the Gulf of St. Lawrence, as well as AZMP-related information concerning particular events, studies, or activities that took place during the previous year.

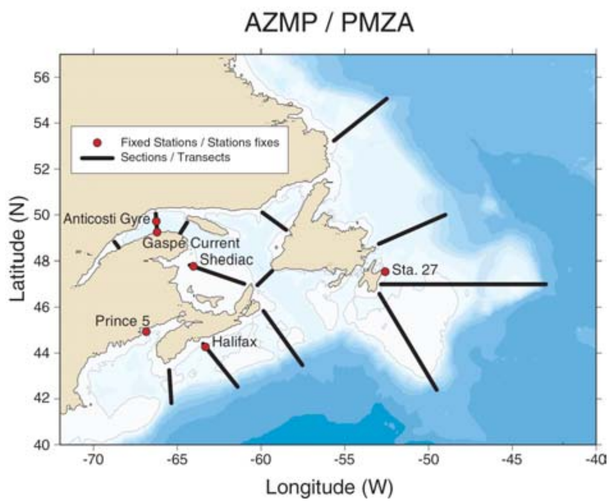


Fig. 1 Location of sections and fixed stations.

Position des transects et des stations fixes.

The Atlantic Zone Monitoring Program

The AZMP was implemented in 1998 with the aim of collecting and analyzing the biological, chemical, and physical field data that are necessary to (1) characterize and understand the causes of oceanic variability at the seasonal, interannual, and decadal scales, (2) provide multidisciplinary data sets that can be used to establish relationships among the biological, chemical, and physical variables, and (3) provide adequate data to support the sound development of ocean activities. AZMP involves the Gulf, Québec, Maritimes, and Newfoundland regions of DFO. Its sampling strategy is based on (1) seasonal and opportunistic sampling along "sections" to quantify the oceanographic variability in the Canadian NW Atlantic shelf region, (2) higher-frequency temporal sampling at more accessible "fixed sites" to monitor the shorter time scale dynamics in representative areas, (3) fish survey and remote sensing data to provide broader spatial coverage and a context to interpret other data, and (4) data from other existing monitoring programs such as CPR (Continuous Plankton Recorder) lines, Sea Level Network, nearshore Long-Term Temperature Monitoring, Toxic Algae monitoring, etc., or from other external organizations (e.g., winds and air temperatures from Environment Canada) to complement AZMP data.

The key element of the AZMP sampling strategy is the oceanographic sampling at fixed stations and along sections. The fixed stations are occupied about every two weeks, conditions permitting, and the sections are sampled from one to three times during the year. The location of the regular sections and the fixed stations are shown in Figure 1. Temperature, salinity, fluorescence, oxygen, chl *a,* nitrates, silicates, and phosphates are measured, and phytoplankton and zooplankton samples are collected. These measurements are carried out following well-established common protocols.

AZMP Personnel

A large number of scientists and technicians carry out the AZMP, either collecting, editing, processing, analyzing, or presenting the data. The following people have each played a significant role in the activities of the program, but the list does not include all of the personnel who have contributed. For those not mentioned in the list, but who have helped during the past years, the AZMP is truly appreciative.

Maritimes Region / Région des maritimes

Ken Drinkwater[1], Doug Gregory[3], Glen Harrison[2], Alex Herman[1], Mary Kennedy[3], Heidi Maass[4], Michel Mitchell[1], Kevin Pauley[2], Brian Petrie[1], Liam Petrie[8], Roger Pettipas[8], Doug Sameoto[2], Jeff Spry[2]

Newfoundland Region / Région de Terre-Neuve

Wade Bailey[1], Charlie Brombey[3], Eugene Colbourne[1], Joe Craig[1], Charles Fitzpatrick[1], Sandy Fraser[2], Daniel Lane[1], Gary Maillet[2], Pierre Pepin[2], Dave Senciall[3], Tim Shears[2], Paul Stead[1]

Le Programme de Monitorage de la Zone Atlantique

Le PMZA a été mis en œuvre en 1998 et vise à collecter et analyser l'information biologique, chimique et physique recueillie sur le terrain afin de (1) caractériser et comprendre les causes de la variabilité océanique aux échelles saisonnières, inter-annuelles et décadales, (2) fournir les ensembles de données pluridisciplinaires qui sont nécessaires pour établir des relations entre les variables biologiques, chimiques et physiques et (3) fournir les données pour le développement durable des activités océaniques. Le PMZA implique les régions du Golfe, du Québec, des Maritimes et de Terre-Neuve du MPO. Sa stratégie d'échantillonnage est fondée sur (1) l'échantillonnage saisonnier et opportuniste le long de «transects» afin de quantifier la variabilité biologique, chimique et physique de l'environnement, (2) l'échantillonnage à plus haute fréquence à des «stations fixes» plus accessibles pour monitorer la dynamique à plus fine échelle de temps dans des régions représentatives, (3) l'utilisation des données provenant des missions d'évaluation de stocks et de la télédétection pour fournir une couverture spatiale plus vaste et le contexte pour l'interprétation des autres données et (4) l'utilisation de données provenant d'autres programmes de monitorage comme les transects CPR («Continuous Plankton Recorder»), les réseaux côtiers de niveau d'eau et de température, le monitorage des algues toxiques, etc., ou provenant d'autres organismes externes (ex. vents et température de l'air de Environnement Canada) pour complémenter les données du PMZA.

L'élément clé de la stratégie d'échantillonnage est la collecte de mesures océanographiques des stations fixes et le long de transects. Les stations fixes sont occupées à toutes les deux semaines, dépendant des conditions, et les sections sont échantillonnées de 1 à 3 fois durant l'année. La localisation des transects et des stations fixes est illustrée à la Figure 1. L'échantillonnage régulier comprend des mesures de température, salinité, fluorescence, oxygène, chl *a*, nitrates, silicates et phosphates, ainsi que la collecte d'échantillons de phytoplancton et de zooplancton. Ces mesures sont effectuées suivant des protocoles communs bien établis.

Personnel du PMZA

Un grand nombre de scientifiques et de techniciens participent au PMZA, soit à la collecte, l'édition, la réalisation, l'analyse ou la présentation des données. Les personnes suivantes ont joué un rôle significatif dans les activités du programme, mais la liste n'inclue pas tout le personnel qui a contribué. Pour ceux qui ne sont pas mentionnés dans la liste, nous aimerions leur exprimer notre gratitude pour l'aide précieuse qu'ils ont fournie au PMZA au cours des dernières années.

Québec Region / Région du Québec

Laure Devine[3], Marie-Lyne Dubé[5], Alain Gagné[5], Yves Gagnon[5], Denis Gilbert[1], Michel Harvey[2], Caroline Lafleur[3], Pierre Larouche[4], Bernard Pelchat[3], Michel Starr[2], Jean-Claude Therriault[2]

Gulf Region / Région du Golfe

Joël Chassé[1], Doug Swain[6]

Marine Environmental Data Service / Service des données sur le milieu marin

Estelle Couture[7], Savi Narayanan[3], Cara Schock[7]

[1] Physical Oceanography / Océanographie physique; [2] Biological Oceanography / Océanographie biologique; [3] Data Management / Gestion des données; [4] Remote Sensing / Télédétection; [5] Sampling & laboratory analyses / Échantillonnage & analyses en laboratoire; [6] Fish Surveys / Missions d'évaluation de poissons; [7] Webmaster / Webmestre; [8] Graphic & data technician / Graphiste et technicien de données.

Environmental Review / Revue environnementale

Physical and Biological Status of the Environment

État de l'environnement physique et biologique

Ken Drinkwater[1] and Pierre Pepin[2]
[1]Bedford Institute of Oceanography, Box 1006, Darmouth, NS, B2Y 4A2
[2]Northwest Atlantic Fisheries Centre, Box 5667, St. John's, NL, A1C 5X1
drinkwaterk@dfo-mpo.gc.ca

Physical Environment

Air temperature and ice cover

During 2002, the North Atlantic Oscillation (NAO) index was below normal for the second consecutive year, indicating a weakening of the Icelandic Low and Azores High during the winter. This caused weaker winds and higher-than-average annual air temperatures from Labrador to the Scotian Shelf. However, the air temperatures fell by approximately 1°C compared to 2001. The relatively warm winter temperatures in eastern Canada resulted in less sea ice than normal off eastern Canada (Fig. 1). While ice generally arrived late and departed early in most areas, causing a shorter ice season than usual, the ice off Newfoundland generally arrived late but remained much longer than usual, resulting in an ice cover duration longer than usual. In contrast, the ice duration within the Gulf of St. Lawrence was the second shortest in the 40-year record. Little ice reached the Scotian Shelf for the fifth consecutive year, and seaward of Cabot Strait the integrated ice area over the ice season was the second lowest in the 41-year record.

Ocean Temperatures

Consistent with the warm air temperatures, above normal sea-surface temperatures (SST) were observed in 2002 throughout most of the Northwest Atlantic. Exceptions included the SST at Halifax and over most of the Scotian Shelf in July. Subsurface temperatures tended to be dominated by positive anomalies. At Station 27 off St. John's, Newfoundland, annual temperatures throughout the water column were warmer than average by up to 0.5°C, conditions that have persisted since the mid to late 1990s. These generally warm conditions resulted in continued low amounts of the cold intermediate layer (CIL) waters during the summer and autumn over the Newfoundland Shelf. Off

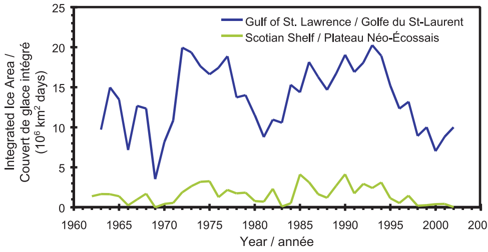


Fig. 1 The integrated area of sea ice (10^6 km^2 x days) over the ice season for the Gulf of St. Lawrence and the Scotian Shelf.

Surface intégrée du couvert de glace de mer (10^6 km^2 x jours) durant la saison des glaces pour le golfe du Saint-Laurent et le plateau Néo-Écossais.

Environnement physique

Température de l'air et couvert de glace

Au cours de 2002, l'index de l'oscillation nord atlantique (ONA) était sous sa valeur normale pour la seconde année consécutive, indiquant un affaiblissement de la basse pression située au-dessus de l'Islande et de la haute pression au-dessus des Azores durant l'hiver. Il en est résulté des vents plus faibles et des températures de l'air plus élevées que la moyenne dans toute la région s'étendant du Labrador jusqu'au plateau continental Néo-Écossais. Cependant, la température moyenne annuelle de l'air a diminué de 1 °C par rapport à 2001. Les températures relativement plus chaudes dans l'est du Canada en hiver ont résulté en une couverture de glace moindre que la normale au large des côtes (Fig. 1). Tandis que dans la plupart des régions, la glace est généralement arrivée plus tard et est partie plus tôt, résultant en une plus courte saison de couverture de glace que la normale, au large de Terre-Neuve, la glace est généralement arrivée plus tard et est demeurée beaucoup plus longtemps que d'habitude, résultant en une durée moyenne d'englacement plus longue qu'à l'habitude. Par contraste, la durée de l'englacement dans le golfe du Saint-Laurent a été la seconde plus courte dans la série de 40 ans de données. Peu de glace a atteint le plateau Néo-Écossais pour la cinquième année consécutive, et au large du détroit de Cabot, la surface intégrée de la région couverte de glace pour toute la saison a été la deuxième plus petite dans la série de 41 ans de données.

Températures océaniques

Cohérent avec l'observation de températures de l'air plus chaudes, les températures de la surface de la mer (TSM) étaient au-dessus de la normale dans toute la région nord-ouest de l'Atlantique en 2002. Les exceptions incluent les TSM à Halifax et sur la plus grande partie du plateau Néo-Écossais en juillet. Les températures sous la couche de surface montraient généralement des anomalies positives. À la station 27 au large de St. John's, Terre-Neuve, les températures annuelles dans toute la colonne d'eau étaient de 0.5 °C plus chaudes que la moyenne; conditions qui perdurent depuis le milieu ou la fin des années 1990. Ces conditions généralement chaudes ont poursuivi la tendance à des quantités relativement faibles d'eau de la couche intermédiaire froide (CIF) au cours de l'été et de l'automne au-dessus du plateau continental de Terre-Neuve. Au large de Bonavista, la surface couverte par la CIF était très semblable à 2001, mais sous la normale à long terme pour la huitième année consécutive; la surface couverte en 2002 est parmi les plus basse observées depuis 1978. À la station de monitorage de Halifax (Station 2) sur la plateau Néo-Écossais, les couches de surface et de fond étaient plus chaudes que la normale. Des eaux particulièrement plus chaudes que la normale ont été observées dans la région est du golfe du Maine et dans la baie de Fundy à toutes les profondeurs. Des eaux chaudes ont aussi été observées à plus de 100 m dans le golfe du Saint-Laurent, dans les parties les plus profondes du détroit de Cabot et dans le

Bonavista, the area of CIL waters was very similar to 2001 and below normal for the eighth consecutive year; the 2002 value is among the lowest observed since 1978. At the Halifax Station 2 monitoring site on the Scotian Shelf, the surface and near-bottom layers were warmer than usual and particularly warm waters were observed in the eastern Gulf of Maine and Bay of Fundy at all depths. Warm waters were also found below 100 m in the Gulf of St. Lawrence, in the deepest reaches of Cabot Strait and in the central Scotian Shelf in Emerald Basin. In contrast to these general warm conditions, the 2002 minimum temperature of the CIL waters within the Gulf of St. Lawrence cooled by 0.1°C relative to 2001. In spite of this cooling, the CIL thickness decreased, which led to a reduction of the bottom area of the Magdalen Shallows covered by CIL waters. Cooling also occurred in 2002 in the near-bottom waters of the northeast Scotian Shelf and in Sydney Bight.

Salinity

Vertically averaged summer salinities at Station 27 and over the Newfoundland Shelf during the fisheries surveys increased by 0.5 over 2001 values to nearly 0.3 above normal, the highest since 1989 (Fig. 2). This appears to end the near decade of record setting low salinities off Newfoundland. Higher salinity conditions dominated during 2002 in sampled areas of the Scotian Shelf and the Gulf of Maine. The vertical stratification in the upper water column (between the surface and 50 m) over the Scotian Shelf continued to weaken in 2002 relative to the last few years and was less stratified than the long-term (1971-2000) average for the second consecutive year.

Chemical and Biological Environment

Nutrients

At Station 27, the seasonal cycle in 0-50 m nutrient concentrations were near normal but were below levels observed in 1999 and 2000 for 50-150 m (Fig. 3).

In the western Gulf of St. Lawrence at the Gaspé Current fixed station, the spring decrease of nitrates and silicates occurred principally in June and coincided with the major pulse of phytoplankton biomass at the Rimouski Station. Silicate and nitrate concentrations in the deep layer (> 50 m) in spring and fall 2002 were comparable to those observed in 2001.

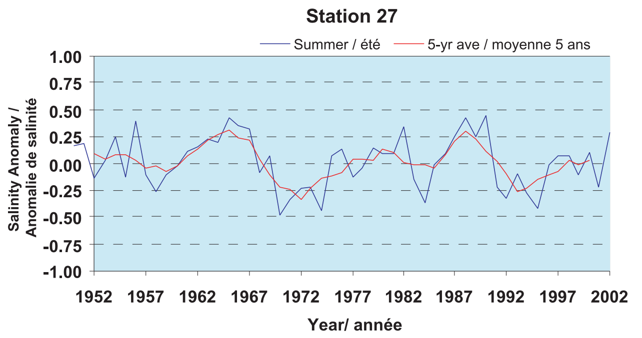


Fig. 2 Average 0-50 m salinity anomalies at Station 27.

Anomalies de salinité moyennes 0-50 m à la station 27.

bassin Emerald situé dans la partie centrale du plateau Néo-Écossais. Contrastant avec ces conditions généralement plus chaudes, la température minimale dans la CIF en 2002 à l'intérieur du golfe du Saint-Laurent a été de 0.1 °C plus froide qu'en 2001. En dépit de ce refroidissement, l'épaisseur de la CIF a diminué, ce qui a conduit à une réduction de la surface du fond occupée par la CIF sur le plateau Madelinien. Un refroidissement s'est aussi produit en 2002 dans les eaux près du fond dans la région nord-est du plateau Néo-Écossais et dans Sidney Bight.

Salinité

La moyenne de salinité en été pour toute la colonne d'eau à la Station 27 et sur le plateau continental de Terre-Neuve durant les missions d'évaluation de stocks de poisson a augmenté de 0.5 en 2001; une valeur près de 0.3 au dessus de la normale, ce qui constitue la plus haute salinité moyenne observée depuis 1989 (Fig. 2). Cette situation représente la fin d'une période de près de dix ans de records de basses salinités établis au large de Terre-Neuve. Des conditions de salinité plus élevées ont cependant été observées en 2002 dans les régions échantillonnées du plateau Néo-Écossais et du golfe du Maine. En 2002, la stratification verticale dans les eaux de surface (0-50 m) au-dessus du plateau Néo-Écossais a continué à diminuer par comparaison avec les dernières années. Ces eaux de surface étaient moins stratifiées que la moyenne à long terme (1971-2000) pour une deuxième année consécutive.

Environnement chimique et biologique

Sels nutritifs

À la station 27, les concentrations des sels nutritifs dans la couche de 0-50 m étaient près des normales saisonnières, mais tout de même sous les niveaux observés en 1999 et 2000 pour la couche de 50-150 m (Fig. 3).

Dans la région ouest du golfe du Saint-Laurent, à la station fixe du courant de Gaspé, la diminution printanière des nitrates et des silicates s'est produite principalement en juin et coïncide avec le pic majeur de biomasse de phytoplancton à la station de Rimouski. Les concentrations de silicates et de nitrates dans la couche profonde au printemps et à l'automne 2002 étaient comparables à celles observées en 2001.

Dans la région des Maritimes, la variabilité saisonnière des sels nutritifs dans les 50 mètres supérieurs de la colonne d'eau, zone dans laquelle les concentrations en sels nutritifs sont fortement influencés par les processus biologiques, indiquent que le pool annuel de sels nutritifs était plus élevé dans les eaux de surface à la station fixe de Shédiac, mais moins élevé à la Station 2 de Halifax en 2002 qu'en 2001. Ce pool de sels nutritifs était cependant significativement plus bas que la moyenne à long terme. Les niveaux annuels à la station Prince 5 étaient semblables en 2002 et en 2001; cependant, les valeurs minimales étaient plus élevées à l'été 2002 que l'année précédente, suggérant peut-être une utilisation biologique moins importante. Les concentrations en sels nutritifs en mai étaient légèrement au-dessus des moyennes à long terme dans le bassin Emerald et dans les eaux profondes de la pente continentale.

Phytoplancton / Chlorophylle

À la station 27, la floraison de phytoplancton a débuté en avril, soit environ un mois plus tôt qu'en 2001. Cependant, les concentrations étaient similaires à 2000 (pic ~11 mg m^{-3}). Le cycle saisonnier de la biomasse de phytoplancton à la station 27 a montré un important pic de concentration dans les 80 m supérieurs de la colonne d'eau en mai. Cependant, la durée de cette floraison où les concentrations de chlorophylle excédaient 1.5 mg m^{-3} était approximativement de 40 jours

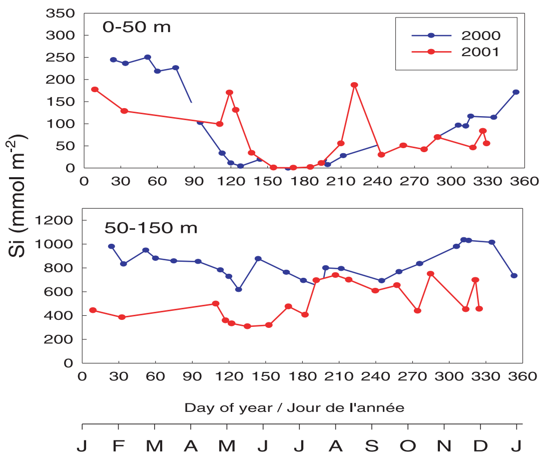


Fig. 3 Integrated silicate concentration in the upper and lower portions of the water column at Station 27.

Concentration intégrée de silicates dans les parties supérieure et inférieure de la colonne d'eau à la station 27.

In the Maritimes Region, seasonal variability in nutrients in the upper 50 m (nominal depth over which nutrient changes are strongly influenced by biological processes) indicated that annual inventories were higher in surface waters at the Shediac Valley fixed station but lower at the Halifax Station 2 in 2002 than in 2001, and significantly lower than the long-term average. Annual levels at Prince 5 were similar in 2002 and 2001; however, summertime minimum values were higher than in previous years, perhaps indicating that biological consumption had decreased. Nutrient concentrations in May were slightly above the long-term average in surface waters but below the average in Emerald Basin and in deep slope waters.

Phytoplankton / Chlorophyll

At Station 27, the onset of the spring phytoplankton bloom occurred in April, about one month earlier than in 2001, but with chlorophyll concentrations (peak ~11 mg m^{-3}) similar to 2000. The seasonal cycle in phytoplankton biomass at Station 27 showed a large peak concentration in the upper 80 m of the water column in May. However, the duration of this bloom, where chlorophyll concentrations exceeded 1.5 mg m^{-3}, was approximately 40 days shorter than in 2000. Following that, there were small amounts of phytoplankton below the surface that persisted throughout the summer and fall.

Compared to our previous observations, the chlorophyll *a* levels in the Gaspé Current and the Anticosti Gyre were generally lower in 2002 than in 1999 but relatively comparable to 2001. For a second consecutive year, we noted the massive presence of the diatom *Neodenticula seminae* in the Gulf of St. Lawrence. This phenomenon is unusual since this species is normally only found in North Pacific waters.

Because of the presence of ice in the southern Gulf in the spring, only the latter phase of the spring bloom is normally caught in sampling at Shediac Valley. Persistently high chlorophyll concentrations, at times exceeding 12 mg m^{-3}, were seen at Shediac Valley throughout the sampling season (Fig. 4). This is in marked

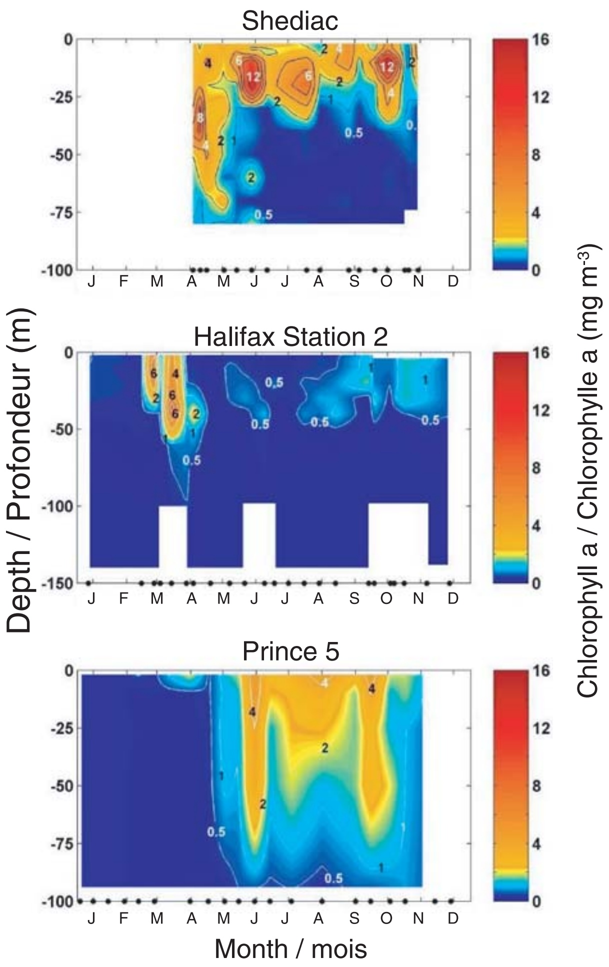


Fig. 4 Seasonal cycle in chlorophyll concentration in the southern Gulf of St. Lawrence (Shediac), Scotian Shelf (Station 2), and Bay of Fundy (Prince 5).

Cycle saisonnier de la concentration en chlorophylle dans le sud du golfe du Saint-Laurent (Shédiac), sur le plateau Néo-Écossais (Station 2) et dans la baie de Fundy (Prince 5).

plus courte qu'en 2000. À la suite de la floraison printanière, une petite quantité de phytoplancton a persisté sous la couche de surface pendant tout l'été et l'automne.

Par comparaison, les niveaux de chlorophylle dans le courant de Gaspé et la gyre d'Anticosti étaient généralement plus bas en 2002 qu'en 1999, mais relativement comparables à 2001. Pour la deuxième année consécutive, nous avons noté la présence massive de la diatomée *Neodenticula seminae* dans le golfe du Saint- Laurent. Ce phénomène n'est pas habituel parce que cette espèce ne se retrouve normalement que dans les eaux du Pacifique Nord.

En raison de la présence de la glace dans le sud du Golfe au printemps, seulement la dernière partie du bloom printanier est normalement observée à la station de Shédiac au cours de la saison d'échantillonnage. Des niveaux élevés persistants, parfois excédant 12 mg m^{-3}, ont été observés à la station de Shédiac tout au cours de la saison d'échantillonnage (Fig. 4). Ceci est en contraste marqué avec les faibles valeurs (< 2 mg m^{-3}) de chlorophylle observées en été et à l'automne à contrast to low (< 2 mg m^{-3}) summer/autumn chlorophyll levels observed at this station in previous years. The phytoplankton growth cycle in 2002 at the Halifax Station 2 was similar to that observed in previous years, characterized by a short-lived spring bloom and moderate (concentrations <2 mg m^{-3}) autumn bloom. In 2002, the spring bloom was earlier by 2 weeks than in 2001 and earlier than the long-term average timing of the bloom. The phytoplankton growth cycle at Prince 5 was characterized by a single sustained burst of growth beginning in early summer and lasting until autumn. The initiation of phytoplankton growth at Prince 5 in 2002 was later by more than 6 weeks compared with 2001.

Near-surface phytoplankton biomass was also assessed from ocean colour data collected by the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) satellite launched by NASA in late summer 1997. Satellite data provide high-resolution (1.5 km) data on the geographical distribution of phytoplankton/ chlorophylle in surface waters. The satellite information is generally consistent with in situ observations. The timing of peak surface chlorophyll concentrations in 2002 had generally returned to near average conditions on the southern part of the Newfoundland Shelf. However, in offshore and northern regions, where the influence of the Labrador Current is more important, the onset of the spring bloom remained later than was observed in the late 1990s. In contrast to 2001, satellite data showed a greater spatial variability in the timing of the spring bloom in the Gulf of St. Lawrence in 2002. The onset of the spring bloom along all the Scotian Shelf sections in 2002 appeared similar to the onset in 2001, but the duration appeared longer on the eastern shelf and shorter on the central shelf in 2002. At the larger scale, it is apparent, for example, that the magnitude of the spring bloom on the Eastern Shelf has steadily decreased since 1998 with the lowest values on record in 2002.

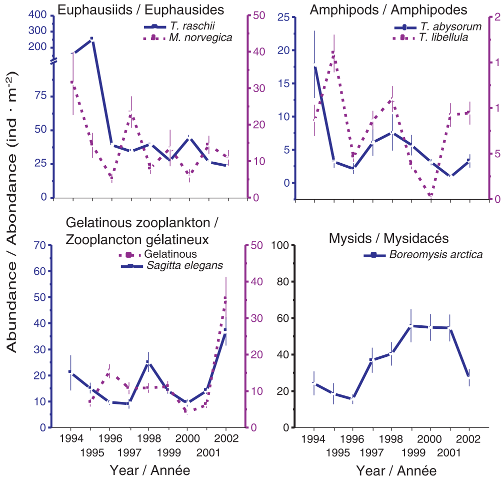


Fig. 5 Mean abundance of the most important species of macrozooplankton in the Lower St. Lawrence Estuary and the northwest Gulf of St. Lawrence from 1994 to 2002.

Abondance moyenne des plus importantes espèces de macrozooplancton dans l'estuaire maritime et le nord-ouest du golfe du Saint-Laurent de 1994 à 2002.

Zooplankton

In 2002, the overall abundance of zooplankton in the Newfoundland region was similar to levels observed in the previous year, although numbers were higher in the winter of 2002 due to an increase in the abundance of two species of small copepods. The overall species composition was similar to that encountered in previous years, but the abundance and occurrence of copepod species normally associated with cold waters (*Calanus glacialis, Calanus hyperboreus*, and *Microcalanus* sp.) have shown a gradual increase since 1999 whereas a species normally found in relatively warm waters, *Temora longicornis*, declined. The onset of

cette station au cours des années précédentes. Le cycle de croissance du phytoplancton en 2002 à la Station 2 de Halifax était similaire à celui observé durant les années précédentes, caractérisé par une courte floraison printanière avec des concentrations modérées (concentrations <2 mg m^{-3}) et une floraison automnale de très courte durée. En 2002, la floraison printanière a débuté deux semaines plus tôt qu'en 2001 et aussi, plus tôt que la moyenne à long terme. Le cycle de croissance du phytoplancton à Prince 5 est caractérisé par un seul pic soutenu de croissance débutant au début de l'été et persistant jusqu'à l'automne. L'initiation de la croissance du phytoplancton à Prince 5 en 2002 était plus tardive de plus de 6 semaines en comparaison avec l'année 2001.

La biomasse de phytoplancton en surface a aussi été estimée à partir des données de la couleur de l'océan collectée par le capteur SeaWiFS («Sea-viewing Wide Field-of-View Sensor») lancé par la NASA à la fin de l'été 1997. Les données satellites fournissent des données haute résolution (1.5 km) sur la répartition géographique du phytoplancton/ chlorophylle à la surface de la mer. L'information satellite est généralement cohérente avec les observations in situ. L'apparition du pic de concentration de chlorophylle en surface en 2002 est généralement revenue vers des conditions moyennes dans la région sud des côtes de Terre-Neuve. Cependant, dans les régions du large et du nord de Terre-Neuve, où l'influence du courant du Labrador est plus importante, le début du bloom printanier est demeuré plus tardif que ce qui avait été observé dans les années 1990. Contrairement à 2001, les données satellites en 2002 dans le golfe du Saint-Laurent ont montré une plus grande variabilité spatiale dans l'apparition de la période de floraison printanière du phytoplancton. Le début de la floraison le long du plateau Néo-Écossais en 2002 apparaissait similaire à celui de 2001, mais la durée de cette floraison a été plus longue dans la région est et plus courte dans la région centrale du plateau continental en 2002 qu'en 2001. À plus grande échelle, il semble, par exemple, que l'amplitude de la floraison printanière dans la région est du plateau continental a diminué régulièrement depuis 1998 avec les plus faibles valeurs de la série observées en 2002.

Zooplancton

En 2002, l'abondance globale du zooplancton dans la région de Terre-Neuve était semblable à celles observées au cours des années précédentes, quoique les nombres étaient plus élevés à l'hiver de 2002, dû à une augmentation dans l'abondance de deux petites espèces de copépodes. La composition spécifique globale était semblable à celles des années précédentes, mais l'abondance et l'apparition d'espèces de copépodes normalement associées avec les eaux froides (*Calanus glacialis, Calanus hyperboreus* et *Microcalanus* sp.) ont montré des augmentations graduelles depuis 1999, tandis qu'une espèce normalement associée avec des eaux relativement chaudes, *Temora longicornis*, a diminué. Le début de la période de reproduction de *Calanus finmarchicus* semble production of *Calanus finmarchicus* appeared to return to normal relative to previous years, with the peak abundance occurring about one month earlier than was observed in 2001. In the summer of 2002, the abundance of most groups of zooplankton appeared to be higher along the Labrador Shelf than was observed in previous years.

The total mesozooplankton biomass observed in September 2002 in the Lower Estuary and in the northwest Gulf of St. Lawrence was ~25% higher than in 2000 and 2001 but comparable to levels observed in the late 1990s. Macrozooplankton biomass was similar to measurements taken between 1998-2001 (Fig. 5). The most notable feature of the mean annual abundance of the various macrozooplankton species in 2002 was an important increase of the abundance of chaetognaths and gelatinous zooplankton and a decrease of the abundance of mysids. In 2002, the overall biomass of zooplankton observed in the Anticosti Gyre was comparable with what we observed in 1999, 2000, and 2001 while the overall zooplankton biomass in the Gaspé Current was slightly higher than in 2001 and 2000. However, the total abundance was generally consistent with previous observations. The zooplankton biomasses observed in 2002 along all sections for both seasons was comparable with observations made in 2001 and 2000.

Zooplankton biomass at all of the Maritimes/Gulf fixed stations was generally lower in 2002 than in 2001. Biomass was the highest on record in 2001, and levels in 2002 appear to have reverted back to levels seen in earlier years. *Calanus finmarchicus* abundance at Shediac Valley has increased over the 4-year observation period while at the Halifax Station 2, it progressively decreased over the same period. *C. finmarchicus* abundance at Prince 5 was also lower in 2002 than in 2001, but numbers at this station were highest on record in 2001; 2002 levels appeared to revert to levels seen in earlier years. Significant numbers of jellies and related plankton were seen at Shediac Valley and Halifax 2 in early summer for the first time and a recurring pulse of echinoderm and barnacle larvae was observed again in 2002 at Prince 5 in spring. Total *C. finmarchicus* abundance dramatically decreased at Halifax Station 2 over the 4-year observation period; trends at the other two stations are not as apparent.

retourner à la normale relativement aux années précédentes, avec un pic d'abondance se produisant environ un mois plus tôt que celui observé en 2001. Durant l'été de 2002, l'abondance de la plupart des groupes de zooplancton semble être plus élevée le long des côtes du Labrador que ce qui a été observé durant les années précédentes.

La biomasse totale de mésozooplancton observée en septembre 2002 dans l'estuaire maritime du Saint-Laurent et dans la région nord-ouest du Golfe était ~25 % plus élevée qu'en 2000 et 2001 mais comparable aux niveaux observés vers la fin des années 1990. La biomasse du macrozooplancton était similaire à celles observées entre 1998 et 2001 (Fig. 5). La caractéristique la plus remarquable de l'abondance annuelle des diverses espèces de macrozooplancton en 2002, était une augmentation importante de l'abondance des chaetognates et du zooplancton gélatineux et une diminution de l'abondance des mysidacés. En 2002, la biomasse globale du zooplancton observée dans la gyre d'Anticosti était comparable avec celle observée en 1999, 2000 et 2001, tandis que dans le courant de Gaspé, la biomasse totale du zooplancton était légèrement plus élevée qu'en 2000 et 2001. Cependant, l'abondance totale était généralement cohérente avec les observations précédentes. La biomasse de zooplancton observée en 2002 le long de toutes les sections aux deux saisons était comparable avec les observations faites en 2001 et 2000.

La biomasse de zooplancton à toutes les stations fixes des régions des Maritimes et du Golfe était généralement plus basse en 2002 qu'en 2001. La plus grande biomasse de zooplancton jamais observée dans la série de données l'a été en 2001 et il semble qu'en 2002, le niveau de la biomasse zooplanctonique soit retourné aux valeurs normales des années précédentes. L'abondance de *Calanus finmarchicus* à Shédiac a augmenté durant les 4 dernières années où l'on possède des observations tandis qu'à la Station 2 de Halifax, la biomasse a progressivement diminué durant la même période. L'abondance de *C. finmarchicus* à Prince 5 était aussi plus basse en 2002 qu'en 2001, mais les niveaux à cette station étaient les plus élevés de la série de données en 2001; les niveaux de 2002 semblent être retournés aux niveaux observés durant les années précédentes. Des nombres significatifs de zooplancton gélatineux et du plancton associé ont été observés à Shédiac et à la station 2 de Halifax en début d'été pour la première fois et un pic récurrent de larves d'échinodermes et de larves de balanes a été observé encore en 2002, à Prince 5, au printemps. L'abondance totale de *C. finmarchicus* a diminué drastiquement à la Station 2 de Halifax durant la période de 4 ans d'observations; les autres stations ne montraient pas aucune tendance.

Publications

Primary Publications / Publications primaires

Colbourne, E. B., and J. T. Anderson. 2003. Biological response of a changing ocean environment in Newfoundland waters during the latter decades of the 1900s. ICES Mar. Sci. Symp. 219: 169-181.

Greenan, B.J.W., B.D. Petrie, W.G. Harrison and N. S. Oakey. 2004. Are the spring and fall blooms on the Scotian Shelf related to short-term physical events? Cont. Shelf Res., in press.

Greene, C.H., A.J. Pershing, A. Conversi, B. Planque, C. Hannah, D. Sameoto, E. Head, P.C. Smith, P.C. Reid, J. Jossi, D. Mountain, M.C. Benfield, P.H. Wiebe and E. Durbin. 2003. Trans-Atlantic responses of *Calanus finmarchicus* populations to basin-scale forcing associated with the North Atlantic Oscillation. Prog. Oceanogr. 58: 301-312.

Head, E.J.H., L.R. Harris and I.M. Yashayaev. 2003. Distributions of *Calanus* spp. and other mesozooplankton in the Labrador Sea in relation to hydrography in spring and early summer (1995-2000). Prog. Oceanogr. 59: 1-30.

Irigoien X., R.P. Harris, H.M. Verheye, P. Joly, J. Runge, M. Starr, D. Pond, R. Campbell, R. Shreeve, P. Ward, A.N. Smith, H.G. Dam, W. Peterson, V. Tirelli, M. Koski, T. Smith, D. Harbour and R. Davidson. 2002. Copepod hatching success in marine ecosystems with high diatom concentrations. Nature. 419: 387-389.

Loder, J., C. Hannah, B. Petrie and E. Gonzalez. 2003. Hydrographic and transport variability on the Halifax section. J. Geophys. Res. 108, doi:10.1029/2001JC001267.

Platt, T., C. Fuentes-Yaco and K.T. Frank. 2003. Spring algal bloom and larval fish survival. Nature. 423: 398-399.

Smith, P.C., C.N. Flagg, R. Limeburner, C. Fuentes-Yaco, C. Hannah, R.C. Beardsley and J.D. Irish. 2003. Scotian Shelf crossovers during winter/spring. 1999. J. Geophys. Res. 108: 8013.

Technical Publications / Publications techniques

NAFO Research Document Series / Séries de Documents de recherche OPANO

Colbourne, E.B. 2002. Oceanographic conditions on the Flemish Cap in NAFO Division 3M during the summer 2002. NAFO SCR DOC. 2002/152. Serial No. 4781. 15 pp.

Colbourne, E.B., and D.C. Orr. 2002. The distribution and abundance of northern shrimp (*Pandalus borealis*) in relation to bottom temperatures in NAFO divisions 3LNO based on multi-species surveys from 1995-2002. NAFO SCR DOC. 2002/153. Serial No. 4782. 14 pp.

Colbourne, E.B., and C. Fitzpatrick. 2003. Physical oceanographic conditions in NAFO subareas 2 and 3 on the Newfoundland and Labrador Shelf during 2002. NAFO SCR DOC. 2003/14. Serial No. N4820. 25 pp.

Colbourne, E.B., and D.C. Orr. 2003. The distribution and abundance of northern shrimp (*Pandalus borealis*) in relation to bottom temperatures in NAFO divisions 3LNO based on multi-species surveys from 1995-2003. NAFO SCR DOC. 2003/081. Serial No. 4922. 14 pp.

Drinkwater, K., B. Petrie, R. Pettipas, W. Petrie and V. Soukhovtsev. 2003. An overview of the meteorological, sea ice and sea-surface temperature conditions in eastern Canada during 2002. NAFO SCR Doc. 2003/30. Serial No. 4845. 32 pp.

Drinkwater, K., B. Petrie, R. Pettipas, W. Petrie and V. Soukhovtsev. 2003. Physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine during 2003. NAFO SCR Doc. 2003/31. Serial No. 4846. 48 pp.

Maillet, G.L., P. Pepin, S. Fraser and D. Lane. 2003. Biological oceanographic conditions in NAFO subareas 2 and 3 on the Newfoundland and Labrador Shelf during 2002. NAFO SCR Doc. 03/19. Serial No. 4826. 32 pp.

Canadian Science Advisory Secretariat (CSAS)-Research Documents / Secrétariat canadien de consultation scientifique (SCCS)-Documents de recherche

Colbourne, E.B. 2003. Physical oceanographic conditions on the Newfoundland and Labrador Shelves during 2002. DFO CSAS Res. Doc. 2003/20. 55 pp.

Colbourne, E.B. 2003. Oceanographic conditions in NAFO subdivisions 3Pn and 3Ps during 2002 with comparisons to the long-term (1971-2000) average. DFO CSAS Res. Doc. 2003/01. 19 pp.

Colbourne, E.B., and E. F. Murphy. 2003. Physical oceanographic conditions in NAFO Division 3P during 2003 - possible influences on the distribution and abundance of Atlantic cod (*Gadus morhua*). DFO CSAS Res. Doc. 2003/093. 18 pp.

Craig, J.D.C., and E.B. Colbourne. 2002. Trends in stratification on the inner Newfoundland Shelf. DFO CSAS Res. Doc. 2002/071. 14 pp.

Craig, J.D.C., E.B. Colbourne and G.L. Maillet. 2001. Preliminary studies of density stratification and fluorescence on the Newfoundland Shelf. DFO CSAS Res. Doc. 2001/085. 26 pp.

Drinkwater, K.F., B. Petrie, R.G. Pettipas and W.M. Petrie. 2003. An overview of meteorologoical, sea ice and sea-surface temperature conditions off eastern Canada during 2002. DFO CSAS Res. Doc. 2003/024. 39 pp.

Drinkwater, K.F., B. Petrie, R.G. Pettipas, W.M. Petrie and V. Soukhotsev. 2003. Physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine during 2002. DFO CSAS Res. Doc. 2003/026. 55 pp.

Harvey, M., J.-F. St-Pierre, A. Gagné, M.-F. Beaulieu and Y. Gagnon. 2003. Oceanographic conditions in the Estuary and the Gulf of St. Lawrence during 2002: zooplankton. DFO CSAS Res. Doc. 2003/077. 19 pp.

Harrison, W.G., D. Sameoto, J. Spry, K. Pauley, H. Maass and V. Soukhovtsev. 2003. Optical, chemical and biological oceanographic conditions in the Maritimes/Gulf Regions in 2002. DFO CSAS Res. Doc. 2003/072. 49 pp.

Pepin, P., G.L. Maillet, S. Fraser and D. Lane. 2003. Biological and chemical oceanographic conditions on the Newfoundland Shelf during 2002. DFO CSAS Res. Doc. 2003/019. 75 pp.

Starr M., L. St-Amand, L. Devine and L. Bérard-Therriault. 2003. State of phytoplankton in the Estuary and Gulf of St. Lawrence during 2002. DFO CSAS Res. Doc. 2003/103. 29 pp.

DFO Technical Reports / Rapports techniques du MPO

Ouellet, M., B. Petrie and J. Chassé. 2003. Temporal and spatial scales of sea-surface temperature variability in Canadian Atlantic waters. Can. Tech. Rep. Hydrogr. Ocean Sci. 238: v + 30 pp.

Ecosystem Status Reports / Rapports d'évaluation de l'écosystème

Canadian Science Advisory Secretariat (CSAS)-Status Reports / Secrétariat canadien de consultation scientifique (SCCS)-Rapports d'état

(All status reports are available in English and French / Tous les rapports d'état sont disponibles en français et en anglais)

DFO (Colburne, E.B.). 2003. 2002 State of the ocean: physical oceanographic conditions in the Newfoundland and Labrador Region. DFO Can. Sci. Advis. Sec. Ecosystem Status Report 2003/003.

DFO (Pepin, P.). 2003. 2002 State of the ocean: chemical and biological oceanographic conditions in the Newfoundland and Labrador Region. DFO Can. Sci. Advis. Sec. Status Rep.: Eco. Over. 2003/001.

MPO (Harvey, M., et M. Starr). 2002. État de l'océan en 2001 : Conditions chimiques et biologiques dans l'estuaire et le golfe du Saint-Laurent. MPO Sciences, Rapport sur l'état des stocks G4-03 (2002).

MPO (Gilbert, D.). 2003. État de l'océan en 2002 : Océanographie physique dans le golfe du Saint-Laurent. Secr. can. de consult. sci. du MPO, Rapp. sur l'état des écosystèmes 2003/006.

Others / Autres

Colbourne, E. B., M. Stein and K. F. Drinkwater. 2003. The 2002 NAFO Annual Ocean Climate Status Summary for the Northwest Atlantic. [On-line: 26 January 2004 under Ocean Climate]<http://www.nafo.ca/activities/Frames/AcFrSci.html>.

Colbourne, E. B. 2002. Monitoring the ocean environment. The Navigator. Vol. 5, No. 11, Nov. 2002.

Gilbert, D. 2003. Temperature and salinity data from the 2002 summer shrimp and groundfish survey in the Gulf of St. Lawrence. [On-line: 25 September 2003] <http://www.osl.gc.ca/en/info/publications/cond-oceano-physiques.html>.

Le Fouest, V., B. Zakardjian, F. Saucier and M. Starr. 2003. A coupled 3D high-resolution climatically-driven ecosystem model for the Gulf of St. Lawrence (Canada). ASLO 2003 Aquatic Sciences Meeting, Book of Abstracts.

Le Fouest, V., B. Zakardjian, F. Saucier and M. Starr. 2003. High-resolution 3D modelling of planktonic production in the Gulf of St. Lawrence, Canada. American Geophysical Union and European Union of Geosciences (EGS-AGU-EUG), Book of Abstracts.

Starr M. 2003. L'Atlantique Nord, un océan changeant. 27e congrès annuel de l'Association des Biologistes du Québec (ABQ), Book of Abstracts.

Starr M., M. Poulin, L. Berard-Therriault and S. Roy. 2003. The rebirth of the diatom *Neodenticula seminae* in the NW Atlantic: a sign of changes in the Arctic Ocean? ASLO 2003 Aquatic Sciences Meeting, Book of Abstracts.

The Relationship Between Scientific Understanding and the Length of Time Series: The CPR Example

Keith Brander[1] and Ken Drinkwater[2]
[1]ICES/GLOBEC Coordinator, ICES, Palaegade 2-4, Copenhagen, DK-1261, Denmark, (keith@ices.dk)
[2]Bedford Institute of Oceanography, Box 1006, Dartmouth, NS, B2Y 4A2

Résumé

L'échantillonnage de plancton réalisé à l'aide du CPR («Continuous Plankton Recorder») est unique en ce qui concerne sa durée dans le temps, ses détails taxonomiques et saisonniers, son étendue géographique et sa continuité et stabilité méthodologique. En plus de l'information spécifique qu'il fournit sur la variabilité du plancton sur une grande échelle de temps et d'espace, cet échantillonnage est aussi un exemple remarquable de la valeur pratique que peuvent avoir les longues séries de données environnementales en général. Durant les soixante-dix années au cours desquelles cet échantillonnage a été en opération, les enjeux concernant l'impact humain sur l'environnement marin ont évolué et le CPR a pu fournir de l'information qui est pertinente à ces enjeux. Ainsi, on a pu observer que la valeur de la série CPR a augmenté avec le temps, avec l'addition continuelle de données. On peut tirer cette conclusion en comparant la longueur de la série d'observations CPR du passé avec les enjeux spécifiques de gestion qui peuvent être abordés tels que par exemple, l'eutrophisation, la biodiversité et l'impact des changements climatiques sur la répartition du plancton.

It is increasingly difficult to fund long-term measurement programs. Duarte et al. (1992) stated that "long-term monitoring programs are, paradoxically, among the shortest projects in marine science, many are initiated but few survive a decade." One reason for this may be the mistaken perception of diminishing returns from long-term monitoring. In fact, there is an increasing scientific value with time. In the following article, we will show this using the 70-year time series of the Continuous Plankton Recorder (CPR) data from the Northeast Atlantic.

The CPR was designed and implemented by Sir Alister Hardy (see http://www.sahfos.org and Reid et al. 2003 for details about the current and past CPR program). In an attempt to resolve the high spatial and temporal variability in plankton, Hardy recognized the need for continuous underway sampling. The design is simple. A towed body funnels water past a moving filter of silk. The plankton that are absorbed onto the surface of the silk are later counted and identified. The different species and their abundances can be determined as a function of location in the ocean from knowledge of the ship's track and speed. Repeat

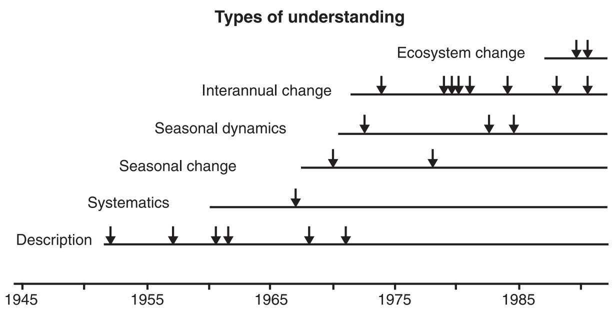
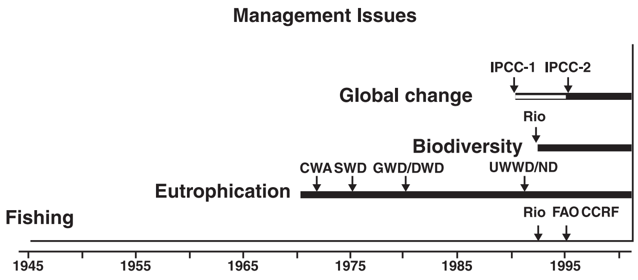


Fig. 1 Types of scientific understanding dealt with by papers written about the CPR as a function of the length of the series (based on the post-war bibliography by Dickson 1995).

Types de compréhension scientifique attendusdans les papiers rédigés sur le CPR en fonction de la longueur de la série (basé sur la bibliographie d'après-guerre de Dickson 1995).



IPCC = Intergovermental Panel on Climate Change, reports 1 and 2
CWA = US Clean Water Act 1972
SWD = European Union (EU) Surface Water Directive (1975)
GWD/DWD = EU Groundwater Directive (1980), Drinking Water Directive (1980)
UWWD/ND = EU Urban Waste Water Directive (1991) and Nitrate Directive (1991)
Rio = Earth Summit in Rio de Janeiro in 1992; Convention on Biological Diversity (CBD) established

FAO CCRF = Code of conduct for Responsible Fisheries (1995)

Fig. 2 The time line of management issues that have been addressed using the CPR data.

Chronologie des enjeux de gestion qui ont été abordés en utilisant la série de données du CPR.

sections measure the temporal variability of the plankton. Hardy started a CPR survey during the 1930s in the northeast Atlantic; this survey has continued with no significant change in either the instrument or analysis for over 70 years. Thus, the time series is fully comparable over the entire record. CPR surveys were later expanded to cover parts of the North Atlantic and, recently, the North Pacific.

When the major papers on plankton in the Northeast Atlantic based on the CPR record are classified by type and date (arrows in Fig. 1), we find that our understanding of the Atlantic plankton and its ecosystem grows steadily with time. Initially, these papers provided a simple description of the species that were present. As the times series grew, the samples became adequate to contribute to the systematics of the plankton then successively to comment on variability at increasing time scales—from seasonal change through seasonal dynamics to interannual change and lastly to ecosystem change, involving a complex of variability across decades and trophic levels. Papers anticipating the planktonic signature of global change have begun to appear. Thus, over seven decades, the value of the time series has grown in terms of the breadth of understanding that we can mine from it. During these past 70 years, we have observed that the ocean and the plankton in it vary over a myriad of time scales. Significant large-scale ecosystem changes have been shown to occur at multi-decadal time scales. To document these changes and improve our scientific understanding of their causes, monitoring time series need to be longer than these scales. As the monitoring time series lengthens, we are able to address questions about the variability at the longer time scales and provide better statistics on the variability at shorter periods, thus increasing the value of the time series.

The management issues supported by the CPR data have become more elaborate and complex with time (Fig. 2). Hardy's initial aim in setting up the CPR survey was to provide a service that would enable fishermen to locate their target species and eventually have some predictive power. He recognized from the beginning that this would take many years. His original objective was not met for many reasons, including the time required to process the CPR data, and, more importantly, the development of new technologies, such as acoustics, that allow fishermen to locate fish more effectively. However, the CPR did prove useful for fisheries in locating new resources of blue whiting and redfish that subsequently have been exploited and developed. The data have also proved immensely valuable in understanding the scale and nature of climate and biological processes affecting fish stocks.

The CPR data set has been used to address several different management issues that were not considered or imagined when the time series began. One example is eutrophication. Increased production of several phytoplankton species in the southern North Sea was originally attributed to eutrophication, but similar responses in the open-ocean plankton, based on the CPR data, confirmed that the plankton production increases were part of a large-scale, naturally occurring phenomenon. In recent years, biodiversity has become a hot scientific topic. In providing information on about 450 taxonomic entities of zooplankton and phytoplankton over many decades over the open ocean and the shelf, it was not surprising that the CPR survey was identified as a major biodiversity monitoring program by the European Environment Agency. The CPR is also being used to address issues of climate change. This is occurring on several different fronts. Combining future climate scenarios and the observed effects of climate variability on plankton from the CPR surveys allows scientists to suggest possible impacts of climate change on plankton. On another front, recent northward movement of several traditionally southern species of plankton is being suggested as a possible signature of anthropogenic climate change.

The CPR monitoring program is an exception to the assertion by Duarte et al. (1992) that long-term monitoring programs are among the shortest projects in marine science. Its duration, and consequently its exceptional data set, has proven very fruitful in providing and continuing to yield insights into plankton dynamics over a broad range of time and space scales. The CPR experience is a strong argument for maintaining carefully designed, long-term monitoring of oceanic variability.

This article is based upon:
Brander, K.M., R.R. Dickson and M. Edwards. 2003. Use of Continuous Plankton Recorder information in support of marine management: applications in fisheries, environmental protection, and in the study of ecosystem response to environmental change. Prog. Oceanogr. 58: 175-191.

References

Dickson, R. R. 1995. The natural history of time-series. *In* Ecological time-series. *Edited by* T.M. Powell and J.H. Steele. Chapman and Hall, New York. pp. 70-98

Duarte, C. M., J. Cebrian and N. Marba. 1992. Uncertainty of detecting sea change. Nature, London. 356: 190.

Reid, P.C., J.B.L. Matthews and M.A. Smith (*Editors*). 2003. Achivements of the continuous plankton recorder survey and a vision for its future. Prog. Oceanogr. 58: 115-358.

BioChem: A National Archive for Marine Biology and Chemistry Data

Doug Gregory[1] and Savithri Narayanan[2]
[1]Bedford Institute of Oceanography, 1 Challenger Drive, Dartmouth, NS, B2Y 4A2, gregoryd@dfo-mpo.gc.ca
[2]Marine Environmental Data Service, 200 Kent Street, Ottawa, ON, K1A OE6, narayanans@dfo-mpo.gc.ca

Résumé

BioChem est une base nationale de données biologiques et chimiques sur le milieu marin qui a été développée pour rencontrer les besoins du Programme de Monitorage de la Zone Atlantique (PMZA) ainsi que pour fournir une infrastructure centrale permettant d'archiver les nombreux autres jeux de données semblables existant au Ministère des Pêches et des Océans (MPO). BioChem contient présentement une portion significative des données du PMZA ainsi que les données historiques de l'institut océanographique de Bedford. La migration des données de toutes les autres régions du MPO s'effectue présentement, et lorsque complétée, BioChem représentera une source d'informations marines inestimable et irremplaçable pour la recherche écosystémique au Canada.

History

The creation of a national DFO archive of marine biological and chemical data, a long-term goal of many dedicated individuals, is a reality. The database development began in 1997, when the DFO Climate Science Coordinating Committee recognized the importance of timely access to known-quality biological and chemical observations and subsequently allocated funds to develop a database model and implementation plan under the guidance of a national group. Following an initial meeting in Ottawa, where a framework for a national biological/chemical database was formulated, workshops were held in 1998 at the Bedford Institute of Oceanography (BIO) and Marine Environmental Data Service (MEDS) to finalize the initial design. This design was presented at the November 1998 meeting of the Atlantic Zone Monitoring Program (AZMP) and was adopted as the model for the zonal monitoring program. The original proposal for AZMP (Therriault et al. 1998) recognized the need to develop a database for archiving biological and chemical data, and AZMP became an enthusiastic supporter and contributor to the development.

The project received a major boost when the Ocean Sciences Division (OSD) and Marine Environmental Sciences Division (MESD) at the Bedford Institute of Oceanography decided that the database development in the Maritimes Region would be a priority as part of their Y2K preparedness. Subsequently, the DFO Investment Management Board recognized data as a capital asset and allocated substantial multi-year funding for this project. During the next four years, the development of BioChem (Biology–Chemistry), as it came to be known, was led by the Maritimes Region through a partnership of data managers in MESD and OSD and database specialists of the Informatics group in the Maritimes Region. The development of the application was a major task; the migration of decades of biological and chemical data observations into the database has been an even greater challenge.

The most recent stage in the BioChem development has been the migration of the system to the Marine Environmental Data Service in 2003, where it will finally achieve its initial goal as a national resource accessible from all DFO regions.

Throughout BioChem's development, AZMP has played a major role in providing funding, scientific and technical guidance, and visibility as the project's major client. Without this endorsement, it would have been difficult to get the regional and national support for BioChem.

The Database

BioChem was originally designed to hold any type of marine scientific data. The main functional areas include plankton, discrete (water samples), continuous (profilers, flow-through systems), and environmental (meteorological) information. Provision is also made to accommodate large binary objects such as satellite images or video. The functional areas are built on a mission/event/measurement detail skeleton reflecting the sources of the information. From the outset, the database was designed as a de-centralized system to ensure that the regional experts responsible for data collection would also be responsible for data archive and quality control. The system would also be web-

Discrete Observation Classes /
Classes d'observations ponctuelles

Heavy metals / Métaux lourds
Hydrocarbons / Hydrocarbones
Light / Lumière
Major ions / Ions majeurs
Nutrients / Sels nutritifs
Organic matter / Matière organique
Oxygen / Oxygène
Particulate matter / Matière particulaire
Physical Properties /
  Propriétés physiques
Pigments / Pigments
Primary production /
  Production primaire
Radionuclides / Radionucléides
Seawater chemistry /
  Chimie de l'eau de mer
Size of organisms /
  Taille des organismes
Stable Isotopes / Isotopes stables
Tracers / Traceurs

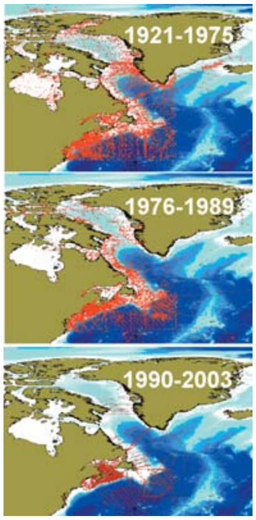


Fig. 1 Distributions of discrete observations in the BioChem database from 1921 to the present.

Répartition des observations ponctuelles dans BioChem de 1921 jusqu'à aujourd'hui.

Plankton Classes /
Classes de plancton

Bacteria / Bactéries
Diatoms / Diatomées
Dinoflagellates / Dinoflagellés
Protozooplankton flagellates /
  Flagellés protozooplanctoniques
Protozooplankton ciliates /
  Ciliés protozooplanctoniques
Cnidaria / Cnidaires
Ctenophora / Cténophores
Mollusca / Mollusques
Ostracoda / Ostracodes
Copepoda / Copépodes
Amphipoda / Amphipodes
Euphausiacea / Euphausiacés
Decapoda / Décapodes
Chaetognatha / Chaetognates
Ichthyoplankton / Ichtyoplancton

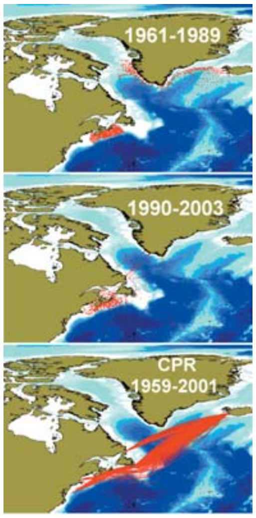


Fig. 2 Distribution of plankton observations in the BioChem database from 1961 to the present. The bottom panel shows observations from the Continuous Plankton Recorder (CPR) since 1959.

Répartition des observations sur le plancton dans BioChem de 1961 jusqu'à aujourd'hui. Le panneau du bas montre les observations provenant du CPR (Continuous Plankton Recorder) depuis 1959.

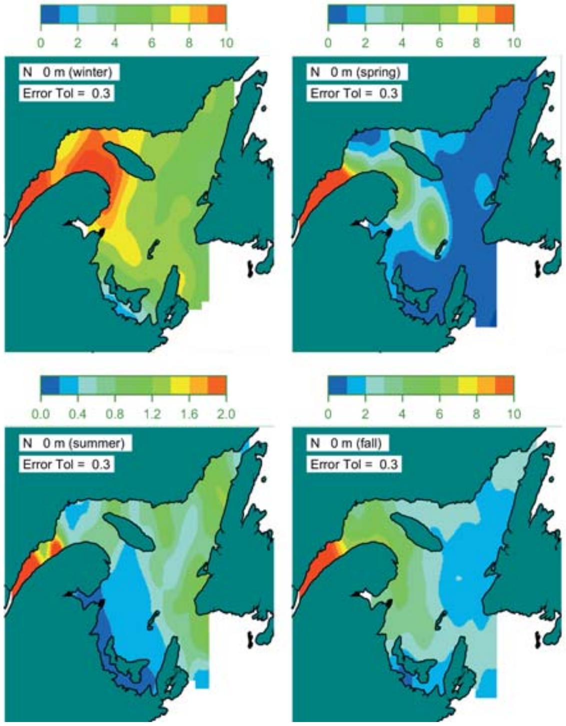


Fig. 3 Seasonal, optimally-estimated surface nitrate concentration (mmol m^{-3}) taken from Brickman and Petrie 2003. The analysis was based in part on nutrient data from the BioChem database.

Concentration saisonnière des estimés optimaux de nitrates en surface (mmol m^{-3}) (Figures tirées de Brickman et Petrie 2003). Cette analyse a été en grande partie réalisée à partir des données de sels nutritifs contenues dans la base de données BioChem.

based to permit broad access. It delivers this capability by providing a centralized archive and web-based query application. Individual data managers have their own set of edit tables where they prepare observations for loading into the archive. A number of additional tools have been constructed to assist data managers in data entry, retrieval, and editing.

Data Holdings

The primary data source is scientific missions originating from DFO research institutions. These are augmented with observations from the MEDS and World Ocean Database (WOD) archives and continuous plankton recorder (CPR) data from the Sir Alister Hardy Foundation for Ocean Science (SAHFOS). The archive covers the Northwest Atlantic (35°-80°N and 40°-100°W) from 1921 to present. The current holdings consist of more than 1575 research missions and in excess of 2.2 million discrete observations from water samples and over 500,000 plankton measurements. The types of observations and their spatial and temporal distributions are summarized in Figures 1 and 2.

Example Applications

BioChem is a new tool to assist researchers in the detection, characterization, and prediction of ecosystem changes. Below we highlight two recent examples of analyses that used BioChem as a source of broad-scale chemical and biological observations.

1) Nitrate, silicate, and phosphate atlas for the Gulf of St. Lawrence (Brickman and Petrie 2003)

In this report, over 36,000 observations for each of nitrate, silicate, and phosphate for the Gulf of St. Lawrence were analyzed to create a nutrient atlas. Data were provided by the Bedford Institute and the Maurice Lamontagne Institute. Figure 3 shows the seasonal concentrations of surface nitrate throughout the Gulf. The atlas features similar presentations at several depths and statistical tables of monthly nutrient concentrations for smaller subareas of the Gulf. Products were produced with data derived for the most part from BioChem. The complete report can be found at <www.mar.dfo-mpo.gc.ca/science/ocean/coastal_hydrodynamics/download/gsl_atlas_CLR.pdf>.

2) Plankton Change in the Northwest Atlantic

In our second example, Sameoto (in preparation) examined Continuous Plankton Recorder (CPR) data collected between Iceland and New England from 1959 to 2001. The analysis indicates that the 1990s decade was one in which large changes in phytoplankton and zooplankton abundance occurred. Figure 4 illustrates the variability in the strength and timing of the spring bloom.

The Future

MEDS has assumed the lead in moving BioChem forward as a truly national archive. Several technical teams have been formed to resolve inter-regional issues and decide on standard practices. The BioChem database is now a reality, but there is still much work to do. Ensuring that all of the legacy data held throughout the department as well as data obtained from universities and other agencies are eventually housed in BioChem will take a major effort, as will educating new data providers to record the necessary support information at source. Data retrieval is only one aspect of BioChem; we must be able to produce products on demand that are syntheses of data held in the database. Finally, we must gain enough confidence in our quality control procedures so that we can move the BioChem system from the Intranet to the Internet, thereby making the data available to a much wider community. Based on our experience over more than a decade with the physical oceanographic databases, BioChem will make a significant contribution to ecosystem research in the oceans surrounding Canada.

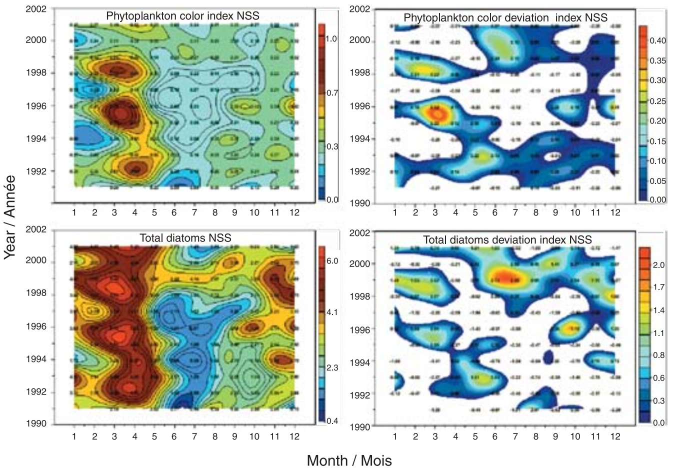


Fig. 4 Monthly abundance (left panels)and deviations (right panels)for the colour index (upper panels) and diatoms (lower panels)on the Scotian Shelf for the decade 1991 to 2001. The analysis was based on CPR data from the BioChem database. (Figures from D. Sameoto, BIO.)

Abondance mensuelle (panneaux de gauche) et deviations (panneaux de droite) de l'index de couleur (panneaux du haut) et du nombre de diatomées (panneaux du bas) sur le plateau Néo-Écossais pour la décade de 1991 à 2001. L'analyse est basée sur les données CPR provenant de la base de données BioChem. (Figures produites par D. Sameoto, BIO.)

References

Brickman, D., and B. Petrie. 2003. Nitrate, silicate and phosphate atlas for the Gulf of St. Lawrence. Can. Tech. Rep. Hydrogr. Ocean Sci. 231: xi + 152 pp.

Therriault, J.-C., B. Petrie, P. Pepin, J. Gagnon, D. Gregory, J. Helbig, A. Herman, D. Lefaivre, M. Mitchell, B. Pelchat, J. Runge and D. Sameoto. 1998. Proposal for a Northwest Atlantic Zonal Monitoring Program. Can. Tech. Rep. Hydrogr. Ocean Sci. 194: vii + 57 pp.

The Annual Cycle of Sea-Surface Temperature and Spatial Scales of Its Anomalies in Canadian Atlantic Waters

Brian Petrie[1], Mathieu Ouellet[2], and Joël Chassé[1,3]
[1]Bedford Institute of Oceanography, Box 1006, Dartmouth, NS, B2Y 4A2
[2]Marine Environmental Data Service, 200 Kent St., Ottawa, ON, K1A 0E6
[3]Gulf Fisheries Centre, Box 5030, Moncton, NB, E1C 9B6
petrieb@mar.dfo-mpo.gc.ca

Résumé

Afin d'évaluer la représentativité des mesures de température de surface de la mer (TSM) pour le Programme de Monitorage de la Zone Atlantique (PMZA), une analyse de la variabilité spatiale et temporelle de la TSM dans les eaux canadiennes atlantiques (40-52 ºN, 40-75º O) est présentée. Les données utilisées consistent en la TSM moyenne par semaine, obtenue du Jet Propulsion Laboratory, de 1981 à 2000 à une résolution de 18 km. Une attention spéciale est prêtée aux stations fixes du PMZA, qui sont situées dans la gyre d'Anticosti, le courant de Gaspé, le sud-ouest du golfe du Saint-Laurent (vallée de Shédiac), au large de St. John's (Station 27), au large de Halifax (Station 2) et à l'embouchure de la baie de Fundy (Prince 5). La moyenne, les harmoniques annuelles, semi-annuelles et tri-anuelles, ainsi que les anomalies de TSM, furent déterminées pour 9253 pixels. Les harmoniques contribuent à plus de 85 % de la variance des séries temporelles de TSM sur le plateau continental, et à plus de 95 % dans certaines parties du golfe du Saint-Laurent, du plateau Néo-Écossais et du golfe du Maine. Dans la région définie par la position moyenne ±1 écart type du front plateau–pente, les harmoniques contribuent de 30 % à 80 % de la variance. Les échelles spatiales furent évaluées en calculant les coefficients de corrélation mutuels entre une série de TSM à un pixel donné et les séries du reste de la grille. La distance à laquelle le coefficient de corrélation 0.7 intercepte la droite de régression des valeurs de corrélation en fonction de la séparation horizontale est définie comme mesure d'échelle spatiale de cohérence. Les plus grandes échelles de cohérence ainsi calculées, d'environ 300 km, se situent au-dessus des Grands Bancs de Terre-Neuve. L'anisotropie des contours de corrélation 0.7 est importante dans les régions situées près de la côte, près d'importantes variations bathymétriques ou encore de caractéristiques océaniques importantes. L'échelle de représentativité temporelle fut estimée en déterminant l'intervalle de temps auquel l'autocorrélation temporelle des anomalies de la TSM tombe à 1/e = 0.37 et s'étend approximativement de 1 à 3 semaines selon la position dans la grille.

Introduction

In order to assess the ability of the AZMP fixed stations and transects to represent the oceanic variability on the Canadian Atlantic continental shelf and adjacent slope areas, a number of analyses have been undertaken using archived and ongoing data sets. In this article, we present the results of an investigation of the annual cycle and the spatial scales of sea-surface temperature (SST) variability in eastern Canadian waters using satellite infrared imagery data. A more complete discussion is given by Ouellet et al. (2003).

Data and Methods

Satellite estimates of SST were extracted from a region bounded by 40-52º N and 40-75º W, resulting in a series of 9253 different locations on a 68x194 grid (Fig. 1). Our source was the Ocean Sciences database at the Bedford Institute of Oceanography and was originally created by the Physical Oceanography Archive Center of the Jet Propulsion Laboratory (Pasadena, California, USA). The data were from the daytime NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite for the period November 1981 to November 2000. The weekly time series have a spatial resolution of approximately ~0.175º in latitude and longitude, which corresponds to ~19.5 km north-south and ~13.6 km east-west in our region. Mason et al. (1998) concluded that the data were useful in examining long-term changes of SST. They compared in situ, near-surface temperatures from three frequently sampled sites (Sta. 27 off St. John's, Halifax Section Station 2, and the Prince 5 station at the mouth of the Bay of Fundy) with satellite-derived SSTs. The slope of their linear regression was 1.04(±0.03) with an intercept of 0.08(±0.15)ºC, an average difference of –0.37ºC, and a standard deviation of 1.27ºC. Thus we expect ~1ºC accuracy for individual estimates of SST from the satellite observations.

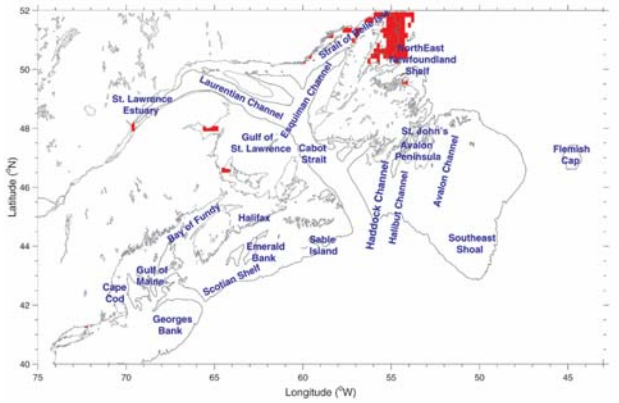


Fig. 1 Names and locations of places mentioned in the text and locations (red pixels) where neighbour averaging was necessary to extract the harmonic signal.

Noms et positions des endroits mentionnés dans le texte et positions (pixels rouges) où une moyenne avec les points voisins fut nécessaire pour extraire le signal harmonique.

Harmonic analysis was used to estimate the annual cycle of SST and the anomalies, defined as the difference between individual data points and the annual cycle on the same day, at all grid points. We define the annual cycle as the sum of the mean and the annual (frequency = $2\pi/365$ d), semi-annual ($4\pi/365$ d), and tri-annual ($6\pi/365$ d) harmonics. The amplitudes and phases of each harmonic component were determined by least-square fitting. Ouellet et al. (2003) established criteria for a minimum number of observations during winter months to ensure good harmonic fits; they also set requirements for the minimum number of common points necessary to calculate correlations between time series.

Results

Harmonic Analysis

Over the continental shelf, the Gulf of Maine, and Gulf of St. Lawrence, 85 to 99%, (average of about 94%) of the SST variance is accounted for by the harmonic fits (Fig. 2a). The amount of variance accounted for decreases over the continental slope at a location that generally corresponds to +1 standard deviation from the mean position of the shelf–slope front south of Georges Bank, the Scotian Shelf, and the Grand Banks of Newfoundland. Off the eastern Grand Banks of Newfoundland (where the front indicates the boundary between the North Atlantic Current and water of Labrador Current origin), the minimum percentage variance accounted for by the harmonic fit (55-65%) is roughly bounded by the ±1 standard deviation of the front from its mean position.

The standard deviations of the residuals were calculated for the entire series (Fig. 2b). Over the upper continental slope and in the Gulf of St. Lawrence, the standard deviations are ~2ºC. The maximum standard deviation of the residuals is bounded by the area described by ±1 standard deviation of the shelf–slope front. The standard deviations of the seasonal residuals show the same general behaviour (Ouellet et al. 2003), with the variance over the shelves lowest in winter (standard deviations of ~1ºC). Thus over the Canadian Atlantic shelf and in the Gulf of St. Lawrence, the magnitude of the SST anomalies will have a range of about 8ºC, corresponding to about ±2 standard deviations.

Mean Annual SST

The results from the harmonic analysis are rich in the identification of circulation features, fronts, and areas of intense mixing. The mean annual SST, for example, reflects a number of well-known oceanographic features (Fig. 3a). The colder waters flowing from the Labrador Shelf are visible as two major flows: the more diffuse inshore branch of the Labrador Current through Avalon Channel and the distinct offshore branch flowing roughly along the 200 m isobath on the eastern edge of Grand Bank. The offshore branch bifurcates north of Flemish Cap into the distinct southward flow through Flemish Pass and an eastward component north of the Cap, whose surface signature rapidly disappears as it encounters the North Atlantic Current front. The surface manifestation of the southward-flowing Labrador Current disappears at the Tail of Grand Bank. The southwestern Grand Bank shows the strong influence of onshore movement of warmer, upper-slope waters. This area is adjacent to the region that features the largest variance in north–south movement of the shelf–slope water front between Georges Bank and the Tail of Grand Bank. The inshore branch of the Labrador Current rounds the southern Avalon Peninsula and tends to move westward toward Haddock and Halibut channels.

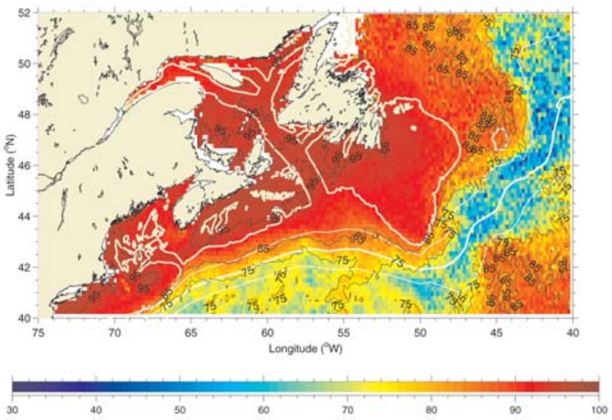


Fig. 2a Percentage of total variance of the sea-surface temperature (SST) accounted for by the harmonic fit. The 200 m isobath is shown as a white line, the thick white line shows the mean position of the shelf– slope front, and the thin white lines are ±1 standard deviation (Horne and Petrie 1988; Drinkwater et al. 1994).

Pourcentage de la variance totale de la température de surface de la mer (TSM) expliqué par la somme des fonctions harmoniques. L'isobathe des 200 m est montrée en blanc, le trait blanc plus large indique la position moyenne du front à l'interface plateau – pente continentale et les lignes fines blanches représentent les contours de ±1 écart type (Horne et Petrie 1988; Drinkwater et al. 1994).

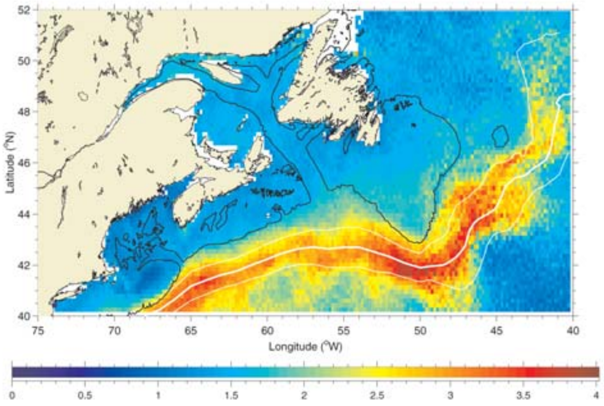


Fig. 2b Standard deviation of SST anomalies (°C).

Écart type des anomalies de TSM (°C).

In the Gulf of St. Lawrence, the coldest mean annual temperatures are found along the north shore; this is probably caused by the inflow of colder Labrador Shelf water through the Strait of Belle Isle and the tendency for persistent wind-driven upwelling. Low annual temperatures are observed in the St. Lawrence Estuary, a region known for strong vertical mixing and upwelling of cold deeper waters in the summer. The area adjacent to Prince Edward Island has the highest annual temperatures in the Gulf.

The influence of colder annual temperatures that are advected from the Gulf through Cabot Strait is seen south of Cape Breton as the Nova Scotia Current and on the western edge of the Laurentian Channel moving along the shelf break towards Sable Island. Warm upper-slope waters move onto the central Scotian Shelf over Emerald and Western banks. The surface expression of the Nova Scotia Current remains confined to the coast before spreading offshore to the west of Halifax. There is a tidally mixed upwelling zone marked by lower SST off southwest Nova Scotia as well as the tidally mixed, cooler area of the

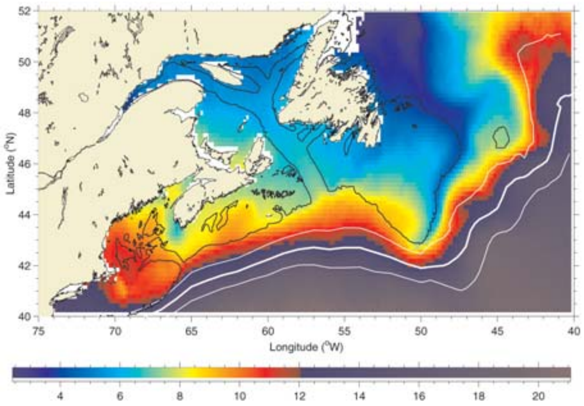


Fig. 3a Annual mean SST (°C). The colour map is enhanced for a more detailed resolution of SST on the shelf.

Moyenne annuelle de la TSM (°C). La palette des couleurs a été modifiée pour faire ressortir davantage la TSM sur le plateau continental.

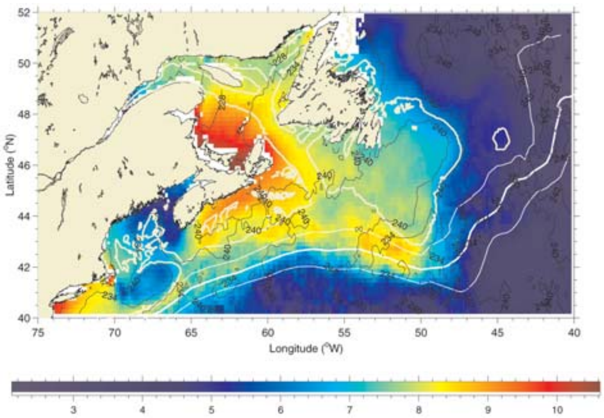


Fig. 3b Annual SST harmonic amplitude (°C) and phase (contours, days).

Amplitude (°C) et phase (contours, jours) du signal harmonique annuel de la TSM.

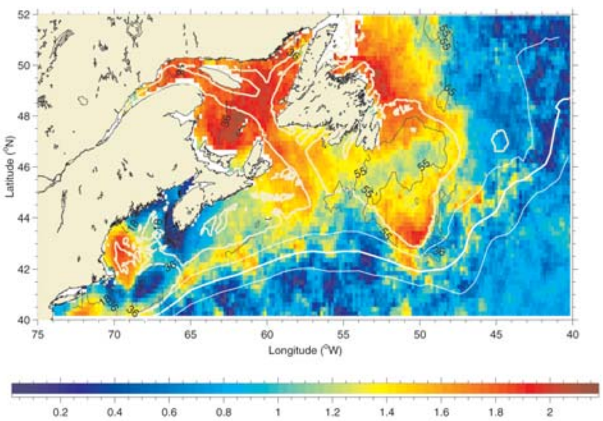


Fig. 3c Semi-annual SST harmonic amplitude (ºC) and phase (contours, days).

Amplitude (ºC) et phase (contours, jours) du signal harmonique semi-annuel de la TSM.

mouth of the Bay of Fundy and a distinct temperature gradient along the Bay. Annual temperatures for Georges Bank and the Gulf of Maine are in the same range, about 10-12ºC, as those over the upper slope. The +1 standard deviation line north of the shelf–slope front from Georges Bank to north of Flemish Cap corresponds roughly to the 11ºC annual mean temperature isoline.

Annual Harmonic

The annual harmonic amplitudes are typically larger over the shelf and in the Gulf of St. Lawrence than in the deeper areas (Fig. 3b). The largest amplitudes, ~10.6 ºC, are in the southern Gulf of St. Lawrence, where freshwater inflows hinder vertical mixing and where, in some areas, shallow depths confine the heat input. In deeper Gulf areas, large freshwater inflows contribute to a strongly stratified shallow surface layer that inhibits the vertical mixing of heat. Winter surface temperatures are near the freezing point. Thus the annual SST range is very high, giving elevated annual harmonic amplitudes. In contrast, the St. Lawrence Estuary has a small annual harmonic (~4ºC) because strong vertical mixing and upwelling of deeper cool waters limits the summer SST. The influence of the Gulf outflow is seen on the Scotian Shelf as a band of coastal water with a large annual harmonic. This region stretches from the Sydney Bight to the west of Halifax, where it veers offshore. This reflects the influence of the Nova Scotia Current that was apparent, but less compelling, in the mean annual temperature field. As in the St. Lawrence Estuary, the areas off southwestern Nova Scotia, the Bay of Fundy, and the coastal region of Maine feature low amplitudes. This is caused by tidally induced mixing that spreads the atmospheric heat fluxes over a thicker upper layer and thereby reduces the amplitude. A similar situation is apparent over Georges Bank except for the shallow central region, where the upper layer reaches to the bottom and results in a higher annual harmonic amplitude. The annual harmonic amplitude decreases significantly at the shelf–slope front from Georges Bank to the Tail of Grand Bank. The advective influence of cold water can be seen in the Newfoundland region, particularly on the northeast Newfoundland Shelf. The area directly south of the Tail and along the southwest slope of Grand Bank has large amplitudes that may be caused by on-bank movement of warmer slope water (Templeman and Hodder 1965).

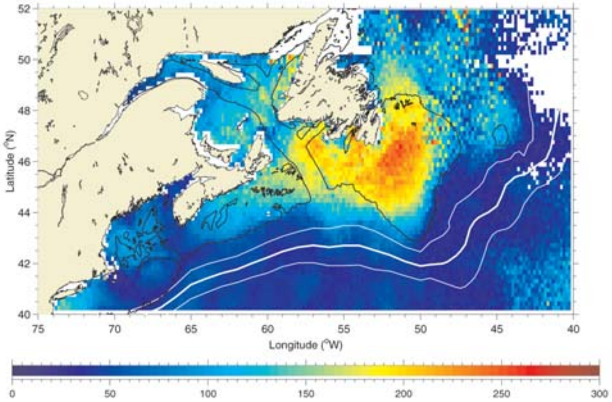


Fig. 4 Spatial scales of variability of weekly sampled SST anomalies defined as the distance (km) where the correlation equals 0.7 and derived from least-square fit of a straight line to the correlation coefficients as a function of distance, independent of direction, from each pixel.

Échelles spatiales de la variabilité de la TSM (échantillonnée hebdomadairement) calculées en tant que la distance (km) à laquelle la corrélation est égale à 0.7 sur une droite obtenue par régression linéaire des coefficients de corrélation en fonction de la distance, indépendamment de la direction, pour chaque pixel.

The phases of the annual harmonics range from day 220 (Aug. 8) to day 240 (Aug. 28) on the shelf, Gulf of St. Lawrence, and Gulf of Maine regions. This limited range is expected because the solar heating cycle is highly coherent and roughly in phase over the region.

Semi-Annual Harmonic

The semi-annual harmonic amplitudes have a maximum value of 2.2ºC (Fig. 3c). Large regions with amplitudes of about 2ºC are found in the Gulf of St. Lawrence and over the eastern Newfoundland Shelf. These areas have winter surface temperatures that are close to the freezing point and remain nearly constant for periods of 2-3 months. They are also areas that feature ice cover during the winter months; ice melting

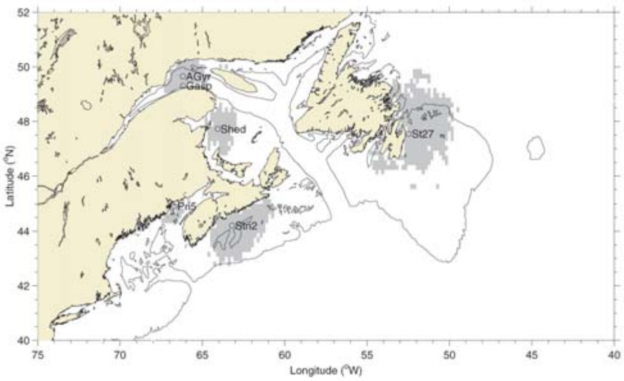


Fig. 5 Composite plot of pixels (shaded) where the correlation is ≥ 0.7 relative to the six AZMP fixed stations.

Carte composite de l'ensemble des pixels (zones ombragées) où le coefficient de corrélation est ≥ 0.7 relativement aux six stations fixes du PMZA.

in late winter and early spring can prolong the period of minimum temperatures. The semi-annual phases are more broadly distributed than the annual ones though still quite well-defined.

The mean and annual harmonic together tend to give temperatures that are too low during winter; the semi-annual harmonic, with its peak amplitudes from day 30-50 (Feb-Mar) is out of phase with the minimum SST due to the annual harmonic and counteracts its tendency to give SST values well below the freezing point. Its second peak in the year occurs in August, generally adding to the peak in the annual harmonic. The semi-annual harmonic is low in areas of strong mixing such as southwest Nova Scotia, the Bay of Fundy, the Maine coastal region, and Georges Bank. Two areas have unexpectedly high semi-annual harmonic amplitudes—the western Gulf of Maine and the area off the Tail of Grand Bank.

The tri-annual harmonic amplitudes (not shown) are patchy, particularly in the deep-water areas, and have a range of 0.0 to 1.5°C over the entire region but are typically < 0.5°C. The phases are very broadly distributed, but the greatest number give rise to peak amplitudes in March-April. The southern Gulf of St. Lawrence is the largest area with consistently high amplitudes (~0.7°C) and a small phase range.

Spatial Scales of Variability

Ouellet et al. (2003) estimated the spatial scales of variability at each pixel using two different methods. The first method consists of ordering correlation coefficients by distance alone from the central pixel and then fitting (least-square) a linear function. The 0.7 correlation coefficient intercept is then taken as the spatial scale of variability for each pixel and is independent of direction (Fig. 4). The second method accounts for asymmetry in the correlations and consequently the scales. We shall only present the results from the first method.

The largest spatial correlation scales (~200-300 km) are found over the Grand Banks of Newfoundland. Intermediate scales of ~100-175 km occur over the northeast Newfoundland Shelf, Flemish Cap, much of the Gulf of St. Lawrence, and the Scotian Shelf. The smallest horizontal scales occur seaward of the shelf break, in the Gulf of Maine, the St. Lawrence Estuary, and the Gaspé Current.

The areas with correlation coefficients ≥ 0.7 relative to the six AZMP fixed stations (Gaspé Current, Anticosti Gyre, Shediac Valley, Station 27, Halifax Station 2, and Prince 5) show that weekly sampling of SST at those sites only will not adequately account for temperature variability for periods of two weeks and longer in the region (Fig. 5). Other types of measurement, like satellite data and in situ observations from AZMP cruises and ships of opportunity, are needed to describe the ocean environment throughout the region at these time scales.

These spatial scales represent a range of variability from two weeks to several years. We filtered the time series to examine the scales associated with longer periods and found that out to seasonal time periods, the spatial scales did not change appreciably. However, preliminary analysis of annual SST anomalies indicates a twofold increase in the spatial correlation scales to about 500 km (Fig. 6). We conclude that the combination of in situ and remotely sensed observations are adequate to assess interannual SST variability. For subsurface physical and surface and subsurface biological and chemical variables (except surface chlorophyll from SeaWiFS), we do not have weekly sampled data. Furthermore, the biological and chemical parameters have additional mechanisms that can introduce greater spatial and temporal variability. This implies that the spatial scales of variability found for SST are likely upper bounds for the biological and chemical ecosystem components.

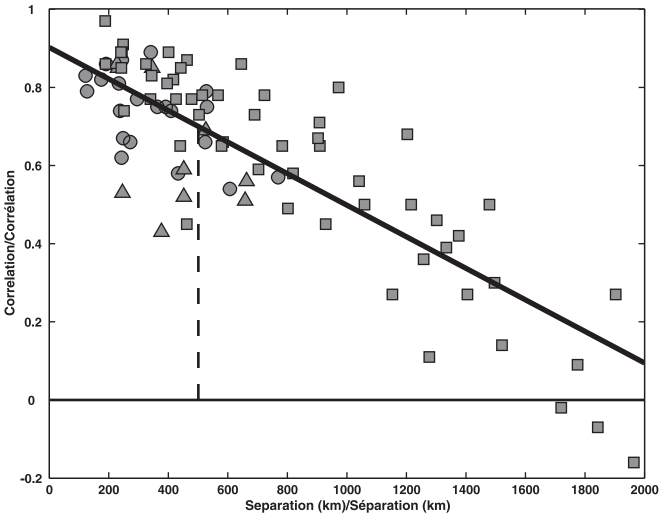


Fig. 6 Correlation as a function of distance between pairs of annual temperature anomaly time series in the Atlantic region. The linear fit is based on all pairs; the symbols show the correlations within regions (squares, Newfoundland–Labrador; triangles, Gulf of St. Lawrence; circles, Scotian Shelf–Gulf of Maine).

Corrélation, en fonction de la distance, entre des paires de séries d'anomalies de température dans la région Atlantique. L'estimation linéaire est basée sur toutes les paires; les symboles montrent les corrélations pour chaque région (carrés, Terre-Neuve et Labrador; triangles, Golfe du Saint-Laurent; cercles, Plateau Néo-Écossais et Golfe du Maine).

References

Drinkwater K.F., R.A. Myers, R.G. Pettipas and T.L. Wright. 1994. Climatic data for the northwest Atlantic: the position of the shelf/slope front and the northern boundary of the Gulf Stream between 50° W and 75° W, 1973-1992. Can. Data Rep. Hydrogr. Ocean Sci. 125, iv+103 pp.

Horne, E., and B. Petrie. 1988. Mean position and variability of the sea surface temperature front east of the Grand Banks. Atmos.-Ocean. 26 (3): 321-328.

Mason, C.S., B. Petrie and B.J. Topliss. 1998. Satellite measurement of sea-surface temperatures and the study of ocean climate. Can. Tech. Rep. Hydrogr. Ocean Sci. 193, vii + 101 pp.

Ouellet, M., B. Petrie and J. Chassé. 2003. Temporal and spatial scales of sea-surface temperature variability in Canadian Atlantic waters. Can. Tech. Rep. Hydrogr. Ocean Sci. 228, v + 30 pp.

Templeman, W., and V. Hodder. 1965. Distribution of haddock on the Grand Bank in relation to season, depth and temperature. ICNAF Special Publ. 6: 171-187.

Station 27 Oceanographic Monitoring Station—A Long History

E. B. Colbourne and C. Fitzpatrick
Northwest Atlantic Fisheries Centre, Box 5667, St. John's, NL, A1C 5X1
Colbourn@dfo-mpo.gc.ca fitzpatrickc@dfo-mpo.gc.ca

Résumé

L'activité de monitorage le long de plusieurs transects traversant le plateau continental de Terre-Neuve et du Labrador a été initiée vers la fin des années quarante. Le transect qui était situé immédiatement au large du port de St. John's, Terre-Neuve, débutait par le nombre séquentiel 27 et était orienté vers le sud-est des Grands Bancs de Terre-Neuve. La première station du transect (Station 27) était située à environ 7 km au large du port de St. John's et avait une profondeur de 176 mètres. Cette station avait été intentionnellement localisée dans le chenal d'Avalon pour monitorer les propriétés de la branche côtière du courant du Labrador. La proximité de cette station avec le port de St. John's en faisait un site pratique pour pouvoir effectuer le monitorage en utilisant les navires de recherche sur les pêches qui partaient ou qui arrivaient de leur mission d'échantillonnage. La base de données pour cette station contient maintenant plus de 1 800 profils de température et plus de 1 500 profils de salinité, ce qui en fait le site le plus fréquemment échantillonné dans les eaux de Terre-Neuve et du Labrador, et de ce fait, l'une des séries les plus utiles pour les études climatiques en océanographie et en pêcheries dans cette région. Avant les années 1980, les données de la Station 27 étaient principalement utilisées par les chercheurs des pêches pour fournir la description physique annuelle de l'habitat du poisson et occasionnellement, pour relier les variations de l'environnement physique aux changements observés dans les pêcheries locales. Même si la description annuelle du climat océanique est encore le principal but de cet échantillonnage, au début des années 1980, on a aussi commencé à utiliser ces données pour aborder des enjeux reliés aux échelles de variabilité, aux changements climatiques, au mélange vertical et aux remontées d'eaux profondes ainsi qu'à la circulation locale. En 1998, avec l'implantation du Programme de Monitorage de la Zone Atlantique (PMZA), un échantillonnage biologique et chimique a été ajouté à l'échantillonnage physique de la station 27. Depuis ce temps, les conditions océanographiques basées sur cet échantillonnage sont disponibles de façon routinière. Ce monitorage devrait contribuer dans le futur à augmenter notre compréhension des écosystèmes marins en général, et nous permettre d'identifier les tendances à long terme du climat océanique.

Sampling History

Oceanographic observations on the Grand Banks of Newfoundland began as early as 1894 and were presented in the annual report of the Newfoundland Department of Fisheries for the year 1895. However, no systematic, regular oceanographic observations were conducted until 1931, when the Newfoundland Fisheries Research Commission opened the Biological Laboratory at Bay Bulls, Newfoundland. This laboratory was destroyed by fire in 1937 and it was not until the commissioning of the *Investigator II* as a full-time research vessel in 1946 that hydrographic work resumed under the directorship of Dr. Wilfred Templeman. During the late 1940s and early 1950s, hydrographic monitoring along several sections crossing the Newfoundland and Labrador Shelf was initiated. The section beginning immediately off St. John's Harbour with Station 27 (47° 32.8' N, 52° 35.2' W) proceeded to the southeast Grand Bank, ending with Station 32. The second station on this line, Station 28, was the first monitoring station on the Flemish Cap section (47° N), with stations numbering 28-42. The southeast Grand Bank section was not sampled regularly, but Station 27 was often included as part of the Flemish Cap section. The site is located about 7 km off St. John's Harbour in a water depth of 176 metres and was intentionally located in the Avalon Channel to monitor the water properties of the inshore branch of the Labrador Current (Fig. 1). In this area, the cold (<0°C) water that forms the cold intermediate layer (CIL) on the continental shelf is present year-round, and variations in water properties are representative of conditions across a broad area of the Newfoundland Shelf. Logistically, the station's proximity to St. John's Harbour also made it a convenient location for sampling by departing and arriving fisheries research vessels.

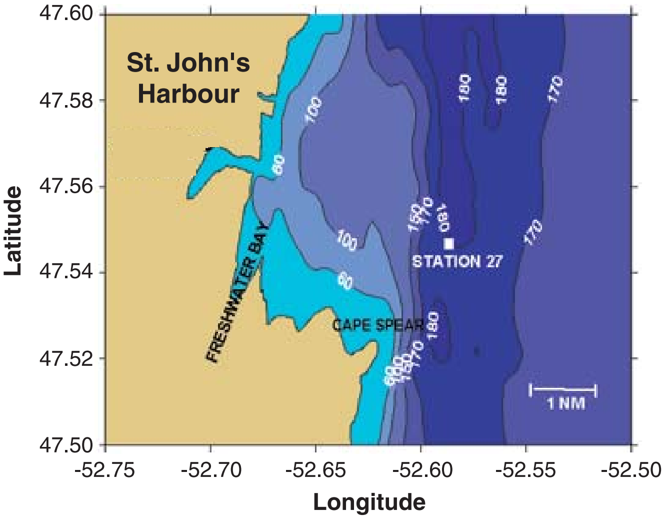


Fig. 1 Map showing the bathymetry (m) and location of Station 27 off St. John's Harbour.

Carte indiquant la bathymétrie (m) et la position de la Station 27 au large du port de St. John's, Terre-Neuve.

The first data from Station 27 were collected in June of 1947, and during the remainder of that year, the station was sampled 14 times. In subsequent years, sampling increased to include all months; there were 15-30 occupations per year up to the late 1970s. In recent years, the station has been sampled about 2-4 times per month on average. Historically, most of the data at Station 27 were collected at standard oceanographic depths (0, 10, 20, 30, 50, 75, 100, 125, 150, and 175 m) using bottles fitted with reversing

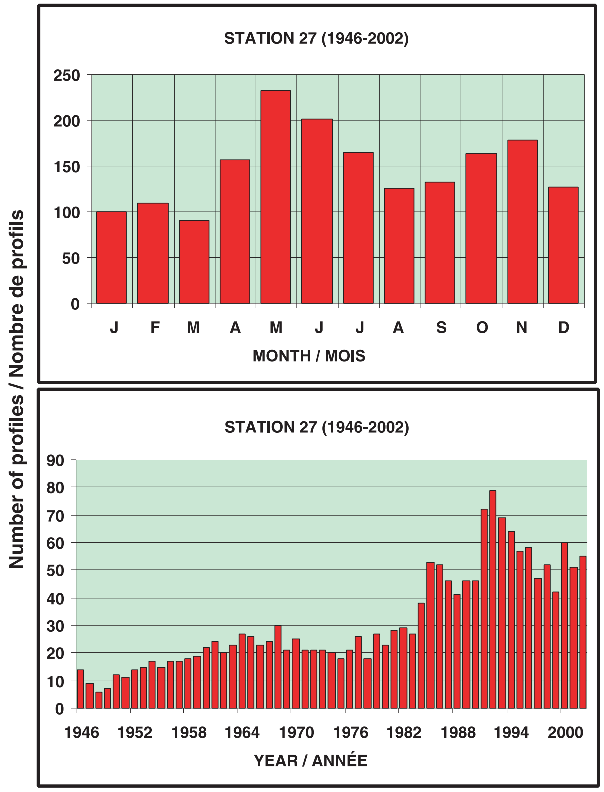


Fig. 2 The total number of temperature profiles collected at Station 27 by month (top panel) and by year (bottom panel).

Nombre total de profils de temperature échantillonnés à la Station 27 par mois (panneau du haut) et par année (panneau du bas).

thermometers. Since the mid 1960s, a considerable amount of data has also been collected using mechanical and electronic bathythermographs. More recently, conductivity-temperature-depth (CTD) recorders have been the instrument of choice. The monthly distribution of the number of temperature profiles collected at Station 27 shows a bias towards sampling in spring and early summer and to some extent during the fall with minimum sampling in winter (Fig. 2, top panel). The number of temperature profiles collected from 1946 to 1979 accounts for about 40% of the data (Fig. 2, bottom panel). Since the mid 1980s, there has been a large increase in data collection at Station 27, with an average of 45 to 55 profiles per year. In fact, the 1990s account for about 36% of the data collected at Station 27 in its 55-year history. The maximum number (>70) of occupations occurred in 1991 and 1992 during the collapse of the northern cod stock. The complete data set contains over 1800 temperature and over 1500 salinity profiles, making it the most frequently sampled site in Newfoundland and Labrador waters.

Use of Data

In the 1950s, Station 27 data mainly provided annual descriptions of the hydrographic conditions; occasionally these were related to changes in local fisheries. The annual report of the Fisheries Research Board of Canada for the year 1950 contains the first detailed description of oceanographic conditions using Station 27 data (Templeman 1951). Templeman described seasonal variations in temperature with depth and attributed unusually large catches of cod and lobsters in shallow water and the greatest abundance of squid for many years in the Newfoundland area to warmer-than-usual surface waters. By the mid 1950s, enough data had accumulated to allow Templeman and Fleming (1956) to compute the first temperature climatology for inshore Newfoundland waters, which was used to describe the thermal habitat of cod during the longlining experiments of 1950-1953 along the east coast of Newfoundland. Beginning in 1954, summaries of temperature and salinity variations at Station 27 were routinely included in the annual proceedings of the International Commission for the Northwest Atlantic Fisheries (ICNAF) (Templeman 1955). As more data accumulated, ICNAF initiated a series of special symposiums describing environmental conditions in the Northwest Atlantic on decadal time scales (ICNAF 1965).

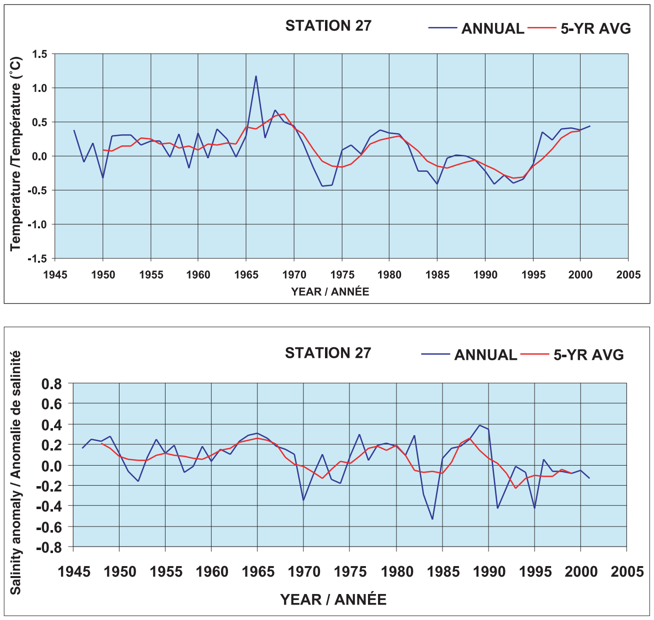


Fig. 3 Station 27 annual bottom temperature anomalies (top panel) and surface salinity anomalies (bottom panel) with their 5-year averages (red lines). The reference period is from 1971-2000.

Anomalies de température du fond (panneau du haut) à la Station 27 et de la salinité de surface (panneau du bas) comparées à leurs moyennes sur 5 ans (ligne rouge). La période de référence s'étend de 1971 à 2000.

Beginning in the 1960s, use of the Station 27 data was extended beyond annual descriptions of the physical environment. Bailey (1961), using data collected from 1946-1958, completed a detailed study of the oceanographic variability in the inshore waters of Newfoundland. He used harmonic analysis to construct annual and seasonal cycles of temperature and salinity at several depths and subsequently computed time series of temperature and salinity anomalies. Shortly afterwards, Templeman (1965a) published a report relating anomalies in sea temperature at Station 27 with air temperatures at St. John's. In the same year, he attributed the mass fish mortalities in the Newfoundland area to cold ocean temperatures (Templeman 1965b).

A series of climatologies of temperature, salinity, and density measured at Station 27 were published that were based on progressively longer time series. Huyer and Verney (1975) produced the first analysis using data from 1950 to 1959; Keeley (1981) extended it to include data from 1946 to 1977. More recently, Colbourne and Fitzpatrick (1994) presented an analysis of the Station 27 data for the years 1978 to 1993 and Fitzpatrick and Colbourne (2000) produced an updated temperature, salinity, and density climatology for Station 27 using data from 1946 to 1999. Currently these data sets are used to construct temperature and salinity anomaly time series for the inner Newfoundland Shelf using standard harmonic analysis and reference periods consistent with the World Meteorological Organization (WMO) (Fig. 3).

Petrie et al. (1988), using Station 27 data along with other environmental observations, presented a comprehensive description of the Newfoundland Shelf temperature variability, specifically the CIL, and concluded from correlation analysis that the spatial scales of variability are coherent over large areas of the Newfoundland Shelf. They then went on to describe in detail the phase and amplitude characteristics of the annual cycle in temperature and salinity (Petrie et al. 1991) and examined the spatial and temporal scales of variability in the residual field (Petrie et al. 1992) on the eastern Newfoundland Shelf. In these studies, the data were used to parameterize vertical diffusion coefficients, and kinematic models were employed to interpret the observations. A follow up to these studies by Umoh et al. (1995) used a vertical diffusion model with a horizontal advection adjustment to quantify the annual variations in the temperature cycle and partition the effects of local air–sea heat flux and advection on the Newfoundland Shelf. Mathieu and deYoung (1995) used temperature and salinity data from Station 27 to examine the influence of vertical diffusion and the importance of salinity in constraining a mixed-layer model for the inner Newfoundland Shelf.

Symonds (1986) used the data to model seasonal sea-ice extent on the Newfoundland Shelf, and Myers et al. (1990) concluded that ice-melt over Labrador and the northern Newfoundland Shelf was primarily responsible for the salinity minimum observed during late summer over much of the Newfoundland Shelf. Colbourne et al. (1994) and Drinkwater (1996) examined inter-decadal climate changes in the Northwest Atlantic using data from Station 27. Numerous other studies have used Station 27 data to examine environmental influences on growth, recruitment, and distribution of many marine organisms in Newfoundland waters (e. g., Myers et al. 1993, Parsons and Lear 2001, Colbourne and Anderson 2003). Stein and Lloret (2001) used the data in statistical models to forecast ocean temperatures for up to one year for fisheries assessment applications. These and other studies have contributed greatly to our understanding of the oceanography on the Newfoundland Shelf and the linkages between ocean climate and the marine ecosystem.

The climatology and year-to-year descriptions dominated the use of the Station 27 data until the mid 1980s. Moreover, annual descriptions of ocean climate that began in 1954 for ICNAF and presently for the Northwest Atlantic Fisheries Organization (NAFO) are still a primary focus and are perhaps one of the longest time series of documentation available anywhere pertaining to ocean climate conditions in the North Atlantic (Colbourne and Fitzpatrick 2002). Beginning in the mid 1980s, there has been increasing use of the data to address issues related to scales of variability, long-term climate changes, vertical mixing, local upwelling, and circulation. During the mid 1990s, oceanographers from Canada began active participation in the ICES Oceanography Committee and its working groups and, using the Station 27 time series, have contributed to the annual ocean climate status summary for the North Atlantic (ICES 2003). National and zonal groups, such as the Fisheries Oceanography Committee (FOC) of Fisheries and Oceans and the regional resource assessment proceedings (RAP), remain primary users of the Station 27 data (Colbourne 2003).

Station 27 and the AZMP Era

In 1992 under the northern cod science program, limited biological sampling was initiated at Station 27 but essentially ended with the termination of the program in 1995. Since 1998, as part of the Atlantic Zone Monitoring Program, biological and chemical sampling has resumed and oceanographic conditions based on these observations are now routinely published (Pepin et al. 2003). With over five years of continuous biological and chemical observations at Station 27, investigators are now beginning to construct short-term mean conditions, much like was done with hydrographic observations throughout the 1950s. Continued monitoring at this site will greatly increase our understanding of physical processes and long-term trends in ocean climate. It is in our understanding of ecosystem processes, however, through ongoing biological and chemical monitoring, that the most significant contribution to ocean science will likely be made in the near future.

References

Bailey, W.B. 1961. Annual variations of the temperature and salinity in the Grand Banks region. Fish. Res. Board Canada, Man. Rep. Ser. No. 74, 30 pp.

Colbourne, E.B. 2003. Physical oceanographic conditions on the Newfoundland and Labrador Shelves during 2002. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/020, 55 pp.

Colbourne, E.B., and J.T. Anderson. 2003. Biological response of a changing ocean environment in Newfoundland waters during the latter decades of the 1900s. ICES Mar. Sci. Symp. 219: 169-181.

Colbourne, E., and C. Fitzpatrick. 1994. Temperature, salinity and density at Station 27 from 1978 to 1993. Can. Tech. Rep. Hydrogr. Ocean Sci. 159, v+117 pp.

Colbourne, E.B., and C. Fitzpatrick. 2002. Physical Oceanographic Conditions in NAFO Sub-areas 2 and 3 on the Newfoundland and Labrador Shelf during 2001. NAFO SCR Doc. 2002/41. Serial No. N4652, 27 pp.

Colbourne, E.B., S. Narayanan and S. Prinsenberg. 1994. Climatic change and environmental conditions in the Northwest Atlantic during the period 1970-1993. ICES Mar. Sci. Symp. 198: 311-322.

Drinkwater, K.F. 1996. Atmospheric and oceanic variability in the Northwest Atlantic during the 1980s and early 1990s. J. Northw. Atl. Fish. Sci. 18: 77-97.

Fitzpatrick, C., and E.B. Colbourne. 2000. Temperature, salinity and density atlas for Station 27. Can. Data Rep. Hydrogr. Ocean Sci. 154, v+99 pp.

Huyer, A., and A. Verney. 1975. Temperature, salinity and sigma-t at Station 27, 1950-1959. Mar. Environ. Data Serv. Tech. Rep. No. 3, 45 pp.

ICES. 2003. The 2002/2003 ICES annual ocean climate status summary. *Edited by* S. L. Hughes and A. Lavin. ICES Cooperative Research Report No. 259, 29 pp.

ICNAF. 1965. Environmental Symposium, 1950-1959. ICNAF Spec. Publ. 6, 914 pp.

Keeley, J.R. 1981. Temperature, salinity and sigma-t at Station 27. An analysis of historical data. Mar. Environ. Data Serv. Tech. Rep. No. 8, 56 pp.

Mathieu, T., and B. deYoung. 1995. Application of a mixed layer model to the inner Newfoundland Shelf. J. Geophys. Res., 100: 921-936.

Myers, R. A., S. A. Akenhead and K. Drinkwater. 1990. The influence of Hudson Bay runoff and ice-melt on the salinity of the Inner Newfoundland Shelf. Atmos.- Ocean. 28: 120-157.

Myers, R.A., K.F. Drinkwater, N. J. Barrowman and J.W. Baird. 1993. Salinity and recruitment of Atlantic cod (*Gadus morhua*) in the Newfoundland region. Can. J. Fish. Aquat. Sci. 50: 1599-1609.

Parsons, L.S., and W. H. Lear. 2001. Climate variability and marine ecosystem impacts: a North Atlantic perspective. Prog. Oceanogr. 49: 167-188.

Pepin, P., G.L. Maillet, S. Fraser and D. Lane. 2003. Biological and chemical oceanographic conditions on the Newfoundland Shelf during 2002. DFO Can. Sci. Adv. Sec. Res. Doc. 2003/019, 70 pp.

Petrie, B., S. Akenhead, J. Lazier and J. Loder. 1988. The cold intermediate layer on the Labrador and northeast Newfoundland Shelves, 1978-1986. NAFO Sci. Coun. Studies 12: 57-69.

Petrie, B., J. Loder, S. Akenhead and J. Lazier. 1991. Temperature and salinity variability on the eastern Newfoundland Shelf: the annual harmonic. Atmos.- Ocean. 29: 14-36.

Petrie, B., J. Loder, J. Lazier and S. Akenhead. 1992. Temperature and salinity variability on the eastern Newfoundland Shelf: the residual field. Atmos.- Ocean. 30: 120-157.

Stein, M., and J. Lloret. 2001. Forecasting of air and water temperatures for fishery purposes with selected examples from the Northwest Atlantic. J. Northw. Atl. Fish. Sci. 29: 23-30.

Symonds, G. 1986. Seasonal ice extend on the Northeast Newfoundland Shelf. J. Geophys. Res. 91: 10,718-10,724.

Templeman, W. 1951. Annual report of the Fisheries Research Board of Canada for 1950, 35-37.

Templeman, W. 1955. Canadian Researches. 1954. Subareas 2 and 3. Ann. Proc. Int. Comm. Northw. Atlant. Fish. 5: 19-22.

Templeman, W., and A. M. Fleming. 1956. The Bonavista Longlining Experiment, 1950-1953. Fish. Res. Board Can., Bulletin No. 109, 55 pp.

Templeman, W. 1965a. Anomalies of sea temperature at Station 27 off Cape Spear and air temperatures at Torbay, St. John's. ICNAF Spec. Publ. 6, 795-806.

Templeman, W. 1965b. Mass mortalities of marine fish in the Newfoundland area presumably due to low temperature. ICNAF Spec. Publ. 6, 137-147.

Umoh, J. U., J. W. Loder and B. Petrie. 1995. The role of air-sea heat fluxes in annual and interannual ocean temperature variability on the Eastern Newfoundland Shelf. Atmos-Ocean 33: 531-568.

Exceptional Environmental Conditions in 1999 in Eastern Canadian Waters and the Possible Consequences for Some Fish and Invertebrate Stocks

Patrick Ouellet[1], François Grégoire[1], Michel Harvey[1], Erica Head[2], Bernard Morin[1], Ginette Robert[2], Louise Savard[1], Stephen Smith[2], Michel Starr[1], and Doug Swain[3]

[1]Maurice Lamontagne Institute, Fisheries and Oceans Canada, 850 route de la mer, Mont-Joli, QC, G5H 3Z4
[2]Bedford Institute of Oceanography, Fisheries and Oceans Canada, Box 1006, Dartmouth, NS, B2Y 4A2
[3]Gulf Fisheries Centre, Fisheries and Oceans Canada, 343 University Ave, Moncton, NB, E1C 9B6

Résumé

Plusieurs indicateurs des conditions atmosphériques indiquent que des températures de l'air anormalement élevées en 1999 ont entraîné une réduction de la glace de mer en hiver et au printemps sur les plateaux continentaux de Terre-Neuve, du Labrador et de la Nouvelle Écosse et une augmentation des températures de l'eau de surface sur l'ensemble de la zone Atlantique. Également, d'autres indices indiquent que le cycle de production biologique (la floraison du phytoplancton) a été initié plus tôt en 1999 dans la plupart des régions de la zone. Ces conditions océanographiques exceptionnelles auraient eu des conséquences positives sur la production (ex. recrutement, croissance) de nombreux stocks de poissons et d'invertébrés dans l'Est du Canada.

Introduction

Climate impacts on marine populations and individuals may operate through different processes, directly (e.g., influence of water temperature on metabolism, distribution) or indirectly by affecting primary and secondary production and trophic interactions in ecosystems. To understand how marine resources respond to forcing, it is important to assemble time series of biological, ecological, and climatological data and, by appropriate analyses, infer the mechanisms linking climate variability and population abundances.

Each year, the biological, chemical, and physical environmental information from different regions of the Atlantic zone (Gulf of St. Lawrence, Scotian Shelf, Newfoundland–Labrador Shelf), mostly coming from the Atlantic Zone Monitoring Program (AZMP), are reviewed by the Fishery Oceanography Committee (FOC) to produce state of the oceanic environment reports for each region. It was quickly realized that the environmental conditions in 1999 were unusual in Eastern Canada. Since then there is mounting evidence that the production of many stocks, both fish and invertebrate species, responded significantly to the particular conditions of the year 1999.

In this article, we describe and discuss briefly the atmospheric and oceanic (physical and biological) conditions for 1999 in relation to past conditions. We also document the response (recruitment) of certain fish and invertebrate stocks and attempt to establish possible links to observed environmental changes.

The Physical and Biological Environments of 1999

The meteorological, physical, and biological data from the AZMP and from other sources are analyzed to produce standardized indices that allow interannual comparisons and an evaluation of changes or variability in the ecosystems. For example, annual mean air temperatures at specific meteorological stations in Eastern Canada, sea-surface temperature, winter ice cover, etc., are estimated as yearly anomalies (i.e., in standard deviation units from the 1971-2000 mean when possible) and compared to those of the recent years. Figure 1 illustrates the recent time series of anomalies in air temperatures, sea-surface and bottom temperatures, and the area of winter ice in three regions: eastern Newfoundland and Labrador, the Scotian Shelf, and the Gulf of St. Lawrence. We can see that air temperatures in recent years (since 1997) were highest in 1999 in all regions. Sea-surface temperature was also especially high at Station 27 (Newfoundland) in 1999, and bottom temperatures were higher (positive anomalies) over the Grand Bank and the Scotian Shelf. Winter ice cover began to diminish in all regions in 1998 and the trend continued in 1999 (Fig. 1). Additional indications that a warming event occurred in 1999 can be found in the reduced volume (negative anomalies) of the cold intermediate layer (CIL) off Newfoundland and the change to a positive anomaly in the minimum temperature of the CIL in the Gulf of St. Lawrence (Fig. 2). Moreover, in 1999 we saw a significant reduction relative to 1998 of the surface area of the bottom covered by cold waters (<0°C or <1°C) in the southern Gulf of St. Lawrence (Fig. 2).

Time series of biological production indices in Eastern Canadian waters, with the exception of the Continuous Plankton Recorder (CPR) and Bedford Basin data sets, are much shorter than for measures of the physical oceanic environmental conditions. Nevertheless, analysis of the timing of the North Atlantic spring bloom from ocean colour satellite data showed that the early bloom in 1999 (compared with the year before and the three years following) was wide-spread, evident from Hudson Strait south to Georges Bank (Fig. 3). On average, the 1999 bloom preceded those in other years by 2-4 weeks. Similarly, weekly monitoring at a fixed station in the St. Lawrence Estuary revealed that the 1999 phytoplankton bloom was one of the earliest and most intense on record (Fig. 4a,b). Data from the CPR time series suggest that *Calanus finmarchicus* abundance increased in the late 1990s (1998 to 2000) in the NW Atlantic, although these values were still below those of the 1960s and early 1970s. For most regions, however, there are no long-term time series of zooplankton production to compare with the physical data series. Nevertheless, zooplankton biomass in the Gulf of St. Lawrence was not different in 1999 compared to the subsequent years, which seems to match the recent phytoplankton biomass (Chl *a*) time series, where relatively comparable high values have been recorded since 1999 (Fig. 4c,d).

The Response of Some Fish and Invertebrate Stocks

Scallops in the eastern Gulf of Maine

The major fisheries for sea scallop (*Placopecten magellanicus*) in the Bay of Fundy and Approaches and on the Canadian side of Georges Bank are managed through quotas and optimal size of capture (Robert et al. 2000, Smith et al. 2003). The optimal size of capture is expressed as a meat count (number of meats or adductor muscles per 500 g sample) and reflects the average weight of adductor muscle expected in the catch for a given level of fishing mortality. This average size is obtained from a yield-per-recruit analysis based on the growth characteristics of shell height as a function of age.

Comparison of growth characteristics between areas, such as the average meat weight at a particular shell height, is complicated by spatial variation in the growth rates of sea scallops (MacDonald and Thompson 1985, Bricelj and Shumway 1991, Smith et al. 2001). In fact, this spatial variation also complicates comparisons within areas over time, especially if there has been a tendency for larger samples of scallops coming from deeper (slow growing) or shallower (fast growing) water. Therefore, linear mixed-effects regressions were fit to the meat weight/shell height data from the annual (in June and August) scallop research surveys for the years 1996 to 2003, except for Georges Bank, for which data were only available until 2002. Predicted meat weights for shell height were derived from these linear models.

The predicted meat weight for a shell height of 100 mm shows the general trend evident at all shell heights (Fig. 5a). In all areas, there was an increase in the meat weight in 1999 with the largest increases from the previous year observed for Brier Island and Lurcher Shoal (outer bay of Fundy) (23 to 24%) and the smallest increases for the middle of the Bay of Fundy (Digby, 11 to 14%; Fig. 5a). These increases in meat weight had different repercussions in the different areas. In the marginal deeper water areas of Lurcher Shoal, meat weights are usually too small to fish according to the legal count of 45 meats per 500 g based upon

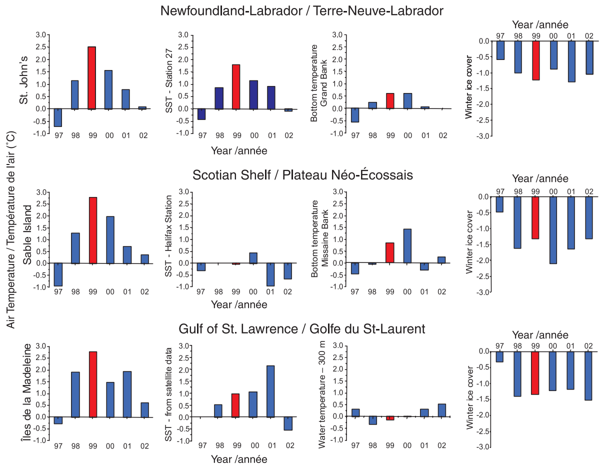


Fig. 1 Recent changes (in standard deviation units relative to the 1971-2000 mean) in selected indices of atmospheric and physical oceanographic conditions (air temperature, sea-surface temperature [SST], bottom temperature, and winter ice cover) for three regions of the Atlantic zone. SST data for the Gulf of St. Lawrence originate from satellite observations in the central region of the Gulf, away from coastal influences.

Changements récents (en unité d'écart type par rapport à la moyenne des années 1971 à 2000) dans différents indices des conditions atmosphériques et océaniques physiques (température de l'air, température de surface de la mer [SST], température au fond et couvert de glace) pour trois régions de la zone Atlantique. Les données SST pour le golfe du Saint-Laurent proviennent d'observations satellites effectuées dans la partie centrale du Golfe, loin de l'influence des côtes.

a minimum shell height of 80 mm. In 1999, the fishermen had no difficulty in staying within the count regulation due to the larger size of the meats (Smith et al. 1999).

An age-based model is used for the stock assessment of Georges Bank scallops. Ages are assigned to shell heights using a constant relationship over all years. Robert et al. (2000) noted that in addition to meat weights, shell heights appeared to have increased faster than expected in 1999 based upon this constant age/shell height relationship. While earlier surveys had identified the 1996 year-class as being particularly strong, larger numbers of age 4 scallops from a previously identified weak 1995 year-class were observed in 1999. This smearing of year-class strength may be due to changes in growth rate.

In addition to being the primary muscle for drawing the two valves of the scallop shell together, the adductor also functions as a storage organ (Robinson et al. 1981). The weight of the adductor undergoes seasonal changes whereby it declines in weight during late summer prior to spawning, recovers during the fall, and then declines in early winter. There is usually a rapid increase in weight during the spring with a peak from April to June before gonad mass peaks. If an increase of food availability is behind the increase in meat weight (and shell height) noted in 1999, then this increase in food may have occurred during the spring phytoplankton bloom in that same year.

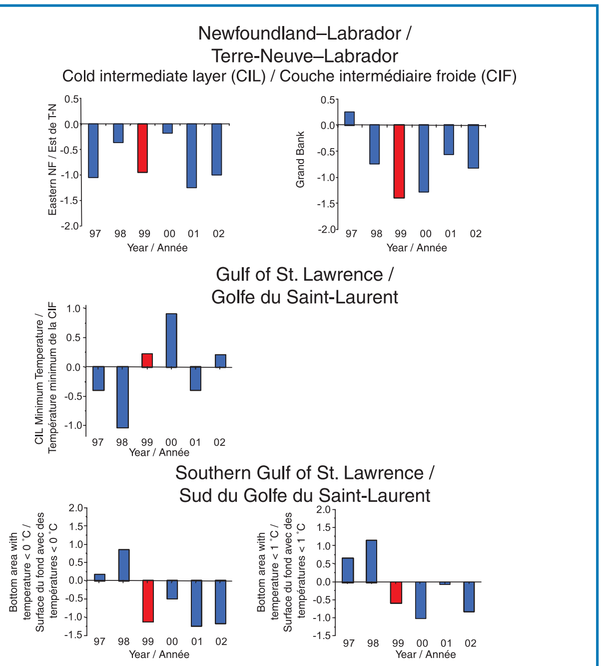


Fig. 2 Recent changes (in standard deviation units relative to the 1971-2000 mean) in the CIL area off eastern Newfoundland–Labrador, the CIL minimum temperature in the Gulf of St. Lawrence, and the area of the bottom covered by <0°C and <1°C water in the southern Gulf of St. Lawrence.

Changements récents (en unité d'écart type par rapport à la moyenne des années 1971 à 2000) dans la CIF à l'est de Terre-Neuve–Labrador, dans la température minimale de la CIF dans le golfe du Saint-Laurent et dans la surface du fond couverte par des eaux <0 °C et <1 °C dans le sud du golfe du Saint-Laurent.

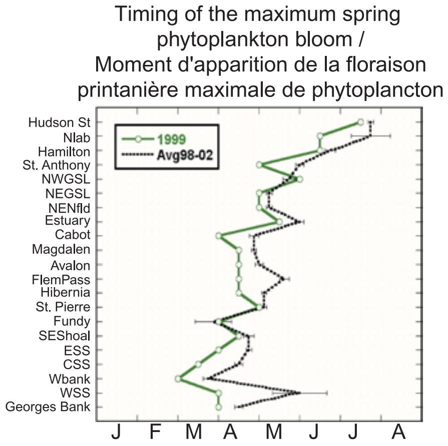


Fig. 3 Timing of the spring bloom maximum for selected coastal regions of the NW Atlantic; 1999 is compared with the mean (± standard error) timing for the years 1998 and 2000-2002.

Moment d'apparition du maximum du bloom printanier à des sites choisis dans les régions côtières de l'Atlantique nord-ouest; 1999 est comparée avec la moyenne (± l'erreur type) pour les années 1998 et 2000 à 2002.

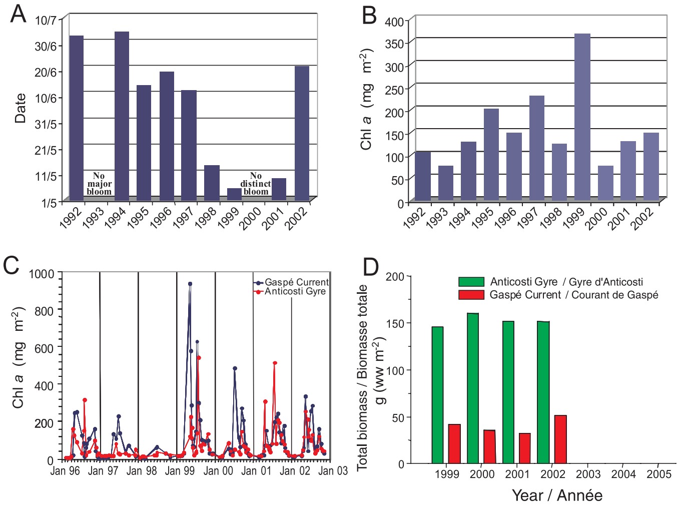


Fig. 4 A) Interannual variations in the timing of the spring phytoplankton bloom in the Lower St. Lawrence Estuary since 1992 showing the early 1999 bloom. B) Time series of integrated (upper 50 m) chlorophyll *a* concentration in the Lower St. Lawrence Estuary showing the intensity of the 1999 event. C) Estimated seasonal evolution of chlorophyll *a* concentrations at two AZMP fixed stations in the northwestern Gulf of St. Lawrence since 1996. D) Time series of total zooplankton abundance at two AZMP fixed stations in the northwestern Gulf of St. Lawrence.

A) Variations annuelles dans le moment d'apparition du bloom printanier de phytoplancton dans l'estuaire du Saint-Laurent depuis 1992 illustrant la date hâtive du bloom en 1999. B) Série temporelle de la concentration de chlorophylle a *(intégrée sur les premiers 50 m) montrant l'intensité de l'événement de 1999. C) Évolution saisonnière de la concentration de chlorophylle* a *à deux stations fixes du PMZA dans le nord-ouest du golfe du Saint-Laurent. D) Série temporelle de la biomasse totale de zooplancton à deux stations fixes du PMZA dans le nord-ouest du golfe du Saint-Laurent.*

Conditions in 1999 may have also had another effect on the scallop populations. Scallops spawn in the late summer–early fall. The larvae are planktonic but settle out to live on the bottom after about 30 to 60 days. Availability of food in the following spring may have a significant impact on the survival of a year-class that had settled the previous fall. For the areas discussed here, the 1998 year-class was one of the strongest at age 2. This year-class has become the mainstay of the Bay of Fundy fisheries in the Digby area and was still observed as being relatively strong in the Lurcher Shoal area. However, stock assessments for Georges Bank have revised estimates of the strength of this year-class downward since 2000 and the latest assessment identified the 1997 year-class as the strongest since 1978 (DFO 2003). Given the increases in growth noted above, it is possible that a large portion of the 1998 year-class may have been misidentified as the 1997 year-class.

Haddock on the Scotian Shelf

Data collected on groundfish surveys (haddock abundance and length-frequency distribution), on monitoring cruises (*C. finmarchicus* abundance and stage composition), and by satellites (sea-surface temperature and chlorophyll concentration) were used to examine the effects of environmental conditions on haddock year-class strength for the 1998-2001 period. Numbers of year-0 haddock on the Scotian Shelf in July 1999 were the highest that have been seen since record keeping began in 1970, and this year-class remained exceptionally strong as 1- and 2-year-old fish (Fig. 5b). The 1998 and 2000 year-classes were also good, but that of 2001 was poor. Individuals spawned on or near Western and Emerald banks dominated the 1999 year-class, and most had settled by July. In contrast, in 1998, 2000, and 2001, other areas made greater contributions to the year-0 population and lower proportions had settled by July. The average length of settled fish in 1999 also indicated that the main contributors to the population had hatched in late February, one or two months before the historical peak haddock-spawning period. A larger proportion of adults might have spawned earlier than usual in 1999, since adult fish showed their summer distribution (concentrated over Western and Emerald banks) in March, but in each of the sampling years, the lengths of year-0s caught in July suggested that some had hatched in late February.

The enhanced survival of early-spawned haddock in 1999 appears to have been linked to an unusually early occurrence of the spring bloom (Platt et al. 2003) and an associated unusually early spawning of *C. finmarchicus*. Both of these events peaked in late February in the region of Western and Emerald banks, where they would have provided an abundant food source to the early haddock larvae of 1999. In the other sampling years, both the spring bloom and *C. finmarchicus* spawning activity peaked in March in the Western Bank/Emerald Bank region, at a time closer to the historical haddock peak spawning time (March/April). Thus, the abundant 1999 year-class seems to be explained by the match between early-hatched haddock and early plankton production.

Mackerel in the Gulf of St. Lawrence

In Eastern Canada, mackerel (*Scomber scombrus*) spawning is concentrated primarily in the southern Gulf of St. Lawrence, though spawning may begin earlier off the coast of Nova Scotia. Typically, spawning starts in early summer (mid June). Eggs are pelagic and development takes only two or three days depending on near-surface water temperatures. Mackerel larvae hatch at ~3 mm and metamorphosis occurs at ~50 mm. Newly metamorphosed juveniles can be seen in August, implying rapid larval growth. The larvae feed on copepod (*C. finmarchicus*) nauplii (Ringuette et al. 2002), and there is evidence for a link between conditions for copepod production and mackerel recruitment in the southern Gulf of St. Lawrence (Runge et al. 1999).

Strong year-classes occur periodically in mackerel. When they do, they tend to dominate the population for a number of years. During the last three decades, there were strong year-classes in 1974, 1982, 1988, and 1999 (Fig. 5c). In 1999, however, spawning seems to have occurred earlier than normal in the southern Gulf of St. Lawrence (MPO 2003). Mackerel from strong year-classes are also particular in having smaller heights of the first annulus of the otoliths. This is interpreted as indicative of a density-dependent effect on growth during the first year. However, the strong year-class of 1999 also seems to show the highest first-year growth rate. This suggests that the exceptionally warm conditions and probable high plankton production levels in the southern Gulf of St. Lawrence in the summer of 1999 were favourable to the development of a strong year-class in mackerel.

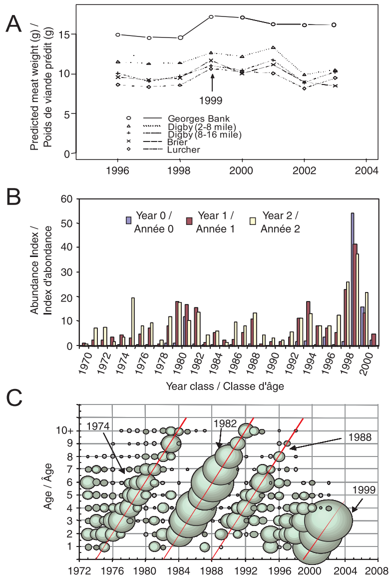


Fig. 5 A) Predicted meat weight for a shell height of 100 mm for sea scallops based on annual (June and August) scallop research surveys. B) Time series of the relative abundance of young haddock showing the high recruitment of the recent years, especially the 1999 year-class. C) Relative abundance of mackerel in the commercial fisheries showing the importance of the 1999 year-class. The strong 1974, 1982, 1988, and 1999 year-classes are indicated by the red lines.

A) Poids moyen de chair de pétoncle prédit pour une hauteur de coquille de 100 mm basé sur les relevés scientifiques annuels (juin et août). B) Série temporelle de l'abondance relative de jeunes aiglefins montrant l'importance du recrutement récent, surtout pour l'année 1999. C) Abondance relative du maquereau dans la pêche commerciale, démontrant l'importance de la classe d'âge de 1999. Les fortes classes de 1974, 1982, 1988 et 1999 sont indiquées par les lignes rouges.

Turbot in the Gulf of St. Lawrence

Greenland halibut or turbot (*Reinhardius hippoglossoides*) has become an important flatfish species for the Gulf of St. Lawrence fisheries. Mature females are observed in January and spent females have been found in April, implying that spawning occurs in winter and early spring (Scott and Scott 1988). However, the precise location of spawning sites and egg and larva distributions are unknown for the northern Gulf of St. Lawrence. Turbot recruitment is defined as the abundance of 1-year-old fish during the summer groundfish survey in the northern Gulf of St. Lawrence. Recruitment has been increasing since the mid 1990s, and the abundance of 1-year-old turbot peaked in 2000 (i.e., the 1999 year-class) (Fig. 6a). There is also a significant stock–recruitment relationship in turbot: the very low recruitment levels from the 1992 to 1994 year-class were apparently the result of the low spawning stock (SS) biomasses. However, the recruitment rate (the number of recruits divided by the number of fish that produced them, R/SS) showed the same pattern as recruitment with an apparent peak in young turbot survival in 1999 (Fig. 6a).

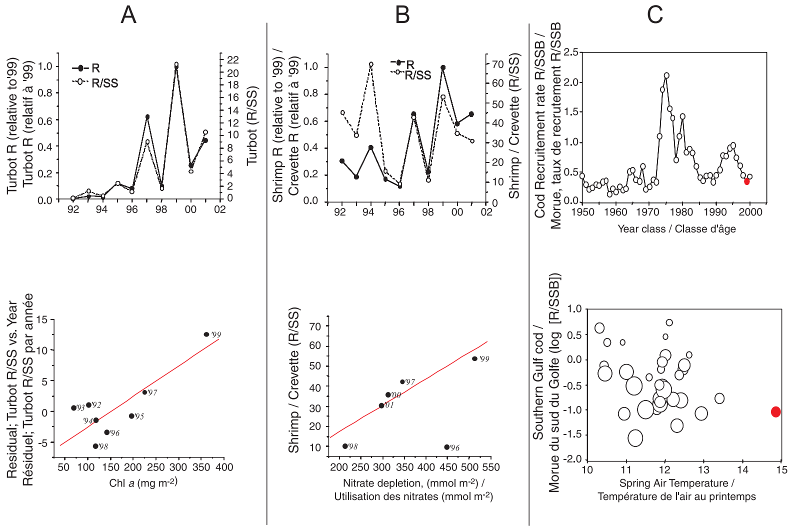


Fig. 6 A) Time series of turbot recruitment and recruitment rate (number of recruits divided by the biomass of the spawning stock that produces them) in the Gulf of St. Lawrence (upper panel), and the correlation between an index of biological production and turbot recruitment (lower panel). B) Time series of shrimp recruitment and recruitment rate (number of recruits divided by the biomass of the spawning stock) in the Gulf of St. Lawrence (upper panel), and the correlation between an index of biological production and shrimp recruitment (lower panel). C) Time series of cod recruitment rate in the southern Gulf of St. Lawrence (upper panel), and the relation between spring temperature and cod recruitment rate (lower panel). Symbol size is proportional to the abundance of the pelagic fish stocks for each year and the solid symbol indicates the 1999 data.

A) Série temporelle de recrutement et du taux de recrutement (nombre de recrues divisé par la biomasse du stock de reproduction correspondant) du turbot dans le golfe du Saint-Laurent (graphique du haut) et corrélation entre l'indice de production biologique et le taux de recrutement (graphique du bas). B) Série temporelle de recrutement et du taux de recrutement (nombre de recrues divisé par la biomasse du stock de reproduction correspondant) de la crevette dans le golfe du Saint-Laurent (graphique du haut) et corrélation entre l'indice de production biologique et le taux de recrutement (graphique du bas). C) Série temporelle du taux de recrutement de la morue dans le sud du golfe du Saint-Laurent (graphique du haut) et relation entre le taux de recrutement et la température de l'air au printemps et en début d'été (graphique du bas). La taille des symboles est proportionnelle à l'abondance des stocks de poissons pélagiques pour chaque année de la relation et le symbole plein indique l'année 1999.

Juvenile turbot are found in abundance in the Lower St. Lawrence Estuary (LSLE). The integrated (0-50 m) chlorophyll *a* biomass at a fixed monitoring station in the LSLE was used as a proxy for biological production to compare with the turbot recruitment rate time series. The significant correlation, albeit driven by the 1999 year-class, found between turbot recruitment rate and the integrated chlorophyll *a* biomass index suggests that spring biological production influences turbot larvae survival (Fig. 6a). This finding is a strong argument for better knowledge of turbot egg and larva distributions and ecology in the Gulf of St. Lawrence ecosystem.

Shrimp in the Gulf of St. Lawrence

Reliable data on northern shrimp (*Pandalus borealis*) recruitment are available for the last decade for the Lower St. Lawrence Estuary and the Northwest Gulf of St. Lawrence (NWGSL). The shrimp recruitment time series was obtained from the abundance of 3-year-old shrimp caught during the summer (August) groundfish survey from 1990 to 2002 (i.e., 1987 to 1999 year-classes) and from the abundance of 1- to 3-year-old shrimp (i.e., 2000 and 2002 year-classes) from a special June survey carried out since 2000. In this recent time series, shrimp recruitment peaked in 1999. However, when standardized by an index of spawning stock abundance (spring catches per unit effort, CPUE), i.e., R/SS or the recruitment rate, the highest recruitment rate in shrimp was observed in 1994 with 1999 the second highest (Fig. 6b).

Berried females aggregate in the NWGSL in early spring, with emergence of the larvae from the end of April to the end of May (Ouellet et al. 1990). The first larval stages are present in the upper water column (Ouellet and Lefaivre 1994) and there is evidence that phytoplankton cells may play a role in the diet of young larvae (Pedersen and Storm 2002). However, it was also shown that shrimp larvae of all stages are efficient predators of small zooplankton (Harvey and Morrier 2003). Therefore, it is suspected that oceanic conditions conducive to high biological production in the spring will be favourable to shrimp larva survival and recruitment to the stocks. As an attempt to validate the hypothesis, a correlation was made between shrimp recruitment rate and the integrated (upper 50 m) nitrate depletion index (nitrate concentration maximum minus nitrate concentration minimum in the spring at the AZMP Anticoti Gyre fixed station; Starr et al. 2003), as a proxy for primary production intensity in the NWGSL. Unfortunately, for the period considered, there were only six years available to correlate the index of spring primary production and shrimp larvae recruitment rate. Nevertheless, there seems to be a positive correlation between shrimp recruitment rate and the nitrate index (Fig. 6b). Notably, the integrated nitrate depletion index (biological production) at the Anticosti Gyre was higher in 1999.

Cod in the Southern Gulf of St Lawrence

The main spawning grounds for cod in the southern Gulf appear to be located in the western Magdalen Shallows in the area of the Gaspé Coast, Miscou Bank, and the Shediac

Valley. Seasonal changes in the gonadosomatic index (i.e., reproductive status) are consistent with peak spawning in late May or early June in recent years (Schwalme and Chouinard 1999). Cod eggs and larvae are pelagic. Recruitment rate increased in the early 1990s (Chouinard et al. 2003), reaching moderately high levels in the mid 1990s, but declined again in the late 1990 (Figure 6c). Estimated recruitment in 1999 was the lowest on record and the estimated recruitment rate was low in both 1999 and 2000, although still within the range observed between 1950 and the early 1970s.

The recruitment rate of southern Gulf cod appears to be affected by the abundance of pelagic fishes, which are potential predators and/or competitors of early life-history stages of cod. An earlier period of remarkably high recruitment rates from the mid 1970s to the early 1980s coincided with the collapse of herring and mackerel stocks in the southern Gulf caused by overfishing in the late 1960s and early 1970s (Swain and Sinclair 2000). Swain and Sinclair (2000) reported a strong negative relationship between the biomass of these fishes, the principle pelagic fishes in the southern Gulf, and cod recruitment rates for the 1963-1994 year-classes. In addition, Swain et al. (2000) examined relationships between the recruitment rate of southern Gulf cod and a number of climate indices. They noted a tendency for recruitment rate to be poor in years when air temperatures were warm in spring and early summer (May-July, the period when cod eggs and larvae are prevalent in the near-surface waters of the southern Gulf), though this relationship was not statistically significant in most analyses over the 1950-1994 period for which data were available.

However, spring and early summer air temperatures over the Magdalen Shallows in 1999 were the warmest recorded in a 50-yr time series and, given this strong signal, the earlier relationship between spring/summer air temperatures and cod recruitment rate in the southern Gulf was re-examined. There was a strong negative effect of pelagic fish biomass on cod recruitment and a weaker but significant negative effect of May-July air temperatures (Fig. 6c). These results suggest that the unusually warm conditions in the spring and early summer of 1999 contributed to the weak recruitment of southern Gulf cod in that year. Given the tendency for cod recruitment to be poor in the southern Gulf in warm years, the long-term trend toward warmer conditions does not bode well for the recovery of southern Gulf cod.

Conclusion

The linkages between the higher trophic levels (e.g., fishes, large invertebrates, mammals) and the primary functions (e.g., physico-chemical conditions, primary production) of an ecosystem are complex, involving a wide range of scales and processes, and sensitive to abrupt changes (either climate-driven or anthropogenic). The relationships inferred above should not be interpreted as means to predict variability in fisheries resources. Nevertheless, this short review illustrates the virtues of patience and perseverance when conducting a monitoring program of the oceanic environment. It seems safe to argue that the longer the time series of basic information, the better will be our understanding of the ecosystem and our capability to elucidate the mechanisms that drive the complex pattern of variability in marine populations.

References

Bricelj, V.M., and S. Shumway. 1991. Physiology: energy acquisition and utilization. *In* Scallops: biology, ecology and aquaculture. *Edited by* S.M. Shumway. Elsevier, Amsterdam, pp. 305-346.

Chouinard, G.A., D.P. Swain, L. Currie, G.A. Poirier, A. Rondeau, H. Benoit, T. Hurlbut and D. Daigle. 2003. Assessment of the southern Gulf of St. Lawrence cod stock, February 2003/ Évaluation du stock de morue du sud du Golfe du St-Laurent, février 2003. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/015. 116 pp.

DFO. 2003. Georges Bank scallop. DFO Sci. Stock Status Rep. 2003/038.

Harvey, M., and G. Morrier. 2003. Laboratory feeding experiments on zoea of northern shrimp (*Pandalus borealis*) fed with natural zooplankton. Mar. Ecol. Prog. Ser. 265: 165-174

MacDonald, B.A., and R.J. Thompson. 1985. Influences of temperature and food availability on the ecological energetics of giant scallop *Placopecten magellanicus* (Gmelin). Growth rates of shell and somatic tissue. Mar. Ecol. Prog. Ser. 25: 279-294.

MPO. 2003. Maquereau bleu du nord-ouest de l'Atlantique en 2002. MPO Sciences, Rapport sur l'état des stocks 2003/010.

Ouellet, P., and D. Lefaivre. 1994. Vertical distribution of northern shrimp (*Pandalus borealis*) larvae in the Gulf of St. Lawrence; implications for trophic interactions and transport. Can. J. Fish. Aquat. Sci. 51: 123-132.

Ouellet, P., D. Lefaivre and V. Koutitonsky. 1990. Distribution of shrimp (*Pandalus borealis*) larvae and hydrographic patterns in the northern Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. 47: 2068-2078.

Pedersen, S.A., and L. Storm. 2002. Northern shrimp (*Pandalus borealis*) recruitment in West Greenland waters. Part II. Lipid classes and fatty acids in *Pandalus* shrimp larvae: implications for survival expectations and trophic relationships. J. Northw. Atl. Fish. Sci 30: 47-60.

Platt, T., C. Fuentes-Yaco and K. T. Frank. 2003. Spring algal bloom and larval fish survival. Nature. 423: 398-399.

Ringuette, M., M. Castonguay, J. Runge and F. Grégoire. 2002. Atlantic mackerel (*Scomber scombrus*) recruitment fluctuations in relation to copepod production and juvenile growth. Can. J. Fish. Aquat. Sci. 59: 646-656.

Robert, G., G.A.P. Black, M.A.E. Butler and S.J. Smith. 2000. Georges Bank scallop stock assessment — 1999. DFO Can. Stock Assess. Secr. Res. Doc. 2000/016.

Robinson, W.E., W. E. Wehling, M. P. Morse and G. C. McLoed. 1981. Seasonal changes in soft-body component indices and energy reserves in the Atlantic deep-sea scallop, *Placopecten magellanicus*. Fish. Bull. 79: 449-458.

Runge, J., M. Castonguay, Y. de Lafontaine, M. Ringuette and J.-L. Beaulieu. 1999. Covariation in climate, zooplankton biomass and mackerel recruitment in the southern Gulf of St. Lawrence. Fish. Oceanogr. 8: 139-149.

Schwalme, K., and G.A. Chouinard. 1999. Seasonal dynamics in feeding, organ weights, and reproductive maturation of Atlantic cod (*Gadus morhua*) in the southern Gulf of St. Lawrence. ICES J. Mar. Sci. 56(3): 303-319.

Scott, W.B., and M.G. Scott. 1988. Atlantic fishes of Canada. Can. Bull. Fish. Aquat. Sci. 219.

Smith, S.J., M.J. Lundy and R. Claytor. 1999. Scallop production areas 2, 3, and 7 in the Bay of Fundy: Stock status update for 1999. DFO Can. Stock Assess. Sec. Res. Doc. 99/171.

Smith, S.J., E. L. Kenchington, M. J. Lundy, G. Robert and D. Roddick. 2001. Spatially specific growth rates for sea scallops (*Placopecten magellanicus*). *In* Spatial Processes and Management of Marine Populations. *Edited by* G.H. Kruse. University of Alaska Sea Grant, AK-SG-01-02, Fairbanks. pp. 211–231.

Smith, S.J, M.J. Lundy, D. Roddick, D. Pezzack and C. Frail. 2003. Scallop production areas in the Bay of Fundy and scallop fishing area 29 in 2002: Stock status and forecast. Can. Sci. Advis. Sec. Res. Doc. 2003/010.

Starr, M., L. St-Amand, L. Devine, and L. Bérard-Therriault. 2003. State of phytoplankton in the Estuary and Gulf of St. Lawrence during 2002. CSAS Res. Doc. 2003/103, 29 pp.

Swain, D.P., and A.F. Sinclair. 2000. Pelagic fishes and the cod recruitment dilemma in the Northwest Atlantic. Can. J. Fish. Aquat. Sci. 57: 1321-1325.

Swain, D.P., A.F. Sinclair, G.A. Chouinard and K.F. Drinkwater. 2000. Ecosystem effects on pre-recruit survival of cod in the southern Gulf of St. Lawrence. CSAS Res. Doc. 2000/147. 23 pp.

State of the Ecosystem Report for the Eastern Scotian Shelf

Kenneth Frank, Jae Choi, Scott Coffen-Smout, Ken Drinkwater, Brian Petrie, Glen Harrison, Heather Breeze, Alida Bundy, and Phil Yeats
Bedford Institute of Oceanography, Box 1006, Dartmouth, NS, B2Y 4A2
frankk@dfo-mpo.gc.ca

Résumé

Plusieurs caractéristiques de l'écosystème situé dans la région est du plateau continental Néo-Écossais ont changé dramatiquement depuis les derniers trente ans. Un événement de refroidissement majeur des eaux de fond qui a persisté pour une décade s'est en effet produit vers le milieu des années 1980, et une augmentation significative de la stratification dans les eaux de la couche de surface a également été observée au cours des dernières années. Ces deux phénomènes sont associés au flux de masses d'eaux provenant des régions en amont. L'indice d'abondance du zooplancton était bas durant la décade des années 1990 lorsque les niveaux d'abondance du phytoplancton étaient hauts, et un patron opposé a été observé durant les années 1960 et le début des années 1970. Des changements structuraux majeurs se sont également produits dans les communautés de poissons. L'abondance des poissons de fond a en effet décliné tandis que les petites espèces pélagiques et les espèces de vertébrés exploités ont augmenté. L'augmentation de l'aire de distribution de quelques espèces de même que l'apparition d'espèces complètement nouvelles dans la région se sont produites, vraisemblablement associées aux changements dans les conditions physiques de l'environnement. Une réduction dans la taille moyenne des poissons de fond s'est aussi produite et il ne reste plus présentement que quelques poissons de grande taille – une situation probablement jamais expérimentée dans le passé. La condition et la croissance de plusieurs espèces de poissons de fond sont demeurées faibles au cours de la dernière décennie contrairement aux attentes. Il n'est cependant pas encore possible de prédire combien de temps cette situation va persister ou encore, si le système va revenir à son état initial dominé par les espèces de poisson de fond. L'industrie de la pêche vise de plus en plus les espèces du bas de la chaîne trophique parce qu'il manque de ressources aux niveaux plus hauts des poissons de fond. L'exploration et le développement pour le gaz et le pétrole ont toujours été très épisodiques quoique récemment cette activité est en croissance. Il y a encore trop peu de données sur la concentration des contaminants dans l'eau, les sédiments et le biote de cette région pour pouvoir établir des patrons temporels et spatiaux. Lorsqu'on tient compte de toutes ces sources de perturbation (e.g., toutes les utilisations humaines), les effets cumulatifs potentiels laissent certainement place à de l'inquiétude.

Introduction

This State of the Ecosystem report is a product of a working group that compiled and analyzed various data relevant to the evaluation of the eastern Scotian Shelf ecosystem. In the past, no one document has provided a comprehensive, integrated assessment of the current status of a large ocean area or ecosystem under Canadian jurisdiction. Our analysis here focuses on all available data series associated with three categories of variables: biotic, abiotic, and human. Biotic variables generally include information on the abundance, distribution, and composition of finfish and invertebrates, phyto- and zooplankton, and marine mammals. Abiotic variables include oceanic and atmospheric data that provide insights into ocean climate conditions. Human variables range from fishery landings, fishery revenue, and activities associated with oil and gas development to contaminants. The current evaluation used over 60 data series, most of which extend to at least 1970. By examining temporal trends in the data, an assessment was made of the current status of the ecosystem relative to its previous state. The report, available from www.dfo-mpo.gc.ca.csas, represents a step toward consolidation and synthesis of the ever-growing body of data from various monitoring programs.

Geographic Area

The Eastern Scotian Shelf (ESS), comprising NAFO Div. 4VW, is a large geographic area (~108,000 km^2) supporting a wide range of ocean uses such as fisheries, oil and gas exploration and development, and shipping. It is currently the focus for the development of an integrated management plan with the intent to harmonize the practices of the various ocean use activities within it (referred to as ESSIM: Eastern Scotian Shelf Integrated Management). The ESS consists of a series of outer shallow banks and inner basins separated by gullies and channels. The mean surface circulation is dominated by southwestward flow, predominantly from the Gulf of St. Lawrence, with anticyclonic circulation tending to occur over the banks and cyclonic circulation around the basins. The northeastern region of the Shelf is the southernmost limit of winter sea ice in the Atlantic Ocean. The area is unique for having a year-round closure for directed fishing of groundfish established in 1987, associated with Emerald and Western banks. In addition, DFO has declared the area associated with The Gully as a pilot marine protected area. Like several other areas in the northwest Atlantic, the once dominant cod fishery collapsed in the early 1990s.

Integration of Data

An overall picture of the changes that have taken place on the Eastern Scotian Shelf since 1970 was addressed by adopting an approach similar to the traffic light framework used in stock assessments and recently utilized by Link et al. (2002) for an ecosystem evaluation in a fisheries management context of Georges Bank. Sixty-four metrics were used in the evaluation, with 50 representing primary indices and 14 indicative of second order indices, i.e., higher level processes such as community composition, ratios of variables, growth, etc. The indices were made directly comparable to one another by expression as anomalies (deviation from long-term mean) in standard deviation units. Colours were used to display the magnitude of the anomalies ranging from strongly negative (red) to strongly positive (green). The colour scheme was not chosen to convey judgment on the direction of change (i.e., good or bad). The metrics were ordered using principal component analysis to identify any coherence in the variations of the indicators over the study period. Thus, the sequence of the indicators reflects the degree of similarity in their temporal dynamics (Fig. 1).

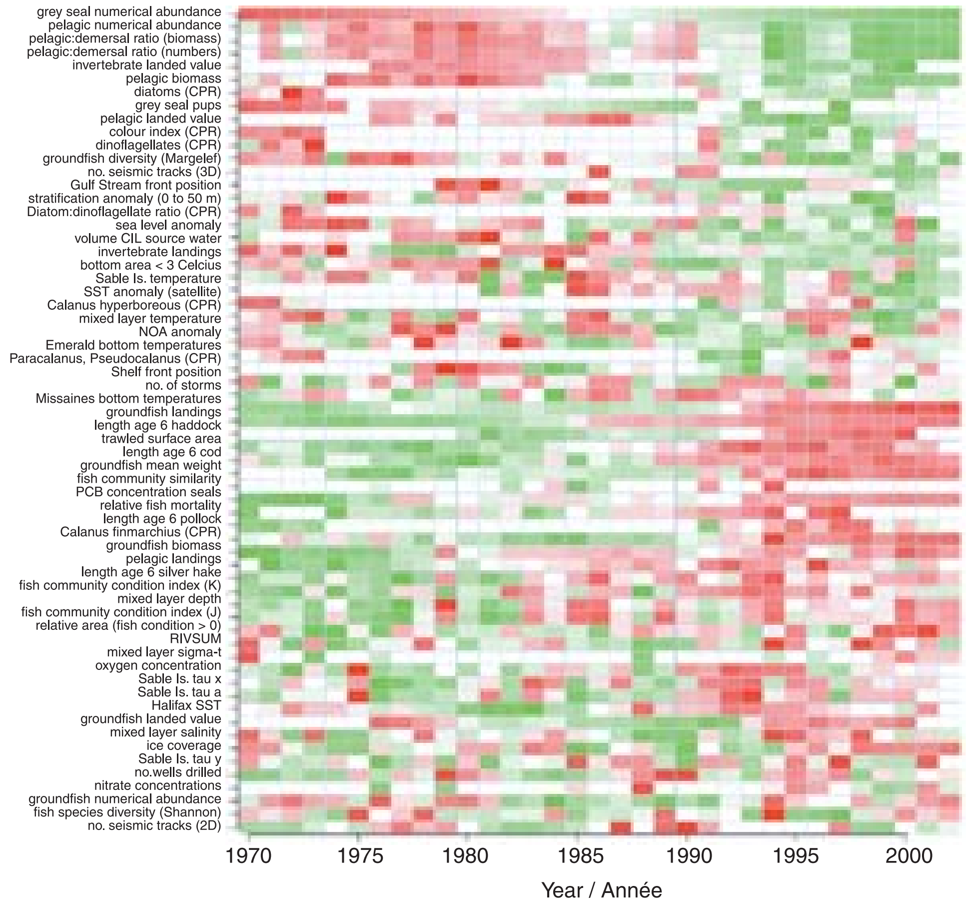


Fig. 1 The time series of annual anomalies of variables for the Eastern Scotian Shelf from 1970 to 2002. Green blocks indicate above-normal and red below-normal conditions. White blocks represent near-normal or missing data.

Série temporelle des anomalies annuelles de plusieurs variables pour la region est du plateau Néo-Écossais entre 1970 et 2002. Les blocs verts indiquent des conditions au-dessus et les rouges au-dessous de la normale. Les blocs blancs représentent des conditions près de la normale ou encore des données manquantes.

Systemic Changes

Seal abundance, pelagic fish abundance, landed value of shellfish, fish species richness, and phytoplankton (greenness) were among the several metrics that changed in a coherent manner relative to those farther down the list during the 1970s to the early 1980s. These metrics all exhibited negative anomalies and subsequently shifted to all positive in the 1990s to present. Conversely, anomalies of bottom temperatures at Misaine Bank, commercial exploitation levels, groundfish landings and biomass, growth rates of cod, haddock, and pollock, average individual fish weight, and copepod counts were all positive during the 1970s to the early 1980s. In addition, warm bottom temperatures, a weakly-stratified summer water column, and a deep mixed-layer depth typified the abiotic conditions at this time. During the 1990s almost all of these positive anomalies became negative at a time when bottom temperature declined, mixed layer depth decreased, and the water column became more intensely stratified. Overall, what is visually striking is the change in state from one extreme to the other for almost all the metrics over the study period, with the transition occurring between the years 1985 to 1990. The changes observed were systemic and coherent.

The causes of these patterns remain as yet unexplained; however, a few key hypotheses deserve consideration: 1) “Top-down” or predator control of food webs is one possible explanation for the reciprocal changes in abundance among alternating trophic levels (Fig. 2). When the indicators of groundfish abundance (total landings) were high during the 1970s/mid 1980s, survey estimates of pelagic abundance were low, zooplankton abundance (counts) was high, and chlorophyll was low. Throughout the 1990s, a reversal of this pattern was evident when the indicators of groundfish abundance were low; 2) Physical changes associated with increased stratification could favour the proliferation of a pelagic-based food web and limit the flux of nutrients to the benthos; and 3) Cooling and increased advection were associated with

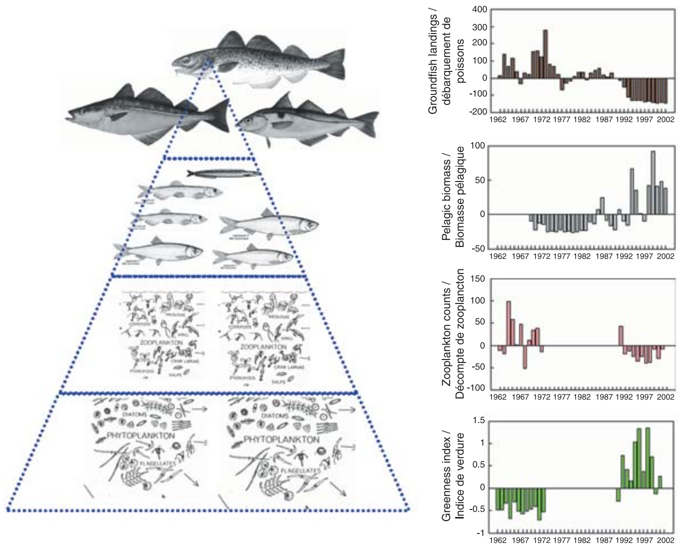


Fig. 2 Pictorial representation of a trophic pyramid based on a simplified food chain starting at the top with groundfish, then pelagics to zooplankton, and finally phytoplankton. Representative data for each trophic level are shown to the right of the pyramid, including annual anomalies of groundfish landings (in thousands of tons), pelagic biomass (in kg per standard tow), zooplankton abundance (data from the Continuous Plankton Recorder [CPR], in counts per tow), and the CPR greenness index (a measure of chlorophyll concentrations).

Image représentant la pyramide trophique basée sur une chaîne trophique simplifiée, partant du haut par les poissons de fond, puis passant aux poissons pélagiques, au zooplancton, et finalement au phytoplancton. Des données représentatives pour chaque niveau trophique sont montrées à la droite de la pyramide incluant les anomalies annuelles de débarquement de poissons de fond (en tonnes x 1 000), de la biomasse pélagique (en kg par trait standard), de l'abondance du zooplancton (données provenant de l'échantillonneur CPR [«Continous Plankton Recorder»] en nombre par trait) et de l'indice de verdure de l'échantillonneur CPR (une mesure de la concentration de chlorophylle).

colonization by subarctic species, increases in abundance of snow crab and shrimp, and declining groundfish productivity. Coupled with high exploitation pressure on groundfish, dominant species such as cod and haddock may have been made more susceptible to these physical changes. It should be noted that the hypotheses are not mutually exclusive and elements of each one may be contributing to the observed patterns.

Focus: the Fish Community

Profound changes in community composition and body size of groundfish have occurred during the past thirty years on the Eastern Scotian Shelf. The historical composition of the top five species based on abundance included redfish, American plaice, silver hake, haddock, and cod. This dominance structure has changed dramatically during the past decade and pelagic species such as sand lance, capelin, and herring are now dominant. Only silver hake and haddock have remained near the top since the early 1980s while cod, redfish, white hake, and thorny skate have decreased. In addition, 10- to 50-fold increases in the abundance of daubed shanny, turbot, snake blenny, and sea poacher were evident in the most recent period relative to 1981-1992. It is notable that the increasing species are all small-bodied, with the exception of turbot. In addition, temperature conditions appear to influence the occurrence of species new to the area, particularly when conditions remain persistently above or below normal. Several species of subarctic origin were first recorded during the anomalous cooling period that began in the mid 1980s, including shorthorn sculpin, sea tadpole, Newfoundland eelpout, two horn sculpin, little grubby, and checker eelpout. Overall, thirty species new to the area have been captured since 1991, with the vast majority less than 35 cm in length. Conversely, during the warm water conditions that began in the late 1970s, several warm temperate/subtropical species were captured, including beardfish, barracudina, batfish, greeneye, common wolfeel, deepwater flounder, and snipe eel (Fig. 3).

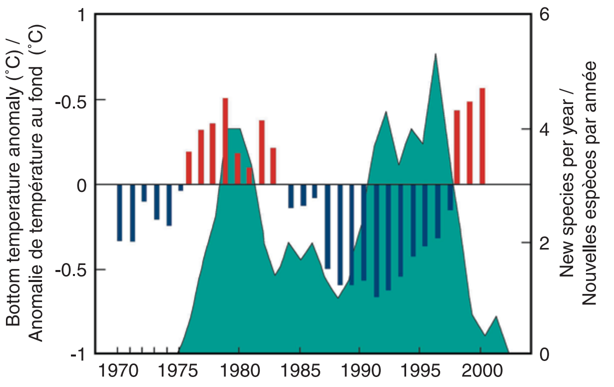


Fig. 3 Time series of annual anomalies of bottom temperatures (bars) at Misaine Bank and the occurrence of species new to the Eastern Scotian Shelf region.

Série temporelle des anomalies de température du fond (barres) sur le banc de Misaine et apparition de nouvelles espèces dans la région est du plateau Néo-Écossais.

The foregoing description of temporal changes in fish species composition and abundance suggests that decreases in length and weight averaged across all groundfish species would be evident. The pattern of reduced weight (kg) was most evident during the 1990s, with the largest reduction in the northeastern areas (Fig. 4). Changes in length mirror these patterns. Declining average weight not only reflects increased abundance of small-bodied species, but also the contracted size distribution of large-bodied species. For example, adult cod, haddock, and pollock (age 5) are now much smaller (~ 30%) in terms of total length at age 5, on average, compared to individuals from the 1970s and 1980s. Reductions in size-at-age have also occurred in silver hake. The trend of reduced size has occurred, despite current low population levels, suggesting that a fundamental population dynamic process (compensatory growth) is not working among these species.

As a direct consequence of the geometric scaling of numerous physiological, population-dynamic, and life-history characteristics with organism size (allometry), there are numerous potential implications of these changes in average body size associated with the formerly large-bodied species of the Eastern Scotian Shelf. The most notable are shorter generation times, increased natural mortality, increased population variability, and decreased bioenergetic efficiencies. For example, direct estimation of natural mortality for cod and haddock was made possible by closure of the directed fishery and revealed levels 2-5 times higher than commonly assumed (DFO 2003, Mohn and Simon

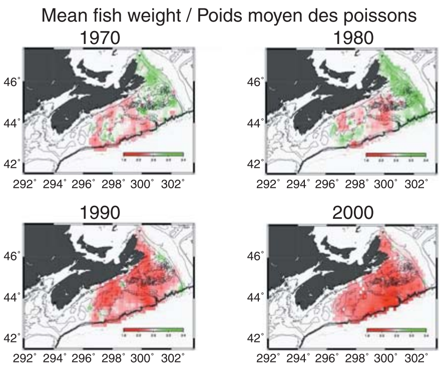


Fig. 4 Mean weight (kg) of fish on the Eastern Scotian Shelf for the 1970s, 1980s, 1990s, and 2000-2002. The scale is logarithmic (base 10) and ranges from 0.063 kg (red) to 2.5 kg (green).

Poids moyen (kg) de poissons dans la région est du plateau Néo-Écossais pour les décades 1970, 1980, 1990 et de 2000 à 2002. L'échelle est logarithmique (base 10) et va de 0.063 kg (rouge) à 2.5 kg (vert).

2002). Such changes do not necessarily translate to an unhealthy ecosystem but do indicate that it is functioning in a vastly different manner than in the past.

Currently, we are estimating system-level "structural" (biomass) and "functional" (metabolic rates, estimated from size-frequency distributions) changes of the fish component of the Scotian Shelf ecosystem. Visualizations of these metrics in a spatial–temporal context and the relative discordance between structure and function will provide a direct estimate of system-level instability of the fish community. Another avenue of research that is being investigated is the use of size-spectral information in the context of "self-organized criticality" (Bak et al. 1989) to provide another means of evaluating system-level instability. Finally, comparative analyses between other systems that have not shown strong ecosystemic changes (e.g., locations where collapses of major fish stocks have not occurred) are planned to help further understand the causes of these large-scale changes in both ecological structure and function and the potential to identify early warning signs of such hystereses.

References

Bak, P., K. Chen and M. Creutz. 1989. Self-organized criticality in the "Game of Life." Nature 342: 780-782.

DFO. 2003. Eastern Scotian Shelf Cod. DFO Sci. Stock Status Report. 2003/020.

Link, J.S., J.K.T. Brodziak, S.F. Edwards, W.J. Overholtz, D. Mountain, J.W. Jossi, T.D. Smith and M.J. Fogarty. 2002. Marine ecosystem assessment in a fisheries management context. Can. J. Fish. Aquat. Sci. 59: 1429-1440.

Mohn, R.K., and J.E. Simon. 2002. Biological information relevant to the management of 4TVW haddock. DFO CSAS Res. Doc. 2002/102. 46 pp.

Coccolithophorid Bloom off the South Coast of Newfoundland

Cynthia McKenzie[1], Gary Maillet[1], Joe Craig[1], Linda Payzant[2], and Trevor Platt[2]
[1]Northwest Atlantic Fisheries Centre, Box 5667, St. John's, NL, A1C 5X1
[2]Bedford Institute of Oceanography, Box 1006, Dartmouth, NS, B2Y 4A2
mckenziec@dfo-mpo.gc.ca

Résumé

Le 29 juillet 2002, le capteur de couleurs vraies de l'instrument à grand champ pour l'observation des mers (SeaWiFS) de la NASA installé sur le satellite OrbView 2 a détecté une prolifération phytoplanctonique spectaculaire au large de la côte sud de Terre-Neuve. Des échantillons d'eau prélevés dans cette prolifération ont permis de confirmer que celle-ci était due à une espèce de phytoplancton appartenant à la famille des coccolithophoracées, *Emiliania huxleyi*. Des profils de conductivité et de température en fonction de la profondeur (CTP) mesurés durant cette prolifération au large de Terre-Neuve ont révélé que la couche de mélange avait une profondeur de 17 m, ce qui est en accord avec les observations de la littérature qui associent les proliférations connues de *E. huxleyi* à la présence d'une masse d'eau hautement stratifiée ayant une profondeur de la couche de mélange habituellement située autour de 10-20 m. Les capteurs de chlorophylle du SeaWiFS et les données de fluorescence enregistrées en mer ont indiqué de faibles concentrations de chlorophylle (1.0 à 1.5 mg m^{-3}) dans cette région de prolifération phytoplanctonique. Les décomptes cellulaires de *Emiliania huxleyi* dans cette prolifération se situaient autour de 2.55 x 10^5 cellules l^{-1}, tandis que le nombre de coccolithes libres, lui, était d'un ordre de grandeur supérieur, soit de 2.35 x 10^6 coccolithes l^{-1}. La présence de ces coccolithes dans l'ensemble de la colonne d'eau est vraisemblablement la cause principale des couleurs turquoise ou blanche révélées par l'imagerie satellitaire du SeaWiFS. Il est bien connu qu'une production accrue de sulfure de diméthyle (DMS) accompagne la prolifération des coccolithophoracées. On sait également que la région centrale de la côte sud de Terre-Neuve dans l'Atlantique Nord-Ouest est une région importante pour l'industrie de la pisciculture, qui y connaît une expansion rapide. L'effet d'une exposition accrue au DMS, ou encore les changements de la température dans les 20 mètres supérieurs de la colonne d'eau qui sont potentiellement associés aux proliférations massives de coccolithophoracées, demeurent des enjeux et des risques importants pour l'élevage des poissons en aquaculture.

On 29 July 2002, NASA's SeaWiFS sensor on the OrbView 2 satellite detected a spectacular phytoplankton bloom off the south coast of Newfoundland. This bloom was visible through the "quasi-true colour" imagery capability of this sensor. Large areas of the Newfoundland coastal and offshore waters appeared bright turquoise or intensely white (Fig. 1). The bloom continued to develop throughout August. The phytoplankton species responsible for this bloom was a spherical single cell about 6 μm in diameter. Scanning electron microscopy confirmed that the organism responsible for the bloom was a coccolithophorid, *Emiliania huxleyi* (insert in Fig. 1).

A CTD (conductivity-temperature-depth) cast and water samples were obtained on 15 August 2002 aboard the CCGS *Teleost* in the vicinity of the bloom. The CTD fluorescence (Fig. 2) and the SeaWiFS chlorophyll sensors (Fig. 3) measured chlorophyll concentrations of about 1.5 mg m^{-3} in the region of the phytoplankton bloom. Holligan et al. (1983) observed a similar bloom along the continental shelf of France in May 1982 that was the first direct confirmation of a coccolithophorid bloom that caused the strong reflectance of visible light detected by the Coastal Zone Color Scanner satellite.

Emiliania huxleyi cell counts conducted on whole water samples collected on 15 August 2002 indicated an order of magnitude more *E. huxleyi* coccoliths than living complete cells (2.35 x 10^6 coccoliths l^{-1} and 2.55 x 10^5 cells l^{-1}). Epifluorescence microscopy (Fig. 4a) was used to determine viability or the photosynthetic capability of the cells. It is the naturally fluorescing chlorophyll *a* within the phytoplankton cells that the SeaWiFS pigment sensors were detecting (Fig. 3). This fluorescence is not visible to the naked eye. Research personnel at sea and residents of Harbour Breton and St. Albans, Newfoundland, reported changes in the water colour on the south coast. Water samples collected from the shore also contained large numbers of *E. huxleyi* cells and scales (1.70 [± 0.82] x 10^5 cells l^{-1} and 1.72 [± 0.27] x 10^6 coccoliths l^{-1}). The 11 November 2002 samples from the southeast Grand Bank transect stations of the Atlantic Zone Monitoring Program (AZMP) contained *E. huxleyi* cells and coccoliths (from 1.9 to 6.2 x 10^4 cells l^{-1}), with similar levels at Station 27. This was the first time *E. huxleyi* cells had been found in abundance from samples collected for the AZMP in the Newfoundland Region.

Low Chlorophyll, Intense Colour

The key to the apparent contradiction in this "bloom" with low chlorophyll values is in the biology and ecology of *E. huxleyi* itself. It is the production of large numbers of minute scales that cover the cells that ultimately explains why this phytoplankton bloom is visible as turquoise water to the naked eye yet only shows low chlorophyll concentrations. The scales or coccoliths are made of calcium carbonate in the form of calcite and average ~3 µm in length. Coccolith numbers vary per cell, but each cell commonly contains 10 to 15 of these scales in a single layer. However, cells are often found with overlapping scales forming multiple layers (Fig. 4b). According to Heimdal (1993), there appears to be an increase in calcification in colder waters. The purpose of the coccoliths is not completely understood, although possible functions include protection, biochemical convenience, sinking rate, and light regulation (Young 1994). *Emiliania huxleyi* may regulate sinking speed by altering the number of coccoliths on the cell surface. In nutrient-limited environments, the cells acquire extra layers of coccoliths, allowing them to sink into deeper nutrient-rich waters. Fewer and more weakly calcified coccoliths are found in low light environments and could delay cells from sinking below the euphotic zone (Paashe 2002). The sinking rates of these individual coccoliths is so low, 13.8 cm d^{-1}, that they persist near the surface, visible in satellite imagery or to the casual observer through their enhancement of refraction and the resulting change of water colour. With regard to the coccolith's role in protection, Wolfe and Steinke (1996) report that the production of dimethylsulphide (DMS) by the *E. huxleyi* cell has been found to be more protection against grazers than the coccolith. Neither method of protection is particularly effective, as zooplankton fecal pellets in Newfoundland waters have been found to contain *E. huxleyi* coccoliths (Urban et al. 1993).

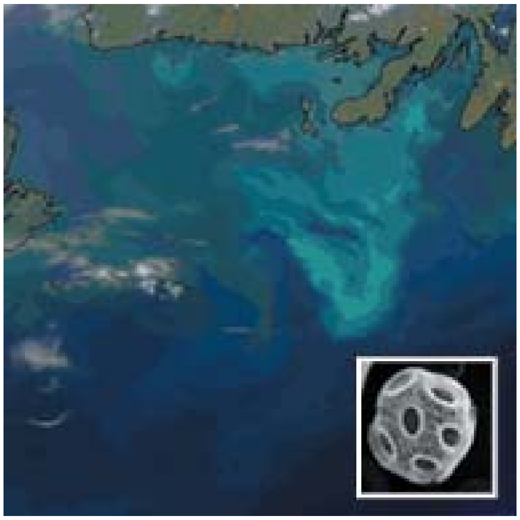


Fig. 1 SeaWiFS colour image of the south coast of Newfoundland acquired on 12 August 2002. The inset is a scanning electron micrograph of *Emiliania huxleyi*, the coccolithophorid responsible from the bloom. The cell is 6 µm in diameter with 3 µm coccoliths (magnification 7 000 X).

Image en couleurs captée le 12 août 2002 par télédétection SeaWiFS sur la côte sud de Terre-Neuve. Le médaillon montre une microphotographie prise à l'aide d'un microscope électronique à balayage de Emiliania huxleyi*, la coccolithophoracée responsable de la floraison (grossissement 7 000 X).*

Emiliania huxleyi

Emiliania huxleyi is the most abundant coccolithophorid in the ocean today, with a wide range of temperature and salinity tolerances. Blooms of up to 10,000 cells ml^{-1} of this species occur routinely in Norwegian fjords, the North Sea, the North Atlantic, and the Gulf of Maine. Satellite records also indicate that a bloom similar to the one in 2002 also occurred in 1999 and 2000 off Newfoundland, although both were farther offshore, south and east of the Avalon Peninsula. Although coccolithophorids in general dominate the phytoplankton in nutrient-poor waters, *E. huxleyi* is more of a pioneer species than other coccolithophorids. It grows best in relatively nutrient-rich, high-light areas. A common hydrographic feature associated with known blooms of *E. huxleyi* is highly stratified water, where the mixed-layer depth is usually ca. 10-20 m and is almost always < 30 m. (Nanninga and Tyrrell 1996). The CTD profile taken during the 2002 Newfoundland bloom showed a mixed-layer depth of ca. 17 m (Fig. 2). Sea-surface temperature (SST) derived from satellite data indicate that the water temperature over a larger region that included the bloom was fairly uniform. Nanninga and Tyrrell (1996), in their study of the importance of light on the formation of *E. huxleyi* blooms, state that the decrease in the penetration of light and heat with depth will concentrate the heat near the surface, where it contributes to establishing and maintaining shallow stratification. Another factor contributing to the dominance of *E. huxleyi* in shallow areas of high light intensity is its lack of photoinhibition up to at least 1000 µE m^{-2} s^{-1}. Most phytoplankton are photoinhibited at about 500-600 µE m^{-2} s^{-1} (Nanninga and Tyrrell 1996).

Implications

Coccolithophorids may play two important roles in relation to global climate forcing. The production of coccolith calcite is accompanied by an output of CO$_2$ to the atmosphere that has potentially important

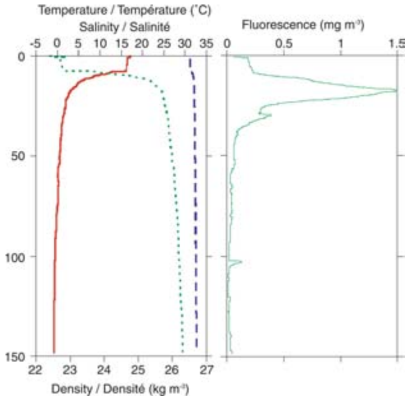
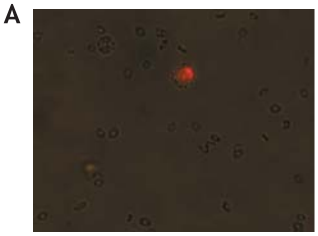


Fig. 2 CTD-fluorescence profile conducted aboard the CCGS *Teleost* on 15 August 2002 at the latitude 46.34°N and longitude 55.71°W, near the main coccolithophorid bloom along the south coast of Newfoundland. Red line: temperature; dashed blue line: salinity; dotted green line: density.

Profils CTD-fluorescence obtenu sur le CCGS Teleost *le 15 août 2002 à la latitude 46.34 °N et à la longitude 55.71 °O, près de la zone principale de floraison le long de la côte de Terre-Neuve. Ligne rouge : température; ligne tiretée bleue : salinité; ligne pointillée verte : densité.*



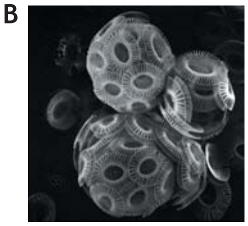


Fig. 4a *Emiliania huxleyi* observed using epifluorescence microscopy, which demonstrates the autofluorescence of the chlorophyll within the photosynthetic cell (magnification 1 000 X in oil immersion).

Emiliania huxleyi *observée par microscope à épifluorescence qui démontre l'autofluorescence de la chlorophylle à l'intérieur de la cellule photosynthétique (grossissement de 1 000 X en immersion dans l'huile).*

Fig. 4b Scanning electron micrograph of *Emiliania huxleyi* cells showing coccolith scale overlap and multiple layers (magnification 4 000 X).

Microphotographie prise par microscopie électronique à balayage de cellules de Emiliania huxleyi *montrant des écailles de coccolithes simples et superposées en plusieurs couches (grossissement 4 000X).*

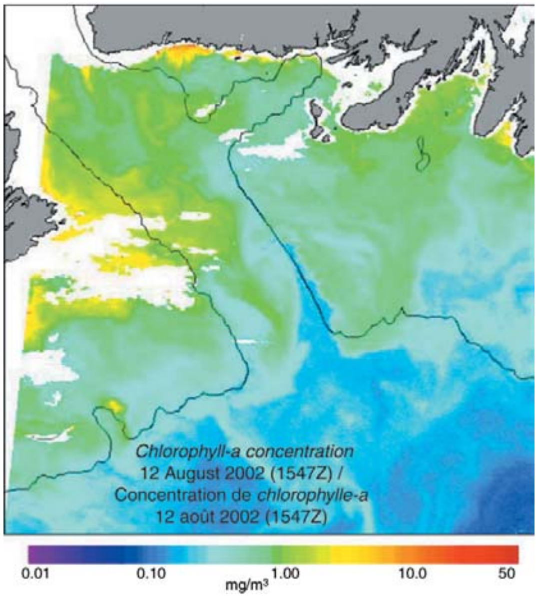


Fig. 3 Near-surface chlorophyll *a* concentrations (SeaWiFS sensor) on 12 August 2002 along the south coast of Newfoundland. The boundary of the coccolithophoriid bloom can be observed in the SeaWiFS ocean colour image.

Concentrations de chlorophylle dans la couche près de la surface mesurées par le capteur satellitaire SeaWiFS le 12 août 2002 dans la région du chenal Laurentien, le long de la côte sud de Terre-Neuve. À noter que la frontière de la région de floraison des coccolithophoracées peut être observée dans l'image de couleur SeaWiFS.

implications for the ability of the ocean to absorb excess carbon (Paasche 2002). Furthermore, the oxidation products of dimethylsulphide (DMS) released into the atmosphere from the bloom could affect atmospheric light reflectance *via* enhanced aerosol scattering and cloud droplet nucleation. The importance of the coccolithophorid role in the transfer of carbon from the atmosphere to the ocean sediments along the continental slope is also an area of interest for researchers studying these organisms. The south-central coast of Newfoundland is an important region for the rapidly expanding finfish aquaculture industry. The effect on caged finfish of increased DMS exposure or changes in ocean temperature resulting from massive coccolithophorid blooms is important in assessing husbandry issues and risk in finfish aquaculture.

References

Heimdal, B.R. 1993. Modern coccolithophorids *In* Identifying Marine Phytoplankton. *Edited by* C.R. Tomas. Academic Press, San Diego, CA. pp. 731-831.

Holligan, P.M., M. Viollier, D.S. Harbour, P. Camus and M. Champagne-Philippe. 1983. Satellite and ship studies of coccolithophore production along a continental shelf edge. Nature (London) 304: 339-342.

Nanninga, H.J., and T. Tyrrell. 1996. Importance of light for the formation of algal blooms by *Emiliania huxleyi*. Mar. Ecol. Prog. Ser. 136: 195-203.

Paasche, E. 2002. A review of the coccolithophorid *Emiliania huxleyi* (Prymnesiophyceae), with particular reference to growth, coccolith formation, and calcification-photosynthesis interactions. Phycologia 40(6): 503-529.

Urban, J. L., C. H. McKenzie and D. Deibel. 1993. Nanoplankton identified from fecal pellet contents of macrozooplankton in coastal Newfoundland waters. Bot. Mar. 36: 267-281.

Wolfe, G.V., and M. Steinke. 1996. Grazing-activated production of dimenthly sulfide (DMS) by two clones of *Emiliania huxleyi*. Limnol. Oceanogr. 41: 1151-1160.

Young, J.R. 1994. Functions of coccoliths. *In* Coccolithophores. *Edited by* A. Winters and W.G. Siesser. Cambridge University Press., Cambridge. pp. 63-82.

Interannual Changes in the Hydrography of the Labrador Sea: 1990-2002

Ross Hendry, Igor Yashayaev, Allyn Clarke, and John Lazier
Bedford Institute of Oceanography, Box 1006, Dartmouth, NS, B2Y 4A2
hendryr@dfo-mpo.gc.ca

Résumé

Des missions océanographiques annuelles effectuées depuis 1990 par la Division des sciences océaniques de la région des Maritimes, Ministère des Pêches et des Océans, Canada, ont permis de détecter un cycle de dix ans dans les changements interannuels des propriétés hydrographiques de la mer du Labrador. On a tout d'abord pu observer une période d'hivers plus froids au début des années 1990 qui étaient caractérisée par une convection hivernale intense et la formation de grandes quantités d'eaux de mer froides et moins salées du Labrador. Les années récentes plus chaudes ont d'autre part mené à une période de convection moins profonde et à une augmentation de la stratification. Les trois derniers hivers dans la mer du Labrador ont été particulièrement plus chauds que la normale. Des observations en début d'été 2002 ont également indiqué la présence de vestiges d'un événement de convection (mélange vertical) jusqu'à une profondeur maximale d'environ 1200 m, contrairement au mélange vertical jusqu'à des profondeurs plus grandes que 2000 m qui avait été observé durant les missions océanographiques de 1993 et 1994. Cette plus faible convection hivernale récente a entraîné des conditions plus chaudes et plus salées dans les 2000 m supérieurs de la colonne d'eau, avec des changements dominants prenant place principalement dans la couche située entre 1000 et 2000 m. La mission AR7W en 2000 a mesuré la plus haute salinité moyenne dans la couche supérieure de 2000 m au cours des treize dernières années. La température moyenne correspondante était également la deuxième plus haute observée durant cette période. Ces plus hautes salinités des années récentes sont accompagnées par une augmentation de l'importance relative des eaux chaudes et salées provenant de la région d'Irminger qui sont transportées dans la mer du Labrador par le courant ouest du Groenland. Il est cependant à noter que des conditions encore beaucoup plus chaudes et salées, incluant encore plus d'eaux de la région d'Irminger, ont déjà été observées durant la période chaude des années 1960.

Introduction

Hydrographic conditions in the Labrador Sea depend on a balance of atmospheric forcing, river runoff and ice melt, advection, and mixing. Wintertime heat loss to the atmosphere in the central Labrador Sea is balanced on average by warm waters entering the Sea in the offshore branch of the West Greenland Current. The excess salt carried by these warm inflows is balanced on average by inflows of fresh polar waters, fresh water from river runoff and ice melt, and an excess of local precipitation over evaporation. The circulation of the Labrador Sea is driven both by buoyancy forcing associated with heat and fresh water fluxes and by wind forcing. Interannual changes in the temperature, salinity, and density of the Labrador Sea are a natural result of changes in these forcing fields.

The Labrador Sea is one of the few regions of the world ocean where deep convection occurs. Wintertime cooling and evaporation increase the density of surface waters in the central Labrador Sea. Wind mixing and vertical overturning form a layer whose depth increases through the cooling season. The winter heat loss, the density increase, and the resulting depth of convection vary with the initial temperature and salinity of the surface waters and with the severity of the winter. Extreme winters have resulted in mixed layers deeper than 2000 m. During milder years, the vertical stratification of temperature, salinity, and density is re-established. The intermediate-depth Labrador Sea Water (LSW) formed by these convective events spreads throughout the northern North Atlantic. Several pathways carry LSW with its varying hydrographic properties into the western and eastern basins of the North Atlantic (Sy et al. 1997; Lavender et al. 2000). A western boundary current carries LSW into the slope regions of eastern Canada, including the slope water south of Nova Scotia.

Interannual changes in deep convection in the Labrador Sea have a major influence on the hydrographic properties of the subpolar gyre of the North Atlantic. Deep convection in the Labrador Sea also provides a pathway for atmospheric gases such as oxygen, carbon dioxide, and chlorofluorocarbons (CFCs) to pass from the surface mixed layer to intermediate depths. As the LSW flows to other regions of the North Atlantic, it distributes these dissolved gases to a large area of the ocean, thereby ventilating the deeper layers.

Because of the importance of this process, the Ocean Sciences Division, DFO Maritimes Region, has monitored hydrographic properties on a line of stations across the Labrador Sea in the early summer of each year since 1990. This line was designated AR7W (Atlantic Repeat Hydrography Line 7 West) during the World Ocean Circulation Experiment (WOCE). Between 1990 and 1997 the work was a contribution to WOCE. Since 1997, the work has continued as a Canadian contribution to the Climate Variability and Predictability (CLIVAR) project of the World Climate Research Programme (WCRP). The annual surveys have also provided a framework for biological and chemical investigations in the Labrador Sea that are largely associated with the sequestration of carbon.

Figure 1 shows a map of the Labrador Sea with station positions for the 23 June–18 July 2002 AR7W survey along with the Bravo mooring site in the central Labrador Sea. A schematic of the surface circulation,

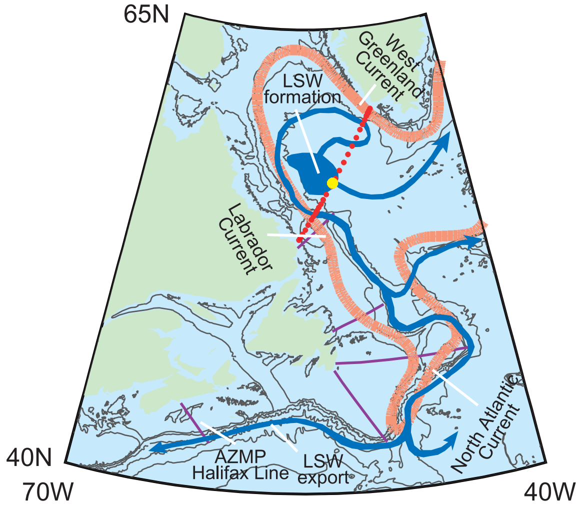


Fig. 1 Positions of the 2002 AR7W stations (red circles) and the Bravo mooring site (yellow circle) superimposed on a schematic circulation (orange) of the subpolar gyre. The general region of Labrador Sea Water formation and possible export pathways are noted (blue). Selected sections of the Atlantic Zone Monitoring Program are also shown (purple).

Localisation des stations AR7W en 2002 (points rouges) et du site de mouillage Bravo (point jaune) superposée sur un patron de circulation schématique (orange) de la gyre sub-polaire. La région générale de formation des eaux de la mer du Labrador et les branches d'exportation possible de ces eaux sont également indiquées (bleu). Certaines sections du Programme de Monitorage de la Zone Atlantique sont également montrées (mauve).

LSW formation region, and LSW export pathways is also shown. The surface circulation includes the West Greenland Current, the Labrador Current, and the North Atlantic Current that comprise the northwest part of the counter-clockwise circulating subpolar gyre.

Atmospheric Forcing

On an annual average, the Labrador Sea loses heat to the overlying atmosphere. Most of the heat loss occurs in the winter season when cold, dry northwesterly winds flow over the Labrador Sea. Especially severe winters lead to large heat losses and enhanced vertical overturning. Monthly-averaged air–sea flux fields produced by the co-operative Reanalysis Project (Kistler et al. 2001) of the U.S. National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) were used to quantify these heat exchanges.

Figure 2 shows a time series of consecutive 12-month June–May averaged NCEP heat flux anomalies near the Bravo mooring site (Figure 1) for the 55-year period from June 1948 to May 2003. The anomalies are relative to the "normal" sea–air heat loss of 66 W m^{-2} defined by the 1971–2000 30-year mean. The June–May averaging period was chosen to isolate each winter as a single value. The quasi-decadal changes in heat flux anomalies show the effects of periods of colder and warmer winters. The late 1980s and early 1990s saw relatively cold winters and high heat fluxes: six consecutive averages during the 1988-1993 period gave higher-than-normal losses. Since 1995, conditions have been generally warmer than normal. Mean heat fluxes for 2001-2002 and 2002-2003 were both about 20% less than normal, with anomalies near -15 W m^{-2}. The decade of the 1960s was also a mild period in the Labrador Sea. Eleven of the twelve averages during the 1959-1971 period were less than the modern-day normal.

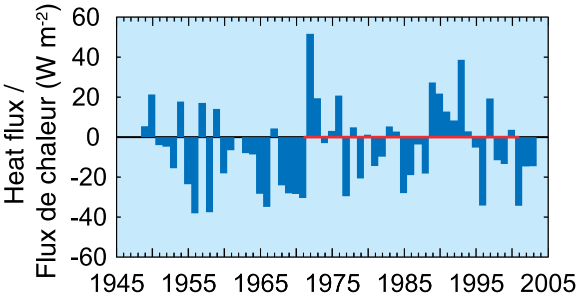


Fig. 2 Twelve-month June–May averages of NCEP/NCAR sea-to-air heat flux anomaly at 56.2ºN and 52.5ºW near the Bravo mooring site from June 1948 to May 2003. The anomalies are relative to a 30-year mean (66 W m^{-2}) for the 1971-2000 period (red line). Positive anomalies correspond to greater-than-normal ocean heat loss to the overlying atmosphere, primarily during colder-than-normal winters.

Anomalies moyennes sur douze mois (juin à mai) du flux mer-air NCEP/NCAR à 56.2ºN et 52.5ºO près du site de mouillage Bravo pour la période de juin 1948 à mai 2003. Les anomalies sont calculées à partir d'une moyenne de 30 ans (66 W m^{-2}) pour la période de 1971 à 2000 (ligne rouge). Les anomalies positives correspondent à une perte de chaleur plus grande que la normale vers l'atmosphère, principalement durant les hivers plus froids que la normale.

Response of the Labrador Sea

Figure 3 shows section plots of potential temperature, salinity, and potential density anomaly for the May–June 1994 and July 2002 AR7W surveys. The horizontal coordinate is along-section distance increasing from the Labrador coast in the southwest to the West Greenland coast in the northeast. Similar section plots from a March 1966 survey are included for comparison. The southward flowing Labrador Current separates cold waters (<2ºC) over the Labrador Shelf from the warmer interior. Still warmer waters (>4ºC) in the upper 500 m near the eastern boundary come from the northward-flowing warm, saline branch of the West Greenland Current. The 1994 survey shows a large area of nearly constant potential temperature, salinity, and potential density in the upper 2000 m that marks Labrador Sea Water formed during the 1993-1994 winter. The 2002 survey shows a much-reduced area of nearly constant potential temperature and salinity in the 600-1200 m depth range, marking a warmer, saltier, and less-dense modern-day vintage of Labrador Sea Water. The patch of water with salinity greater than 34.88 near 2000 m depth in the 2002 survey is actually a remnant of the denser LSW formed during the early 1990s. Upper-layer conditions in March 1966 were still warmer and saltier than seen in the 2002 survey. The 1966 survey shows little evidence of recent deep convection.

Irminger Water Influences

The offshore branch of the West Greenland Current supplies the Labrador Sea with warm and saline waters that originate in the Irminger Current, itself a branch of the North Atlantic Current system. These warm and saline waters enter the Labrador Sea at the southern tip of Greenland and flow northward along the west coast of Greenland (Buch 2000). In this article, we refer to waters with potential temperature in the range 4-6°C and salinity greater than 34.85 as Irminger Water.

Figure 4 shows the occurrences of Irminger Water in the 1994 and 2002 AR7W annual surveys, the 1966 survey, and a rare early-winter survey from December 2002. The sections show greatly varying amounts of Irminger Water. It is almost absent from the 1994 survey and other surveys of the early 1990s. The 2002 survey showed intermediate amounts that are characteristic of recent years. The March 1966 survey showed particularly large amounts of Irminger Water in the eastern half of the Labrador Sea and traces near the western boundary, marking waters that circled the Labrador Sea to appear in the southward flows near the western boundary. Long-term changes in the amount of Irminger Water in the Labrador Sea result from changes in the input of these waters and changes in mixing and dilution with cooler, fresher LSW during periods of weak or intense convection. A comparison of the July 2002 and December 2002 surveys shows an increase in Irminger Water on the eastern side of the Labrador Sea and the appearance of Irminger Water at several stations near the western boundary. The likely causes of these short-term changes include both seasonal and short-term changes in the West Greenland Current and seasonal changes in the mixing and dilution with LSW.

Changes in Heat and Salt Content

Figure 5 shows time series of the heat and salt content from the 13 1990-2002 annual summer AR7W surveys averaged over stations in the distance range 320-520 km. The values shown are anomalies relative to the mean for all 13 surveys. The 320-520 km range in the west-central Labrador Sea is chosen to represent the most active area of convection. Bottom depths in this distance range lie between 3300 and 3600 m. Three curves are shown for each case, giving heat or salt content integrated over 150-1000 m, 1000-2000 m, and the combined 150-2000 m depth ranges. The 0-150 m layer is excluded because there is a strong seasonal signal in the properties in this layer and the AR7W occupations do not take place at exactly the same time each year. A warming of a 1850 m thick column of water (150-2000 m depth range) by 0.13°C gives an increase in heat content of about 1 GJ m^{-2}. A salinity increase of 0.005 for the same column of water gives an increase in salt content of about 10 kg m^{-2}.

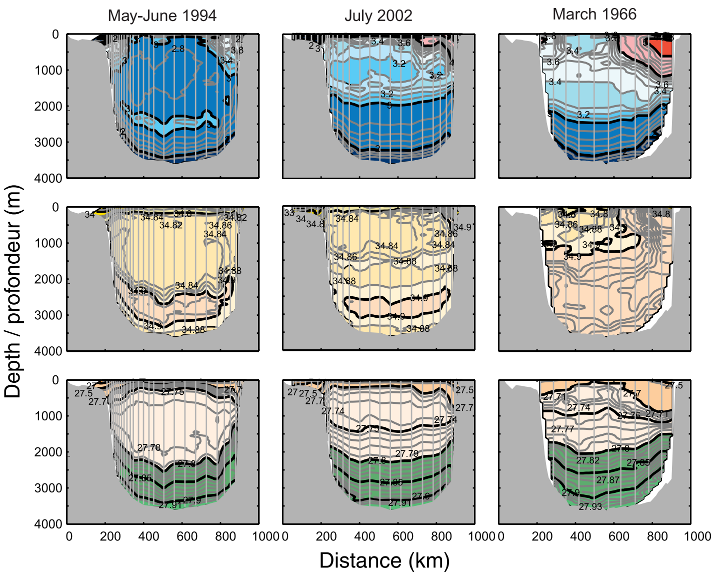


Fig. 3 Section plots of potential temperature (°C; upper panels), salinity (middle panels), and potential density anomaly (kg m^{-3}; lower panels) for the 1994 and 2002 AR7W surveys and for the 1966 Hudson survey. Vertical lines mark the station locations.

Tracés de la température potentielle (°C; panneaux du haut), de la salinité (panneaux du milieu) et des anomalies de densité potentielles (kg m^{-3}; panneau du bas) pour les missions océanographiques AR7W 1994 et 2002, et pour la mission du Hudson en 1966. Les lignes verticales marquent les positions des stations.

The heat content in the 150-1000 m layer and the 1000-2000 m layer both decreased during the first part of the 1990s to a minimum in 1994 and have since increased. The changes in heat content in the convectively active depth range closely followed the cumulative sea–air heat loss over the decade (Lazier et al. 2002). Since the deeper layer has been cut off from direct contact with the atmosphere since 1994 or 1995, the deep warming since that time must be related to horizontal advection. The 2002 150-2000 m mean temperature was the second highest observed during the 13 annual surveys.

The 150-1000 m salt content increased to a maximum in 1993 during the period of active convection as saltier water from deeper levels mixed with shallower waters. The salt content of the 150-1000 m layer showed considerable high-frequency variability during the later part of the 1990s. There has been an increasing trend in salt content in the 1000-2000 m layer since 1994-1995. The 150-2000 mean salinity in early summer 2002 was the highest observed in the 13 annual AR7W surveys. The mechanisms controlling the interannual changes in salt content are complex. Each summer, a pulse of fresh water from ice melt enters the surface layers of the Labrador Sea and mixes down to deeper depths in succeeding months. The Irminger Water inflows occur primarily at sub-surface levels; the patterns of seasonal variability in these inflows are not well known. The observed interannual salt changes are greater than can be explained by changes in local precipitation and evaporation. They must result from changes in the production, advection, and mixing of remote sources of fresh water and salt.

The recent warm and saline conditions are less extreme than conditions in the mid-1960s. The 150-2000 m heat and salt content anomalies from the March 1966 survey were 3.3 GJ m^{-2} and 92 kg m^{-2} respectively. The 1966 heat content anomaly was nearly twice the 2002 heat content anomaly. The 1966 salt content anomaly was more than four times the 2002 salt content anomaly. Both values are off-scale for the heat and salt time series plots in Figure 5.

Changes in Sea Level

The density of seawater decreases with increasing temperature and increases with increasing salinity. Temperature effects generally dominate density changes in the upper 2000 m of the Labrador Sea. The warm and saline conditions of the last years have reduced the density of the upper layers of the Labrador Sea. Density changes affect the height of a column of water of fixed mass. Sea level changes related to this effect are called steric sea level changes.

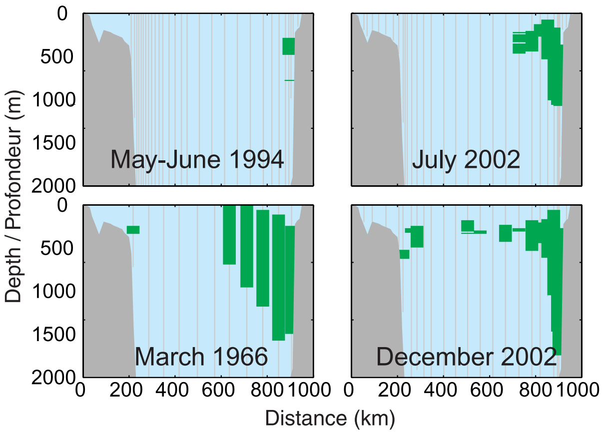


Fig. 4 Section plots showing Irminger Water on the 1994 and 2002 AR7W sections. Similar plots from March 1966 (Hudson 66002) and December 2002 (Hudson 2002-075) are also shown. Vertical lines mark station positions. At each station, green bars indicate the vertical extent of Irminger Water (as defined in the text).

Tracés montrant les eaux de la région d'Irminger sur le transect AR7W en 1994 et 2002. Des tracés similaires sont également montrés pour mars 1966 (mission du Hudson 66002) et décembre 2002 (mission du Hudson 2002-075). Les traits verticaux indiquent la position des stations. À chaque station, les barres d'histogramme en vert indiquent l'étendue verticale des eaux provenant de la région d'Irminger (telles que définies dans le texte).

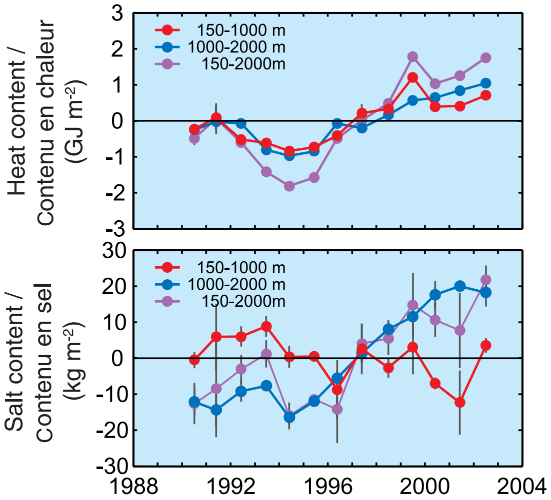


Fig. 5 Time series of heat and salt content anomalies in the upper 2000 m of the west-central Labrador Sea excluding the seasonally active upper 150 m. Mean values over ~4 stations in the 320-520 km distance range and associated standard deviations are shown.

Série temporelle des anomalies du contenu en chaleur et en sel dans les 2000 m supérieurs de la colonne d'eau dans la partie centrale ouest de la mer du Labrador, excluant la couche supérieure de 150 m qui varie avec les saisons. Les valeurs moyennes pour ~ 4 stations (distance de 320 à 520 km) et les écarts types associés sont montrés.

Figure 6 shows time series of sea level changes near the Bravo mooring site from gridded maps of sea level anomaly produced by the French *Archivage, Validation et Interprétation des données des Satellites Océanographiques (AVISO)* (http://www-aviso.cls.fr/) from the TOPEX/POSEIDON (T/P) altimetric satellite. T/P data were available for the period October 1992 through August 2002. The anomalies are relative to 1993-1999 mean sea level. Low-passed time series with and without a fitted seasonal signal are shown. The seasonal signal has a range of just less than 0.09 m. Also shown are changes in steric sea level for the 150-2000 dbar pressure range, equivalent to the 150-2000 m depth range, from the annual AR7W surveys. Each value is an average of approximately 4 stations in the 320-520 km distance range. Standard deviations for each survey are also shown. The reference steric sea level was chosen to match the T/P reference sea level based on comparisons with the 10 AR7W surveys during the T/P mission. The close agreement of the two curves suggests that much of the interannual variability in sea level can be related to changes in heat and salt content of the upper 2 km of the water column. The residual differences are ~0.01-0.02 m. Since surface currents and sea-level slope are linked through the geostrophic balance, some of the residual sea level may be related to interannual changes in the wind-driven surface circulation.

Figure 7 shows spatial maps of T/P sea level anomalies averaged over 12-month (June–May) periods for 1994-1995, 1998-1999, and 2001-2002. The maps provide a spatial context for interpreting the heat and salt anomaly time series in Figure 5 and the T/P sea level anomaly time series in Figure 6. The 1994-1995 map shows that the AR7W survey line captured the minimum values of the low sea level period of the early 1990s and the 1998-1999 map shows that the AR7W survey line crossed the maximum values of that high sea level period. The 2001-2002 map shows relatively high sea level over a broad area including the Bravo mooring site, but with the maximum to the southeast.

Summary and Outlook

The hydrographic properties of the Labrador Sea show strong interannual variability. This variability is linked to the larger-scale variability of the North Atlantic climate. Our surveys during 1990-2002 monitored a period of intense deep convection and abundant Labrador Sea Water formation, followed by a period of restratification and the present-day trend to warmer and more saline conditions. Even warmer and saltier conditions were observed in the mid-1960s. The cold winter of 1971-1972 gave rise to record-high sea–air heat fluxes in the Labrador Sea (Figure 2). Lazier (1980) documented the resulting renewal of deep convection during the winter of 1971-1972 using Ocean Weather Ship Bravo data from 1964 to 1974. Only the future will show if the temperature and salinity of the upper levels of the Labrador Sea will reach the values seen in the mid-1960s. The historical record suggests that natural variability will provide yet another period of cold winters to renew deep convection and reset the system. Of course, the balances controlling Labrador Sea properties would change with any shift in climatic conditions such as global warming. Continued AR7W surveys have the potential to monitor these changes as they occur and make an important contribution to the international study of climate variability. We continue to seek a better understanding of the effects of these changes on east-coast waters of direct Canadian interest.

References

Buch, E. 2000. Air-sea-ice conditions off southwest Greenland, 1981–97. J. Northw. Atl. Fish. Sci. 26: 123-126.

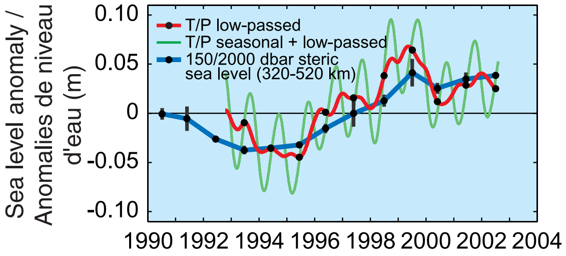


Fig. 6 Low-passed T/P sea level anomaly time series relative to the 1993-1999 mean near the Bravo mooring site (bold red line), sum of low-passed T/P sea level anomaly and the fitted seasonal cycle (green line), and 150-2000 dbar steric sea level anomalies from 13 annual AR7W surveys (bold blue line). Values at AR7W survey times are shown as solid circles. The steric sea level anomalies are averages for stations in the 320-520 km distance range. The vertical bars are standard deviations.

Série temporelle des anomalies (par rapport à la moyenne de 1993-1999) de niveau de la mer T/P filtrée avec un filtre passe bas près du site de mouillage Bravo (ligne rouge en gras), sommes des anomalies de niveau de la mer T/P filtrées avec un filtre passe bas et du cycle saisonnier ajusté (ligne verte) et anomalies stériques 150-2000 dbar pour les 13 missions annuelles AR7W (lignes bleue en gras). Les valeurs mesurées lors des missions AR7W sont montrées comme des cercles pleins. Les anomalies de niveau d'eau stériques sont moyennées pour les stations distancées de 320 à 520 km. Les barres verticales représentent les écart types.

Kistler, R., E. Kalnay, W. Collins, S. Saha, G. White, J. Woollen, M. Chelliah, W. Ebisuzaki, M. Kanamitsu, V. Kousky, H. van den Dool, R. Jenne and M. Fiorino. 2001. The NCEP–NCAR 50-year reanalysis: Monthly means CD-ROM and documentation. Bull. Am. Met. Soc. 82: 247-268.

Lavender, K.L., R.E. Davis and W.B. Owens. 2000. Mid-depth recirculation observed in the interior Labrador and Irminger Seas by direct velocity measurements. Nature 407: 66-69.

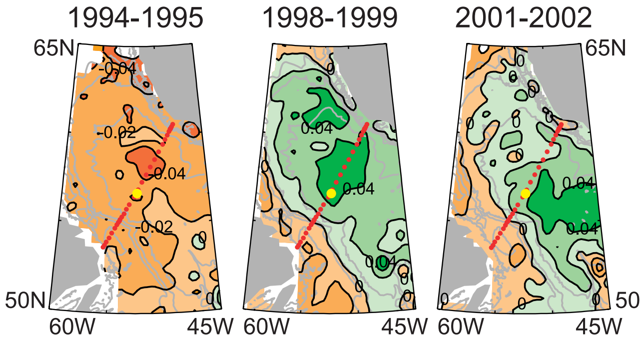


Fig. 7 Maps of 12-month June-May mean T/P sea level anomalies (relative to the 1993-1999 mean) for 1994-1995, 1998-1999, and 2001-2002. The contour interval is 0.02 m. Areas with at least 90% data return are included. July 2002 AR7W station positions (red circles) and the Bravo mooring location (yellow circle) are shown.

Cartes des anomalies moyennes de niveau de la mer T/P sur 12 mois entre juin et mai (par rapport à la période moyenne de 1993 à 1999) pour les années 1994-1995, 1998-1999 et 2001-2002. Les intervalles de contour sont de 0.02 m. Les régions avec un retour de données d'au moins 90 % sont inclues. Les positions des stations pour la mission AR7W de juillet 2002 (points rouges) et la localisation de la station de mouillage Bravo (points jaunes) sont montrées.

Lazier, J.R.N. 1980. Oceanographic conditions at Ocean Weather Ship Bravo, 1964-1974. Atmosphere-Ocean 18: 227-238.

Lazier, J., R. Hendry, A. Clarke, I. Yashayaev and P. Rhines. 2002. Convection and restratification in the Labrador Sea, 1990-2000. Deep-Sea Res. 49: 1819-1835.

Sy, A., M. Rhein, J.R. Lazier, P. Koltermann, J. Meincke, P. Putzka and M. Bersch. 1997. Surprisingly rapid spreading of newly formed intermediate waters across the North Atlantic Ocean. Nature 386: 675-679.

Toward Prediction of the Ecosystem: 3D Simulations of the Coupled Biological Production and Hydrodynamics in the Estuary and Gulf of St. Lawrence

Vincent Le Fouest[1], Marina Chifflet[2], Michel Starr[2], Bruno Zakardjian[1], and François Saucier[1,2]
[1]Université du Québec à Rimouski, Institut des sciences de la mer de Rimouski (ISMER), Rimouski, QC, G5L 3A1, Canada
[2]Fisheries and Oceans Canada, Maurice Lamontagne Institute, Mont-Joli, QC, G5H 3Z4, Canada

Résumé

Les variations spatio-temporelles dans la dynamique du plancton sont une caractéristique importante des écosystèmes marins et elles ont été liées aux variations dans le recrutement des espèces exploitables. Nous présentons ici les premiers essais d'utilisation d'un modèle tridimentionnel couplé physique-biologique pour simuler la variabilité observée dans l'estuaire et le golfe du Saint-Laurent à l'aide des données générées par le Programme de Monitorage de la Zone Atlantique (PMZA). Ces résultats préliminaires indiquent que le modèle peut reproduire les cycles spatio-temporels moyens dans la production primaire, incluant les cycles diurnes, les effets des marées, des vents, du cycle saisonnier dans la circulation et la transformation des masses d'eau et des glaces de mer, et finalement des mélanges turbulents associés à ces cycles. Les données du PMZA constituent une ressource irremplaçable pour le développement et l'amélioration des modèles biologiques et pour augmenter notre capacité à prédire les impacts des changements et des variations climatiques sur les écosystèmes marins.

Prior to any attempt to predict the effect of global climate variability and change on the Gulf of St. Lawrence (GSL), we must first acquire a better knowledge of the links between the physical environment and the short-term to interannual variations in planktonic production. The chief importance of hydrographic processes in the St. Lawrence Estuary on the whole ecosystem of the GSL has long been established (e.g., Steven 1974, Bugden et al. 1982, Therriault et al. 1990). The intense, tidally-induced mixing between freshwater and saltwater masses that occurs in this area is responsible for the high biological production of the Estuary and southern Gulf of St. Lawrence. The GSL experiences marked synoptic variations of wind forcing that produce coastal upwelling that can lead to increased planktonic production (Fuentes-Yaco et al. 1997). More generally, the large variations in atmospheric, hydrologic, and oceanic forcing on the Gulf waters, coupled with its dimensions, generate a complex hydrodynamic system where eddies, upwelling, fronts, and jets superimpose on the mean estuarine-like circulation (e.g., Koutitonsky and Bugden 1991, Saucier et al. 2003). The subarctic climate that prevails over the GSL, with a seasonal sea-ice cover of 4-5 months (January to April)—which makes it one of the areas with the most southern extent of sea ice in the northern hemisphere—also dramatically affects the seasonal cycle of planktonic production (e.g., de Lafontaine et al. 1991). Recent observations confirm that the high interannual fluctuations in plankton biomass in the Estuary (Starr and Harvey 2000, Starr et al. 2001), the recruitment of fish stocks in the southern Gulf (Runge et al. 1999), the aggregation of krill and whales at the channel head (Simard and Lavoie 1999, Lavoie et al. 2000), and the water mass properties of the Gulf (Saucier et al. 2003) are strongly linked to the influences of climate and freshwater input on the mixing and circulation processes.

Given the richness of the physical conditions in the Gulf of St. Lawrence, it is clear that even an intensive monitoring program like the Atlantic Zone Monitoring Program (AZMP, Therriault et al. 1998) cannot fully capture the complexity of the hydrodynamic and ecosystem processes. To gain insight, we need to develop modelling tools that will allow us to interpolate, extrapolate, and understand the observed seasonal and interannual variability in the primary and secondary production cycles. A 3D high resolution baroclinic model of circulation developed for the Estuary and Gulf of St. Lawrence is now operational (Saucier et al. 2003). The model is fully deterministic and tracer conserving, driven by detailed hydrologic, atmospheric, and oceanic forcing from hourly to multi-year periods. The model incorporates the influences of the variation of sea ice, tides, momentum, heat and salt fluxes, and river discharge on a grid with 5 km horizontal and 5 m vertical resolution. It reproduces the high frequency to interannual variations of the circulation, water mass types, and sea-ice cover under observed or simulated atmospheric and hydrologic forcing. Simulations over the 1996-2001 period were successfully compared to temperature and salinity data, sea-ice cover, water levels, and past analyses of transport in the St. Lawrence Estuary and Gulf (Saucier et al. 2003). Recently, we coupled a planktonic ecosystem model of intermediate complexity to our physical model (Le Fouest et al. 2003a, b), which allows the simulation of primary and secondary production in the Estuary and Gulf of St. Lawrence. For the first time, detailed physical and biological models for this region work together toward a comprehensive description of variability of the St. Lawrence ecosystem over seasons to years using data generated in part by the AZMP monitoring program.

Figure 1 first shows the structure of the coupled model and how it is linked with the AZMP data set. This biological model includes both the herbivorous and microbial food chains characteristic of bloom and post-bloom conditions, respectively, as generally observed in temperate and subarctic coastal waters. Primary producers are size-fractionated into large (>5 µm) and small (<5 µm) phytoplankton (LP and SP, respectively) both growing on nitrate (NO_3) and ammonium (NH_4). Similarly, the secondary producers are divided into mesozooplankton (200-2000 µm, MEZ) and microzooplankton (20-200 µm, MIZ). Two detrital compartments close the cycling of nitrogen: particulate and dissolved organic nitrogen (PON and DON, respectively). A tight coupling between small phytoplankton growth and microzooplankton grazing, autochthonous nitrogen release and DON remineralization to NH_4 is assumed to represent the dynamics of the microbial food chain. Bacteria are not considered in the model but could be included in future developments. Biological functions (e.g., phytoplankton growth rate, grazing, and regeneration) are derived from classical formulations using mean parameters found in the literature.

The AZMP data set is used to define initial conditions for a particular year. The 3D fields are initialized with averaged profiles of nitrate and total phytoplankton concentrations from AZMP data for the autumn (November/December) of the previous year. We assume equal concentrations of large and small phytoplankton. Due to the lack of data for the other scalars, we used idealized profiles. Values of 1 mmol N m^{-3} for ammonium, 0.05 mmol N m^{-3} for DON, and 0.005 mmol N m^{-3} for PON were assigned to each depth interval from the surface to the bottom. Concentrations for both mesozooplankton and microzooplankton were set to 0.4 mmol N m^{-3} in the upper 25 m and to 0 below this depth. In this first version, the model uses boundary conditions that are constant in time and similar to the initial conditions, and no nutrients or biomass inputs from rivers. Future refinements of the model will include time-varying boundary conditions obtained from the AZMP data set. For the first run, we chose the year 1997 because it presents environmental (hydrologic and atmospheric) conditions close to the Gulf's climatological mean. Data used to initialize the simulation are from the 1996 Ice Forecast mission and are now incorporated into the AZMP data set.

Solutions produced by the 3D coupled biological–physical model at the regional and subregional scale for 1997 are in overall agreement with historical observations (e.g., Steven 1974, de Lafontaine et al. 1991, Roy et al. 2001). The mean (i.e., spatially averaged over the whole Gulf and Lower Estuary) simulated seasonal cycle shows a large phytoplankton-dominated spring bloom whose onset in the Gulf is set by sea-ice melting with subregional differences in timing due to local sea-ice dynamics (Fig. 3a-b). The concomitant nitrate depletion of surface waters leads to the bloom decline and the establishment of a deep (~30 m) chlorophyll *a* maximum. Regenerated production mainly supports the total autotrophic production in summer, which is typical for the Gulf of St. Lawrence (de Lafontaine et al. 1991, Roy et al. 2001). The model fails to reproduce the delay of the spring bloom in the Lower St. Lawrence Estuary (Therriault et al. 1990), but this can be attributable to the fact that it does not include turbidity due to freshwater discharges, mainly from the St. Lawrence River. A first sensitivity test has shown that the use of a coefficient of diffuse attenuation due to particulate matter linearly related to salinity can solve this discrepancy. Despite the report of a late summer/fall bloom in the Gulf of St. Lawrence, it is absent in our seasonal cycle for 1997 when averaged over the entire Gulf (Fig. 2). The autumn bloom is classically interpreted as the result of decreased stratification due to cooling and increased turbulent mixing events driven by autumn storms leading to enhanced

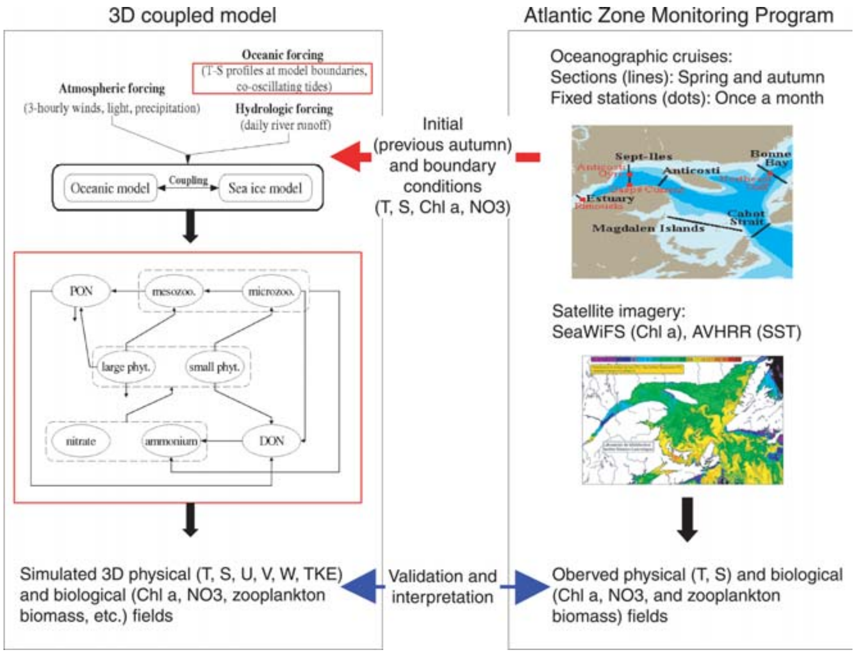


Fig. 1 Structure of the 3D coupled biological–physical model and its links with the AZMP database. For the Estuary and Gulf of St. Lawrence, the AZMP sampling program was initiated two years (i.e., 1996) before its official announcement. (The French version of this figure is available on request).

Structure du modèle couplé physique–biologique tridimensionnel et ses liens avec les bases de données du PMZA. Pour l'estuaire et le golfe du Saint-Laurent, le programme d'échantillonnage du PZMA a été initié deux ans (i.e. 1996) avant son annonce officielle. (La version française de cette figure est disponible sur demande).

T=temperautre/ *température;* S=salinity / *salinité;* U=east–west current component / *composante du courrant est–ouest;* V=north–south current component / *composante du courrant nord–sud;* W=vertical current component / *composante du courrant vertical;* TKE=turbulent eddy diffusivity / *diffusion turbulente;* PON=particulate organic nitrogen / *azote organique particulaire;* DON=dissolved organic nitrogen / *azote organique dissout;* SST=sea-surface temperature / *température de la surface de l'océan.*

nitrate fluxes into euphotic zone. The autumn mixing seems not to be strong enough in the 1997 simulation. Nevertheless, the model reveals the occurrence of a fall bloom that could be related to local environmental conditions such as pulsed inflows of Labrador water in the northeastern Gulf or wind-induced upwelling along the south shore of Anticosti Island. Finally, it is interesting to note that during fall and early winter, both phytoplankton and zooplankton biomasses continued to decrease to values near the pre-bloom conditions, a characteristic that allows multi-year simulations to be run.

As implied by satellite images from other years, our simulation reveals a marked heterogeneity of primary production in the Gulf of St. Lawrence (see Fig. 3 for an example of phytoplankton biomass), where different physical processes (cloud cover, sea-ice cover, tidal mixing, density-driven circulation, wind-induced coastal upwelling) drive the planktonic production at different time and space scales. On the spatial scale, the model reproduces well the high summer planktonic production in the St. Lawrence Estuary, which is largely due to nutrient fluxes driven by the high tidal mixing in this subregion (e.g., Therriault et al. 1990). The buoyancy-driven circulation induced by the runoff of the St. Lawrence River, which shows a marked interannual variability, also generates a typical mesoscale variability acting on a weekly to seasonal time scale that leads to higher productivity in the northwestern Gulf. Coastal upwellings along the north shore of the GSL and south of Anticosti Island are shown to increase algal biomass mainly by increases in large phytoplankton. These upwelling events are linked with the synoptic wind variability, which is typically 3-9 days in eastern Canada (Koutitonsky and Bugden 1991) but may vary in frequency and duration from year to year. Considering their impact on planktonic productivity at the subregional scale, those physical processes can play a significant role in the interannual variability of the Gulf of St. Lawrence production.

The model also simulates the effects of hydrodynamics and climatic forcing on the competition between the herbivorous and microbial food chains, a prerequisite for carbon flux estimates as it is known that the ecosystem structure drives the carbon flux at depth (e.g., Legendre and Rivkin 2002). The highest variations of biomass in the mean seasonal cycle concern the herbivorous food chain while the simplified microbial food chain constitutes a background of biomass with only slight variations throughout the year, as previously reported in the region. Increasing large phytoplankton production and biomass and, consequently, secondary production, also occurs, especially in summer, in response to tidal mixing, wind-induced coastal upwelling, and buoyancy-driven gyres and eddies. Large phytoplankton biomass and production were found to be favoured in summer in the frontal zone of the Gaspé Current, which is known to be a highly productive system. On an annual basis, more productive subregions exhibit a higher production of faecal pellets by mesozooplankton due to the intense activity of the herbivorous food chain compared to less productive subregions. By contrast, primary production egested by microzooplankton varies less. The increased activity of the herbivorous food chain in response to mesoscale circulation is a common feature in oceanic and coastal environments.

First comparisons with AZMP data show an overall agreement between simulated and observed nitrate and chlorophyll *a* concentrations (Fig. 4). Observed data on the scatter plots of Figure 4 are from bottle measurements made during the June and November 1997 AZMP cruises. Simulated data from the model for the same dates and geographical positions are shown. The simulated nitrate concentrations are close to the observations despite a tendency for lower simulated nitrate concentrations at mid-depth (50-200 m) at the end of the simulation (November). We examined two hypotheses that could account for this tendency. The first one involves the oversimplification of the nutrient recycling at depth in the model. Respiratory activity in the intermediate and deep layers is not considered while it has been recognized as a key process in nutrient dynamics in the GSL (Savenkoff et al. 2001). A second hypothesis involves boundary conditions at the Strait of Belle Isle. Inflowing cold Labrador waters spread at mid-depth

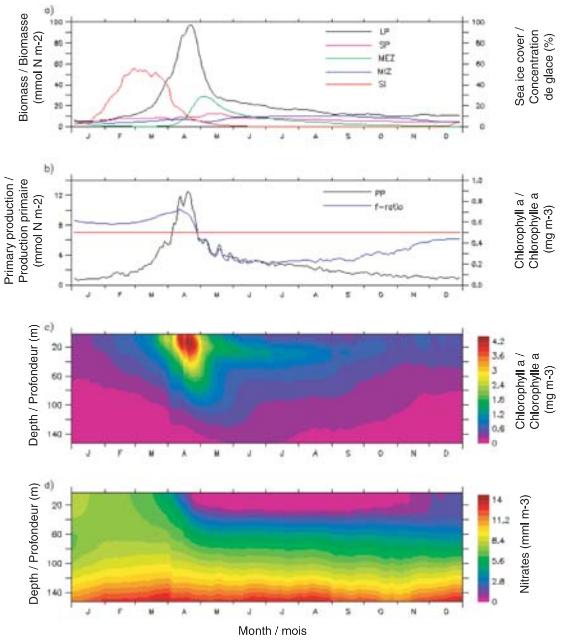


Fig. 2 Simulated seasonal cycle of a) phytoplankton, zooplankton, and sea-ice concentrations, b) primary production and f-ratio (ratio new production: total production), and the vertical structure of the c) chlorophyll *a* and d) nitrates in 1997. Data were spatially averaged over the whole St. Lawrence system.

Cycle saisonnier simulé du a) phytoplancton, zooplancton et de la concentration en glace, b) de la production primaire et le «f-ratio» (rapport production nouvelle : production totale) et de la structure verticale c) de la chlorophylle a *et d) des nitrates en 1997. Les données ont été moyennées pour l'ensemble du Saint-Laurent.*

LP=Phytoplankton >5 µm / *Phytoplancton >5 µm;*
SP=Phytoplankton <5 µm / *Phytoplancton <5 µm;*
MEZ=Mesozooplankton / *Mésozooplancton;*
MIZ= Microzooplankton / *Microzooplancton;*
SI=Sea-ice cover / *Couverture de glace*

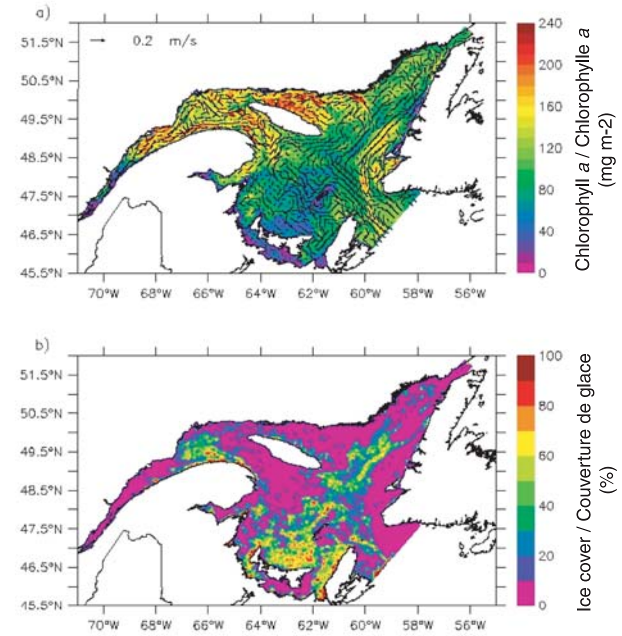


Fig. 3 An example of results obtained from the 3D high-resolution ecosystem model for 1997 (April 10). A) Colours: integrated chlorophyll *a* concentrations (mg m^{-2}; 0 - 37.5 m); arrows: surface currents (m s^{-1}). B) Simulated ice concentrations for the same period.

Un exemple de résultat obtenu à partir du modèle écosystème 3D pour 1997 (10 avril). A) Les couleurs: la concentration intégrée en chlorophylle a *(mg m^{-2} ; 0 - 37.5 m); les flèches: les courants de surface (m s^{-1}). B) Les concentrations de glace simulées pour la même période.*

(50-120 m) along the north shore and leak into the northwestern Gulf and Lower St. Lawrence Estuary in less than a year (Saucier et al. 2003). The intermediate nitrate gradient would then be sensitive to the nitrate concentrations prescribed at the Strait of Belle Isle, which are assumed constant in our first simulations. As the inflow of cold Labrador waters is more marked in autumn (Petrie et al. 1988, Saucier et al. 2003), nitrate boundary conditions may also be an important factor for the preconditioning of the next year's bloom. Boundary conditions at the Strait of Belle Isle are far less monitored than those at Cabot Strait; given their possible effects on the simulation, they would need an increased sampling effort. The comparison of simulated and observed chlorophyll *a* concentrations also shows good overall agreement. Using a mean carbon/chlorophyll *a* mass ratio of 55 for both phytoplankton size classes, the model reproduces the right order of magnitude of chlorophyll *a* concentrations despite a tendency for higher simulated chlorophyll concentrations in June. It is well known that the carbon/chlorophyll *a* and C/N ratios vary considerably in nature, and this could explain the deviation between simulated and observed chlorophyll concentrations. In spite of that, and considering the overall agreement between the simulated and observed nitrate concentrations, we are confident that the model reasonably captures the seasonal cycle of primary production in the Gulf.

In conjunction with the AZMP, this powerful modelling tool gives us the capacity of integrating small scales and complex ecosystem relationships. The present paper highlights the abilities and limitations of this first coupled model. We are considering improvements to the model that will address its limitations (freshwater-related turbidity, nutrient regeneration, boundary condition sensitivity) and are beginning to simulate the interannual variability in the primary and secondary production cycles in the Estuary and Gulf of St. Lawrence over the past 10 years. The model will be evaluated against the existing data set, including observations from the AZMP. Particular attention will be directed towards the influence of exceptional climatic conditions (e.g., abnormally warm years especially during the 1997-2001 period, above-normal water levels in 1999 and 2001 in the St. Lawrence basin) that prevailed during the last 10 years and could be responsible for significant changes in the timing and magnitude of the spring bloom in the St. Lawrence Estuary during the last decade (Starr et al. 2001). This is a crucial step in order to predict how climate changes may alter the global productivity of the St. Lawrence. Then, the model will be used to assess the impact of climate changes (doubling and tripling CO_2 levels) and man-made changes in the hydrological cycle on vertical mixing, transports, nutrient inputs, and the productivity and spatial distribution of critical ecosystem components (primary and secondary production). The regional

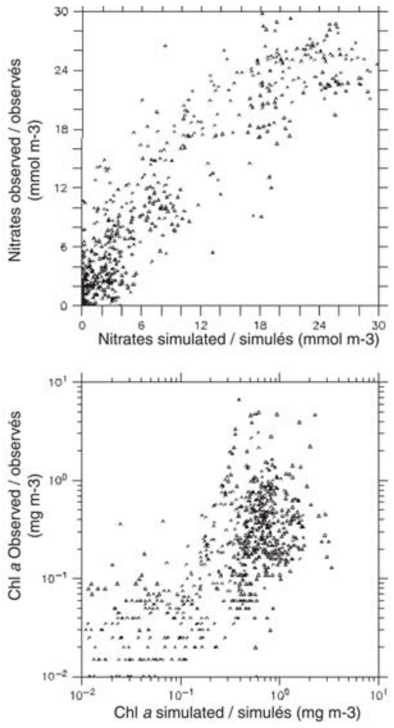


Fig. 4 Comparaison bewteen observed (AZMP) and simulated (model) nitrate and chlorophyll *a* values.

Comparaison entre les valeurs de nitrate et de chlorophylle a *observées (PMZA) et simulées (model).*

circulation model is now fully coupled with the Canadian Regional Climate Model (RCM) and with the Canadian Global Environmental Multiscale Model, with the aim of furthering our understanding of regional-scale coastal climate processes and to produce realistic climate change scenarios for the Estuary and Gulf of St. Lawrence. The first realistic climate change scenarios for the St. Lawrence will be available soon and will be used to study the sensitivity of the St. Lawrence ecosystem to climate changes.

Acknowledgement

This work is supported by grants from the Natural Sciences and Engineering Research Council, Fisheries and Oceans Canada, and the Canadian Foundation for Innovation. The contributions of F. Roy (IML), S. Senneville (IML), and J. Caveen (ISMER), who assisted in the technical development of numerical tools are gratefully acknowledged.

References

Bugden, G.L., B.T. Hargrave, M.M. Sinclair, C.L. Tang, J.-C. Therriault and P.A. Yeats. 1982. Freshwater runoff effects in the marine environment: the Gulf of St. Lawrence example. Can. Tech. Rep. Fish. Aquat. Sci. 1078.

de Lafontaine, Y., S. Demers and J. Runge. 1991. Pelagic food web interactions and productivity in the Gulf of St. Lawrence: A perspective. *In* The Gulf of St. Lawrence: small ocean or big estuary? *Edited by* J.-C. Therriault. Can. Spec. Publ. Fish. Aquat. Sci. 113: 99-123.

Fuentes-Yaco, C., A.F. Vézina, P. Larouche, C. Vigneau, M. Gosselin and M. Levasseur. 1997. Phytoplankton pigment in the Gulf of St. Lawrence, Canada, as determined by the Coastal Zone Color Scanner. Part I: Spatio-temporal variability. Cont. Shelf Res. 17(12): 1421-1439.

Koutitonsky, V.G., and G.L. Bugden. 1991. The physical oceanography of the Gulf of St. Lawrence: A review with emphasis on the synoptic variability of the motion. *In* The Gulf of St. Lawrence: small ocean or big estuary? *Edited by* J.-C. Therriault. Can. Spec. Publ. Fish. Aquat. Sci. 113: 57-90.

Lavoie, D., Y. Simard and F.J. Saucier. 2000. Aggregation and dispersion of krill at channel heads and shelf edges: the dynamics in the Saguenay-St. Lawrence Marine Park. Can. J. Fish. Aquat. Sci. 57: 1853-1869.

Le Fouest, V., B. Zakardjian, F.J. Saucier and M. Starr. 2003a. High-resolution 3D modelling of planktonic production in the Gulf of St. Lawrence, Canada. 2003 EGS-AGU-EUG Joint Assembly. Geophysical Abstract.

Le Fouest, V., B. Zakardjian, F.J. Saucier and M. Starr. 2003b. A coupled 3-D high-resolution climatically-driven ecosystem model for the Gulf of St. Lawrence, Canada. 2003 ASLO Ocean Sciences Meeting, Book of Abstracts.

Legendre, L., and R.B. Rivkin. 2002. Fluxes of carbon in the upper ocean: Regulation by food-web control nodes. Mar. Ecol. Prog. Ser. 242: 95-109.

Petrie, B., B. Toulany and C. Garrett. 1988. The transport of water, heat and salt through the Strait of Belle Isle. Atmos.-Ocean 26: 234-251.

Roy, S., B. Sundby, A.F. Vézina and L. Legendre. 2001. A Canadian JGOFS process study in the Gulf of St. Lawrence. Introduction. Deep-Sea Res. II 47(3-4): 377-384.

Runge, J.A., M. Castonguay, Y. de Lafontaine, M. Ringuette and J.-L. Beaulieu. 1999. Covariation in climate, zooplankton biomass and mackerel recruitment in the southern Gulf of St. Lawrence. Fish. Oceanogr. 8: 139-149.

Saucier, F.-J., F. Roy, D. Gilbert, P. Pellerin and H. Ritchie. 2003. Modeling the formation and circulation processes of water masses and sea-ice in the Gulf of St. Lawrence. J. Geophys. Res. 108(C8): 1-20.

Savenkoff, C., A.F. Vézina, P.C. Smith and G. Han. 2001. Summer transports of nutrients in the Gulf of St. Lawrence estimated by inverse modelling. Estuar. Coast. Shelf Sci. 52(5): 565-587.

Simard, Y., and D. Lavoie. 1999. The rich krill aggregation of the Saguenay - St. Lawrence Marine Park: Hydroacoustic and geostatistical biomass estimates, structure, variability, and significance for whales. Can. J. Fish. Aquat. Sci. 56: 1182-1197.

Starr, M., and H. Harvey. 2000. State of phytoplankton and zooplankton in the Estuary and northwestern Gulf of St. Lawrence during 1999. DFO Science Stock Status Report C4-18.

Starr, M., L. St-Amand, P. Joly and J.-C. Therriault. 2001. Variations spatio-temporelles du phytoplancton dans l'estuaire maritime du Saint-Laurent. AZMP Bulletin 1: 21-23.

Steven, D. M. 1974. Primary and secondary primary production in the Gulf of St. Lawrence. McGill Univ. Mar. Sci. Centre MS Rep. 26, 116 pp.

Therriault, J.-C., L. Legendre and S. Demers. 1990. Oceanography and ecology of phytoplankton in the St. Lawrence estuary. *In* Oceanography of a large-scale estuarine system: The St. Lawrence. *Edited by* M.L. El-Sabh and N. Silverberg. Springer-Verlag, New York, Coastal Estuarine Studies 39: 269-295.

Therriault, J.-C., and 11 co-authors. 1998. Proposal for a Northwest Atlantic Zonal Monitoring Program. Can. Tech. Rep. Hydrogr. Ocean Sci. 194, 57 pp.

Oceanographic Buoy Network in the Gulf of St. Lawrence

Pierre Larouche and Bernard Pettigrew
Institut Maurice-Lamontagne, Ministère des Pêches et des Océans,
B.P. 1000, Mont-Joli, QC, Canada G5H 3Z4
LaroucheP@dfo-mpo.gc.ca

Résumé

Le Laboratoire de Télédétection de l'Institut Maurice-Lamontagne reçoit et traite des images NOAA-AVHRR et SeaWiFS afin d'utiliser la couleur et la température de surface de l'eau comme outils de suivi de l'environnement. Pour ce faire, des algorithmes standards développés à l'aide de données océanographiques sont utilisés. Cependant, l'utilisation de ces algorithmes pour les eaux des mers intérieures comme celles du golfe du Saint-Laurent et de la baie d'Hudson cause problème puisque ces environnements sont fortement influencés par de forts débits d'eau douce qui transportent avec eux une grande quantité de matières organiques particulaires et dissoutes qui ont une influence significative sur les mesures de télédétection. De plus, l'atmosphère au-dessus de ces mers intérieures est influencée par des aérosols de type continentaux, ce qui affecte la qualité des mesures. Il est donc très important de pouvoir valider ces algorithmes avec des mesures de terrain et/ou encore, d'en développer de nouveaux qui sont mieux adaptés aux conditions particulières des régions sous forte influence des débits d'eau douce. Nous avons entrepris un tel projet dans le golfe du Saint-Laurent avec l'aide de l'Agence Spatiale Canadienne. Comme la fréquence d'échantillonnage (toutes les deux semaines) aux stations fixes du Programme de Monitorage de la Zone Atlantique (PMZA) n'est pas bien adaptée à ce type de travail de validation d'images satellites, nous avons opté pour le développement d'une nouvelle bouée océanographique qui permettrait d'obtenir des mesures de terrain en temps réel. Nous avons donc décidé de mettre en place un réseau d'observation du Saint-Laurent composé, dans un premier temps, de 3 bouées localisées dans des régions très différentes de l'écosystème du Saint-Laurent (l'estuaire, le sud et le nord-est du Golfe). L'accès en temps réel aux résultats des bouées peut se faire en consultant l'adresse Internet suivante : www.osl.gc.ca. Dans le présent article, nous décrivons le projet plus en détail et nous présentons quelques résultats provenant des deux premières années d'échantillonnage de la bouée mouillée à la station de Rimouski (IML-4). Ces résultats indiquent qu'il existe une relativement bonne concordance entre les données provenant de la bouée et celles provenant du monitorage régulier à cette station pour le suivi de la variabilité saisonnière. Toutefois, les données de la bouée indiquent également qu'il existe une grande variabilité à plus courte échelle de temps et qu'il est possible de détecter des événements océanographiques importants qui peuvent passer complètement inaperçus à l'échelle de temps du monitorage régulier (deux semaines). En plus de contribuer au monitorage environnemental, les données obtenues par les bouées océanographiques peuvent aussi servir à des projets de recherche scientifique de nature plus fondamentale. Par exemple, les données optiques obtenues indiquent qu'il pourrait être possible de développer un algorithme utilisant des données de télédétection de couleur de la mer pour mesurer la salinité dans les milieux possédant de forts gradients horizontaux. La mise en place de notre réseau de bouées n'est pas encore terminée. Nous comptons ajouter une seconde bouée en 2004 à la station de monitorage de Shédiac (sud du golfe, IML-6) et une troisième bouée est prévue pour 2005 à la station du Banc Beaugé (nord-est du golfe, IML-2). Il convient en terminant de noter qu'il sera facilement possible d'intégrer de nouveaux senseurs aux bouées de base afin de les rendre plus polyvalentes et ainsi participer encore plus fortement aux activités du PMZA.

Introduction

The St. Lawrence marine ecosystem, located in eastern Canada, is a complex environment that possesses both estuarine and oceanic characteristics. Freshwater runoff, large-scale meteorological events, winds, and tides acting at different temporal and spatial scales and coupled to the complex bathymetry contribute to generating strong spatial and temporal variability in the physical and biological properties within this ecosystem.

The Atlantic Zone Monitoring Program aims at a better understanding and eventual quantification of environmental changes on the east coast of Canada, including the St. Lawrence system. As part of this program, remote sensing techniques are used to provide a regular large-scale view of the ecosystem. The Maurice Lamontagne Institute (MLI) Remote Sensing Laboratory has been receiving NOAA satellite data since 1994 and routinely generates weekly and bi-monthly composite images of sea-surface temperature (SST) over eastern Canada (including Hudson Bay) that are available for a wide variety of uses (support for research cruises, fisheries, marine mammal distribution, etc.). The Remote Sensing Laboratory is also an official backup receiving site for SeaWiFS ocean colour images having the same geographical coverage. These can be used for the production chlorophyll concentration maps. However, the responsibility to produce composite SeaWiFS remote sensing maps on a routine basis for the AZMP is assumed by the remote sensing laboratory of the Maritimes Region. Remote sensing products such as SST and chlorophyll maps are generated using algorithms provided by either NASA or NOAA. These algorithms were developed using a set of in situ measurements and statistical analyses of oceanic conditions. For the SST, the data sets used to develop the algorithms are mostly representative of open ocean conditions and the overlying atmosphere. In the coastal zone, and in particular in Canadian inland seas (Hudson Bay and the Gulf of St. Lawrence), we are faced with the basic problem that the atmosphere is more complex and variable, being affected by particles of continental origin, thus generating remote sensing products that are less accurate. For ocean colour, the main problem in the coastal regions is the effect of freshwater-related constituents (sediments, dissolved organic matter) that change the water's spectral absorption properties and contaminate the radiometric signature of the phytoplankton biomass. These waters are referred to as Type II in contrast to oceanic regions, where the colour is dominated by the phytoplankton biomass and its covariant constituents, and which are referred to as Type I waters. For both SST and phytoplankton biomass products, there is a need to validate the remote sensing products in order to evaluate the potential error introduced by the standard processing algorithms and eventually to build better algorithms adapted to regional conditions.

Project Description

The AZMP provides regular sampling of a network of monitoring stations to collect basic information on physical, chemical, and biological oceanographic conditions. However, considering cloud cover and the temporal variability of both water and atmosphere, this sampling is too infrequent to adequately validate remote sensing images. To do this, we needed to improve our ship-based sampling program by installing a network of oceanographic buoys allowing higher frequency in situ sampling. The Canadian Space Agency provided the necessary start-up funding for the development of a satellite validation network in the Gulf of St. Lawrence (sea-surface temperature and fluorescence). This buoy network consists of three buoys installed at key or representative locations or regions in the Gulf of St. Lawrence (Fig. 1). The data are transmitted to the Maurice Lamontagne Institute for processing and storage in a dedicated database. These data are then further analyzed and used for the validation of the remote sensing images produced in an operational mode by the remote sensing laboratory at MLI. These real-time data are available to research scientists and environmental managers as well as to the general public through the web portal of the St. Lawrence Observatory (www.osl.gc.ca).

The first phase of the project aimed at the development of a low cost buoy capable of hosting various sensors measuring key physical and biological oceanic variables as well as some atmospheric instrumentation. A standard navigation buoy was selected as the platform for this development (Fig. 2). The buoy was also equipped with sensors to measure its heading, tilt, and roll together with battery voltage, energy generated by the solar panels, and energy consumed by the system. We then built a controller powerful and flexible enough to handle the large number of sensors installed on the buoy and the high sampling frequency necessary to measure the changing environment. This controller is based on an Intel 80C188EB 16-bit processor. It can accept inputs from 16 sensors using analog outputs and 10 sensors using RS-232 outputs, and can control four instruments through on/off gates. It also has 16 I/O analog interrupt channels. Because of this capacity, the buoy can easily be modified to incorporate other sensors, such as a Doppler current profiler, a nutrient sensor, or a SeaHorse profiler. One of its most important characteristics is the presence of a solid-state memory allowing storage of the entire season's data in case of a failure of the data transmission module, preventing any data loss.

Optical, oceanic, and atmospheric variables (Table 1) are acquired at 15-minute intervals, allowing for an almost concurrent measurement with any satellite overpass. Bromine is used to avoid biological fouling of the sensors measuring temperature, salinity, chlorophyll fluorescence, and coloured dissolved organic matter (CDOM). A copper bio-shutter is also used to protect the immersed optical sensors and copper foils are wrapped around the sensors to further protect them against fouling. The instruments sample at 6 Hz over a one-minute period and the controller calculates the mean and the standard deviation of each variable before transmission to MLI. When possible, data transmission to MLI is done using a UHF modem. A more expensive satellite link is used for stations located too far from MLI. The data are transmitted immediately after acquisition using the UHF link while the buoys equipped with satellite modems transmit their data four times per day (every six hours). The raw data are then processed using custom-built software, displayed on a dedicated computer, and transferred to the remote sensing web page hosted on the St. Lawrence Observatory portal within a few minutes.

Temperature / Température
Salinity / Salinité
Chlorophyll fluorescence / Fluorescence de la chlorophylle
Coloured dissolved organic matter fluorescence / Fluorescence de la matière organique dissoute colorée
Wind speed and direction / Vitesse et direction du vent
Gusts / Coups de vent
Atmospheric pressure / Pression atmosphérique
Air temperature and relative humidity / Température de l'air et humidité relative
Irradiance (7 channels) / Éclairement (7 canaux)
Radiance (7 channels) / Luminance (7 canaux)
Photosynthetically available radiation (PAR) / Radiation disponible pour la photosynthèse

Table 1. Variables measured by the oceanographic buoy.
Tableau 1. Variables mesurées par la bouée océanographique.

A prototype buoy was first tested at sea in the fall of 2001 in the St. Lawrence Estuary. The excellent results gathered during this trial mooring indicated that the buoy was performing well in the St. Lawrence environment (Larouche et al. 2002). The maximum observed tilt was less than 20° for a wind speed of up to 60 km h^{-1}. Wind climatology from the nearest weather station (~30 km) indicates that summer winds above 30 km h^{-1} occur only 14% of the time, meaning that mean buoy tilt should almost always be less than 10°, which is very important for the quality of optical measurements. Following this successful test, it was decided to go ahead with the deployment of the buoy network. The first buoy (IML-4) was moored in 2002 at a monitoring site off Rimouski, about 30 km upstream of the Maurice Lamontagne Institute (Fig. 1). This location was selected because it is visited weekly during summer and fall and because of its proximity to MLI, allowing easy access in case of problems.

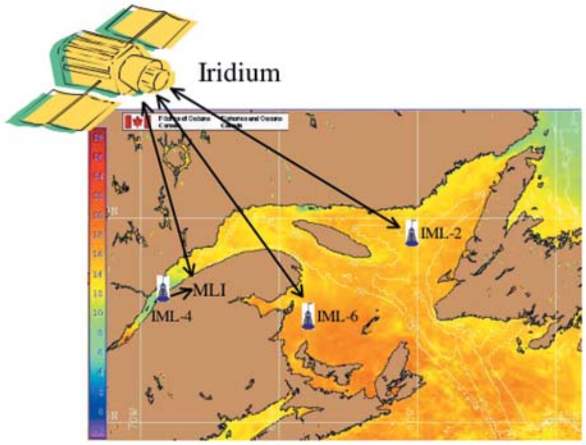


Fig. 1 Basic buoy network for the St. Lawrence ecosystem superimposed on a sea-surface temperature image (composite image for 1-15 August 2003).

Réseau de bouées de base pour l'écosystème du Saint-Laurent superposé à une image de température de surface de la mer (image composite pour la période du 1 au 15 août 2003).

Results

The comparison between the buoy data and the weekly measurements from a small boat (Fig. 3) indicates that both series resolve relatively well the seasonal trends in temperature and salinity. However, large differences were observed for the fluorescence measurements between the two series, particularly when the fluorescence levels were high in the surface waters. The buoy series showed high fluorescence variability at short temporal scales, suggesting the occurrence of high frequency transient events (e.g., for day 250) that were completely missed by the vessel-based sampling. In the context of remote sensing validation, it then becomes evident that the improved sampling frequency of the buoy network is an essential tool to decrease the spatio-temporal aliasing that is associated to any vessel-based sampling.

The IML-4 operational buoy was moored off Rimouski for a second year in 2003. Figure 4 compares the results obtained for the time series of temperature, salinity, and chlorophyll fluorescence obtained for 2002 and 2003. The data series from both years showed the occurrence of strong temporal variability at short time scales superimposed on longer term variability at the seasonal scale. Figure 4 also indicates the existence of significant interannual differences in the amplitude and timing of events for these oceanographic variables at the Rimouski station. In that context, it is interesting to note that the mean surface water temperature was 1.2°C lower in 2003 than in 2002 while the mean salinity was slightly above the 2002 level. This is possibly related to the lower mean atmospheric temperatures (by 0.6°C) observed in 2003 at the buoy location and the smaller spring freshet from the St. Lawrence (www.osl.gc.ca/fr/donnees/debits/donnees.html). Another striking observation in the mean fluorescence signal is the occurrence of much higher fluorescence levels in 2002 compared to 2003, resulting in the occurrence of two large peaks of fluorescence measured around days 220 and 250. Similar peaks of fluorescence were not recorded in 2003 at the buoy location.

Besides monitoring, satellite validation, and modeling applications, the buoy platform data can be used for basic scientific research. A good example is the possibility to observe salinity from ocean colour images (Larouche and Pettigrew 2003). The 2002 data gathered by the buoy clearly indicate that a strong relationship exists between the concentration of CDOM (coloured dissolved organic matter) and salinity. There is also a strong correlation between CDOM and the ratio of remote sensing reflectance (R412/R669) as measured by the onboard radiometers. Even though these observations are only preliminary, they clearly indicate that in the case of coastal waters mainly influenced by one source of freshwater, where relatively large surface gradients (ΔS=10) can be observed, the potential exists to remotely determine the large-scale distribution of surface salinity using ocean colour satellite data. This potential will be further evaluated in 2004 using the buoy data from the second year, and the validity of the observations will also be tested using independent ocean colour observations concurrent with in situ sampling.

Fig. 2 Oceanographic buoy IML-4.

Bouée océanographique IML-4.

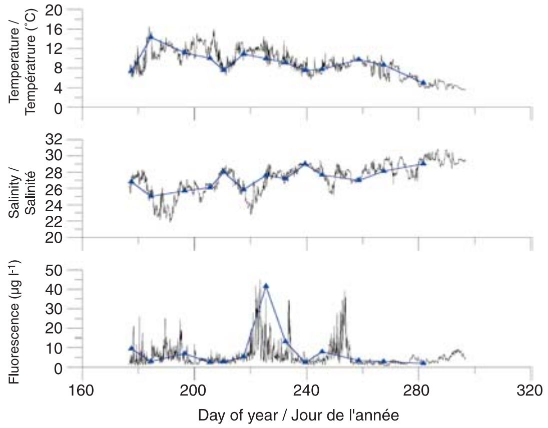


Fig. 3 Comparison between the time series of temperature, salinity, and fluorescence at the surface from the buoy (black) and from the in situ monitoring station IML-4 at Rimouski (blue) in 2002.

Comparaison entre les séries temporelles de température, salinité et fluorescence en surface pour la bouée (noir) et le monitorage in situ à la station IML-4 de Rimouski (bleu) en 2002.

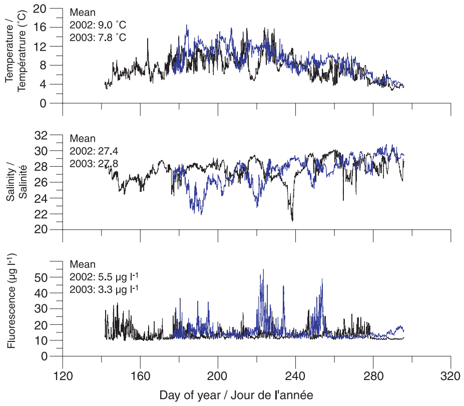


Fig. 4 Comparison between the time series of temperature, salinity, and fluorescence at the surface from years 2002 (blue) and 2003 (black) at the Rimouski station IML-4.

Comparaison entre les séries temporelles de température, salinité et fluorescence en surface pour les années 2002 (bleu) et 2003 (noir) à la station IML-4 de Rimouski.

A second buoy is scheduled to be moored in 2004 at the Shediac monitoring station in the southern Gulf of St. Lawrence (IML-6, Fig. 1). A third buoy is under construction and will be deployed in 2005 at the Banc Beaugé station (IML-2, Fig. 1) in the northeastern Gulf. Although this is a good starting point, we recognize that three buoys cannot provide all the data we need to fully characterize the ecosystem of the Gulf of St. Lawrence. We believe that a full network of at least eight buoys is required to adequately cover the different oceanographic features in the St. Lawrence. If equipped with instrumentation to measure vertical water properties (Doppler current profilers, SeaHorse sampler, etc.), this buoy network could become a major element of the AZMP sampling strategy in the future years, providing a source of high frequency temporal data at the most important locations in the Gulf system at low cost for operational applications and/or science projects.

Acknowledgements

The development of the first prototype buoy was successful in great part because of the dedication and competence the DFO's technical staff at MLI (Roger Pigeon, Rémi Desmarais, and Sylvain Cantin). The important contribution of Multi-Électronique in the development of the data logger and buoy control system is also acknowledged.

References

Larouche, P., and B. Pettigrew. 2003. Optical buoy network in the St. Lawrence estuary and Gulf. HABWATCH symposium, Villefranche-sur-mer, France, 11-21 June 2003.

Larouche, P., B. Pettigrew, R. Pigeon and J. St-Pierre. 2002. Optical buoy network in the St. Lawrence estuary and Gulf. Proceedings of the Seventh International Conference on Remote Sensing for Marine and Coastal Environments, Miami, Florida, 20-22 May 2002.

The AZMP Program Contributes to the Scientific Investigation of the Smith Sound Mass Fish Kill of April 2003

E.B. Colbourne[1], J. Brattey[1], G. Lilly[1], and G.A. Rose[2]
[1]Northwest Atlantic Fisheries Centre, Box 5667, St. John's, NL, A1C 5X1
[2]Fisheries Conservation Chair, Marine Institute, Memorial University, St. John's, NL, A1C 5R3
Colbourn@dfo-mpo.gc.ca bratteyj@dfo-mpo.gc.ca lillyg@dfo-mpo.gc.ca grose@mi.mun.ca

Résumé

L'existence du Programme de Monitorage de la Zone Atlantique (PMZA) a grandement facilité l'enquête scientifique concernant une mortalité massive de poissons observée en avril 2003 dans Smith Sound, un fjord situé dans la baie Trinity sur la côte est de Terre-Neuve. Il s'agit en fait de la plus importante mortalité naturelle de poissons jamais observée dans les eaux côtières du Labrador et de Terre-Neuve. L'existence d'une importante agrégation de morues dans Smith Sound avait tout d'abord été établie en 1995 à l'occasion d'évaluations acoustiques. On a par la suite estimé que cette biomasse a varié entre 10 000 tonnes métriques durant le milieu des années 1990 jusqu'à environ 25 000 tonnes métriques au début des années 2000. Au début du printemps 2003, les résidents de Smith Sound ont observé un nombre important de morues et de sébastes flottant à la surface ou encore accumulés le long de la berge. Huit cent tonnes métriques de morues flottant à la surface et représentant environ 4 % de la biomasse maximale estimée ont subséquemment été recueillies par des pêcheurs sur une période de trois semaines pour être traitées dans une usine locale de transformation de poissons. Après examen, on a déterminé que ces poissons étaient morts gelés ou encore parce qu'ils contenaient des cristaux de glace. Les conditions climatiques dans l'Atlantique canadien durant cette période étaient parmi les plus froides jamais observées au cours de la dernière décennie. Des mesures océanographiques, effectuées au début du printemps durant cet événement de mortalité massive, ont révélé que la colonne d'eau s'était considérablement refroidie depuis le mois de janvier précédent, et aussi par rapport aux dix années précédentes. Il a ainsi été découvert que le détroit Smith Sound tout entier avait été envahi par une masse d'eau très froide, caractérisée par des températures minimales de -1.73 °C à mi-profondeur et d'environ -1.6 °C près du fond, à 200 m. Il a par la suite été établi que ces eaux extrêmement froides qui ont envahi Smith Sound au cours du printemps 2003 provenaient d'un événement de convection hivernale très intense qui a eu lieu sur le plateau continental de Terre-Neuve et du Labrador au cours des mois d'hiver précédents. Ces eaux très froides qui subissent une advection continuelle vers le sud en raison du courant du Labrador ont ensuite pénétré à l'intérieur de Smith Sound au début d'avril. Le taux de diminution de la température qui est passé de 0.5 °C à la fin janvier à un minimum de -1.73 °C au début d'avril est anormalement élevé et a probablement été un facteur significatif qui a mené à la mortalité massive de poissons observée.

Introduction

The existence of the Atlantic Zone Monitoring Program has greatly facilitated the scientific investigation of the mass fish kill of Smith Sound in April 2003. Smith Sound is a fjord of about 20 km in length located on the east coast of Newfoundland on the north side of Random Island within Trinity Bay (Fig. 1). The fjord is about 1-2 km wide with water depths to 210 m and a sill depth of 155 m. During April 1995, a large and dense aggregation of cod was discovered in Smith Sound. Subsequent hydroacoustic surveys of the aggregation estimated the biomass to range from about 10,000 metric tons (t) during the mid-1990s to about 25,000 t during the early 2000s (Rose 2003). This group of fish now represents the largest known single spawning aggregation of the once abundant northern cod stock. Recaptures from tagging studies determined that most of these fish move out of Smith Sound during late spring and early summer and migrate north along the east and northeast coasts of Newfoundland, remaining in the inshore regions. They return to Smith Sound in late autumn to overwinter. In early April 2003, this group of fish suffered the largest documented natural mortality in Newfoundland and Labrador waters. On Saturday 5 April, residents of the Sound discovered a significant number of cod and redfish floating on the surface and washing onto the shoreline. Dead cod were subsequently harvested from the surface by fishers during a three-week period, and approximately 800 t, representing nearly 4% of the maximum estimated biomass, was processed by local fish plants. An examination determined that the fish were either frozen or contained ice crystals.

The Atlantic Zone Monitoring Program (AZMP) of the Department of Fisheries and Oceans first surveyed Smith Sound during its annual fall survey in November of 2002. On 8-10 April 2003, AZMP team members participated in a special DFO mission to Smith Sound to determine the extent of the fish kill and to conduct an oceanographic survey of the area. A follow-up survey was conducted by the AZMP on 1-2 May 2003 to measure changes in the oceanographic conditions immediately after the mass mortality incident and to sample cod for antifreeze testing. Detailed biological sampling and dissolved oxygen measurements were also made. During the remainder of 2003, the AZMP team conducted two more surveys of Smith Sound, one in early August on the annual summer survey and one in early December during the fall survey. Historically, the first systematic set of oceanographic observations available in Smith Sound and vicinity were made in March of 1991 during acoustic studies of cod behaviour and migration (Wroblewski et al. 1993). Throughout the 1990s and early 2000s, several studies on cod in Smith Sound by Memorial University of Newfoundland and the Department of Fisheries and Oceans have collected oceanographic data within the Sound. The most recent survey by Memorial University took place in late January of 2003, immediately preceding the fish kill.

In this article we present some of the results of the scientific investigation of factors surrounding the fish kill, specifically the oceanographic conditions encountered in the Sound in 2003 and how they compare with previous data.

Historical Oceanographic Conditions in Smith Sound

Water temperatures during the March 1991 survey indicate that conditions were very cold throughout the Sound, with minimum values of around -1.5°C. Near-surface values were about -1.0°C and near-bottom temperatures were approximately -1.2°C. In general, temperatures throughout the inshore waters of Newfoundland and Labrador during the early 1990s were among the coldest on record. Moreover, other data collected by Wroblewski et al. (1993, 1994a) in adjacent fjords showed that minimum temperatures of -1.7°C were not unusual in this area during the winter and early spring. In fact, temperatures along the east coast of Newfoundland observed at Station 27 indicate that these cold conditions were established in the late 1980s, reached a minimum in the early-1990s, and started to moderate in 1995. During 1996, water temperatures increased to above normal values over most regions; from 1997 to 1999, ocean temperatures continued to increase, with 1999 being one of the warmest years in the past couple of decades (Colbourne 2002). Temperatures measured within Smith Sound during an April 1996 survey showed that conditions had warmed considerably, with surface values of 0.5°C, minimum temperatures at mid-depth of around -0.75°C, and near-bottom values of -0.5°C (Fig. 2). An April 1997 survey showed nearly identical temperatures. Oceanographic data collected in January of 2000 and 2003 generally showed warmer temperatures at depth than those from the spring months due to the intense vertical mixing of the summer-heated upper layers in the previous fall. In January 2000, temperatures ranged from 0.5°C near the bottom to 0.75°C in the upper water column; slightly cooler conditions prevailed in January 2003, with upper layer values generally <0°C and near-bottom values near 0.3°C (Fig. 3). These water temperatures are in sharp contrast to the cold conditions observed during the winters of the early 1990s (Wroblewski et al. 1993, 1994a, 1994b).

Environmental Conditions During the Winter and Spring of 2003

The North Atlantic Oscillation (NAO) index was slightly positive (0.4) during the winter of 2003, similar to 2002. The sea-level pressure anomaly pattern, however, was not that of a typical positive NAO index year, as anticyclonic conditions persisted over Scandinavia and a deep cyclonic circulation pattern dominated the Labrador Sea (ICES 2003). Sea-level pressure anomalies over the northeastern regions of Newfoundland and the Labrador Sea decreased to >5 mb below the long-term average during the winter months. Consequently, cold Arctic outflow dominated the atmospheric circulation pattern over much of eastern Canada. Historically, these conditions are typical of a strongly positive NAO index, which normally brought cold ocean conditions to this region. During February of 2003, air temperatures had dropped to below normal values over much of eastern Canada, by 1.3°C over Labrador and nearly 1°C over southern Newfoundland. During March, air temperatures had decreased even further, to 3.5°C below normal over Labrador (Cartwright) and to 2.5°C below normal over Newfoundland (St. John's). By April, conditions improved somewhat, but air temperatures remained near 1.5°C below the long-term average (Environment Canada, 2003 Web Site). These anomalies were among the lowest observed in almost a decade and resulted in heavier and more extensive sea-ice cover than normal on the Newfoundland and Labrador Shelf during the winter and spring of 2003 (Canadian Ice Service 2002). The sea-ice edge, for example, reached as far south as Cape Race in the inshore regions and as far south as 45.5°N latitude in the offshore areas by late March (Canadian Ice Service 2003 Web Site).

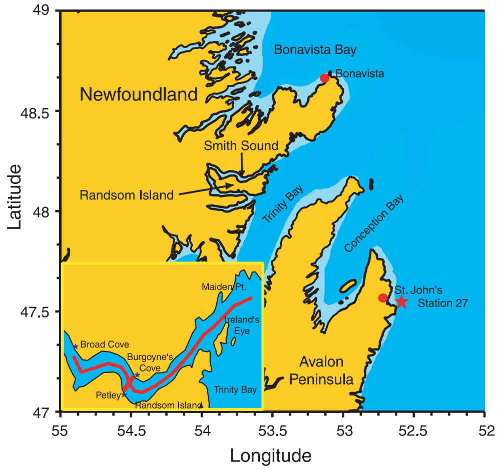


Fig. 1 Map showing the location of Smith Sound within Trinity Bay on the east coast of Newfoundland. The inset shows the positions of oceanographic sections sampled within the Sound during the surveys of 8-10 April and 1-2 May 2003.

Carte localisant Smith Sound dans la baie Trinity sur la côte est de Terre-Neuve. L'encart montre les positions des transects océanographiques qui ont été échantillonnés dans le fjord durant les missions océanographiques du 8-10 avril et du 1-2 mai 2003.

Oceanographic Conditions in Smith Sound During 2003

Oceanographic data collected during the late fall of 2002, both by the AZMP and during DFO multi-species surveys, provided the first indication of a significant negative temperature anomaly developing on the Newfoundland and Labrador Shelf. During these surveys, upper-layer temperatures along standard AZMP sections across the Grand Bank showed temperatures as low as 2-3ºC below normal over the entire Grand Bank (Colbourne 2003). Temperatures measured in Smith Sound in late January, however, were still above 0°C near bottom and around -0.25°C at the surface (Fig. 3). By the time of the April 2003 survey to Smith Sound, the water column had cooled significantly, with temperatures ranging from -1.4°C at the surface to -1.73°C near 100 m, and about -1.6°C near bottom at 200 m (Fig. 4). In effect, the entire Sound was flooded by extremely cold water.

The only areas with water temperatures above -1.4°C were outside of the fjord in the deeper waters of Trinity Bay, where values were >0.5°C below 300 m, and near shore at the head of the fjord, where surface temperatures were about -1.2 to -1°C. In general, temperatures decreased by 1°C at the surface and by about 2°C near bottom from late January to early April, a period of only two months (Fig. 3 and 4). The vertical temperature cross-section constructed along the axis of the fjord shows evidence of a tongue of cold intermediate layer water (CIL) being advected into the Sound from the inner Newfoundland Shelf. Temperatures in the core of the CIL were near freezing, with values generally below -1.65°C and minimum values as low as -1.73°C (the freezing point is -1.78°C at a salinity of 32.8 at atmospheric pressure). The main aggregation of cod in the Sound during the early April survey was detected below this tongue of cold CIL water in the general vicinity of Petley to Bluff Head, where most of the dead fish were found (Fig. 1 and 4).

Sea water of salinity <24.7 has a higher temperature of maximum density than its freezing point and so behaves in a way similar to a body of freshwater in which rapid overturning can occur during the winter. Salinities within the Sound during early April, however, ranged from 32.63 at the surface to 32.82 near the bottom, indicating a very weakly stratified but stable water column. In the absence of stratification, a body of seawater at salinities >24.7 must be cooled to its freezing point before surface freezing commences. The vertical salinity structure in Smith Sound during the spring of 2003 showed that while salinity values generally increased with depth, the water column was nevertheless nearly isohaline. These conditions may have promoted enhanced vertical mixing by convective currents deeper into the water column, compared to the offshore regions where the vertical salinity gradient is generally much larger. Consequently, local convection and mixing within the Sound after an icebreaker removed the ice cover in late March no doubt contributed to the extremely cold water conditions. Except in the near-shore zone, however, it is unlikely that ice crystals formed in the upper water column could have penetrated to the bottom, particularly to the depths normally inhabited by cod (~200 m) during the winter and spring months. It has been demonstrated that ice crystals can act as a seeding agent to initiate the freezing process of super-cooled cod (Fletcher et al. 1997).

Data collected on the follow-up survey in early May showed that temperatures in Smith Sound had warmed to 0.5°C at the surface and to -1 to -1.5°C near the bottom. Dissolved oxygen levels, also measured on this survey, indicated super-saturated levels (>110%) in upper layers and values ranging from 90-95% in the depth range of 100-200 m. There was no evidence of oxygen depletion anywhere in the Sound, and the concentrations were much higher than the reported 39% saturation levels that can lead to anaerobiosis in cod (Claireaux and Dutil 1992). Also, during the May survey, a large dense aggregation of cod was detected in the warm waters of Trinity Bay (temperature 0.5°C) at the entrance to Smith Sound extending all the way in the fjord to Petley, in water temperatures of -1.5°C. These fish were in excellent condition and no dead fish were observed anywhere within the fjord. Oceanographic conditions observed in the offshore areas during this survey revealed CIL minimum temperatures of -1.7°C with temperatures as low as 1.5°C below normal near the east coast of Newfoundland and 1-2°C below normal on the Grand Bank, the coldest in nearly a decade. Temperatures in Smith Sound by early August had warmed to >12.5°C at the surface and to 0.0 to -0.5°C at the bottom. Dissolved oxygen levels, also measured on this survey, still indicated super-saturated levels (>110%) in upper layers and values ranging from 80-90% near bottom.

Discussion and Conclusion

In summary, ocean temperatures during early spring of 2003, both on the Newfoundland Shelf and in the inshore regions along the east coast, were among the coldest observed since the early 1990s. This followed an unusually cold winter that brought the heaviest ice cover to the region in about a decade. The available data from Smith Sound indicate

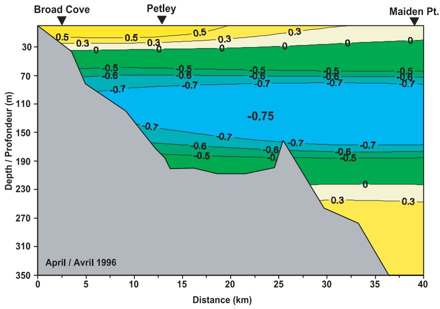


Fig. 2 Vertical distribution of water temperature (°C) along the longitudinal axis of Smith Sound during mid April of 1996.

Répartition verticale de la température de l'eau (°C) selon l'axe longitudinal de Smith Sound vers la mi-avril 1996.

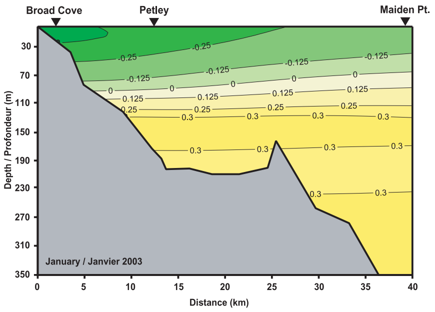


Fig. 3 Vertical distribution of water temperature (°C) along the longitudinal axis of Smith Sound during late January of 2003.

Répartition verticale de la température de l'eau (°C) selon l'axe longitudinal de Smith Sound à la fin janvier 2003.

that cold conditions prevailed during the early 1990s and lasted at least until 1994. During 1995, conditions began to moderate and increased to above normal values over most regions during 1996. From 1997 to 1999 ocean temperatures continued to warm, with 1999 being one of the warmest years on record. Since 1999, however, ocean temperatures have been decreasing from the record highs but remained above normal in most areas until the spring of 2003.

It appears likely that the extremely cold subsurface water within Smith Sound during the spring of 2003 was the result of intense winter convection and mixing on the Newfoundland and Labrador Shelf. These cold subsurface waters that are continuously advected southward by the Labrador Current penetrated deep into Smith Sound by early April. Since the Sound was covered with sea ice during most of the winter, local cooling within the Sound would have been reduced. However, after an icebreaker removed the ice cover in late March, local convection and mixing probably contributed to further cooling of the water column since air temperatures remained below normal. In addition, an examination of local wind data at Bonavista and St. John's in late March indicates that the prevailing direction was generally from the west, with average speeds in excess of 30 km h^{-1} and peak gusts of over 70 km h^{-1}, which were significantly stronger than normal. Similar wind conditions most likely existed in Smith Sound; this would have cleared the ice rapidly and may have contributed to the local circulation, allowing the cold sub-surface CIL shelf waters to penetrate into the Sound.

Many unanswered questions remain as to why the fish, cod in particular, but also an undetermined number of redfish, froze to death. Experiments by Wroblewski et al. (1994b) successfully overwintered cod during the cold winter of 1993-1994, when temperatures dropped to -1.7ºC. These fish had developed antifreeze protection to -1.1ºC and were therefore super-cooled by -0.6ºC with a 4% mortality rate. Incidentally, the number of fish processed by fish plants amounted to about 4% of the hydroacoustic estimate of the biomass (20,000 t) in January 2003, although there were an undetermined number of dead fish also observed on the bottom. According to Fletcher et al. (1997), cod can develop antifreeze protection to a minimum temperature of -1.2ºC, but can be further super-cooled by at least 0.5ºC. The reason why so many fish in Smith Sound during the spring of 2003 did not adapt to the ambient temperature (-1.6º to -1.73ºC) of the surrounding water is not clear. However, it is certain from existing data that the 2003 temperatures were near critical values, substantially colder than the previous 8-10 years. It is possible, therefore, that this may have been the first time that this fish population was exposed to near-freezing water. Furthermore, the rate of decrease in temperatures at 200 m depth, from near 0.5ºC in late January 2003 to a minimum of -1.73ºC by early April 2003, is anomalous and may have been a significant factor that led to the mass mortality.

There are numerous other observations that are currently being compiled surrounding this incident. Further research to determine the full circumstances that led to perhaps the largest documented natural mortality of cod in Newfoundland and Labrador waters is currently being carried out both at Memorial University and by Fisheries and Oceans Canada. We do not yet have a hypothesis that is consistent with all observations, but it is becoming clear that the extremely cold water that these fish were subjected to during early spring was the underlying cause of the mass mortality.

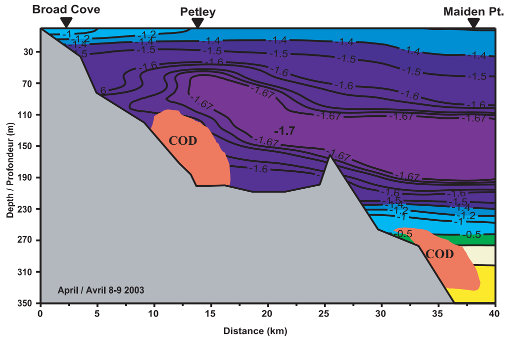


Fig. 4 Vertical distribution of water temperature along the longitudinal axis of Smith Sound during 8-10 April 2003. Locations where cod were detected are indicated schematically by the red areas.

Répartition verticale de la température selon l'axe longitudinal de Smith Sound durant la période du 8-10 avril 2003. Les positions où ont été détecté les bancs de morues sont indiquées approximativement par les zones rougeâtres.

References

Canadian Ice Service. 2002. Sea ice climatic atlas: Northern Canadian waters 1971-2000. Environment Canada, Ottawa, 249 pp.

Canadian Ice Service–Environment Canada. 2003 Web Site. <http://ice-glaces.ec.gc.ca/>.

Claireaux, G., and J.D. Dutil. 1992. Physiological response of the Atlantic cod (*Gadus morhua*) to hypoxia at various environmental salinities. J. Exp. Biol. 163: 97-118.

Colbourne, E.B. 2002. Physical oceanographic conditions on the Newfoundland and Labrador shelves during 2001. DFO CSAS Res. Doc. 2002/23, 56 pp.

Colbourne, E.B. 2003. Physical oceanographic conditions on the Newfoundland and Labrador shelves during 2002. DFO CSAS Res. Doc. 2003/20, 55 pp.

Environment Canada. 2003 Website.
<http://www.climate.weatheroffice.ec.gc.ca/prods_servs/>.

Fletcher, G.L., J.S. Wroblewski, M.M. Hichey, B. Blanchard, M. H. Kao and S.V. Goddard. 1997. Freezing resistance of caged Atlantic cod (*Gadus morhua*) during a Newfoundland winter. Can. J. Fish Aquat. Sci. 54 (Suppl. 1): 94-98.

ICES. 2003. The 2002/2003 ICES annual ocean climate status summary. *Edited by* S. L. Hughes and A. Lavin. ICES Cooperative Research Report No. 259. 29 pp.

Rose, G.A. 2003. Monitoring coastal northern cod: towards an optimal survey of Smith Sound, Newfoundland. ICES J. Mar. Sci. 60: 453-462.

Wroblewski, J.S., A. Collier and W. Bailey. 1993. Ocean temperatures in the Random Island region of Trinity Bay, 1991-1992. The NSERC/Fisheries Products International/National Sea Products Chair in Fisheries Oceanography, Data Rep. No. 1. Memorial University, St. John's, NL.

Wroblewski, J., W. Bailey and R. K. Smedbol. 1994a. Behavior of farmed cod released in Trinity Bay, Newfoundland, 1992-1993. The NSERC/Fisheries Products International/National Sea Products Chair in Fisheries Oceanography, Data Rep. No. 2. Memorial University, St. John's, NL.

Wroblewski, J., W. Bailey and K. A. Howse. 1994b. Observations of adult Atlantic cod (*Gadus morhua*) overwintering in near-shore waters of Trinity Bay, Newfoundland. Can. J. Fish Aquat. Sci. 51: 142-150.