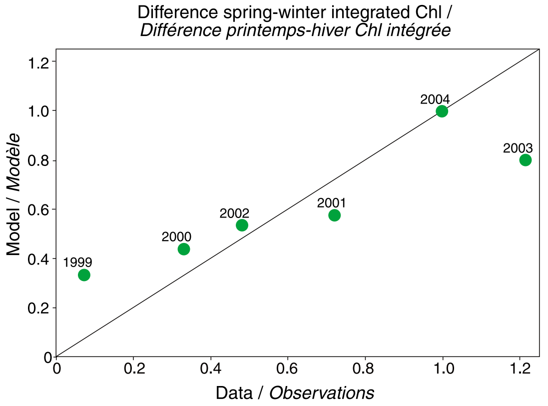

Fig. 4 Observed and modelled spring–winter differences in integrated chlorophyll for each year from 1999 to 2004. The root mean squared difference was calculated with respect to the 1:1 line. Numbers indicate years. Overestimates at the low end and underestimates at the high end indicate that the long-term variability is not well reproduced by the model.

Différences printemps–hiver dans la chlorophylle intégrée observée et simulée pour chaque année entre 1999 et 2004. La différence de la moyenne quadratique a été calculée par rapport à la ligne 1:1. Les nombres indiquent les années d'observations. La sur-évaluation pour les valeurs faibles et la sous-évaluation pour les fortes valeurs indiquent que la variabilité à long terme n'est pas bien reproduite.

ters of the ecological model were adjusted to match the average seasonal cycle in nutrients, chlorophyll and zooplankton over that period. Therefore, the simulated interannual variability of these ecological variables is an independent test of the model's sensitivity to simulated physical changes. Figure 3 shows interannual changes in vertically integrated chlorophyll simulated by the model and as observed at Station 2. The model correctly reproduces the general pattern of interannual trends and year-to-year variability for the spring and winter seasons (Fig. 3 and Table 1). Modelled spring-winter differences also largely follow the observed pattern (Fig. 4), but the model overestimates summer biomass and predicts increasingly strong fall blooms over the period whereas the data indicate that fall blooms have weakened over that same period (Fig. 2, upper two panels). The model estimates the change over the 1999-2004 period better than the year-to-year variability (Fig. 4 and Table 1). We are making substantial progress but work on improving the model must continue. To that end, we performed sensitivity analyses to investigate which aspects of this inter-disciplinary model should be given priority for further development. In general terms, our results indicate that improving the physical and ecological models should be given equal attention. More specifically, a better representation of vertical advection (upwelling, downwelling; see Fig. 2, third panel) seems critical to improve the results, both in terms of the seasonal cycle and interannual variability (Greenan et al. 2004). On the ecological side, the representation of zooplankton grazing turns out to be critical. With the same physics, changing the way grazing works in the model has dramatic impacts on the simulated seasonal and interannual patterns. Widely used models of grazing (e.g., Ivlev, Michaelis-Menten) do less well in reproducing the observed chlorophyll dynamics than an empirical model (Peters 1994). There is a strong need to develop new and more realistic grazing functions for ecological models.

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Phytoplankton Monitoring in Bedford Basin, the Scotian Shelf and the Labrador Sea: a Large-Scale Multi-Year Coherence

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Sommaire

L'abondance du phytoplancton a été enregistrée pour des périodes de 13, 9 et 12 ans respectivement dans le bassin de Bedford, dans trois régions du plateau Néo-Écossais (plateau ouest, centre et est), et dans trois régions de la mer du Labrador (bassin central du Labrador, plateau du Labrador et plateau du Groenland). Cinq autres stations de la région de Western Isles dans la baie de Fundy ont également été étudiées pendant quelques mois. Les cellules phytoplanctoniques ont été comptées par cytomètre en flux et les résultats de ces analyses fournissent une perspective de la communauté photo-autotrophe qui est différente de celle offerte par les mesures de biomasse ou de dénombrement par microscopie des diatomées et des dinoflagellés. L'ensemble de ces données indique une cohérence générale en ce qui a trait au développement saisonnier du phytoplancton dans les différentes régions étudiées. Ces données indiquent également une grande cohérence dans l'évolution annuelle de l'abondance du phytoplancton au cours de plusieurs années, suggérant que des organismes avec des temps de reproduction aussi courts (e.g., les microbes) peuvent répondre d'une façon cohérente à un mécanisme de forçage environnemental commun. Dans ce contexte, le bassin de Bedford, qui est échantillonné de façon hebdomadaire, peut donc s'avérer un outil important de surveillance permettant de bien intégrer la réponse régionale du phytoplancton faces aux changements environnementaux.

Phytoplankton are unicells. They contain light-harvesting chromophores that make it possible to detect them remotely by visible spectral radiometry or in bulk samples by precise pigment quantification or crude colorimetric estimation. Thus, the respective use of satellite ocean colour, particulate chlorophyll concentration and Continuous Plankton Recorder green index to monitor the biomass of phytoplankton by proxy are important elements of AZMP (Atlantic Zone Monitoring Program). However, detection of phytoplankton as single cells requires visual examination by light microscopy or electronic discrimination by flow cytometry. Only these latter methods are useful for understanding biodiversity because they explicitly recognize phytoplankton as phylogenetically distinct biotic units expressive of evolutionary traits and ecological interactions. Phytoplankton cells are entities that undergo binary fission susceptible to selection pressures. These cells are also the entities eaten by consumers: small ones are engulfed by protistan zooplankton and large ones are captured by metazoan zooplankton. Conventional light microscopy is labour-intensive and biased towards the larger phytoplankton (microplankton such as diatoms and dinoflagellates). Flow cytometry is semi-automated and biased toward the smaller phytoplankton (pico- and nanoplankton). A combination of both methods provides detailed characterization of the phytoplankton community.

The abundance of phytoplankton is scaled to cell mass according to an allometric rule with a power exponent of negative ¾ (Belgrano et al. 2002). This highly uneven distribution is counterbalanced by the scaling of metabolic rate to cell mass according to a power exponent of positive ¾ (West et al. 2002). The equal and opposite scaling of abundance (cells m^{-3}) and cellular photosynthesis (mg C $cell^{-1}$ d^{-1}) ensures that their product, primary production (mg C m^{-3} d^{-1}), is invariant with size. Here, we report on the flow cytometric monitoring of phytoplankton abundance in different parts of the western North Atlantic Ocean. The results indicate a perspective of phytoplankton coherence across the entire region that is not evident in analyses of bulk pigment or microphytoplankton alone.

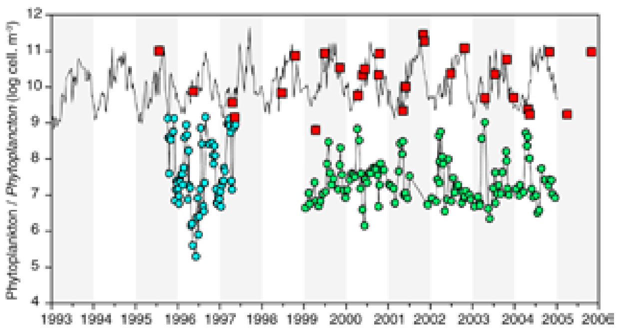

Fig. 1 Phytoplankton abundance in Bedford Basin and Halifax Station 2 (HL2). Measurements were made by flow cytometry (Bedford Basin = continuous line; HL2 = red squares) and by light microscopy (Bedford Basin = blue circles; HL2 = green circles).

Abondance du phytoplancton dans le bassin de Bedford et à la station 2 du transect de Halifax. (HL2). Les mesures ont été effectuées par flux cytométrie (bassin de Bedford = ligne continue; HL2 = carrés rouges) et par microscopie optique (bassin de Bedford = cercles bleus; HL2 = cercles verts).

Phytoplankton is monitored in three regions of the Canadian Atlantic zone using sampling and flow cytometric techniques described elsewhere (Li and Harrison 2001). Bedford Basin is the inner portion of Halifax Harbour and has been sampled once every week since 1992 at the Compass Buoy station (Li and Dickie 2001). The Scotian Shelf has been sampled once every spring (April or May) and every fall (October) since 1997 along a western section (Browns Bank Line, BBL), a central section (Halifax Line, HL), and an eastern section (Louisbourg Line, LL), all normal to the coast and each comprising seven stations (Therriault et al. 1998). At station 2 of the Halifax Line (HL2), there is supplementary sampling once every two weeks in order to delineate higher frequency events. The Labrador Sea has been sampled every spring or early summer (May-July) since 1994 along the AR7W transect (Lazier et al. 2002). Ice conditions permitting, 28 stations are sampled starting from Hamilton Bank on the Labrador Shelf (LS), through the central Labrador Basin (LB), ending at Cape Desolation on the Greenland Shelf (GS).

The 52-week cycle of phytoplankton in Bedford Basin is consistent from year to year (Fig. 1). Although week-to-week variations are large, the climatological cycle indicates a direct progression from the winter minimum on week 6 to the maximum on week 37, which is near the autumnal equinox (Li and Dickie 2001). A short series of microphytoplankton counts from fall 1995 to spring 1997 (Fig. 1) indicates diatom and dinoflagellate blooms (Li et al. 1998). The mean abundance of microphytoplankton is 2.5 x 10^{8} cells m^{-3} and that of the other phytoplankton is 2.5 x 10^{10} cells m^{-3}: a ratio of exactly 1 to 100.

At HL2, the record of phytoplankton counts by flow cytometry is much less complete, but available observations appear to correspond well to those in Bedford Basin (Fig. 1). The semi-monthly microscope counts of microphytoplankton at HL2 establish a continuous time series since 1999 (Fig. 1); HL2 is characterized by intense diatom blooms in spring. The mean abundance of microphytoplankton at HL2 is 7.0 x 10^{7} cells m^{-3}, which is about 700 fold less than the mean abundance of other phytoplankton.

Over the entire Scotian Shelf, the semi-annual counts of phytoplankton at HL, BBL and LL all show cross-shelf 7-station average values that are low in spring and high in fall, with concentrations not greatly different from those in Bedford Basin at the given times of the year (Fig. 2). In the Labrador Sea (Fig. 3), the 12-station average phytoplankton abundance in LB and the 10-station average in LS also show convincing agreement with the Bedford Basin time series. The 5-station average in GS was less well matched.

A consolidation of the data viewed as a 366-day cycle (Fig. 4a) emphasizes the general coherence of phytoplankton seasonality at virtually all the monitoring sites. The low bias in the GS values is clearly evident here. There may be a delay of about a month in the peak of phytoplankton on the shelves and open ocean compared to the inshore, but this cannot be confirmed until the former are sampled during the autumnal equinox.

In the Western Isles region of the Bay of Fundy, counts of phytoplankton were made by flow cytometry in the summer and fall of 2001 (Li et al. 2002). The developmental progression of

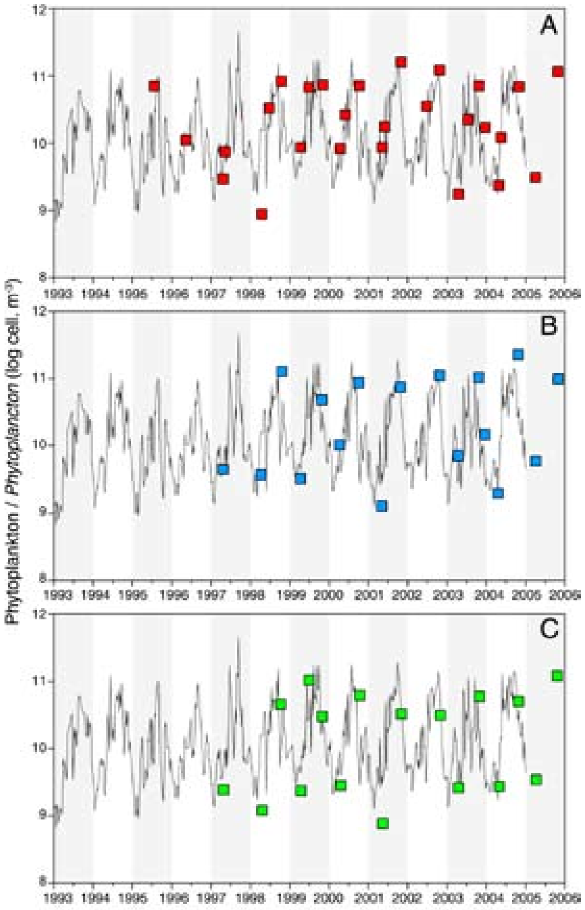

Fig. 2 Phytoplankton abundance in surface waters of Bedford Basin (continuous line) and the Scotian Shelf (coloured symbols) on the (a) Halifax Line, (b) Browns Bank Line, (c) Louisbourg Line. The Bedford Basin time series was constructed from weekly samples taken at 5 m depth. On each Scotian Shelf section, the values represent an integrated sample (average of 0, 5, 10 m) averaged over seven stations distributed along the different lines.

Abondance du phytoplancton dans les eaux de surface du bassin de Bedford (ligne continue) et du plateau Néo-Écossais (symboles colorés) le long du transect de Halifax (a), du transect de Browns Bank (b) et de celui de Louisbourg (c). La série temporelle de données pour le bassin de Bedford a été construite à partir des échantillons récoltés hebdomadairement à une profondeur de 5 m. Pour chaque transect du plateau Néo-Écossais, les valeurs utilisés représentent une intégration moyenne des échantillons (moyenne de 0, 5 et 10 m) provenant de 7 stations situées le long du transect.

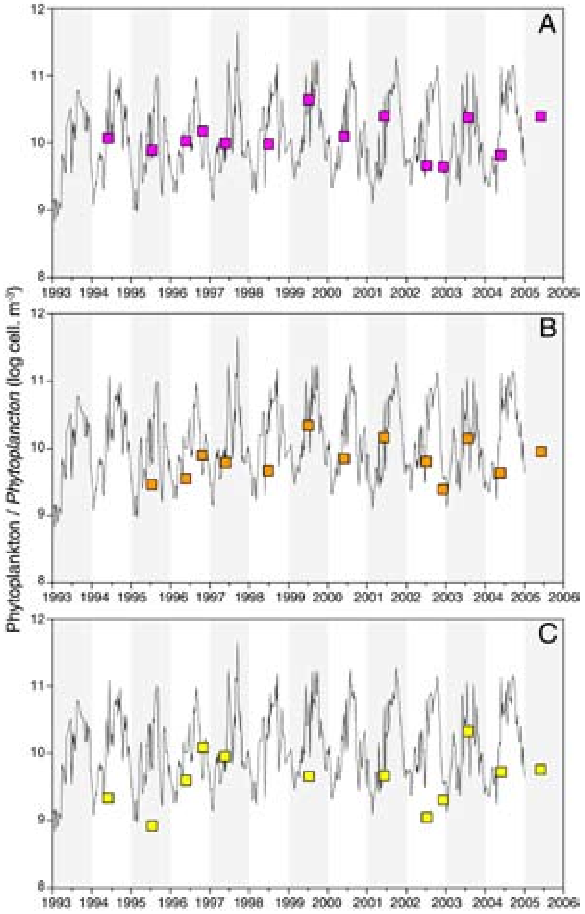

Fig. 3 Phytoplankton abundance in surface waters of Bedford Basin (continuous line) and the Labrador Sea (coloured symbols) in the (a) Labrador Basin, (b) Labrador Shelf and the (c) Greenland Shelf. The Bedford Basin time series was constructed from weekly samples taken at 5 m depth. In each subarctic region, the values represent integrated samples (average of 0, 5, 10 m) averaged over several stations distributed along the AR7W transect.

Abondance du phytoplancton dans les eaux de surface du bassin de Bedford (ligne continue) et de la mer du Labrador (symboles colorés) dans les régions du bassin du Labrador (a) du plateau du Labrador (b) et du plateau du Groenland (c). La série temporelle de données pour le bassin de Bedford a été construite à partir des échantillons récoltés hebdomadairement à une profondeur de 5 m. Pour chaque région subarctique, les valeurs utilisées représentent une intégration moyenne des échantillons (moyenne de 0, 5 et 10 m) provenant de plusieurs stations situées le long du transect AR7W.

phytoplankton at the five New Brunswick stations was almost perfectly matched to that in Nova Scotia (Fig. 4b). Moreover, the counts in Brandys Cove and mid Passamaquoddy Bay were almost identical to those in the Bedford Basin, which is situated much further away.

The coherence of regional phytoplankton on a seasonal basis (Figs. 2-4) appears to extend to a multi-year scale as well (Fig. 5). Here, we seek evidence for change in phytoplankton abundance on a year-to-year basis at the seasonal level. In Bedford Basin, phytoplankton in spring (average of Mar-Apr-May values) has been increasing at a rate of 6.6% y^{-1}. A similar increase (6.8% y^{-1}) is also occurring in the fall (average of Sep-Oct-Nov values). On the Scotian Shelf, the spring increase is 4.4% y^{-1} and the fall increase is 3.0% y^{-1}. In the Labrador Sea, the spring increase is 4.2% y^{-1}. It appears that phytoplankton abundance is not changing as fast on the shelves and open ocean as it is in Bedford Basin, but the statistical significance of these trends is very weak. A conclusive comparison cannot be expected until all the time series become longer. Notwithstanding uncertainties in the rate of change, it is remarkable that the direction of change is positive everywhere.

The seasonality of phytoplankton abundance (cells m^{-3}) and phytoplankton biomass (mg carbon m^{-3} or mg chlorophyll m^{-3}) are very different (Li and Dickie 2001). The former has a single peak that occurs at the autumnal equinox. The latter has two peaks: the first at the vernal equinox and the second at

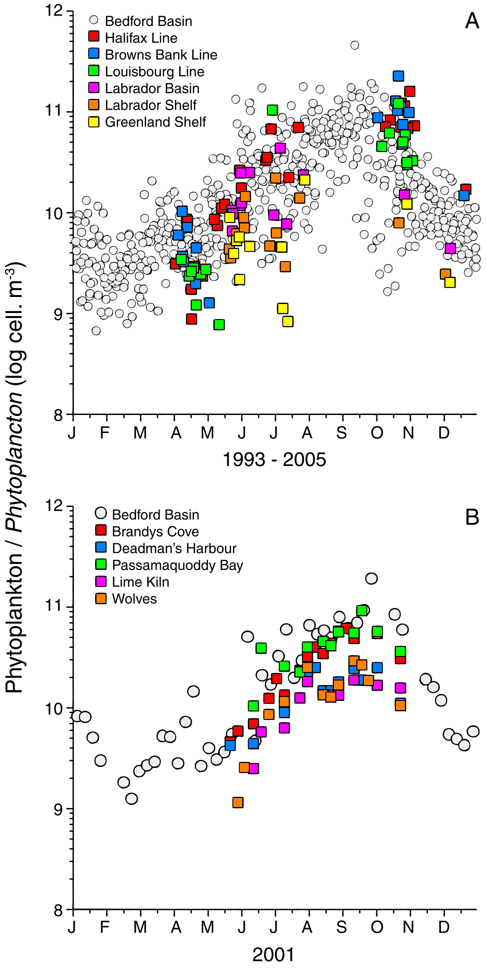

Fig. 4 (a) Annual cycle of phytoplankton in the Bedford Basin, Scotian Shelf and Labrador Sea consolidated over all years of observation and (b) phytoplankton development during 2001 in Bedford Basin and five sites in the Western Isles region of the Bay of Fundy.

(a) Cycle annuel du phytoplancton dans le bassin de Bedford, le plateau Néo-Écossais et la mer du Labrador construit à partir de toutes les années d'observation et (b) développement du phytoplancton au cours de l'année 2001 dans le bassin de Bedford et à cinq sites dans la région de Western Isles dans la baie de Fundy.

the autumnal equinox. The spring peak of biomass is due to a relatively small number of large cells (mainly diatoms), while the fall peak of biomass is due to a large number of small cells (mainly cyanobacteria and diverse eukaryotic picoplankton). In general, waters having high concentrations of chlorophyll are characterized by a relatively equitable distribution of cells across different size categories. On the other hand, waters having low concentrations of chlorophyll are heavily dominated by large numbers of small cells and contain only small numbers of large cells (Li 2002). Essentially, biomass is the product of abundance and cell mass: the macroecological inter-relationships of these three quantities may be explored in a straightforward manner (Li 2006).

Long-term change in the phytoplankton of marine ecosystems is often viewed from the perspective of biomass (e.g., Reid et al. 1998). An alternative is to view the number of reproductive entities, which is the basis for evolutionary change. In the northeast Atlantic, there is already evidence of multi-decadal change in microphytoplankton abundance (Richardson and Schoeman 2004) and phenology (Edwards and Richardson 2004) associated with climate change. Our observations in the northwest Atlantic have been carried out for a much shorter duration, and there is only a weak hint of change. However, the coherence in the seasonal development of phytoplankton cells across diverse environments (Fig. 4) and the coherence in directional change across many years (Fig. 5) suggest that organisms with short generation times (i.e., microbes) may be responding in a coherent fashion to a large-scale common forcing. Multiyear trends of chlorophyll concentration discerned from repeating annual cycles can be meaningfully interpreted in the context of climate variability (McClain et al. 2004). In other coastal oceans, a significant

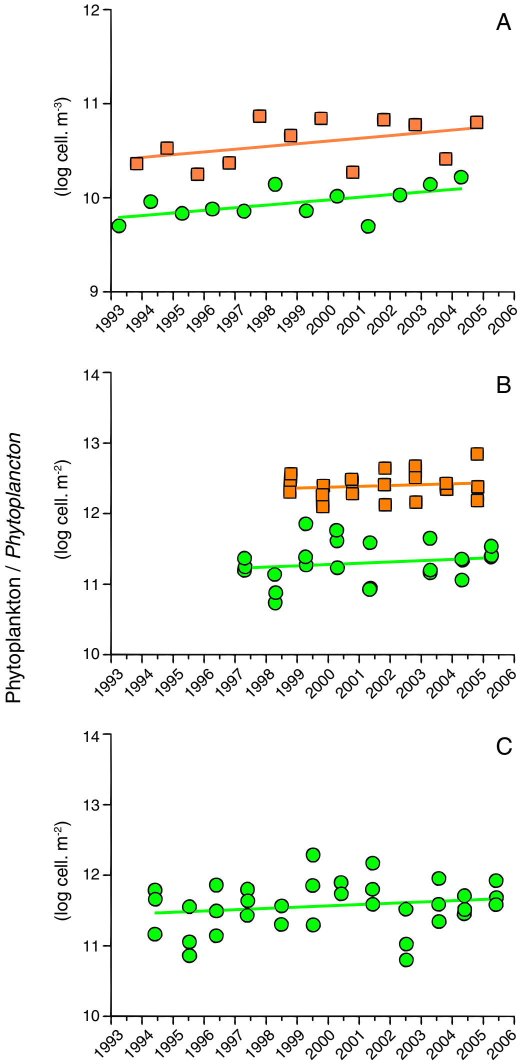

Fig. 5 Multi-year trends of phytoplankton abundance during spring (green circles) and fall (orange squares) in the (a) Bedford Basin: volumetric abundance (cells m^{-3}) at 5 m depth, (b) the Scotian Shelf: depth-integrated abundance (cells m^{-2}) from surface to 100 m at HL, BBL and LL, and (c) the Labrador Sea: depth-integrated abundance (cells m^{-2}) from surface to 100 m at LB, LS and GS.

Tendances multi-annuelles de l'abondance du phytoplancton au printemps (cercles verts) et à l'automne (carrés oranges) dans (a) le bassin de Bedford : abondance volumétrique (cellules m^{-3}) à 5 m, (b) le plateau Néo-Écossais : abondance intégrée de la surface jusqu'à 100 m (cellules m^{-2}) à HL, BBL, et LL, et (c) la mer du Labrador : abondance intégrée de la surface jusqu'à 100 m (cellules m^{-2}) à LB, LS et GS.

average increase (10% y^{-1}) in recent years has been described as a possible response to enhanced coastal upwelling or anthropogenic influences (Gregg et al. 2005).

It appears that Bedford Basin may be a useful sentinel for the regional phytoplankton response. It is sampled at a frequency twice that at which remotely sensed ocean colour is composited at BIO for regional maps, and it has a time series of considerable length. Few datasets of this nature exist, almost none of which include total phytoplankton abundance.

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MERICA-Nord Program: Monitoring and Research in the Hudson Bay Complex

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Sommaire

Le complexe de la baie d'Hudson (comprenant la baie d'Hudson, le détroit d'Hudson ainsi que le bassin de Foxe) représente probablement le plus grand estuaire nordique du monde. Cet estuaire est une composante importante du courant du Labrador qui exerce une influence prédominante sur le climat de la partie est de l'Amérique du Nord. La dynamique de circulation des masses d'eau dans cette région nordique est fortement influencée par les écoulements d'eau douce provenant notamment des bassins de drainage de la baie d'Hudson et de l'arctique. Cette région abrite près de la moitié des populations Inuits du Nunavut et du Nunavik, et est caractérisée par une forte biodiversité reflétant l'influence significative des eaux arctiques et subarctiques de l'Atlantique Nord. Cet écosystème nordique a été identifié comme un « point chaud » pour la conservation de la biodiversité marine, mais aussi comme l'une des régions les plus sensibles aux changements et à la variabilité climatique.

Afin de pouvoir détecter, comprendre, suivre et prédire les changements environnementaux dans cette région nordique, les scientifiques du MPO, région du Québec, ont initié en 2003 un programme de monitorage appelé MERICA-nord (pour études des MERs Intérieures du CAnada). Ce programme de monitorage complémente celui effectué dans la mer intérieure du golfe du Saint-Laurent (MERICA-sud). Dans sa conception, sa réalisation et son échantillonnage de base, ce programme de monitorage s'inspire du Programme de Monitorage de la Zone Atlantique. Il accommode en plus plusieurs programmes de recherche associés qui sont effectués par des partenaires tant à l'interne qu'à l'externe du MPO, comme par exemple le secteur universitaire. MERICA-nord est supporté par le Centre national d'excellence pour la recherche aquatique dans l'Arctique (N-CAARE en anglais). Un élément clé du programme est l'intégration des besoins des scientifiques avec l'expertise et la capacité de support logistique de la Garde côtière canadienne; ce programme a en effet profité jusqu'à maintenant de temps de navire offert par la Garde côtière canadienne sur une base d'opportunité. MERICA-nord permet finalement au MPO d'assumer ses obligations nationales et internationales de base en ce qui concerne l'étude des milieux marins nordiques, afin de répondre aux enjeux sociaux et globaux émergents que soulèvent l'impact de l'activité humaine (ex., les développements hydroélectriques) ou encore des changements climatiques. Dans ce contexte, l'environnement du complexe de la baie d'Hudson est encore bien peu connu.