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Recent intrusion of Labrador Shelf waters into the Gulf of St. Lawrence and its influence on the plankton community and higher trophic levels

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Abstract

Wintertime hydrographic data obtained in the Gulf of St. Lawrence (GSL) since 1996 suggest large intrusions of dense and cold surface waters from the Labrador shelf in 2001. These intrusions contributed significantly to the summertime coldness of the intermediate layer in the GSL despite relatively mild winter conditions. Several changes in the plankton community were associated with this intrusion. A major change is the first occurrence of the diatom *Neodenticula seminae* covering most of the GSL in spring 2001. This is very unusual since this diatom is usually found in the North Pacific, not in the North Atlantic. Because of its parallel occurrence on the Labrador Shelf, it is inferred that this Pacific species was introduced into the GSL via natural advection processes across the Arctic and down the Labrador Current. Other phytoplankton observations of typical Labrador shelf waters in the GSL support this hypothesis. Another important change is a highly significant increase in the abundance of the Arctic hyperiid amphipod *Themisto libellula.* Numbers increased from 0.17 ind. m^{-2} in 2000 to 10 ind. m^{-2} in September 2001. This is the most important increase in abundance of this species in the last decade. These changes in ocean circulation processes probably have a significant impact on higher trophic level interactions as suggested by an increase of the occurrence of this zooplankton species in the cod diet.

Keywords: Gulf of St Lawrence, Labrador shelf water, advection processes, *Neodenticula seminae, Themisto libellula*

Introduction

A number of recent publications have indicated that global warming has already induced significant changes in ocean circulation, particularly in the Northern latitudes. One of the possible factors that could have caused these changes is the accelerated sea-ice melting that has already been observed in Arctic and Antarctic regions. Such environmental changes probably have an important influence on trophic interactions. In this paper we present results suggesting that accelerated sea-ice melting in the high Arctic has triggered large intrusions of dense and cold surface waters from the Labrador shelf into the Gulf of St. Lawrence in 2001. These intrusions have introduced new Arctic phytoplankton and zooplankton species into the Gulf system that potentially have a significant influence on trophic interactions.

Results and Discussion

Winter time hydrographic data

Oceanic water intrusions into the Gulf of St. Lawrence (GSL) occur through Cabot Strait in the south and the Strait of Belle-Isle in the northeast (See Figs. 4 and 5). The latter is, however, a more direct route of entry for cold Arctic waters coming from the Labrador Shelf. The few current meter measurements that have been made in the Strait of Belle-Isle indicate that Arctic water inflow is more pronounced during the winter months. A yearly March survey was initiated in 1996 to study the characteristics of the water masses in the GSL during winter. Results of this survey indicate large interannual differences in the salinity and temperature characteristics of the water masses. These differences are associated with the variability of both, the local convection and the inflow of Labrador Shelf waters through the Strait of Belle-Isle.

Figure 1 shows the Temperature *vs* Salinity diagram for the observations made in 2001. Most of the Gulf waters in the surface 50-100 meters are colder than –1 ^{o}C, are concentrated close to the freezing line (red line in Fig 1), and are of salinity varying between 30.5 and 32.8. The formation mechanism of these surface waters is related to the local cooling of the surface waters, forcing convective mixing that together with wind mixing homogenizes the surface layer to a depth exceeding 100 m in some locations. When the freezing point is reached, ice formation occurs accompanied by brine rejection into the surface mixed layer which slightly increases the surface water salinity and enhance vertical mixing. However, it is difficult to distinguish waters that are formed locally in the Gulf by this process from waters that have originated from oceanic inflows into the Gulf. But some of the cold waters shown in Fig. 1 are just too saline to be formed locally in the Gulf and must be from outside origin. If an *ad hoc* cutoff salinity value of 32.35 is chosen (vertical blue line in Fig 1), it can be observed that most of the waters with this salinity are typically found at depth greater than 50-100 m and are warmer than 0 to 1 ^{o}C. It would have been impossible to bring these deep waters into contact with the atmosphere in the GSL in order to cool them down to near-freezing temperatures. Brine rejection from local sea-ice formation is also insufficient to account for the creation of near-freezing waters (to the right of the blue line) from a less saline GSL surface source. These cold surface waters with higher salinity values must have originated from the Labrador Shelf outside the GSL and have been advected into the Gulf *via* the Strait of Belle-Isle.

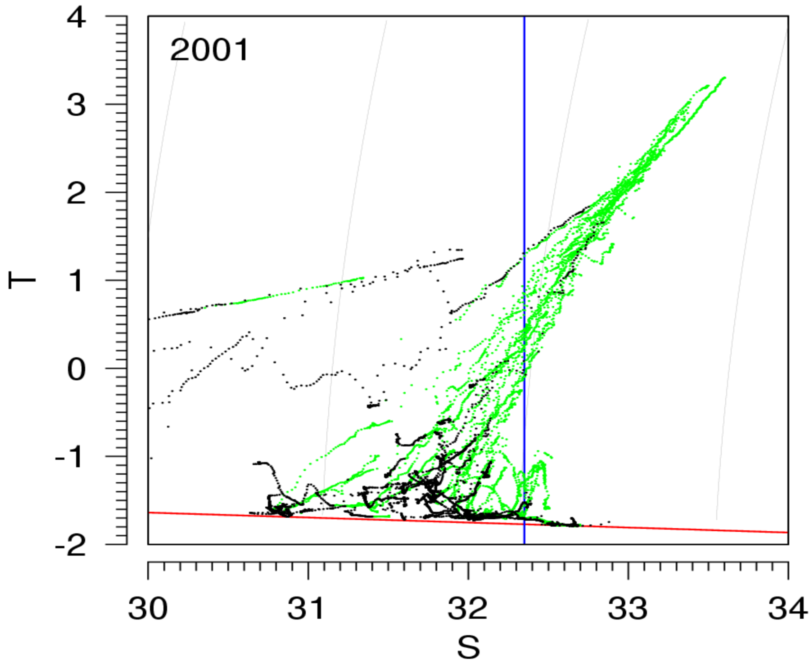

Figure 1. *Temperature-Salinity diagram for March 2001 data. The slanted red line near the bottom is the freezing line as function of salinity. The vertical blue line represents the ad hoc salinity value (32.5) beyond which waters must be from Labrador Shelf origin. Data in black comes from depths shallower than 50 m while those in green are from greater depths.*

Figure 2 shows the geographic extent of the sub-zero and more saline waters that have originated from the Labrador shelf. The percentage of these more saline waters coming from all sampled waters colder than –1 °C is also indicated in each panel. Cold water intrusions reach as high of 22% in 2001 and 2002. Prior to the winter of 2001, there was no massive intrusion of more saline Labrador Shelf waters into the GSL recorded by the March survey. There was some cold water inflow that penetrates far into the GSL in 1998, but this intrusion occurred in a 60-m thick layer at greater depths. It did not account for a large percentage of the cold waters of the GSL. A higher inflow was observed in 1999, but the geographic extent of this intrusion was mostly limited to the proximity to the strait. This percentage was also biased because there was much less cold surface waters formed locally in 1999, enhancing the relative importance of the cold water intrusion.

For yet unknown reasons, the winter dynamics in the GSL changed in 2001 and 2002 as compared to prior years going back to 1996. Figure 2 shows that higher than usual inflow of more saline Labrador shelf waters occurred for these years. When the Gulf waters restratify in the spring due to sea-ice melting and runoffs, these cold and more saline waters are denser than the locally formed cold waters and remain deeper and, therefore, are better protected from summer warming processes occurring above the pycnocline. This contributes to the formation of an important summer Cold Intermediate Layer (CIL) in the Gulf that keep its cold integrity in spite of locally warm winter conditions in the Gulf in 2001 and 2002.

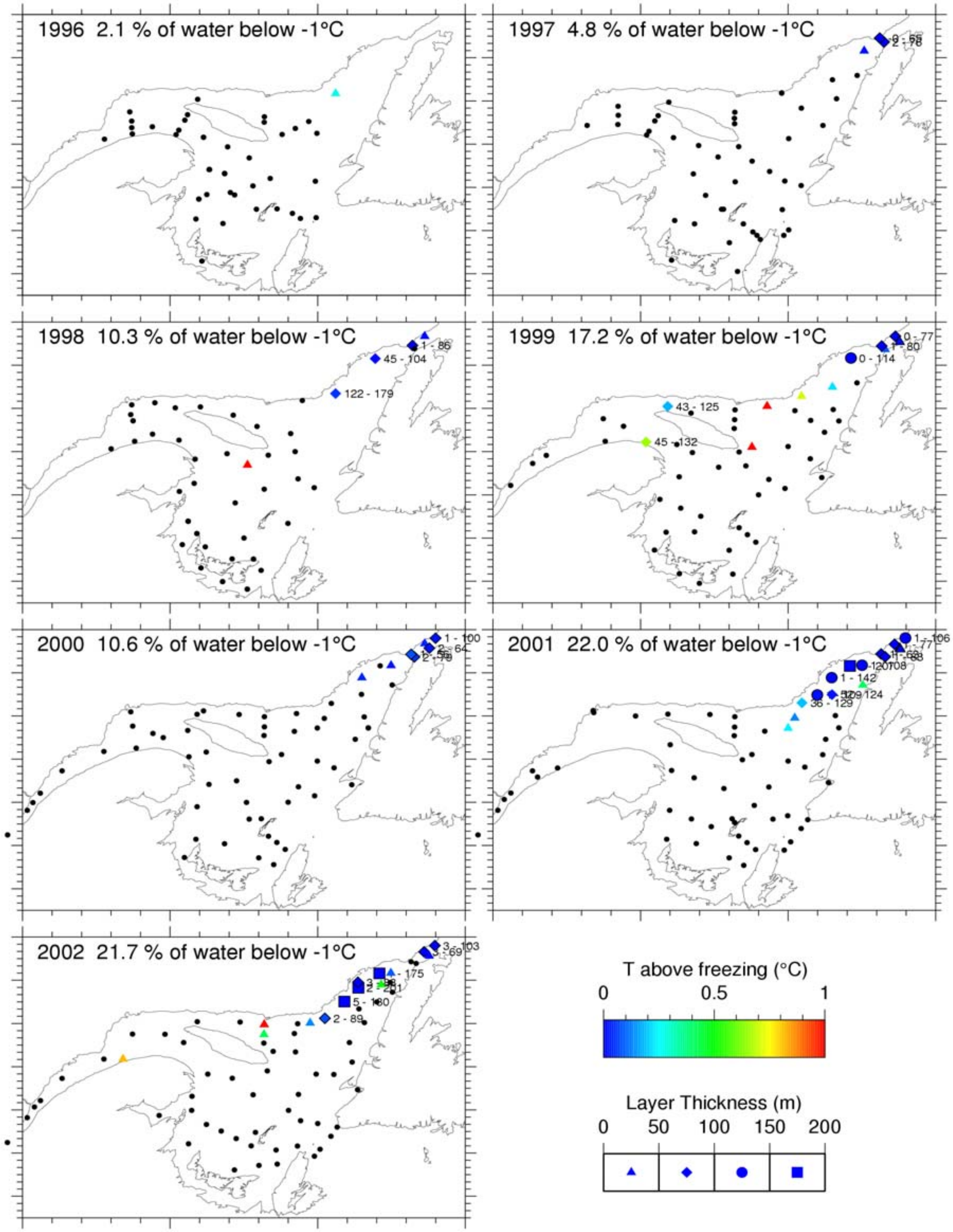

Figure 2. *Distribution of cold waters with a salinity higher than 32.35. The color indicates the temperature difference relative to the freezing point and the symbols represent the layer thickness. Black dots indicate stations where this water mass was not observed. The depth range is shown at the right of the symbols for layer thickness greater than 50 m. A black outline around a symbol indicates that the layer is ventilated at the surface. Only water layers colder than 0 °C are shown, excluding old warmer waters that are deeper in the GSL.*

Phytoplankton data

Neodenticula seminae (Fig. 3) is an important member of the modern diatom assemblage in the Bering Sea and at middle and high latitudes in the North Pacific. In the Atlantic Ocean, this species has only been recorded in Quaternary sediments of middle to high latitudes. The occurrence of *N. seminae* in the North Atlantic has principally been attributed to the presence of low salinity surface waters in the Atlantic during the early Quaternary. Here, we report, for the

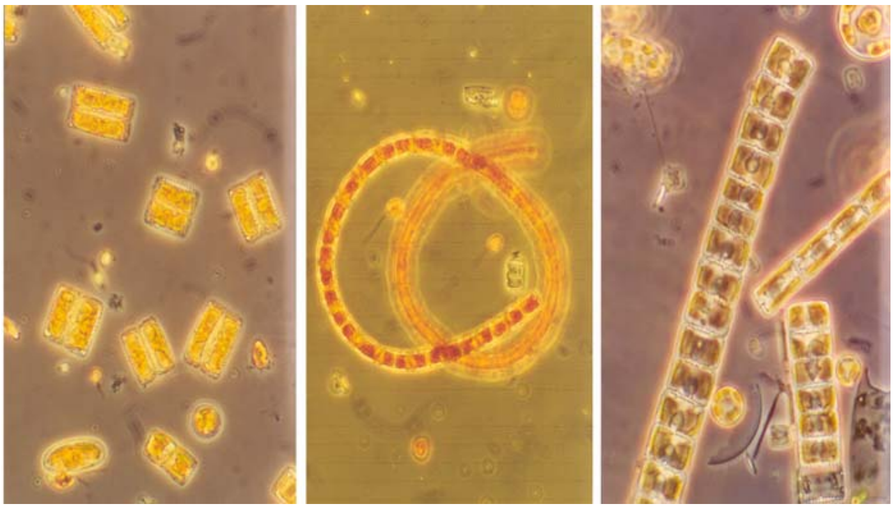

Figure 3*. Light photomicrographs of the diatom Neodenticula seminae confirming its presence in the Gulf of St. Lawrence and Labrador Slope waters, NW Atlantic. This species is a small pennate diatom that belongs to the family Bacillariaceae. It can occur solitary or in chains, sometimes quite long and curved. The frustule is rectangular with rounded corners. The cells measured from 9 – 31.5 µm in lenght (mean: 20.6) to 7 - 15 µm in width (mean : 10.2). The pseudosepta are equally spaced, 7.5 - 9.5 striae / 10 µm, and usually 2 - 4 primary pseudosepta per valve.*

first time since its total disappearance in the Atlantic, an intense spring bloom of *N. seminae* in the Atlantic coastal waters. This bloom was observed in late April 2001 and covered most areas of the Gulf of St. Lawrence with concentrations up to 1.9 x 10^6 cells l^{-1} (Fig. 4). Taxonomic identification was confirmed by several experts. Because this unusual spring bloom coincided with a massive intrusion of Labrador Slope waters into the Gulf of St. Lawrence (Figs. 2 and 5), it is believed that this Pacific species was introduced naturally into the GSL across the Arctic and down the Labrador Current, rather than via ballast waters. The observation of the occurrence of *N. seminae* in water samples from the Labrador Shelf during spring-summer 2001 supports this assertion. The return of *N. seminae* on the Atlantic coast coincides with recent changes in the circulation and oceanographic conditions (e.g., increased sea-ice melting) in the Arctic Ocean, including a greater influx of Pacific waters into the North Atlantic and the freshening of the Arctic and sub-polar North Atlantic waters (Dickson B., 1999).

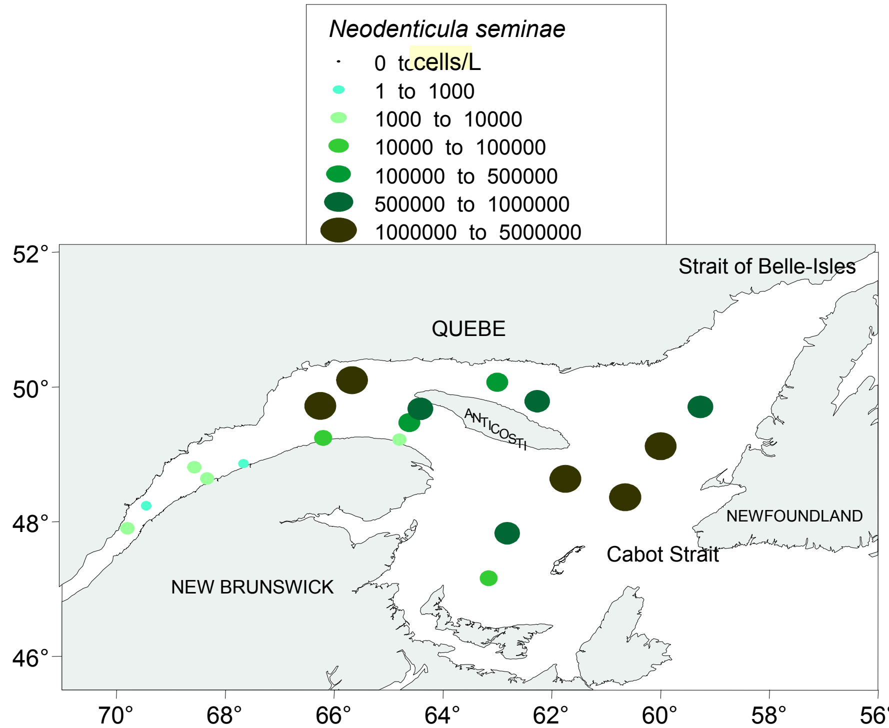

Figure 4. *Abundance of the diatom Neodenticula seminae in late April 2001 in the surface waters of the Estuary and Gulf of St. Lawrence, Eastern Canada. The highest abundances were recorded at stations over the Laurentian and Esquiman channels, where it represented between 64 and 91% of the total number of diatoms. Accompanying species included Corethron hystrix and Membraneis challengeri along with more common species such as Chaetoceros spp., Eucampia groenlandica, Fragilariopsis spp., Leptocylindrus spp., Thalassiosira spp., and many flagellates and choanoflagellates.*

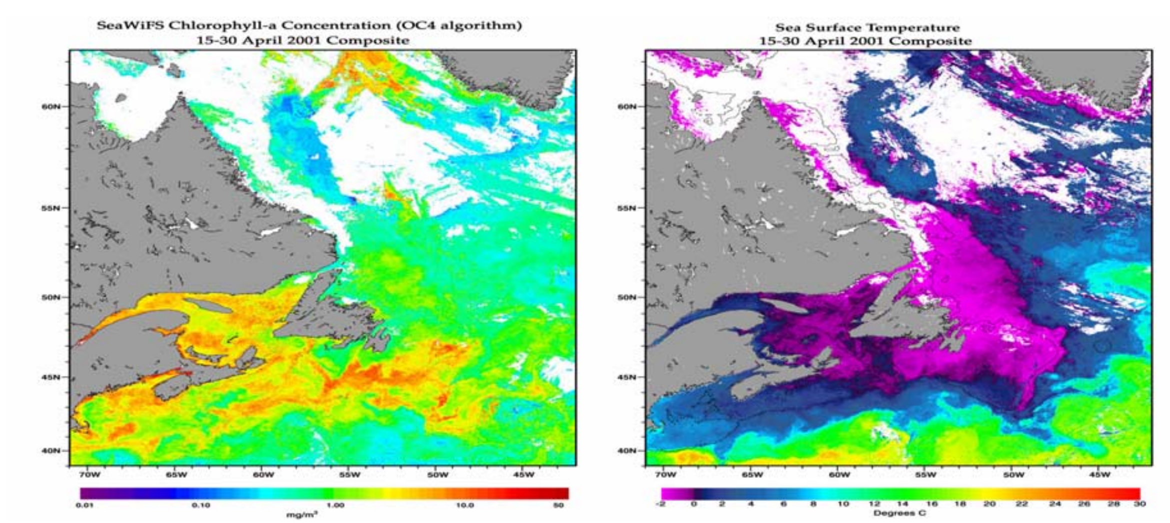

Figure 5. *SeaWiFS composite images showing the distribution of chlorophyll and temperature in the NW Atlantic for the period 15-30 April 2001. This figure supports field observations indicating a massive intrusion of cold Labrador Slope waters into the Gulf of St. Lawrence at the same time that we observed the bloom of Neodenticula seminae. (Composite images kindly provided by G. Harrison and T. Platt from the Bedford Institute of Oceanography).*

Zooplankton data

An annual zooplankton survey was also initiated in 1994 to follow the variability of the zooplankton abundance and biomass in the Lower St. Lawrence Estuary and the Northwest Gulf of St. Lawrence. This survey is conducted in September and involves sampling with a 1 m^2 BIONESS plankton net equipped with nets 333-µm mesh size at 44 stations along eight transects covering the Lower Estuary and the Northwest Gulf of St. Lawrence from Les Escoumins to Sept-Îles (Figure 6).

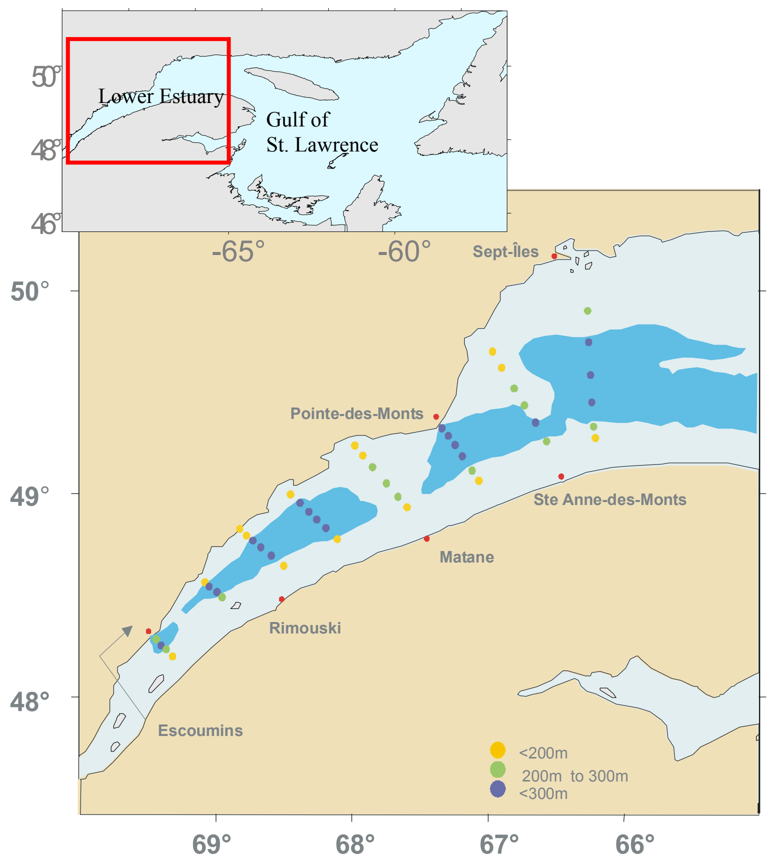

Figure 6. Map showing the station locations of the annual zooplankton survey in the Lower St. Lawrence Estuary and the Northwest Gulf of St. Lawrence.

Samples were analyzed to determine wet weight, species composition, size and abundance of the macro- (adult size > 1 cm) and mesoplankton (adult size < 1 cm). Integrated biomass and abundance for the water column were then calculated by multiplying the standardized wet weight and abundance by the depth interval sampled.

Figure 7 shows that the integrated macro- and mesoplankton abundances did not vary significantly from 1995 to 2001. However, this figure also indicates that the relative abundance the three most important macrozooplankton groups (euphausiids, mysids and hyperiid amphipods) in terms of biomass were showing much more interannual variations in the Lower St. Lawrence Estuary and in the Nortwest Gulf of St. Lawrence.

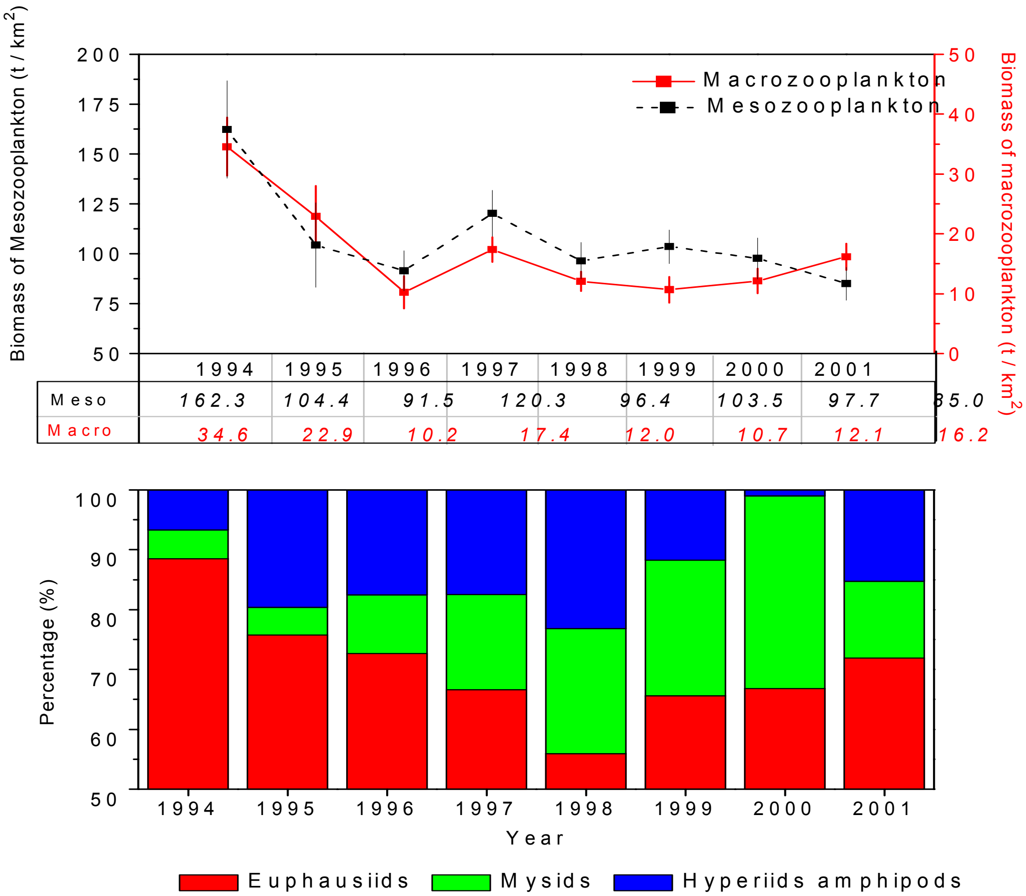

Figure 7. *Mean biomass of meso- and macrozooplankton in the Lower St. Lawrence Estuary and the Northwest Gulf of St. Lawrence from 1994 to 2001 (upper panel) and relative abundance the three most important macrozooplankton groups in terms of biomass (lower panel).*

The most prominent feature of the mean annual abundance of the various macrozooplankton species in 2001 (Fig. 8) was a highly significant increase in the abundance of the Arctic hyperiid amphipod *Themisto libellula* (from 0.17 ind. per m^2 in 2000 to 10 ind. per m^2 in 2001). This means that over 10 billions individuals per km^2 were present in 2001 as compare to 170 000 individuals per km^2 in 2000. This is the most important increase of the mean abundance of this species in the last decade. This significant increase in the mean abundance of *T. libellula* in 2001 as compared to 2000 is probably associated to an important intrusion, into the Gulf of St. Lawrence, of cold waters from the Labrador shelf via the Strait of Belle-Isle (See Figs 2 and 5). This assertion is strongly supported by the fact (1) that greater abundances of *T. libellula* are usually associated with the Cold Intermediate Layer in the Lower Estuary and Northwest Gulf as indicated by the observation of a significant negative relationship (R^2 = 0.72) between the annual CIL core temperature index and the mean annual abundance of T. *libellula* sampled since 1994 (Fig. 9), and (2) that *T. libellula* distributed over the whole sampling area were all adult, implying that these individuals could not have hatched in the Estuary and the Gulf of St. Lawrence during the previous summer because they were all older than one year old (Percy 1993) and also because they were not particularly abundant in September 2000 (mean abundance 0.17 ind. m^{-2}).

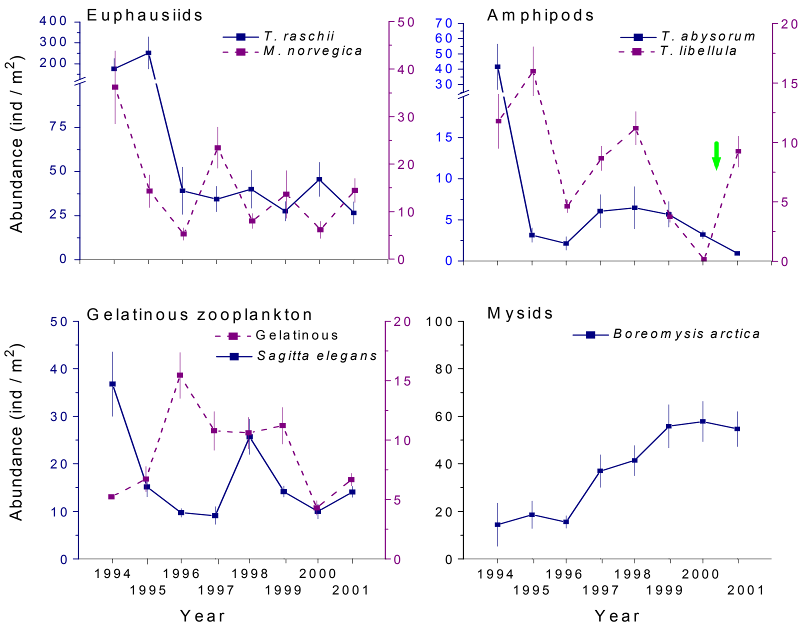

***Figure 8**. Mean abundance of the most important species of macrozooplankton in the Lower St. Lawrence Estuary and the Northwest Gulf of St. Lawrence from 1994 to 2001.*

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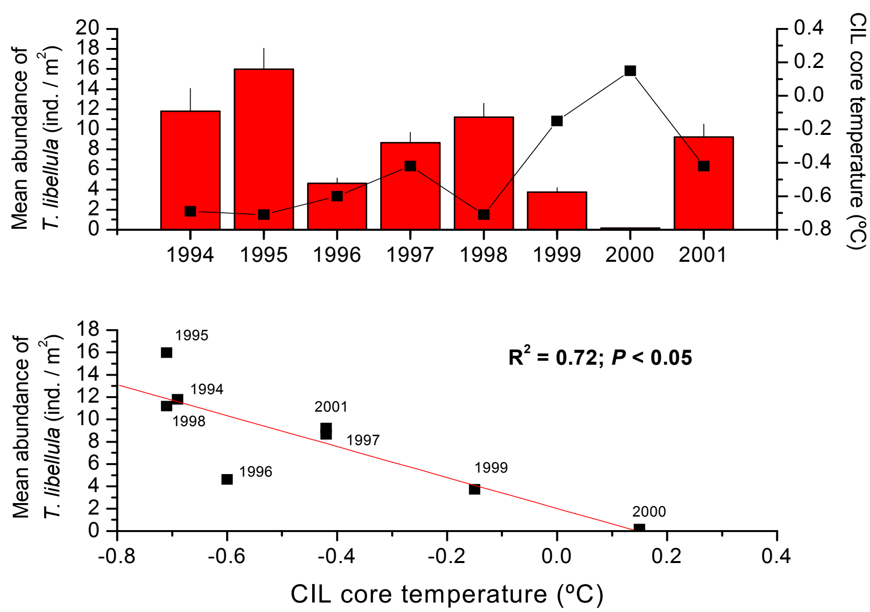

***Figure 9.** Relationships between the annual CIL core temperarure index and the annual mean abundance of the hyperiid amphipod Themisto libellula in the Lower St. Lawrence Estuary and the Northwest Gulf of St. Lawrence from 1994 to 2001.*

Trophic interactions

Based on the hydrographic and biological data presented above, it seems evident that an important intrusion of cold waters into the Gulf of St. Lawrence, via the Strait of Belle-Isle, occurred in 2001. This cold water mass, originating from the Labrador Shelf, contained an important biomass of imported Arctic phytoplankton and zooplankton species that has surely influenced the trophic interactions in the Gulf. For example, an early phytoplankton bloom of the magnitude and extent shown in Fig. 5 certainly has a significant influence on the carbon and nutrient cycle/budget in the GSL. On the other hand, the hyperiid amphipod *Themisto libellula* is a very efficient predator species and, consequently, the episodic invasions of this species in the Gulf of St. Lawrence and the Lower Estuary probably has a significant impact on the zooplankton standing stock through direct predation or via the survival and recruitment of fish larvae, or else, through direct competition with fish larvae for copepod preys. We also observed, between 1994 and 2001, a highly significant positive correlation between the abundance of *Themisto libellula* sampled in the in the Lower Estuary and the Northwest Gulf of St. Lawrence and their relative abundance in cod stomachs (Fig. 10). This suggests that cod eat *T. libellula* in proportion to its availability in the field. The impact on cod growth and productivity remain to be studied.

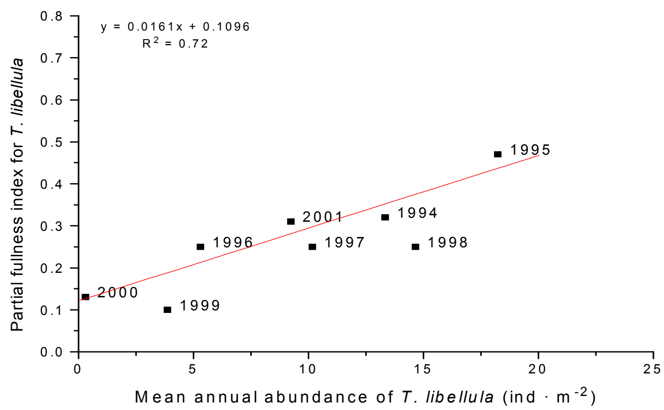

Figure 10. *Relationship between the mean abundance of Themisto libellula sampled between 1994 and 2001 and their relative abundance in cod stomachs*

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