SPATIO-TEMPORAL VARIABILITY OF PHYTOPLANKTON PIGMENTS IN THE GULF OF ST. LAWRENCE AS MEASURED BY CZCS

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ABSTRACT

This study examined surface phytoplankton pigments distribution (chlorophyll *a* plus phaeophytin) in the Gulf of St. Lawrence (GSL), Canada using eighty Coastal Zone Color Scanner (CZCS) images taken between April and September from 1979 to 1981. The results generally agree with historical knowledge of phytoplankton pigment distribution in the gulf obtained using traditional shipboard methods. However, the CZCS imagery allowed better identification of both temporal (seasonal and interannual) and spatial (mesoscale) pigment patterns. The results suggest that the seasonal cycle appears to be dominated by increases in pigment concentration in late summer-early fall. Finaly, the results also indicate that interannual variations in pigment concentration may exceed those observed on an seasonal scale.

RÉSUMÉ

Cette étude examine la distribution des pigments phytoplanctoniques (chlorophylle *a* plus pheophytine) dans le Golfe du saint-Laurent à l'aide de quatre-vingt images du capteur Coastal Zone Color Scanner (CZCS) captées entre le mois d'avril et septembre des années 1979 à 1981. Les résultats concordent généralement avec la connaissance de la distribution du phytoplancton obtenue à l'aide des techniques d'échantillonnage traditionnelles. Les images CZCS ont toutefois permis de mieux identifier les patrons de distribution temporels (saisonniers et interannuels) et spatiaux (méso-échalle). Les résultats suggèrent que le cycle saisonnier est dominé par une augmentation de la concentration des pigments chlorophylliens à l'automne. Finallement, les résultats indiquent aussi que la variation inter-annuelle de la concentration des pigments puisse excéder la variabilité saisonnière.

1. INTRODUCTION

Due to its large scale and because the seasonal phytoplankton cycle is influenced by the local oceanographic (circulation, stratification, runoff, ice) and meteorological (wind, radiation, temperature) characteristics as well as by the availability of nutrients, the Gulf of St. Lawrence (GSL) located in eastern Canada cannot be considered a homogeneous ecosystem. Knowledge of phytoplankton pigments and primary production gathered over the years during oceanographic cruises shows broad patterns of spatio-temporal variability to exists in the GSL. The recent problems encountered with eastern Canadian fish stocks emphasized the need for long-term time series of primary production in the GSL. Due to the existing spatio-temporal variability of its driving physical forces, it is however almost impossible to devise a monitoring system of primary production over the entire GSL using traditional oceanographic methods of sampling. Other approaches were thus sought to better evaluate this important parameter of the ecosystem. In the light of previous results obtained using CZCS data and the future availability of new ocean color sensors (SeaWiFS, OCTS, MODIS), a research program was builded to evaluate primary production in the GSL using remote sensing techniques. As a first step of this program, it was decided to analyze the historical CZCS data set in order to gain some insight of the large scale physical-biological interactions occuring in the GSL ecosystem.

Several particularities make the GSL a complex optical medium for the retrieval of phytoplankton pigments using remote sensing. First, regional and local atmospheric conditions cause dynamic interactions between marine and terrestrial aerosols. Second, the basin receives the enormous output from the St. Lawrence river, including organic and inorganic matter which affects the remote sensing of phytoplankton pigments (Case II waters). Finally, diverse phytoplankton communities also contribute differently to the water leaving radiances. In particular, the GSL is known for its sporadic occurences of coccolithophores blooms.

The objectives of this paper are thus to use CZCS imagery to estimate the concentrations of the major photosynthetic pigment (chlorophyll *a* plus phaeophytin) in the GSL and to characterize their spatio-temporal distribution. This study is the first to provide a synoptic view of phytoplankton pigments in the whole Gulf of St. Lawrence using remote sensing data.

2. METHODOLOGY

Study area

The GSL system (Figure 1) is a semi-enclosed sea of about 200 000 km^2, located between 45-52 °N and 56-70 °W. It is connected with the Atlantic Ocean through Cabot Strait (104 km wide and 480 m deep), and Belle-Isle Strait (16 km wide and 60 m deep). The bathymetry of the gulf is dominated by the Laurentian Channel (350 m), running from Cabot Strait to the Saguenay River with a branch toward the northeast. The southern part of the gulf is a large shallow area of average depth 50 m. Due to a large annual freshwater input of about 424 km^3 (Bugden *et al*, 1982), most of which (75%) originating from the St. Lawrence River system, circulation of the GSL waters is basically density-driven and the water column in the gulf is vertically stratified into three layers during the summer.

Image analysis

Surface phytoplankton pigments (chlorophyll *a* plus phaeophytin) in the GSL were evaluated using a set of 80 CZCS images taken between March and September during the first three years of the satellite life (1979-1981). Only these years were considered because the sensor was affected by erratic loss of sensitivity afterward (Evans and Gordon, 1994). Radiometric corrections were done using the sensor sensitivity reduction correction factors of Gordon *et al.* (1983*b*) and the calibration coefficients provided by Williams *et al.* (1985). Clouds and land were masked using the Ekstein and Simpson (1991*a*) method, while pixels contaminated by signal overflow were detected with the Mueller (1988) procedure. Only gain 1 and 2 images were used in this study because higher gains generated problems related to molecular spread correction. The molecular scattering (Rayleigh) was evaluated using a single scattering model (Gordon *et al.*, 1983*a*), on the basis that single-Rayleigh scattering is comparable to the multiple-Rayleigh scattering method (Simpson, 1993). However, the single scattering model was modified using an extraterrestrial solar radiance coefficient (Ekstein and Simpson, 1991*b*) and an ozone optical depth value (Sturm, 1981).

Aerosol subtraction was done using an interactive removal technique (Arnone and LaViolette, 1984). This approach was selected because many problems prevented the use of the clear water pixel method in the GSL. It allows the operator to select the optimum Angström coefficient for each of the first three CZCS channels. After the atmospheric corrections were completed, the phytoplankton pigments were calculated using the algorithm proposed by Gordon *et al.* (1983*a*).

Sediment contaminated waters were detected by transforming the reflectances at 443, 520 and 550 nm into a IHS image. Spectral signatures of sediment contaminated waters were then calculated in this new color space and used to filter the images using a supervised classification method.

The images were then geometrically corrected by using the georeferenced data included in the CZCS raw data to produce a first approximation correction which was then fine-tuned by rectifying the images on a stereographic projection using the World Data Bank Feature Codes. The nearest-neighbour method was used as the resampling scheme to avoid distorting the pixel's pigment content.

Finally, the mean pigment value of overlaping pixels free from clouds, overflow, and suspended matter from each geometrically corrected image was calculated. Seasonal analysis was based on bi-monthly groups: April-May, June-July, and August-September, (hereafter refered to spring, summer, and fall). Interannual variability was evaluated using the mean of all the available images for each of the three years.

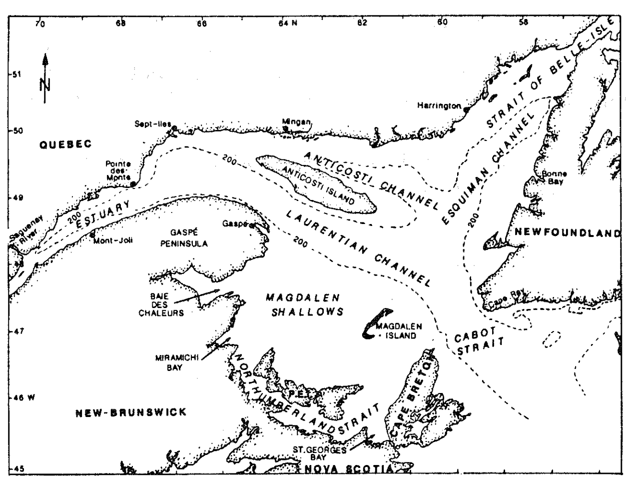

Figure 1. The St. Lawrence Gulf (from de Lafontaine *et al.*, 1991)

Data validation

The scarcity of available *in situ* measurements simultaneous with the CZCS images made the data validation process difficult. Using all the known available data, the mean chlorophyll *a* plus phaeophytin values for the top fifth of the euphotic layer was calculated to compare with evaluated pigment values from the satellite images (Morel and Berthon, 1989). Results of the linear regression showed that the two data sets were highly correlated with a r^2 of 0.89. Moreover, the spatial pattern of *in situ* values in the northeastern gulf between 20 and 28 May 1981 corresponds closely with two images taken during that time frame bringing further confidence in the selected atmospheric correction process.

Variability of underwater signal contamination

The IHS analysis showed that the areas contaminated principally by suspended matter in the lower St. Lawrence estuary (LSLE) and western GSL or by coccoliths in the eastern GSL were relatively small and well defined in time and space. They also appeared to covary positively with the temporal pigment averages. The pigment concentrations estimated by the selected approach should thus be reasonably accurate for most of the times and areas covered by the database.

3. RESULTS AND DISCUSSION

In this paper, a powerful and useful remote sensing tool was used to measure phytoplankton pigment concentrations in the GSL and build the first complete data set of satellite images showing the pigment distribution in the GSL (Fuentes-Yaco *et al.*, 1995). This data set will be now analyzed to evaluate both the spatial and temporal variability of phytoplankton pigments in the GSL.

Spatial patterns

The major spatial feature seen in the seasonal (Fig. 2) and annual (Fig. 3) composites is the persistent west to east gradient between the LSLE, the northwest gulf and the central-eastern gulf regions. This global distribution of pigments in the GSL is closely linked to major dynamical features known to exist. The LSLE, Gaspé Current, and northwestern gulf exhibited the highest concentrations of chlorophyll-like pigments throughout the year due to the presence of gyres and wind-induced upwellings. In this regard, these areas may be considered as pigment pumps, helping to increase concentration in the central and southern regions (Magdalen Shallows) by advection through the Honguedo Strait. In shallower areas such as Baie des Chaleurs and the Magdalen Islands, other factors, including wind stress, contribute to the increase in pigment concentrations through vertical mixing and local nutrient enrichment. Downwelling processes in the northeastern GSL appear to be responsible for the low surface pigment concentrations usually found throughout the year in this region. However, some limited production was detected in northern Esquiman Channel, which may be linked to wind-driven upwelling.

Seasonal variability

The calculated seasonal pigment composites (Fig.2) showed high pigment concentrations in spring and low ones in summer (Table 1). However, the results also indicated that the highest pigment concentrations occurred during fall, which has not been reported previously. The observed seasonal cycle of chlorophyll-like pigments is characterized mostly by changes in the areal extent of high pigment values rather than in a general large-scale rise and fall in concentrations. These areas extend far eastward during August and September and cover even larger areas than during spring.

Table 1. Statistics (mean and standard error) of phytoplankton pigment concentration (mg m^{-3}), by season and year.

Region	Statistic	Annual means			Seasonal means			
		Spring	Summer	Fall	1979	1980	1981	Average
LSLE	mean	1.3	1.4	1.4	1.4	1.6	1.2	1.4
	SE	0.2	0.2	0.2	0.3	0.2	0.2	0.1
GSL	mean	0.6	0.6	0.8	0.6	0.8	0.5	0.6
	SE	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Interannual variability

Yearly means showed that 1980 had the highest phytoplankton pigment concentrations of the three years studied (Table 1), with the area of strong pigment concentration in the western GSL extending from the LSLE to Northumberland Strait (Figure 3). During that year, high pigment values were also observed along the northern shore of the GSL and around the Magdalen Islands. The year 1979 was characterized by intermediate mean values, with the areal pigment distribution being close to the three-year average. Finally, 1981 seemed to have the lowest concentrations of the three years. However, the northwestern Esquiman Channel showed elevated and persistent pigment concentrations in 1981.

The observed temporal variations of the spatial chlorophyll patterns parallel to some extent the differences in salinity as influenced by estuary runoff (Bugden *et al.*

1982). Other regions with high pigment concentrations can also be associated with known areas of upwelling, or areas influenced by intense tidal mixing (mouth of the Saguenay River, the western part of Jacques-Cartier Strait, Northumberland and Belle-Isle straits, and the Magdalen Shallows). Therefore, interannual changes in freshwater output and wind forcing are the most likely factors governing the observed variability.

4. CONCLUSION

Remote sensing using the CZCS has allowed us to make important new observations regarding phytoplankton distribution in the GSL, including the presence of an automnal bloom that has not been previously described. In addition, our study suggests that interannual variations in the concentration and distribution of pigment biomass could be higher than seasonal changes. The mean pigment concentration in the GSL was 25% higher in 1980 than in 1979 and 38% than in 1981. The area covered by high pigment concentration was also greater during 1980. Knowledge gained during this project, using a limited number of images, will be much more valuable when long time series measurements become available from the SeaWiFS and MODIS sensors.

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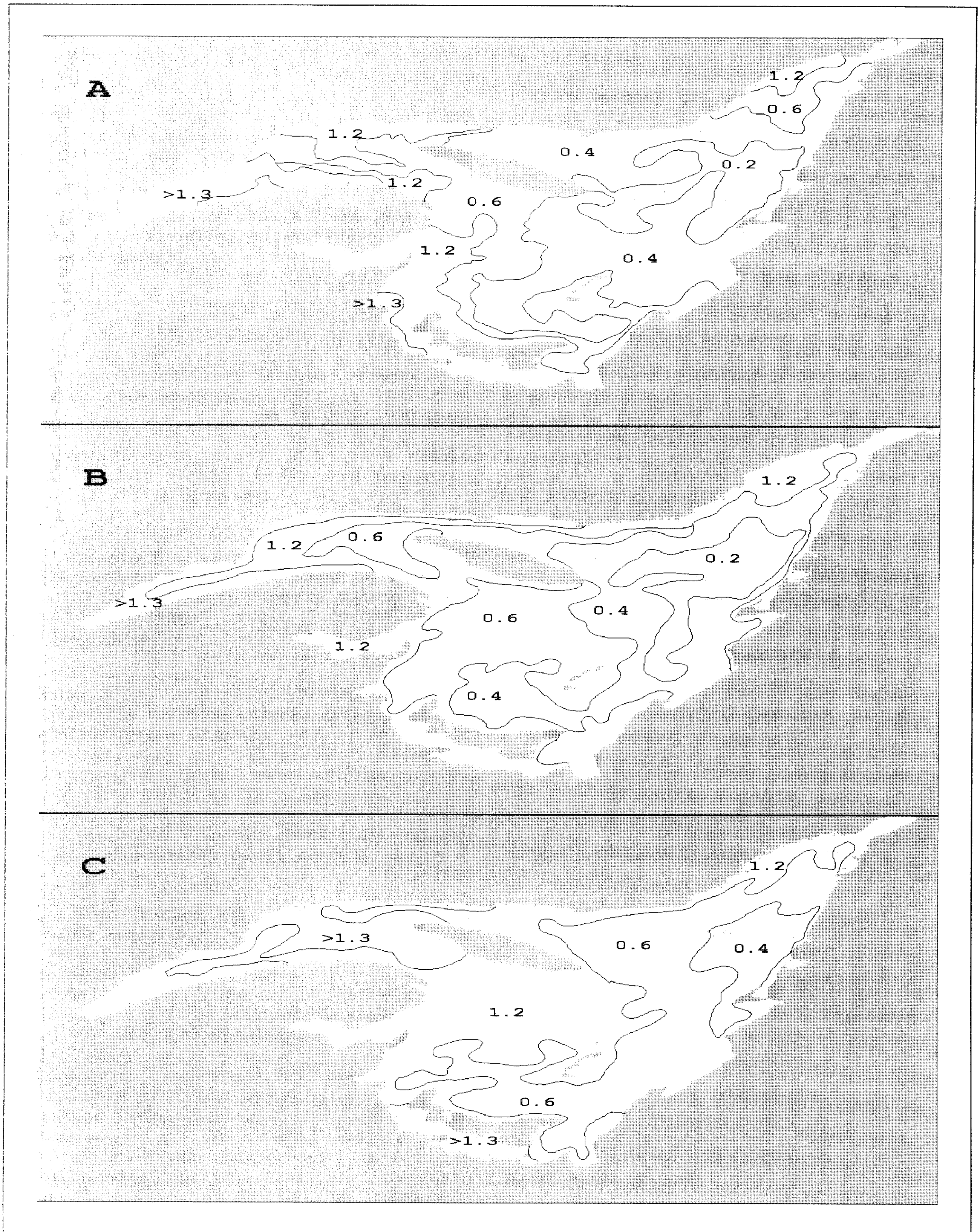

Figure 2. Seasonal means of chlorophyll-like pigments in the Gulf of St. Lawrence: a) spring (April-May); b) summer (June-July); c) fall (August-Septembre). Chlorophyll concentrations are in mg m^{-3}.

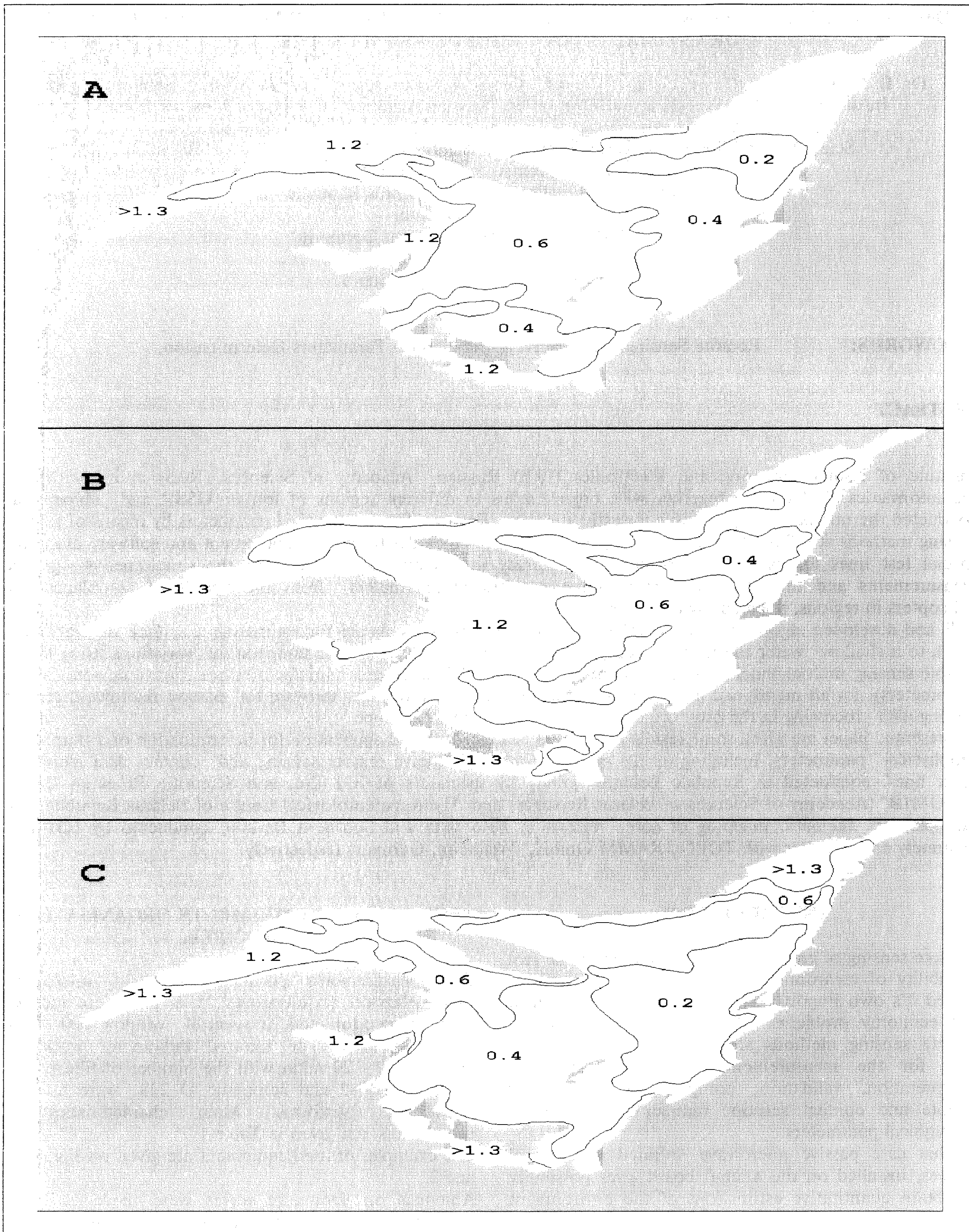

Figure 3. Annual means of chlorophyll-like pigments in the Gulf of St. Lawrence: a) 1979; b) 1980; c) 1981. Chlorophyll concentrations are in mg m^{-3}.