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Mapping areas of high phytoplankton biomass in the offshore component of the Scotian Shelf Bioregion: A remotely-sensed approach

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The main purpose of this document is to identify phytoplankton-rich areas in the Scotian Shelf Bioregion, designated as areas of persistent elevated chlorophyll concentration detected by remote sensing. Regions that contain comparatively higher biomass than surrounding areas are considered Ecologically and Biologically Significant Areas under the Fisheries and Oceans Canada (DFO) Aggregation criterion and possibly the Convention on Biological Diversity Biological Productivity criterion, so they can be considered in Marine Protected Area network development for the Scotian Shelf Bioregion (DFO 2014). The study area was subdivided based on physical and biological conditions; it comprises the mid- and outer-Scotian Shelf separated into western, central and eastern sub-areas, together with the slope, rise and abyssal plain which integrate the off-shore region. MODIS-Aqua weekly composites of chlorophyll at 1.5 km spatial resolution for the time period 2003 to 2013 were processed at the Remote Sensing Unit of the Bedford Institute of Oceanography. Climatology composites for each of the forty-eight weeks from January to December were the main source of data (a forty-eight week convention has been used for analytical purposes). Maps of high and persistent phytoplankton biomass regions were produced at annual and seasonal temporal resolution; frequency histograms of the number of pixels in decile classes of persistent elevated chlorophyll concentrations complete the description of results. The results distinguish between different zones on the mid- and outer-Scotian Shelf, where traditional fisheries are located. The outward open-water region (rise and slope) stands out as an environment recurrently inhabited by large pelagic fishes and mammals, such as tuna and whales.

Cartographie des zones de biomasse phytoplanctonique élevée dans la composante hauturière de la biorégion du plateau néo-écossais : une approche par télédétection

RÉSUMÉ

L'objectif principal de ce document est d'identifier des zones riches en phytoplancton dans la bio-région du plateau néo-écossais représentées par la concentration élevée et persistante en chlorophylle mesurée par télédétection. Des régions ayant la biomasse comparativement plus élevée que les régions avoisinantes sont considérées comme zones d'importance écologique et biologique sous le critère de l'agrégation du Pêches et Océans Canada (MPO) et, éventuellement, le critère de productivité biologique de la Convention de la diversité biologique, donc elles peuvent être considérées dans le développement du réseau de zones de protection marine dans la bio-région de plateau néo-écossais (DFO 2014). La région étudiée a été subdivisée en fonction des conditions physiques et biologiques; elle comprend le secteur du milieu - et externe du plateau néo-écossais séparé en sous-régions occidentale, centrale et orientale; ainsi que la pente, la montée et la plaine abyssale qui intègrent la région de haute mer. Des images composites climatologiques pour chacune des quarante-huit semaines de janvier à décembre ont été la principale source de données. Des cartes des régions de la biomasse phytoplanctonique élevée et persistante ont été produites pour des périodes annuelle et saisonnière; des histogrammes de fréquence du nombre de pixels classés en déciles de ces concentrations de chlorophylle complètent la description des résultats. Ces résultats font une distinction entre les différentes zones du milieu - et externe du plateau néo-écossais, où se trouvent les pêches traditionnelles. La zone de haute mer (la pente et la montée) apparaît comme un environnement exceptionnel, habité continuellement par des grands poissons pélagiques et des mammifères, comme le thon et les baleines.

1. INTRODUCTION

1.1 PURPOSE

Information and knowledge on the conditions of regional biological production is of particular importance to effective oceans management on the Scotian Shelf because it is a core biological indicator of the health of the marine ecosystem (Hall *et al.* 2011; McCuaig and Herbert 2013). DFO (2010) has identified areas that support high biological production as Ecologically and Biologically Significant Areas (EBSAs) under Fisheries and Oceans Canada (DFO) and the Convention on Biological Diversity (CBD) Biological Productivity criteria (Doherty and Horsman 2007). Consequently, regions that contain comparatively higher biomass than surrounding areas are considered EBSAs under the DFO Aggregation criterion and possibly the CBD Biological Productivity criterion. The main purpose of this document is to identify phytoplankton-rich areas (designated in this study as areas of persistent elevated chlorophyll concentration detected by remote sensing), so they can be considered in Marine Protected Area (MPA) network development for the Scotian Shelf Bioregion (DFO 2014).

1.2 PHYTOPLANKTON AT THE BASE OF THE FOOD CHAIN

Phytoplankton constitute the primary level, or the base of the food chain, in the sea. Healthy, productive phytoplankton convert sunlight into organic material for consumption by higher life forms near the surface, in the water column and on the sea floor. For this reason, persistent or recurring areas of high phytoplankton biomass offer core ecosystem services that support production at higher trophic levels (DFO 2010). In addition to forming the base of the food chain, phytoplankton play an essential role in the global carbon cycle. During photosynthesis, phytoplankton remove carbon dioxide from sea water, release oxygen as a by-product, and store the carbon in the form of organic materials. When phytoplankton die, some of their cellular carbon is transferred to different layers of the ocean where it is consumed by other organisms, which themselves reproduce, generate waste, and die. Other dead phytoplankton sink to the ocean floor, carrying with them much of the carbon stored in their cells. The carbon in the phytoplankton is either consumed by benthic organisms or gradually covered by other materials that sink to the ocean floor through sedimentation.

Phytoplankton that sink to lower layers are a food source for some zooplankton, which produce faecal pellets that either sink and retain carbon in the ocean or float and release carbon back into the atmosphere (Turner 2002). Approximately 40% of carbon dioxide from the atmosphere is transformed not just into sinking microscopic faecal pellets, but also into non-labile carbon in the shells of larger phytoplankton, or even into recalcitrant carbon in detritus or marine snow made of agglomerates of minerals that sink into the deep ocean. In this way, the oceans act as a global carbon sink. The flux of particulate matter to the deep ocean varies on time scales ranging from days to years. However, the sinking vector of particles that make up the biological pump can have a much stronger horizontal than vertical component in hydrodynamically active regions. This means that the locations where the particles are formed may occur far away (10s and up to100s of km distant) from their collection in a sediment trap. The flux of particles to the deep ocean is highly variable and is influenced by several factors. These include surface hydrographic characteristics in the area, nutrient supply to the euphotic zone, phytoplankton size structure and life strategy, primary production, recycling processes and deep carbon flux, all of which undergo annual variations and seasonal cycles (Deuser *et al*. 1990; Siegel *et al*. 2008).

A suggestion that the continental Scotian Shelf and Slope may be a sink in the global carbon budget is supported by Grant *et al*. (1987) with their study on the continental shelf and slope off Nova Scotia. The patterns of sedimentation occurring in this region are similar to the areas studied using remotely-sensed images of phytoplankton pigment conducted by Deuser *et al*. (1990) in the Sargasso Sea, and results from statistical funnel modeling in areas above sediment traps north of Hawaii in the Pacific Ocean (Siegel *et al*. 2008). Seasonal changes of hydrographic variability and circulation pattern on the Scotian Shelf (Han *et al*. 1997; Hannah *et al*. 2001; Smith *et al*. 2003; Drinkwater and Gilbert 2004) suggest a close analysis of its vertical/horizontal fluxes is needed to properly assess the contribution toward regional pelagic and benthic communities.

An illustrative example is provided by a study, on a small spatial scale, of Bedford Basin, which adjoins the Scotian Shelf proper. Cranford *et al*. (2005) monitored suspended particle flocculation and floc settlement and its utilization by a cohort of sea scallops (*Placopecten magellanicus*) during a spring phytoplankton bloom. Their research tried to determine the effect of bloom flocculation and settling on food acquisition and utilization by scallops, and to assess the potential role of flocculation in enhancing the bioavailability of trophic resources and particle-reactive contaminants to bivalve filter feeders. They observed abundant flocs in the surface layers with high daily vertical particle flux associated with relatively high clearance rates of scallops during the period of bloom settlement, with the clearance rates declining rapidly after the bloom settlement. They concluded that settlement of flocs produced during the spring bloom appears to be important in regulating sea scallops' physiological energetics and enhancing the bioavailability of fine particles (including picoplankton) and particle-reactive contaminants. Another relevant example for this study is represented by The Gully Ecosystem, the largest and one of the deepest submarine canyons in the western North Atlantic (Rutherford and Breeze 2002). This ecosystem, based on a bottom-up structure, contains many diverse habitats and is highly productive with a high specific diversity. Found within this area are deep-diving, squid-eating whales, seabirds that pluck fish from surface waters, marine worms that live in soft mud, corals that are attached to rocks and boulders, and many other species and assemblages of species.

Seasonal change in phytoplankton community structure is important in regions of persistently high phytoplankton concentration. Zhai *et al*. (2010) state that phytoplankton carbon-to-chlorophyll ratio (C:Chl) varies with the trophic status of the ecosystem and the associated community structure of phytoplankton. They found that the ratio may range from 47 to 110 throughout the year in the Northwest Atlantic, with low C:Chl ratio during spring blooms (47 to 60) associated with the dominance of diatoms. This ratio increases to 90 after the bloom as the species composition of the phytoplankton community becomes dominated by flagellates. Seasonal variability of this export of phytoplankton might be related to population structure with large size species dominating in spring, whereas small organisms tend to dominate in summer and autumn. This is an important difference because small autotrophic cells tend to better support pelagic fish production, whereas large phytoplankton tend to better support benthic communities (Marquis *et al*. 2011).

The findings of Marquis *et al*. (2011) highlight the fate of primary production, which depends on the path carbon takes within planktonic food webs. This is important for secondary consumers in the abundant and persistent phytoplankton areas because it affects the quality of the ingested food. Using a coupled plankton/small pelagic fish system, these authors examined the relationship between planktonic food web functioning and the system's capacity to export biogenic carbon to small pelagic fish during spring in the Bay of Biscay, an area of similar spatial scale to the Scotian Shelf. They investigated two estimates of export to higher pelagic levels: (i) export consistent with the available data on fish abundance, and (ii) potential export; that is, the maximum carbon flux that can support pelagic fish production given constraints on primary production and food web structure. They found that a planktonic food web dominated by microbial pathways had the highest trophic efficiency owing to the tight coupling between planktonic trophic levels and predation pressure on mesozooplankton by fish. Moreover, planktonic food webs dominated by small autotrophic cells channeled most of their available carbon to pelagic fish production, whereas food webs dominated by large phytoplankton were better suited to benthic communities with a large loss of carbon through sedimentation.

Limited information exists on the overlap of rich and persistent phytoplankton areas with fish larval diversity. However, a study by Beaugrand (2005) highlights that plankton play an important role in the functioning of marine ecosystems and in biogeochemical cycles, because the tiny organisms form a key component of the trophodynamics of pelagic ecosystems. Plankton also represent the first level of integration of hydroclimatic forcing in the pelagic food web. Planktonic organisms embody a major source of energy for fish for at least some stage of their life cycle, and there is a direct link with fish even if this link may only exist during a short period of time; it can be crucial, in particular, for larval fish survival and growth (Platt *et al*. 2003). Recently, Fisher *et al*. (2011) advanced a model reporting the results of explorations of Scotian Shelf and Bay of Fundy marine fish ecology and analyses of the match between community composition and habitat environmental factors during time periods significant to fisheries.

1.3 REMOTELY-SENSED STUDIES

Remote sensing is the scientific endeavour of obtaining information about objects or areas from a distance, typically from aircraft or satellites. For oceanography and limnology applications, remotely-carried sensors provide data to identify and to quantify fundamental physical and biological characteristics in highly resolved temporal and synoptic spatial coverage. Such coverage is not possible to obtain by any other measurement techniques, such as from ships and buoys. These instruments detect the reflected energy from Earth and can act as passive or active sensors. They usually are on polar orbits around the Earth (approximately 700 km), with typical synoptic spatial scales of measurement (from 10^1 to 10^6 km^2) and at high temporal frequency (days). Traditional satellite sensors (e.g. Landsat, AVHRR, SeaWiFS, MODIS, MERIS, RADARSAT), have been measuring sea-surface temperature, chlorophyll *a* (an index of phytoplankton biomass), water transparency, sediment concentrations, oil spill indicators, and salinity among others. Their measurements are used to trace surface circulation, to assess wave heights, to track sea ice, to study the impact of hurricanes, and to identify water mass fronts and upwelling that might be linked to abundance of biological and fishery resources.

All phytoplankton contain chlorophyll *a* which modifies the ocean colour. By detecting the presence of pigments in particular parts of the visible light spectrum using optical instruments on satellites, the amount and distribution of phytoplankton in the ocean can be inferred. This is then calibrated in terms of chlorophyll concentration, usually given in units of milligrams per cubic metre of water. A few examples of satellite-derived information and use in the analysis of phytoplankton spatial and temporal variability and on the flux of particles from surface to deeper layers include those of Deuser *et al*. (1990), Siegel *et al*. (2008) and Zhai *et al*. (2010). The major role of planktonic organisms is as a source of energy for fish at some stage of their life cycle, in particular during the crucial larval fish stage (Platt *et al*. 2003); it is also important for crustacean survival and growth (Fuentes-Yaco *et al.* 2007; Koeller *et al.* 2009). Palacios *et al.* (2006) and Kobayashi *et al.* (2011) used satellite observations to underline the importance of considering areas of persistently high phytoplankton concentration in the context of conservation and sustainable resource management. The present study applies remotely-sensed images of chlorophyll to identify areas of persistently elevated phytoplankton concentration, and contributes information to aid description of regions for precautionary management in the offshore of the Canadian Scotian Shelf.

2. METHODS

2.1 STUDY AREA

The study area encompasses the Scotian Shelf, which is a wide, submerged portion of the continental shelf lying off Nova Scotia, that is 700 kilometres in length and between 125 and 230 kilometres wide (Figure 1).

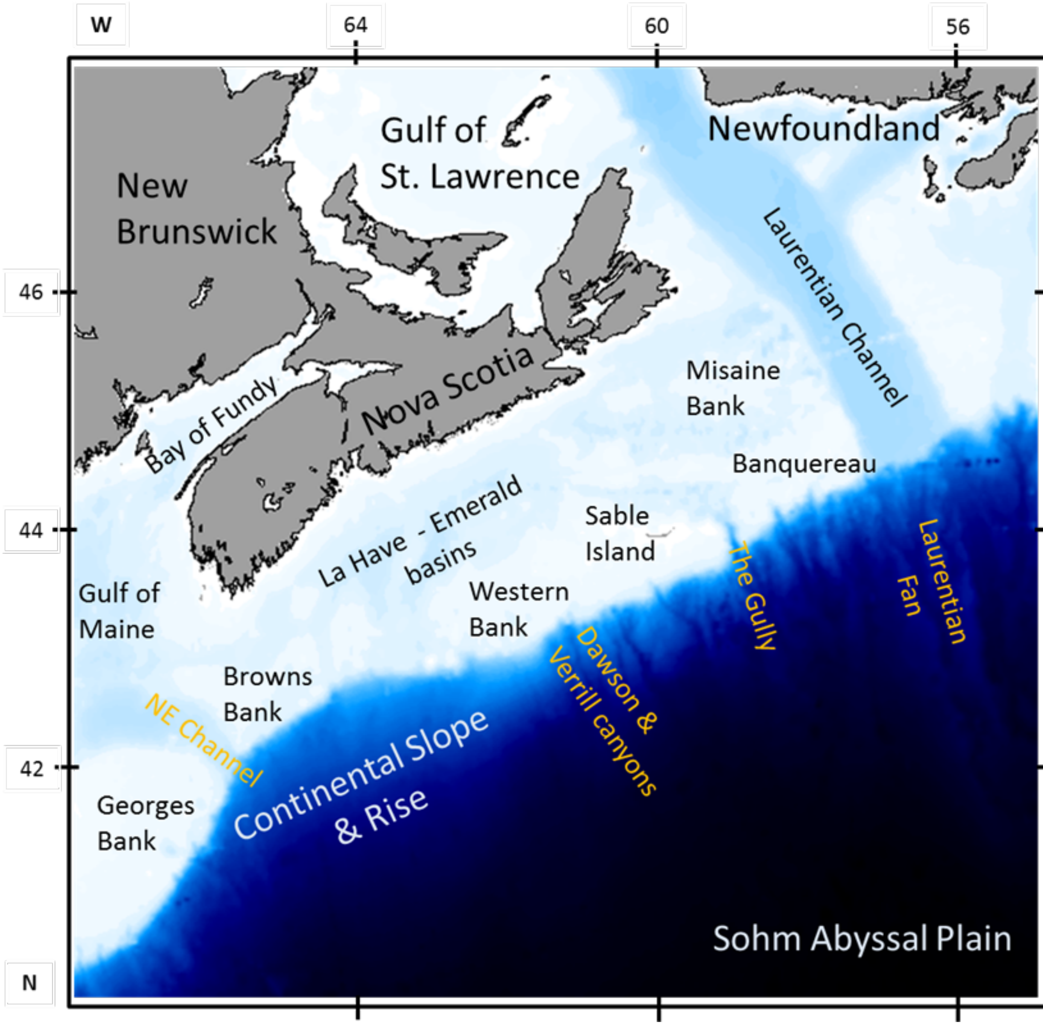

Figure 1. The study area.

The Laurentian Channel is the boundary with the Newfoundland Shelf to the northeast; the Laurentian Fan is a large, delta-like deposition area down the slope from the Channel. The study area has its southwest limits with the eastern parts of the Gulf of Maine and Georges Bank, which are separated from the Scotian Shelf by Northeast Channel. This channel connects the Bay of Fundy and Gulf of Maine with the rest of the Northwest Atlantic, and strong tidal currents are typical in the area. For the purposes of this analysis, the study area includes the Scotian Slope and Rise (the area from the edge of the continental shelf, which starts at about 200 m depth, seaward to the abyssal plain), and the abyssal plain itself within Canada's Exclusive Economic Zone.

Loder *et al.* (1998) indicate that the Northwest Atlantic continental shelves are mainly influenced by a coastal current originating in the Labrador Sea, flowing toward the equator and reaching as far south as the Gulf Stream. Most of this current flows onto the Northeast Newfoundland Shelf and continues southward into the Grand Banks region; a small amount is diverted toward the Gulf of St. Lawrence via the Strait of Belle Isle. The Scotian Shelf in particular contains a mixture of waters from the Gulf of St. Lawrence, the Labrador Current and Continental Slope waters (a mix of the Gulf Stream and the Labrador Current); the resulting composition is relatively fresh and seasonally very cold. Seasonal heating of surface layers traps a cold intermediate water layer beneath the seasonal thermocline that intrudes from beyond the shelf edge creating three distinct water types. Frontal dynamics at the shelf break result from localized areas of vigorous tidal mixing and upwelling, such as off southwestern Nova Scotia, where the main current enters the Gulf of Maine and subsequently moves into the Middle Atlantic Bight. The physiography (coastline and bottom) plays a fundamental role in the local circulation (Towsend *et al.* 2006).

The state of phytoplankton on the Scotian Shelf and the Scotian Slope is monitored on an ongoing basis by DFO oceanographic sampling (Atlantic Zone Monitoring Program) and by commercial vessels of opportunity (Continuous Plankton Recorder). Annual reports on the state of the plankton are published via the Canadian Science Advisory Secretariat (Johnson et al. 2013), and are supplemented by other technical contributions (Li 2014).

2.2 SUBDIVISIONS

The process of identifying areas of persistent high chlorophyll concentrations in the bioregion involved a subdivision of the study area based on physical and biological conditions. Most notably, the inner shelf (the underwater extension of Nova Scotia's coastal areas, extending from the coastline to depths of about 100m) was separated from the middle shelf. The inner shelf is an optically complex region (i.e. Case 2 waters) (Morel and Prieur 1977), and may generate confusion in the algorithm to identify chlorophyll *a*. Consequently, the study area comprises the mid- and outer-Scotian Shelf, Rise, Slope and the Abyssal Plain (Figure 1). The mid- to outer-shelf is characterized by a wide, intricate network of valleys, ridges and banks in the east, large, deep basins in the central area, and a smaller bank and basin in the western region. These banks separate waters of the shelf from deeper zones. The eastern border of the study area is limited by Cabot Strait (separation from Gulf of St. Lawrence) and Laurentian Channel (a deep trough of 180 to 550 m). The western study area includes the eastern parts of the Gulf of Maine, Northeast Channel and Georges Bank. The Scotian Slope (where the seafloor descends steeply from about 200 m to 2000 m depth), Rise and Abyssal Plain (depth of about 5000 m) are the offshore limits of the study area. A series of steep-sided submarine canyons are found along the shelf edge and slope (MacLean *et al.* 2013).

For the purposes of this study, the continental mid- to outer-shelf was separated into three zones. In addition to the bathymetry, the characteristics are formed by different features such as the main tidal circulation (Ohashi *et al.* 2009) and surface circulation (Hebert *et al.* 2013), as seen in Figures 2 a and b. Furthermore, the inner Scotian Shelf current is an important feature, as well as the strong tidal currents in the Gulf of Maine; their synergetic action was a determinant in defining the western study subdivision. The bottom temperature and salinity were fundamental in the areas' identification (Figures 2c and d). These data, along with preliminary results from DFO 2014, suggested the separation of La Have and Emerald basins as independent subdivisions.

Bathymetric differences separate the offshore zones from the shoreline (Figure 3). The 200 m isobath is the threshold of the deepest subdivision which includes the continental slope, rise and the abyssal plain. However, among the most important considerations taken into account to determine the four regional subdivisions are the spatial and temporal features distinguished on the remotely-sensed weekly-climatology images of chlorophyll (Appendix 1). In particular, the spatial pigment concentrations in the Eastern compared with the Western areas.

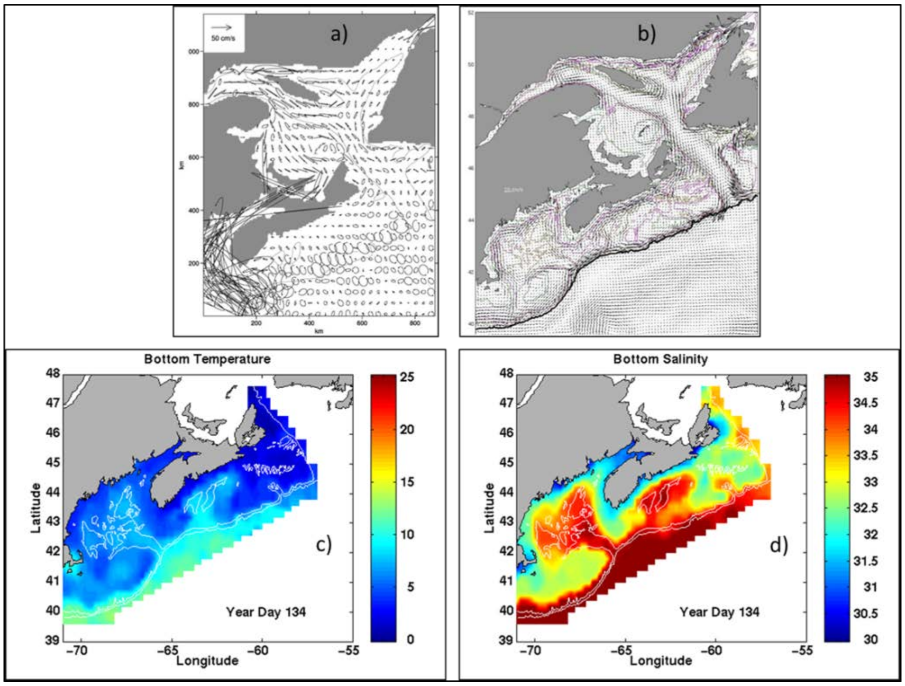

Figure 2. a) The Scotian Shelf modeled surface M2 tidal current ellipses in August (Figure 2 in Ohashi et al. 2009) (upper left panel), b) Annual average depth-averaged circulation (Figure 28 in Hebert et al. 2013) (upper right panel), c) Climatological bottom temperature during day of year 134 in degrees Celsius (lower left panel), and d) Climatological bottom salinity during day of year 134 (lower right panel). Note that panels c and d are from Bedford Institute of Oceanography, DFO.

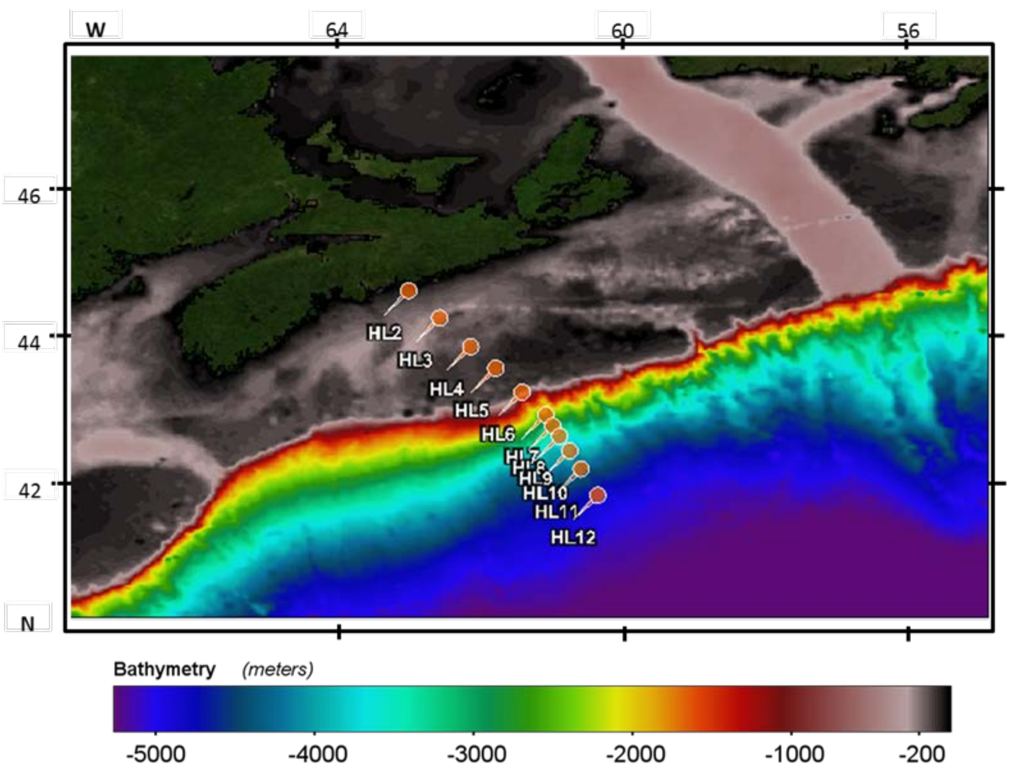

Figure 3. Bathymetry with a colour bar representing depth in meters. Stations 2 to 12 of Halifax Line from The Atlantic Zone Off-Shelf Monitoring Program are also shown.

2.3 SATELLITE-DERIVED DATA

The Remote-Sensing Unit of the Bedford Institute of Oceanography (RSU/BIO) downloads Level-2 daily data of Moderate Resolution Imaging Spectroradiometer (MODIS_Aqua) from NASA's Ocean Color anonymous ftp site. NASA uses real-time attitude/ephemeris files which are required for precise geolocation, and the most recent near real-time (not climatological) MET/OZONE files for atmospheric processing. Details about this processing flow can be found on NASA's Ocean color website showing the overview of MODIS aqua data processing and distribution. RSU/BIO processes the Level-2 images to obtain chlorophyll concentrations. Further description about the algorithm can be found on the NASA's ocean color chlorophyll (OC) v6 webpage.

The information is processed using NASA's SeaDAS software in an OS/X environment. The resulting files have a nominal resolution of 1 km^2, and do not need to be geographically navigated because the geolocation values are estimated to be within 100 m of the actual locations. The following masks are applied: radiance above knee, high solar zenith angle, and extreme sun glint. Information used in this research is from the 2012 reprocessing by the Ocean Biology Processing Group. Daily images are averaged to produce Level-3 weekly composite images and resampled at 1.5 km of spatial resolution.

The data and methods used to develop satellite-derived maps of high chlorophyll concentrations in the offshore component of the Scotian Shelf bioregion fulfil several of the EBSA and CBD criteria to represent biological production. The computation was implemented in several steps. Initially, forty eight Level-3 (weekly), 11-year climatological maps of the study area were calculated using all available MODIS composites from January to December, between 2003 and 2013 (a forty-eight week convention has been used for analytical purposes). Subsequent steps are detailed in the next section.

2.4 PHYTOPLANKTON CONTRIBUTION

For each sub-region and weekly climatology composite image, the median and standard deviation of chlorophyll concentration (mg/m^3) were computed. Every pixel in the composite image was compared against a specific threshold value represented by its own median plus a half standard deviation (½ σ). Pixels above the threshold were assigned a value of one, the remaining were set to zero. These assigned values are termed transformed chlorophyll indicators.

To account for the variability in chlorophyll concentrations throughout the year, the climatology was separated into seasonal layers. For each pixel, transformed chlorophyll indicators were added, then multiplied by 100 and divided by 12, which is the total number of weekly layers for each season.

$$p_i^1 = \left(\frac{\sum_{j=1}^{12} c_{ij}}{12}\right) \times 100$$

$$p_i^2 = \left(\frac{\sum_{j=13}^{24} c_{ij}}{12}\right) \times 100$$

$$p_i^3 = \left(\frac{\sum_{j=25}^{36} c_{ij}}{12}\right) \times 100$$

$$p_i^4 = \left(\frac{\sum_{j=37}^{48} c_{ij}}{12}\right) \times 100$$

In this notation p^1 is winter contribution (%) to high phytoplankton biomass, p^2 is spring contribution (%), p^3 is summer contribution (%), p^4 is autumn contribution (%), i is pixel number, j is week number and c is the transformed chlorophyll indicator having a value of 1 or 0. The weeks are numbered in a sequence with j =1-12 in winter (Dec-Jan-Feb), j = 13-24 in spring (Mar-Apr-May), j = 25-36 in summer (Jun-Jul-Aug), and j = 37-48 in autumn (Sep-Oct-Nov).

For the year as a whole, the annual contribution (%) to high phytoplankton biomass at each pixel (P_i) is calculated in a similar manner, with the summation taken over 48 weeks.

$$P_i = \left(\frac{\sum_{j=1}^{48} c_{ij}}{48}\right) \times 100$$

This procedure allowed maps showing the proportion (percent) of each pixel's contribution to high phytoplankton biomass at seasonal and annual time scales.

3. RESULTS

3.1 SUBDIVISIONS

Maps of surface and tidal currents, climatology of bottom temperature and salinity, as well as the preliminary analyses of spatial and temporal phytoplankton distribution were the basis for the subdivision of the Scotian Shelf Bioregion. The four subdivisions are named W*estern*, *Central*, *Eastern* and *Slope*. The total study area is represented by an average of 221,861 available pixels, equivalent to approximately 333 x 10^3 km^2.

The Western subdivision includes portions of the eastern Gulf of Maine, Georges Bank, and Browns Bank; an elongate area on the northeast including Roseway Basin, completes the zone. The region has an average of 28,605 pixels by composite, the equivalent of around 43 x 10^3 km^2 (red area in Figure 4).

The Central subdivision is mainly composed by La Have and Emerald basins. The western limits are around 64° W; on the eastern side it contours the Western Bank. The Scotian Gulf is the southern limit. The zone has a mean of 13,242 pixels, which represent approximately 20 x 10^3 km^2, and is illustrated as yellow in Figure 4.

The Eastern subdivision consists of the Laurentian Channel, Misaine and Banquereau banks, and includes Sable Island and its surrounding areas. A narrow band north of the Central subdivision partially circumscribes the region. This is the second largest area with an average of 41,147 pixels, an equivalent of almost 62 x 10^3 km^2 (green in Figure 4).

The Slope subdivision integrates the Continental Slope, Rise and Sohm Abyssal Plain, located between 55° W and 68° W. The Laurentian Fan and main canyons such as The Gully, Dawson and Verrill form part of this subdivision. It represents the largest of the four zones, and has as average 138,866 pixels for a surface area approximately 210 x 10^3 km^2 (blue in Figure 4).

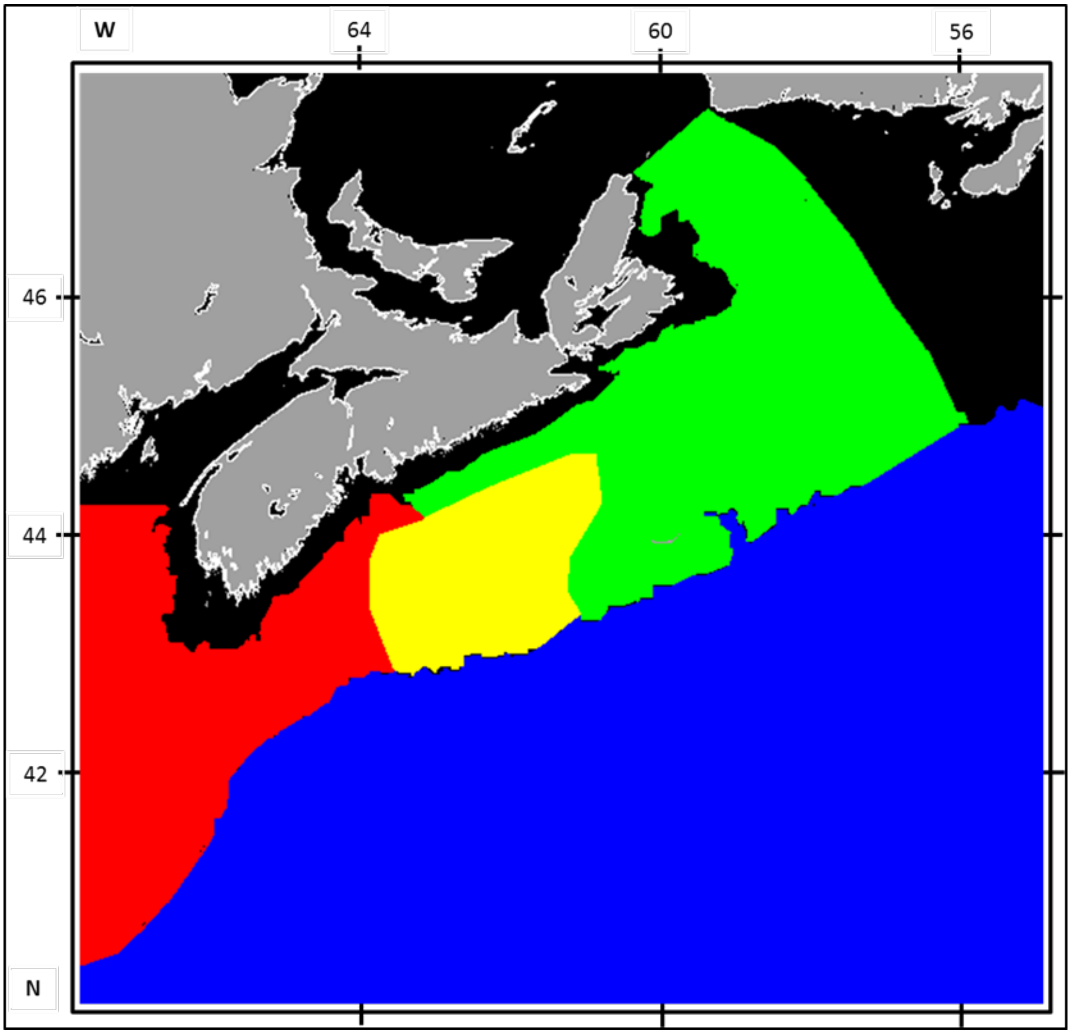

Figure 4. Subdivisions of the Scotian Shelf Bioregion: Western (red), Central (yellow), Eastern (green) and Slope (blue).

3.2 SATELLITE-DERIVED DATA

The climatology composite images of chlorophyll for each of the forty-eight weeks from January to December, and eleven years (2003 to 2013) are shown in Appendix 1 (again, a forty-eight week convention has been used for analytical purposes).

A comparison of *in situ* chlorophyll measurements and weekly MODIS-derived data was performed. The time-series used in this exercise correspond to stations 2 to 12 of the Halifax Line from the Atlantic Zone Off-Shelf Monitoring Program (see Figure 3 for geographic locations). Two statistical regressions were tested on the 170 pairs of data, an Ordinary Least-Square (OLS) regression, and a Model II regression. The second method consisted of a Standard Major Axis (SMA) regression typically used for situations where both variables are random (Legendre 2015). The coefficients of correlation (r), and determination (R squared) were 0.73 and 0.53, respectively. Figure 5 shows that *in situ*-derived pigment values below -0.5 Log (mg/m^3) are slightly overestimated by the sensor, and values above 0.5 Log (mg/m^3) are somewhat underestimated by MODIS. Even if the comparison is not a formal validation because of the different temporal scales of the two data sets, the results (in particular the SMA regression) justify the use of chlorophyll MODIS weekly-composites data as indices of phytoplankton pigment in this study.

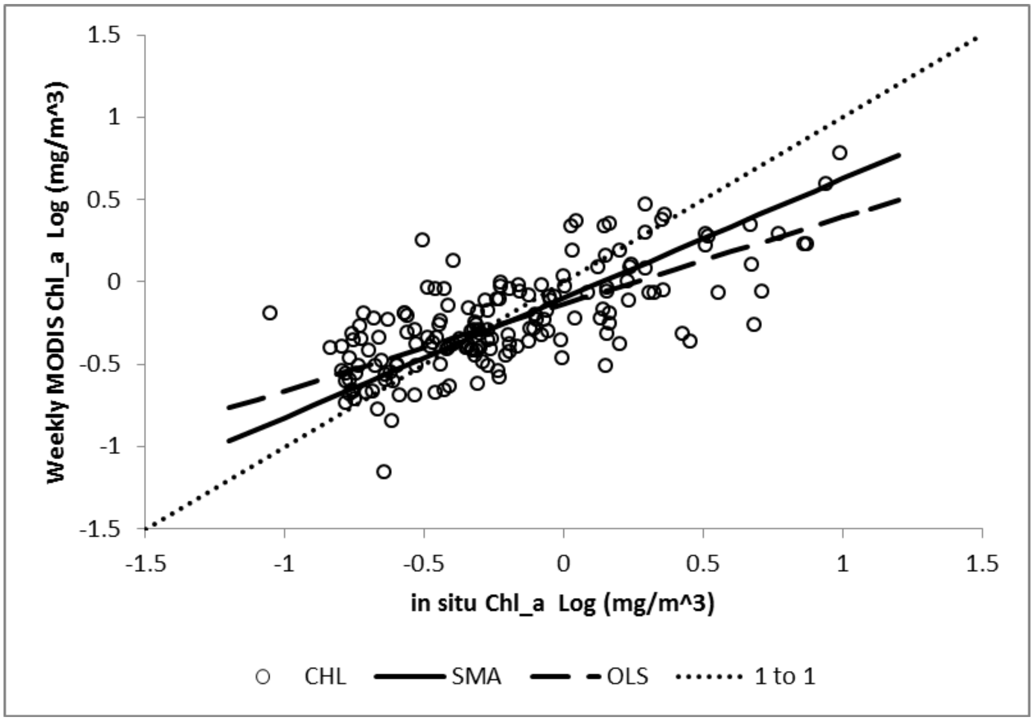

Figure 5. Comparison of in situ chlorophyll measurements and weekly MODIS-derived data, units are Log (mg/m^3). Values correspond to stations 2 to 12 of the Halifax Line from the Atlantic Zone Off-Shelf Monitoring Program (see Figure 3), between 2008 and 2013. The empty circles represent chlorophyll data (CHL), solid line is a Standard Major Axis regression (SMA), dashed line is Ordinary Least-Square regression (OLS), and the dotted line is a 1 to 1 line.

Identification of areas of persistent high chlorophyll concentrations offshore from the Scotian Shelf was assessed from satellite-derived maps containing a total of more than 10.5 x 10^6 pixels, over the 11 years of MODIS data that were included in this study. The Western subdivision contributes about 1.5 x 10^6 pixels, the Central subdivision adds approximately 0.6 x 10^6 pixels, the Eastern subdivision provides about 2.0 x 10^6 pixels, and finally the Slope subdivision adds almost 7.0 x 10^6 pixels. Weekly climatology values for each subdivision of the median (mg/m^3), the number of pixels, the standard deviation (σ), and the median plus half of σ are compiled in Appendix 2.

Figure 6 shows the annual evolution of weekly climatology values of chlorophyll (median plus half of σ) for each subdivision. These data represent the threshold for determining high and persistent phytoplankton biomass pixels. The general pattern shows a slight bi-modal curve with high pigment concentrations during the spring and moderate to low values during the autumn. Winter shows relatively low values but summer has the lowest pigment concentrations. The Western subdivision has persistently more phytoplankton biomass throughout the year, except in winter when the Eastern and Central zones show slightly more pigment. The Eastern region has the second highest phytoplankton biomasses throughout the year. The Central subdivision is the area with the third highest chlorophyll values during the annual cycle. Finally, the Slope subdivision has the lowest phytoplankton concentrations during most times of the year.

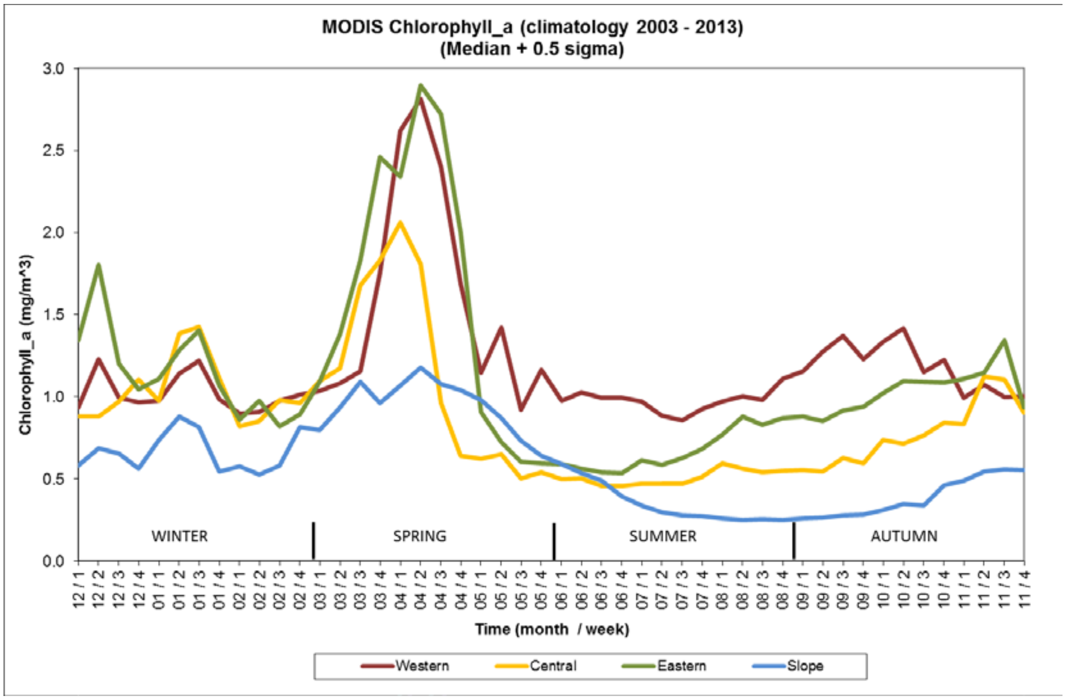

Figure 6. Chlorophyll_a weekly climatology, median plus half of σ (mg/m^3) (note that time starts in December), for each of the four Scotian Shelf subdivisions: Western (red), Central (yellow), Eastern (green) and Slope (blue). Seasons are shown on the abscissa axis.

3.3 PHYTOPLANKTON CONTRIBUTION

3.3.1 Annual Persistence

The percent of annual contribution of high phytoplankton biomass in the four subdivisions is shown in Figure 7. The Western subdivision's annual persistent phytoplankton is characterized by the predominance of high values (≥ 75%) on Georges Bank (Figure 7a). The Gulf of Maine contributes relatively high percentages (between 25 and 50%), as well as the northern regions of Emerald Basin. The lowest values are in Browns Bank, Northeastern Channel and Georges Basin (≤ 10%) (Figure 7a).

The Central subdivision reveals a semicircular pattern of annual chlorophyll contributions (Figure 7b). A radial gradient is shown with the highest percentages seen on the western, northern and eastern sides (25 to 75%). Low values are shown in the centre and southern areas (≤ 10%).

Eastern subdivision, the second largest area, shows well-defined annual patterns of phytoplankton percentages. High values are seen along the coastal side (≥ 50%), in particular in the western Laurentian Channel at the eastern extreme of Nova Scotia. Here, a wide band starts with high values and gets narrow as it goes south, along Cape Breton Island (46°N, 58.8°W). In contrast, on the middle shelf (Misaine Bank), the widest area with high contributions is detected; this feature spreads to the western side of the subdivision. Sable Island and the surrounding shallow areas also show high and persistent phytoplankton (≥ 50%). The lowest values in this subdivision are on Banquereau Bank and in the Laurentian Channel (≤ 10%) (Figure 7c).

Slope is the largest subdivision of the Scotian Shelf Bioregion, where a three-belt feature of pigment persistence is evident (Figure 7d). The segment with the highest values overlaps all the continental slope including the Laurentian Fan with values above 50 percent. Patches of values close to 90% are seen from the northeastern Georges Bank border until The Gully canyon. A narrow strip of chlorophyll persistence (20 to 30%), with a south-west to north-east direction is revealed between 40°N and 43°N (3000 m to 4000 m isobaths). The Sohm Abyssal Plain, the broadest area in this subdivision, shows contributions lower than 10%; below 4500 m depth there are no contributions in a large number of pixels (white patches in Figure 7d).

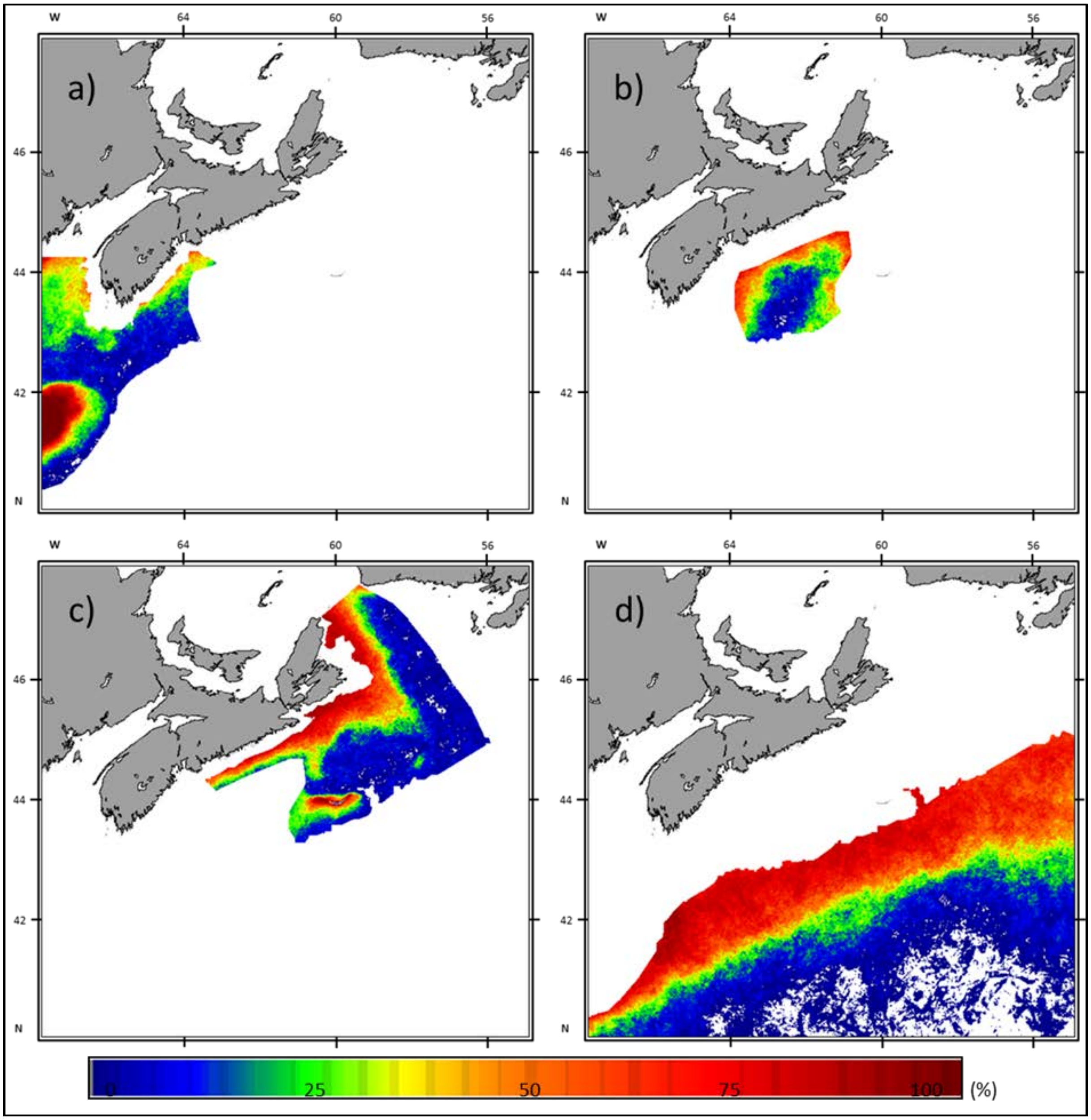

Figure 7. Annual contributions (%) of High Phytoplankton Biomass in the a) Western (upper left panel), b) Central (upper right panel), c) Eastern (lower left panel), and d) Slope subdivisions of the Scotian Shelf Bioregion (lower right panel).

The histograms of frequency of percent contribution to annual high phytoplankton biomass in the Scotian Shelf bioregion are shown in Figure 8, and the values are listed in Table 1. In the Western subdivision, the highest frequencies (approximately 14 x 10^3 pixels) are for very low (10-20%) phytoplankton contribution; it can be seen in Figure 7a that these low contributions are for Browns Bank, Northeastern Channel and Georges Basin. The histogram also shows that about 10 x 10^3 pixels contribute between 30 and 50% phytoplankton; these contributions are from the Gulf of Maine and northern regions of Emerald Basin. The lowest frequencies (approximately 3 x10^3 pixels), correspond to high phytoplankton contribution from Georges Bank (Figure 7a, Table 1 and Figure 8a).

A right-skewed distribution characterizes the Central subdivision histogram. The largest frequencies (approximately 11 x 10^3 pixels), correspond to the external borders of the semi-circular feature. However, the highest percentages match the lowest frequencies in the central and southern regions (approximately 2 x 10^3 pixels) (Figure 7b, Table 1 and Figure 8b).

The Eastern subdivision shows an exponential decreasing frequency histogram (Figure 8c). The largest frequency contribution (approximately 15 x 10^3 pixels) is from Banquereau Bank and the Laurentian Channel, which showed the lowest percentages. The transition between offshore waters toward coastal areas, including Sable Island, contributes approximately 16 x 10^3 pixels. The asymptotic part of the graph corresponds to the lowest frequencies and maximum percentages with a total of approximately 11 x 10^3 pixels (Figure 7c and Figure 8c).

A bimodal graph of frequencies represents the Slope subdivision (Figure 8d). The first and largest part of the curve is for the low percentages and highest frequencies (approximately 90 x 10^3 pixels), and corresponds to areas below 3000 m depth (Figure 7d). The second part of the curve is for the continental slope and Laurentian Fan, where high percentages contribute a total of approximately 50 x 10^3 pixels.

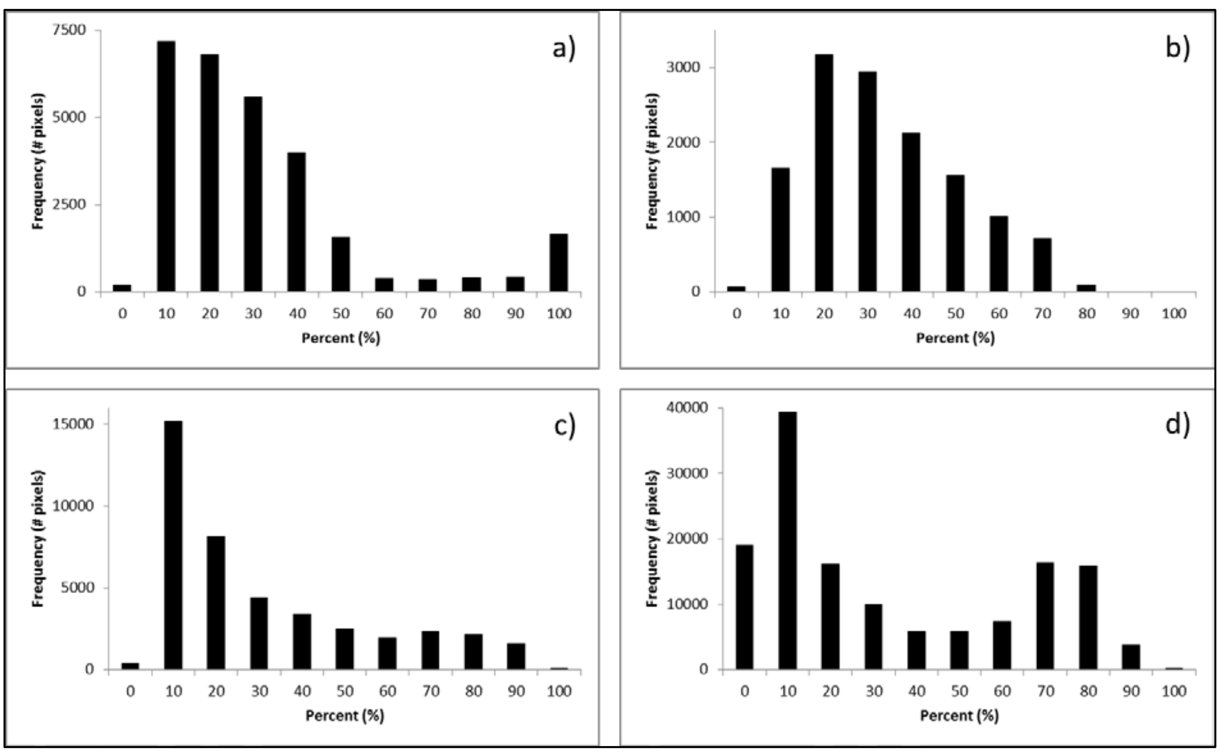

Figure 8. Frequency histograms (number of pixels) of annual contributions (%) to High Phytoplankton Biomass in the a) Western (upper left panel), b) Central (upper right panel), c) Eastern (lower left panel), and d) Slope subdivisions of the Scotian Shelf bioregion (lower right panel). Note the different scales on the ordinate axis.

3.3.2 Seasonal Persistence

Seasonal maps (winter, spring, summer and autumn) and frequency histograms of contributions to high chlorophyll concentrations in the Scotian Shelf subdivisions are shown for Western in Figures 9 and 10, Central in Figures 11 and 12, Eastern in Figures 13 and 14 and Slope in Figures 15 and 16; data are presented in Table 1.

Table 1. Number of pixels (Frequency) of the annual and seasonal percent contribution (%) to High Phytoplankton Biomass in the Scotian Shelf subdivisions: Western, Central, Eastern and Slope.

Percent	Western (Frequency)					Central (Frequency)				
	Annual	Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn
0	207	7706	5009	12669	7705	61	831	638	1839	3717
10	7177	5677	7230	2421	4943	1651	2176	1606	1477	2720
20	6794	3837	5388	1391	2897	3171	3013	2333	1748	1342
30	5587	2478	3366	1092	1935	2941	2552	2691	1923	812
40	4000	1847	2396	757	2067	2118	1789	2023	1464	644
50	1572	2555	2197	1403	4590	1559	1873	2556	2272	996
60	381	775	335	1095	1571	1005	426	1011	928	413
70	365	641	165	1389	488	714	265	383	780	526
80	417	638	176	1790	239	92	180	71	511	726
90	445	553	161	1386	193	0	164	0	249	770
100	1660	1898	2182	3212	1977	0	43	0	121	646
Percent	**Eastern (Frequency)**					**Slope (Frequency)**				
	Annual	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**
0	402	9185	3611	17422	12565	18969	47342	24933	58578	65703
10	15165	10927	7525	6013	8815	39399	17536	21920	13550	12100
20	8148	6089	8679	3115	4472	16081	12539	16809	7621	5173
30	4431	3599	6047	2031	2644	9946	10531	13730	4809	3395
40	3410	2190	3902	1580	1845	5770	10385	13626	3340	2697
50	2495	3610	5511	2541	3369	5789	19250	27900	5160	4464
60	1942	2372	2155	1212	1686	7349	8079	9392	3098	2547
70	2341	1993	1562	887	1750	16371	6471	5514	5090	3383
80	2125	1209	1356	994	1331	15843	4349	2996	9964	4762
90	1616	780	995	1092	1396	3812	2171	1889	10036	7758
100	105	226	837	5293	2307	285	961	905	18368	27632

In the Western subdivision (Figure 9), the most persistent feature is elevated percentages on Georges Bank in all seasons, where the high phytoplankton area seems to be largest in summer and smallest in winter. Gulf of Maine has the second highest contribution, with summer and autumn showing high percentages. The northern regions of Emerald Basin also show high contribution during the winter. The remaining areas generally have low surface phytoplankton contribution (Figure 9).

The number of pixels (frequency histograms) of seasonal contribution for the Western subdivision is displayed in Table 1 and Figure 10. In three seasons these plots show exponential decreasing frequencies (except in summer), with in general a high number of pixels (approximately 5 to 13 x 10^3) with zero percent contribution, diminishing to approximately 0.1 to 1.4 x 10^3 pixels in the 90% contribution range. These values increase again (approximately 2 to 3 x 10^3 pixels) at 100% contribution (Figure 10).

The semicircular pattern of pigment persistence in the Central subdivision shows a wide-ranging seasonal variability (Figure 11).The radial gradient with high percentages on the sides is present during spring, summer and autumn; however during winter only the eastern side shows high phytoplankton contributions. Low values are persistently shown in the centre and southern areas, with relatively extended areas of zero contribution in summer and autumn (Figure 11).

Central subdivision's frequency histograms have right-skewed distributions for all seasons except autumn, when an exponential shape is shown. The highest frequencies in winter, spring and summer seasons vary between approximately 0.6 and 2.7 x 10^3 pixels which correspond with 30 to 50% contribution. Autumn contributions decrease exponentially from approximately 4.0 x 10^3 pixels at 0% contribution to approximately 0.6 x 10^3 pixels at 100% contribution (Table 1 and Figure 12).

The second largest subdivision (Eastern) shows persistent seasonal high chlorophyll contributions on the western side of Laurentian Channel and along the coast of Nova Scotia and Cape Breton Island, including Misaine Bank (Figure 13). The highest percentages are in summer and the lowest in winter; autumn is intermediate. Spring does not show the highest percentages, but high rates of contribution are as widespread as in summer. Sable Island reveals an interesting monotonic percentage decrease in size and value from winter until autumn. The south-west to north-east strip on the western-side of the subdivision is also important during winter, but the highest percentages are from a band closer to the coast in autumn; spring shows intermediate percentages covering across the band length and summer has the lowest values (Figures 13 and 14).

The seasonal frequency histograms for the Eastern subdivision show both types of graph shapes seen in these results, right-skewed and exponential decreasing. The former shapes develop during winter and spring seasons with maximum number of pixels around 10 x 10^3. The latter shapes correspond to histograms for the summer and autumn seasons with highest frequencies (approximately 13 to 17 x 10^3 pixels) matching zero percent contributions (Table 1 and Figure 14).

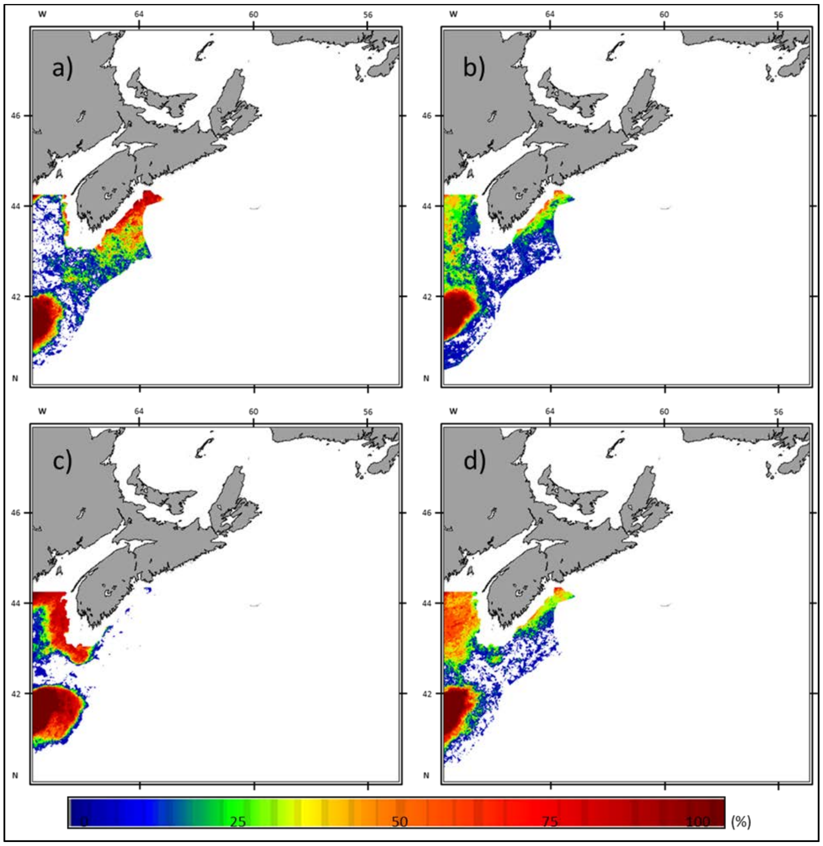

Figure 9. Seasonal contributions (%) of High Phytoplankton Biomass in the Western offshore subdivision of the Scotian Shelf bioregion: a) Winter (upper left panel), b) Spring (upper right panel), c) Summer (lower left panel), and d) Autumn (lower right panel).

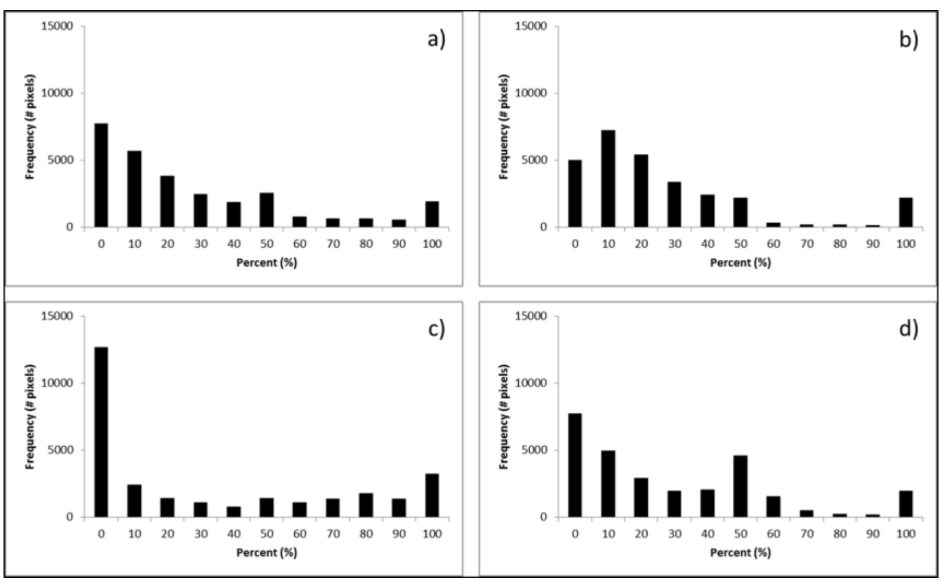

Figure 10. Frequency histograms (number of pixels) of the seasonal contribution (%) of High Phytoplankton Biomass in the Western subdivision component of the Scotian Shelf bioregion: a) Winter (upper left panel), b) Spring (upper right panel), c) Summer (lower left panel), and d) Autumn (lower right panel).

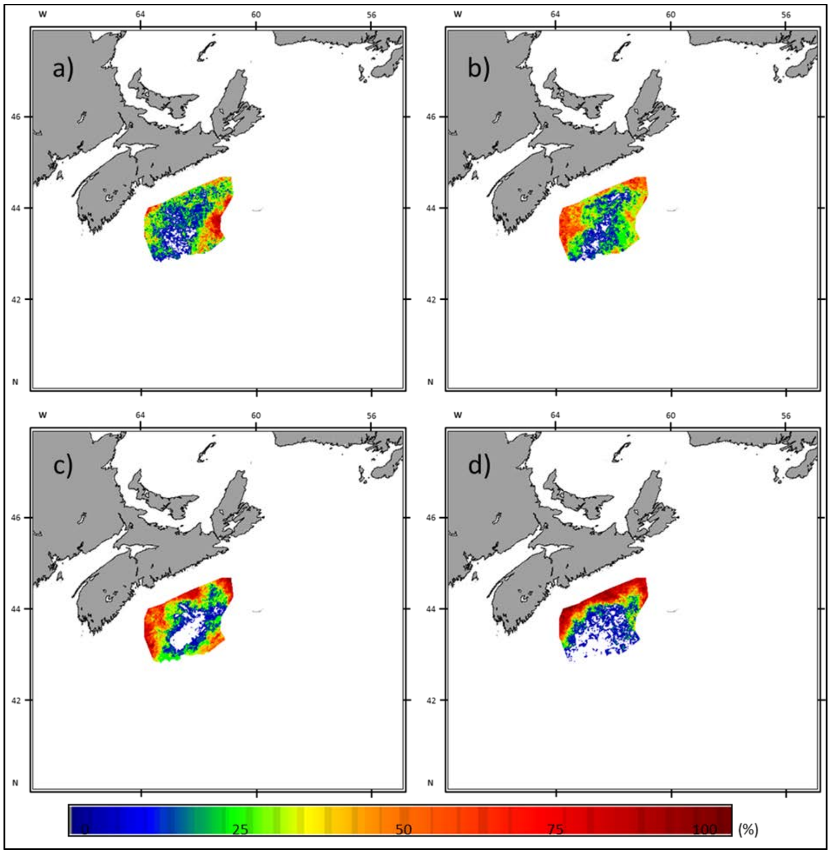

Figure 11. Seasonal contributions (%) of High Phytoplankton Biomass in the Central offshore component of the Scotian Shelf bioregion: a) Winter (upper left panel), b) Spring (upper right panel), c) Summer (lower left panel), and d) Autumn (lower right panel).

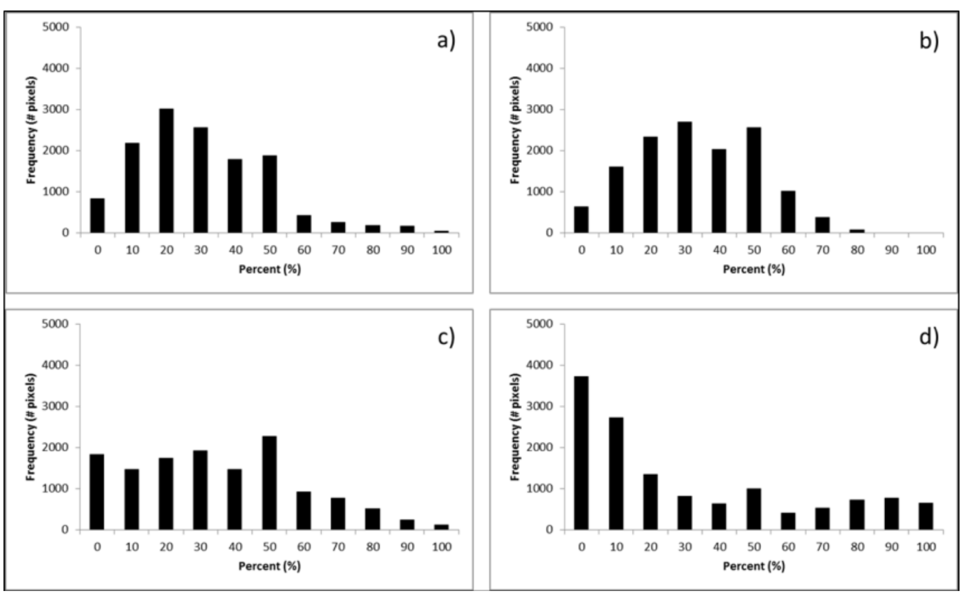

Figure 12. Frequency histograms (number of pixels) of the seasonal contribution (%) of High Phytoplankton Biomass in the Central offshore component of the Scotian Shelf bioregion: a) Winter (upper left panel), b) Spring (upper right panel), c) Summer (lower left panel), and d) Autumn (lower right panel).

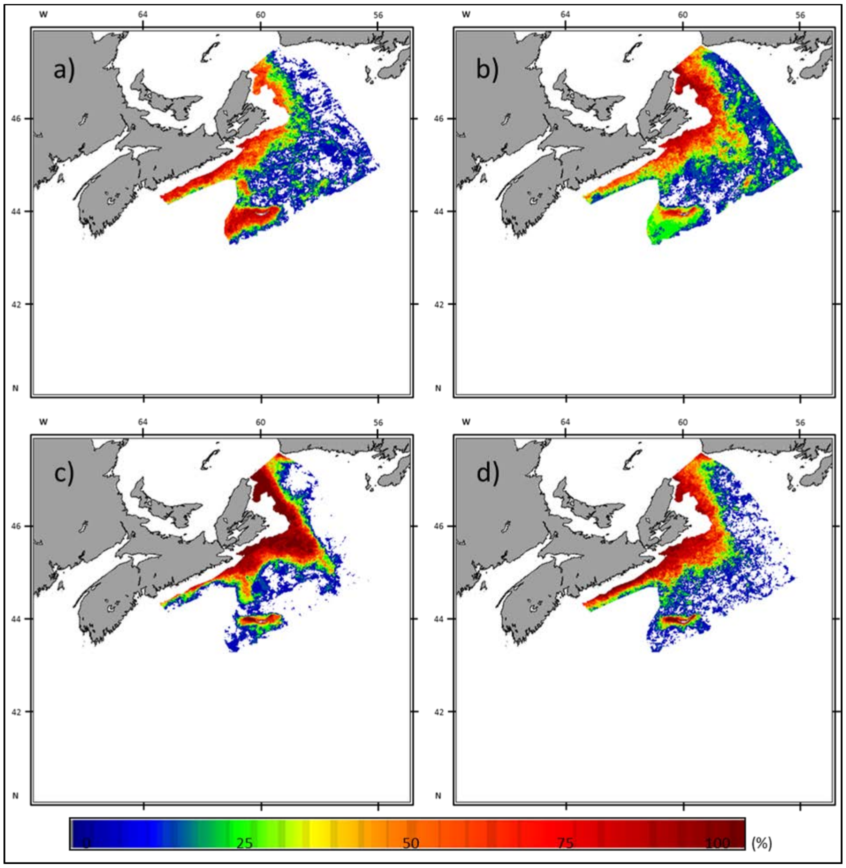

Figure 13. Seasonal contributions (%) of High Phytoplankton Biomass in the Eastern offshore subdivision of the Scotian Shelf bioregion: a) Winter (upper left panel), b) Spring (upper right panel), c) Summer (lower left panel), and d) Autumn (lower right panel).

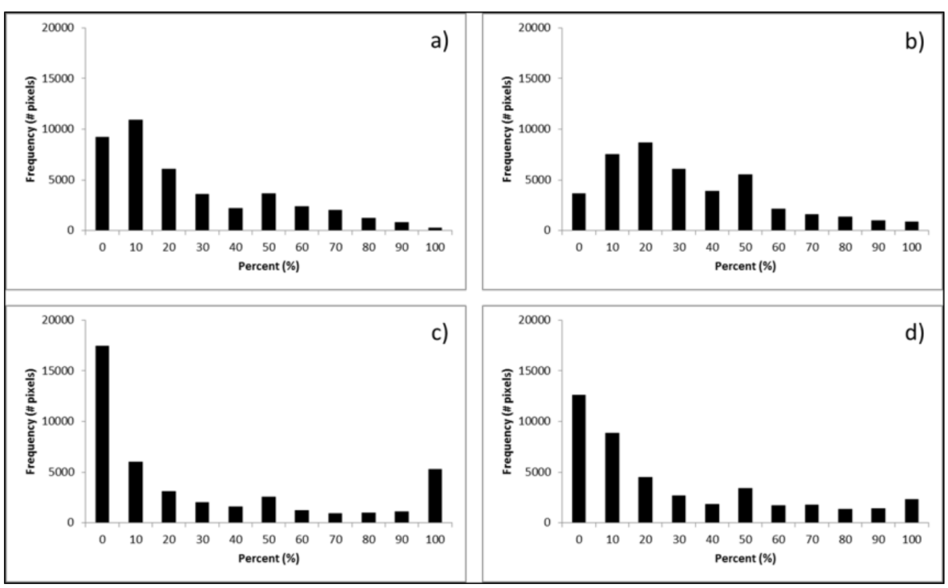

Figure 14. Frequency histograms (number of pixels) of the seasonal contribution (%) of High Phytoplankton Biomass in the Eastern offshore subdivision of the Scotian Shelf bioregion: a) Winter (upper left panel), b) Spring (upper right panel), c) Summer (lower left panel), and d) Autumn (lower right panel).

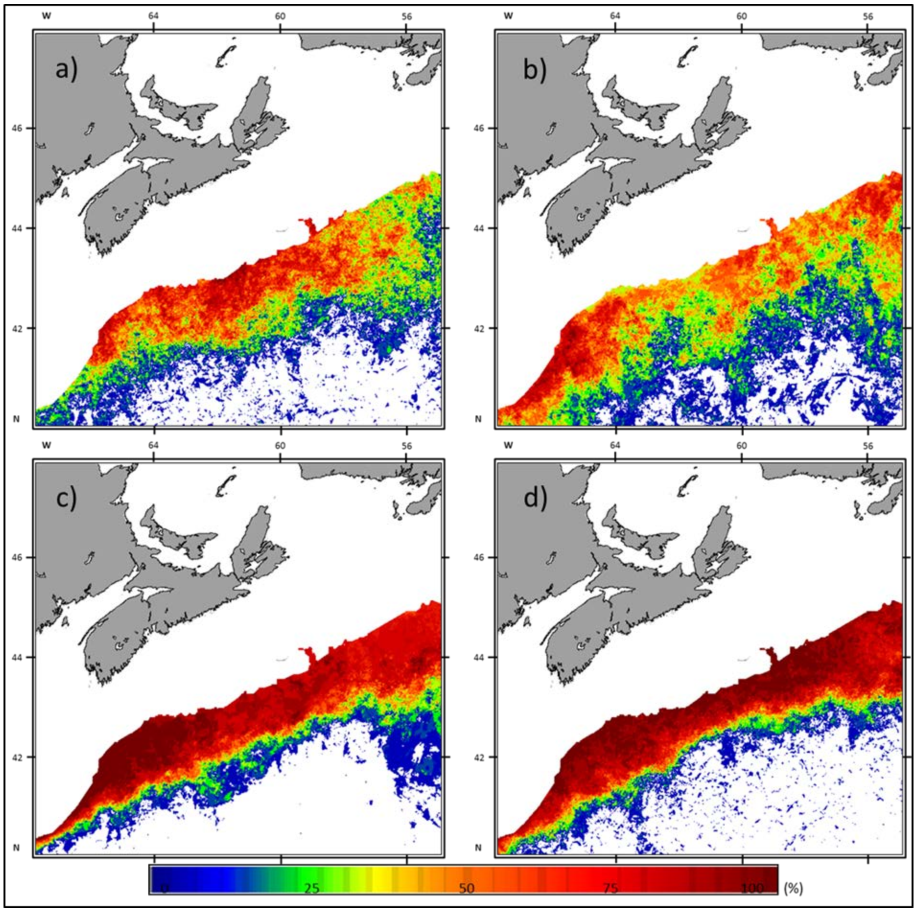

Figure 15. Seasonal contribution (%) of High Phytoplankton Biomass in the Slope offshore subdivision of the Scotian Shelf bioregion: a) Winter (upper left panel), b) Spring (upper right panel), c) Summer (lower left panel), and d) Autumn (lower right panel).

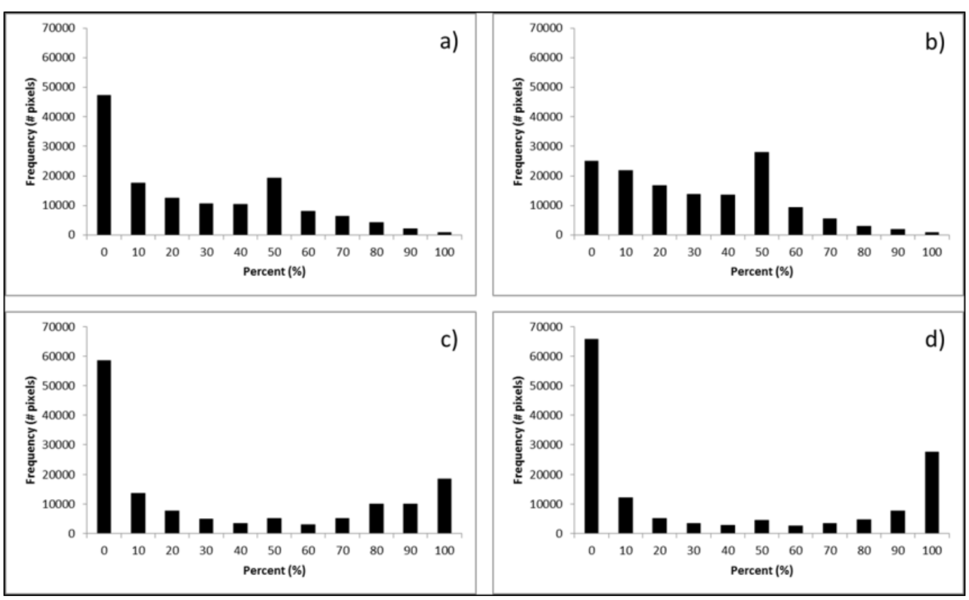

Figure 16. Frequency histograms (number of pixels) of the seasonal contribution (%) of High Phytoplankton Biomass in the Slope offshore subdivision of the Scotian Shelf bioregion: a) Winter (upper left panel), b) Spring (upper right panel), c) Summer (lower left panel), and d) Autumn (lower right panel).

The Slope retains the three-belt feature of pigment contribution throughout the four seasons (Figure 15). Winter becomes particularly important for its contributions on the continental slope and rise, between the 58° and 66° W. Spring also has significant persistence along the same longitudes as in winter, but high percentages additionally emerge at the south-western and north-eastern extremes. Spring is the only season when significant areas on the abyssal plain show detectable phytoplankton biomass contributions. Notwithstanding, there are periods in summer and autumn when extremely high contribution is shown all along the continental slope, with values above 90%.

The seasonal histograms for the Slope are similar for winter and spring (Figure 16); in both seasons they are right-skewed, but with higher frequencies at 50%. Summer and autumn graphs are U-shaped, with the highest percentages of contribution from the continental slope and rise representing (approximately 20 x 10^3 pixels), and the largest number of pixels (approximately 60 x 10^3) with low percentages, corresponding to the wide and deep abyssal regions.

4. DISCUSSION

4.1 ANNUAL PERSISTENCE

The synoptic view of annual persistence of phytoplankton biomass in the Scotian Shelf bioregion shows the complexity of biologically rich areas (Figure 17). These persistent regions are associated with a variety of habitats that different marine species exploit throughout their life histories. It is well known that marine populations tend to aggregate for reproduction, feeding, protection, and migration, and their ability to perform these functions is dependent not only on interactions with other organisms, but on features of their physical environment. In general, physical oceanographic features such as eddies, meanders, and fronts provide the mechanisms that result in aggregation and enhanced primary production (Palacios *et al.* 2006).

4.1.1 Commercial Fisheries

The largest subdivision in this study, the Slope, is a highly and persistently phytoplankton-rich area, compared to the abyssal plain (Figure 17). This could explain why highly migratory species (albacore, bigeye and yellowfin tunas, swordfish, and porbeagle, mako and blue sharks), which do not directly consume phytoplankton, are caught along the border of the continental slope seaward of the Scotian Shelf (Breeze and Horsman 2005). Even if this region has low absolute concentrations of phytoplankton throughout the year compared to coastal regions (Appendix 1), it is rich relative to off-shelf waters and it seems to sustain an important path for the migration of these large pelagic fishes. The Central subdivision also shows low absolute values of chlorophyll throughout the years even though high numbers of large pelagic fish are caught in this region (Figure 18a).

Populations of crabs find suitable habitat in the northeastern area of the Eastern subdivision (Figures 17 and 18b). Commercial exploitations of red and snow crabs, as well as northern shrimp are successful in this area (Breeze and Horsman 2005).

The Western subdivision, with high phytoplankton biomass in particular on Georges Bank and Gulf of Maine (Figure 17), is well known for ground fish abundance. Main locations of commercial species captures are shown in Figure 18c. The fisheries include cod, pollock, flatfishes, (e.g. yellowtail, witch and winter flounders, and American plaice), silver hake, and redfish. Other species are white hake, cusk, skate, monkfish and sculpin. Scallop and lobster are also abundant in this subdivision (Breeze and Horsman 2005).

Oceanographic processes controlling the dispersion of phytoplankton are important for pelagic species, and fish larvae stand to benefit in phytoplankton-rich areas. Shackell and Frank (2000) and Horsman and Shackell (2009) studied the dynamics of biomass and diversity of fish larvae on the Canadian Scotian Shelf. Recently, Fisher *et al.* (2011) advanced a model reporting the results of explorations of Scotian Shelf and Bay of Fundy marine fish ecology and analyses of the match between community composition and habitat environmental factors during time periods significant to fisheries. These works advocate the use of remotely-sensed ecological indices to find spatial and temporal trophic matching between phytoplankton and fish larvae. Figure 18d suggest these links in the Western and Central subdivisions.

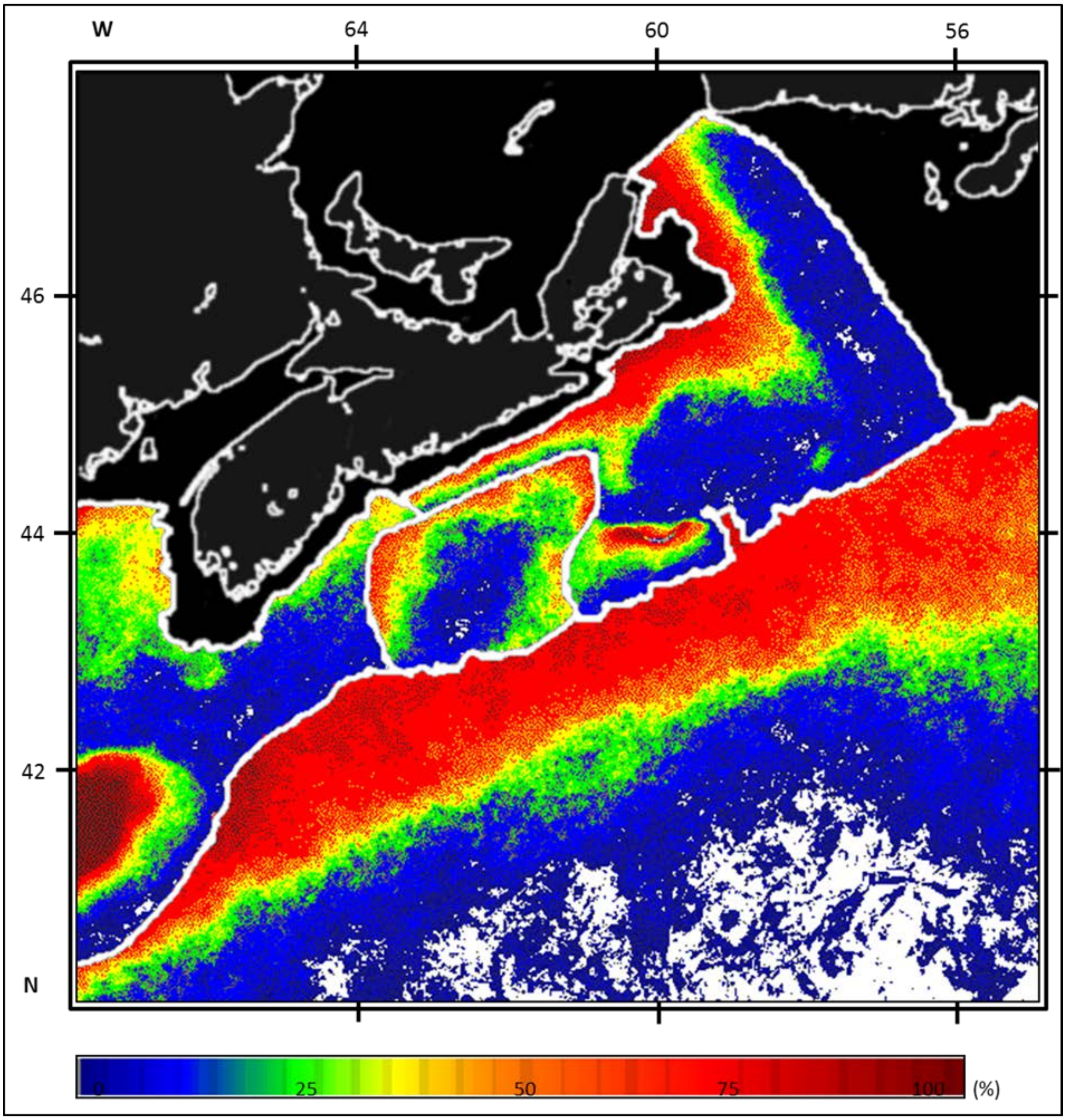

Figure 17. Synoptic maps of annual contributions (%) of High Phytoplankton Biomass in the Scotian Shelf bioregion. The four subdivisions (Western, Central, Eastern and Slope) are separated by a thick white line.

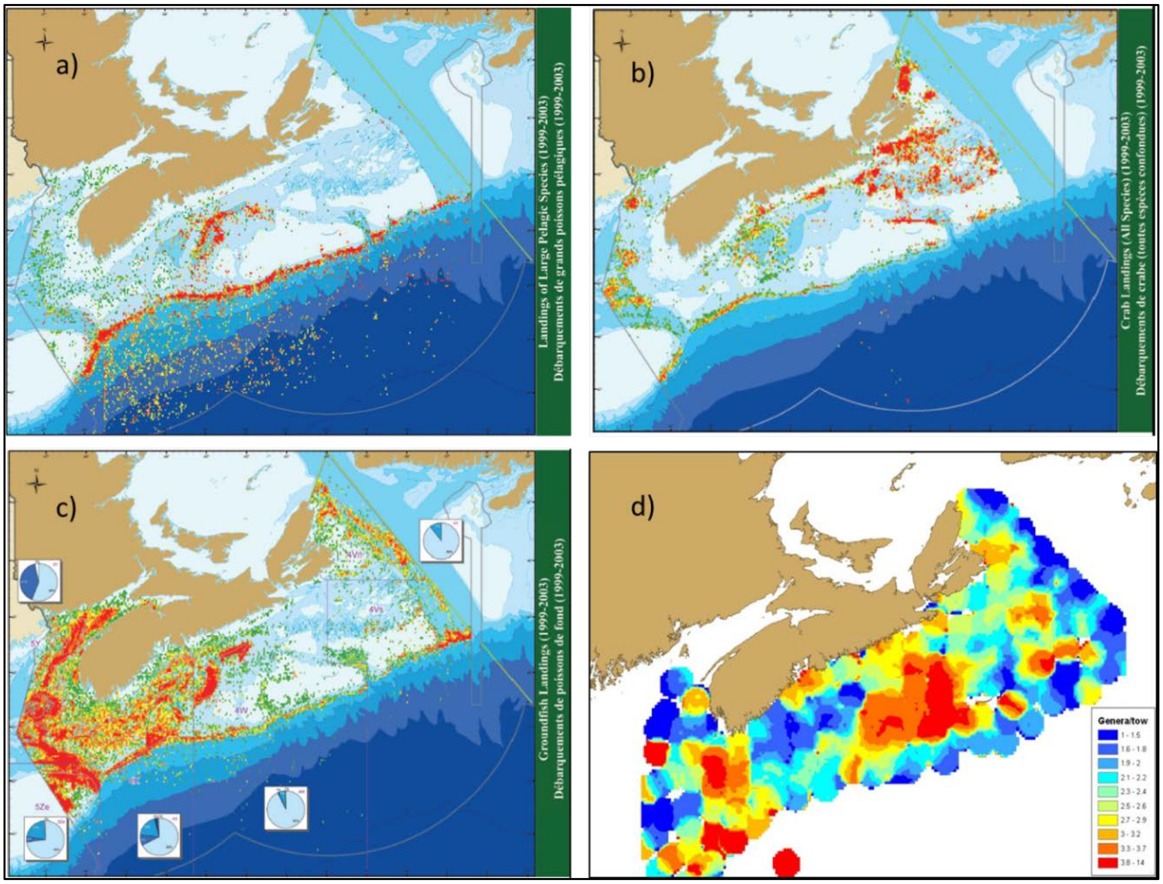

Figure 18. Landings of a) large pelagic species (1999-2003) (upper left panel), b) crabs (upper right panel), and c) groundfish (lower left panel) from Breeze and Horsman (2005) and d) fish larvae diversity (lower right panel) from Anna Serdynska (pers. comm.).

4.2 SEASONAL PERSISTENCE

Synoptic seasonal high-phytoplankton biomass in the middle and outer shelf subdivisions are closely associated with the physiographic and oceanographic characteristics. Maps of persistent chlorophyll contributions for winter, spring, summer and autumn are displayed in Figure 19. In addition to apparent associations for fish and crustaceans with phytoplankton-rich areas as previously discussed, marine mammals also show apparent associations with abundant phytoplankton biomass (as shown for whales in Figure 20).

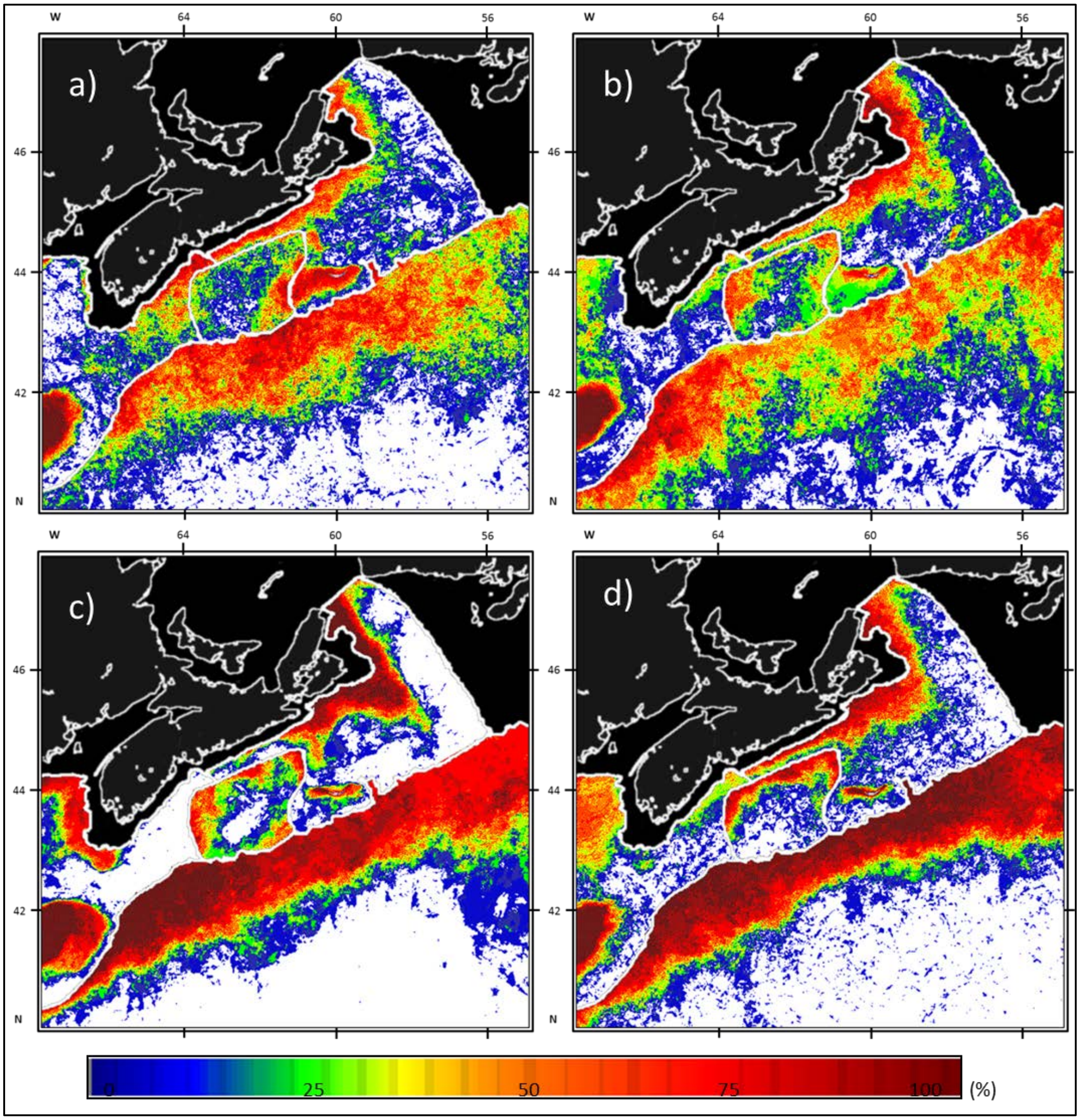

Figure 19. Synoptic maps of seasonal contributions (%) of High Phytoplankton Biomass in the Scotian Shelf bioregion: a) Winter (upper left panel), b) Spring (upper right panel), c) Summer (lower left panel), and d) Autumn (lower right panel).The subdivisions are separated by a thick white line.

4.2.1 Marine Mammals

The Scotian Shelf bioregion is well known for providing habitat to whales, dolphins and seals. Along the shelf break and in deeper water basins, there have been historical season-related observations of whales from late spring until early fall. However, as Breeze *et al*. (2002) noted, the reports are presumably biased because of fewer observation efforts on the eastern than western sides of the shelf and slope.

In spite of these caveats, spatial maps of occurrence for Sei, Blue, Sperm and Beaked whales (Figure 20) show that these habitats are persistently used by whales; for example, North Atlantic right, Minke, Fin, Humpback, and Northern bottlenose (Breeze *et al*. 2002). The association with phytoplankton-rich and persistent areas is evident.

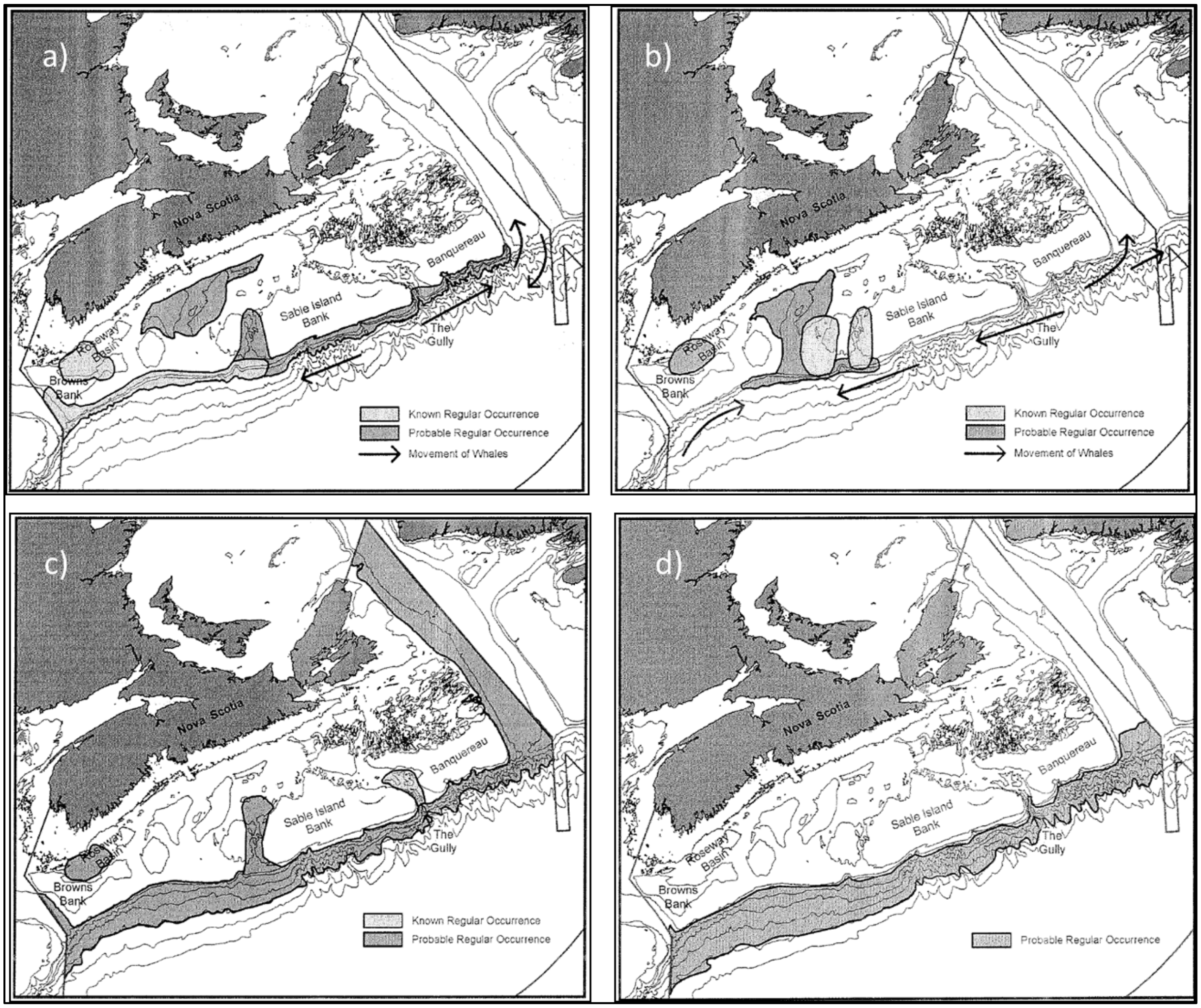

Figure 20. Areas of occurrence: a) Sei whale (upper left panel), b), Blue whale (upper right panel), c) Sperm whale (lower left panel), and d) Beaked whale (lower right panel) from Breeze et al. (2002).

In summary, this study has identified areas in the Scotian Shelf bioregion that exhibit persistent and elevated chlorophyll concentration, as indicated by significant positive departures from climatological norms. The results distinguish between western, central and eastern zones on the mid- and outer-Scotian Shelf, where traditional fisheries are located. The outward open-water region (rise and slope) appears as an outstanding environment recurrently inhabited by large pelagic fishes and mammals. Annual and seasonal analyses undergird the relative spatial and temporal significance of each subdivision. These results can be the basis for future studies focused on the fate of surface phytoplankton through analyses of vertical and horizontal dynamics of the water masses.

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APPENDICES

APPENDIX 1

Eleven year (from 2003 to 2013) climatology composite images of chlorophyll_a (mg/m^3) for each of the forty-eight weeks from December to January are shown in Figures AP1-1 to AP1-12.

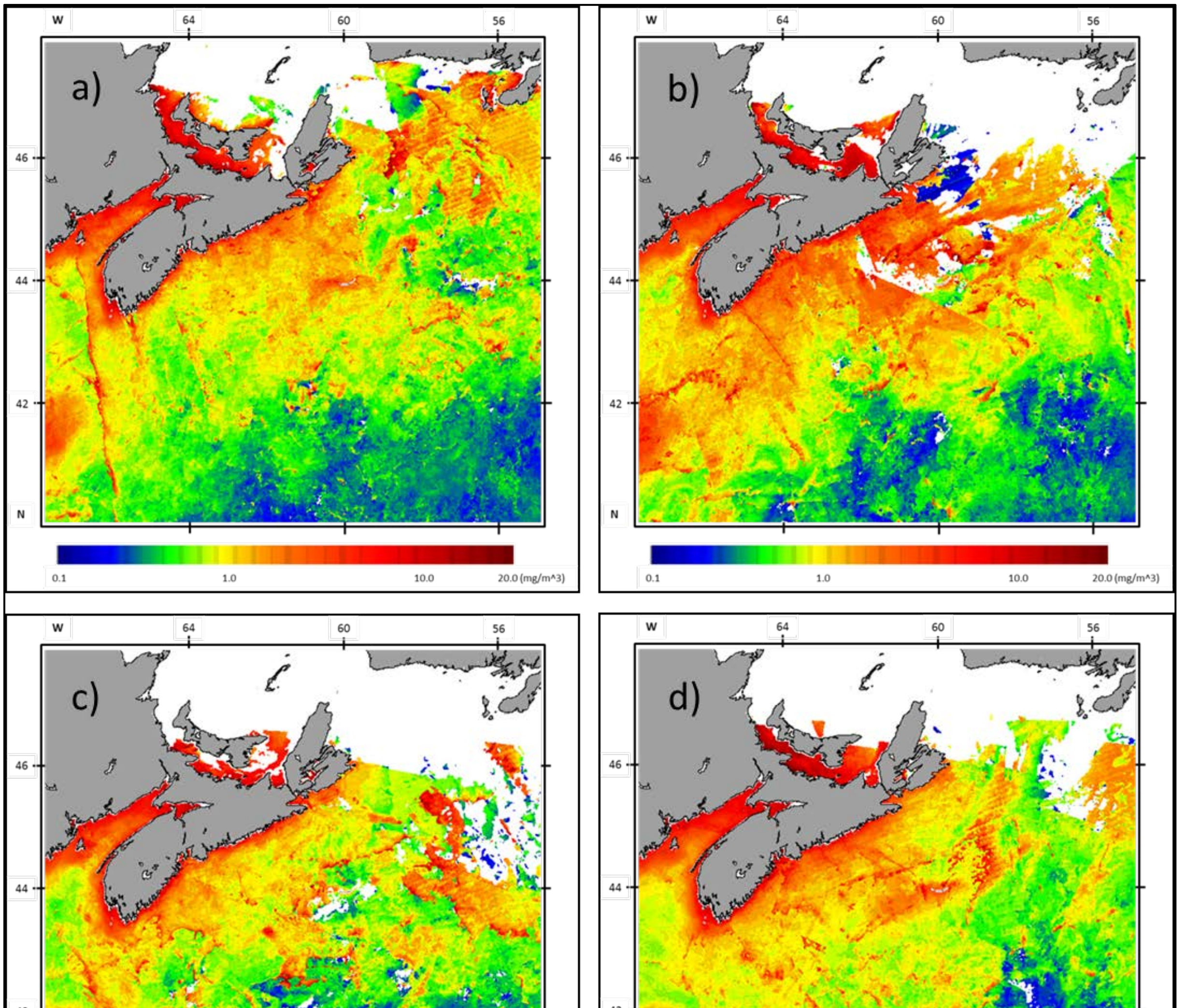

Figure AP1-1. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, December: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

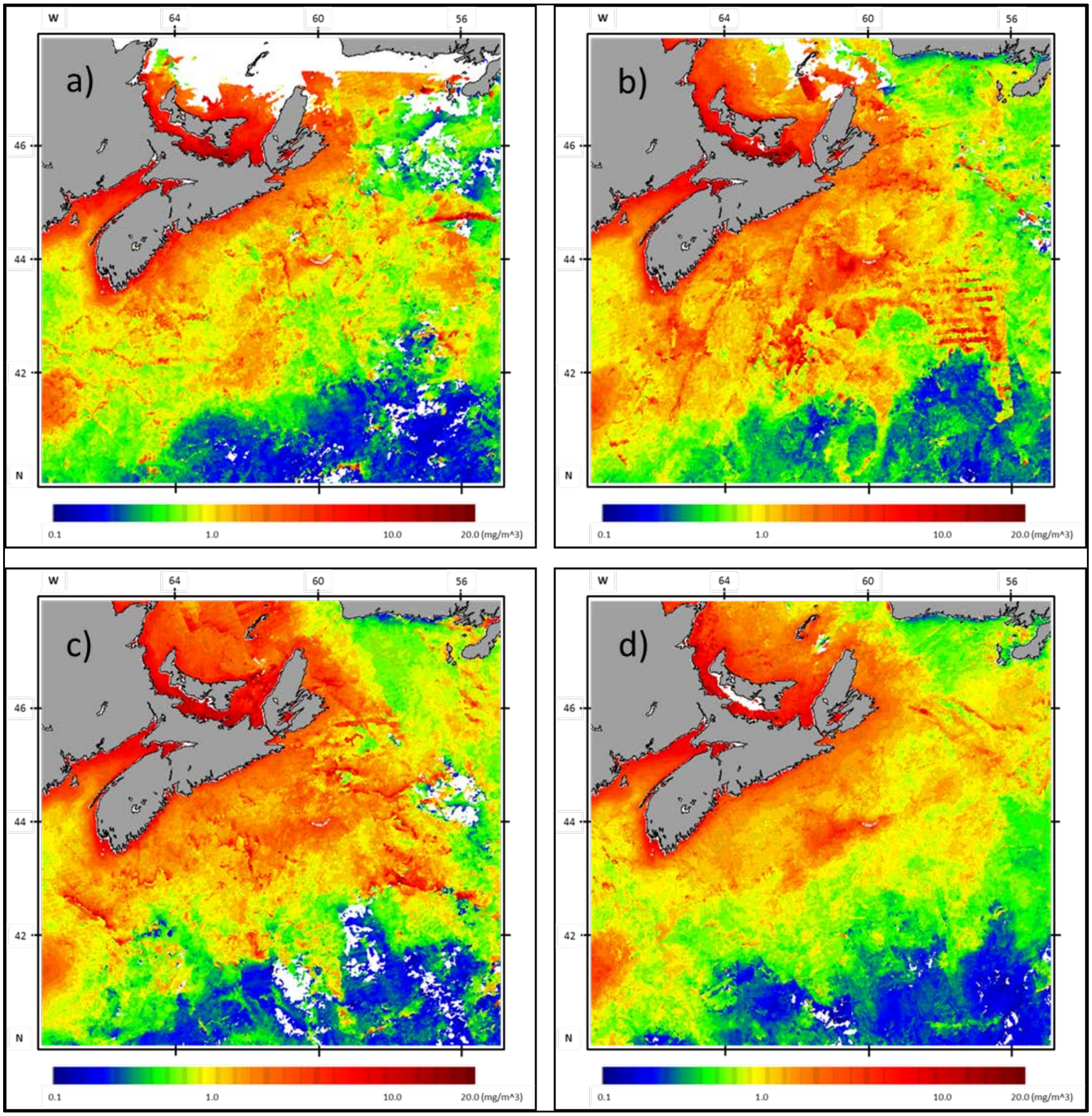

Figure AP1-2. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, January: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

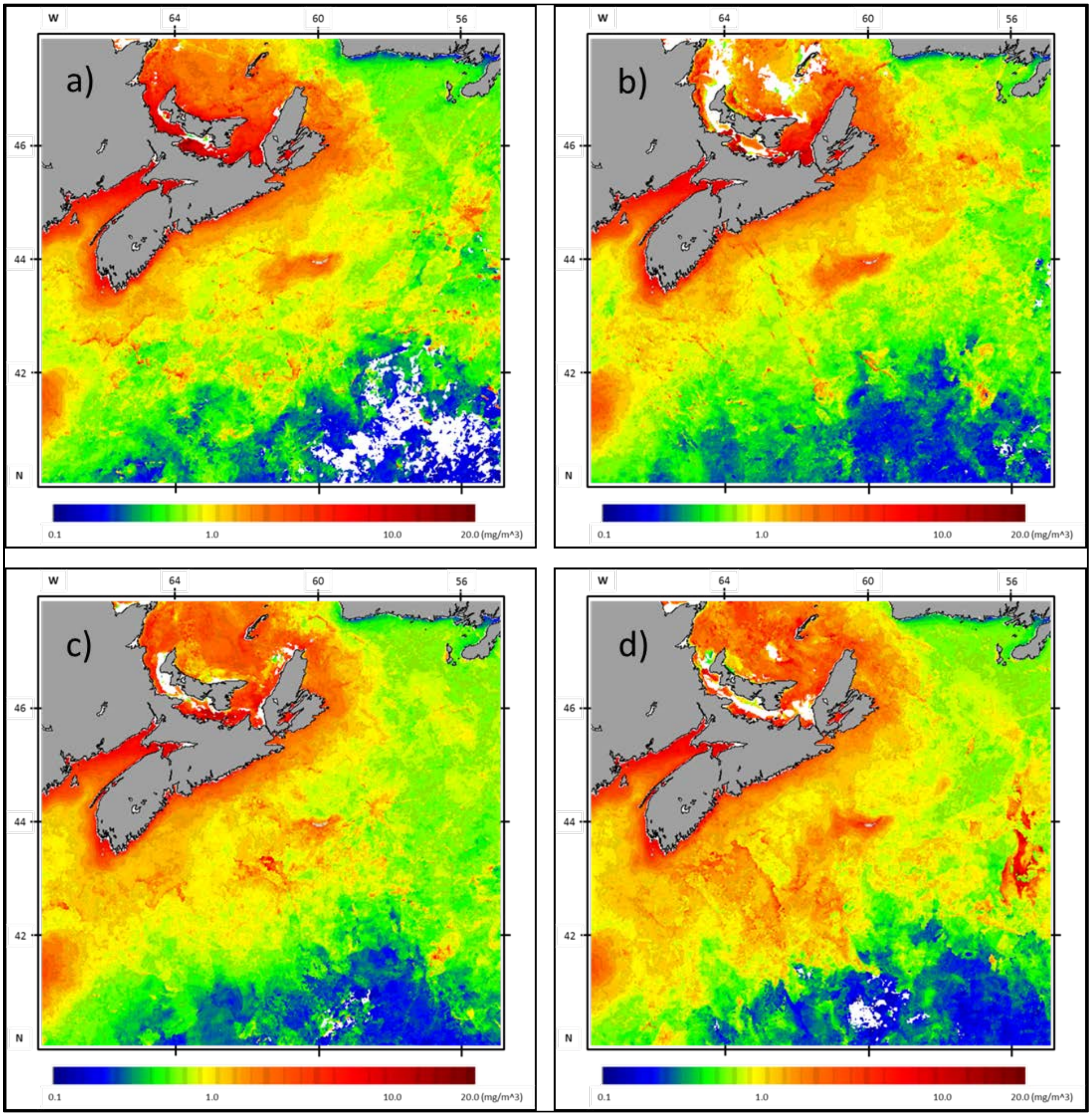

Figure AP1-3. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, February: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

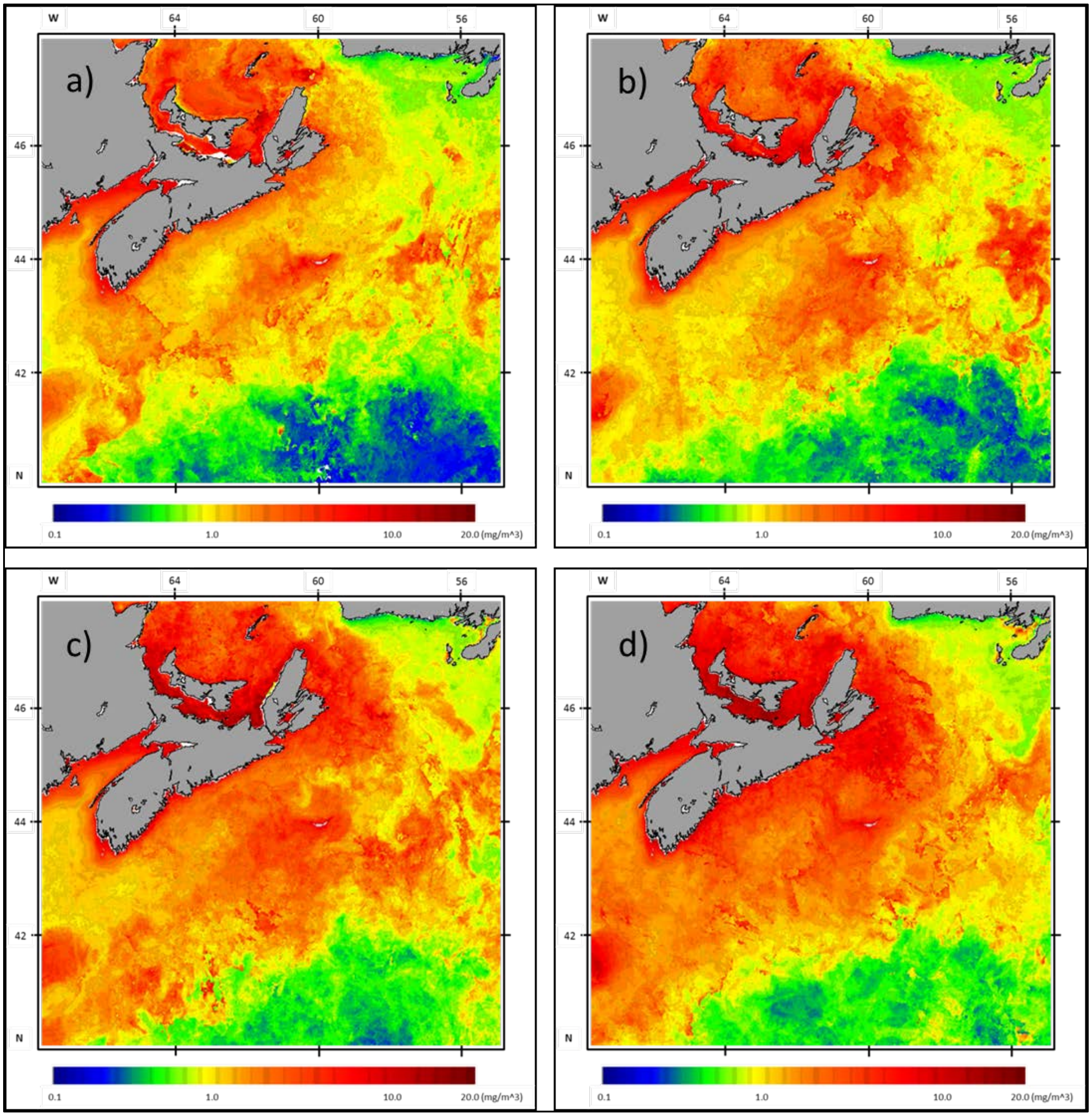

Figure AP1-4. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, March: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

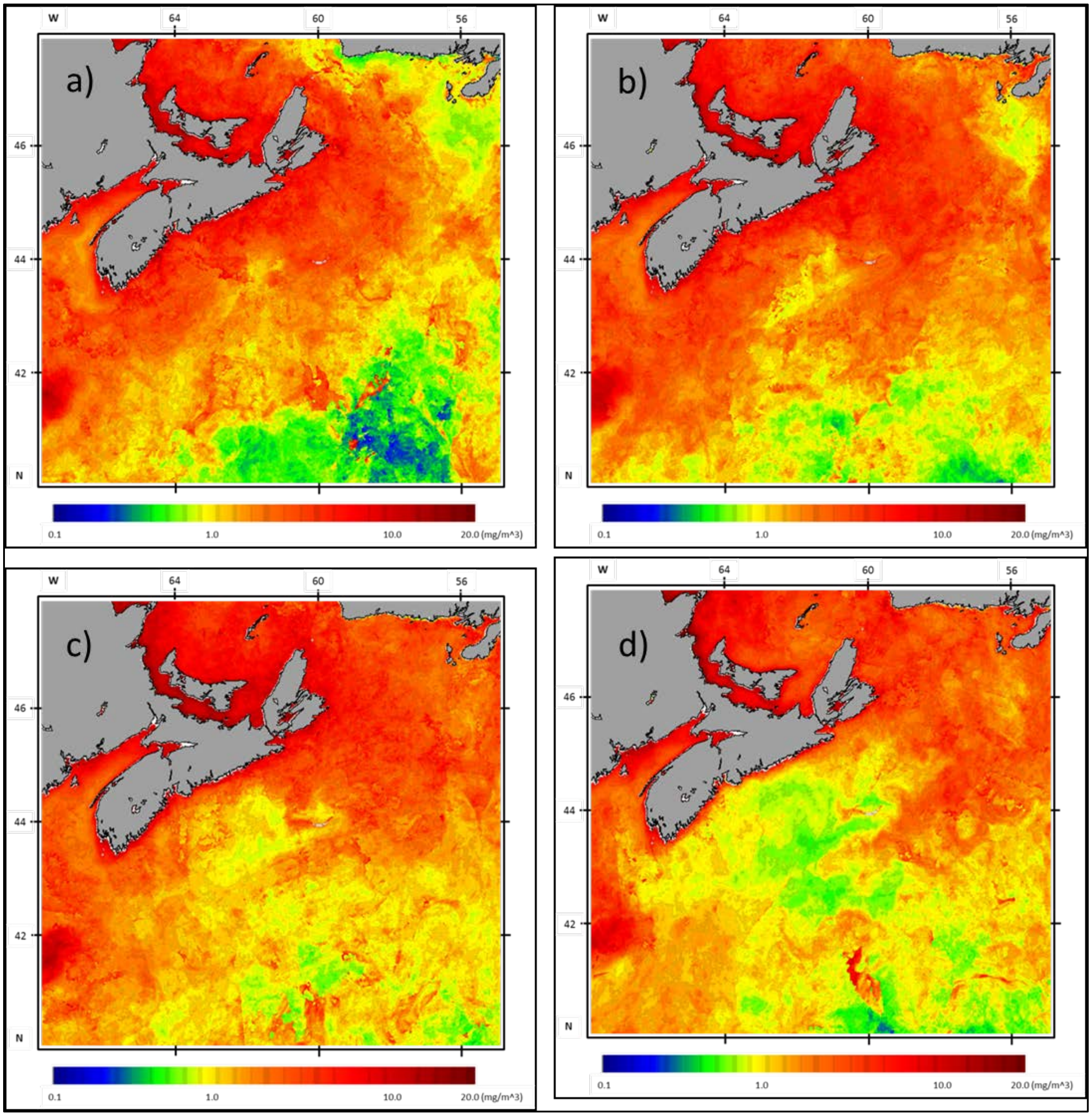

Figure AP1-5. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, April: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

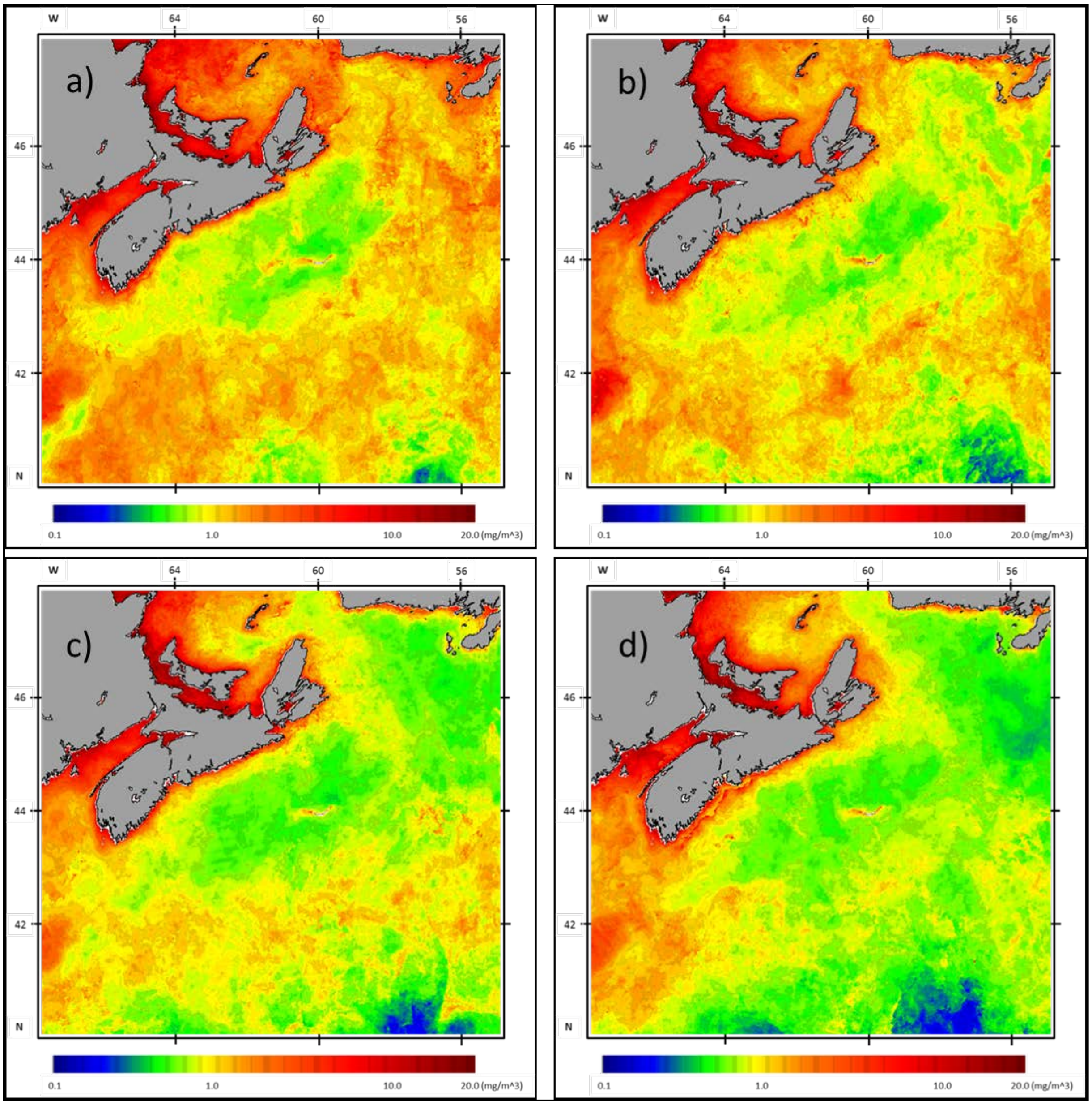

Figure AP1-6. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, May: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

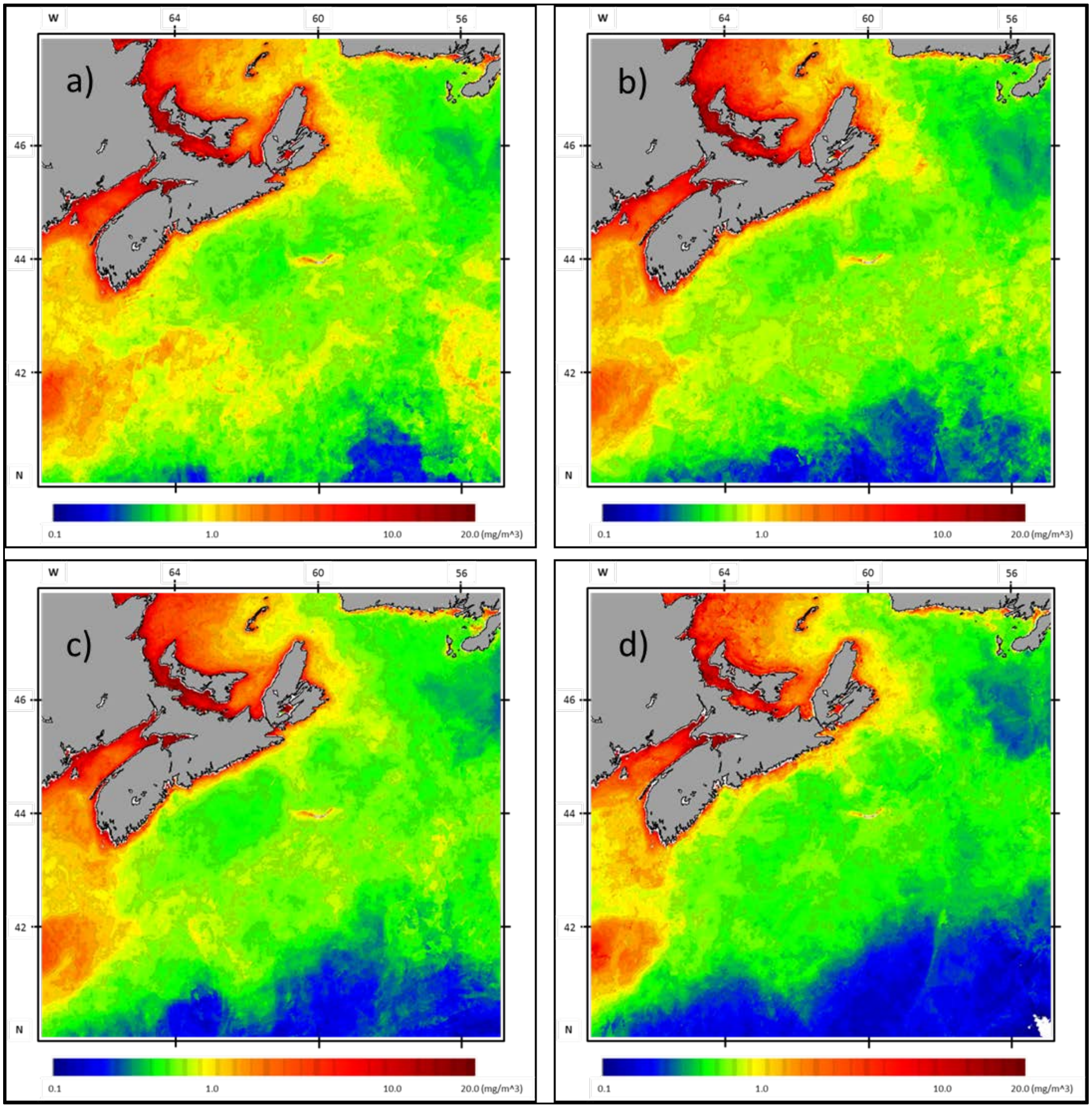

Figure AP1-7. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, June: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

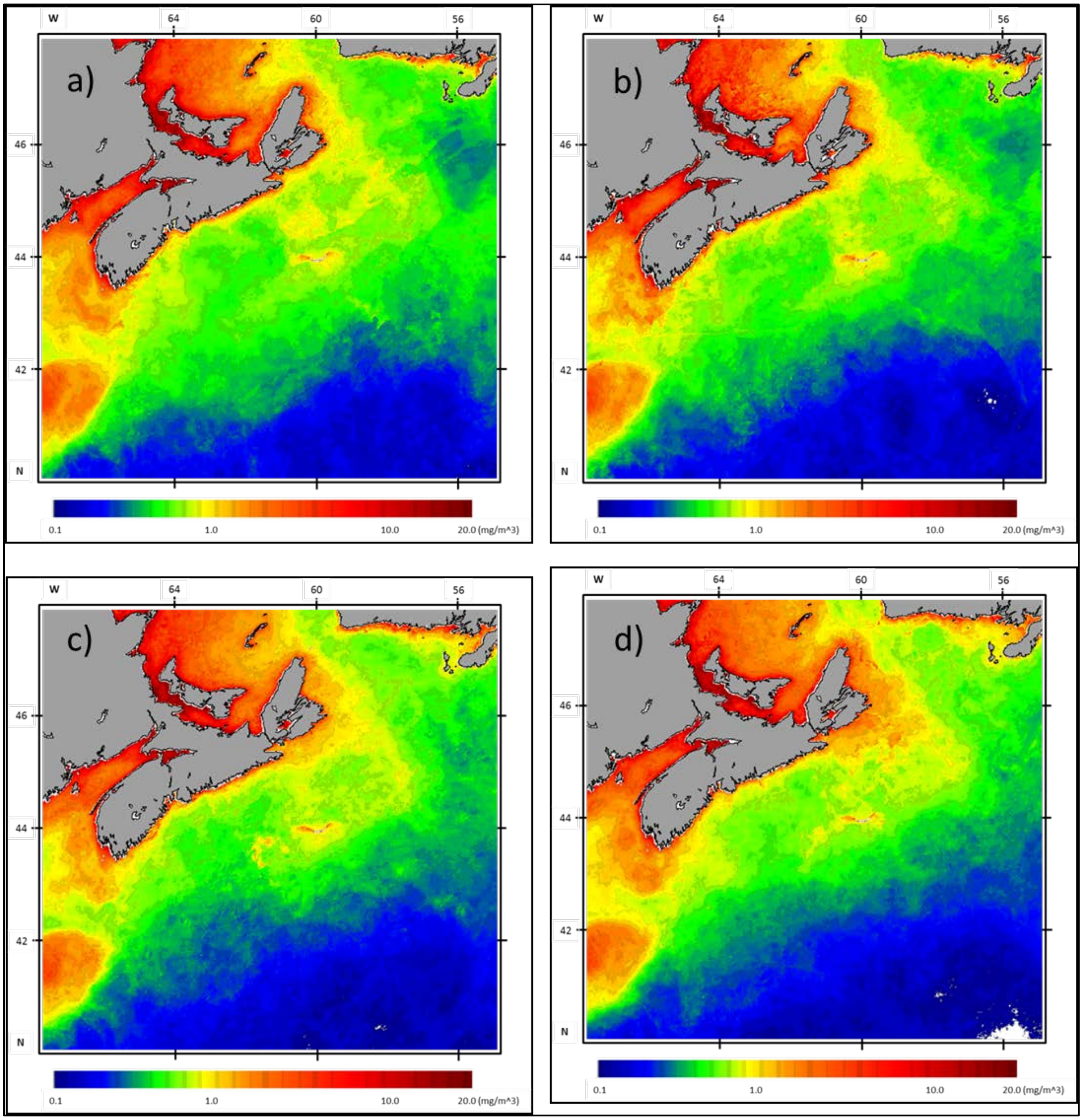

Figure AP1-8. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, July: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

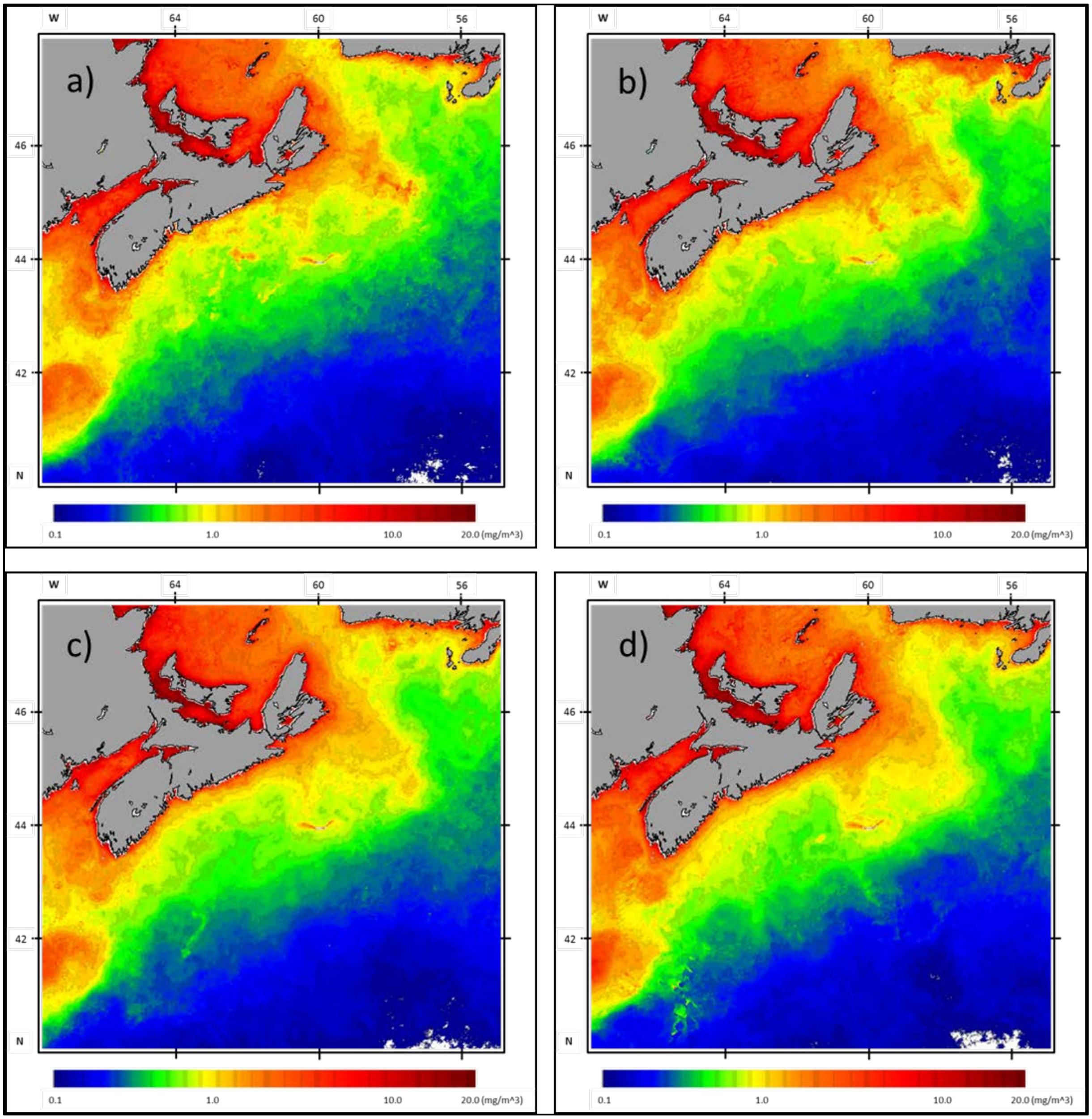

Figure AP1-9. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, August: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

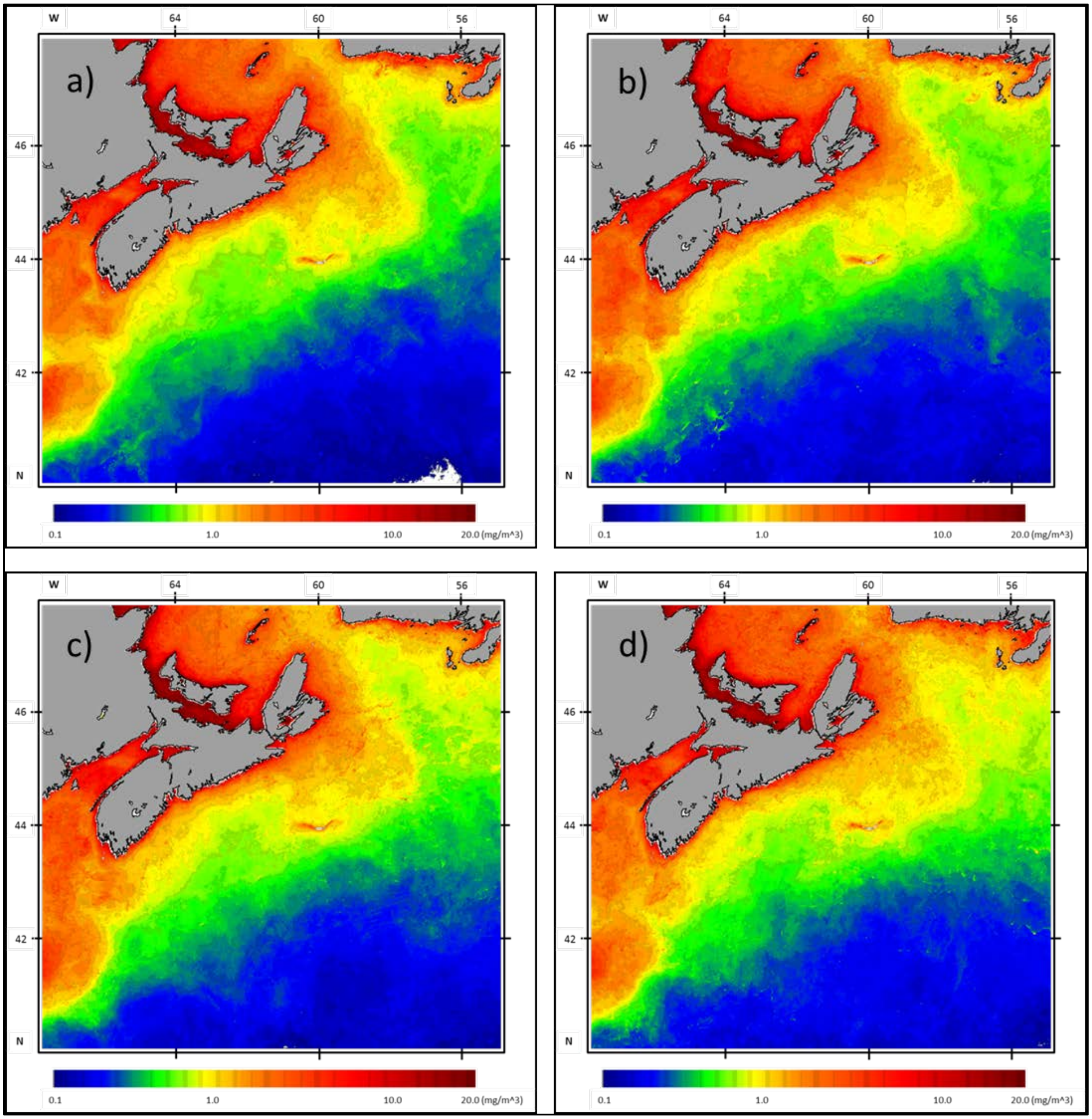

Figure AP1-10. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, September: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

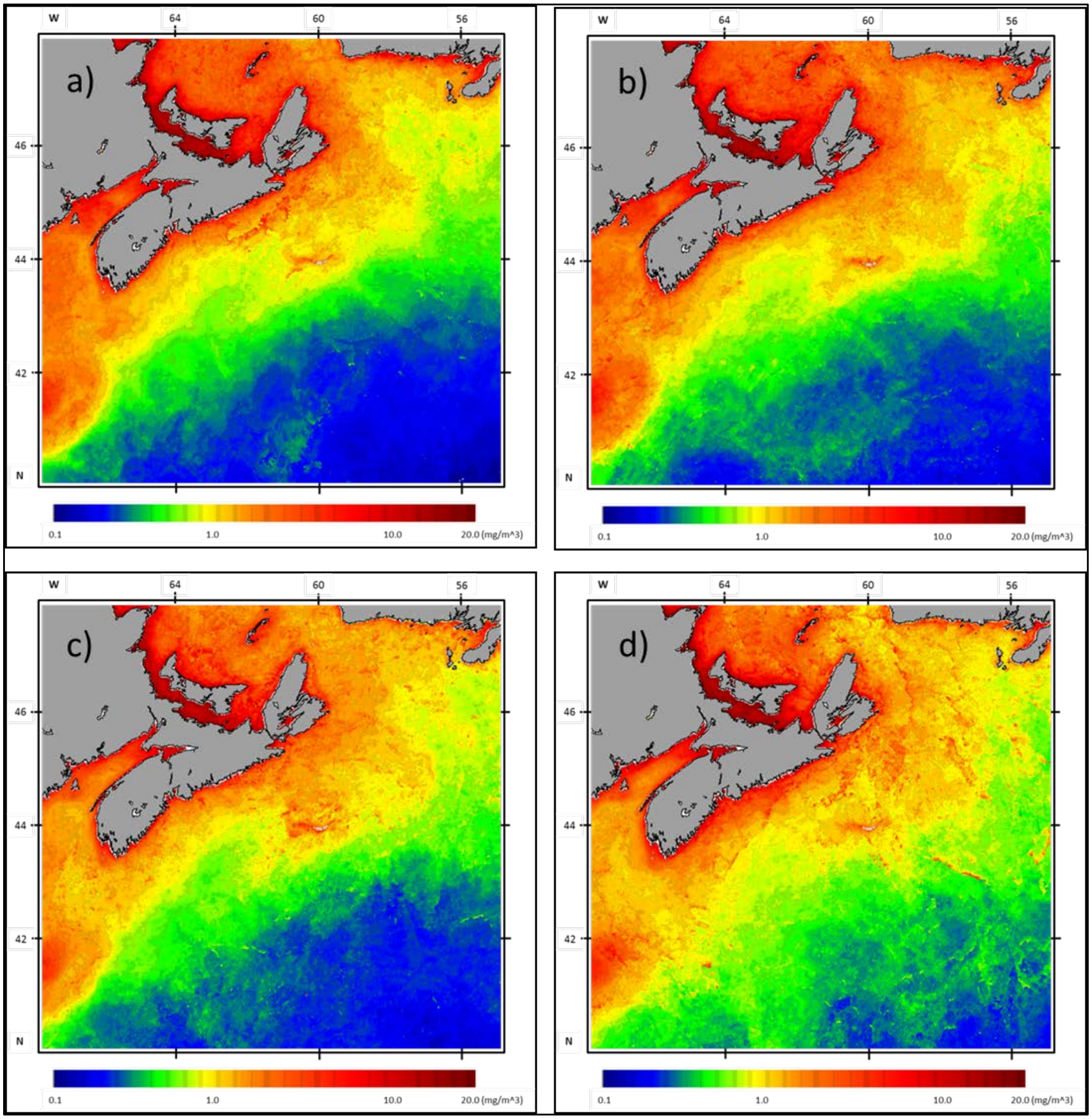

Figure AP1-11. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, October: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

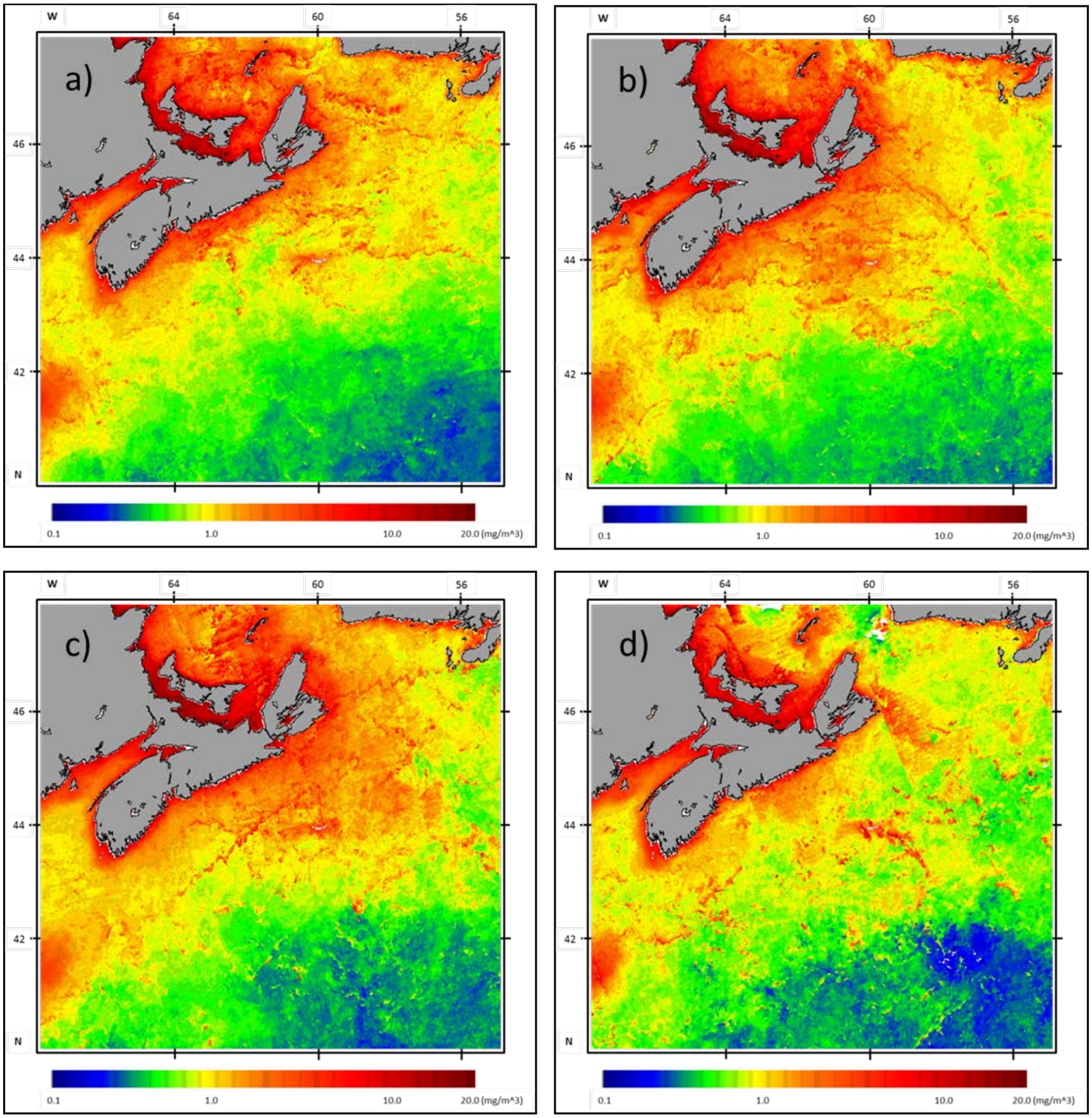

Figure AP1-12. Chlorophyll_a (mg/m^3) MODIS climatology 2003-2013, November: a) week 1 (upper left panel), b) week 2 (upper right panel), c) week 3 (lower left panel), and d) week 4 (lower right panel).

APPENDIX 2

Table AP2-1. Data from the climatology images of weekly Chlorophyll-a concentration. They correspond to four Scotian Shelf subdivisions: Western, Central, Eastern and Slope. The median chlorophyll_a (mg/m^3), number of pixels, standard deviation (σ), and median plus half of σ are shown.

Time (mo / wk)	Western				Central				Eastern				Slope			
	Median (mg/m^3)	Number pixel	Std Dev (σ)	Median (+ 0.5 σ)	Median (mg/m^3)	Number pixel	Std Dev (σ)	Median (+ 0.5 σ)	Median (mg/m^3)	Number pixel	Std Dev (σ)	Median (+ 0.5 σ)	Median (mg/m^3)	Number pixel	Std Dev (σ)	Median (+ 0.5 σ)
12 / 1	0.700	28605	0.474	0.937	0.776	13312	0.206	0.879	0.831	37783	1.021	1.341	0.417	139016	0.331	0.582
12 / 2	0.939	28604	0.580	1.229	0.776	9984	0.210	0.881	1.099	27203	1.410	1.804	0.475	138219	0.420	0.685
12 / 3	0.738	28605	0.512	0.994	0.756	13311	0.428	0.970	0.684	27446	1.035	1.201	0.374	134240	0.561	0.655
12 / 4	0.751	28605	0.432	0.967	0.868	13312	0.472	1.104	0.745	32368	0.601	1.046	0.424	139014	0.274	0.561
01 / 1	0.753	28605	0.445	0.976	0.816	13305	0.316	0.974	0.830	39241	0.555	1.107	0.487	136038	0.503	0.738
01 / 2	0.888	28605	0.508	1.142	1.124	13312	0.526	1.387	0.904	41567	0.757	1.283	0.536	138963	0.684	0.878
01 / 3	0.920	28605	0.596	1.218	1.094	13312	0.665	1.427	1.051	41831	0.709	1.406	0.490	131297	0.647	0.814
01 / 4	0.794	28605	0.382	0.985	0.973	13312	0.286	1.116	0.875	42132	0.388	1.069	0.439	138323	0.212	0.545
02 / 1	0.773	28605	0.248	0.897	0.730	13312	0.179	0.820	0.713	42132	0.295	0.860	0.454	128165	0.247	0.578
02 / 2	0.783	28605	0.246	0.906	0.762	13312	0.180	0.852	0.825	42113	0.305	0.977	0.434	139090	0.181	0.525
02 / 3	0.868	28605	0.218	0.977	0.791	13312	0.375	0.979	0.682	42131	0.274	0.819	0.482	139166	0.196	0.580
02 / 4	0.890	28605	0.242	1.011	0.849	13312	0.230	0.964	0.742	42148	0.299	0.891	0.551	138133	0.524	0.813
03 / 1	0.909	28605	0.255	1.037	0.958	13312	0.272	1.094	0.856	42141	0.468	1.090	0.585	139535	0.421	0.795
03 / 2	0.837	28605	0.492	1.083	1.021	13312	0.303	1.173	1.000	42136	0.758	1.379	0.657	139614	0.558	0.936
03 / 3	0.927	28605	0.459	1.157	1.448	13312	0.459	1.677	1.382	42144	0.897	1.830	0.831	139614	0.518	1.090
03 / 4	1.280	28605	0.944	1.752	1.570	13312	0.524	1.832	1.803	42146	1.318	2.462	0.743	139614	0.435	0.960
04 / 1	1.983	28605	1.277	2.622	1.656	13312	0.811	2.061	1.911	42144	0.863	2.342	0.843	139608	0.453	1.070
04 / 2	2.184	28605	1.260	2.814	1.471	13312	0.675	1.809	2.487	42147	0.818	2.896	0.952	139614	0.448	1.176
04 / 3	1.693	28605	1.411	2.398	0.820	13312	0.285	0.962	2.264	42142	0.914	2.721	0.888	139614	0.378	1.077
04 / 4	1.073	28605	1.226	1.686	0.597	13312	0.092	0.643	1.584	42135	0.835	2.001	0.820	139614	0.441	1.040
05 / 1	0.884	28605	0.526	1.147	0.583	13312	0.079	0.623	0.732	42138	0.346	0.905	0.869	139614	0.226	0.982
05 / 2	0.958	28605	0.930	1.423	0.604	13312	0.089	0.648	0.624	42154	0.197	0.723	0.764	139614	0.216	0.872
05 / 3	0.785	28605	0.275	0.923	0.478	13312	0.050	0.503	0.539	42131	0.130	0.604	0.654	139614	0.156	0.732
05 / 4	0.981	28605	0.364	1.163	0.493	13312	0.095	0.540	0.522	42145	0.142	0.593	0.557	139614	0.163	0.639
06 / 1	0.806	28605	0.344	0.978	0.470	13312	0.052	0.496	0.522	42145	0.141	0.592	0.513	139614	0.155	0.590
06 / 2	0.867	28605	0.316	1.025	0.480	13312	0.044	0.502	0.493	42134	0.142	0.564	0.467	139614	0.134	0.534
06 / 3	0.839	28605	0.312	0.995	0.435	13312	0.042	0.456	0.488	42143	0.104	0.540	0.422	139614	0.131	0.488
06 / 4	0.756	28605	0.480	0.996	0.435	13312	0.045	0.457	0.459	42135	0.150	0.534	0.334	139614	0.114	0.391
07 / 1	0.804	28605	0.331	0.969	0.447	13312	0.048	0.471	0.541	42132	0.144	0.613	0.287	139614	0.104	0.339
07 / 2	0.722	28605	0.324	0.884	0.451	13312	0.043	0.472	0.527	42139	0.121	0.587	0.250	139614	0.096	0.298
07 / 3	0.688	28605	0.333	0.854	0.430	13312	0.080	0.470	0.564	42144	0.127	0.628	0.234	139614	0.087	0.278
07 / 4	0.767	28605	0.316	0.925	0.490	13312	0.046	0.513	0.588	42137	0.193	0.684	0.229	139614	0.093	0.275
08 / 1	0.801	28605	0.345	0.973	0.535	13312	0.117	0.593	0.637	42145	0.262	0.768	0.218	139614	0.088	0.262
08 / 2	0.825	28605	0.360	1.005	0.519	13312	0.083	0.561	0.732	42142	0.299	0.882	0.210	139614	0.082	0.251
08 / 3	0.807	28605	0.351	0.983	0.501	13312	0.074	0.538	0.700	42144	0.258	0.829	0.213	139614	0.086	0.256
08 / 4	0.875	28605	0.465	1.108	0.509	13312	0.077	0.547	0.708	42145	0.329	0.873	0.204	139614	0.091	0.249
09 / 1	0.920	28605	0.467	1.154	0.520	13312	0.064	0.552	0.733	42147	0.294	0.880	0.214	139614	0.094	0.261
09 / 2	1.006	28605	0.539	1.275	0.508	13312	0.078	0.547	0.698	42142	0.311	0.853	0.220	139614	0.087	0.263
09 / 3	1.108	28605	0.523	1.370	0.581	13312	0.088	0.625	0.777	42149	0.280	0.917	0.228	139614	0.098	0.277
09 / 4	1.018	28605	0.425	1.230	0.547	13312	0.094	0.594	0.784	42147	0.314	0.941	0.229	139614	0.109	0.284
10 / 1	1.133	28605	0.403	1.334	0.639	13312	0.200	0.739	0.842	42145	0.358	1.021	0.254	139614	0.109	0.308
10 / 2	1.165	28605	0.501	1.416	0.658	13312	0.111	0.713	0.930	42142	0.336	1.098	0.286	139614	0.122	0.347
10 / 3	0.981	28605	0.335	1.149	0.671	13312	0.185	0.764	0.944	42134	0.290	1.089	0.275	139614	0.127	0.338
10 / 4	0.992	28605	0.467	1.226	0.733	13312	0.221	0.843	0.904	42132	0.364	1.086	0.379	139614	0.164	0.461
11 / 1	0.807	28605	0.378	0.996	0.668	13312	0.334	0.835	0.865	42135	0.490	1.110	0.405	139614	0.169	0.490
11 / 2	0.845	28605	0.457	1.074	0.932	13312	0.386	1.125	0.918	42138	0.455	1.146	0.436	139614	0.212	0.542
11 / 3	0.854	28605	0.293	1.000	0.869	13312	0.470	1.104	1.084	42140	0.520	1.344	0.440	139614	0.239	0.560
11 / 4	0.757	28605	0.490	1.002	0.734	13312	0.338	0.903	0.704	42042	0.457	0.933	0.414	139512	0.283	0.555