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Monitoring the North Atlantic using ocean colour data

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Abstract. The Remote Sensing Unit (RSU) at the Bedford Institute of Oceanography (BIO) has been monitoring the North Atlantic using ocean colour products for decades. Optical sensors used include CZCS, POLDER, SeaWiFS, MODIS/Aqua and MERIS. The monitoring area is defined by the Atlantic Zone Monitoring Program (AZMP) but certain products extend into Arctic waters, and all-Canadian waters which include the Pacific coast. RSU provides Level 3 images for various products in several formats and a range of temporal and spatial resolutions. Basic statistics for pre-defined areas of interest are compiled for each product. Climatologies and anomaly maps are also routinely produced, and custom products are delivered by request. RSU is involved in the generation of Level 4 products, such as characterizing the phenology of spring and fall phytoplankton blooms, computing primary production, using ocean colour to aid in EBSA (Ecologically and Biologically Significant Area) definition and developing habitat suitability maps. Upcoming operational products include maps of diatom distribution, biogeochemical province boundaries, and products from sensors such as VIIRS (Visible Infrared Imaging Radiometer Suite), OLCI (Ocean Land Colour Instrument), and PACE (Pre-Aerosol, Clouds and ocean Ecosystem) hyperspectral microsatellite mission.

1. Introduction

Ocean colour is determined by light at the surface of the ocean, some of which penetrates and interacts with water molecules and other water constituents. In off-shore waters the most important constituent that influences water colour is phytoplankton, the microscopic green-plant community at the base of the oceanic food web. These plants consist almost entirely of organisms that contain chlorophyll, which modifies ocean colour. By detecting the presence of pigments in specific parts of the visible light spectrum using optical instruments on satellites, the amount and distribution of phytoplankton can be detected and calibrated in terms of chlorophyll concentration. Remotely-sensed estimation of chlorophyll is much more difficult in near-shore waters, where ocean colour is affected by coloured dissolved organic matter (CDOM), river runoff, and resuspension of sand and silt from the bottom.

The main goal of this document is to report on some of the satellite-derived products processed, and applications developed, at the Remote Sensing Unit (RSU) of the Bedford Institute of Oceanography. Routinely, RSU begins the analyses by downloading Level 2 data (derived geophysical variables grouped into a few product suites such as ocean colour and SST (sea-surface temperature) - http://oceancolor.gsfc.nasa.gov/cms/products), from NASA's (National Aeronautics and Space

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Administration) website (http://oceancolor.gsfc.nasa.gov/cms/dataaccess). This information is processed at RSU to generate Level 3 and Level 4 products (see definitions below), with different spatial and temporal resolutions. The Level 3 products are mainly derived from the photosynthetic pigment chlorophyll a (chlor_a). However, other products produced include Photosynthetically Active Radiation (PAR), Diffuse Attenuation Coefficient (Kd_490), Total Suspended Matter (TSM), Coccolithophore concentration and Sea Surface Temperature (SST). Some Level 4 products and their applications consist of primary production (PP), phytoplankton phenology and its significance on haddock and Northern shrimp, development of habitat suitability maps for Bluefin tuna, identification of ecological provinces, phytoplankton-rich areas and their contribution to habitat suitability maps for whales. The majority of products can be viewed at RSU's website: http://www.bio-iob.gc.ca/science/newtech-technouvelles/sensing-teledetection/index-en.php, and are available by request from Carla Caverhill (Caverhillc@mar.dfo-mpo.gc.ca).

2. Level 3 products

NASA defines Level 3 products as "derived geophysical variables that have been aggregated/projected onto a well-defined spatial grid over a well-defined time period" (http://oceancolor.gsfc.nasa.gov/cms/products). RSU develops many Level 3 products at various temporal and spatial scales. A few examples are described in the following section.

2.1. Chlorophyll concentration

RSU's Level 3 chlorophyll a products for the Northwest Atlantic are derived from Level 2 data. The chlor_a values are estimated by comparing the ratio of blue to green light and relating those ratios to known chlorophyll concentrations from the same times and locations as the satellite observations. The algorithm description can be found at http://oceancolor.gsfc.nasa.gov/REPROCESSING/R2009/ocv6/. Specific masks are applied on individual satellite passes at RSU; these include radiance above knee, high solar zenith angle, high satellite zenith angle and extreme sun glint. All available data for the selected period are combined to produce composite images; where there are multiple pixels at any location, they are averaged. Operational data are compiled at different spatial scales: 1.5, 4 and 9 km/pixel. Temporal scales include individual pass, day, week, semi-month, month, season, annual, multiannual and climatology.

The Biological Oceanography Division of BIO had been collecting measurements of phytoplankton pigment profiles for many years prior to the launch of the first ocean colour sensor, CZCS, in 1978 [1, 4]. Following CZCS, other sensors have been utilised at the RSU to study chlorophyll. Sensors include POLarization and Directionality of the Earth's Reflectances (POLDER), Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS), and Medium-Spectral Resolution Imaging Spectrometer (MERIS).

Derived synoptic maps are a useful complement to ship-based measurements of chlorophyll that cannot come close to the frequency and spatial coverage provided by satellite data. Results of a simple comparison of *in situ* measurements and satellite-derived data allow an approximation of the accuracy of satellite estimates of chlorophyll-a in the Northwest Atlantic [5].

Time-series of satellite-derived chlorophyll values are constructed to compute statistics for each of the AZMP regions. Climatologies are implemented and scorecard indices are calculated based on normalized, and seasonally adjusted annual anomalies, a compact format used to better understand the Northwest Atlantic ecosystem's spatial and temporal variability [6, 7 and 8]. Time-series data of surface chlorophyll facilitate inter-annual comparison of phytoplankton bloom phenology, which is of particular interest for studying species of scientific and commercial importance. Figure 1 shows SeaWiFS derived seasonal climatologies (1999 - 2010), illustrating the Northwest Atlantic patterns of variability.

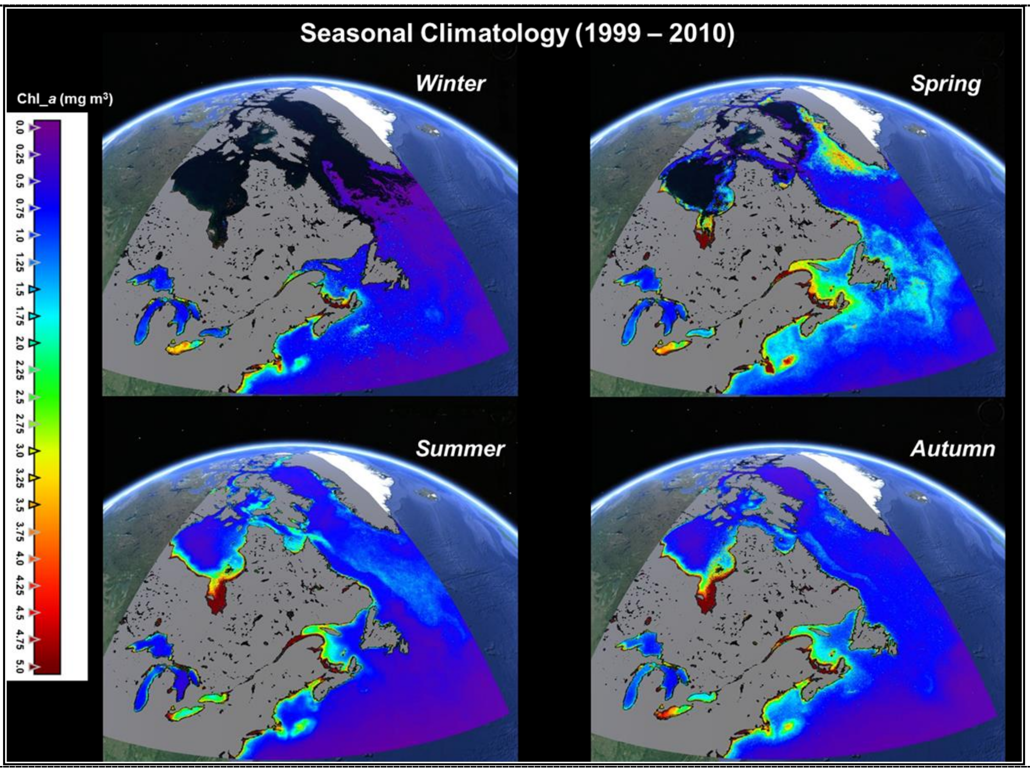

Figure 1. SeaWiFS-derived seasonal climatologies of chlorophyll (mg m^{-3}) for the Northwest Atlantic (1999 - 2010).

3. Level 4 products

NASA considers Level 4 data as "model output or results from analyses of lower level data (e.g., variables derived from multiple measurements)" (http://oceancolor.gsfc.nasa.gov/cms/products). Various L4 products and applications developed at RSU are described in the next two sections.

3.1. Primary Production

RSU/BIO/DFO has been at the forefront of satellite-derived ocean colour exploration, in particular researching how this new technology can be used to estimate primary production [1]. Computation of remotely-sensed PP starts with satellite estimates of phytoplankton content in the surface waters of the ocean. This information, combined with *in situ* data on the vertical chlorophyll distribution and the phytoplankton's photosynthetic response to light are the first materials needed to estimate water-column primary production. Early investigations established and tested the theory on CZCS data [2]; this set the stage for analysing future datasets from other remote-sensing instruments. The proof-of-concept calculations of PP used latitude and water-depth categories to partition the North Atlantic into biogeochemical regions, which were assigned seasonal parameters describing vertical biomass distribution and photosynthetic response [3].

Improvements on the PP methodology have been applied on larger areas of the ocean [9]. Figure 2 illustrates SeaWiFS-derived seasonal climatologies of PP (mg C m^{-2} d^{-1}) for the Northwest Atlantic (1999 - 2010). In 1995, a BIO-based study estimated global primary production in the ocean using CZCS data [10]. This research demonstrated that at large scales, ocean-colour data provide an ideal vehicle for studying the effects of major events such as El Niño on the global marine ecosystem, making it important in studies of the ocean carbon cycle, greenhouse gas effect and climate change. Future work at RSU will recreate the global-scale primary production maps using the next generation of ocean colour sensors.

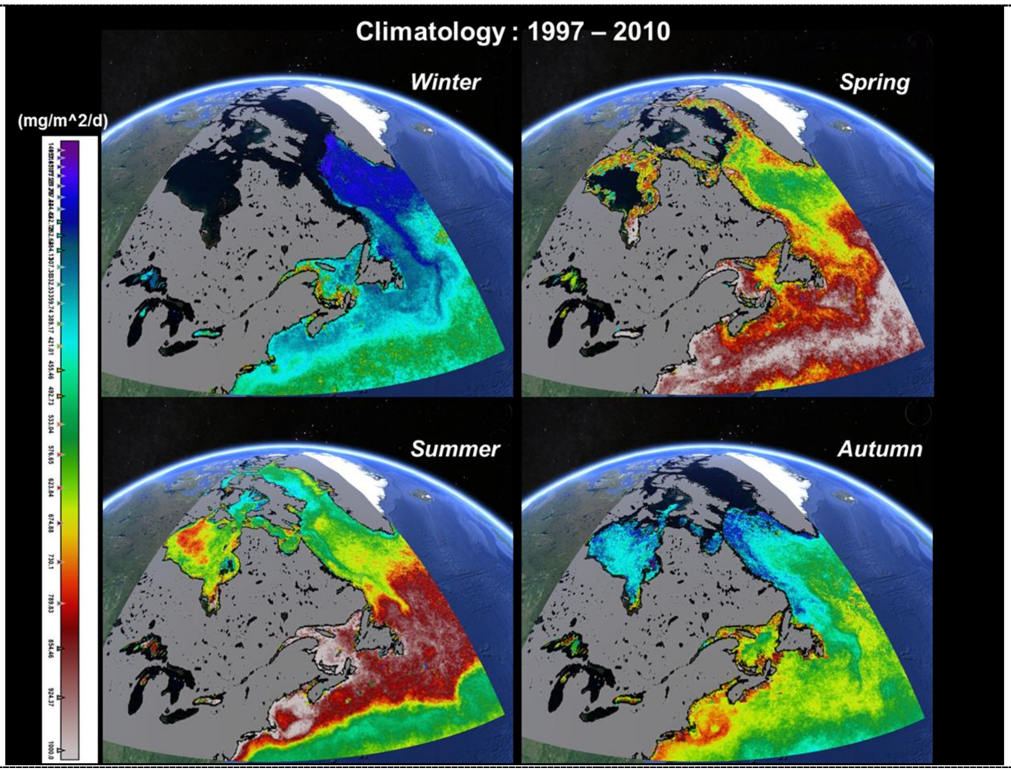

Figure 2. SeaWiFS-derived seasonal climatologies of PP (mg C m^{-2} d^{-1}) for the Northwest Atlantic (1999 - 2010).

3.2 Phenology of phytoplankton blooms

Another seminal application of satellite-derived ocean colour data at RSU is studying the phenology of phytoplankton blooms in the North Atlantic [11]. The seasonal phytoplankton phenology has been characterised by objective and quantitative criteria [12]. The indices that can be estimated include maximum observed chlorophyll-a (intensity); time when biomass first exceeds a threshold value of the maximum (initiation); time when the maximum intensity occurs (timing); and the period during which the biomass remains above the threshold (duration).

It has been found that inter-annual fluctuations in the timing of spring bloom account for a significant fraction of the inter-annual variance in survival of haddock larvae (autotrophic dependence) [11]. Significant correlations have also been obtained between the phytoplankton bloom intensity and timing and the size of young Northern shrimp [13]. Timing of northern shrimp egg hatching has been matched with that of the local spring phytoplankton bloom as a function of latitude [14]. In most parts of the North Atlantic, egg hatching for Northern shrimp stocks occurs within one week of the initiation of the spring phytoplankton bloom.

3.3 Additional examples of Level 4 products

The delineation of dynamic ecological province boundaries in the North West Atlantic [15] is another example of a Level 4 product developed at BIO. This study combined 10 years of satellite-derived phytoplankton biomass and community composition data and sea-surface temperature in association with depth, latitude, and longitude.

One more example of an RSU Level 4 product is maps of habitat suitability for the Atlantic Bluefin Tuna (*Thunnus thynnus*), a species that migrates seasonally in the Southern Gulf of St. Lawrence. The method includes the combination of satellite-derived composites of chlor_a and TSM from MERIS (provided by the European Space Agency), and SST from AVHRR (provided by P. Larouche

IML/DFO), information on *in situ* catches (2002 to 2011) and a map of bathymetry. The spatial and temporal location of fish captures provided information on the physical and biological tuna preferences used to build weekly habitat suitability maps. Figure 3 shows the climatological habitat suitability map. This study was conducted in collaboration with Dr. Alex Hanke from St. Andrews Biological Station (SABS/DFO). It is important to mention that since 2011 the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed Atlantic Bluefin Tuna as endangered. COSEWIC states that “This iconic fish has been heavily exploited for over 40 years and the current abundance of spawning individuals is the lowest observed” [16].

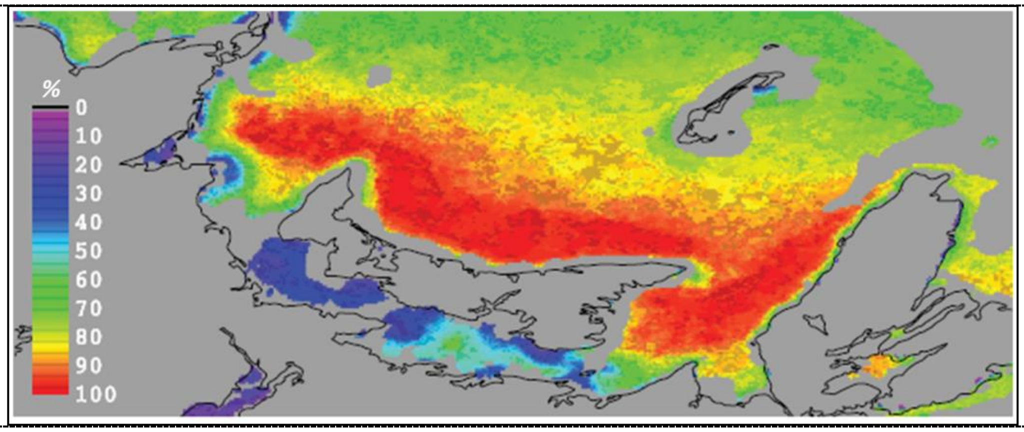

Figure 3. Habitat suitability map of Bluefin tuna in the southern Gulf of St. Lawrence.

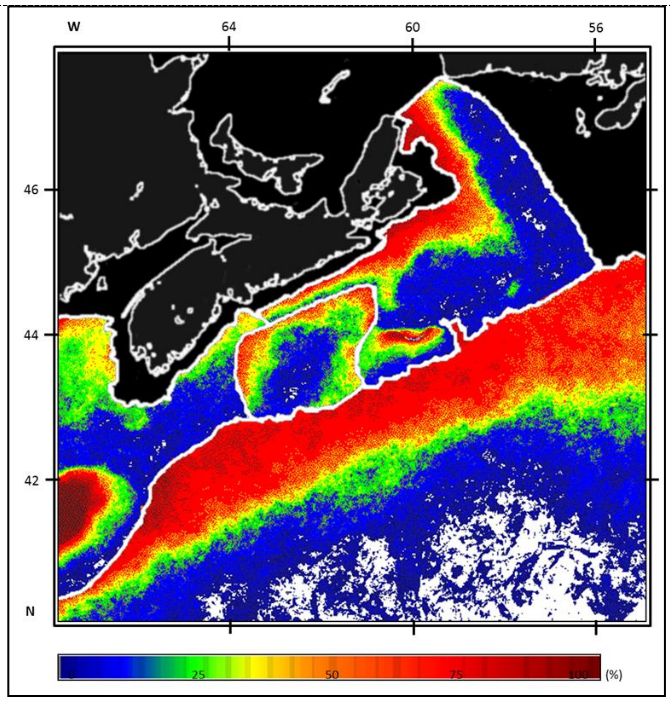

Figure 4. Map of phytoplankton-rich areas on the Scotian Shelf, represented by contributions (%) of remotely-sensed (MODIS) persistent elevated chlorophyll concentration [16].

Other Level 4 products have been recently developed at RSU; one of them is a method for the identification of phytoplankton-rich areas, represented by remotely-sensed persistent elevated chlorophyll concentration. These areas, derived from ocean colour, have been a useful aid in EBSA (Ecologically and Biologically Significant Area) definition and the development of habitat suitability maps. Figure 4 illustrates a synoptic map of the Scotian Shelf bioregion where areas with different percentage contribution are distinguished 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, such as tuna and whales [17].

3.4 Case-studies of present activities

An ongoing collaboration with Newfoundland-based researchers is incorporating the new satellite-derived concept of phytoplankton-rich areas [17], to study the distribution of endangered whales in Atlantic Canada [18]. This approach identify persistently and biologically rich spaces such as the Slope, where 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. The area clearly identifies the regular and relatively phytoplankton biomass important zones on this large-scale oceanic environment, where the blue and bottlenose whales have been sightseen. The ocean colour-derived data are associated with other information such as cetacean sighting, ocean depth, a topographic complexity index, bottom aspect, and sea-surface temperature, to generate habitat suitability maps. Two species under study are the Blue Whale (*Balaenoptera musculus*) and Northern Bottlenose whale (*Hyperoodon ampullatus*). Development of maps used data on phytoplankton-rich areas, with 26% of contribution for the Blue Whale (not shown), and 28% of contribution for Northern Bottlenose (Figure 5). Due in part to their small population size in Canadian waters as well as the increasing number of human activities in the

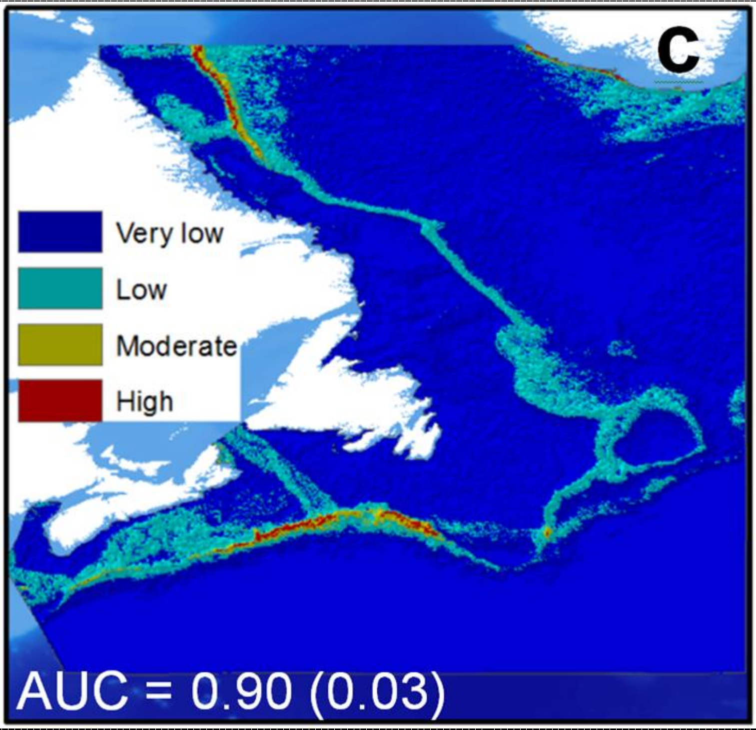

Figure 5. Habitat suitability map for Northern Bottlenose Whale (phytoplankton rich area = 28% contribution) [18].

Canadian Atlantic Ocean, the northwest Atlantic Blue Whale population and the Scotian Shelf Northern Bottlenose whale population are listed as Endangered under the Species at Risk Act (SARA) [19, 20].

3.5 Future research
The next generation of ocean-colour sensors includes VIIRS (Visible Infrared Imaging Radiometer Suite), the follow-up sensor to MODIS. VIIRS is a NASA/NOAA project that provides measurements of pigment concentrations, water clarity, suspended particulates, sea-surface temperature and other products. There will also be datasets from OLCI (Ocean and Land Colour Instrument), which is the follow-up sensor to MERIS from the European Space Agency. OLCI will provide ocean colour data at a 300m resolution. RSU is also planning to incorporate data from the Pre-Aerosol, Clouds and ocean Ecosystem (PACE) hyperspectral microsatellite mission, which will provide ecological information on coastal waters.

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