

Comparison of *in situ* and remotely-sensed (SeaWiFS) chlorophyll-*a* in the Northwest Atlantic

César Fuentes-Yaco^{1,2*}, Emmanuel Devred^{1,2}, Shubha Sathyendranath^{1,2}, Trevor Platt², Linda Payzant², Carla Caverhill², Cathy Porter², Heidi Maass², George N. White III²

¹ Department of Oceanography, Dalhousie University, Halifax, NS, B3H 4J1, Canada

² Department of Fisheries and Oceans, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, NS, B2Y 4A2, Canada

*[E-mail: Fuentes-YacoC@mar.dfo-mpo.gc.ca]

Received 1 November 2004, revised 6 April 2005

Field measurements of phytoplankton pigment (chlorophyll-*a*) from the Northwest Atlantic are compared with concurrent pigment concentrations derived from SeaWiFS data using NASA/SeaDAS algorithms known as Ocean Chlorophyll 2 (OC2) and OC4 (versions 4.1 and 4.3). The results showed broad agreement but estimates using the NASA algorithms tended to show uncertainties, with lower than *in situ* values at concentrations greater than 1 mg chl-*a* m⁻³. Regionally-, and seasonally-, adapted empirical corrections are developed in an attempt to reduce the bias. The magnitude of errors was quantified using linear regression. Further progress will require application of a theoretical regional ocean-colour model.

[Key words: Ocean colour, remote sensing, SeaWiFS, chlorophyll-*a*, phytoplankton pigment, Northwestern Atlantic]

[IPC Code: Int.Cl.⁷ G01J 3/28, G06K 7/10]

1. Introduction

Synoptic chlorophyll fields, derived from remotely-sensed data on ocean colour, play an increasingly important role in biological oceanography. Quantification of the accuracy and precision of the satellite-derived products will enhance their scientific utility. Studies on phytoplankton pigments measured *in situ* and by satellites have already been performed in the Northwest Atlantic (NWA) coastal areas. A primary study¹ analysed Coastal Zone Color Scanner (CZCS) images from the Scotian Shelf, and concluded that turbidity of coastal waters was a significant obstacle to successful interpretation of the ocean-colour archive. The Gulf of St. Lawrence has also been studied using CZCS imagery by Fuentes-Yaco *et al.*². Their methodology applied interactive procedures to the aerosol correction in the pigment calculations, which led to reasonable agreement between satellite-derived and *in situ* values. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) represented a new generation of sensors for satellite remote sensing³. Some previous studies have

compared phytoplankton pigment results obtained using the SeaWiFS from NWA with field data⁴⁻⁸. However, a comprehensive, large-scale comparison has not yet been attempted for the NWA region.

The main objective of this study is to compare chlorophyll-*a* measurements derived from SeaWiFS with coincidentally-collected *in situ* data, in an effort to help understand the performance of the algorithms. The standard NASA algorithms, used for a large diversity of bio-optical provinces^{9,10}, show mismatches in the NWA region: under-, and over-, estimation of *in situ* pigment values are observed above and below a threshold of ~1.0 mg chl-*a* m⁻³ respectively. Here, we explore how the chlorophyll retrieval might be improved by implementation of seasonal algorithms for the region. It is recognised that there is a cyclical domination of large cells (diatoms) during spring and small cells (flagellates) during summer in the Northwest Atlantic, as the result of seasonal succession¹¹. These naturally-occurring changes in phytoplankton assemblages modify the optical characteristics of phytoplankton, with a consequent impact on the performance of pigment retrieval algorithms applied to satellite data¹²⁻¹⁴.

* Corresponding author: C. Fuentes-Yaco

This study is not intended to be a validation of satellite algorithms: the mismatch in the scales of observation precludes it see for example the SeaWiFS protocols in the Sensor Intercomparison and Merger for Biological and Interdisciplinary Ocean Studies (SIMBIOS) Project¹⁵. Instead, this work outlines insights that can be garnered from a direct comparison of *in situ* and satellite-derived phytoplankton pigment data. The analysis is done for the Northwest Atlantic Region, a region of the world where *in situ* and satellite-derived measurements do not agree well when the global algorithm is applied¹⁶. When such comparisons are made, the results may often be affected by the small time lags in data collection, and by the differences in the scales of observation. However, by making a distinction between random and systematic errors, and by identifying the potential sources of differences, we can gain insight into the performance of the algorithm, and thus serve validation goals indirectly. It is an effective method when used judiciously, in the sense that it exploits a wealth of high-quality *in situ* data to improve the interpretation of satellite data. One of the prerequisites of such an analysis is that a large number of quality-controlled, matched pairs of data be available, to allow the use of appropriate statistical tools to identify sources of discrepancy. In this work, such a data set has been established, and is used in a careful analysis to draw some conclusions on the performance of the SeaWiFS algorithm in the North Western Atlantic.

2. Material and Methods

2.1 Study area

The Northwest Atlantic zone is defined here as the area between 39° N to 62.5° N and 42° W to 71° W (Fig. 1). According to Longhurst¹⁷, the study area includes several different biomes and provinces in the biogeochemical partition of the world oceans. The Atlantic Polar Biome includes the Atlantic Arctic and Boreal Polar provinces. The Gulf Stream and North Atlantic Drift provinces are enclosed in the Atlantic Westerly Winds Biome. The Atlantic Coastal Biome contains the Northwest Atlantic Shelves Province. Geographically, the study region includes from north to south: Davis Strait, Ungava Bay, Hudson Strait, Labrador Sea, Newfoundland Basin, Gulf of St. Lawrence, Laurentian Channel, Scotian Shelf, Georges Bank, and some portions of the Gulf Stream.

The advective circulation in the region of study is complex but can be characterised by the flow of

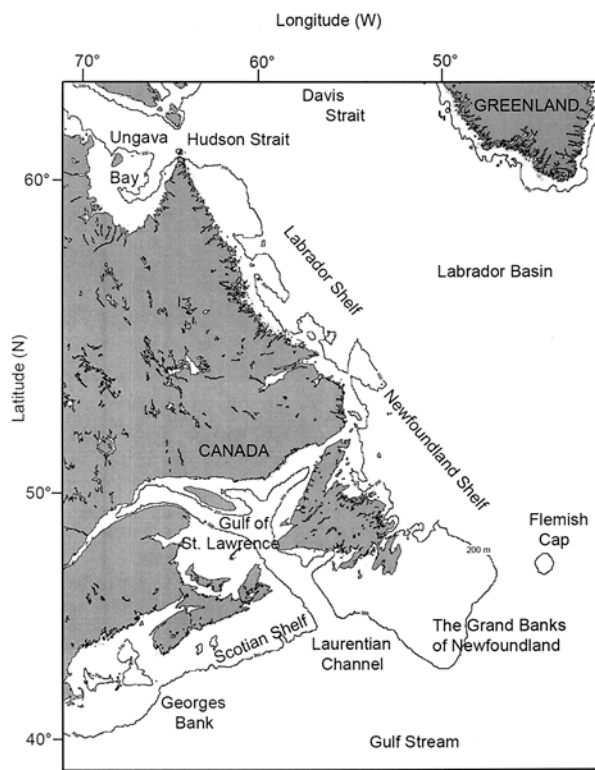


Fig. 1- Study area: Northwest Atlantic region (39°N to 62.5°N and 42°W to 71° W). Some geographical locations and the isobath of 200 m are indicated.

subpolar water toward the equator. Briefly, Loder *et al.*¹⁸ indicate that the main physical forcing in the region provides transport of relatively cool and fresh water from the Baffin Island Current to the Labrador and Newfoundland shelves and then onward to the Gulf of St. Lawrence, Scotian Shelf, and the Gulf of Maine. The influence of freshwater generally decreases downstream in spite of the St. Lawrence discharge. Sea surface temperature is controlled by solar radiation with a latitudinal gradient during summer. The winter season is characterised by cool temperatures with important losses of latent and sensible heat. Wind stress and the Gulf Stream exert strong influences on the regional circulation. High positive values of the North Atlantic Oscillation index (the difference in sea level barometric pressure between Iceland and the Azores) enhance the northwest wind stress, which can increase the southward advection of subpolar water. The influence of Gulf Stream in the southern region of the study area is through slope water intrusions and transient rings, varying as a function of the geographical position of the current. The study area is a region where physical forcing largely controls biological

responses. For example, during winter, wind stress and heat loss at the sea surface combine to force deep mixing against the remaining summer stratification of the water column, supplying nutrients from the bottom layers to the sea surface. During spring, stabilisation of the water column by solar heating supports by far the most extensive and strongest spring bloom anywhere in the oceans¹⁷.

2.2. *In situ* data

In situ data come from research cruises of the Bedford Institute of Oceanography (BIO), the Northwest Atlantic Fisheries Centre, the Maurice Lamontagne Institute and the St. Andrews Biological Station (all of them belong to the Canadian Department of Fisheries and Oceans) in the Northwestern Atlantic (Table 1). Chlorophyll-*a* concentrations measured at stations and along cruise tracks are used in the study for comparison with satellite-derived data. Water samples were collected at stations with Niskin bottles, in general every 5 or 10 m from the surface to 110 m. Water samples were also collected along ship tracks from a flow-through system with inflow located 4 m below the surface. Chlorophyll-*a* was measured by filtering replicate 100 ml samples through 25 mm Whatman MFS GF75 glass fibre filters under 200–250 mm mercury vacuum. Chlorophyll was extracted with 90% acetone at ambient temperature and placed at -20°C in the dark for 24 hours¹⁹. Chlorophyll-*a* was estimated from the samples using the fluorometric (Turner 10-005 fluorometer) technique of Yentsch & Menzel²⁰ as modified by Holm-Hansen *et al.*²¹, with and without acidification²². Station data were used to

estimate averages for the top 20 m of the water column. Data collected between 1997 and 2000 were used in the comparison.

2.3. Satellite data

The data described here are collected by the SeaWiFS sensor on OrbView-2 satellite, captured in real time at the receiving station in the remote-sensing laboratory of the Biological Oceanography Section at Bedford Institute of Oceanography, and processed in-house to obtain chlorophyll-*a* concentrations. In the NASA protocol for SeaWiFS data processing, ratios of water-leaving radiance in different spectral bands are used in empirical algorithms to retrieve chlorophyll concentration¹⁰. The software used for conventional retrieval is the SeaWiFS Data Analysis System (SeaDAS) [<http://seadas.gsfc.nasa.gov/>]. The catalogue of processed data consists of daily images from 1997 until present. From this data set, 123 images between 1997 and 2000 with 460 (451 for OC2 algorithm) corresponding *in situ* data were selected for testing the biomass-retrieval algorithms. The satellite-derived values were extracted before map projection and represent a mean of nine pixels (3 × 3 matrix) around the central pixel corresponding to the location of the *in situ* sample site. We used the 3 × 3 pixel matrix instead of the central pixel value to assess the local variability in the satellite-derived data. Only those pairs of satellite and *in situ* data collected on the same day are compared to evaluate algorithm performance. As in Casey & Gregg¹⁶, the pixel value obtained was considered to be the representative value for the day.

Table 1 — Research cruises for sampling *in situ* data in the Northwestern Atlantic. The responsible institution, location, date and number of data are indicated.

Institution	Cruise Location	Date	Number of data
BIO*	Scotian Shelf	October, 1997	18
BIO	Scotian Shelf	April, 1998	63
NAFC*	Labrador Sea	April, July, 1998	24
BIO	Scotian Shelf	October, 1998	36
MLI*	Gulf of St. Lawrence	November, 1998	18
BIO	Scotian Shelf	April, 1999	22
BIO	Labrador Sea	June – July, 1999	33
BIO	Scotian Shelf	October – November, 1999	43
BIO	Scotian Shelf	December, 1999	6
BIO	Scotian Shelf	April, 2000	61
NAFC	Scotian Shelf	April – May, 2000	15
BIO	Scotian Shelf	May – June, 2000	31
NAFC	Scotian Shelf	July, 2000	21
BIO	Scotian Shelf	October, 2000	69

*BIO = Bedford Institute of Oceanography, NAFC = Northwest Atlantic Fisheries Centre, MLI = Maurice Lamontagne Institute

2.4. Selection criteria

To identify satellite pixels for comparison with *in situ* data, in the first instance, the procedures established by NASA were followed, i.e.: no land, no clouds or ice, no sun glint, and total radiance to be above the knee value for SeaWiFS bands 7 (765 nm) and 8 (865 nm). This led to selection of 460 (or 451 for OC2) matched pairs of satellite and *in situ* data. Next, to minimise misleading results due to inclusion of problem pixels in the analysis, we also applied some additional selection criteria to the matched satellite data. These included: *a*) no failure of atmospheric correction algorithm; *b*) application of the satellite zenith angle mask, and *c*) low normalised water leaving radiance at 555 nm. Furthermore, we also applied a more stringent cloud mask. The SeaDAS package has the provision to apply a cloud mask²³, based on a threshold value for cloud albedo. The threshold value was modified for this study based on an analysis of paired images. For this analysis, we used 16 pairs of level-2 images from the same day with partially-overlapping passes (see example in Fig. 2A). Chlorophyll and cloud albedos were extracted for the overlapping pixels of each pair of images. The percentage differences in chlorophyll-*a* [(absolute difference / mean of the values) $\times 100$], for each pair of overlapping pixels was calculated for each image pair. The percentage difference for all the paired pixels were sorted into bins according to the value of cloud albedo (higher of the two values for each overlapping pair of pixels) in the range from 0.4 to 1.1 (the default cut-off value for SeaDAS OC4v4.1), with a bin size of 0.02. Only those containing more than 100 pixel pairs were retained for further analysis. Figure 2B shows the average of percentage difference in chlorophyll-*a* plotted against cloud albedo. The figure shows that the default threshold for cloud albedo (1.1) is probably too high for the present study area (NWA), since the percentage difference in retrieved chlorophyll is very high at this cloud albedo value.

In a related analysis, we determined whether, for any given overlapping pixel pair, the pixel with the higher cloud albedo produced the higher value of retrieved chlorophyll. These results are listed for all the 16 overlapping satellite passes in Table 2. For every pair of overlapping passes except one, higher values of retrieved chlorophyll were associated with the higher value cloud albedo. Based upon these results we adopted a cut-off for cloud albedo of 0.6 instead of the SeaDAS default threshold of 1.1. (In the

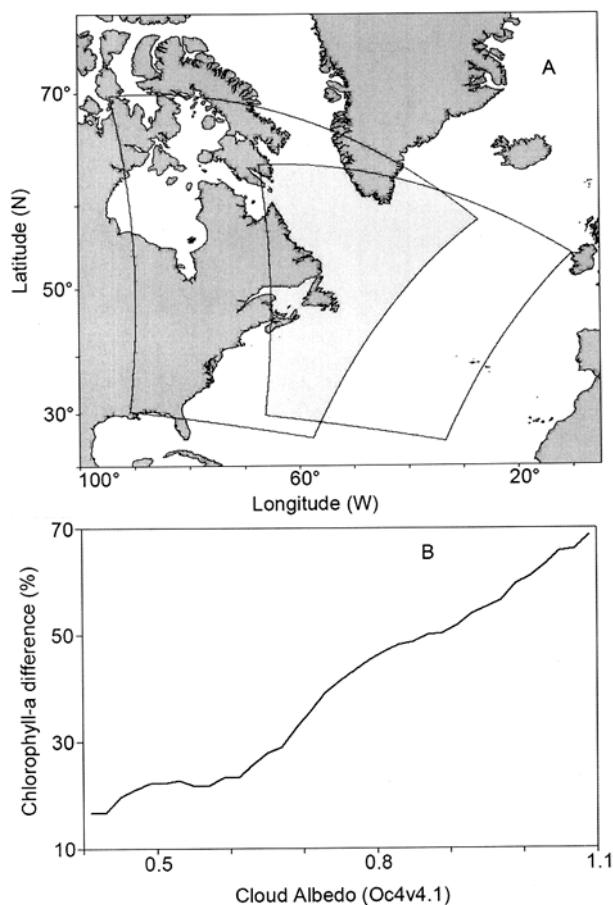


Fig. 2- A) Overlapping SeaWiFS passes over the Northwest Atlantic for May 15th, 2000. Left pass (S20001251712) corresponds to 17:12 UTM, and right pass (S20001251535) to 15:35 UTM. B) Plot of the average percentage difference in Chlorophyll-*a* and cloud albedo. See text for details in computations.

SeaDAS OC4 version 4.3, the scaling of the cloud mask parameter was changed compared with the earlier version of SeaDAS (OC4v4.1). In SeaDAS OC4v4.3, the equivalent parameter value corresponding to 0.6 in the earlier versions is 0.015.)

The angle between the SeaWiFS viewing direction and each pixel along a scan line varies from nadir to scan edge. An apparent effect of high view angles is that high values of computed pigment concentration are from along the lateral border of the images. This bias, which is a function of satellite zenith angle, may be produced because of the bidirectional structure of the upwelling radiance beneath the ocean surface and the emerging radiance fields²⁴. High view angles increase the difficulty of both accurate navigation and atmospheric correction²³. Eplee & McClain²⁵ propose three primary sources for the observed bias at high view angles: i) variations in the instrument response

Table 2 — Overlapping SeaWiFS passes with the number of matching pixels where the higher cloud albedo produced (Yes) or not (No) the higher value of retrieved chlorophyll; percentages are also indicated. The filenames represent: satellite name (S), year (yyyy), Julian day (ddd), and time (Universal Time Coordinated System: hours, minutes; hhmm), for the satellite pass.

Overlapping SeaWiFS Passes	Number of matching pixel pairs		
	Yes	No	Percentage
S20001251535 / S20001251712	27609	12406	69
S20001631518 / S20001631655	20512	11536	64
S20001661550 / S20001661727	49361	18798	72
S20001771536 / S20001771714	26778	17779	60
S20001791525 / S20001791702	24402	8930	73
S20002251555 / S20002251734	29233	19273	60
S20002281627 / S20002281805	31729	11673	73
S20002361541 / S20002361719	29937	16763	64
S20010681521 / S20010681658	12883	11191	54
S20010751526 / S20010751703	6965	14544	32
S20010981528 / S20010981705	21398	20326	51
S20011281531 / S20011281708	28375	11862	71
S20011401551 / S20011401729	26634	12376	68
S20011421539 / S20011421716	37048	23760	61
S20011441526 / S20011441703	17716	14423	55
S20011481502 / S20011481637	34434	14939	70

as a function of pixel number within the scan (scan modulation effects); ii) variations in the atmospheric correction as a function of optical path depth; and iii) variations in ocean reflectance. NASA/SeaDAS software has the option to cut off pixels with high satellite zenith angles, to avoid use of pixels contaminated by this particular source of error. Figure 3A shows examples of satellite zenith angles for SeaWiFS passes over the study area between April 19th and 21th, 2001. Figure 3B shows high chlorophyll concentrations in the Scotian Shelf during April 20th associated with high zenith angles. Therefore, pixels with zenith angles greater than 60 degrees were eliminated from the comparison, even though the image size was reduced considerably as consequence. This is the recommended cut off value in SeaDAS OC4v4.3.

In addition, the satellite values were eliminated if the 3×3 pixel matrix corresponding to the location of the *in situ* sampling did not meet the following criteria: first, the pigment values in at least five of the nine pixels had to be positive, and hence valid; second, the coefficient of variation computed for the valid pixels had to be less than 0.2 admittedly. The satellite data and the *in situ* data are not collected at time and space scales that are well matched. When

such data are compared, one may observe random differences that arise from these mismatches. However, this problem by itself is unlikely to be the source of systematic errors, especially when data from different cruises, seasons and locations are pooled, as is the case here. Such apparent errors can be minimised by limiting the comparisons to those areas that are characterised by low variability. The tests on the number of valid pixels and on the coefficient of variation were adopted here to minimise the use of matrices potentially contaminated by neighbouring pixels with retrieval errors, and also to avoid the use of data from a locality with high variability in pigment values.

These more stringent selection criteria reduced from 460 to 185 the number of *in situ* data points with concurrent satellite data. They were distributed in the following manner: 110 values in the spring, 42 in the summer and 33 in the fall seasons (Fig. 4 A - C).

2.5 Testing of NASA algorithms

Chlorophyll-*a* was first computed using the OC2v2 algorithm in the NASA/SeaDAS software²⁶. The model uses a two-band ratio (490 nm / 555 nm) of water-leaving radiance: we applied it first in combination with climatological ancillary data on

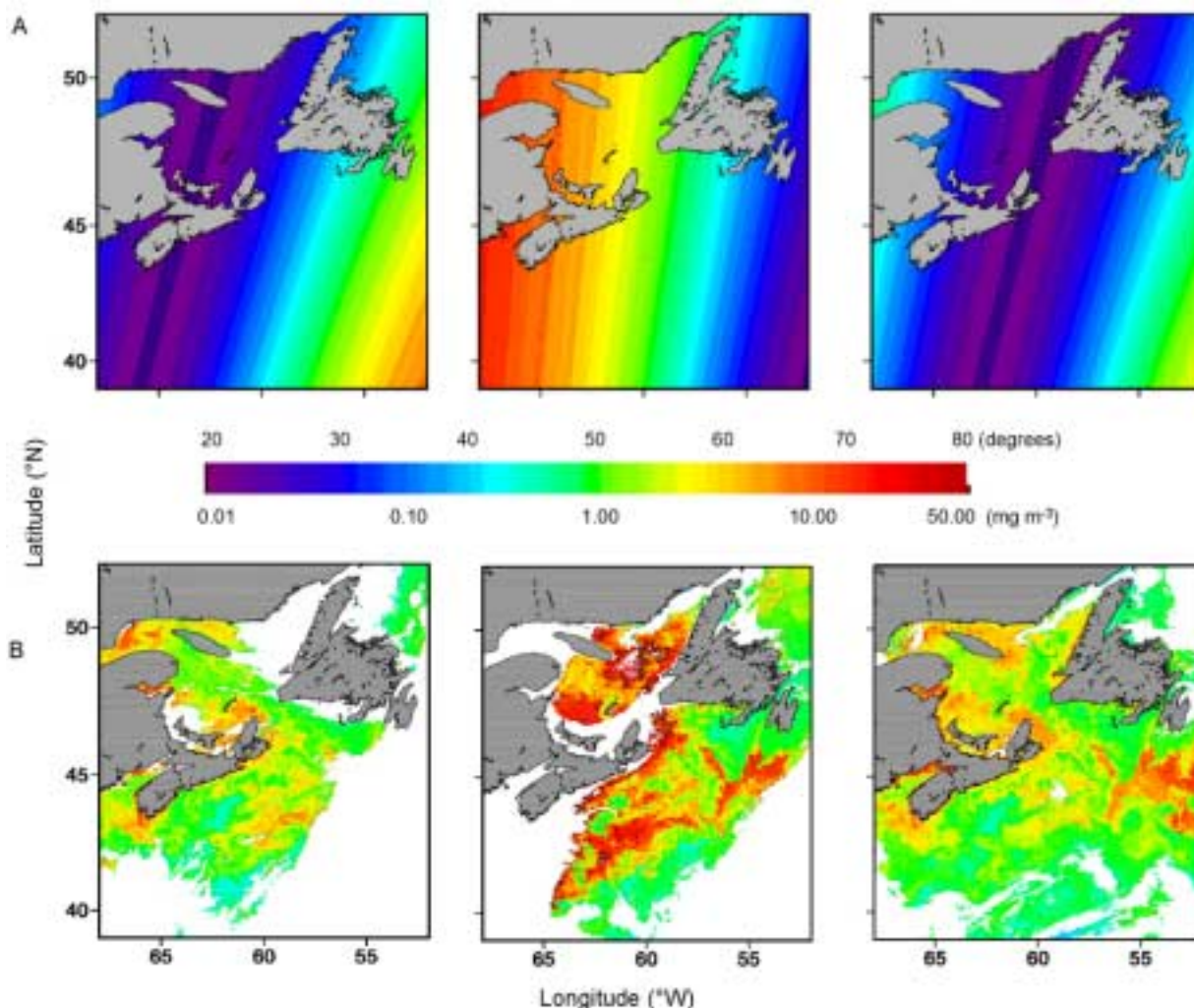


Fig. 3- A) Sensor zenith angle for SeaWiFS passes over the Scotian Shelf area between April 19th, 20th, and 21st, 2001. The colour bar is in degrees. B) Chlorophyll-*a* concentration for the same dates as above. The colour bar indicates concentrations in mg m⁻³.

ozone concentration and meteorological conditions (wind speed, oxygen concentration, water vapour and atmospheric pressure) for the atmospheric correction. The pigment concentration was next computed using the NASA/SeaDAS algorithm¹⁰ OC4 version 4.1. This algorithm computes ratios of the signal at 443, 490 and 510 nm to that at 555 nm. The maximum of these ratios is then used in an empirical algorithm to retrieve chlorophyll-*a*. Finally, because of the high variability of ozone concentration and meteorological conditions over short time intervals in the NW Atlantic, we replaced the climatological inputs to the atmospheric correction with near-concurrent data, also provided by NASA.

NASA/SeaDAS software version 4.3 was released in August 2002. This version was used in combination with the companion data on quasi-simultaneous atmospheric conditions. This algorithm also computes

chlorophyll-*a* using the highest of the signals at 443, 490 and 510 nm, but modifications to the sensor calibration, near infrared correction, atmospheric correction, mask and flags, and navigation improvements have been incorporated. Details of these improvements can be found in Casey & Gregg¹⁶ and Patt *et al.*²⁷, also at the SeaWiFS Reprocessing #4 website: <http://oceancolor.gsfc.nasa.gov/REPROCESSING/SeaWiFS/R4/>

Linear regressions were used to quantify differences between satellite and *in situ* chlorophyll estimates. The calculations were performed using standard major axis Model II regression^{28, 29} of log-transformed values, as employed by O'Reilly *et al.*²⁶. Ordinary least-squares Model I (MI)³⁰ regression results are provided for comparison. MII is, however, recommended for the reasons given by O'Reilly *et al.*²⁶. The match between *in situ* and satellite-derived chlorophyll concentration was considered to be

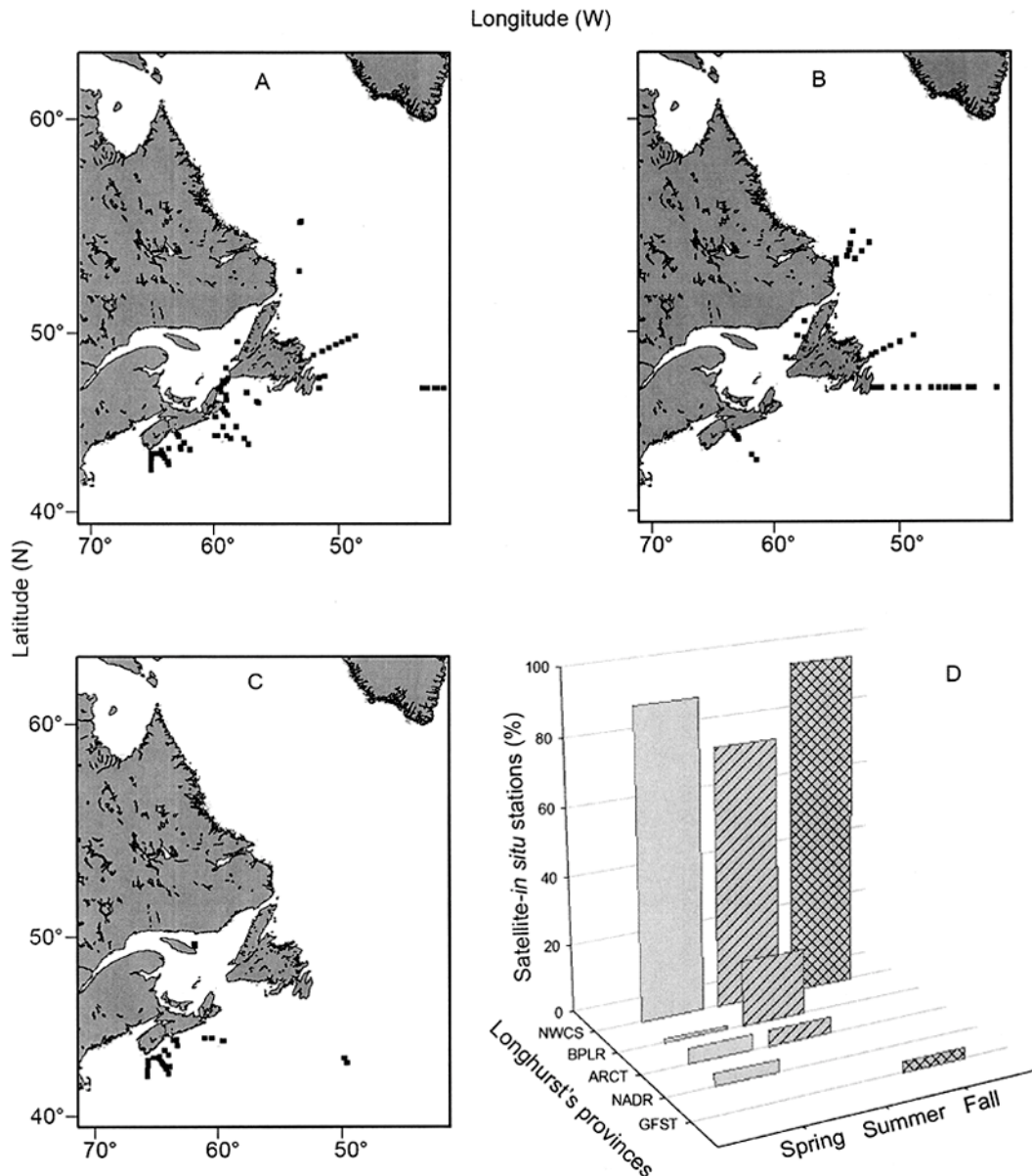


Fig. 4- Seasonal distribution of *in situ* data points with concurrent satellite data: A) 110 values in the spring, B) 42 values in the summer and C) 33 values in the fall. D) Seasonal distribution of concurrent satellite-*in situ* stations according with Longhurst¹⁷'s provinces [NWCS –Northwest Atlantic Shelves, ARCT –Atlantic Arctic, NADR –North Atlantic Drift, BPLR –Boreal Polar, and GFST –Gulf Stream].

improved (high accuracy) when the intercept b moved closer to 0 and the slope m approached 1. Root mean square errors (rms) were calculated to provide an estimate of the precision of the estimate. In addition, we calculated the differences between field and satellite data for SeaDAS OC4 algorithm (versions 4.1 and 4.3). These differences were plotted against their means as an independent way of assessing the relationships between the two types of data. These plots indicated the patterns of the individual differences and the limits of agreement³¹. A simple

linear regression Model I was fitted to the differences plotted against the means. The intercept and slope moving closer to zero, in addition to the small root mean square error, implied less bias.

3. Results and Discussion

SeaWiFS images of chlorophyll-*a* were computed for the NWA region using NASA/SeaDAS OC2 and OC4 (versions 4.1 and 4.3) algorithms (see an example for April 19th, 1998 in Fig. 5). Logarithmic transforms of satellite-derived values were compared

against logarithms of *in situ* measurements through MI and MII linear regressions (Table 3), for all the 460 (or 451 in the case of OC2) data, for 185 data points that remained after the more stringent selection criteria were applied, and for the 185 data after partitioning into seasons. The comparisons are also presented in Figs 6 to 10. Finally, logarithm transforms of the differences between field and satellite measurements are plotted against logarithm transforms of their means (Fig. 11). A detailed analysis of the results follows.

3.1 NASA Algorithms

Images derived using NASA algorithm OC2 in combination with climatological ancillary data for the atmospheric correction showed acute bias in the pigment retrieval. The satellite-derived chlorophyll fields showed several regions with values well above those reported in the literature for the present study

area (Fig. 5 A). The comparison of OC2 output with *in situ* data (Fig. 6A) also showed high scatter. The data, when fitted to MI and MII linear regressions (Table 3), indicate that only a low proportion of the total variance ($r^2 = 0.418$) is explained by the linear fits. The data were strongly dispersed around the predicted line and had high mean square errors ($rms_1 = 0.340$, and $rms_2 = 0.375$).

Calculations using the OC2 algorithm and the climatological atmospheric parameters highlighted some methodological weak points. A potential weak point is the limitation in the atmospheric correction, as applied here: it is well known that the impacts of ozone concentrations and other atmospheric elements are particularly high over high latitudes, requiring that particular care be taken in assigning the related parameters in the atmospheric correction routine. The use of near-concurrent ozone and meteorological ancillary data

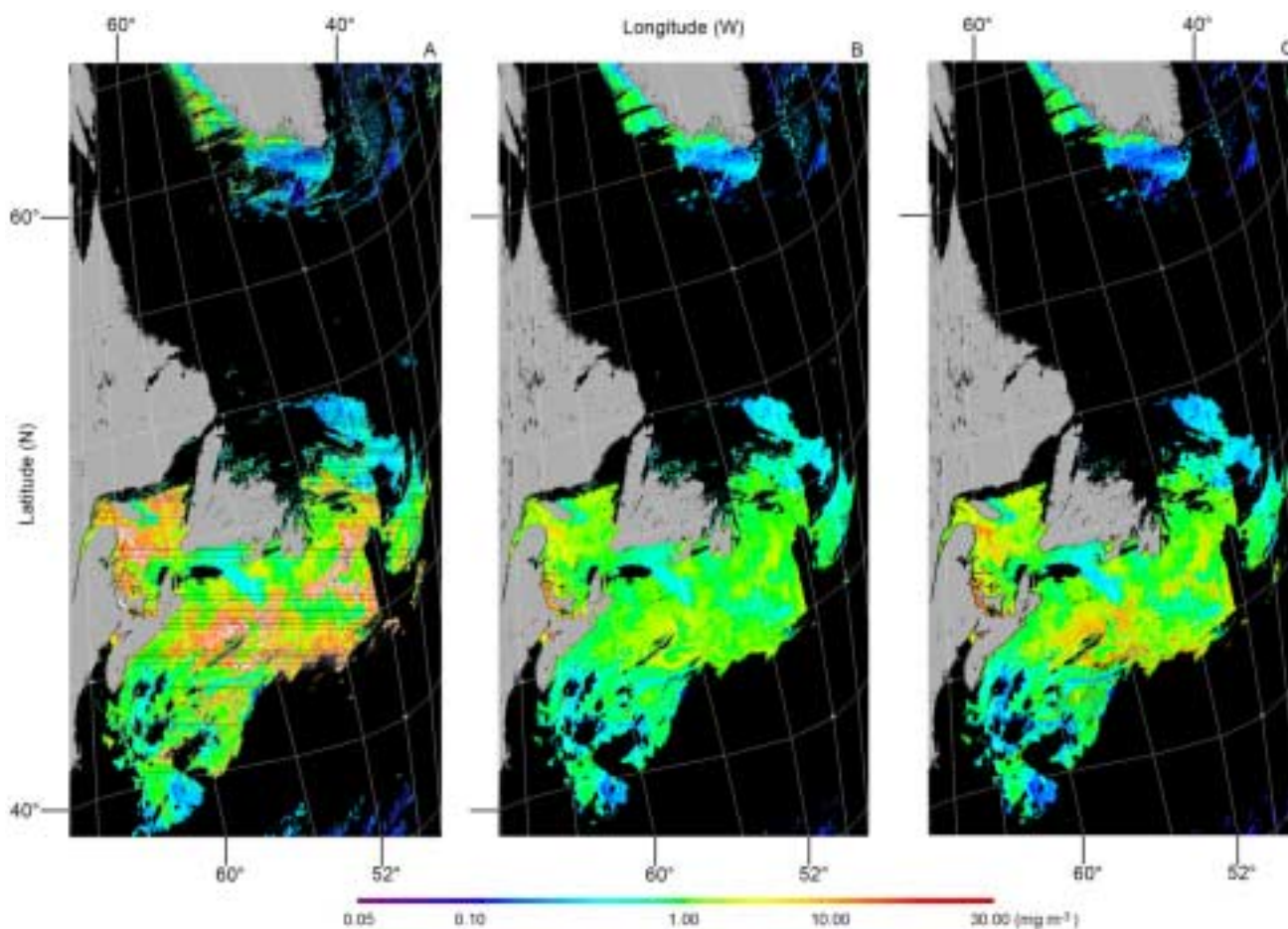


Fig. 5- Sample SeaWiFS images of April 19th, 1998 processed using NASA/SeaDAS algorithms: OC2 algorithm (A), OC4v4.1 (B) and OC4v4.3 (C). The colour bar indicates chlorophyll-*a* concentrations in mg m^{-3} . Black areas represent no available data or clouds and white regions correspond to pigment values above 30 mg m^{-3} .

Table 3 — Coefficients and statistics for the Linear Regression Model I (Least Squares) and Model II (Standard Major Axis) derived using *in situ* and satellite-derived values for the Northwest Atlantic. The model results correspond to the NASA/SeaDAS OC2 and OC4 (v4.1 and v4.3) algorithms. The fitting and statistics were computed on logarithms of all data and by seasonal sets. The slope for both models, I and II (m_1 and m_2), intercept (b_1 and b_2), and root mean square error (rms_1 and rms_2) are indicated. Adjusted coefficient of correlation (r^2) and number of satellite-*in situ* data pairs (n) are also included.

Algorithm	m_1	m_2	b_1	b_2	rms_1	rms_2	r^2	n
OC2 all data	0.662	1.022	0.140	0.119	0.340	0.375	0.418	451
OC4v4.1 all data	0.538	0.708	0.050	0.040	0.200	0.214	0.575	460
OC4v4.1 seasons	0.668	0.766	-0.072	-0.082	0.178	0.183	0.760	185
OC4v4.3 seasons	0.718	0.819	-0.058	-0.066	0.187	0.193	0.768	185
OC4v4.1 spring	0.622	0.727	-0.074	-0.105	0.156	0.162	0.729	110
OC4v4.3 spring	0.783	0.923	-0.103	-0.145	0.203	0.211	0.717	110
OC4v4.1 summer	0.785	1.043	-0.091	0.011	0.214	0.228	0.556	42
OC4v4.3 summer	0.545	0.686	-0.157	-0.101	0.130	0.137	0.622	42
OC4v4.1 fall	0.492	0.535	0.087	0.082	0.074	0.075	0.841	33
OC4v4.3 fall	0.546	0.607	0.088	0.081	0.093	0.095	0.805	33

in this step was noted to improve the results significantly.

The second pigment computation made with NASA/SeaDAS algorithm OC4 version 4.1, and near-simultaneous atmospheric data reduced the size of the areas of excessively-high satellite-derived pigment concentrations (Fig. 5B, and Fig. 6B). Table 3 shows that the linear regression of 460 concurrent data points clearly improved the intercept ($b_1 = 0.050$, $b_2 = 0.040$) and the statistics ($r^2 = 0.575$, $rms_1 = 0.200$, and $rms_2 = 0.214$). Notwithstanding the resultant improvements, a bias in the satellite-retrieved pigment values is noted, relative to the *in situ* measurements: values of chlorophyll above 1 mg m^{-3} appear to be underestimated and values below 1 mg m^{-3} appear to be overestimated (Fig. 6B). When the same analysis is carried out on the reduced data set of 185 points remaining after the application of the additional criteria for matching data points, the results are better (Fig. 7). Regression models I and II on both SeaDAS OC4 algorithms (v4.1 and v4.3) produced higher coefficients of correlation ($r^2 = 0.760$ and 0.768 , respectively). Improvements are also seen in the reduction of the root mean square errors and slopes that are closer to one (Table 3). However, there is still a residual bias in the satellite-derived signal (Fig. 7) relative to the *in situ* observations, for both OC4v4.1 and OC4v4.3.

In fact, both NASA/SeaDAS OC2 and OC4 algorithms have been used in diverse oceanic regions around the world with varying results. Bailey *et al.*³² show comparisons of chlorophyll-*a* values derived

from SeaWiFS (SeaDAS OC4 algorithm) and *in situ* measurements from the SeaWiFS Bio-optical Archive and Storage System (SeaBASS) data archive, which contains information from different geographical sources. These authors found reasonably good agreement between the two types of data for concentrations between 0.02 and $7 \text{ mg chl-}a \text{ m}^{-3}$. Hooker & McClain³³ compared satellite data derived using NASA OC2 algorithm with *in situ* values. They reported that although the data at low ($< 0.3 \text{ mg m}^{-3}$) and high ($> 3 \text{ mg m}^{-3}$) concentrations were not confined to $\pm 35\%$ of the 1:1 line, the majority of the data were within the limits. Chavez *et al.*³⁴ also argued for good agreement between satellite and *in situ* observations over a range of chlorophyll concentrations from ~ 0.05 to $>1 \text{ mg chl-}a \text{ m}^{-3}$ in two Equatorial Pacific sites: 0° , 155°W , and 2°S , 170°W .

On the other hand, several other studies in different locations came to conclusions at odds with those in the previous paragraph. In general, they show satellite overestimation of chlorophyll concentrations. Comparisons in particular regions of the Northwest Atlantic gave the following results: Cota^{4,6} worked in the Labrador Sea and Canadian Arctic Archipelago and showed chlorophyll retrievals over two (NASA OC2v2 algorithm) to three (OC2v1 algorithm) times the observed values, especially where phytoplankton were highly abundant ($\sim 25 \text{ mg chl-}a \text{ m}^{-3}$). Working in the Gulf of Maine, Balch^{7,8} found that field measurements below $1 \text{ mg chl-}a \text{ m}^{-3}$ are overestimated by the satellite, as the present study shows, though contrary to our findings, he reports that

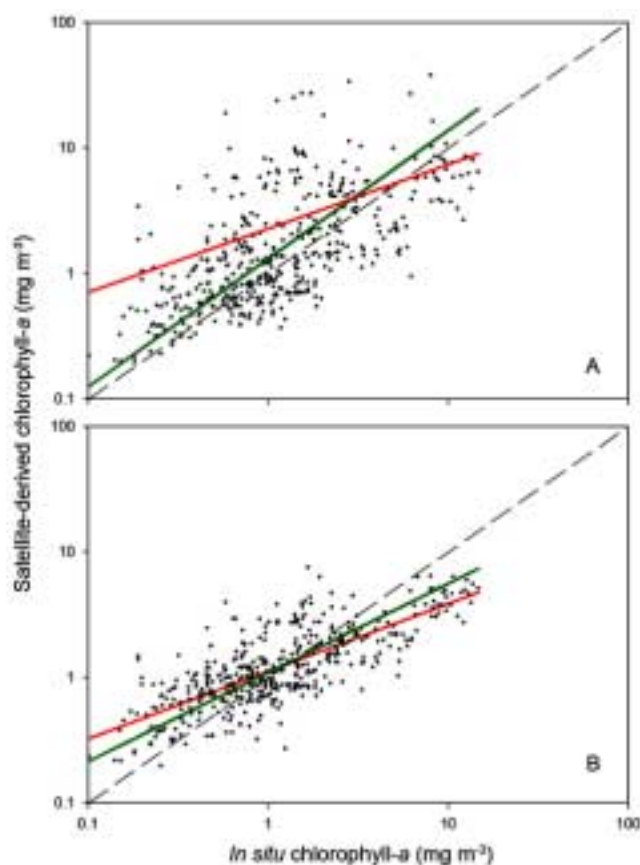


Fig. 6- Comparison of chlorophyll-*a* values (mg m^{-3}) derived from SeaWiFS and *in situ* measurements from the Northwest Atlantic. A) NASA/SeaDAS algorithm OC2 is represented with 451 data pairs. Predicted linear regression lines are shown in red for Model I and in green for Model II fittings. Similar code is used elsewhere in subsequent Figures 7, 8 and 9. B) NASA/SeaDAS algorithm OC4v4.1 is plotted with 460 data pairs. This one and subsequent Figures 7 to 10 show the 1:1 relationships indicated in dashed lines. Associated coefficients for the regression and statistic are also shown in Table 3.

SeaDAS OC4 algorithm overestimated chlorophyll by $\sim 0.25 \text{ mg m}^{-3}$, for values above 1 mg m^{-3} . Recently, Casey & Gregg¹⁶ used 9-km resolution SeaWiFS images to compare with the SeaBASS data set and concluded that for regional match-ups there is some bias, depending on the oceanic basin compared. These studies report a poor correspondence between satellite and *in situ* data for the North Atlantic. Indeed, their results compare well with those presented in present study and show similar patterns in the distribution of data around the 1:1 line. Other comparisons showed overestimation of pigment concentrations by NASA algorithms, for example in the Barents Sea³⁵, the Western Pacific Ocean³⁶, the Mediterranean Sea³⁷⁻³⁹, and the Chesapeake Bay⁴⁰. Conversely, and in

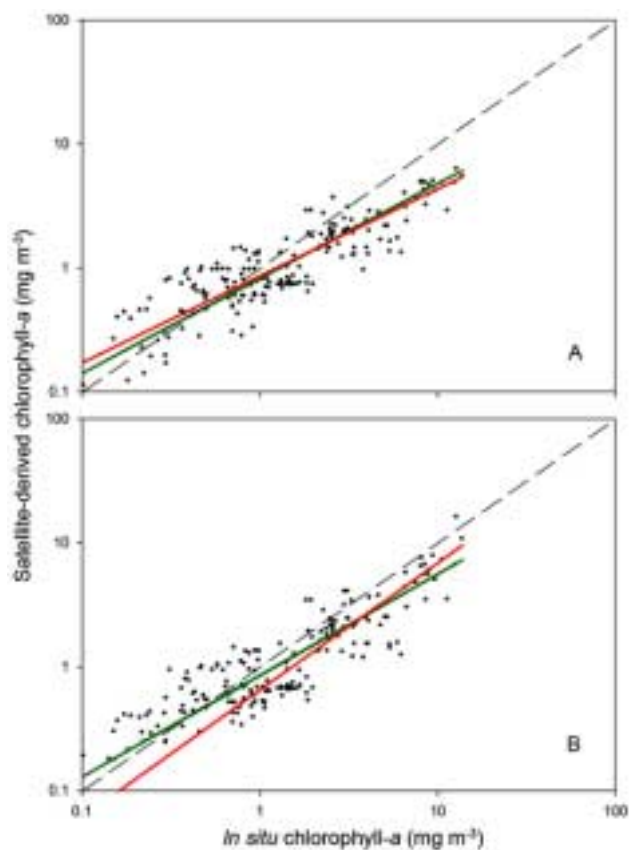


Fig. 7- Comparison of seasonal satellite-derived and *in situ* chlorophyll-*a* pigment concentrations (mg m^{-3}) for three seasons together: spring, summer and fall. A) Values derived from NASA/SeaDAS OC4v4.1 algorithm are plotted against 185 *in situ* pairs (mg m^{-3}). B) NASA/SeaDAS algorithm OC4v4.3 is plotted with an equal number of data pairs.

addition to this study, other authors have shown satellite underestimation of pigment concentrations above 1.0 mg m^{-3} . Our results are in agreement with those of Cota^{4,6}, who observed underestimation of high chlorophyll concentrations in the Arctic and the Labrador Sea, respectively, by the NASA/SeaDAS OC4 algorithm. Mitchell⁴¹ used both OC2v2 and OC4v4 NASA algorithms in the California Current and Southern Ocean, and found satellite overestimation of low pigment values but underestimation of high pigment values. The Northwest coast of Spain also shows satellite underestimation of high chlorophyll using the NASA/SeaDAS OC4 algorithm⁴². Finally, a study in the north polar region of the Atlantic⁴³ shows that the current NASA global algorithms OC2, OC4, and chlor-MODIS generally overestimate chlorophyll in these region by a factor of about 2 at low pigment concentrations ($< 0.2 \text{ chl-}a \text{ m}^{-3}$)

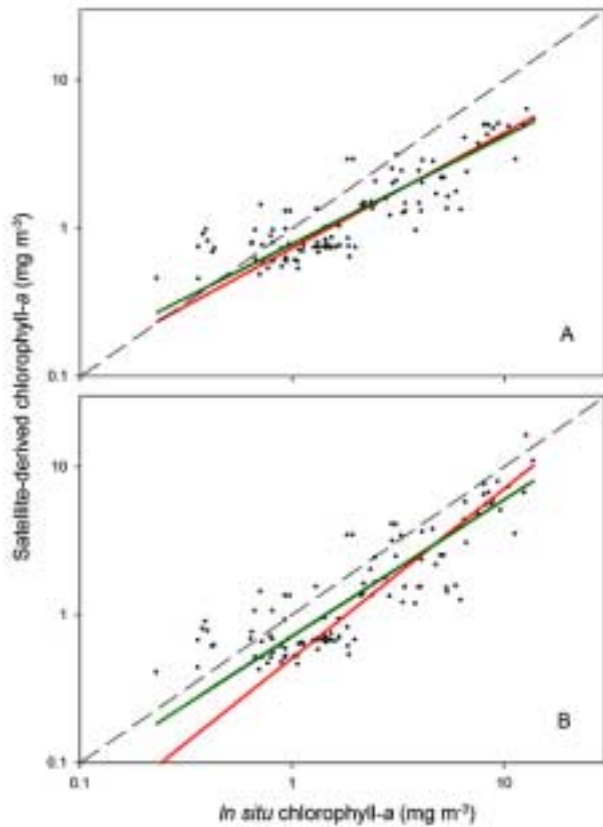


Fig. 8- Comparison of seasonal satellite-derived and *in situ* chlorophyll-*a* pigment concentrations (mg m^{-3}) for the spring. A) Values derived from NASA/SeaDAS OC4v4.1 algorithm are plotted against 110 *in situ* pairs (mg m^{-3}). B) NASA/SeaDAS algorithm OC4v4.3 is plotted with an equal number of data pairs.

and underestimate chlorophyll at higher concentrations (20-50% at 2-3 $\text{chl-}a \text{ m}^{-3}$).

When the more stringent selection criteria are applied to the data, there is a decrease in the scatter (increase in r^2 and decrease in root mean square error, Table 3). The slope is also better when the results for OC4v4.1 are compared, in the sense that the slopes for the two models are closer to one. The decrease in scatter indicates that the data selection criteria applied here, designed to reduce random errors due to mismatches in the spatial and temporal scales of observation, have in fact been effective. The analysis highlights the difficulties one encounters when comparing such data, but it also points to ways for minimising such errors by careful elimination of pixels that would not lend themselves easily to such a comparison. It also highlights the need for a large data bank as a basis for such an analysis. Even though we started the analysis with an initial set of over 450

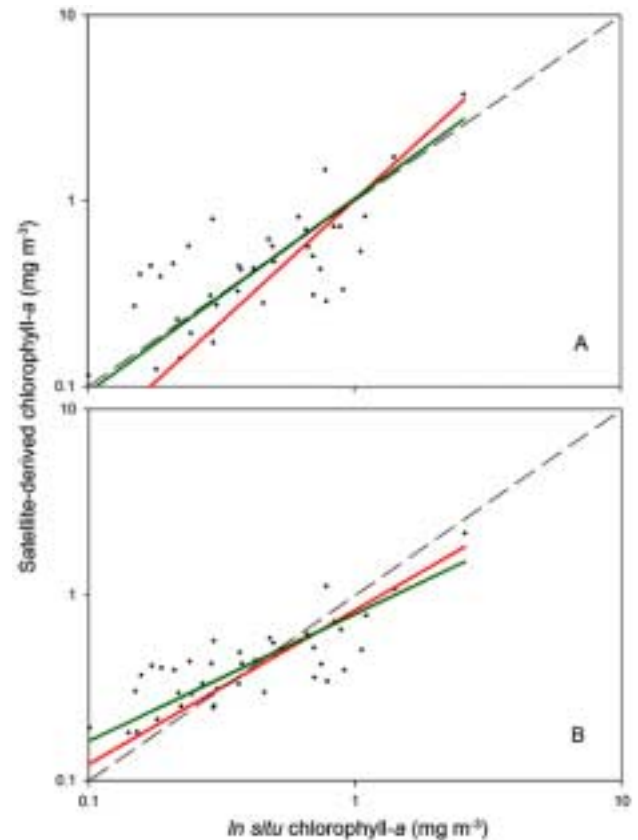


Fig. 9- Comparison of seasonal satellite-derived and *in situ* chlorophyll-*a* pigment for the summer. There are 42 chlorophyll-*a* pairs of values (mg m^{-3}). A) SeaDAS OC4v4.1 algorithm results generate the predicted linear regressions. B) Algorithm SeaDAS OC4v4.3 results are plotted with an equal number of data pairs.

matched pairs of observations collected over a number of years, the number was reduced to 185 when the additional criteria were applied. Clearly, such an analysis would lead to inconclusive results, if the initial pool of data were small to begin with.

The sources of systematic error identified here (high cloud albedo and high viewing angles) are both potential sources of overestimation in the satellite-derived pigment concentrations. In fact, comparison of Figs 6 and 7 show that the positive intercept present when all the data are used is significantly reduced when the analysis is applied to the more limited data that result after application of the more stringent criteria. Thus, the analysis presented here gives clear guidance on how to minimise some sources of systematic error.

Even though high albedo and high view angles have been identified here as potential causes of

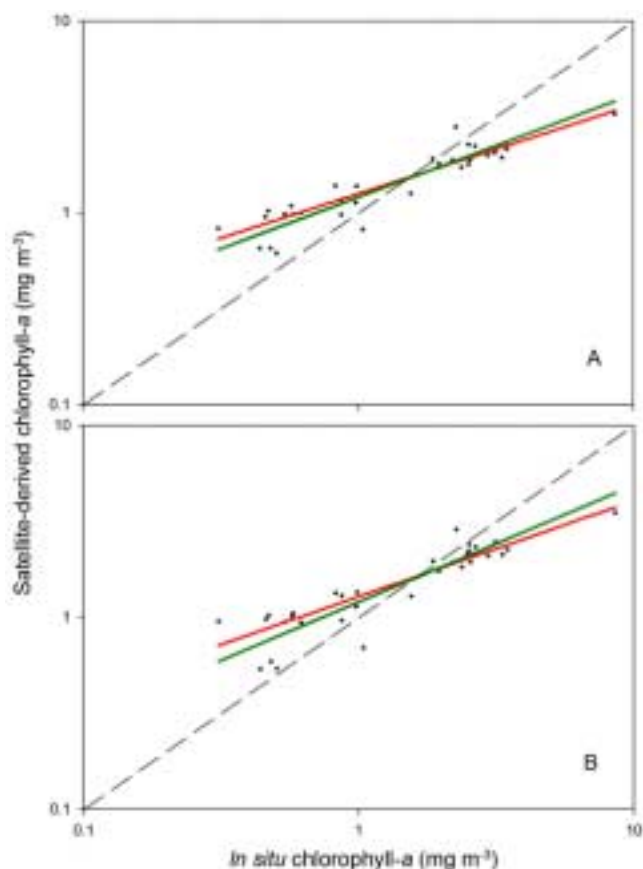


Fig. 10- Comparison of seasonal satellite-derived and *in situ* chlorophyll-*a* pigment for the fall. The plots show 33 pairs of pigment values (mg m^{-3}). A) Results derived from SeaDAS OC4v4.1 algorithm produced the predicted linear regressions illustrated. B) Results from algorithm SeaDAS OC4v4.3, with the same number of data pairs are plotted.

systematic overestimation of chlorophyll-*a* concentrations, it remains to be pointed out that none of the sources of error identified so far could explain the systematic underestimation observed in the data for high chlorophyll concentrations. To understand this, we have to turn towards other possible sources of error. A potential candidate could be errors related to changes in the optical characteristics of in-water constituents.

3.2 Seasonal approach

In the North Western Atlantic, naturally occurring variations in phytoplankton community structure are known to influence the optical properties of the population there, with consequences for pigment retrieval using remote sensing¹⁴. The possibility that seasonal succession of phytoplankton populations can introduce systematic biases in the retrieved values of

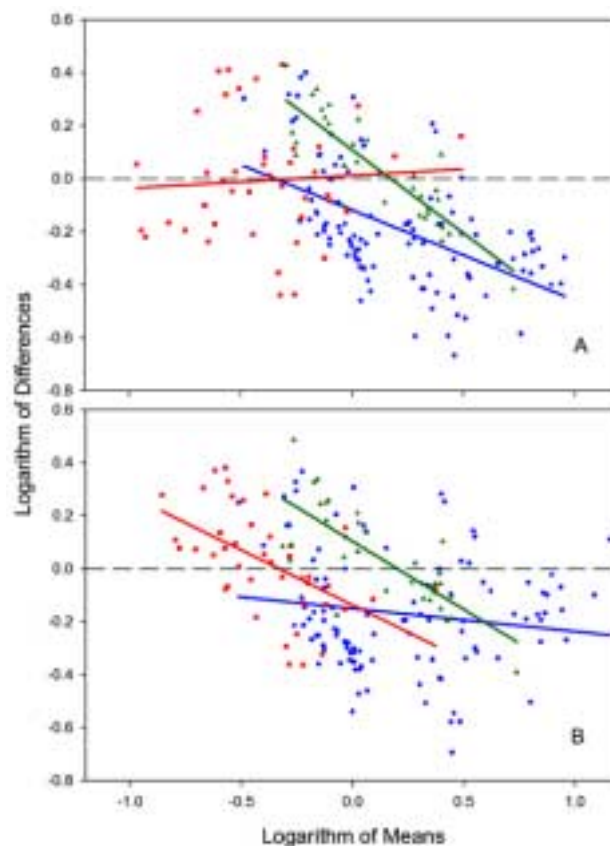


Fig. 11- Comparisons of seasonal mean and difference of satellite-derived and *in situ* chlorophyll-*a* pigment. Computation of Model I linear regression was based on 460 log-transformed data pairs to derive the predicted lines, also plotted. A) NASA/SeaDAS algorithm OC4v4.1. Blue represents spring with 100 pair of values, red corresponds to summer with 42 data-pairs and green indicates fall with 33 pair of values. B) NASA/SeaDAS algorithm OC4v4.3. The colour code and number of data by season are the same as above. Zero value of differences are indicated by dashed lines. Associated coefficients for the regression and statistic are shown in Table 4. [see text for more details].

pigment concentrations led to the idea of examining seasonal variations in the performance of the algorithms. Seasonal distribution of concurrent satellite and *in situ* stations within the provinces of Longhurst¹⁷ is shown in Fig. 4D. Separation of the data selected using the more stringent criteria into seasons improved results. In spring, (Fig. 8A) the fit was better for OC4v4.1 ($r^2 = 0.729$, $n = 110$). In the summer season (Fig. 9A), when the 42 pairs that passed the selection criteria were used we note that the slope is close to one for OC4v4.1 and the intercept close to zero (Table 3), suggesting that the systematic bias is lower during this season. The r^2 values are lower, perhaps as a consequence of the small number of data points

Table 4 — Coefficients and statistics for the Linear Regression Model I (Least Squares) computed using means and differences of the *in situ* and satellite-derived values using SeaDAS OC4 (v4.1 and v4.3) algorithms. The fitting and statistics were computed on logarithms of seasonal data sets. The slope (m), intercept (b), and root mean square error (rms) are indicated. Adjusted coefficient of correlation (r^2) and number of satellite-*in situ* data pairs (n) are also included.

Algorithm	m	b	rms	r^2	n
OC4v4.1 spring	-0.341	-0.117	0.188	0.275	110
OC4v4.1 summer	0.048	0.013	0.223	0.000	42
OC4v4.1 fall	-0.628	0.110	0.098	0.733	33
OC4v4.3 spring	-0.087	-0.149	0.219	0.013	110
OC4v4.3 summer	-0.413	-0.136	0.162	0.270	42
OC4v4.3 fall	-0.514	0.104	0.118	0.576	33

available ($n = 42$). Finally, for the fall season (Fig. 10A), for which no more than 33 data-pairs remained, the explained variance increased to almost 85% and reduced the residuals: $rms_1 = 0.074$, and $rms_2 = 0.075$. The linear regressions on the seasonal partition showed improvements when compared with results using the entire data-set (Table 3).

Results obtained with the more recent NASA/SeaDAS algorithm OC4v4.3 show some improvements, in particular for high pigment values in spring (see Fig. 5). These modifications are evident for the chlorophyll-*a* concentrations close to 10 mg m⁻³ (Fig. 8B); the slope shifted closer to 1 ($m_1 = 0.783$, $m_2 = 0.923$, Table 3). The fit to summer data (Fig. 9B) did not come closer to the 1:1 line, but reduced the data dispersion ($rms_1 = 0.130$, and $rms_2 = 0.137$). Except for improvement to the slope ($m_1 = 0.546$, $m_2 = 0.607$, Table 3), the fit for the fall season did not change significantly (Fig. 10B).

Analyses of the fitting of differences between the field and satellite measurements and their means clearly showed seasonal patterns (Fig. 11). The coefficients and statistics (Table 4) for the linear fit emphasized the trends. Figure 10A shows results corresponding to SeaDAS OC4v4.1 algorithm. Spring and fall regression patterns match the patterns already described: underestimation at high pigment concentrations and overestimation at low values. The fitted line for summer (almost parallel to the abscissa) is misleading. There is high residual error ($rms = 0.223$); so that the results are less good than they appear at first sight. Results for SeaDAS OC4v4.3 algorithm are plotted in Fig. 11B. Coefficients and statistics from Table 4 confirm that summer and fall seasons also show bias of satellite under(over)estimation at high(low) *in situ* pigment concentrations. In addition, the fitted line for the spring season suggests

a systematic satellite underestimation. Again, the root mean square error ($rms = 0.219$) stresses the misleading agreement.

The results clearly suggest that the biases in the algorithm when compared with the *in situ* data have a strong seasonality, with the deviations from the 1:1 line being most pronounced during the spring and fall seasons. Previous published work documenting the strong variability in the optical properties of phytoplankton in the region, and their seasonal succession, provides a possible explanation for these observations

4. Conclusion

When all the satellite-derived chlorophyll data for the study area are compared with the corresponding *in situ* observations, the agreement is poor. The analysis presented here has shown that the results can be improved significantly when more stringent criteria are applied to match up the *in situ* and satellite observations. Incorporation of near-concurrent meteorological and ozone data in the processing improved results over the use of climatological data. Furthermore, an analysis by season emphasises seasonal changes in the performance of the algorithms, presumably consequent upon the variation in floristic composition and related optical properties during the seasonal succession of phytoplankton.

The regressions reveal systematic biases between satellite-derived and *in situ* chlorophyll values. The statistical results presented in Table 3 can be used to apply an empirical correction to chlorophyll values retrieved from ocean-colour data using various versions of the NASA algorithms.

To elucidate the underlying causes of the bias in retrieved chlorophyll, and thus improve the algorithm further, the next step should be a regional and seasonal

theoretical analysis based upon the first principles of ocean colour (Devred *et al.*¹⁴.) as suggested by Sathyendranath *et al.*¹⁴.

Acknowledgement

We thank Brian Irwin, Glen Harrison, Jeff Anning, Jeff Spry, Kevin Pauley, Tim Perry, (Bedford Institute of Oceanography, DFO), Gary Maillet (Northwest Atlantic Fisheries Centre, DFO), Fred Page (St. Andrews Biological Station, DFO), Laure Devine-Castonguay, Liliane St-Amand and Michel Starr (Maurice Lamontagne Institute, DFO), for their contribution to the *in situ* chlorophyll database. The ocean colour data used in this study were provided by the SeaWiFS project at Goddard Space Flight Center.

References

- 1 Topliss, B.J., Payzant, L.A., Hurley, P.C.F., Miller, J.R., & Freemantle, J. Interpretation of multi-season, multi-year colour imagery for a continental shelf region, *Oceanol. Acta*, 14 (1991) 533-547.
- 2 Fuentes-Yaco, C., Vézina, A.F., Larouche, P., Vigneau, C., Gosselin, M. & Levasseur, M. Phytoplankton pigment in the Gulf of St. Lawrence, Canada, as determined by the Coastal Zone Color Scanner –Part I: spatio-temporal variability, *Cont. Shelf Res.*, 17 (1997) 1421-1439.
- 3 McClain, C.R., Cleave, M.L., Feldman, G.C., Gregg, W.W., Hooker, S.B. & Kuring, N., Science quality SeaWiFS data for global biosphere research, *Sea Technology*, September, (1998) 10-16.
- 4 Cota, G.F., Remote sensing of ocean color in the Arctic: algorithm development and comparative validation, in: *SIMBIOS Project 1999 Annual Report*, edited by C.R. McClain, & G. Fargion, (NASA Tech. Memo. -1999-209486), 1999, pp. 55-57.
- 5 Cota, G.F., Remote sensing of ocean color in the Arctic: algorithm development and comparative validation, in: *SIMBIOS Project 2000 Annual Report*, edited by G. Fargion, & C.R. McClain, (NASA Tech. Memo. -2001-209976), 2001, pp. 65-70.
- 6 Cota, G.F., Harrison, W.G., Platt, T., Sathyendranath, S. & Stuart, V., Bio-optical properties of the Labrador Sea, *J. Geophys. Res.*, 108 (C7), (2003), 3228, doi: 10.1029/2000JC000597.
- 7 Balch, W.M., Validation of surface bio-optical properties in the Gulf of Maine as a means for improving satellite primary production estimates, in *SIMBIOS Project 1999 Annual Report*, edited by C.R. McClain & G. Fargion, (NASA Tech. Memo. -1999-209486), 1999, pp. 30-36.
- 8 Balch, W.M., Validation of surface bio-optical properties in the Gulf of Maine as a means for improving satellite primary production estimates, in *SIMBIOS Project 2000 Annual Report*, edited by G. Fargion, & C.R. McClain, (NASA Tech. Memo. -2001-209976), 2001, pp. 26-33.
- 9 McClain, C.R., SeaWiFS postlaunch calibration and validation overview, *SeaWiFS Postlaunch Technical Report Series*, NASA Tech. Memo. 2000-206892, 9 (2000) 4-12.
- 10 O'Reilly, J.E., and 24 authors, Ocean color chlorophyll a algorithms for SeaWiFS, OC2 and OC4: version 4, in: *SeaWiFS Postlaunch Technical Report Series*, edited by S.B. Hooker & E.R. Firestone, NASA Tech. Memo. 2000-206892, 11, (2000) 9-23.
- 11 Li, W.K.W., Macroecological patterns of phytoplankton in the northwestern North Atlantic Ocean, *Nature*, 419 (2002) 154-157.
- 12 Sathyendranath, S., Longhurst, A., Caverhill, C.M. & Platt, T., Regionally and seasonally differentiated primary production in the North Atlantic, *Deep-Sea Res. -I*, 42 (1995) 1773-1802.
- 13 Kyewalyanga, M.N., Platt, T., Sathyendranath, S., Lutz, V.A. & Stuart, V., Seasonal variations in physiological parameters of phytoplankton across the North Atlantic, *J. Plankton Res.*, 20 (1998) 17-42.
- 14 Sathyendranath, S., Cota, G., Stuart, V., Maass, H. & Platt, T., Remote sensing of phytoplankton pigments : a comparison of empirical and theoretical approaches, *Int. J. Remote Sens.*, 22 (2001) 249-273.
- 15 Mueller, J.L., Fargion, G.S. & McClain, C.R. (Eds.), Ocean optics protocols for satellite ocean color sensor validation, Revision 4, Vols. I-VII, (NASA Tech. Memo., TM-2003-211621) 2003.
- 16 Casey, N.W. & Gregg, W.W., Comparing SeaWiFS reprocessing versions (R3 vs. R4), (NASA Tech. Memo. – 212235), 2003.
- 17 Longhurst, A., *Ecological geography of the sea*, (Academic Press, San Diego) 1998, pp. 398.
- 18 Loder, J.W., Petrie, B. & Gewarkiewicz, G., The coastal ocean off northeastern North America: a large scale view, coastal segment (1, w), in: *The global coastal ocean: Regional studies and synthesis, Chapter 5. The Sea, Vol. 11*, edited by A.R. Robinson & K.H. Brink, (John Wiley & Sons, Inc., New York) 1998, pp. 105-133.
- 19 Irwin, B., Anning, J., Caverhill, C. & Platt, T., Primary production on the Labrador Shelf and in the Strait of Belle Isle in May 1988, *Can. Data Rep. Fish. Aquat. Sci.*, No. 784, (1990), p: 96.
- 20 Yentsch, C.S. & Menzel, D.W., A method for the determination of phytoplankton chlorophyll and phaeophytin by fluorescence, *Deep-Sea Res.*, 10 (1963) 221-231.
- 21 Holm-Hansen, O., Lorenzen, C.J., Holmes, R.W. & Strickland, J.D.H., Fluorometric determination of chlorophyll, *J. Cons. Int. Explor. Mer.*, 30 (1965) 3-15.
- 22 Welschmeyer, N.A., Fluorometric analysis of chlorophyll a in the presence of chlorophyll b and pheopigments, *Limnol. Oceanogr.*, 39 (1994) 1985-1992.
- 23 McClain, C.R., Evans, R.H., Brown, J.W. & Darzi, M., SeaWiFS quality control masks and flags: initial algorithms and implementation strategy, in: *SeaWiFS Technical Report Series, Vol. 28, SeaWiFS Algorithms, Part 1*, edited by S.B. Hooker, C.R. McClain, & J.G. Acker, (NASA Tech. Memo. – 104566) 1995, pp. 3-7.
- 24 Morel, A. & Gentili, B., Diffuse reflectance of oceanic waters. III. Implication of bidirectionality for the remote-sensing problem, *Appl. Optics*, 35 (1996) 4850-4862.
- 25 Eplee, R.E., McClain, C.R., Along-scan effects in SeaWiFS data, in: *SeaWiFS Postlaunch Calibration and Validation Analyses, Part 2*, edited by S.B. Hooker, & E.R. Firestone, (NASA Tech. Memo. –2000-206892), Vol. 10, (2000), pp. 34-38.

- 26 O'Reilly, J. E., Maritorena, S., Mitchell, B. G., Siegel, D. A., Carder, K. L., Garver, S. A., Kahru, M., McClain, C., Ocean color chlorophyll algorithms for SeaWiFS, *J. Geophys. Res.*, 103 (C), (1998) 24,937-24,953.
- 27 Patt, F.S., and 17 authors, Algorithm updates for the fourth SeaWiFS data reprocessing, *SeaWiFS Postlaunch Technical Report Series, Vol. 22*, (NASA Tech. Memo. –206892), 2003.
- 28 Sokal, R.R. & F.J. Rohlf, *Biometry – The principles and practice of statistics in biological research*, 3rd edition, (W.H. Freeman, New York), 1995, pp. 887.
- 29 Legendre, P., *Model II regression – User's guide*, Département des sciences biologiques, Université de Montréal, pp. 23. Available from the WWW web site <http://www.bio.umontreal.ca/Casgrain/en/labo/model-ii.html>, 2001.
- 30 Seber, G. A.F., *Linear regression analysis*, (Wiley, New York), 1977, pp. 475.
- 31 Altman, D.G., & Bland, J.M., Measurement in medicine: the analysis of method comparison studies, *Statistician*, 32 (1983) 307-317.
- 32 Bailey, S.W., McClain, C.R., Werdell, P.J. & Schieber, B.D., Normalized water-leaving radiance and chlorophyll-*a* match-up analyses, in: *SeaWiFS Postlaunch Technical Report Series, Volume 10: SeaWiFS Postlaunch Calibration and Validation Analyses, Part 2*, edited by S.B. Hooker & E.R. Firestone, (NASA/TM-2000-206892) 2000, pp. 45-52.
- 33 Hooker, S.B. & McClain, C.R., The calibration and validation of SeaWiFS data. *Prog. Oceanogr.*, 45 (2000) 427-465.
- 34 Chavez, F.P., Strutton, P.G., Kuwahara, V.S. & Drake, E., in: *SIMBIOS Project 2001 Annual Report*, edited by G.S. Fargion, & C.R. McClain, (NASA Tech. Memo. –2002-210005) 2002, pp. 31-39.
- 35 Burenkov, V.I., Vedernikov, V.I., Ershova, S.V., Kopelevich, O.V. & Sheberstov, S.V., Application of the ocean color data gathered by the SeaWiFS satellite scanner for estimating the bio-optical characteristics of waters in the Barents Sea, *Oceanology*, 41 (2001) 461-468.
- 36 Bukin, O.A., Pavlov, A.N., Permyakov, M.S., Yu Major, A., Konstantinov, O.G., Maleenok, A.V. & Ogay, S.A., Continuous measurements of chlorophyll-*a* concentration in the Pacific Ocean by shipborne laser fluorometer and radiometer: comparison with SeaWiFS data, *Int. J. Remote Sens.*, 22 (2001) 415-427.
- 37 Bricaud, A., Bosc, E., Antoine, D., Algal biomass and sea surface temperature in the Mediterranean Basin. Intercomparison of data from various satellite sensors, and implications for primary production estimates, *Remote Sens. Environ.*, 81 (2002) 163-178.
- 38 Santoleri, R., Liberti, G.L., Gobbi, G.P. & Barnaba, F., Validation of SeaWiFS ocean and atmospheric products in the Mediterranean Sea, in: *SIMBIOS Project 2001 Annual Report*, edited by Fargion, G.S. & C.R. McClain, (NASA Tech. Memo. –2002-210005), 2002, pp. 176-184.
- 39 D'Ortenzio, F., Marullo, S., Ragni, M., Ribera d'Alcalá, M. & Santoleri, R., Validation of empirical SeaWiFS algorithm for chlorophyll-*a* retrieval in the Mediterranean Sea. A case study for oligotrophic seas, *Remote Sens. Environ.*, 82 (2002) 79-94.
- 40 Harding, L.W. & Magnuson, A., Bio-optical and remote sensing observations in Chesapeake Bay, in: *SIMBIOS Project 2001 Annual Report*, edited by Fargion, G.S. & C.R. McClain, (NASA Tech. Memo. –2002-210005), 2002, pp. 52-61.
- 41 Mitchell, B.G., Bio-optical measurement and modelling of the California Current and polar oceans, in: *SIMBIOS Project 2000 Annual Report*, edited by Fargion, G.S. & C.R. McClain, (NASA Tech. Memo. –2001-209976), 2001, pp. 91-96.
- 42 Smyth, T.S., Groom, S.B., Cummings, D.G. & Llewellyn, C.A., Comparison of SeaWiFS bio-optical chlorophyll-*a* algorithms within the OMEXII programme, *Int. J. Remote Sens.*, 23 (2002) 2321-2326.
- 43 Stramska, M., Stramski, D., Hapter, R., Kaczmarek, S. & Stoń, J., Bio-optical relationships and ocean color algorithms for the north polar region of the Atlantic, *J. Geophys. Res.*, 108 (C5), (2003) 3143, doi:10.1029/2001JC001195.
- 44 Devred E., Fuentes-Yaco C., Sathyendranath S., Caverhill C., Maass H., Stuart V., Platt T. & White G., A semi-analytic seasonal algorithm to retrieve chlorophyll-*a* concentration in the Northwest Atlantic Ocean from SeaWiFS data, *Indian J. Mar. Sci.*, 34 (2005) 356-367.