Evaluation of ocean color algorithms in the southeastern Beaufort Sea, Canadian Arctic: New parameterization using SeaWiFS, MODIS, and MERIS spectral bands

Sélíma Ben Mustapha, Simon Bélanger, and Pierre Larouche

Abstract. With the increasing interest for Arctic Ocean resources and faced with its sensitivity to climate change, it is important to accurately monitor the chlorophyll-a (Chl\textsubscript{a}) concentration that is a key indicator of phytoplankton biomass and marine productivity. The performances of three operational algorithms (OC4v6, OC3Mv6, OC4Mev6), two Arctic adapted algorithms (OC4L, OC4P), and one semi-analytical (GSM01) algorithm to estimate Chl\textsubscript{a} were evaluated using in situ measurements collected in the southeastern Beaufort Sea. All evaluated algorithms clearly overestimated Chl\textsubscript{a} by a factor of three to five. A high contribution of colored dissolved organic matter and nonalgal particles to the blue light absorption appeared as the source of that poor performance. It was also found that fluorometrically measured Chl\textsubscript{a} were two times greater than those determined from high-performance liquid chromatography, contributing to the observed discrepancies between our findings and previous studies carried out in the Arctic. We propose regionally adapted and new algorithms allowing accurate estimation of Chl\textsubscript{a} in the southeastern Beaufort Sea. Finally, a matchup analysis of coincident in situ data and satellite overpass showed that the normalized water-leaving reflectance and the blue-to-green ratio retrieval were more accurate for SeaWiFS than for MODIS and MERIS.

Résumé. Avec l’intérêt croissant pour les ressources de l’océan Arctique et face à sa sensibilité aux changements climatiques, il est important de suivre de façon précise la concentration de la chlorophylle-a (Chl\textsubscript{a}) qui est un indicateur clé de la biomasse phytoplanctonique et de la productivité marine. La performance de trois algorithmes opérationnels (OC4v6, OC3Mv6, OC4Mev6), deux algorithmes adaptés pour l’Arctique (OC4L, OC4P) et un algorithme semi-analytique (GSM01) estimant la Chl\textsubscript{a} a été évaluée à l’aide de mesures en situ recueillies dans le sud-est de la Mer de Beaufort. Tous les algorithmes évalués surestimaient clairement la Chl\textsubscript{a} par un facteur variant entre 3 et 5. La forte contribution de la matière organique coloree dissoute et des particules non algales à l’absorption de la lumière bleue apparaissait comme la source principale de ces mauvaises performances. Il a aussi été montré que les mesures de Chl\textsubscript{a} par la méthode de fluorométrie étaient deux fois plus élevées que celles mesurées par la méthode de chromatographie liquide à haute performance contribuant aux différences observées entre nos résultats et les études précédentes réalisées dans l’Arctique. Nous proposons des algorithmes adaptés ainsi que de nouveaux algorithmes permettant une estimation plus précise de la Chl\textsubscript{a} dans le sud-est de la Mer de Beaufort. Finalement, une comparaison entre des données en situ coïncidentes à des images satellitaires a montré que la réflectance normalisée à la surface de même que le ratio bleu-vert étaient plus précis pour le capteur SeaWiFS que pour MODIS et MERIS.

List of Symbols

- $a_\lambda$ absorption coefficient, m\textsuperscript{-1}
- $a_{CDOM}(\lambda)$ absorption coefficient for colored dissolved organic matter, m\textsuperscript{-1}
- $a_{PHY}(\lambda)$ absorption coefficient for phytoplankton, m\textsuperscript{-1}
- $a_{NAP}(\lambda)$ absorption coefficient for nonalgal particles, m\textsuperscript{-1}
- $a_p(\lambda)$ absorption coefficient for particles, m\textsuperscript{-1}
- $a_{w}(\lambda)$ absorption coefficient of pure seawater, m\textsuperscript{-1}
- $a_{CDM}(\lambda)$ absorption coefficient for colored detrital material, m\textsuperscript{-1}
- $b_b(\lambda)$ backscattering coefficient, m\textsuperscript{-1}
- $b_{bp}(\lambda)$ backscattering coefficient of pure seawater, m\textsuperscript{-1}
- $b_{bp}(\lambda)$ backscattering coefficient for particles, m\textsuperscript{-1}

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Introduction

Global climate models indicate that the Arctic will be the region most affected by climate change with still unknown impacts on the regional oceanic productivity. In polar regions polynyas are oases that play a major ecological and biogeochemical role (Smith and Gordon, 1997; Tremblay and Smith, 2007), hosting large phytoplankton spring blooms that fuel secondary producers (Lewis et al., 1996; Klein et al., 2002; Arrigo and van Dijken, 2004; Arrigo et al., 1998; Smith and Gordon, 1997). The Cape Bathurst polynya, located in the Amundsen Gulf, is the third largest polynya of the northern hemisphere, offering habitats for some of the highest densities of birds and mammals found in the Arctic (Harwood and Stirling, 1992; Dickson and Gilchrist, 2002). This region is part of the Northwest Passage, the traditional shipping route through the Canadian arctic between the north Atlantic and the Pacific. Faced with increased ship traffic and the associated environmental risks due to longer ice-free seasons, it is thus important to fully understand this biologically important arctic ecosystem. This is why major multidisciplinary programs such as the Canadian Arctic Shelf Exchange Study (CASES), the Circumpolar Flaw Leads (CFL) project, Malina, and ArcticNet have been conducted in this area over the last 10 years. Unfortunately, access to the region is still difficult leading to a bias in the data availability toward the early to late fall period (August–October).

Satellite remote sensing is a powerful tool for monitoring key environmental parameters at global, regional, and local scales that can help solve the temporal ship-based under sampling. Remote sensing has been used to detect temporal trends of phytoplankton biomass and to evaluate primary production in the Arctic Ocean (Arrigo and van Dijken, 2011; Kahru et al., 2010; Perrette et al., 2011). Coastal regions are normally considered to be areas where most of the oceanic primary production occurs. Thus, these are important regions where accurate chlorophyll-a (Chla) estimations are necessary.

In the Arctic coastal regions, two studies used ocean color remote sensing to assess the spatio-temporal variability of Chla (Arrigo and van Dijken, 2004) and particulate organic carbon fluxes (Forest et al., 2010) in the Cape Bathurst Polynya and the Amundsen Gulf in the southeastern Beaufort Sea. Arrigo and van Dijken (2004) applied an empirical algorithm tuned for the Arctic Ocean (OC4L; Wang and Cota, 2003; Cota et al., 2004) to Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data to derive Chla and then to calculate primary production (PP) rates. Very high values for the satellite-derived Chla (often $> 2$ mg m$^{-3}$) and PP (90–165 g C m$^{-2}$ y$^{-1}$) obtained by Arrigo and van Dijken (2004) suggested that the Cape Bathurst Polynya was among the most productive arctic marine ecosystem of the Arctic seas. These results, however, contrast remarkably with measurements of phytoplankton productivity in this area from Carmack et al. (2004) (12–16 g C m$^{-2}$ y$^{-1}$), Tremblay et al. (2008) (18 g C m$^{-2}$ y$^{-1}$, based on nitrate deficit), or Lavoie et al. (2009) (22.7–27.7 g C m$^{-2}$ y$^{-1}$; from a coupled biological-physical model). Part of the observed differences may be because the PP model used by Arrigo and van Dijken (2004) assumed a homogeneous water column. However, the large discrepancy also points toward a potentially significant overestimation of the satellite-derived Chla, which could originate from inaccuracies of either the atmospheric correction scheme, the sensor calibration, or the bio-optical algorithms that were not adapted to the presence of colored dissolved organic matter (CDOM) in the coastal waters.

Previous studies in the western Beaufort Sea indicated that National Aeronautics and Space Administration (NASA) standard algorithms for SeaWiFS (OC4V4) and Moderate Imaging Spectroradiometer (MODIS; OC3M) overestimated the Chla concentration as a result of different optical properties of the phytoplankton and the presence of CDOM (Cota et al., 2004; Matsuoka et al., 2007). The southeast Beaufort Sea is influenced by the presence of the Mackenzie River, the largest North American source of freshwater to the Arctic Ocean (Stewart et al., 1998), carrying large amounts of particulate inorganic and organic matter (Telang et al., 1991) and CDOM (Retamal et al., 2007; Osburn et al., 2009). Results from surveys in fall 2003 and spring–summer 2004 in the Amundsen Gulf region showed that light absorption at short wavelengths (400–450 nm) was dominated by the presence of a large pool of CDOM (Matsuoka et al., 2009; Bélanger et al., 2008), which could potentially lead to a significant overestimation of Chla by current bio-optical algorithms.

The main goals of this work are thus (i) to assess the ability of current remote sensing bio-optical algorithms to estimate Chla in the SE Beaufort Sea area using in situ data and (ii) to assess the quality of satellite-derived ocean reflectance and Chla retrievals based on a matchup analysis.

\[
\begin{align*}
\text{Chla} & \quad \text{chlorophyll-\textit{a} concentration, mg m}^{-3} \\
\alpha_{\text{ph}}(\lambda) & \quad \text{chlorophyll-\textit{a} specific absorption coefficient, m}^{-1} \\
E_s(0^+, \lambda) & \quad \text{downwelling irradiance just above the sea surface, W m}^{-2} \text{nm}^{-1} \text{sr}^{-1} \\
L_d(0^-, \lambda) & \quad \text{upwelling radiance just below the surface, W m}^{-2} \text{nm}^{-1} \text{sr}^{-1} \\
L_d(z, \lambda) & \quad \text{upwelling radiance at depth } z, \text{ W m}^{-2} \text{nm}^{-1} \text{sr}^{-1} \\
L_w(0^+, \lambda) & \quad \text{water-leaving radiance just above the sea surface, W m}^{-2} \text{nm}^{-1} \text{sr}^{-1} \\
L_w(0^-, \lambda) & \quad \text{water-leaving radiance just below the sea surface, W m}^{-2} \text{nm}^{-1} \text{sr}^{-1} \\
R_{rs}(\lambda) & \quad \text{remote sensing reflectance, sr}^{-1} \\
\lambda & \quad \text{Light wavelength, nm} \\
S_{\text{CDM}} & \quad \text{Spectral slope of absorption due to colored dissolved and detrital organic matters, nm}^{-1} \\
\mu & \quad \text{Power law exponent for particulate backscattering coefficient (unitless)} \\
g_i & \quad \text{Geometrical factor (constant)}
\end{align*}
\]
We first evaluated the performances of operational band-ratio algorithms for the MODIS (OC3M), SeaWiFS (OC4v6), and MERIS (OC4Me) sensors and then those of the Arctic OC4L and OC4P algorithms. We also tested the semi-analytical algorithm (GSM01) developed by Garver and Siegel (1997) and tuned by Maritorena et al. (2002) as it is operationally used in the data merging procedure implemented by the GlobColour project (http://www.globcolour.info/). Finally, we examined the quality of ocean color parameters retrieval using a small set of matchups between in situ measurements and satellite data.

**Material and methods**

**Study area**

The study area is composed by the Mackenzie Shelf and the Amundsen Gulf. The Mackenzie Shelf is a rectangular shallow shelf delineated by the Mackenzie Canyon to the west, the Amundsen Gulf to the east, and the Canada Basin to the north. The Amundsen Gulf is located at the western end of the Northwest Passage, connecting the Dolphin and Union Straits, and the Prince of Wales Strait with the Beaufort Sea and the Arctic Ocean (Figure 1).

The oceanography of this region has been the subject of several studies. The different water masses present in the southeast Beaufort Sea are the polar mixed layer (0–50 m) that sits over the Pacific halocline (50–200 m) that itself overlays Atlantic waters (>200 m) (Carmack and MacDonald, 2002). The surface circulation in the Amundsen Gulf and the surrounding domain is driven mainly by large-scale wind forcing, the Mackenzie River discharge, and thermohaline convection associated to sea ice formation (Carmack and Chapman, 2003). Continental runoff and snowmelt are the dominant sources of Arctic freshwater (Aksenov et al., 2010). The general surface circulation in the Beaufort Sea normally brings the outflow from the Mackenzie River toward the Amundsen Gulf (Macdonald et al., 1987), favoring haline stratification, which limits the nutrient replenishments in the surface layer during the winter leading to a relatively small surface phytoplankton bloom in the spring (Jones et al., 2003; Tremblay et al., 2008). The low concentration of nitrate in the Polar mixed layer is consumed rapidly in the spring, inducing to a nitrogen limitation above the nutricline (Tremblay et al., 2008). During summer, the Mackenzie plume is more variable and can be advected off shelf due to wind forcing (Macdonald et al., 1999, 2002; O’Brien et al., 2006).

Break-up begins in early June while freeze-up usually starts in mid-October. In the winter, sea ice along the continental margin of the Beaufort Sea consists of offshore polar pack ice, shore fast ice, and first-year ice that forms between the offshore and inshore zones (Barber and Hanesiak, 2004). Recently, the Beaufort Sea perennial pack has undergone a change in its ice types where perennial

![Figure 1](image)

**Figure 1.** Map of the study area showing the location of stations where SPMR (circles), ASD (triangles), and IOP measurements were made. Stations with salinity under 20‰ are represented with squares.
ice has been replaced by seasonal ice in winter (Galley et al., 2008). The offshore pack ice is mobile (Carmack and MacDonald, 2002) with landfast sea ice forming annually within the coastal margins over the continental shelves. A flaw lead polynya system is usually located on the shelf break between the Amundsen Gulf and the Beaufort Sea. The Cape Bathurst Polynya complex consists of a series of leads and a latent heat polynya within the Amundsen Gulf. The polynya generally starts forming during May, and the sea ice continues to retreat during summer leading to largely ice-free conditions in the Amundsen Gulf by August (Barber and Hanesiak, 2004) when open water in a normal year may extend 180–300 km off the Canadian coast. Consequently, phytoplankton production initiates about a month earlier in the Amundsen Gulf than elsewhere. As nutrients are depleted in the surface waters following the spring bloom, deep Chl \( a \) maximum forms during the summer (Carmack et al., 2004).

Although most phytoplankton production occurs during spring and summer, the only in situ data published to date for the region are from late-summer and fall (Ardyna et al., 2011; Brugel et al., 2009; Tremblay et al., 2009).

**Discrete water samples and analyses**

Field data for this study were collected in the southeast Beaufort Sea during the Canadian Arctic Shelf Exchange Study (CASES) expedition that took place between 4 June and 2 August 2004 on board the icebreaker CCGS Amundsen. Twenty litres of surface water was collected using a clean bucket at a series of stations shown on Figure 1. Sub-samples were immediately filtered for spectrophotometric absorption coefficients of solute (\( a_{\text{CDOM}}(\lambda) \)) and particulate matter (\( a_{p}(\lambda) \)) and for total suspended matter (TSM) and phytoplankton pigment concentrations.

Seawater samples for \( a_{\text{CDOM}}(\lambda) \) analyses were filtered through 0.2 \( \mu \)m Anotop syringe filters prerinsed with 50 mL of milliQ water and collected directly into acid-cleaned 100 mL amber glass bottles, which were immediately frozen at \(-20^\circ C\) and kept in the dark until analyzed, within two months from collection. Spectral absorption by particles retained on 0.7 \( \mu \)m Whatman Grade GF/F Glass Fiber Filters, stored frozen at \(-80^\circ C\) until analysis, was determined following the method described by Tassan and Ferrari (1995, 2002). Nonalgal particles absorption (\( a_{\text{NAP}} \)) and phytoplankton absorption (\( a_{\text{PHY}} \)) coefficients were further obtained following the protocol of Kishino et al. (1985) (for details on the spectrophotometer method see Bélanger et al. (2008)).

TSM (in triplicate) was concentrated by filtering up to 2 L of seawater through preweighted 0.2 \( \mu \)m 47 mm Anodiscs filters. After filtration, the filters were dried for approximately 4 h at 60 \(^\circ\)C and stored at \(-80^\circ\)C until analysis. In the laboratory, the filters were thawed, dried again in desiccators, and weighted using a Mettler MT5 electrobalance. TSM (in \( \mu g \) L\(^{-1}\)) was calculated as the difference between the filter weight with and without particle and normalized by the volume of filtered seawater. The triplicate measurements were checked to eliminate abnormal values (coefficient of variation > 10\%), and the mean of the remaining samples was calculated at each station.

Particulate matter for pigment analysis was collected by filtration of seawater through 25 mm GF/F filters (pore size of 0.7 \( \mu \)m) under low vacuum. Samples were flash frozen in liquid nitrogen after the filtration and kept at \(-80^\circ\)C until analysis. After the cruise, the filters were sent to the Laboratoire Océanographique de Villefranche for pigment analysis by high-performance liquid chromatography (HPLC). The pigment concentrations were determined following the method described by Van Heuken and Thomas (2001) as modified by Ras et al. (2008). For this study total chlorophyll-\( a \) concentration (Chl \( a \)\text{HPLC}) was calculated as the sum of Chlorophyll-\( a \), Divinyl Chlorophyll-\( a \), and Chlorophyllide-\( a \), as recommended by the NASA protocol for ocean color algorithms development and validation (Hooker et al., 2005).

In addition to the HPLC measurements, fluorometric-determined concentrations of the phytoplankton pigment chlorophyll-\( a \) (Chl \( a \)\text{Fluo}) were performed aboard the ship using a 10-AU Turner Designs fluorometer, following 24 h extraction in 90\% acetone at 5 \(^\circ\)C in the dark without grinding (Parsons et al., 1984). Concentrations of Chl \( a \) were corrected for phaeopigments by acidification of the extract (Knapp et al., 1996). It is important to mention that surface waters for Chl \( a \)\text{Fluo} were sampled, unlike Chl \( a \)\text{HPLC}, using Niskin bottles attached to the rosette sampler. The mean vertical difference between the 52 HPLC and fluorometric surface samples was 1.45 m. Considering that the surface mixed layer depth was more than 8 m (Brugel et al., 2009; Ardyna et al., 2011), there should not be any major difference between the surface samples collected using the two methods. There was no vertical difference for the other 64 water samples, collected at other depths using the rosette, that were used to compare HPLC and fluorometrically derived Chl \( a \).

**Apparent optical properties**

Multiple upwelling radiance measurements, \( L_{d}(z, \lambda) \) (in \( \mu W cm^{-2} nm^{-1} sr^{-1} \)), were performed at each station using a Satlantic free-falling profiler SPMR (SeaWiFS Profiling Multichannel Radiometer) with 13 channels (405, 412, 434, 442, 490, 510, 520, 532, 555, 590, 665, 683, and 700 nm) coupled to a surface reference SMSR (SeaWiFS Multichannel Surface Reference) for simultaneous incident irradiance measurement (\( E_{i}(0^+, \lambda) \)) (in \( \mu W cm^{-2} nm^{-1} \)). Profiles were made until the upwelling radiance was less than 0.001\% of incident light.

Data were processed following the NASA protocols (Mueller et al., 2003) as detailed in Bélanger et al. (2008). Each cast was first checked for constant \( E_{i} \) during the profile. Each upwelling radiance profile was extrapolated to the sub-surface, \( L_{d}(0^-, \lambda) \) (the notation 0 indicating “measurement just below the surface”), using a linear fit to all
orth-log-transformed $[\ln(L_a(z, \lambda))]$ data points measured within the surface layer (0 to 5–6 m). $L_a(0^-, \lambda)$ was corrected for instrument self-shading following Gordon and Ding (1992) and Zibordi and Ferrarri (1995). The above-water leaving radiance $L_a(0^+, \lambda)$ was calculated by propagating $L_a(0^-, \lambda)$ through the water–air interface using a factor of 0.543. The spectral remote sensing reflectance $(R(\lambda))$ is calculated as the ratio between $L_w(0^+, \lambda)$ and $E_r(0^+, \lambda)$:

$$R(\lambda) = L_w(0^+, \lambda) / E_r(0^+, \lambda)$$

For each station, we averaged $R(\lambda)$ obtained from the multiple casts (2–4) after elimination of the spectra that were different from the mean value by more than 10% in the blue. A total of 32 SPMR profiles were collected in the southeast Beaufort Sea for the analysis.

We also performed $R(\lambda)$ measurements from above the sea surface at 13 stations when the surface waters were stratified and (or) in shallow waters using a hyperspectral Analytical Spectral Device radiometer (see Bélanger et al., 2008).

The measurements of the radiance (acceptance angle of 10°) coming from sea surface ($L_r$), downwelling sky ($L_{sky}$), and a calibrated lambertian reflector (grey Spectralon; approx. 90% reflectance) ($L_p$) were performed using a unique sensor to avoid calibration issues, which generally result from the use of several sensors. The above-water remote sensing reflectance is calculated as (Mobley, 1999):

$$R(\lambda) = (L_r(\lambda) - \rho_{sky} \cdot L_{sky}(\lambda) \cdot R_p \cdot \Pi \cdot L_p(\lambda))$$  (1)

where $\rho_{sky}$ is the air–water interface specular reflection coefficient for radiance, and $R_p$ is the albedo of a calibrated lambertian panel. As recommended by Mobley (1999), $L_r$ was measured with a viewing zenith angle of approximately 40° and a relative azimuth angle to the sun of approximately 135°. An additional spectrally neutral correction was applied to $R(\lambda)$ based on the known spectral shape of $R_a(\lambda)$ in the near infrared (NIR) part of the spectrum at low turbidity (Doron et al., 2011; Ruddick et al., 2006). A total of 45 $R(\lambda)$ were thus available for the algorithm validation and development.

### Empirical algorithms

Empirical algorithms for Chla estimation are generally based on the relationship between the surface pigment concentrations and a blue-to-green band-ratio of remote sensing reflectance. The wavelength for the blue-to-green ratios varies slightly among sensors with the blue wavelengths being approximately 443, 488–490, 510–532 nm and the green wavelength approximately 551–560 nm (Table 1).

Table 1. Description of the evaluated chlorophyll-a algorithms (Equation (2)).

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Coefficients $a_q, n = 0,1,2,..,M$</th>
<th>$R$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC4v6 (SeaWiFS)</td>
<td>$[0.327 -2.994 2.721 -1.1225 -0.568]$</td>
<td>$R = \log_{10} [\max {R_a(443), R_a(490), R_a(510)/R_a(555)}]$</td>
<td>O’Reilly et al. (1998; 2000)</td>
</tr>
<tr>
<td>OC3M v6 (MODIS)</td>
<td>$[0.242 -2.582 1.705 -0.341 -0.881]$</td>
<td>$R = \log_{10} [\max {R_a(443), R_a(488)/R_a(551)}]$</td>
<td>O’Reilly et al. (2000)</td>
</tr>
<tr>
<td>OC4Mev6 (MERIS)</td>
<td>$[0.325 -2.767 2.44 -1.128 -0.499]$</td>
<td>$\rho = \log_{10} [\max {R_a(443), R_a(490), R_a(510)/R_a(560)}]$</td>
<td>Morel and Antoine (1999)</td>
</tr>
<tr>
<td>OC4L (Arctic)</td>
<td>$[0.592 -3.607]$</td>
<td>$R = \log_{10} [\max {R_a(443), R_a(490), R_a(510)/R_a(555)}]$</td>
<td>Cota et al. (2004)</td>
</tr>
<tr>
<td>OC4P</td>
<td>$[0.271 -6.278 26.29 -60.94 45.31]$</td>
<td>$R = \log_{10} [\max {R_a(443), R_a(490), R_a(510)/R_a(555)}]$</td>
<td>Wang and Cota (2003)</td>
</tr>
</tbody>
</table>

where $R$ is the base 10 logarithm of the maximum band ratio (see Table 1 for sensor specific band ratios) and $a_q$ is empirical or semi-empirical coefficients.

While SeaWiFS and MODIS algorithm coefficients (Version 6) were obtained using a global in situ data set mainly from mid-latitudes and Case 1 waters (O’Reilly et al., 1998, 2000), the MERIS (OC4Me) parameterization was determined using a semi-analytical reflectance model (MM01) for Case 1 waters (Antoine and Morel 1999; Morel and Maritorena, 2001; MERIS–ATBD 2.9, 2007).

For Arctic waters, Wang and Cota (2003) and Cota et al. (2004) proposed a polynomial and a linear version of the OC4 algorithm (Arctic OC4L and OC4P) tuned using 686 in situ measurements made in the Canadian Arctic waters.

### Chla algorithm description and evaluation criteria

Operational band-ratio algorithms for the MODIS (OC3Mv6), SeaWiFS (OC4v6), and MERIS (OC4Me) sensors, and the Arctic OC4L and OC4P algorithms were evaluated. We also tested the semi-analytical algorithm (GSM01) developed by Garver and Siegel (1997) and tuned by Maritorena et al. (2002) as it is operationally used in the data merging procedure implemented by the ESA- and NASA-founded GlobColour and MEaSUREs projects (Maritorena et al., 2010).
(Resolute Bay and Labrador sea) and in the western Arctic (Chukchi and Beaufort seas).

**Semi-analytical algorithm (GSM01)**

The GSM01 algorithm allows the retrieval of oceanic inherent optical properties (IOPs), namely the absorption ($a$) and backscattering ($b$), coefficients, of the seawater reflectance inversion (Garver and Siegel, 1997). The GSM01 algorithm is based on a quadratic relationship between the water-leaving reflectance and the $a(\lambda)$ and $b(\lambda)$ coefficients:

$$R_{kw}(\lambda) = \left[ \sum g_i(b_i(\lambda)/b(\lambda) + a(\lambda)) \right]^2 \tag{3}$$

Where $g_i$ are factors ($g_1 = 0.0949$ and $g_2 = 0.0794$) obtained from Gordon et al. (1988). The absorption coefficient is further decomposed as a linear summation of seawater absorption, $a_{nw}(\lambda)$, phytoplankton absorption, $a_{ph}(\lambda)$, and the combined absorption of dissolved and detrital particulate (CDM), $a_{CDM}(\lambda)$. The backscattering coefficient is partitioned into terms due to seawater, $b_{sw}(\lambda)$, and suspended particulates, $b_{sp}(\lambda)$. The spectral absorption and scattering terms are parameterized as a known shape with an unknown magnitude

$$a_{ph}(\lambda) = Chl a_{ph}(\lambda) \tag{4}$$

$$a_{CDM}(\lambda) = a_{CDM}(\lambda_0) \exp[-S_{CDM}(\lambda - \lambda_0)] \tag{5}$$

$$b_{sp}(\lambda) = b_{sp}(\lambda_0) \left( \lambda/\lambda_0 \right)^{-\eta} \tag{6}$$

where the model parameters are the Chl-specific absorption coefficient ($a_{ph}(\lambda)$), the spectral decay constant for CDM absorption ($S_{CDM}$), the power law exponent for particulate backscattering coefficient ($\eta$), and $\lambda_0$ is the reference wavelength (here equal to 443 nm). The three unknowns are $Chl$, $a_{CDM}$, and $b_{sp}$ at 443 nm. The model parameters were optimized for the Chl estimation using a data set of Case 1 nonpolar measurements (Maritorena et al., 2002). $S_{CDM}$ equals 0.0206 nm$^{-1}$, $\eta$ is 1.0337, and $a_{ph}^*$ (412, 443, 490, 510, 555) is [0.00665, 0.05582, 0.02055, 0.0191, 0.01015 m$^2$ (Chl mg$^{-1}$)].

**Evaluation criteria**

To evaluate the performance of the algorithms, the mean normalized bias (MNB) (systematic error) and mean absolute percentage difference (APD) were calculated. These errors (in percent) are defined as follows:

$$\text{MNB} = \sum_{n=1}^{N} \left( \frac{Chl_{alg} - Chl_{in situ}}{Chl_{in situ}} \right) \frac{1}{N} \times 100 \tag{7}$$

$$\text{ADP} = \sum_{n=1}^{N} \left| \frac{Chl_{alg} - Chl_{in situ}}{Chl_{in situ}} \right| \frac{1}{N} \times 100 \tag{8}$$

where $Chl_{alg}$ is the chlorophyll concentration estimated from the algorithm and $Chl_{in situ}$ is the observed value (in situ). We also used the statistics log_re based on the logarithm of the ratio between the algorithm-derived and the measured values, which is a good measure of data scatter for log-normally distributed variable such as Chl concentration (Darecki et al., 2005)

$$\text{log}_\text{bias} = \text{mean} \left[ \log \left( \frac{Chl_{alg}}{Chl_{in situ}} \right) \right] \tag{9}$$

$$\text{log}_{\text{rms}} = \text{SD} \left[ \log \left( \frac{Chl_{alg}}{Chl_{in situ}} \right) \right] \tag{10}$$

Finally, we applied a reduced major axis (RMA) regression model of type II (Legendre and Legendre, 1998) to estimate the slope (S) and the intercept (I) of the linear regression as well as their 95% confidence intervals.

**Matchup analysis and satellite data processing**

The performance of satellite-derived ocean color products is ultimately accomplished through an end-to-end exercise comparing products derived from ocean color sensors with in situ measurements (matchup analysis). Here we followed the recommendations of Bailey and Werdell (2006) in terms of criteria for a "good" matchup. In brief, we used a series of exclusion criteria to discard invalid or redundant data from the 5 × 5 box centered on the in situ target. It is based on temporal windows and quality control masks and flags such as clouds, stray light on scenes, atmosphere correction failure, sun glint, total radiance above the knee value, high satellite zenith angle, coccolithophores, and low normalized water-leaving radiance at 555 nm (a flag used to identify cloud-shadowing pixels). Considering the temporal variability of seawater optical properties, we defined the temporal threshold to be less than three hours between the in situ sampling and the satellite overpass.

**SeaWiFS and MODIS-AQUA**

SeaWiFS and MODIS-AQUA level 1A Local Area Coverage (MLAC, 1.1 km resolution at nadir) were downloaded from the NASA Ocean Color Web site (http://www.oceancolor.gsfc.nasa.gov). The level 1A MLAC contains raw radiance values for each SeaWiFS band (412, 443, 490, 510, 555, 670, 765, and 865 nm) and MODIS band (412, 443, 488, 513, 551, 667, 678, 748, and 869 nm). The images were processed to Level 2 using the SeaWiFS Data Analysis Software (SeaDAS version 5.2.0). We applied the NASA standard atmospheric correction algorithm (AC), which includes a clear water scheme for open ocean pixels (Gordon and Wang, 1994; Gordon, 1997) and an iteration scheme for moderately turbid waters where the black pixel assumption is violated (see Stumpf et al., 2003).
MERIS

The MERIS matchups were processed using the reduced resolution level 2 MERIS data (MER_RR). The protocol for extracting data is explained in “MERIS Optical Measurement Protocols. Part A: Reflectance” (2011), available on the MERIs MAchup In-situ Database (MERMAID) website (http://hermes.acri.fr/mermaid/dataprot). In brief, MERIS Level 0 data are received by the company ACRI-ST (Sofia Antipolis, France) through DDS (Data Dissemination System) and locally archived. From the geographic and temporal information, ACRI-ST processes the relevant L0 products with the MERIS Ground Segment Dissemination System) and locally archived. From the website (http://hermes.acri.fr/mermaid/dataprot). In brief, ACRI-ST processes the relevant L0 products with the MERIS Ground Segment data processing prototype (MEGS 8.0) up to L2.

Extraction is achieved on 5 × 5 pixels around the site corresponding to in situ acquisition following the procedure described by Bailey and Wedell (2006). This procedure concerns time elapse between in situ and satellite measurement, flag selections, and statistical screening.

The MERIS L2 ocean-color products in MERMAID included in this study are the normalized water reflectance, pwn (λ) as computed from AERONET-OC normalized water-leaving radiance; Lwn (λ) at bands of 412, 443, 490, 510, 560, 620, 665, 681, and 709 nm; and Chla. pwn (λ) was divided by π to obtain Rs (λ).

Results and discussion

In situ Chla concentration determination: HPLC versus fluorometry

Previous ocean color validation studies in arctic waters relied on in situ Chla determined by the classical fluorometric (ChlaFluo) method rather than HPLC (ChlaHPLC). There are, however, indications pointing out discrepancies between both methods at high latitudes. In the Southern Ocean, the ChlaFluo/ChlaHPLC ratio was 2.43 (Marrari et al., 2006), while Darecki et al. (2005) observed a ratio of 1.56 for ChlaFluo/ChlaHPLC in the Baltic sea and subsequently transformed all their fluorometric measurements into HPLC-equivalent Chla values. In contrast, Stramska et al. (2003, 2006) did not find a significant difference between the two methods in the northern Atlantic waters. In the southeast Beaufort Sea, we found a value 2 (±1.2) for ChlaFluo/ChlaHPLC based on a set of 116 co-incident measures of Chla using both analytical methods. As indicated in the Materials and methods section, 52 samples were not taken at exactly the same depth (those at the surface) which could have induced a bias in the comparison. Calculating the ChlaFluo/ChlaHPLC ratio using the 64 samples taken at exactly the same depth gave a ratio of 1.8 (±1.1) which is not significantly different from the value calculated using the whole data set. Marrari et al. (2006) suggested that the high ChlaFluo/ChlaHPLC ratio found in the southern oceans was likely a result of the relatively low concentration of chlorophyll-b and relatively high concentration of chlorophyll-c pigments in their phytoplankton assemblage. HPLC pigment analysis generally indicates that the same dominance of chlorophyll-c was present in the Amundsen Gulf in the summer–fall period (Brunelle et al., 2012). Considering the rather large ChlaFluo/ChlaHPLC ratio, the algorithm evaluation was performed using both methods to allow comparison with previous studies.

At the time of the cruise (June–July), only small ChlaHPLC concentrations in the surface layer of the southeast Beaufort Sea were measured. Higher ChlaHPLC concentrations, though moderate, were observed over the Shelf near the Cape Bathurst polynya (2–4 mg m⁻³) where frequent upwellings occur (Tremblay et al., 2011) and near the Mackenzie River plume (approx. 1–2 mg m⁻³). The in situ data set thus covers a limited range of variability in terms of surface ChlaHPLC concentration, which varies between 0.026 and 3.51 mg m⁻³ with an average concentration of 0.36 mg m⁻³ and a median value of 0.13 with standard deviation (SD) of 0.65. Most of the data, however, fall within a more restricted range (0.04–0.20 mg m⁻³), which is in the lower range as reported in the literature (Cota et al., 2004).

Bio-optical algorithms validation

Figure 2a shows the comparison between ChlaHPLC estimated using various algorithms applied to in situ Rs measurements. The three operational empirical algorithms (OC4v6, OC3Mv6, and OC4Mev6) and the Arctic versions of the SeaWiFS algorithm (OC4L and OC4P) overestimated ChlaHPLC by a factor varying from 2.8 to 5.6 depending on the sensor and algorithm (Table 2). The best performance (APD = 284%) among tested algorithms was obtained with the semi-analytical algorithm GSM01. The Chla overestimation is high for both low and high concentrations (Figure 2b). The Pearson correlation coefficient (r²) of the retrieved Chla versus ChlaHPLC shows almost no difference between the various algorithms tested (0.66 to 0.75). The log-rms values for the bio-optical algorithms ranged from 0.26 to 0.36 for ChlaHPLC and ChlaFluo, respectively. Results using ChlaFluo also indicate a strong overestimation (Table 2). All the algorithms are thus well above the 35% precision goal of the ocean color community. This overestimation is thus very high compared with the values for the western Beaufort and Chukchi seas reported by Matsuoka et al. (2007) (within 25% and 30% over a 0.1–2 mg m⁻³ range, respectively), Wang and Cota (2003) (1.5 × factor), and Hill and Zimmerman (2010) who found some overestimation by the OC4L when Chla concentration is less than 0.1 mg m⁻³ (RMS error of 32%). Chla overestimations by roughly a factor of five have only been reported for the Laptev Sea near the Lena river output (Vetrov et al., 2008) and the Black Sea (Oguz and Ediger, 2006), but these two studies were made using satellite-derived Chla values and thus also included potential atmospheric correction induced errors. Validation studies based on in situ optical measurements reported MNB of 183% for the Baltic Sea (Darecki...
and Stramski, 2004), 78% for the Mediterranean Sea (Volpe et al., 2007), 140% near the Rhone river output (Ouillon and Petrenko, 2005), 66% for the South China Sea (Tang et al., 2008), and approximately 130% for the Black Sea / Mediterranean Sea (Sancak et al., 2005). The measured overestimation in the southeastern Beaufort Sea is thus the highest reported to date for coastal seas influenced by freshwater, and it appears to be specific to this area.

To evaluate if the presence of stations near the Mackenzie River plume biased the comparison, we excluded stations with salinity below 20 (Figure 1). Results still showed a large overestimation by all algorithms indicating that the proximity to the freshwater source cannot explain the results (not shown).

The relative importance of river runoff in the southeast Beaufort Sea may be greater than in previously investigated arctic regions (i.e., Chukchi, western Beaufort Sea, Resolute Bay, Labrador Sea), which would partly explain the large overestimation. For instance, the CDOM absorption coefficient at 443 nm had a mean value of 0.12 m⁻¹ (Table 3; range, 0.014–0.75 m⁻¹), which is typical of coastal regions such as the Chesapeake Bay, Georgia Strait, and the Baltic sea (Kirk, 1994; Twardowski and Donaghay, 2001; Kowalczyk et al., 2005) where standard algorithms also fail. In addition, the sum of the CDOM and NAP absorption coefficients (i.e. $a_{CDM}$) largely dominates the blue absorption budget (Figure 3), which has been shown to lead to large overestimations of Chla in oligotrophic oceans (Dierssen, 2010). The contribution of $a_{CDM}$ to the nonwater absorption in the southeast Beaufort Sea was on average 87% at 443 nm with minimum and maximum values of 60% and 96%, respectively. There are almost no variations observed (85%) if the data close to the Mackenzie River are not used. This compares (Table 4) with values measured in the spring–summer period in the Amundsen Gulf (79%) and in the western Beaufort and Chukchi seas (77%) (Matsuoka et al., 2011). For other seasons, $a_{CDM}$ also dominates light absorption in this area with values ranging between 89% and 93% (Matsuoka et al., 2009; Brunelle et al., 2012). It is thus highly probable that the overestimation factor (approx. 5 ×) that was measured in the summer season also exists during other seasons.

The $a_{CDM}$ versus Chla relationship indicates that the southeast Beaufort Sea waters contained higher concentration of colored detrital material compared with other Arctic regions, and this was well above the classical case 1 waters (Figure 4a) but not in the lower Chla range. This high background in CDM is thus partly responsible for the large overestimation by the current empirical algorithms in the southeast Beaufort Sea. Our database, however, contains two notable exceptions to this rule at stations located in the coastal upwelling of Pacific waters near Cape Bathurst where the highest Chla concentrations were observed ( > 2 mg m⁻³). Interestingly, standard algorithms performed well at these two particular stations where CDM was comparable with previous studies (Figure 2b).

In addition, the relationship between the Chla and NAP absorption coefficient at 443 nm ($a_{NAP}$) is generally higher than those reported in previous studies except in the Western Arctic (Wang et al., 2005) where $a_{NAP}$ (443) was higher for Chla < 0.10 mg m⁻³ (Figure 4b). According to these results, the presence of particles may be more important in the southeast Beaufort Sea than in most other arctic regions. Higher particle backgrounds should therefore increase the backscattering coefficients and potentially contribute to the large overestimation we observed.
Table 3. Statistics for the absorption coefficients at 443 nm for colored dissolved organic matter, nonalgal particles, and phytoplankton in the southeast Beaufort Sea.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No. of stations*</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Average ± SD</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{CDOM}(443)$</td>
<td>45</td>
<td>0.014</td>
<td>0.75</td>
<td>0.062</td>
<td>0.12 ± 0.15</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>0.014</td>
<td>0.75</td>
<td>0.049</td>
<td>0.08 ± 0.12</td>
<td>66.66</td>
</tr>
<tr>
<td>$a_{NAP}(443)$</td>
<td>45</td>
<td>0.0021</td>
<td>0.25</td>
<td>0.012</td>
<td>0.030 ± 0.04</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>0.0021</td>
<td>0.11</td>
<td>0.01</td>
<td>0.019 ± 0.02</td>
<td>95</td>
</tr>
<tr>
<td>$a_{PHY}(443)$</td>
<td>45</td>
<td>0.0015</td>
<td>0.077</td>
<td>0.010</td>
<td>0.015 ± 0.01</td>
<td>66.66</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>0.0015</td>
<td>0.077</td>
<td>0.009</td>
<td>0.017 ± 0.01</td>
<td>58.82</td>
</tr>
</tbody>
</table>

*a45 represents all the stations and 37 represents data excluding stations near the Mackenzie River (see Figure 1).

Note: CV is the coefficient of variation, corresponds to the ratio between SD and mean value.

Table 2. Performance of the various algorithms tested ($N = 45$).

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>MNB</th>
<th>APD</th>
<th>Log_bias</th>
<th>Log_rms</th>
<th>$R^2$</th>
<th>Intercept*</th>
<th>Slope*</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC4v6 HPLC</td>
<td>482.72</td>
<td>483.42</td>
<td>−0.60</td>
<td>0.26</td>
<td>0.72</td>
<td>0.51 [0.42, 0.62]</td>
<td>0.76 [0.65, 0.90]</td>
</tr>
<tr>
<td>FLUO</td>
<td>188</td>
<td>192.99</td>
<td>0.26</td>
<td>0.26</td>
<td>0.72</td>
<td>0.27 [0.22, 0.34]</td>
<td>0.76 [0.65, 0.89]</td>
</tr>
<tr>
<td>OC3Mv6 HPLC</td>
<td>479.27</td>
<td>480.11</td>
<td>−0.67</td>
<td>0.28</td>
<td>0.69</td>
<td>0.56 [0.45, 0.68]</td>
<td>0.84 [0.70, 0.99]</td>
</tr>
<tr>
<td>FLUO</td>
<td>186.33</td>
<td>192.23</td>
<td>0.26</td>
<td>0.28</td>
<td>0.69</td>
<td>0.30 [0.24, 0.38]</td>
<td>0.84 [0.71, 0.99]</td>
</tr>
<tr>
<td>OC4Mev6 HPLC</td>
<td>519.86</td>
<td>520.67</td>
<td>−0.60</td>
<td>0.27</td>
<td>0.72</td>
<td>0.50 [0.41, 0.60]</td>
<td>0.71 [0.61, 0.84]</td>
</tr>
<tr>
<td>FLUO</td>
<td>206.40</td>
<td>211.18</td>
<td>0.21</td>
<td>0.27</td>
<td>0.72</td>
<td>0.27 [0.22, 0.33]</td>
<td>0.71 [0.60, 0.83]</td>
</tr>
<tr>
<td>OC4L HPLC</td>
<td>564.63</td>
<td>564.63</td>
<td>−0.97</td>
<td>0.30</td>
<td>0.73</td>
<td>0.86 [0.71, 1.01]</td>
<td>1.19 [1.00, 1.37]</td>
</tr>
<tr>
<td>FLUO</td>
<td>228.53</td>
<td>231.54</td>
<td>0.23</td>
<td>0.30</td>
<td>0.73</td>
<td>0.49 [0.41, 0.59]</td>
<td>1.17 [1.00, 1.43]</td>
</tr>
<tr>
<td>OC4P HPLC</td>
<td>527.74</td>
<td>527.74</td>
<td>−1.07</td>
<td>0.36</td>
<td>0.66</td>
<td>0.79 [0.62 0.96]</td>
<td>1.22 [1.01, 1.44]</td>
</tr>
<tr>
<td>FLUO</td>
<td>210.29</td>
<td>220.77</td>
<td>0.53</td>
<td>0.36</td>
<td>0.66</td>
<td>0.41 [0.31 0.52]</td>
<td>1.22 [1.02, 1.43]</td>
</tr>
<tr>
<td>OC4L HPLC</td>
<td>282.36</td>
<td>284.06</td>
<td>−0.51</td>
<td>0.26</td>
<td>0.75</td>
<td>0.51 [0.40, 0.64]</td>
<td>1.00 [0.86, 1.17]</td>
</tr>
<tr>
<td>FLUO</td>
<td>89</td>
<td>101.67</td>
<td>0.49</td>
<td>0.26</td>
<td>0.75</td>
<td>0.20 [0.12, 0.27]</td>
<td>1.00 [0.84, 1.15]</td>
</tr>
<tr>
<td>OC4P HPLC</td>
<td>58.27</td>
<td>80.7</td>
<td>0.18</td>
<td>0.27</td>
<td>0.76</td>
<td>0.20 [0.065, 0.34]</td>
<td>1.10 [0.94, 1.28]</td>
</tr>
<tr>
<td>OC4P HPLC</td>
<td>16.78</td>
<td>48.95</td>
<td>0.88</td>
<td>0.26</td>
<td>0.73</td>
<td>−0.11 [−0.21, 0.004]</td>
<td>0.85 [0.73, 1.00]</td>
</tr>
<tr>
<td>OC4P HPLC</td>
<td>17.75</td>
<td>50</td>
<td>0.94</td>
<td>0.26</td>
<td>0.72</td>
<td>−0.10 [−0.20, −0.008]</td>
<td>0.85 [0.73, 1.00]</td>
</tr>
<tr>
<td>OC4P HPLC</td>
<td>17.56</td>
<td>50.37</td>
<td>0.93</td>
<td>0.26</td>
<td>0.72</td>
<td>−0.10 [−0.20, 0.01]</td>
<td>0.86 [0.74, 1.01]</td>
</tr>
<tr>
<td>OC4P HPLC</td>
<td>19.53</td>
<td>52.41</td>
<td>0.96</td>
<td>0.27</td>
<td>0.70</td>
<td>−0.10 [−0.20, 0.01]</td>
<td>0.85 [0.72, 1.00]</td>
</tr>
<tr>
<td>OC4P HPLC</td>
<td>20.76</td>
<td>55.29</td>
<td>1.01</td>
<td>0.29</td>
<td>0.65</td>
<td>−0.14 [−0.25, −0.02]</td>
<td>0.81 [0.67, 0.96]</td>
</tr>
<tr>
<td>OC4P HPLC</td>
<td>17.08</td>
<td>50.86</td>
<td>0.25</td>
<td>0.25</td>
<td>0.74</td>
<td>−0.09 [−0.19, 0.019]</td>
<td>0.87 [0.74, 1.02]</td>
</tr>
<tr>
<td>OC4P HPLC</td>
<td>17.81</td>
<td>51.41</td>
<td>0.73</td>
<td>0.26</td>
<td>0.73</td>
<td>−0.10 [−0.20, 0.01]</td>
<td>0.86 [0.73, 1.01]</td>
</tr>
<tr>
<td>OC4P HPLC</td>
<td>17</td>
<td>49.87</td>
<td>0.96</td>
<td>0.25</td>
<td>0.75</td>
<td>−0.09 [−0.18, 0.018]</td>
<td>0.88 [0.75, 1.01]</td>
</tr>
</tbody>
</table>

*Numbers in brackets are for the range of 95% confidence interval computed for a type II regression using reduced major axes.

Note: The rows refer to the statistical parameters between the measured and retrieved Chl$a$ using Equation (2) in Table 1, and Equations (3), (7), (8), (9), and (10). $R^2$, Intercept and Slope stand, respectively, for root correlation coefficient, intercept and slope of the linear regression between the log-transformed algorithm-derived and in situ Chl$a$ values. Rows 6 and 7 correspond to statistical parameters of the GSM01 ($N = 44$) and the GSM01 modified (GSM MOD) ($N = 42$); rows 8 and 9 correspond to statistical parameters of the adapted algorithms for the southeast Beaufort Sea; rows 10–15 correspond to statistical parameters of the regional developed algorithms for the southeast Beaufort Sea described in Tables 5 and 6.
Regional algorithms for the southeastern Beaufort Sea

Considering the inaccuracy of the previous algorithms, we propose a regionally tuned version of current algorithms as well as new empirical forms. These algorithms account for the optical particularities of the area reducing significantly the error in Chl retrieval from space.

Empirical algorithms

The empirical approach has often been used with success to develop regional algorithms (Wang and Cota, 2003; Cota et al., 2004; Darecki and Stramski, 2004; Mélin et al., 2007; Hyde et al., 2007; Tang et al., 2008; Gitelson et al., 2009; Mitchell and Kahru, 2009). The empirical approach directly relates the remote sensing signal to the parameter of interest using statistical techniques. It has a proven capacity to provide reliable information for specific areas, and it is a most convenient choice in terms of computational simplicity (Matthews, 2011). Readaptation or regional tuning of the coefficients in a band-ratio algorithm to specific water types is often used as a simple mean to improve the accuracy of remote sensing retrievals in noncase 1 waters. The procedure consists of redefining the algorithm coefficients to minimize the RMS residual errors between the evolving band-ratio algorithm outputs and the in situ data.

The coefficients for the adapted Chl algorithms are $[-0.32 -2.33 4.02 -31.64, 48.54]$ for the SeaWiFS and MERIS sensors and $[-0.35 -1.52 -2.44 -12.80, 30.48]$ for MODIS. As expected, higher correlations with in situ data (Figure 5) were obtained providing a much lower MNB (20%) and APD (50%) than actual operational algorithms, with a log rms around 0.26 (Table 2). Even though these errors were still higher than the 35% precision goal of the ocean color community, they provided a great improvement over operational algorithms.

We also examined if other algorithm formulations could provide further improvements. We tested 28 possible band-ratio combinations using the in situ $R_S$ data set (45 stations). Because of the relatively small number of stations it was necessary to limit the analysis to second-degree polynomials as higher degrees lead to unstable algorithm behavior outside the range of the data set.

The multiple regression analysis between retrieved and in situ Chl gives a variety of configurations (log-log and linear graphs). To select the most useful algorithmic equations among these configurations, we defined some criteria such as high correlation coefficient $R^2$ between in situ Chl and algorithm output, low ADP (%), and low

Table 4. Relative contributions (mean ± 1 SD) of absorption coefficient for colored dissolved organic matter, phytoplankton, and nonalgal particles to the total nonwater absorption at 443 nm.

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Area</th>
<th>$N$</th>
<th>Date (d/m)</th>
<th>$a_{CDOM(443)}/a_{t-w(443)}$</th>
<th>$a_{Ph(443)}/a_{t-w(443)}$</th>
<th>$a_{NAP(443)}/a_{t-w(443)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babin et al. (2003)</td>
<td>Coastal waters around Europe</td>
<td>317</td>
<td>03/04–25/09</td>
<td>0.41 ± 0.14</td>
<td>0.36 ± 0.14</td>
<td>0.22 ± 0.13</td>
</tr>
<tr>
<td>Matsuoka et al. (2007)</td>
<td>Western Beaufort and Chukchi</td>
<td>183</td>
<td>09/09–10/15</td>
<td>0.76 ± 0.11</td>
<td>0.16 ± 0.11</td>
<td>0.08 ± 0.05</td>
</tr>
<tr>
<td>Matsuoka et al. (2009)</td>
<td>Southeastern Beaufort Sea</td>
<td>30</td>
<td>13/09–14/10</td>
<td>0.84 ± 0.08</td>
<td>0.07 ± 0.04</td>
<td>0.09 ± 0.06</td>
</tr>
<tr>
<td>Matsuoka et al. (2011)*</td>
<td>Western Beaufort and Chukchi</td>
<td>61</td>
<td>05/05–15/06</td>
<td>0.63 ± 0.17</td>
<td>0.22 ± 0.12</td>
<td>0.14 ± 0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>109</td>
<td>16/07–26/08</td>
<td>0.55 ± 0.15</td>
<td>0.29 ± 0.13</td>
<td>0.16 ± 0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>179</td>
<td>01/09–13/10</td>
<td>0.73 ± 0.14</td>
<td>0.18 ± 0.12</td>
<td>0.09 ± 0.05</td>
</tr>
<tr>
<td>Brunelle et al. (2012)</td>
<td>Amundsen Gulf</td>
<td>20</td>
<td>08/05–06/07</td>
<td>0.72</td>
<td>0.21</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>10/10–15/10</td>
<td>0.68</td>
<td>0.11</td>
<td>0.21</td>
</tr>
<tr>
<td>Brunelle et al. (2012)</td>
<td>Canadian Archipelago</td>
<td>6</td>
<td>10/10–15/10</td>
<td>0.65</td>
<td>0.21</td>
<td>0.14</td>
</tr>
<tr>
<td>This study</td>
<td>Southeastern Beaufort Sea</td>
<td>46</td>
<td>04/06–02/08</td>
<td>0.70 ± 0.14</td>
<td>0.13 ± 0.09</td>
<td>0.17 ± 0.10</td>
</tr>
<tr>
<td>This study</td>
<td>Southeastern Beaufort Sea</td>
<td>37</td>
<td></td>
<td>0.69 ± 0.16</td>
<td>0.14 ± 0.10</td>
<td>0.17 ± 0.11</td>
</tr>
</tbody>
</table>

*Data from Matsuoka et al. (2011) are for $\lambda = 440$ nm.

Note: Available coefficients from literature are also shown for comparison.
RMS (mg m\(^{-3}\)). The preference was given to algorithms involving the wavelengths available in the SeaWiFS, MODIS, and MERIS sensors such as 443, 490, 510, 555, and 665 nm.

It has sometimes been shown that green-to-red (Gitelson et al., 2009) and red-to-red (Moses et al., 2009; Sokoletsky et al., 2011) ratios are more correlated to Chl\(_a\) in case 2 waters as they are normally less influenced by CDOM absorption. It was not possible to test the red-to-red approach using the SPMR data, but, in our tests, the use of green-to-red band ratios did not provide better results than the use of more traditional blue-to-green ratios (not shown). This probably results from the fact that the southeast Beaufort Sea is mostly oligotroph (low Chl\(_a\) concentrations) so that the red chlorophyll absorption peak is not observable due to the strong light absorption by water at these wavelengths (Gons et al., 2008). The algorithms using a single band-ratio (one variable, two bands) are given in Table 5 and the algorithms using two band-ratios (two variables, at least three bands) are given in Table 6. The multiple regressions with two-band ratios globally show the best statistical performance overall in terms of APD and log rms (Table 2). Excluding the Mackenzie stations further reduced the APD errors to 37\%, log rms of approximately 0.21 and \(R^2\) approximately 0.84 (not shown). The overall performance of the adapted and multiple regression algorithms were similar to other published case 2 algorithms also based on a low (< 50) number of measurements (Wang and Cota, 2003; D’Sa and Miller, 2003; Sancak et al., 2005; Montes-Hugo et al., 2005; Chang and Gould, 2006; Tang et al., 2008; Komick et al., 2009; Dogliotti et al., 2009).

**Semi-analytical algorithms**

Given that the semi-analytical algorithm GSM01 had the best performance of the algorithms tested, we attempted to optimize it using our data set. Based on a limited number of stations (\(N = 45\)), it was not possible, however, to adopt advanced optimization methodologies such as the one employed by Maritorena et al. (2002) or Kostadinov et al. (2007). Many runs were thus performed changing the model parameters individually i.e., the phytoplankton Chl\(_a\)-specific absorption spectrum \(a_{ph}(\lambda)\), the spectral slope of CDOM \((S_{CDM})\), and the exponent of the power law used to model \(b_{bp}(\eta)\) over a range slightly larger than the one observed in the southeast Beaufort Sea. In brief, we tested:

- 11 values of \(S_{CDM}\) from 0.015 to 0.025 nm\(^{-1}\), with an increment of 0.001 nm\(^{-1}\);
- 11 values of \(\eta\) from 0 to 2, with an increment of 0.2; and
- 8 values that multiplies the GSM01 spectra (red curve on Figure 6d) from 0.6 to 2, with an increment of 0.2.

The rational for the use of a factor that multiplies the GSM01 \(a_{ph}\) was because the algorithm’s performance was not improved by imposing our measured mean or median \(a_{ph}\) spectrum (green curve on Figure 6d) from 0.6 to 2, with an increment of 0.2.
COST = 0.1N\text{neg} + \left[ \sum_{k=1}^{3} \left( a_k |1 - R_k^2| + b_k |1 - \text{slope}_k| \right) + c_k \log_{\text{rms}}_k \right] \quad (11)

where \(N\text{neg}\) is the number of negative retrievals, \(R_k^2\) is the square of the correlation coefficient between the \(k\)th measured and retrieved variable, \(\text{slope}_k\) is the slope of the type II regression of \(k\)th retrievals on the measurements in the log 10 space, and \(\log_{\text{rms}}_k\) is root mean square error for

**Figure 5.** Computed Chla using the OC4v6, the adapted OC4v6 with in situ Chla, and the Amundsen–SWF–MB algorithm.

| Table 5. Regional new algorithms in the southeast Beaufort Sea region. |
|-----------------|-----------------|---------------|
| Algorithm* | Coefficients \(a_n\), \(n = 0,1,2,...,M\) | \(R\) |
| Amundsen–MOD | \([-0.52, -3.4, -0.87]\) | \(R = \log_{10}\left[ R_{490}/R_{532} \right]\) |
| Amundsen–SWF | \([-0.37, -2.1, -1.1]\) | \(R = \log_{10}\left[ R_{490}/R_{555} \right]\) |
| Amundsen–MER | \([-0.63, -6.7, 2.66]\) | \(R = \log_{10}\left[ R_{490}/R_{510} \right]\) |

*The algorithms are expressed as: Chlorophyll (mg m\(^{-3}\)) = \(10^\left( a_0 + a_1 R + a_2 R^2 \right)\) \quad (12)

where \(R\) is the base 10 logarithm of the band ratio and \(a_i\) are empirical coefficients.

| Table 6. Regional new algorithms using a two-band ratio in the southeast Beaufort Sea region. |
|-----------------|-----------------|---------------|
| Algorithm | Coefficients \(a_n\), \(n = 0,1,2,...,M\) | \(BR\) |
| Amundsen–MOD–MB | \([-0.23, 1.57, -8.79]\) | \(BR_1 = R_{443}/R_{590}\) |
| | | \(BR_2 = R_{510}/R_{532}\) |
| Amundsen–SWF–MB | \([0.11, 7.09, -3.65]\) | \(BR_1 = R_{443}/R_{490}\) |
| | | \(BR_2 = R_{443}/R_{555}\) |
| Amundsen–MER–MB | \([0.73, 0.64, -3.90]\) | \(BR_1 = R_{443}/R_{665}\) |
| | | \(BR_2 = R_{490}/R_{555}\) |

The algorithms are expressed as: Chlorophyll (mg m\(^{-3}\)) = \(10^\left( a_0 + a_1 BR_1 + a_2 BR_2 \right)\) \quad (13)

where \(R\) is the base 10 logarithm of the two bands ratio (\(BR_1\) and \(BR_2\)), (\(R = \log_{10}\left[BR_1/BR_2\right]\)) and \(a_i\) are empirical coefficients.

Note: MB, multiple bands.
the \( k \)th variable (see Equation (10)). The \( a_k \), \( b_k \), and \( c_k \) are weighting factors for the \( k \)th variable. Because we were mainly interested in Chl \( a \) retrieval and we approximated \( b_{bp}(443) \) (our measured \( b_p(443) \) multiplied by the ratio \( b_{bp}/b_p \) assumed to be 0.015 (Twardowski et al., 2001), we put more weight to the metrics used to evaluate the Chl \( a \) retrieval than \( b_{bp} \). For \( a_{CDM}(443) \) \( a \), \( b \), and \( c \) were set to 1, 1.5, and 1, respectively, as in Kostadinov et al. (2007). Then for Chl \( a \), \( b \), and \( c \) were set to 1.25, 1.875, and 1.25, respectively, and 0.75, 1.125 and 0.75, respectively, for \( b_{bp}(443) \).

The best performance (lower COST) was obtained for \( S_{CDM}/C_30 \) = 0.018 nm\(^{-1} \), \( \eta = 1.4 \), and \( a'_{ph} \) multiplied by a factor of 1.4. The retrieved values versus measured values are presented in Figure 6. As expected, GSM01-MOD retrievals show improved agreement with in situ Chl \( a \) relative to GSM01 (Table 3, slope of 1.1, \( R^2 = 0.76 \), log\_rms = 0.27, Figure 6a), but the positive MNB of 58\% indicates that Chl \( a \) are still positively biased. Thus, the semi-analytical model did not perform better than the regionally tuned empirical algorithm presented previously.

One advantage of the semi-analytical algorithm, however, is its capability to estimate other optically significant constituents such as \( a_{CDM} \) and \( b_{bp} \). Good agreement \( (R^2 = 0.76) \) was found between measured and retrieved \( a_{CDM} \) using GSM01 despite a negative bias of 31\% (Table 7; Figure 6b). Maritorena et al. (2002) made an ad hoc correction for the bias of \( a_{CDM} \) in the operational version of GSM01, which lowered the values by a factor of 0.75. Interestingly, removing this correction factor (GSM01 no bias) reduced the bias to –9\%. In contrast, Wang and Cota (2003) found a positive bias and a relatively poor linear relationship between predicted and in situ \( a_{CDM} \) \( (R^2 = 0.56) \) in the western Beaufort and Chukchi seas. A strong linearity was also found between modelled and particulate back-scattering estimated from our \( b_p \) measurements \( (R^2 = 0.85) \), but with a slope significantly > 1.0, consistent with the findings of Wang and Cota (2003) (Table 7; Figure 6c). We acknowledge that our estimated in situ \( b_{bp}(443) \) may introduce some bias in this analysis.

Figure 6d presents the \( a_{ph}' \) as determined from filter pad measurements during CASES (median values) and the spectrum obtained from the local tuning. For comparison, we also plotted \( a_{ph} \) used by the GSM01 (Maritorena et al., 2002) and the spectrum obtained from the local tuning.

\[ \text{Figure 6. Results of the local tuning of the GSM algorithm for (a) Chl} \ a, \ (b) \ CDM, \text{and (c) } b_{bp}. \text{ (d) The specific chlorophyll-}\ a\text{ absorption values as determined by the local tuning. For comparison purposes, the GSM globally tuned values of Maritorena et al. (2002) are included, as well as the CASES median measured values, and the model values of Bricaud et al. (1998) computed for the CASES median Chl} \ a = 0.13 \text{ mg m}^{-3}. \]
Table 7. Statistics of $a_{CDM}(443)$ and $b_{bp}(443)$ retrieved by GSM01, GSM01 with no bias and GSM modified.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>MNB</th>
<th>APD</th>
<th>Log_bias</th>
<th>Log_rms</th>
<th>$R^2$</th>
<th>Intercept*</th>
<th>Slope* (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{CDM}(443)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSM01</td>
<td>31.25</td>
<td>35.10</td>
<td>1.44</td>
<td>0.187</td>
<td>0.76</td>
<td>−0.23 [−0.37, −0.08]</td>
<td>0.96 [0.82, 1.10]</td>
</tr>
<tr>
<td>GSM 01 (no bias)</td>
<td>−8.85</td>
<td>27.54</td>
<td>1.23</td>
<td>0.187</td>
<td>0.76</td>
<td>−0.11 [−0.25, 0.0332]</td>
<td>0.96 [0.82, 1.10]</td>
</tr>
<tr>
<td>GSM MOD</td>
<td>3.75</td>
<td>32.71</td>
<td>0.92</td>
<td>0.18</td>
<td>0.77</td>
<td>0.056 [−0.10, 0.21]</td>
<td>1.04 [0.88, 1.19]</td>
</tr>
<tr>
<td>$b_{bp}(443)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSM01</td>
<td>−17.39</td>
<td>36.33</td>
<td>1.05</td>
<td>0.22</td>
<td>0.85</td>
<td>0.58 [0.19, 0.96]</td>
<td>1.29 [1.13, 1.45]</td>
</tr>
<tr>
<td>GSM MOD</td>
<td>−3.23</td>
<td>35</td>
<td>1.01</td>
<td>0.20</td>
<td>0.85</td>
<td>0.56 [0.17, 0.95]</td>
<td>1.25 [1.09, 1.41]</td>
</tr>
</tbody>
</table>

1GSM01 with no bias is calculated without considering the GSM01 model bias (a correction to avoid negative values, Maritorena et al., (2002)).

*Numbers in brackets are for the range of 95% confidence interval computed for a type II regression using reduced major axes.

Notes: GSM01 and GSM01 (no bias): $N = 46$, GSM Mod: $N = 44$ for $a_{CDM}(443)$. GSM01: $N = 44$ (same values of Chl$\alpha$ for GSM01 and for GSM01 no bias), GSM MOD $N = 42$ for $b_{bp}(443)$. $R^2$, Intercept and Slope are the root correlation coefficient, intercept, and slope of the linear regression between the log-transformed algorithm-derived and in situ $a_{CDM}(443)$ values and in situ $b_{bp}(443)$ values, respectively.

2002) as well as the empirically modelled values obtained using a Chl$\alpha$ of 0.13 mg m$^{-3}$, i.e., the CASES median value, in the case 1 model of Bricaud et al. (1998). The CASES local tuning spectrum had the same shape as the GSM01, as we simply multiplied the latter by a given factor to tune GSM01. Despite the relatively low values at 412 and 490 nm, the locally tuned $a'_{ph}$ was closer to the one measured relative to GSM01. Note that the median $a'_{ph}$ from CASES was slightly below the Bricaud’s curve expected in temperate waters suggesting some degree of pigment packaging as in many northern waters (e.g., Brunelle et al., 2012; Mitchell, 1992; Matsuoka et al., 2007, 2009; Cota et al., 2003; Wang et al., 2005).

The local optimization procedure presented here clearly improved the performance of the original GSM01 model, but a full optimization of $a'_{ph}$ would be necessary. However, this task is still hampered by the lack of in situ optical observations (i.e., both AOPs and IOPs) in the Arctic. Efforts must thus be made to build a larger Arctic data set including a wider range of optical conditions.

**Matchups analysis**

In this section, we assess the quality of satellite retrieval of $R_s(\lambda)$ and Chl$\alpha$ from SeaWiFS, MODIS, and MERIS. Adhering to the criteria defined previously in “Match-up analysis and satellite data processing”, a total of 23 matchups between satellite images and in situ measurements (8 for SeaWiFS, 6 for MODIS, and 9 for MERIS) were found. Note that for a given station several images may be available, which resulted in 14 different stations with matchups (Appendix A1).

**Water-leaving reflectance retrievals**

The quality of the satellite-derived Chl$\alpha$ depends on the accuracy of the water-leaving radiance retrievals. Figure 7 shows the comparisons of measured and retrieved $R_s$ at different wavelengths. For all sensors, the error is higher at 412 and 665 nm than at intermediate wavelengths. Overall, SeaWiFS performance in terms of APD and MNB was better than MODIS and MERIS (Figure 8). Indeed MERIS $R_s$ showed a strong positive MNB (>37%) at all wavelengths (Figures 7c and 8b). At 412 nm, APD reached as much as 128%, 115%, and 94% for MODIS, MERIS, and SeaWiFS, respectively. SeaWiFS tends to underestimate $R_s$ at 412 (MNB = −7.85%); whereas, MERIS systematically overestimated and MODIS showed no clear patterns. This wavelength is important to obtain good retrieval with semi-analytical algorithm. Validation studies done in various water types showed similar patterns for SeaWiFS with the largest differences observed at 412 and 665 nm (Antoine et al., 2008; Zibordi et al., 2006; Darecki and Stramski, 2004; García et al., 2005; Bailey and Werdell, 2006; Mélin et al., 2007; Tilstone et al., 2011). The retrieval of the $R_s$ band-ratio used by the empirical algorithms showed that for the ratio $R_s(443)/R_s(555)$, the APD for was equal to 15% for SeaWiFS, 55% for MODIS, and 20% for MERIS. For the ratio $R_s(490)/R_s(555)$, the APD was about 8% for SeaWiFs and MODIS and 11% for MERIS. Thus, both ratios were better estimated for SeaWiFS ($R^2$ = approx. 0.85; MNB < 3%) than for MODIS and MERIS. Also, for all sensors $R_s(490)/R_s(555)$ was better retrieved than $R_s(443)/R_s(555)$.

Many factors can affect the retrieval of satellite-derived water-leaving radiances. In particular, in coastal waters located at the proximity of freshwater sources large inputs of particulate matter reflecting in NIR region of the spectra negates the dark pixel assumption that is used to initiate the atmospheric correction. Lavender et al. (2005) suggested that water-leaving NIR reflectance can be significant with TSM as low as 2 mg L$^{-1}$. In the southeast Beaufort Sea, TSM ranged between 0.15 and 5.56 mg L$^{-1}$ with a mean value of 1.024 (SD = 1.036) mg L$^{-1}$ and a median value of 0.64 mg L$^{-1}$. With the exception of the Mackenzie plume station (903, 906, 909) where TSM concentrations exceeded 2.5 mg L$^{-1}$, all CASES stations show TSM < 2 mg L$^{-1}$ suggesting that turbidity should not be problematic for atmospheric correction. Other factors include (i) the presence of sea ice (Bélanger et al., 2007; Wang and Shi, 2009), (ii) low solar elevation, (iii) inappropriate atmospheric aerosol models, and (iv) accuracy of the sensor calibration. The first two factors are not believed to play a role in our
Figure 7. (a) Scatterplots of the in situ reflectance measurements against the reflectance values derived from the SeaDAS v5.2 atmospheric correction output for SeaWiFS data matchups, (b) same as (a) but from MODIS-aqua, (c) same as (a) but for MERIS data matchups derived from the MERMAID data base extraction.

Figure 8. (a) Absolute percentage difference of $R_{rs}(\lambda)$ derived from SeaWiFS, MODIS and MERIS – in situ reflectance measurements. (b) Mean normalised bias of $R_{rs}(\lambda)$ derived from SeaWiFS, MODIS and MERIS – in situ reflectance measurements.
validation exercise as in situ data were located far from any ice, and solar elevation was at least 33° (i.e., θ_s < 70°). More matchups would be necessary to confirm if the bias observed, particularly in MERIS data, is generalized over the whole Arctic Ocean and sub-arctic seas. In any case, accuracy of the sensor calibrations, the effect of low solar elevation (e.g., on the accuracy of Rayleigh look-up-table), and the aerosol model selections cannot be discarded at this point.

Chl_a retrievals

Satellite retrieval of Chl_a was strongly overestimated using operational empirical algorithms (Figure 9a). The overestimation reached 552% with a log_rms of 0.44 mg m⁻³ when considering the statistics of all sensors (N = 23) with no significant difference among sensors. Chl_a retrieved with GSM01 (Figure 9b) were overestimated by a factor of approximately 2.5 (N = 15), but the algorithm failed to converge on 8 out of 23 stations. An examination of the satellite-derived water-leaving reflectance where GSM01 did not converge revealed that the failure happened only when R gs(412) were negative (N = 3) or anomalously low relative to in situ measurements (N = 5). The latter is illustrated in Figure 10, which shows a typical example of the R gs and Chl_a retrieval by the three sensors at one station (309) sampled on 19 July 2004 in the Amundsen Gulf. SeaWiFS R gs retrievals in the 490–555 nm range was in good agreement with in situ data except at 412 nm. Consequently, the GSM01 failed to estimate Chl_a because of this abnormal R gs shape at short wavelengths. MODIS retrieval was good in terms of the spectral shape, but it was slightly higher in magnitude relative to in situ measurements; whereas, MERIS showed a systematic overestimation of R gs at all wavelengths. The best Chl_a estimation for this particular station was achieved by MODIS with GSM01 (0.26 mg m⁻³) and the regionally tuned GSM version (0.11 mg m⁻³). For comparison, the adapted new algorithms developed using the in situ data set provided a much better estimation of Chl_a concentration (not shown). There was no degradation of precision compared with the use of the development in situ R gs data set for the SeaWiFS algorithm (APD was 47%); whereas, the MERIS and MODIS precision was slightly worse (APD was 92% and 72%, respectively).

An important outcome of this analysis is that the number of valid pixels will be smaller with the use of GSM01 (even smaller for the regionally tuned GSM) relative to standard empirical algorithms. However, the satellite Chl_a products obtained by this particular semi-analytical algorithm will be of greater quality in the southeast Beaufort Sea.

Conclusion

Based on a regional dataset acquired during the CASES expedition, we showed that the current operational ocean color algorithms are inappropriate to estimate Chl_a in the southeast Beaufort Sea. The semi-analytical algorithm tested (GSM01) performed better than empirical algorithms (OC4, OC3M, OC4ME, Arctic-OC4L, and -OC4P). We derived adapted empirical algorithms developed specifically for the southeast Beaufort Sea that greatly improve the accuracy of Chl_a retrievals. The regionally tuned semi-analytical algorithm (GSM) was not able to derive more accurate Chl_a than the tuned empirical algorithms despite the dominance of colored detrital material in the blue light absorption budget, but it allowed the retrieval of additional optically significant constituents such as CDM absorption and particulate backscattering coefficients. This confirms that empirical algorithms are as good as the data they are based on, and how representative the data are of the environment where the algorithms are to be applied (Claustre and Maritorena, 2003). Finally, the comparison between satellite-derived and in situ data showed the difficulty to correctly estimate remote sensing reflectances.
in the Arctic possibly due to inaccurate atmospheric corrections.

Our study was based on a limited in situ data set and the new proposed algorithms can only be applied to the Beaufort shelf east of Mackenzie canyon and in the Amundsen Gulf. However, despite having been derived using data from the southeast Beaufort Sea, our results clearly show that standard algorithms do not work well in high CDOM – low chlorophyll areas. Even if the entire Arctic ocean is characterized by a DOM content that is much higher than the Atlantic and Pacific oceans (Benner et al., 2005), it is mostly in its surrounding seas that the CDOM content has the potential to dominate the light budget and thus affects the remote sensing estimation of Chl (Arrigo et al., 2011). The Arctic Ocean receives the highest amount of river runoff relative to the other oceans (Rachold et al., 2004) with 80% of it being discharged over the huge Eurasian continental shelves (East Siberian, Laptev, Kara, and Barents Seas) (McClelland et al., 2012). We hypothesize that the southeast Beaufort Sea waters are optically similar to a large, though unknown, proportion of the coastal Arctic waters. For instance, the Chuckchi Sea is characterized by low Chl a and high CDOM (Pegau, 2002), while the Kara and Laptev seas have low Chl a concentrations (Mosharov, 2010; Vetrov et al., 2008). Lack of in situ optical data over the Siberian shelves prevents us from extrapolating our findings to other Arctic regions, but there are indications that current Chl a operational algorithms should be used with care over the Eurasian Arctic shelves (Vetrov and Romankevich, 2007; Vetrov et al., 2008). Indeed the matchup analysis leads to the conclusion that the semi-analytical approach should be preferred over globally tuned empirical algorithms but its parameterisation must be improved using a pan-arctic optical data set. In any case, further work must be carried out to assess the quality of satellite-derived water-leaving reflectance on which bio-optical algorithms are applied.

Acknowledgements

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References


Appendix A1

Details of the matchups (location, date, time, and the sun zenith angle at the time of sampling).

<table>
<thead>
<tr>
<th>CASES station</th>
<th>Date (m-d-y)</th>
<th>Time (UTC)</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>Instrument</th>
<th>In situ sun zenith angle (°)</th>
<th>Image (YYYYDDDHHMMSS) (AYYYYDDDHHMMSS)</th>
<th>Pixel solar zenith angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>406</td>
<td>06-15-2004</td>
<td>18:31:48</td>
<td>71.29</td>
<td>−127.74</td>
<td>SPMR</td>
<td>50.8</td>
<td>A2004167201500</td>
<td>47.98</td>
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<td>06-17-2004</td>
<td>20:12:00</td>
<td>70.7</td>
<td>−129.11</td>
<td>ASD</td>
<td>47.60</td>
<td>A2004169200500</td>
<td>47.51</td>
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<td>07-02-2004</td>
<td>18:37:48</td>
<td>70.63</td>
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<td>51.80</td>
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<td>71.12</td>
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<td>50.55</td>
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<td>309-2</td>
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<td>71.17</td>
<td>−126.2</td>
<td>ASD</td>
<td>50.28</td>
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<td>50.55</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td>50.77</td>
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<tr>
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<td>−125.09</td>
<td>SPMR</td>
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<td>54.79</td>
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<td>70.85</td>
<td>−123.52</td>
<td>SPMR</td>
<td>67.40</td>
<td>S2004212225019</td>
<td>57.48</td>
</tr>
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<td>69.84</td>
<td>−133.29</td>
<td>ASD</td>
<td>62.36</td>
<td>S2004208232426</td>
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<td>SPMR</td>
<td>67.90</td>
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