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New atmospheric correction technique to retrieve the ocean colour from SeaWiFS imagery in complex coastal waters

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Received 22 November 2006, accepted for publication 27 March 2007
Published 2 May 2007
Online at stacks.iop.org/JOptA/9/511

Abstract
There exists a large demand for an accurate atmospheric correction of satellite ocean colour data over highly turbid coastal waters, where the standard atmospheric correction (SAC) algorithms designed for open ocean water turn out to be unsuccessful because of eventual interference of elevated radiances from suspended materials and perhaps the shallow bottom with the corrections based on the two near-infrared bands at 765 and 865 nm in which the water-leaving radiances are discarded (or modelled) in order to estimate aerosol radiative properties and extrapolate these into the visible spectrum in the atmospheric correction of the imagery. Furthermore, in the presence of strongly absorbing aerosols (e.g. Asian dust and Sahara dust) the SAC algorithms often underestimate water-leaving radiance values in the violet and blue spectrum or completely fail to deliver the desired biogeochemical products for coastal regions. To make the satellite ocean colour data offer unrivaled utility in monitoring and quantifying the components of ecologically important coastal waters, this study presents a more realistic and cost-effective image-based atmospheric correction method to accurately retrieve water-leaving radiances and chlorophyll concentrations from SeaWiFS imagery in the presence of strongly absorbing aerosols over highly turbid Northwest Pacific coastal waters. This method is a modified version of the spectral shape matching method (SSMM) previously developed by Ahn and Shanmugam (2004 Korean J. Remote Sens. 20 289–305), re-treating the assumption of spatial homogeneity of the atmosphere using simple models for assessing the contributions of aerosol and molecular scattering. Because of the difficulties in making atmospheric measurements concurrently with each overpass of SeaWiFS the atmospheric diffuse transmittance values are dependent on a standard method with the SAC scheme designed for processing SeaWiFS ocean colour data. The new method is extensively tested under the presence of various atmospheric conditions using SeaWiFS imagery and the results are compared with in situ (ship-borne) measurements in highly turbid coastal waters of the Korean Southwest Sea (KSWS). Such comparison demonstrates the efficiency of SSMM in terms of removing the effects of strongly absorbing aerosols (Asian dust) and improving the accuracy of water-leaving radiance retrieval with an RMSE deviation of 0.076, in contrast with 0.326 for the SAC algorithm which masked most of the sediment-laden and aerosol-dominated coastal areas. Further comparison in the Yellow Sea waters representing a massive phytoplankton bloom on 27 March 2002 revealed that the SAC algorithm caused an excessive correction for the visible bands, with the 412 nm band being affected the most, leading to severe overestimation of chlorophyll concentrations in the bloom-contained waters. In contrast, the SSMM remained very effective in terms of reducing errors of both water-leaving radiance and chlorophyll concentration estimates.

Keywords: SeaWiFS, ocean colour, atmospheric correction, SAC algorithm, SSMM, absorbing aerosols, Northwest Pacific coastal waters

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1. Introduction

Coastal waters are ecologically very important and also a major resource for human populations, contributing a large share of the world fisheries catch and supporting a rapidly growing mariculture industry. These waters are generally recognized as Case II waters [2] that contain constituents other than phytoplankton, such as suspended sediments (SS) and dissolved organic matter (DOM). Such additional components resulting from terrestrial inputs and bottom resuspension make these waters optically more complex than Case I waters, where most of the quantitative applications of ocean colour remote sensing have focused on determining the abundance and distribution of phytoplankton chlorophyll and understanding the ocean biological and biogeochemical processes since the late 1970s [3–9]. Interpreting satellite ocean colour data for such applications required algorithms to first correct for atmospheric effects using detailed models of radiative transfer in the atmosphere and then retrieve information on the biogeochemical variables in ocean waters using fairly simple empirical relationships. Such algorithms specifically developed for ocean waters are found inadequate in optically complex turbid coastal waters (Case II), which require new algorithms based on new approaches dealing with both atmospheric correction and retrievals of ocean bio-optical properties from water-leaving radiance [10, 11]. The current study concentrates on atmospheric correction of satellite ocean colour data in Case II waters. The term ‘atmospheric correction’ is the key procedure in ocean colour data processing as it removes about 80–90% of the top-of-atmosphere (TOA) signal recorded by the sensor [1, 12]. The remaining signal is the desired water-leaving radiance ($L_w$) that carries immense information concerning biogeochemical properties of the ocean waters. This demonstrates the necessity of an accurate atmospheric correction that eliminates radiance backscattered from the atmosphere (due to air molecules and aerosols) and possibly reflected by the sea surface but never entering the ocean. For major satellite ocean colour missions such as Coastal Zone Colour Scanner (CZCS) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Gordon and Wang have proposed standard atmospheric correction (SAC) algorithms to retrieve water-leaving radiance from the total radiance measured by CZCS and SeaWiFS at the TOA [13, 14]. Due to difficulties in deriving information regarding aerosol properties which vary in time and space, these atmospheric correction schemes assume the water-leaving radiances in the bands centred at 670, 765 and 865 nm to be zero in order to estimate aerosol optical properties and extrapolate these into the visible spectrum. Such approaches, referred to as the dark-pixel atmospheric correction techniques, have been widely accepted for clear ocean waters, where satisfactory results have been achieved with uncertainties <20% in chlorophyll concentrations from CZCS, <5% in water-leaving radiance and <35% in chlorophyll concentrations from SeaWiFS [3, 15].

In more optically complex turbid coastal waters, however, the SAC schemes do not work well because of the assumption of negligible water-leaving radiance at 670, 765 and 865 nm, invalidated by the turbid water constituents (suspended sediments and possibly bottom reflection) that contribute significant amounts of water-leaving radiance to these bands. Such an assumption ultimately leads to the satellite determination of water-leaving radiance in the violet and blue (e.g. SeaWiFS Bands B1 and B2) to severely underestimate the in situ observations for highly productive and sediment-dominated waters. To overcome the black-pixel assumption, researchers have proposed alternate methods of atmospheric correction for processing CZCS data [16, 17] and SeaWiFS data [18–20] whereby the water-leaving radiances at 670, 765 and 865 nm are taken into account by estimating values of water-leaving radiances at the shorter wavelengths using empirical band ratio relations in the case of CZCS or the assumption of spatial homogeneity and nearest-neighbour method in the case of SeaWiFS. These modified algorithms have been successfully applied and significant improvements have been achieved over the SAC algorithm, particularly in regions of weakly absorbing aerosols. However, implementing the SAC or modified algorithms in the presence of strongly absorbing aerosols would result in underestimation of water-leaving radiance values in the blue leading to unrealistic chlorophyll concentrations in the coastal waters [21, 22].

Instead of the SAC schemes comprising of more complex radiative transfer codes (RTCs), several researchers have attempted to develop the atmospheric correction procedures solely depending on the image properties themselves. Such procedures are referred to as the image-based atmospheric correction methods. It is worth mentioning some of these methods, namely the dark-object subtraction method [23], the invariant object method [24], the histogram matching method [25], the cosine estimation of atmospheric transmittance method [26], the contrast reduction method [27], the path extraction method [28] and the spectral shape matching method (SSMM) [1]. Studies indicate the performance of these methods to be satisfactory for land applications using Landsat TM [29, 30], Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) [31] and QuickBird [32] and coastal and inland water applications using Landsat TM [28, 33] and SeaWiFS [1]. Note that several of the above methods, which retrieve land-surface reflectance properties with good accuracy, are questionable in performing an accurate atmospheric correction of satellite ocean colour imagery over aquatic environments. This is because, for aquatic applications, the atmospheric path signal includes the surface (Fresnel) reflection of the skylight and specular reflection of the direct solar beam, which is subsequently scattered to the sensor after reflection. For land applications, the path radiance represents the light without reaching the surface. This is because the surface-reflected light generally does not contain information of a water body [34]. Furthermore, the water-leaving radiance signal contributes only 10–20% of the TOA signal which is much smaller than the contribution of land surface-reflected light to the TOA signal.

Since SeaWiFS has been designed to provide relatively high frequency synoptic information over large areas, data from this sensor can be very useful in monitoring sediment transport, detecting various spatial extents of phytoplankton blooms including the highly toxic red tides and delineating circulation patterns around coastal zones. In order to allow the application of SeaWiFS in these areas this study presents a new atmospheric correction method which is modified from
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The previously developed spectral shape matching method (SSMM) by Ahn and Shanmugam [1]. In the following sections the theoretical basis of this method is described and its efficiency in removing the atmospheric effects and retrieving water-leaving radiance and pigment concentrations from SeaWiFS imagery in the presence of various atmospheric conditions (including typical Asian dust aerosols in the spring of 2000 and 2001) over the Northwest Pacific waters off the Korean and Chinese coasts is assessed. The method is further tested on SeaWiFS images of highly turbid coastal waters in the Korean Southwest Sea (KSWS) and waters with a massive phytoplankton bloom in the Yellow Sea (YS). The results are compared with field measurements and those from standard atmospheric correction and bio-optical algorithms included in the NASA SeaWiFS Data Analysis System version 4.4 (SeaDAS v.4.4).

2. Methods

2.1. SeaWiFS characteristics and the standard atmospheric correction (SAC) algorithm

The SeaWiFS ocean colour instrument was successfully launched on 1 August 1997, measuring the top-of-atmosphere signal in eight narrow bands spanning the visible and near-infrared (henceforth NIR) parts of the electromagnetic spectrum. Table 1 describes the radiometric specifications for SeaWiFS which includes the bands centred at 412, 443, 490, 545–565 (555), 660–680 (670), 745–785 (765), and 845–885 (865) nm (corresponding to bands 1, 2, 3, 4, 5, 6, 7 and 8, respectively) with full width half-maximum bandwidths (FWHM ~ nm) of 20 nm ($\lambda < 700$ nm) and 40 nm ($\lambda > 700$ nm). It also describes the values of the total signal for typical ocean water ($L_{\text{ocean}}$), noise equivalent signal and Signal-to-noise ratio ($S/N$) ratio for $L_{\text{ocean}}$ and the mean values of extraterrestrial solar irradiance [35, 36].

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (centre) (nm)</th>
<th>$L_{\text{ocean}}$ (counts)</th>
<th>$L_{\text{ocean}}$ (mW cm$^{-2}$ $\mu$m$^{-1}$ sr$^{-1}$)</th>
<th>Noise (counts)</th>
<th>$S/N$ ratio for $L_{\text{ocean}}$</th>
<th>$E_{\text{s}}$ (mW cm$^{-2}$ $\mu$m$^{-1}$ sr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>402–422 (412)</td>
<td>638.4</td>
<td>9.10</td>
<td>0.645</td>
<td>990</td>
<td>172.81</td>
</tr>
<tr>
<td>2</td>
<td>433–453 (443)</td>
<td>618.2</td>
<td>8.41</td>
<td>0.566</td>
<td>1091</td>
<td>190.20</td>
</tr>
<tr>
<td>3</td>
<td>480–500 (490)</td>
<td>613.0</td>
<td>5.68</td>
<td>0.524</td>
<td>1170</td>
<td>196.26</td>
</tr>
<tr>
<td>4</td>
<td>500–520 (510)</td>
<td>612.2</td>
<td>5.64</td>
<td>0.531</td>
<td>1152</td>
<td>188.02</td>
</tr>
<tr>
<td>5</td>
<td>545–565 (555)</td>
<td>607.1</td>
<td>4.57</td>
<td>0.506</td>
<td>1069</td>
<td>183.06</td>
</tr>
<tr>
<td>6</td>
<td>660–680 (670)</td>
<td>574.9</td>
<td>2.46</td>
<td>0.749</td>
<td>781</td>
<td>151.15</td>
</tr>
<tr>
<td>7</td>
<td>745–785 (765)</td>
<td>531.6</td>
<td>1.61</td>
<td>0.619</td>
<td>859</td>
<td>122.29</td>
</tr>
<tr>
<td>8</td>
<td>845–885 (865)</td>
<td>513.5</td>
<td>1.09</td>
<td>0.707</td>
<td>726</td>
<td>96.19</td>
</tr>
</tbody>
</table>

Table 1. SeaWiFS performance specifications. (Noise (NEdR—noise equivalent differential spectral radiance) = $L_{\text{ocean}}$/SNR.

For processing data from the SeaWiFS sensor, the standard atmospheric correction algorithm developed by Gordon and Wang [14] is generally employed in order to estimate the water-leaving radiance and subsequently derive the desired geophysical products. Implementation of this algorithm into the SeaWiFS data processing system is accomplished through the use of lookup tables that were generated with >25 000 radiative transfer simulations for Rayleigh scattering, aerosol contributions and effects of the atmospheric diffuse transmittance. To describe the SAC algorithm and its implementation in the data processing system, the observed radiance is converted to the dimensionless reflectance $\rho(\lambda_i)$ using equation (1)

$$\rho(\lambda_i) = \frac{\pi L(\lambda_i)}{F_0(\lambda_i) \cos \theta_0} \tag{1}$$

where $L(\lambda_i)$ is the radiance, $F_0(\lambda_i)$ is the mean extraterrestrial solar irradiance and $\theta_0$ is the solar zenith angle. The SeaWiFS measured reflectance at the TOA system can be written as,

$$\rho_T(\lambda_i) = \rho_a(\lambda_i) + \rho_a(\lambda_i) + t_{0-\infty} \rho_a(\lambda_i) \tag{2}$$

where $\rho_T(\lambda_i)$ is the total reflectance measured by SeaWiFS, $\rho_a(\lambda_i)$ is the reflectance resulting from Rayleigh scattering (which also includes the Fresnel reflectance at the sea surface), $t_{0-\infty} \rho_a(\lambda_i)$ is the reflectance resulting from aerosol scattering (also includes the interaction term between aerosol–Rayleigh scattering), $t_{0-\infty} \rho_a(\lambda_i)$ is the atmospheric diffuse transmittance and $\rho_a(\lambda_i)$ is the desired water-leaving reflectance to be derived from $\rho_T(\lambda_i)$.

In the above equation, computation of Rayleigh reflectance $\rho_a(\lambda_i)$ in the visible and near-infrared wavelengths is rather straightforward because of its dependence on the molecular composition of the atmosphere [37]. Thus this term can be achieved with good accuracy without use of the remotely sensed data. However, the problem is deriving aerosol reflectance $\rho_a(\lambda_i)$ which cannot be easily estimated without having prior knowledge because it varies significantly over time and space scales. To achieve this term, Gordon and Wang [14] created a set of aerosol lookup tables consisting of 12 candidate aerosol models (Maritime, Coastal, Troposphere, and Oceanic aerosols with various relative humidities) for different solar and viewing geometries. Assuming the $\rho_a$ to be equal to zero or estimating this term in the two NIR bands at 765 and 865 nm (from an in-water model included in SeaDAS version 4.4) $\rho_a(765)$ and $\rho_a(865)$ can be derived from the Rayleigh-corrected TOA reflectance in these bands. Based on the ratio of these two, the aerosol type defined by $\varepsilon = \rho_a(765)/\rho_a(865)$ is determined and $\rho_a$ and diffuse transmittance ($t_{0-\infty}$) in the visible wavelengths (Bands 1–6) are computed from the pre-computed lookup tables, in order to estimate the desired water-leaving reflectance in these bands.

This correction procedure enables accurate retrieval of water-leaving radiance (within ±5% error) in open ocean waters [6], but eventually fails in turbid coastal waters where an increased water-leaving radiance from suspended sediments of both organic and inorganic origin and perhaps a shallow bottom contribute to the atmospheric correction bands 765 and
Comparison of near-simultaneous match-ups of SeaWiFS and field observations of water-leaving reflectance showed that in turbid coastal waters the SAC algorithm often retrieved negative water-leaving reflectance in 412 and 443 nm bands and its retrievals in these bands became even worse in waters with chlorophyll concentrations $>2$ mg m$^{-3}$ [19, 20]. The large errors toward lower wavelengths would result primarily owing to excessive aerosol path radiance removal from an inappropriate extrapolation over a greater wavelength range. Validation studies demonstrated that these errors were significantly reduced after the NIR signals were taken into account in the atmospheric correction of SeaWiFS/CZCS imagery in turbid coastal waters [16, 19, 20, 39].

Hu and his co-workers evaluated a turbid water atmospheric correction scheme in moderately turbid Gulf of Maine waters where they found that SeaWiFS estimates of normalized water-leaving radiance in 412 and 443 nm bands were still lower than the in situ observations [18]. This was attributed to another problem that the SAC algorithm is facing without inclusion of the lookup tables for strongly absorbing aerosols over coastal areas. Figures 1(a) and (b) are good examples of how the strongly absorbing aerosols (referred to as Asian dust or Yellow dust by Iwasaka and his co-workers [40]) of the Spring 2001 are transported by wind from the Chinese desert to Northwest Pacific ocean waters, where the SAC algorithm severely overestimated the aerosol reflectance ratio, yielding very low or improbable negative water-leaving radiances (at 412 and 443 nm) in relatively low aerosol areas (green colour signature in the ES) and showing a complete failure of atmospheric correction for the high aerosol areas off the Chinese and Korean coasts. The SAC algorithm retrieves $\rho_w$ at 443 nm with an error $<0.001–0.002$ for non- and weakly absorbing aerosols, which is usually the case for open ocean regions where aerosols occur locally. However, for the coastal regions large errors or complete failure of this algorithm occur because these regions usually have both Case II waters in which the $\rho_w$ at the two NIR bands are discarded or the estimated $\rho_w$ in these bands are not sufficient to deal with turbid water and strongly absorbing aerosols [41]. This underlines the necessity of a set of more realistic aerosol models with representative characteristics of absorbing aerosol to be used in the aerosol lookup tables.

### 2.2. The spectral shape matching method (SSMM)

The modified version of the SSMM atmospheric correction scheme starts with radiance instead of reflectance. Therefore the total signal recorded by SeaWiFS at the TOA in a spectral band centred at a wavelength $\lambda_i$ can be defined by

$$L_T(\lambda_i) = L_{\text{sn}}(\lambda_i) + t_{(o\rightarrow s)} L_{\text{sg}}(\lambda_i) + t_{(o\rightarrow s)} L_{\text{wc}}(\lambda_i)$$

where $L_T(\lambda_i)$ is the total radiance at the TOA, $L_{\text{sn}}(\lambda_i)$ is the path radiance resulting from scattering in the atmosphere and from specular reflection of atmospherically scattered light (skylight) from the sea surface, $L_{\text{sg}}(\lambda_i)$ is the radiance of direct sunglint from the sea surface, $L_{\text{wc}}(\lambda_i)$ is the radiance of whitecaps at the sea surface and $L_{\text{sn}}(\lambda_i)$ is the desired water-leaving radiance. The terms $t_{(o\rightarrow s)}(\lambda_i)$ and $t_{(o\rightarrow s)}(\lambda_i)$ are direct (sun $\rightarrow$ ocean) and diffuse (ocean $\rightarrow$ sensor) transmittances of the atmospheric column, respectively. The $t_{(o\rightarrow s)}$ is appropriate for sun glitter $L_{\text{sg}}(\lambda_i)$ that is highly directional except at high
wind speeds, while \( t_{\text{w-as}} \) is pertinent for water-leaving radiance and the whitecap radiance as they have a near-uniform angular distribution [42]. Because SeaWiFS has been designed to have a provision for tilting the scan plane away from the specular image of the sun, the \( L_{\text{T}} \) may be disregarded for brevity. The whitecap contribution \( L_{\text{wc}} \) in SeaWiFS imagery can be estimated by using a previously established reflectance model with the input of sea surface wind speed [43]. However, SeaWiFS observations show that the whitecap reflectance model used in the SAC algorithm produces unacceptable errors (overestimation of the whitecap contribution) when the sea surface wind speed is greater than 7–8 m s\(^{-1}\) [14]. This results in low estimates of water-leaving radiances. To avoid such a miscalculation, the current SSMM ignores the whitecap contribution \( L_{\text{wc}} \) in the atmospheric correction of SeaWiFS imagery. Thus, equation (3) becomes

\[
L_T(\lambda_i) = L_{\text{path}}(\lambda_i) + t_{\text{w-as}}L_{\text{w}}(\lambda_i).
\] (4)

Here the path radiance \( L_{\text{path}}(\lambda_i) \) can be decomposed into two broad components as follows

\[
L_{\text{path}}(\lambda_i) = L_{\text{ra}}(\lambda_i) + L_{\text{aw}}(\lambda_i) \approx \gamma_a(\lambda_i) + \gamma_w(\lambda_i)
\] (5)

where \( L_{\text{ra}}(\lambda_i) \) is the Rayleigh radiance due to single and multiple scattering by air molecules in the absence of aerosols, \( L_{\text{aw}}(\lambda_i) \) is the aerosol radiance due to single and multiple scattering by aerosol particles in the absence of air molecules, \( \gamma_a(\lambda_i) \) is the Rayleigh factor and \( \gamma_w(\lambda_i) \) is the aerosol factor (\( \gamma \) factor is relative to radiance). For simplicity, the complex term between molecular and aerosol scattering is neglected in the image-based atmospheric correction scheme.

Accurate estimation of \( L_{\text{ra}}(\lambda_i) \) and \( L_{\text{aw}}(\lambda_i) \) requires in situ field measurements of aerosol type, optical thickness, air pressure, ozone optical thickness, wind, water vapour, etc., at the time of each image acquisition. These measurements are frequently unavailable or are of questionable quality which makes routine and accurate atmospheric correction of images with radiative transfer models difficult [44]. Furthermore, scattering and absorption by aerosols are difficult to characterize due to their variation in time and space [14], thus constituting the most severe limitation to the atmosphere correction of satellite data [45]. Thus, instead of modelling the atmospheric optical properties, the image-based SSMM scheme takes advantages of the two SeaWiFS NIR bands in order to estimate the magnitude of \( L_{\text{aw}} \) in the NIR2 using the following expression

\[
\gamma_w(\lambda_{\text{NIR2}}) = Q(\lambda_{\text{NIR2}}) \times (L_T(\lambda_{\text{NIR2}}), \Lambda(\lambda_{\text{NIR1}}, \lambda_{\text{NIR2}})) - (C \times \Phi_{\text{SS}}(\lambda_{\text{NIR2}}))
\] (6)

where \( \gamma_w(\lambda_{\text{NIR2}}) \) is the aerosol factor in the spectral band \( \lambda_{\text{NIR2}} \). \( \Lambda(\lambda_{\text{NIR1}}, \lambda_{\text{NIR2}}) \) is the ratio of \( L_T(\lambda_{\text{NIR2}}) \) at \( \lambda_{\text{NIR2}} \) to \( L_T(\lambda_{\text{NIR1}}) \), \( L_T(\lambda_{\text{NIR2}}), \Lambda(\lambda_{\text{NIR1}}, \lambda_{\text{NIR2}}) \) is related to \( L_T(\lambda_{\text{NIR2}}) \) and the ratio \( \Lambda(\lambda_{\text{NIR1}}, \lambda_{\text{NIR2}}) \) at the two NIR bands, \( L_T(\lambda_{\text{NIR2}}) \) is the total radiance at \( \lambda_{\text{NIR2}} \), and \( \Phi_{\text{SS}}(\lambda_{\text{NIR2}}) \) is related to the backscattered signal by suspended sediments (SS) at \( \lambda_{\text{NIR2}} \). Two unknown constants \( Q(\lambda_{\text{NIR2}}) \) and \( C \) are to be determined for \( L_T(\lambda_{\text{NIR2}}), \Lambda(\lambda_{\text{NIR1}}, \lambda_{\text{NIR2}}) \) and \( \Phi_{\text{SS}}(\lambda_{\text{NIR2}}) \), respectively. These can be accomplished by using an iterative convergence method. The term \( Q(\lambda_{\text{NIR2}}) \) is spectrally dependent on the aerosol type

\[\left( L_T(\lambda_{\text{NIR2}}), \Lambda(\lambda_{\text{NIR1}}, \lambda_{\text{NIR2}}), \right), \text{while } C \text{ is stable with respect to suspended sediments. Since } \gamma_w(\lambda_{\text{NIR2}}) \text{ contains a smaller amount of backscattered signal by SS in shallow coastal waters, } \Phi_{\text{SS}}(\lambda_{\text{NIR2}}) \text{ must be estimated and eliminated from } \gamma_w(\lambda_{\text{NIR2}}) \text{ before extrapolating to the visible bands. This will result in a correct retrieval of water-leaving radiance in the visible bands. To do this, the aerosol-corrected radiance is obtained by subtracting the first estimate of the aerosol factor (for which } C \times \Phi_{\text{SS}}(\lambda_{\text{NIR2}}) = 0 \text{) from the TOA radiance at } \lambda_{\text{NIR2}}. \text{ From the computed histogram of the aerosol-corrected radiance image, for example, figures 2(a) and (b) show the histograms of TOA radiance and aerosol-corrected radiances \text{(mW cm}^{-2}\mu m^{-1}\text{sr}^{-1}) \text{ from the pixels of SeaWiFS imagery collected on 21 March 2001 (rectangular box in figure 1(a)). The aerosol corrected radiance provides us the possibility of distinguishing the turbid water pixels (0.6–0.68) from the relatively clear water pixels (0.58–0.6) around the Korean Southwest Sea.} \]
The estimated aerosol factor \( \gamma_{\text{a}}(\lambda_{\text{NIR2}}) \) is then extrapolated and removed in the visible. This is achieved by using the lookup table of aerosol spectral models generated from the iterative convergence method. The aerosol factor \( \gamma_{\text{a}}(\lambda_{\text{NIR2}}) \) simply multiplied by the term \( Q(\lambda_i) \) gives rise to the aerosol factor \( \gamma_{\text{a}}(\lambda_i) \) of a visible spectral band centred at a wavelength \( \lambda_i \) according to,

\[
\gamma_{\text{a}}(\lambda_i) = Q(\lambda_i) \times \gamma_{\text{a}}(\lambda_{\text{NIR2}}).
\]

If the aerosol type is fixed over the spatial scale of 100–1000 km \([18]\) or some time over 1000 km, then the aerosol factor may vary from one pixel to another pixel with respect to the aerosol concentrations observed by SeaWiFS in eight spectral bands. Using equation (7), the aerosol radiance is computed and subtracted from \( L_T(\lambda_i) \), which derives the aerosol-corrected radiance \( L_{\text{ac}}(\lambda_i) \) as follows,

\[
L_{\text{ac}}(\lambda_i) = (L_T(\lambda_i) - L_{\text{ac}}(\lambda_i)) = L_{\text{ac}}(\lambda_i) + l_{(0-\text{sn})} L_w(\lambda_i). \tag{8}
\]

Unlike the aerosol, the Rayleigh scattering component is spatially nearly stable \([14]\) and can be approximated from \( L_{\text{ac}}(\lambda_i) \) using simple linear equations. Here SSMM makes an assumption that the spectral shape of the water-leaving radiance of clear ocean waters is stable compared to that of turbid coastal waters whose constituents with respect to tidal currents and bottom circulation significantly modify the spectral shape of the water-leaving radiance in these waters \([28]\). With the known/measured water-leaving radiance of ocean waters this assumption allows estimation of \( L_{\text{sw}}(\lambda_i) \) from \( L_{\text{ac}}(\lambda_i) \) as follows,

\[
L_{\text{sw}}(\lambda_i) = L_{\text{ac}}(\lambda_i) - l_{(0-\text{sn})} L_{\text{wcl}(\lambda_i)}. \tag{9}
\]

Here a match-up of the \textit{in situ} water-leaving radiance of relatively clear ocean waters is used to achieve the first estimate of \( L_{\text{sw}}(\lambda_i) \) at one point using equation (9). Note that the in situ water-leaving radiance values are translated to the top of the atmosphere using the \( l_{(0-\text{sn})}(\lambda_i) \) values derived from a standard method as discussed later. Gould and Arnone \([39]\) proposed a similar equation taking the difference between \( L_T(\lambda_i) \) and \( L_{\text{wcl}(\lambda_i)} \) to assess the path radiance \( L_{\text{path}}(\lambda_i) \) which was kept constant and applied over the entire image, with the assumption that the atmosphere (Rayleigh and aerosol scattering, and possibly surface reflection) does not vary over the spatial scale of that image. It may be valid for a low altitude sensor like the compact airborne spectrogaphic imager (CASI), but it does not hold for high altitude/polar orbiting sensors observing a wide area. To assess contributions of the \( L_{\text{sw}} \) component for the pixels of a SeaWiFS image a set of simple linear equations is derived relating the \( L_{\text{sw}}(\lambda_i) \) to \( L_{\text{ac}}(\lambda_i) \) through

\[
\gamma_{\text{a}}(\lambda_i) = \alpha[L_{\text{ac}}(\lambda_i)] + \beta \approx L_{\text{sw}}(\lambda_i). \tag{10}
\]

The Rayleigh factor \( \gamma_{\text{a}}(\lambda_i) \) is proportional to the Rayleigh radiance and varies from one pixel to another depending on the magnitude of the signal observed at \( \lambda_i \). The empirical coefficients \( \alpha \) and \( \beta \) for each SeaWiFS band are given in Table 2. Note that these coefficients are better consistent for SeaWiFS measurements of near noon time and different water types similar to those off the Korean and Chinese coasts. Now, substituting equations (5)–(10) into equation (4) yields the desired water-leaving radiance as follows,

\[
L_w(\lambda_i) = \frac{(L_T(\lambda_i) - L_{\text{sw}}(\lambda_i) - L_{\text{a}}(\lambda_i))}{l_{(0-\text{sn})}(\lambda_i)}. \tag{11}
\]

In equations (3) and (11), the term atmospheric diffuse transmittance \( l_{(0-\text{sn})}(\lambda_i) \), which propagates the water-leaving radiance from the ocean surface to the sensor (o–sn) and has a multiplicative effect caused by both scattering and absorption, needs to be assessed accurately in order to recover the water-leaving radiance just above the ocean surface \( L_{\text{sw}}(\lambda_i) \) from \( l_{(0-\text{sn})}(\lambda_i)L_w(\lambda_i) \). However, accurate correction for the multiplicative effect due to transmittance usually requires \textit{in situ} field measurements of atmospheric optical depth \([30]\), which is not always practical during each satellite overpass, and therefore, the average transmittance values computed for the different spectral bands in the visible wavelength and for the different atmospheric conditions were taken into account in atmospheric correction of satellite data \([26, 32]\). The current SAC scheme devised for SeaWiFS enables a good approximation of \( l_{(0-\text{sn})}(\lambda_i) \) values from tables containing data of \( \approx 25000 \) simulations using exponential fitting \([46]\) as given below

\[
l_{(0-\text{sn})}(\lambda_i) = X(\lambda_i, \theta) \exp[-Y(\lambda_i, \theta) \tau_{\text{sw}}(\lambda_i)] \tag{12}
\]

where \( X(\lambda_i, \theta) \) and \( Y(\lambda_i, \theta) \) are fitting coefficients for the eight SeaWiFS spectral bands, 12 aerosol models, and various solar and viewing angle geometries. \( \tau_{\text{sw}}(\lambda_i) \) is the aerosol optical thickness. The \( l_{(0-\text{sn})}(\lambda_i) \) values from the tables are accurate with an accuracy within 0.1% \([41]\).

The derived water-leaving radiance can be converted to the reflectance (using equation (1)) which is divided by \( \pi \) sterradians to compare to the remote-sensing reflectance: \( 1/\pi \rho(\lambda) \approx R_g(\lambda) \) \([2]\). Figure 3 summarizes the overall correction scheme of the SSMM to retrieve water-leaving radiance and chlorophyll concentrations from SeaWiFS imagery in coastal waters.

### 2.2.1. Aerosol spectral models

Developing the aerosol spectral models for image-based atmospheric correction of SeaWiFS data necessitates better understanding of the type, characteristic, source and composition of the aerosols of the regions, either from the historical data sets from \textit{in situ} measurements or from previously demonstrated results.
from satellite data. It has been found that both absorbing and non-absorbing aerosols often occur above the Northwest Pacific waters off the Korean and Chinese coasts. The most commonly observed aerosols of these regions are Asian dust, carbonaceous (biomass burning/urban), sulfate (Continental/Maritime origin) and sea salt (Maritime) aerosols. Asian dust, which is often referred to as Yellow dust [40], is strongly absorbing in the violet and blue because it contains an abundance of ferro-magnesium minerals in the 0.5–17 μm size range. These mineral particles are blown by wind in the Chinese desert regions and are transported over the Northwest Pacific ocean waters during spring [47–49]. In contrast, sulfate aerosol particles are generally small in size and weakly absorbing, while carbonaceous aerosol particles are more complicated in their composition and optical properties but recognized as moderately or strongly absorbing aerosols with inclusion of soot particles [50]. Sea salt or maritime aerosols are weakly absorbing and are commonly found in the oceanic boundary layer of the atmosphere, with sizes mostly below 0.05 μm [12].

To build the aerosol spectral models and understand the spectral behaviour of different aerosols, SeaWiFS data collected from the high resolution picture transmission (HRPT) station at the Korea Ocean Research and Development Institute (KORDI) during 1999–2005 were processed and six aerosol types were discerned based on a visual interpretation and digital classification of SeaWiFS data [50] and in situ data [47, 49, 51]. These are the bright aerosol 1 (BA1), bright aerosol 2 (BA2), mixture aerosol, yellowish brown aerosol 1 (YB1), yellowish brown aerosol 2 (YB2) and yellowish brown aerosol 3 (YB3) (table 3, figure 4). The Asian dust aerosols represented by YB were detected over the East China Sea (ECS), Yellow Sea (YS), Korean Seas (KS), East Sea (ES) and often the North Pacific during spring–
null
the total radiance images of 6 April 2000 and 21 March 2001 generated from the three SeaWiFS bands centred at 865 nm (red), 490 nm (green) and 412 nm (blue). Note that the black areas denote the non-water mask (land and cloud) based on a threshold value at NIR2. Inevitably, there are a large number of intense-aerosol covered ocean pixels also included in that mask in figure 5(b), which will be dealt with later. These two images clearly illustrate the spatial distribution of the yellowish brown Asian dust aerosols, which were transported widely over East China, Korea and Japan during spring 2000 and 2001. The brighter areas represent the Asian dust aerosols in the TOA radiance images and suspended sediment distribution in the water-leaving radiance images excluding the western boundary areas of the ES in figure 6(d). While SSMM was capable of retrieving the water-leaving radiance values for the intense aerosol pixels of the ECS, YS, ES and Korean Sea, the SAC algorithm showed a complete failure of the scheme in these areas (indicated by arrows), yielding low and negative water-leaving radiance values at 412 and 443 nm in the less-intense aerosol pixels of the ES, ECS and YS (figures 6(c) and (f)). This may be owing to an extensive overcorrection of aerosol effects in the ES, ECS, YS, and Korean Sea, the SAC algorithm showed a complete failure of the scheme in these areas (indicated by arrows). Figures 6(a)–(f) provide a better comparison of the results in eight bands (bands 1–8) before and after the SAC and SSMM algorithms were employed on SeaWiFS images of 6 April 2000 and 21 March 2001. The brighter areas represent the Asian dust aerosols in the TOA radiance images and suspended sediment distribution in the water-leaving radiance images excluding the western boundary areas of the ES in figure 6(d). While SSMM was capable of retrieving the water-leaving radiance values for the intense aerosol pixels of the ECS, YS, ES and Korean Sea, the SAC algorithm showed a complete failure of the scheme in these areas (indicated by arrows), yielding low and negative water-leaving radiance values at 412 and 443 nm in the less-intense aerosol pixels of the ES, ECS and YS (figures 6(c) and (f)).

To further assess the efficiency of SAC and SSMM algorithms chlorophyll concentrations were retrieved from the atmospherically corrected SeaWiFS images of 6 April 2000 and 21 March 2001 using the standard NASA OC2v4 bio-optical algorithm included in SeaDAS v4.4 (table 5). This algorithm is purely empirical and uses a simple band ratio, $R_{\text{rs}}(490)/R_{\text{rs}}(555)$, to estimate chlorophyll concentrations from SeaWiFS data [53]. Figures 7(a)–(d) compare retrievals of the chlorophyll concentrations with SAC-OC2v4 and SSMM-OC2v4 algorithms on SeaWiFS data. One can observe that the results from these two algorithms are very different in terms of the coverage and magnitude of the chlorophyll concentrations. SSMM appears to be successful in removing much of the influence of the Asian dust aerosols.

![Image](image1.png)

![Image](image2.png)

![Image](image3.png)

### Table 4. Atmospheric diffuse transmittances ($t_{\text{sn}}$) computed from SeaWiFS images for the period 2000–2003.

<table>
<thead>
<tr>
<th>Image data</th>
<th>Atmospheric conditions</th>
<th>412</th>
<th>443</th>
<th>490</th>
<th>510</th>
<th>555</th>
<th>670</th>
<th>765</th>
<th>865</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/04/2000</td>
<td>Asian dust</td>
<td>0.8035</td>
<td>0.8413</td>
<td>0.8822</td>
<td>0.8943</td>
<td>0.9161</td>
<td>0.9479</td>
<td>0.9621</td>
<td>0.9698</td>
</tr>
<tr>
<td>21/03/2001</td>
<td>Asian dust</td>
<td>0.7783</td>
<td>0.8289</td>
<td>0.8828</td>
<td>0.8984</td>
<td>0.9265</td>
<td>0.9646</td>
<td>0.9795</td>
<td>0.9863</td>
</tr>
<tr>
<td>19/03/2002</td>
<td>Asian dust</td>
<td>0.7979</td>
<td>0.8345</td>
<td>0.8745</td>
<td>0.8869</td>
<td>0.9091</td>
<td>0.9380</td>
<td>0.9555</td>
<td>0.9630</td>
</tr>
<tr>
<td>16/04/2004</td>
<td>Asian dust</td>
<td>0.8225</td>
<td>0.8592</td>
<td>0.8980</td>
<td>0.9092</td>
<td>0.9296</td>
<td>0.9575</td>
<td>0.9693</td>
<td>0.9745</td>
</tr>
<tr>
<td>15/04/2005</td>
<td>Asian dust</td>
<td>0.7993</td>
<td>0.8381</td>
<td>0.8801</td>
<td>0.8922</td>
<td>0.9147</td>
<td>0.9472</td>
<td>0.9615</td>
<td>0.9693</td>
</tr>
<tr>
<td>Mean transmittance (AD)</td>
<td></td>
<td>0.8003</td>
<td>0.8404</td>
<td>0.8853</td>
<td>0.8962</td>
<td>0.9192</td>
<td>0.9511</td>
<td>0.9656</td>
<td>0.9726</td>
</tr>
<tr>
<td>04/09/2002</td>
<td>Bright aerosol</td>
<td>0.8200</td>
<td>0.8595</td>
<td>0.9023</td>
<td>0.9146</td>
<td>0.9367</td>
<td>0.9668</td>
<td>0.9794</td>
<td>0.9850</td>
</tr>
<tr>
<td>06/08/2003</td>
<td>Bright aerosol</td>
<td>0.8296</td>
<td>0.8643</td>
<td>0.9015</td>
<td>0.9123</td>
<td>0.9303</td>
<td>0.9584</td>
<td>0.9704</td>
<td>0.9759</td>
</tr>
<tr>
<td>11/08/2004</td>
<td>Bright aerosol</td>
<td>0.8109</td>
<td>0.8451</td>
<td>0.8825</td>
<td>0.8937</td>
<td>0.9142</td>
<td>0.9435</td>
<td>0.9575</td>
<td>0.9645</td>
</tr>
<tr>
<td>26/03/2005</td>
<td>Bright aerosol</td>
<td>0.7948</td>
<td>0.8348</td>
<td>0.8787</td>
<td>0.9203</td>
<td>0.9140</td>
<td>0.9465</td>
<td>0.9618</td>
<td>0.9690</td>
</tr>
<tr>
<td>08/05/2005</td>
<td>Bright aerosol</td>
<td>0.8271</td>
<td>0.8618</td>
<td>0.8987</td>
<td>0.9060</td>
<td>0.9288</td>
<td>0.9565</td>
<td>0.9680</td>
<td>0.9735</td>
</tr>
<tr>
<td>04/09/2002</td>
<td>Bright aerosol</td>
<td>0.8200</td>
<td>0.8595</td>
<td>0.9023</td>
<td>0.9145</td>
<td>0.9367</td>
<td>0.9668</td>
<td>0.9794</td>
<td>0.9850</td>
</tr>
<tr>
<td>Mean transmittance (BA)</td>
<td></td>
<td>0.8165</td>
<td>0.8531</td>
<td>0.8927</td>
<td>0.9094</td>
<td>0.9248</td>
<td>0.9543</td>
<td>0.9674</td>
<td>0.9736</td>
</tr>
<tr>
<td>28/08/2001</td>
<td>Clear</td>
<td>0.7776</td>
<td>0.8156</td>
<td>0.8582</td>
<td>0.8710</td>
<td>0.8945</td>
<td>0.9295</td>
<td>0.9450</td>
<td>0.9540</td>
</tr>
<tr>
<td>24/02/2002</td>
<td>Clear</td>
<td>0.7828</td>
<td>0.8239</td>
<td>0.8700</td>
<td>0.8835</td>
<td>0.9095</td>
<td>0.9450</td>
<td>0.9615</td>
<td>0.9695</td>
</tr>
<tr>
<td>08/10/2003</td>
<td>Clear</td>
<td>0.7867</td>
<td>0.8255</td>
<td>0.8715</td>
<td>0.8814</td>
<td>0.9050</td>
<td>0.9383</td>
<td>0.9538</td>
<td>0.9614</td>
</tr>
<tr>
<td>10/10/2003</td>
<td>Clear</td>
<td>0.8233</td>
<td>0.8565</td>
<td>0.8925</td>
<td>0.9025</td>
<td>0.9235</td>
<td>0.9515</td>
<td>0.9645</td>
<td>0.9705</td>
</tr>
<tr>
<td>Mean transmittance (Clear)</td>
<td></td>
<td>0.7950</td>
<td>0.8328</td>
<td>0.8753</td>
<td>0.8873</td>
<td>0.9102</td>
<td>0.9428</td>
<td>0.9577</td>
<td>0.9652</td>
</tr>
<tr>
<td>Overall mean transmittance</td>
<td></td>
<td>0.8039</td>
<td>0.8421</td>
<td>0.8838</td>
<td>0.8976</td>
<td>0.9180</td>
<td>0.9494</td>
<td>0.9635</td>
<td>0.9704</td>
</tr>
</tbody>
</table>
Figure 5. (a), (b) Colour composite images of 6 April 2000 and 21 March 2001 (typical Asian dust event days) from the top-of-atmosphere (TOA) radiance (mW cm\(^{-2}\) μm\(^{-1}\) sr\(^{-1}\)) in SeaWiFS bands (B841) centred at 865 nm (red), 490 nm (green) and 412 nm (blue). (c) and (d) The corresponding images from water-leaving radiances \(L_w\) (mW cm\(^{-2}\) μm\(^{-1}\) sr\(^{-1}\)) retrieved from the SSMM atmospheric correction scheme. Note that SSMM retrieves water-leaving radiances from SeaWiFS image over the regions of dense Asian aerosol dusts off the Korean and Chinese coasts. The lines denote the 500 km S/N transects running across the East Sea.

Table 5. Standard SeaWiFS chlorophyll retrieval algorithms and their coefficients [53, 63].

<table>
<thead>
<tr>
<th>SeaWiFS algorithm</th>
<th>(a_0)</th>
<th>(a_1)</th>
<th>(a_2)</th>
<th>(a_3)</th>
<th>(a_4)</th>
<th>(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC2v4</td>
<td>0.319</td>
<td>-2.336</td>
<td>0.879</td>
<td>-0.135</td>
<td>0.871</td>
<td>(\log_{10}(R_{443}/R_{555}))</td>
</tr>
<tr>
<td>OC4v4</td>
<td>0.366</td>
<td>-3.067</td>
<td>1.930</td>
<td>0.649</td>
<td>1.532</td>
<td>(\log_{10}((R_{443} &gt; R_{490}) &gt; R_{510}))/R_{555}))</td>
</tr>
</tbody>
</table>

and recovering large previously unprocessed areas from the April 2000 and March 2001 images. The newly derived water-leaving radiances allow more accurate estimates of chlorophyll concentrations in turbid coastal waters as well as areas severely affected by the aerosols (figures 7(c) and (d)). Several complex anticyclonic eddy features in the vicinity of the ES and an intense chlorophyll pattern along the North Korean and Russian coastal areas are evident in these images. These might
be related to frequent spring blooms caused by a combination of enhanced irradiance with the effect of vertical mixing and elevated nutrients in spring [54, 55]. In contrast, the SAC algorithm shows particularly high chlorophyll concentrations in the ECS and YS waters, primarily because of a background of the Asian dust aerosols (figure 7(a)), creating masks over highly turbid coastal waters and the areas dominated by intense aerosols off the Korean and Chinese coasts (indicated by the arrows in figures 7(a) and (b)). Nevertheless the low chlorophyll concentrations inferred from the SAC algorithm along the Russian coast does not significantly identify the intense phytoplankton blooms from other water types. Such results demonstrate an efficiency of the SAC algorithm for processing SeaWiFS imagery of highly turbid coastal waters in the presence of intense mineral dust aerosols. For several images of the Asian dust aerosols of spring, SSMM retrieved approximately the same concentrations in the YS and ES as it did in the absence of dust, proving to be a very effective method in deriving information on biogeochemical variables and allowing SeaWiFS applications to turbid coastal waters.

To understand why the SSMM scheme was unable to retrieve the chlorophyll concentrations for the pixels of a very thick aerosol plume layer (encircled areas in figure 7(d)), the signal-to-noise ratio (SNR) was computed as the ratio of $\gamma_{\text{TOA}}(\lambda_{\text{NIR2}})$ to TOA radiance at NIR2 using SeaWiFS images of 6 April 2000 and 21 March 2001. Figures 8(a) and (b) illustrate variations of SNR and TOA radiance along the 500 km transects running across the ES from North Korean coastal areas to ES offshore in the case of the 6 April 2000 image and from Korean east coastal areas to ES offshore in the case of the 21 March 2001 image (transects in figures 5(a) and (b); profiles in figures 8(a) and (b)). Clearly, the SNR diminished when the concentration and vertical depth of the Asian dust aerosol plume increased to influence the TOA radiance signal from the offshore to coastal areas of the ES. On 6 April 2000, the SNR appeared to be higher than the TOA radiance before it converged close to the North Korean coast area, where the aerosol intensity was rather high. In contrast, on 21 March 2001 the SNR values were higher than the TOA radiances over a dispersed phase of the Asian dust aerosols from 500 to 130 pixels, but abruptly decreased with increasing aerosol plume intensity in the transect area 130–0 pixels. This suggests that magnification of the vertical structure and abundance of Asian dust aerosols might have hindered emergence of the water signal out of the thick layer of the aerosol plume in this region. Under these circumstances, retrieval of water-leaving radiances with any atmospheric correction algorithms remains limited, and therefore, such areas should be probably masked while processing the satellite ocean colour data.

3.2. Validation with in situ data
A first validation of the methods with in situ measurements was performed in highly turbid coastal waters of the Korean Southwest Sea. This region is relatively shallow (5–30 m) where strong semidiurnal tides combine with frequent strong winds to cause relatively high concentrations of suspended
Figure 7. SeaWiFS chlorophyll (mg m$^{-3}$) images of 6 April 2000 and 21 March 2001 processed using the SAC-OC2 bio-optical algorithm ((a) and (b)) and SSMM-OC2 bio-optical algorithm ((c) and (d)). Arrow marks indicate the masked areas due to failure of the SAC algorithm in the presence of the intense Asian dust aerosols. Even in the aerosol less-intense areas, OC2 chlorophyll was overestimated primarily because of blue-overcorrection of the SAC algorithm. SSMM retrieved more realistic estimates in these areas.
New atmospheric correction technique to retrieve the ocean colour from SeaWiFS imagery in complex coastal waters

Interval of 1.4 nm were averaged over bandwidth of each SeaWiFS band, and some measurements which had occurred around very shallow and small/narrow tidal channel areas were discarded from the validation because of possible discrepancies from sub-pixel variability and surface adjacency effects caused by the spatial resolution (1.1 km) of SeaWiFS sensor.

SeaWiFS images of the above periods were processed by use of the SAC and SSMM algorithms and the retrieved water-leaving radiances, for example, at 412, 555 and 865 nm, for 23 October 1998 are compared in figure 9. This image is shown because the effect of ignoring water signal or its poor estimates in the NIR1 and NIR2 is greatest at the shorter wavelengths of the spectrum. Though the SAC algorithm retrieved the water-leaving radiances in relatively less turbid waters off the complex islands, it showed a complete failure to retrieve these quantities in shallow waters (<15 m) with very high SS concentrations around the islands and tidal channel areas. This may be attributable to the single scattering aerosol reflectance ratio \( \varepsilon = \rho_{\text{as}}(765)/\rho_{\text{as}}(865) \) deduced from the image by the SAC algorithm, which reached higher values causing error flagging of the algorithm. Allowing these calculations to process the data would have resulted in large errors of the algorithm associated with negative water-leaving radiances in the violet and blue bands. Note that the turbid water pixels around the island areas previously masked by the SAC algorithm were successfully recovered by the SSMM algorithm, which exhibits a highly reflective water mass movement with a clear spatial structure towards the offshore. The retrieved water-leaving radiances correlated well with the known SS distributions. In contrast, the invalid assumption/inappropriate in-water model associated with SAC algorithm led to an overestimated \( \varepsilon = \rho_{\text{as}}(765)/\rho_{\text{as}}(865) \) which removed excessive aerosol path radiance in the violet and blue bands, resulting in very low and improbable negative water-leaving radiances for these waters.

Figure 8. Horizontal profiles of SNR and TOA radiance (mW cm\(^{-2}\) μm\(^{-1}\) sr\(^{-1}\)) at NIR2 along the 500 km transects from SeaWiFS images of 6 April 2000 and 21 March 2001 in the East Sea (figures 5(a) and (b)). Note that to maximize variations the S/N ratio values (Y-axis in (b)) are scaled.

Figure 9. Comparison of the water-leaving radiances (mW cm\(^{-2}\) μm\(^{-1}\) sr\(^{-1}\)) at three wavelengths 412, 555 and 865 nm retrieved from SeaWiFS imagery (23 October 1998) using the SAC and SSMM algorithms. The upper panels indicate failure of the SAC algorithm to retrieve the \( L_w \) which led to the masking of the largest part of the turbid coastal areas. The bottom panels indicate efficiency of SSMM in recovering the previously masked turbid coastal waters. The rectangular box in the bottom panel (412 nm image) indicates the ship transect area covering the coastal areas of the Korean Southwest Sea in October 1998.
These wavelengths for remote estimation of SS from satellites exploit the usefulness of single band radiance or reflectance at long wavelengths, which drew the attention of researchers and encouraged them to move towards the longer wavelengths. This increase in SS concentrations augmented backscattering values across the whole spectrum. Markedly increased with SSMM, it recovered the water-leaving radiances which closely matched the SAC algorithm. SAC masked these areas, whereas SSMM appeared to be successful in highly turbid Korean southwest coastal waters (SS = 3.5–28 g m⁻³).

To better illustrate the merit of atmospheric correction, satellite estimates of water-leaving radiances were compared with the corresponding in situ measurements in each band of the SeaWiFS images collected on 20 and 23 October 1998. Statistical analyses were also performed to provide additional information on how accurately the satellite retrieval agrees with in situ ship measurements. Thus, the mean relative error (MRE) to characterize the bias of the algorithms (negative, if the algorithm underpredicts; positive, if it overpredicts) was computed using equation (13):

\[
\text{MRE} = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{\text{retrieved} - \text{measured}}{\text{measured}} \right)
\]

and the root mean square error (RMSE) to characterize the bias of the algorithms in absolute terms was computed using equation (14):

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{\text{retrieved} - \text{measured}}{\text{measured}} \right)^2}
\]

Scatter plots of satellite versus in situ measurements of water-leaving radiances in each band were also generated (figure 11), for which the coefficient of determination \(r^2\), slope \(S\) and intercept \(I\) were inspected for both the SAC and SSMM algorithms. The in situ spectra of \(L_w\) collected on 20 October 1998 were used for the SAC algorithm (because it showed a complete failure for the ship transect area on 23 October 1998) and 20 and 23 October 1998 for the SSMM algorithm.

Table 6 depicts the values of the MRE and RMSE of water-leaving radiances in each band that were generated (figure 11), for which the coefficient of determination \(r^2\), slope \(S\) and intercept \(I\) were inspected for both the SAC and SSMM algorithms. The in situ spectra of \(L_w\) collected on 20 October 1998 were used for the SAC algorithm (because it showed a complete failure for the ship transect area on 23 October 1998) and 20 and 23 October 1998 for the SSMM algorithm.

Table 6. Mean relative error (MRE) and RMSE deviation (band averaged). Note that MRF and RMSE decrease by a significant amount after the SSMM atmospheric correction scheme was applied to SeaWiFS image data of 20 and 23 October 1998.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Method</th>
<th>412</th>
<th>443</th>
<th>490</th>
<th>510</th>
<th>555</th>
<th>670</th>
<th>765</th>
<th>865</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC</td>
<td>-0.52</td>
<td>-0.33</td>
<td>-0.28</td>
<td>-0.26</td>
<td>-0.3</td>
<td>-0.5</td>
<td>-0.79</td>
<td>-0.81</td>
<td>0.326</td>
<td></td>
</tr>
<tr>
<td>SSMM</td>
<td>0.16</td>
<td>0.42</td>
<td>0.16</td>
<td>0.08</td>
<td>-0.08</td>
<td>-0.003</td>
<td>-0.044</td>
<td>0.46</td>
<td>0.076</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 10.** Comparison of in situ measurements (from ASD FieldSpec Pro Dual UV/VNIR Spectroradiometer) of water-leaving radiance (a) with coincident spectra (b) from SeaWiFS image on 23 October 1998 in highly turbid coastal waters of the Korean Southwest Sea. Satellite \(L_w\) are from the SSMM.

Figures 10(a) and (b) compare the in situ water-leaving radiance spectra (see the ship transect area in figure 9) with concurrent spectra retrieved from the SeaWiFS image (of 23 October 1998) by use of the SSMM in highly turbid Korean southwest coastal waters (SS = 3.5–28 g m⁻³). While the SAC algorithm masked these areas, SSMM appeared to have recovered the water-leaving radiances which closely match the measured spectra in these waters. The water-leaving radiance values across the whole spectrum markedly increased with increasing SS concentrations that augmented backscattering more than absorption towards the longer wavelengths. This drew the attention of the researchers and encouraged them to exploit the usefulness of single band radiance or reflectance at these wavelengths for remote estimation of SS from satellites e.g. [28, 56, 57]. This also suggests the invalidity of the assumption of negligible water-leaving radiance at 765 and 865 nm in these waters. Notice that the retrieved water-leaving radiance values are slightly lower than the measured values, probably due to sub-pixel variability of the sediment features observed by the SeaWiFs sensor.

Scatter plots of satellite versus in situ measurements of water-leaving radiances in each band were also generated (figure 11), for which the coefficient of determination \(r^2\), slope \(S\) and intercept \(I\) were inspected for both the SAC and SSMM algorithms. The in situ spectra of \(L_w\) collected on 20 October 1998 were used for the SAC algorithm (because it showed a complete failure for the ship transect area on 23 October 1998) and 20 and 23 October 1998 for the SSMM algorithm.

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Figure 11. Comparison of in situ (ship-measured) and satellite water-leaving radiances (mW cm$^{-2}$ μm$^{-1}$ sr$^{-1}$) from the SAC and SSMM algorithms on SeaWiFS images of 20 and 23 October 1998 in the coastal bays (Jin-do and Wan-do) of the Korean Southwest Sea. Match-up of $L_w$ on 20 October 1998 was used for the SAC algorithm and 20 and 23 October 1998 for the SSMM algorithm. This is because the SAC algorithm was unable to retrieve water-leaving radiance values (circled area in the 864 m image) from the SeaWiFS imagery of 23 October 1998 in highly turbid coastal waters of the KSS.

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retrieved from SSMM agree well with in situ data. In contrast, the SAC algorithm had poor estimates, exhibiting a clear bias toward underestimation in all the SeaWiFS bands. This could be partly explained by the expressions in equation (6) in which the water-leaving radiance values at the NIR bands are assumed to be negligible (in the past version of SeaDAS) or modelled values by the SAC algorithm are not sufficient to deal with turbid waters.
Figure 12. Comparison of the chlorophyll concentrations (mg m$^{-3}$) retrieved from (a) SAC-OC2 algorithms (notice the atmospheric correction failure which necessitates masking of the turbid coastal areas and also leads to high chlorophyll values in the aerosol-dominated regions off the North Korean and Chinese coasts) and (b) SSMM-OC2 algorithms (success of atmospheric correction recovering the previously masked turbid coastal areas and showing reliable estimates of chlorophyll concentrations in the aerosol-dominated areas) using SeaWiFS imagery on 27 March 2002 over the YS environment.

The second validation of atmospheric correction took place in the YS, where the in situ measurements of chlorophyll, suspended sediments, nutrients (NO$_3$–N, PO$_4$–P, SiO$_2$–Si), salinity and temperature were performed before and during the decomposition phase of a massive phytoplankton bloom on 27 March 2002. SeaWiFS imagery collected on this day was atmospherically corrected by using the SAC and SSMM algorithms and subsequently processed to chlorophyll by using the OC2v4 bio-optical algorithm. Figures 12(a) and (b) show the distribution of chlorophyll concentrations in and around the YS waters. First, notice the large discrepancies between these images, particularly in waters along the west coastal areas of Korea (north), where the SAC algorithm actually processed the image but yielded concentrations that are too high because of the high SS and DOM concentrations and a background Asian dust aerosol. In addition, the SAC algorithm masked most of SS-dominated waters along the Chinese and Korean southwest coastal areas (indicated by arrows). This puts forward the failure of both the black-pixel assumption for the NIR and the iterative NIR water-leaving radiance correction scheme [22, 58]. This is in contrast with the results of SSMM recovering the previously masked coastal areas and allowing chlorophyll estimates that are consistent with the field observations.

To better exemplify the differences between the SAC and SSMM algorithms a transect (in figure 12(a)) of the chlorophyll concentrations and water-leaving radiances was established running across the bloom from Korean west coastal waters to Chinese coastal waters. Figures 13(a) and (b) display the horizontal variations of chlorophyll concentrations and water-leaving radiances in the SeaWiFS bands centred at 412, 443, 490 and 865 nm along this transect area. Both atmospheric correction schemes retrieved markedly elevated water-leaving radiance values (in these bands) in the vicinity of coastal areas and reduced values from 45–105 pixels in the central YS. Such strong/elevated water-leaving radiances can be related to high reflective SS materials while the reduced/weaker signal to profound absorption by pigments. However, one can observe that the SAC algorithm
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Figure 14. Comparison of in situ chlorophyll concentrations (mg m$^{-3}$) along the ship-transect lines (A–E in figure 12(b)) with the SeaWiFS measurements on 27 March 2002 in the Yellow Sea. Field measurements of chlorophyll indicate the absence of the bloom in February 2002 and occurrence of the bloom in April 2002.

Note that at most of the stations the previously estimated chlorophyll concentrations were brought down closer to the field measurements by SSMM-OC2 algorithms. Due to the time difference between the in situ and satellite observations, there was some disagreement resulting from spatial and temporal variabilities of the spring bloom in the YS.

4. Conclusions

Coastal ocean colour observations specifically require accurate atmospheric correction algorithms that take into account the non-zero water-leaving radiances in the NIR and include specialized aerosol spectral models for correcting the effects of strongly absorbing aerosols over the coastal regions. However, the current SAC algorithm developed for SeaWiFS does not adequately address these conditions, thus limiting the SeaWiFS applications mostly to the open ocean waters [11] where the assumption of zero water-leaving radiances in the NIR bands is valid [14]. In turbid coastal waters this assumption is invalided by the additional particulate scattering due to suspended sediments. Occurrence of non-zero water-leaving radiances in the NIR ultimately leads to an overestimation of atmospheric effects (typically derived from NIR bands) which results in an atmospheric overcorrection in the visible spectrum. The tendency of such an overcorrection is still well pronounced in the presence of absorbing aerosols from a thick vertical structure [21]. This leads to the water-leaving radiances of the violet and blue wavelengths to be severely, negatively or completely affected [10, 58].

More recent atmospheric correction algorithms account for the non-zero water-leaving radiances in the NIR bands by applying a combined approach to separation of the atmospheric and turbid water contributions to the signals [19, 20, 34, 38, 59, 60]. Although these approaches demonstrated a significant improvement over the SAC algorithm, an extensive research was required to provide more reliable correction procedures because the retrieval of water-leaving radiances and derivation of geophysical products

retrieved comparatively low water-leaving radiance values in all the bands throughout the transect area, particularly yielding negative water-leaving radiances at 412 nm in the bloom-dominated waters (from 45 to 105 pixels) of the YS (figure 13(a)). The negative and nearly zero water-leaving radiance values at 412 and 865 nm may result in part from use of the inappropriate in-water model to estimate the contributed signal in the NIR bands. In contrast, the effect of the SSMM in raising water-leaving radiances at these bands is clearly seen throughout the transect area in figure 13(b). This improvement in terms of increasing water-leaving radiances in the violet and blue bands led to better estimates of chlorophyll concentrations than those overestimated by the SAC algorithm in bloom-dominated and turbid coastal waters.

Figure 14 compares the in situ measurements of chlorophyll concentrations with satellite estimates from the SAC-OC2 bio-optical algorithm, SAC-OC4 bio-optical algorithm (table 5) and SSMM-OC2 bio-optical algorithm on SeaWiFS imagery of 27 March 2002 in the YS. Note that very low chlorophyll concentrations were observed during the absence of the phytoplankton bloom in February and high chlorophyll concentrations during the decomposition phase of the bloom in April 2002 (one–two weeks time difference with satellite overpass). Whilst the atmospheric correction was performed by the SAC algorithm on SeaWiFS imagery, two different bio-optical algorithms such as the OC2 and OC4 behaved differently in terms of yielding chlorophyll concentrations: i.e. the OC4 algorithm gave improved estimates of chlorophyll concentrations over the OC2 algorithm at all stations. This is primarily because the OC4 uses the maximum band ratios compared to the OC2 algorithm (table 5). Nevertheless, both the algorithms showed a clear tendency of an overestimation of the chlorophyll concentrations in the bloom-dominated waters (A3, A7, B3, B5, B7, C5, C7, C9, D7, D9, E9) off the Korean west coast. Such large errors (overestimation) might result from a pronounced overcorrection of atmospheric effects in the violet and blue wavelengths, particularly in productive waters with chlorophyll concentrations $>$2 mg m$^{-3}$ [10, 20].

Note that at most of the stations the previously estimated chlorophyll concentrations were brought down closer to the field measurements by SSMM-OC2 algorithms. Due to the time difference between the in situ and satellite observations, there was some disagreement resulting from spatial and temporal variabilities of the spring bloom in the YS.
were not possible from satellite ocean colour imagery in the presence of strongly absorbing aerosols over the coastal oceans (e.g., dust from Sahara desert in North Africa and Gobi desert in Northern China). More recent investigations [22, 42] used a spectral matching algorithm, with the assumption that the water-leaving radiances in the NIR are negligible, for retrieving pigment concentrations from SeaWiFS imagery acquired in the region of Sahara dust transport off the coast of Africa. Results of such specific studies revealed a considerable promise for processing SeaWiFS imagery in the presence of mineral dust, but pigment retrievals were not fully achieved and/or not feasible when the aerosol optical thickness observed was rather high for the dusty pixels. This suggests a likely error in the estimation of the magnitude of aerosol radiance by this optimization technique.

To overcome these limitations associated with the SAC algorithm, a simple image-based atmospheric correction method (SSMM) has been described and tested using the SeaWiFS imagery in this paper. The development of this method is in response to a large demand from the ocean colour community for generating the desired geophysical products for the coastal regions. SSMM shows a good promise in delivering such products for these regions, with reduced time and cost when compared to the SAC algorithm.

For example, a preliminary validation in turbid coastal waters of the Korean Southwest Sea demonstrated that the SAC algorithm tended to have underestimated the water-leaving radiances values with large errors toward the shorter wavelengths and completely failed when regions of extremely turbid water were identified in the top-of-atmosphere radiances for the NIR. SSMM reduces these errors and provides a good reproduction of in situ water-leaving radiances spectra in these waters. The second validation, which was conducted using SeaWiFS images of spring 2000 and 2001 (periods of strongly absorbing aerosols) off the Korean and Chinese coasts (regions of great interest for the northeast Asian coastal managers, fishing community and naval operations), demonstrated that the SAC algorithm was unable to process the pixels of the aerosol-dominated areas and severely underestimated water-leaving radiances in the violet and blue spectral regions, leading to very high chlorophyll concentrations over the less intense aerosol areas in the ES. This limited the potential utility of SeaWiFS imagery for these regions. In contrast, the SSMM has been successful in removing much of the influence of Asian dust aerosols from SeaWiFS imagery and yielding reasonable estimates of both water-leaving radiances and chlorophyll concentrations for a greater coverage area. The results, with an improved accuracy, highlight existing anticyclonic eddy features, phytoplankton blooms and suspended sediment transport off the Korean and Chinese coasts. A further comparison of the match-ups of existing anticyclonic eddy features, phytoplankton blooms and in situ data in turbid coastal waters.

Implementation of the SSMM on SeaWiFS images suggests that accurate retrievals of the water-leaving radiances and chlorophyll concentrations are doubtful in the regions where the effects of straylight and bright signal at the scan edges are strong enough to influence the SeaWiFS measurements at the TOA. Our results indicated an overestimation of the water-leaving radiance retrieval by about 1.5–2 times for such areas which might be disregarded. In the future refinement of SSMM, it is planned to include a procedure to remove the whitecaps effects, additional aerosol spectral models for both the weakly and strongly absorbing aerosols, and conduct extensive validation with numerous match-ups of SeaWiFS and in situ data in turbid coastal waters.

Acknowledgments

This research has been a part of the Development of Case II water Bio-optical and Atmospheric correction Algorithms for the Geostationary Ocean Colour Sensor (GOCI) on Communication Ocean Meteorological Satellite (COMS) in 2008 and Multispectral Camera (MSC) on Korea Multipurpose Satellite 2 (KOMPSAT-2) in 2006, receiving support from the Ministry of Maritime Affairs and Fisheries (MOMAF) and Ministry of Science and Technology (MOST) through KORDI contracts PM 294-00 and PN 524-00. We thank the anonymous reviewers for their valuable comments and suggestions.

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