SeaWiFS maps water quality parameters of the White Sea

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1. Introduction

The White Sea has relatively recently become a subject of inquiry for scientists of various disciplines. This is mostly due to the onset of a new stage of development of natural resources both of the White Sea per se and its watershed. The expected industrial recovery of diamonds, mining of gold, intensification of fishing and harvesting of the mariculture, and transportation through the White Sea of the natural gas from the Shtockman gas-fields located in the Barents Sea are all likely to alter significantly the present ecological status of both marine and terrestrial environments in the region.

Unfortunately, present knowledge of the White Sea ecosystem's intrinsic functioning and its dynamics remains insufficient and requires further extensive interdisciplinary studies. Among other issues, these should include investigations of the White Sea hydrodynamics, hydrochemistry and hydrobiology.

Given the large dimensions of the White Sea (the water surface is about 90,000 km²), and pronounced temporal dynamics of in-water processes, satellite remote sensing monitoring can be an efficient and appropriate observational tool. Conjointly with in situ shipborne measurements and mathematical ocean circulation and ecosystem modelling, remote sensing could provide highly valuable data bridging the spatial and temporal gaps in observations as well as serving for the model validation.

Importantly, the incident solar radiation in the visible spectral region is solely capable of substantially penetrating into the water medium. Partly backscattered into the atmosphere by the water molecules as well as other substances co-existing in the upper layers of the water column, the solar radiance leaving the water surface...
Figure 1. Retrieval of chl (the scale is in mg m$^{-3}$) in the White Sea (10 July 2001) applying the SeaDAS code.

carries information about the water quality properties, and hence is reflective of a wealth of in-water processes related to hydrochemistry and hydrobiology.

However, utilization of satellite optical sensors for studying the White Sea is challenged by at least two major impediments.

The first one arises from the fact that the White Sea waters are spatially highly heterogeneous. This heterogeneity is primarily generated by inflow of several full-flowing rivers whose deltas grow into very large appendix-like bays. The rivers bring into the sea considerable amounts of suspended minerals and dissolved organics as well as nutrients. Therefore, the coastal waters are definitely non-case I waters (according to the Morel classification (Morel and Prieur 1977)) and their optical properties vary in the off-shore direction to eventually become pelagic waters in the central part of the sea. However, even the pelagic waters can hardly be ascribed to case I water, mostly because of enhanced and spatially variable concentration of
dissolved organics. It implies that the standard SeaDAS algorithm (O’Reilly et al. 1999) for retrieval of phytoplankton chlorophyll concentrations is unsuitable for the White Sea hydro-optical conditions, and some more sophisticated water quality retrieval techniques are likely to be eligible for this purpose.

The second encumbrance resides in the fact that the atmosphere over the White Sea is not typical of maritime atmospheres because of the influence of the ambient continent encapsulating this sea. It necessitates application of an atmospheric correction algorithm other than the one imbedded into the SeaDAS package, the latter being reportedly (for references, see Pozdnyakov et al. (2000)) most appropriate for clear atmospheres over off-shore oceanic and marine waters, and fails to perform properly in the case of atmospheric conditions strongly influenced by terrigenous and industrial aerosols.

2. Methodology

Obtained between 1998 and 2001, several Sea-viewing Wide Field-of-view Sensor (SeaWiFS) images have been analysed by us. In the present study, one selected SeaWiFS image of the White Sea taken on 10 July 2001 is discussed. To atmospherically correct the processed SeaWiFS image, two codes were comparatively exploited: (i) the SeaDAS standard algorithms and (ii) the MUMM algorithm (Ruddick et al. 2001). Two water quality retrieval procedures were employed: (i) the standard SeaDAS chlorophyll retrieval code (OC4; O’Reilly et al. 1999), and (ii) the
Figure 3. Retrieval of \( sm \) (the scale is in g m\(^{-3}\)) in the White Sea (10 July 2001) applying the L–M code.

Levenberg–Marquardt technique (described in detail in, for example, Kondratyev et al. (1990)).

The Levenberg–Marquardt (L–M) technique was applied employing the Lake Ladoga hydro-optical model (spectral absorption and backscattering cross-sections for phytoplankton (chl), suspended minerals (sm), and dissolved organics (doc)), and the parametric expression relating subsurface remote sensing reflectance, \( R_{rsw} \) (defined as the upwelling radiance just beneath the water surface normalized by the downwelling irradiance at the same level) and coefficients of bulk water absorption and backscattering (generally denoted as \( a \) and \( b_b \) respectively—Kondratyev et al. (1990)).

Jerome et al. (1996) have shown that for nadir viewing, a flat water surface and a very wide range of in-water optical conditions (the backscattering probability varying between 0.0133 and 0.0440, as well as sun zenith angles \( \theta_0 \) varying from 15° to 89°), the value of \( R_{rsw} \) averaged over the above ranges can be related to the inherent optical properties (IOPs), i.e. \( a \) and \( b_b \) as follows (correlation coefficient \( r = 0.99 \), and rms error = 9%):

\[
R_{rsw} = -0.00036 + 0.110(b_b/a) - 0.0447(b_b/a)^2
\]  

(1)

It can easily be shown (Bukata et al. 2001) that \( R_{rsw} \) is related to remote sensing reflectance (defined as the upwelling radiance just above the water surface normalized by the downwelling irradiance at the same level), which is inferable from atmospherically corrected satellite sensor data: indeed, neglecting the contribution to downwelling irradiance just beneath the water surface from subsurface upwelling irradiance that
undergoes internal reflection, $R_{rs}$ and $R_{rsw}$ are related by

$$R_{rs}(\theta_0) = R_{rsw}(\theta_0)[(1 - \rho_{surf})(1 - \rho_{int}(\theta_0))/n^2]$$  \hspace{1cm} (2)

where $\rho_{surf}$ is the surface reflectivity for incident downwelling irradiance (a function of both sun zenith angle $\theta_0$ and the fraction $F$ of diffuse (sky) irradiance in the incident irradiance), $\rho_{int}$ is the internal surface reflectivity for an incident angle $\theta_0$ ($\theta_0$ is the in-water solar zenith angle, related to in-air solar zenith angle, $\theta_0$ through Snell’s law), $n$ is the relative index of refraction in water $\approx 1.333$. It was also shown (Jerome et al. 1996) that

$$\rho_{int}(\theta_0) = 0.271 + 0.249 \mu_0$$  \hspace{1cm} (3)

where $\mu_0 = \cos(\theta_0)$. The results of application of atmospheric correction of SeaWiFS images taken over the White Sea indicate convincingly that compared to the SeaDAS, the utilization of the MUMM code does not lead to negative water-leaving radiances in the blue for a water body encapsulated by a single continent, such as the White Sea.

3. Results of retrieval and discussion

The results of retrieval of water quality parameters as obtained with the application of the SeaDAS and L–M codes are illustrated, respectively in figures 1 (cover) and 2–4.

The adequacy of the retrievals attained through applying the SeaDAS (OC4) and L–M algorithms can be assessed from a comparison (exemplified in table 1) of
Table 1. A comparison of the results of retrieval of water quality variables with the use of the SeaDAS and L–M codes in Onega Bay, July 2001.

<table>
<thead>
<tr>
<th>Date of in situ measurements</th>
<th>chl-a (in situ), $\mu$g l$^{-1}$</th>
<th>doc (in situ), mgC l$^{-1}$</th>
<th>sm (in situ), mg l$^{-1}$</th>
<th>Date of SeaWiFS overflight</th>
<th>chl-a (SeaDAS), $\mu$g l$^{-1}$</th>
<th>chl-a (L–M), $\mu$g l$^{-1}$</th>
<th>doc (L–M), mgC l$^{-1}$</th>
<th>sm (L–M), mg l$^{-1}$</th>
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<td>8.3</td>
<td>0.25</td>
<td>10 Jul 2001</td>
<td>3.7</td>
<td>1.3</td>
<td>6.5</td>
<td>0.8</td>
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<td>5.8</td>
<td>0.25</td>
<td>10 Jul 2001</td>
<td>3</td>
<td>1.2</td>
<td>5.5</td>
<td>0.7</td>
</tr>
<tr>
<td>10 Jul 2001</td>
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<td>5.9</td>
<td>0.65</td>
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<td>3.2</td>
<td>1.1</td>
<td>4.5</td>
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<td>4.5</td>
<td>1.0</td>
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</table>
shipborne in situ determinations of concentrations of chl, sm and doc for a number of stations conducted in Onega Bay (the southernmost bay of the White Sea) on the date of the satellite overflight. As seen from table 1, the waters of Onega Bay are typically non-case I waters inasmuch as the concentrations of chl, sm and doc are fairly high and mutually uncorrelated. The application of the SeaDAS OC4 code results in the chl concentrations far exceeding the respective in situ values. At the same time, the L–M procedure provides the values of chl, which compare mostly very well with the respective in situ data. The accuracy of the retrieval of doc is also quite satisfactory (generally, within ~20%). The retrieval of sm seems to be less accurate (although, in several instances it also proves to be quite precise). One of the possible reasons might reside either in the existence of large amounts of terrigenous particles that are too fine for the exploited filters to retain, or enhanced heterogeneity of the sm spatial distribution along with relatively more uniform fields of chl and doc. Indeed, SeaWiFS values are pixel-averaged (one SeaWiFS pixel measures 1.1 by 1.1 km), whereas the in situ data pertain to measurements in a concrete location within this pixel area.

Based on these comparisons between in situ measurements, SeaDAS and L–M retrieval data, it appears justifiable to assume that the L–M procedure assures an adequate restoration of the desired water quality parameters even in optically complex waters (i.e. non-case I waters) in the White Sea.

For the pelagic waters (which optically are generally less complex), the task of retrieval is easier and, hence obviously credible when processed with the L–M method. Consequently, the simultaneously recovered spatial distributions of chl, sm and doc (figures 2–4) are believed to be the first trustworthy images of water quality parameter fields in the White Sea obtained from space.

Acknowledgments

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References


