Improvement of MERIS level 2 products in Baltic Sea coastal areas by applying the Improved Contrast between Ocean and Land processor (ICOL) – data analysis and validation*

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Abstract

In this paper we compare the following MERIS processors against sea-truthing data: the standard MERIS processor (MEGS 7.4.1), the Case 2 Regional processor (C2R) of the German Institute for Coastal Research (GKSS), and the Case 2 Water Properties processor developed at the Freie Universität Berlin (FUB). Furthermore, the Improved Contrast between Ocean and Land processor (ICOL), a prototype processor for the correction of adjacency effects from land, was tested on all three processors, and the retrieval of level 2 data was evaluated against sea-truthing data before and after ICOL processing.

The results show that by using ICOL the retrieval of spectral reflectance in the open sea was improved for all processors. After ICOL processing, the FUB

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The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

showed rather small errors in the blue, but underestimated in the red −34% Mean Normalised Bias (MNB) and 37% Root Mean Square (RMS). For MEGS the reflectance in the red was underestimated by about −20% MNB and 23% RMS, whereas the reflectance in the other channels was well predicted, even without any ICOL processing. The C2R underestimated the red with about −27% MNB and 29% RMS and at 412 nm it overestimated the reflectance with about 23% MNB and 29% RMS. At the outer open sea stations ICOL processing did not have a strong effect: the effect of the processor diminishes progressively up to 30 km from land.

At the open sea stations the ICOL processor improved chlorophyll retrieval using MEGS from −74% to about 34% MNB, and TSM retrieval from −63% to about 22% MNB. Using FUB in combination with ICOL gave even better results for both chlorophyll (25% MNB and 45% RMS) and TSM (−4% MNB and 36% RMS) in the open Baltic Sea. All three processors predicted TSM rather well, but the standard processor gave the best results (−12% MNB and 17% RMS). The C2R had a very low MNB for TSM (1%), but a rather high RMS (54%). The FUB was intermediate with −16% MNB and 31% RMS.

In coastal waters, the spectral diffuse attenuation coefficient $K_{\mathrm{d}}(490)$ was well predicted using FUB or MEGS in combination with ICOL (MNB about 12% for FUB and 0.4% for MEGS). Chlorophyll was rather well predicted in the open Baltic Sea using FUB with ICOL (MNB 25%) and even without ICOL processing (MNB about 15%). ICOL-processed MEGS data also gave rather good retrieval of chlorophyll in the coastal areas (MNB of 19% and RMS of 28%). In the open Baltic Sea chlorophyll retrieval gave a MNB of 34% and RMS of 70%, which may be due to the considerable patchiness caused by cyanobacterial blooms.

The results presented here indicate that with the MERIS mission, ESA and co-workers are in the process of solving some of the main issues regarding the remote sensing of coastal waters: spatial resolution; land-water adjacency effects; improved level 2 product retrieval in the Baltic Sea, i.e. the retrieval of spectral reflectance and of the water quality products TSM and chlorophyll.

1. Introduction

Owing to its synoptic measuring abilities, ocean colour remote sensing is an effective method for assessing water quality. The spectral data collected by the space borne sensor is made interpretable by a thorough understanding of light behaviour in the atmosphere and water body. Whereas much is known about the optics of open ocean waters, we still need a better understanding of the more complex optics of coastal waters. The optical water classification system introduced by Morel & Prieur (1977) will be used in the following, which distinguishes between optical case 1 and optical case 2 waters. Case 1 waters have optical properties dominated by phytoplankton and, to a minor extent, their co-varying degradation products, whereas case 2 waters have optical properties dominated by other in-water constituents, such as total suspended matter (TSM, also referred to as suspended particulate matter, SPM) or coloured dissolved organic matter

(CDOM[1], also termed yellow substance). From a remote sensing point of view, optical case 1 waters are those for which the global algorithms for the estimation of chlorophyll work, whereas they tend to break down over optical case 2 waters. The Baltic Sea can be classified as optical case 2, and its optical properties are to a large extent dominated by exogenous CDOM because of the high freshwater input and the slow exchange rate with the North Sea.

A fair part of present-day research in marine remote sensing is aimed at improving procedures for the atmospheric correction of spectral data from coastal waters where the remote sensing reflection is highly variable. This variability can be partly ascribed to the hydrodynamics of the coastal zone, driven by wind and terrestrial run-off, often resulting in considerable heterogeneity even within quite small areas (i.e. in the range of hundreds of metres). But the aerosol composition of the transition zone between land and sea is also complex and variable (Zieliński & Petelski 2006), posing a challenge for the procedures aimed at correcting the remote sensing signal from the coastal zone for atmospheric influence.

MERIS (Medium Resolution Imaging Spectrometer) is an ocean colour sensor onboard the ESA Earth observation satellite ENVISAT, which was launched in 2002. It has a wide dynamic range and was developed for both marine and terrestrial observations. MERIS has 15 programmable channels, most of them tuned to detect the spectral signatures of water-leaving radiance in the visible, as well as atmospheric properties in the near infra-red. MERIS has a spatial resolution of 300 m (full resolution), which is a significant improvement compared to the standard resolution of approximately 1 km for ocean colour sensors, such as SeaWiFS and MODIS operated by NASA, although MODIS has higher resolution in some channels. MERIS registers all data in FR but in order to cope with the vast amount of information, the full resolution data are reduced to 1.2 km over the open ocean. Figure 1 shows a comparison of a MERIS full resolution scene over Himmerfjärden and a MERIS reduced resolution scene (1.2 km resolution). This comparison illustrates the improvement in numbers of pixels gained when moving from 1.2 km to 300 m resolution. Using MERIS FR data, there is a substantial improvement in retrieval of water pixels within Himmerfjärden.

[1]The actual yellow substance product from the MERIS standard processor is YSBPA (sum of CDOM and bleached particle absorption), but because of the clear dominance of yellow substance in the Baltic Sea (Kratzer & Tett 2009), we use yellow substance as a proxy for YSBPA. For consistency with published data in the field of ocean colour remote sensing (as well as the SeaWiFS protocols) we use the term CDOM for yellow substance.

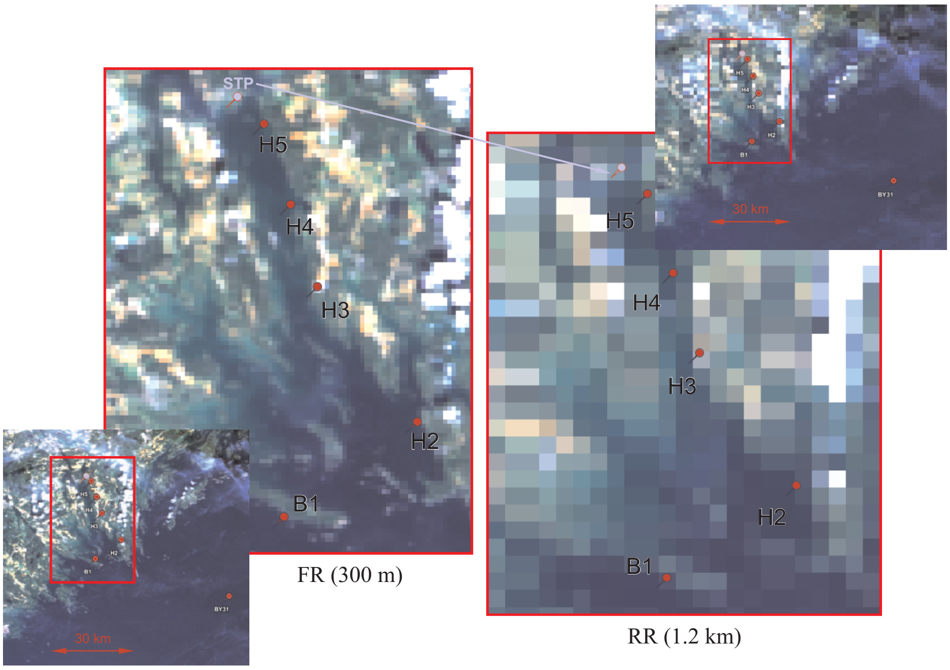

Figure 1. RGB composite images from 19 August 2002 over Himmerfjärden, both in full resolution (FR) and reduced resolution (RR). This comparison shows that the 300 m resolution of MERIS is more appropriate for coastal applications than the usual 1 km resolution of ocean colour sensors. Note that the images have not been corrected for adjacency effects

The 'top of the atmosphere signal' measured at satellite sensor height, is influenced by atmospheric, oceanic, and coupled atmosphere-ocean effects. In shallow waters, the optical signal may be influenced by bottom effects. As a global average, the water signal is about 10% of the signal measured at sensor height within the visible and near-infrared region of the electromagnetic spectrum. Almost 90% of the signal thus originates from atmospheric processes. For water quality monitoring, the atmospheric contribution of the detected signal is unwanted and therefore needs to be removed. This is usually referred to as atmospheric correction (Fischer & Fell 2001, Doerffer & Schiller 2006, Schroeder et al. 2007a). The atmosphere over the Baltic Sea is relatively clear (Carlund et al. 2005) with optical properties differing from atmosphere compositions over the North Sea from which much of the model calibration data has been collected.

The signal-to-noise ratio for the Baltic is low because of the high CDOM content, leading to high CDOM absorption in the blue to green part of the spectrum, and relatively low reflectances. This is why a good atmospheric correction is crucial for accurate water quality monitoring over the Baltic Sea. Besides the optical complexity of coastal waters and the variable aerosol composition above these waters, adjacency effects from land onto the water body may cause additional errors in the measured remote sensing reflectance data, e.g. stray light from land. The Improved Contrast between Ocean and Land processor (ICOL) was recently developed by Santer et al. (2007) and Santer & Zagolski (2009). It is a prototype processor correcting for stray land reflection in water pixels in relation to the sun angle, taking the coupling between Rayleigh scattering and Fresnel reflection into account. It is freely available as a plug-in to the BEAM VISAT software, which was used in this study.

The majority of current water quality algorithms are trained on case 1 waters, and the MERIS standard processor has been mostly trained on North Sea data. For quality assessment and improvement of MERIS data in different natural water bodies, ESA has established the MERIS Validation Team (MVT). The main tasks of MVT are sea-truthing, whereby MERIS data are validated against temporally and spatially matching in situ data. The quality-assured data are then added to the MERIS Matchup In-situ Database (MERMAID).

Products derived from ocean colour remote sensing are commonly categorised into three levels (Bukata 2005). Level 1 products are calibrated and geo-located radiances, at sensor height, i.e. at the top of the atmosphere (TOA). Level 2 products are retrieved from the top-of-the-atmosphere radiances after atmospheric correction. Besides the optical in-water components, one can also derive the so-called inherent optical properties describing the propagation of light in the water, such as absorption and scattering, as well as the diffuse attenuation coefficient, K_{d}, characterising the rate of light attenuation. Level 3 products are space and/or time binned data sets of level 2 products that are used to generate seasonal climatologies, and to analyse long-term global trends. The current focus in MERIS validation has recently shifted from validating water quality parameters (chlorophyll, total suspended matter and CDOM) to validating level 2 reflectance and MERIS-derived aerosol products, i.e. aerosol optical thickness and the Ångström coefficient. This was a necessity as many coastal waters differ in their specific inherent optical properties, which adds an additional error when water quality products are derived from the reflectance spectra e.g. using a coupled sea-atmosphere model.

Several processors for the interpretation of MERIS data from coastal waters have been developed recently (Schroeder et al. 2007b, Doerffer & Schiller 2008), which may be better adapted than the MERIS standard processor to the optically complex waters of the Baltic Sea.

In this paper we present the results from an investigation of the following MERIS processors: the standard MERIS processor (MEGS 7.4.1 which is equivalent to IPF 5.05, i.e. the second reprocessing of the ground segment), the Case 2 Regional (C2R) of the Institute for Coastal Research (GKSS-Forschungszentrum Geesthacht, Germany) and the Case 2 Water Properties processor (FUB processor) developed at the Freie Universität Berlin. The C2R and the FUB case 2 processors are not part of the ESA ground segment but are provided as plug-ins for the VISAT BEAM software. Furthermore, the effect of the earlier-mentioned ICOL processor, also provided as a BEAM plug-in, was evaluated along with the three processors. In the following we present the result of each processor before and after ICOL processing, evaluating the level 2 reflectance as well as the level 2 water quality products chlorophyll, CDOM and TSM, as well as the spectral diffuse attenuation coefficient for downwelling irradiance $K_{\mathrm{d}}(490)$ empirically derived using a local algorithm (Kratzer et al. 2008, Vinterhav 2008). All of these level 2 products were compared against sea-truth data.

2. Area of investigation

The area of investigation was Himmerfjärden Bay and the surrounding areas of the north-western Baltic Sea, including Landsort Deep (station BY31 in Figures 2 and 3), the deepest part of the Baltic Sea (459 m). The Baltic Sea is a brackish marine ecosystem with many distinguishing characteristics. It can be described as a large fjord-like estuary with brackish water. The salt water input is restricted to the south, where North Sea water enters via the Kattegatt and the Belt Sea. The freshwater input is considerable with a mean annual contribution of ~ 450 km^3 from an extensive catchment area. Wind is the main driver of the circulation, which is vertically limited owing to the prevailing halocline at 50–70 metres depth (Jansson 2003). From a remote sensing point of view the Baltic Sea comprises optical case 2 waters with its high concentration of exogenous CDOM (Kratzer et al. 2003 and 2008, Kratzer & Tett 2009). During summer months the Baltic Sea tends to be dominated by cyanobacteria blooms, which in their late stages may result in extensive surface accumulations clearly visible to the eye, on site as well as on the MERIS images. The type of land use around Himmerfjärden is predominantly forestry with some agriculture.

3. Field work

The sampling was conducted from the 'Limanda', a vessel operated by the Askö Laboratory. The sea-truth sampling was carried out during eight days in July 2008 (9, 15, 18, 24, 25, 28, 30 and 31 July), chosen on the basis of scheduled ENVISAT overpasses as predicted by the online application EOLI-SA. The sampling stations are aligned in three transects (Figure 2). The first transect starts at the head of Himmerfjärden, close to the outlet of the Himmerfjärden sewage treatment plant, and samples a series of

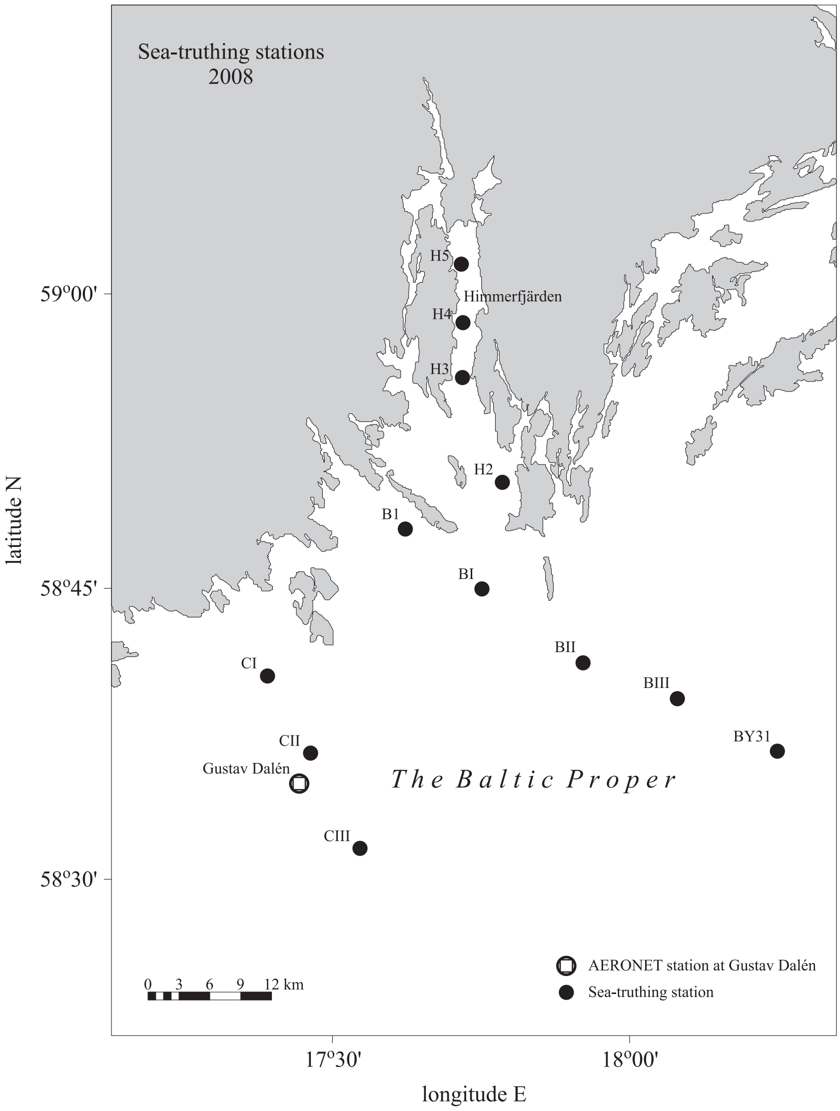

Figure 2. Positions of sea-truthing stations during the sea-truthing campaign in July 2008. Note that stations H2–H5 as well as stations B1 and BY31 (Landsort Deep) are part of the Swedish monitoring programme. Table 1 lists the transect dates and times. The island of Askö is situated north-east of station B1

different basins in Himmerfjärden at stations H5–H2, which are part of the Swedish coastal monitoring programme. This transect is of special interest for coastal zone management because of the ongoing nitrogen experiment at the Himmerfjärden sewage treatment plant, which is situated close to station H5. In this project, there was no nitrogen treatment during 2007 –08, but full nitrogen treatment during 2009–10. The second transect starts at station B1, south-west of Askö, and ends at Landsort Deep, the deepest part of the Baltic Sea with a water depth of 459 m. B1 and BY31 are part of the Swedish national monitoring programme; some additional bio-optical stations (BI-BII-BIII) were placed between these two stations (Kratzer et al. 2003, Kratzer & Tett 2009). A third transect from the coastline to 30 km off shore was chosen on the basis of a previously noted gradient of backscatter (Vinterhav 2008), defined by three stations (CI–CIII), passing

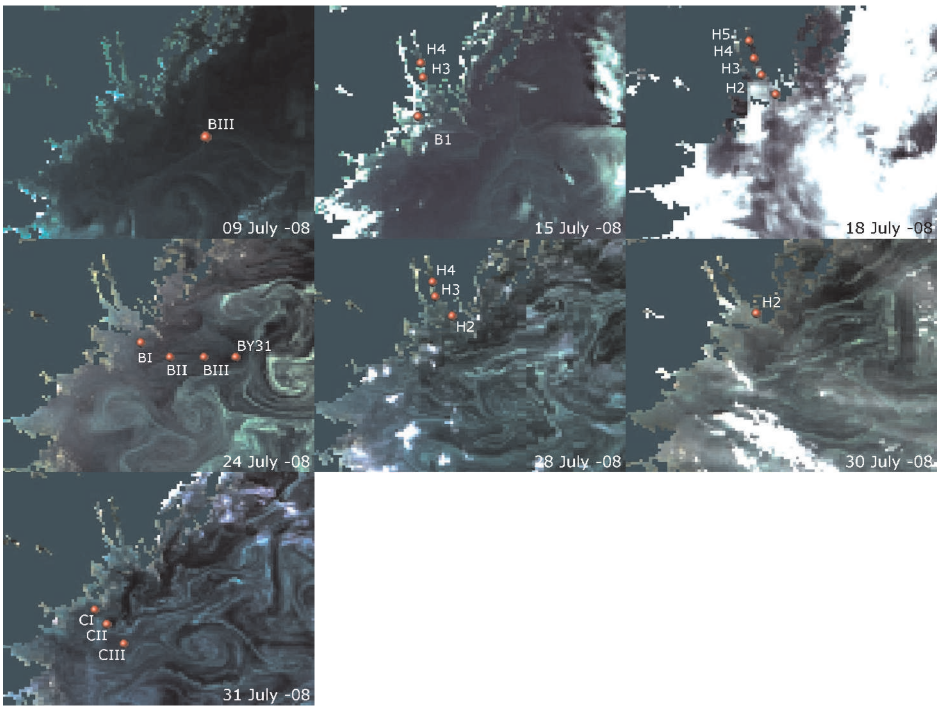

Figure 3. Sampling stations and transects during the Askö field campaign in 2008 (see PINS on each RR scene). The conditions were very good for sea-truthing (at least for this area of investigation). The MERIS RR RGB composites downloaded from the MERCI server (quick-looks) show how patchy the waters become during good conditions in summer. Note that the image from 25 July 2008 was not included in this overview because there was a problem with the level 2 data and it was not available through the MERCI server (quality control)

Gustaf Dahlén lighthouse, which houses a NASA Aeronet-OC station to derive sea surface reflectance for MERIS validation. The stations of both transects are located at distances from land ranging from 0.5 to 32 km. All dates except 15 July 2008 offered more or less cloud free sampling conditions, as shown in the reduced resolution scenes in Figure 3. Unfortunately, the MERIS data from 25 July 2008 were faulty and are not available on the MERCI server (i.e. the MERIS Catalogue and Inventory). The MERIS overpass times and the sea-truthing stations are listed in Table 1.

Table 1. Match-up stations during sea-truthing campaign in July 2008

Date	Sea-truth sampling station	Time of sampling (GMT)	MERIS overpass (GMT)
2008–07–09	BIII	09:38	09:25
2008–07–15	B1 H3 H4	06:53 09:43 10:42	09:36
2008–07–18	H5 H4 H3 H2	08:16 09:10 10:01 10:48	09:42
2008–07–24	BY31 BIII BII BI	08:58 10:01 10:53 11:37	09:53
2008–07–25	CI CII CIII	08:35 09:20 10:14	09:24
2008–07–28	H4 H3 H2	10:06 10:48 11:30	09:29
2008–07–30	H2	08:55	10:36
2008–07–31	CIII CII CI	10:14 11:10 12:00	09:35

4. Sea-truthing data

A Tethered Attenuation Coefficient Chain Sensor (TACCS, Satlantic Inc., Canada) was used for validating MERIS reflectance data at the sea-surface. This multi-channel radiometer includes 7 channels for upwelling radiance, L_{u} (unit: μW cm^{-2} nm^{-1} sr^{-1}) at 412, 443, 490, 510, 560, 620 and 670 nm, and 3 channels for downwelling irradiance, E_{d} (unit:

μW cm^{-2} nm^{-1}, above the surface) at 443, 491 and 670 nm. At each station, the TACCS was set to record for 2 minutes at a rate of 1 sample per second, having first been allowed to float 10–20 m away from the vessel in order to avoid shading. The data was converted from binary to calibrated engineering units using Satlantic SatCon software. The spectral attenuation coefficient $K_\mathrm{d}(490)$ was estimated from a chain of four sensors for downwelling irradiance at 490 nm, $E_\mathrm{d}(490)$, with a 10 nm bandwidth. The $E_\mathrm{d}(490)$ sensors were fixed on a cable at 2, 4, 6 and 8 m depth (also termed a $K_\mathrm{d}(490)$ chain). The natural logarithm of the measured downwelling irradiance was plotted against depth and the slope of the line taken as $K_\mathrm{d}(490)$. In the next step, spectral K_d was derived from $K_\mathrm{d}(490)$ according to the method described in Kratzer et al. (2008), using the appropriate slope factors derived from AC9 data for coastal and opens sea waters in the north-western Baltic Sea. The upwelling radiance just below the surface was estimated from the upwelling radiance at 50 cm depth by extrapolating each reading to the surface with the estimated K_d values for each radiance channel.

The radiance above the surface was then derived from the upwelling radiance just below the surface by multiplying the radiance values with the interface factor of 0.547 (Mueller & Austin 1995). The reflectance ρ_w was calculated from the ratio of upwelling radiance to downwelling irradiance, multiplied by π (3.14159).

The water sampling and processing was done according to a protocol described in Kratzer et al. (2003) and Kratzer & Tett (2009). All samples were taken just below the sea surface using a sampling bucket. Concentrations of organic and inorganic suspended matter were measured in triplicate by gravimetric analysis using the method of Strickland & Parsons (1972). Kratzer (2000) showed that the gravimetric method for deriving total suspended matter had an error of 10% for 29 Baltic Sea duplicates sampled in different bottles.

For the determination of CDOM, the water was passed through 0.2 μm membrane filters, then measured spectrophotometrically (300–850 nm) in a 10 cm quartz cuvette using a Shimadzu UVPC 2401 spectrophotometer. The optical density (OD), i.e. the absorbance at 440 nm, was corrected for OD at 750 nm; g_{440}, the absorption coefficient for CDOM at 440 nm was derived as follows:

$$\mathrm{g}_{440} = \ln(10) \times (\mathrm{OD}_{440} - \mathrm{OD}_{750}/\mathrm{L} \ \ [\mathrm{m}^{-1}],\ \text{Kirk (1994)},$$

where L is the path length of the cuvette in metres (in this case 0.1 m).

For the estimation of photosynthetic pigments, the spectrophotometric method was applied (Jeffrey & Humphrey 1975, Parsons et al. 1984), using GF/F filters and extraction into 90% acetone. Chlorophyll was calculated according to the trichromatic method (Parsons et al. 1984), which uses the absorption at 664, 647 and 630 nm, corrected for the reading at 750 nm, to account for particle scattering. The algorithm used gave the best results when spectrophotometric methods were compared with high performance liquid chromatography (HPLC) (Jeffrey & Welschmeyer 1997); it is included in the MERIS protocols (Doerffer 2002). Kratzer (2000) showed that the trichromatic method to derive chlorophyll had an error of 7% for 27 Baltic Sea duplicates sampled in different bottles. An international chlorophyll intercalibration exercise was coordinated by the Norwegian Institute of Water Research (NIVA) for the MERIS validation team in 2002; it included both HPLC and spectrophotometric measurements. The results of the intercalibration (Sørensen et al. 2003) showed that our spectrophotometric chlorophyll measurements of natural water samples were within 8.6% of the median value of the international group.

5. Image analysis

The eight matchup-scenes were delivered in full resolution (300 m resolution) level 1b by Brockmann Consult (Germany) and were further processed with the ICOL processor (1.0.4) for adjacency effect correction. The level 2 processing employed by the FUB case 2 processor (version 1.0.2) and the C2R (version 1.3.2) processors was invoked from the BEAM VISAT platform (4.5.1), whereas the standard level 2 processing, here represented by MEGS 7.4.1, was performed by staff at the ACRI-ST processing facilities (France). The MEGS level 2 images based on ICOL-corrected level 1b imagery were provided by ACRI-ST along with a corresponding set of non-ICOL processed images from the same processing session. This was a precaution to avoid errors resulting from the use of differing processing versions. Pin pixels corresponding to coordinates of the sampling stations were extracted as 3 by 3 pixel matrices and filtered for invalid data identified by the processor-specific flags. The FUB case 2 and C2R flags used for filtering were ATM_OUT and ATC_OOR respectively, each flag identifying unrecognised reflectance data after atmospheric correction. For the filtering of pixels from the standard level 2 processing the following flags were considered: HIGH_GLINT, ICE-HAZE, CLOUD, LOW_SUN and the standard flag PCD_1_13 (which indicates negative reflectance at measured wavelengths between 412 to 865 nm, excluding 760 nm). Each of those matrices with a minimum of five valid pixels remaining after this flag filtering were averaged and the result used as the remote sensing value for that station to be validated against the sea-truth measurement. The level 2 products included in the evaluation were level 2 water-leaving reflectances of MERIS bands 1–7 (412–670 nm), chlorophyll concentration (CHL [μg dm^{-3}]) and total suspended matter (TSM [g m^{-3}]). All of these parameters were evaluated for the three processors before and after ICOL processing.

6. Results

6.1. Water samples

The chlorophyll values ranged from 1.5 to 22.5 μg dm^{-3} for the whole campaign, with a mean value of 5.1 μg dm^{-3} and a standard deviation of 4.35 μg dm^{-3}. The observed range of chlorophyll was very high compared to the corresponding values measured in previous campaigns, ranging from 1.2 to 11.6 μg dm^{-3} with a mean of 3.5 μg dm^{-3} and a standard deviation of 2 μg dm^{-3} (Kratzer et al. 2003, Pierson et al. 2008, Kratzer & Tett 2009). The sample on 18 July 2008 with 22.5 μg dm^{-3} at station H5 close to the sewage treatment plant was clearly an exceptionally high value; it is also reflected in the Secchi depth of about 1.9 m and the very high $K_{\rm d}(490)$ value of 1.19 m^{-1}. These high chlorophyll and $K_{\rm d}(490)$ values are most likely related to the ongoing nitrogen experiment in Himmerfjärden. There was also an exceptional bloom of the prymnesiophyte *Chrysochromulina* spp. that was observed over the whole of the Baltic Sea area during spring and summer 2008, and on 18 July 2008, large numbers of the euglenophyte *Eutreptiella* spp. were also observed (personal communication from Susanna Hajdu, 2010) at H5.

The g_{440} values for CDOM absorption ranged from 0.36 to 1.18 m^{-1} with a mean value of 0.53 m^{-1} and a standard deviation of 0.19, but there was a problem with the filtering apparatus, so these values should be treated with caution; they are not included in the further analysis. However, the values still lie within the range of previous years, apart from two exceptionally high values at station H4 and H5 on 18 July 2008 (0.83 and 1.18 m^{-1}); these also coincided with high $K_{\rm d}(490)$ of 1.19 and 0.76 m^{-1}.

The range of $K_{\rm d}(490)$ in 2008 was 0.31–1.19 m^{-1} with a mean of 0.53 m^{-1} and a standard deviation of 0.23 m^{-1}, which is rather high compared to previously measured data from 2000–02 (Kratzer et al. 2003, Pierson et al. 2008, Kratzer & Tett 2009), which had a range of 0.30 –0.77 m^{-1}, a mean of 0.43 m^{-1} and a standard deviation of 0.1 m^{-1}.

TSM values ranged from 0.78 to 3.25 g m^{-3} with a mean value of 1.81 g m^{-3} and a standard deviation of 0.71 g m^{-3}. There were very high values in the inner part of Himmerfjärden (H3–H5) during 15 and 18 July, in both the organic and inorganic fractions. This is presumably related to the nitrogen experiment and the high abundance of phytoplankton.

6.2. Satellite data in relation to sea-truthing

The most striking result regarding the MERIS data was that all three processors delivered radiances that were too low, even after ICOL processing. The C2R algorithm gave the same number of valid pixels before and after ICOL processing. This basically means that it does not have a very rigorous flagging scheme for invalid pixels in coastal waters. For the FUB processor ICOL improved the retrieval of valid pixels from 44 to 72% along the transects. For the standard processor no valid pixels were processed in the coastal areas before ICOL processing, most likely because of the very rigorous flagging system.

CDOM was badly underestimated using all processors when compared to historical data, and was least well detected using C2R. We did not include CDOM in the following statistical analysis as there was, as mentioned before, a problem with the filtration unit.

Figure 4a shows the reflectance spectra extracted from MERIS FR data derived from the three processors before and after ICOL processing, and plotted against sea-truthing along the transect H4-H3-H2 through Himmerfjärden during 28 July 2008. Note the atypical spectral shape of

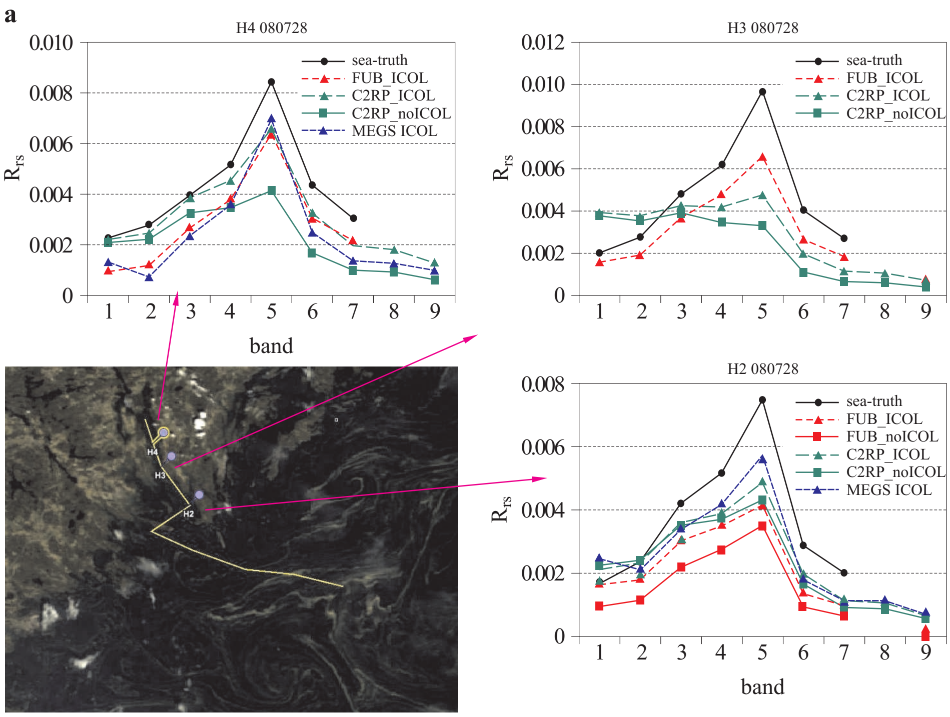

Figure 4. (*continued on next page*)

b

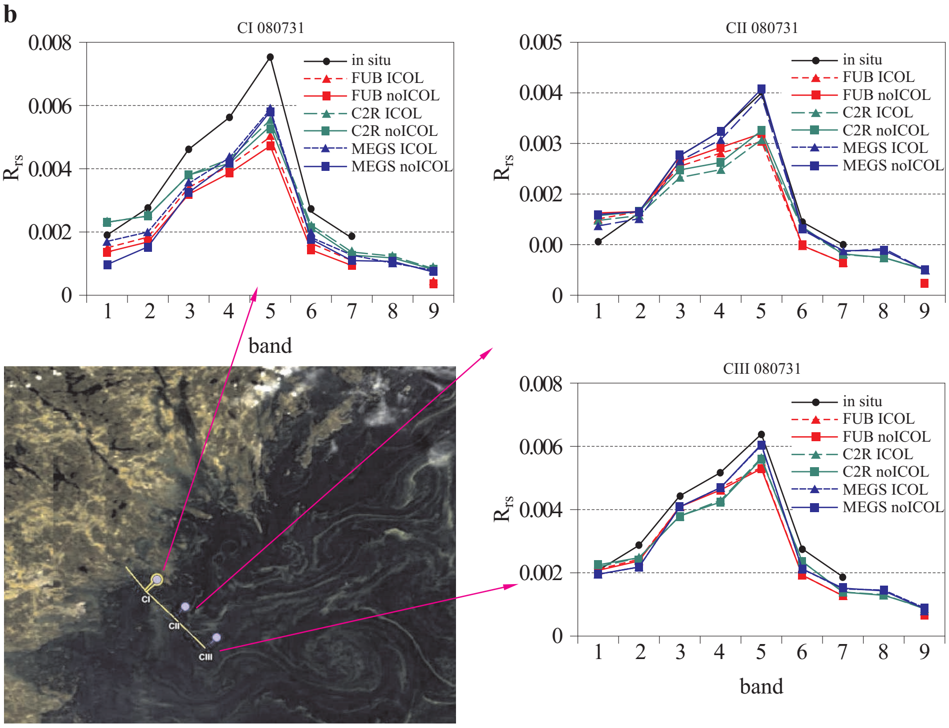

Figure 4. (a) Reflectance spectra extracted from MERIS FR data derived from the three processors before and after ICOL processing, and plotted against sea-truthing data (black dots) along the transect H4-H3-H2 through Himmerfjärden during 28 July 2008. Note the atypical spectral shape of the C2R processor with far too high values in the blue. (b) Reflectance spectra extracted from MERIS FR data derived from the three processors before and after ICOL processing, and plotted against sea-truthing data (black dots) for the transect stations CI-CII-CIII (approximately 7, 16 and 27 km offshore) during 31 July 2008. The data show that the ICOL processor had no effect at a distance of 27 km

the C2R processor with far too high values in the blue. Figure 4b shows the same for the transect stations CI-CII-CIII (approximately 7, 16 and 27 km offshore) during 31 July 2008. The data shows that the ICOL processor had no effect at a distance of 27 km, which is to be expected as the ICOL processor had the strongest effect close to the coast, and tails off at about 15–20 km from the coast (Santer & Zagolski 2009). The coastal adjacency effect extends only up to approximately 10 km from the coast in the principal plane, but ICOL corrects for the adjacency effect for an area up to 30 km perpendicular to the coast, in order to avoid visible jumps in the image (personal communication from Carsten Brockmann, 2009).

After this initial evaluation we changed the flagging for the standard processor to ignore the PCD_1_13 flag (which indicates negative reflectance at the measured wavelength between 412 to 865 nm, excluding wavelength 760 nm). Instead, pin pixels holding negative reflectances at 412 nm were filtered out, as this criterion was found to be an effective indicator of failed atmospheric correction without being as strict as PCD_1_13.

Figure 5 shows a chlorophyll transect passing the Gustaf Dahlén lighthouse derived from the three processors before and after ICOL processing and compared to the measured chlorophyll values at stations CI, CII and CIII (yellow squares on the graph). Chlorophyll was overestimated by all the processors with increasing tendencies for overestimation towards higher chlorophyll concentrations. MEGS 7.4.1 showed a high scatter (noise) in the non-ICOL processed data, but this improved after ICOL processing. Taking all stations into consideration, the FUB data is closest to the measured chlorophyll values, both before and after ICOL processing.

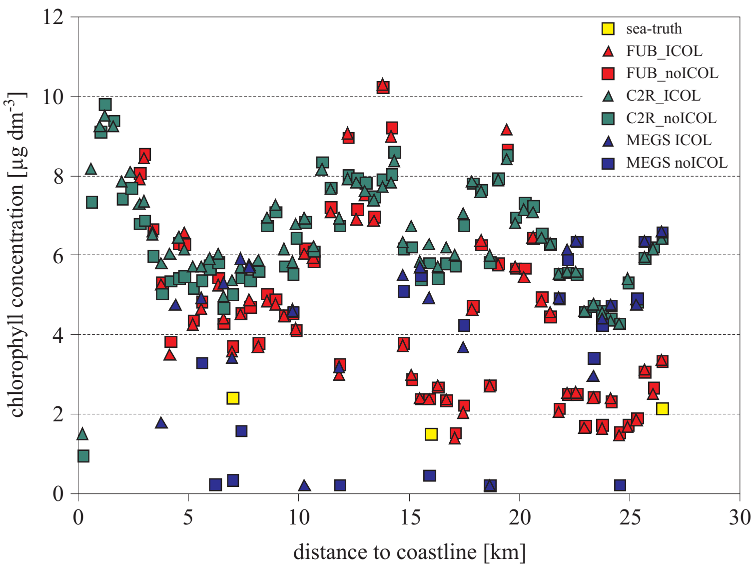

Figure 5. Chlorophyll *a* transect passing the Gustaf Dahlén lighthouse (see Figure 4b) derived from the three processors before and after ICOL processing and compared to the measured chlorophyll values at stations CI, CII and CIII (yellow squares on the graph). All the processors mostly overestimated chlorophyll. MEGS 7.4.1 had an unusual scatter in the non-ICOL processed data, but this was improved after ICOL processing. Taking all stations into consideration, the FUB data were closest to the measured chlorophyll values, both before and after ICOL processing

All processors gave good results for the retrieval of TSM after ICOL processing. By way of example we plotted the TSM values estimated

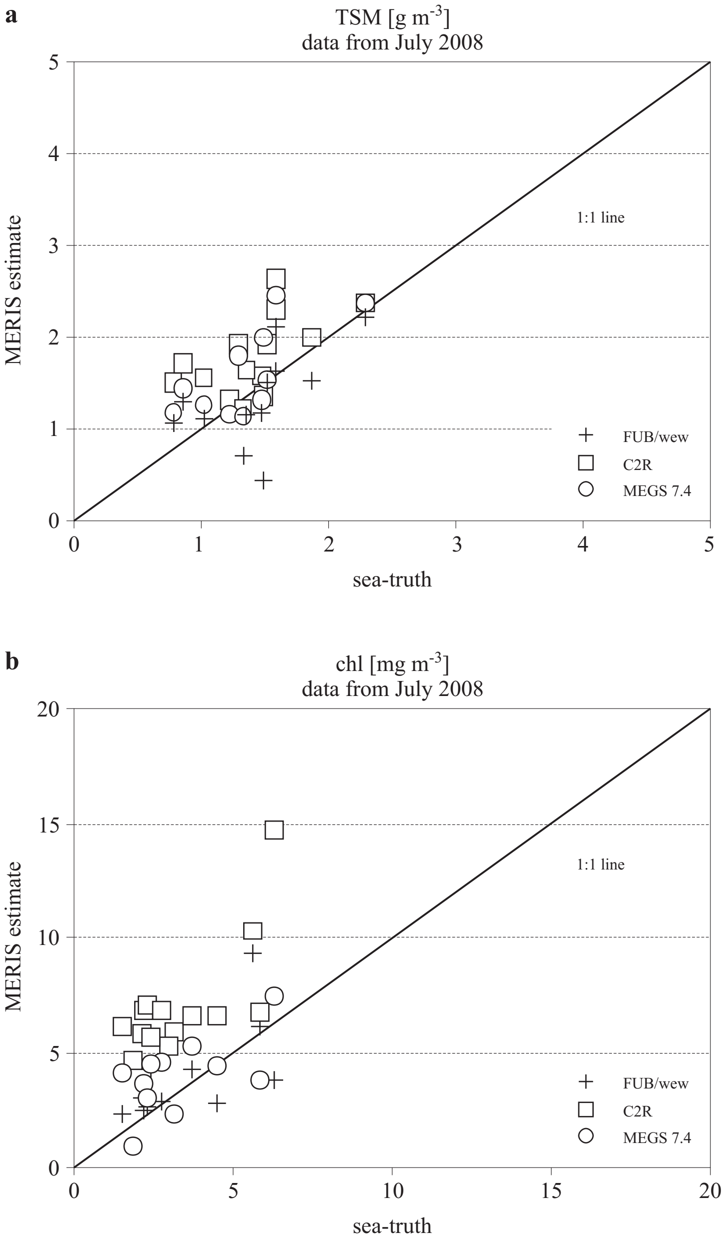

Figure 6. (a) MERIS processor estimates of the retrieved TSM load at the outer Himmerfjärden and the open sea stations using the three different processors combined with ICOL processing and plotted against measured data (sea-truth). FUB gave the best results with an MNB and RMS of −4% and 33.5% respectively (see Table 2). (b) MERIS processor estimates of retrieved chlorophyll concentration at the outer stations in Himmerfjärden and the open sea stations using the three different processors combined with ICOL processing (*continued on next page*)

(**Figure 6.** *continued*) and plotted against measured data (sea-truth). FUB gave the best results with an MNB and RMS of 25% and 46% respectively (see Table 2)

by a different MERIS processor in Himmerfjärden against the sea-truth measurements (Figure 6a). Figure 6b shows the same for chlorophyll.

Figure 7 shows MERIS processor estimates of level 2 reflectance derived from MERIS FR data from the open sea stations in 7 different channels in the visible spectrum using the three different processors, and plotted against sea-truthing data. Here we show only the results after flag filtering and ICOL processing. They show that for the blue channels the data is well spread around the 1:1 line, whereas at higher wavelengths the MERIS estimates lie below the 1:1 line. The C2R processor seems to have the strongest deviation from the 1:1 line of all channels, and gives especially low reflectances in the red part of the spectrum, and too high values in the blue. This means that the C2R clearly gives the wrong spectral shape in this study.

6.3. Statistical analysis

In order to quantify the discrepancy between matching sea-truth and satellite data we used the 'Mean Normalised Bias' (MNB):

$$\mathrm{MNB} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{y_i - x_i}{x_i}\right) \times 100\% \tag{1}$$

and the 'Root Mean Square' (RMS):

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{y_i - x_i}{x_i}\right)^2} \times 100\% \tag{2}$$

as described in Cristina et al. (2008) for MERIS validation in Portuguese coastal waters. We derived the MNB and RMS for spectral reflectance, chlorophyll and TSM before and after ICOL processing, both in the inner fjord as well as for the stations classified as 'open sea'. When we saw the positive results of the ICOL processing, we also derived the statistics for our $K_{\mathrm{d}}(490)$ algorithm (Kratzer et al. 2008, Vinterhav 2008).

The results in Table 2 reveal differences in the respective performance of the processors in the estimation of surface reflectance and, as expected, most notably in the areas close to land where the atmospheric correction often fails. In this table we treated all stations in Himmerfjärden apart

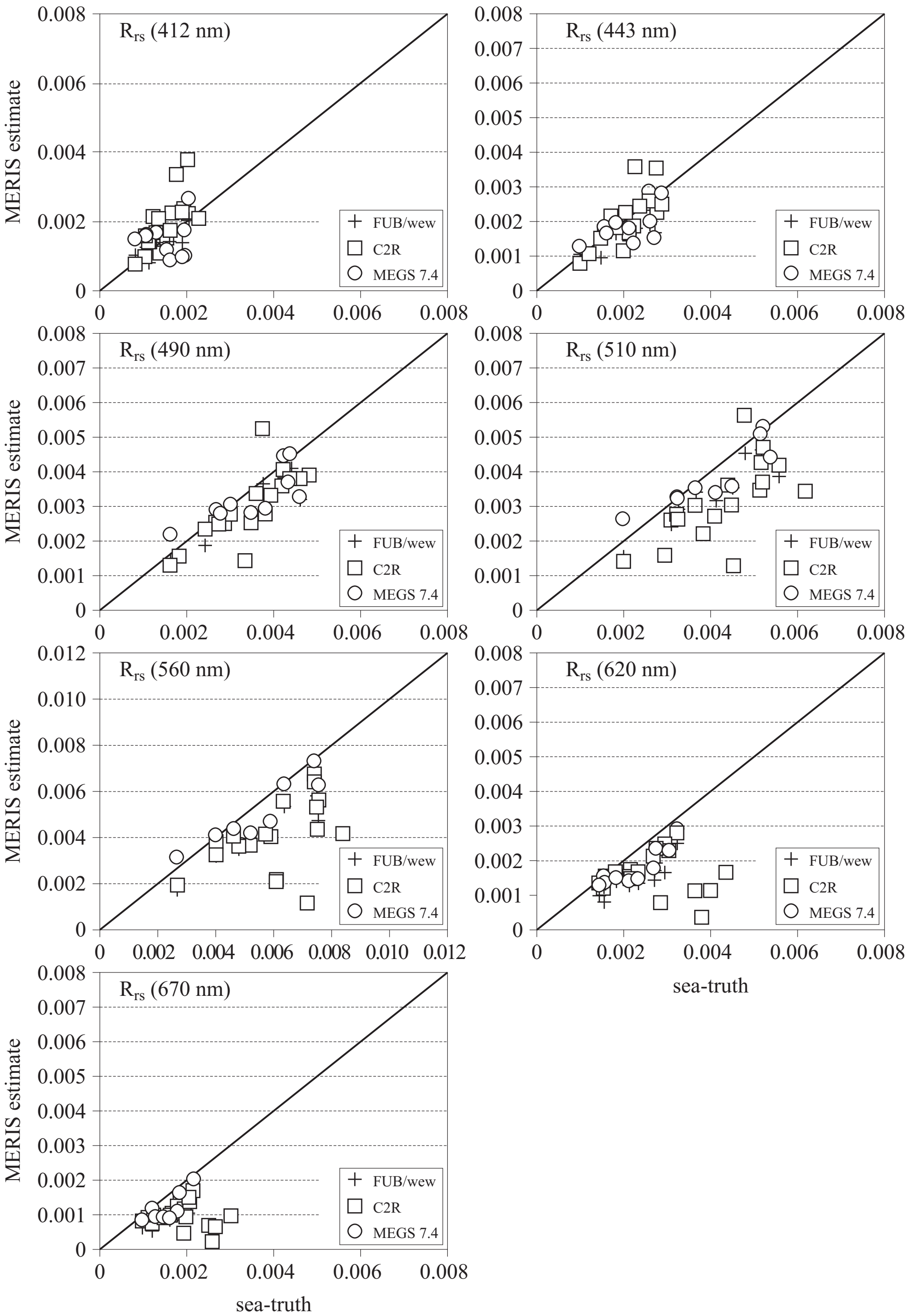

Figure 7. MERIS processor estimates of reflectance measurements derived from MERIS FR data for the 7 different channels (after filtering and ICOL processing) plotted against measured data (sea-truth). (*continued on next page*)

(**Figure 7.** *continued*) The data includes all valid pixels from the open sea stations (including B1 and H2). The statistics are shown in Table 2, in which the stations are divided into open sea and coastal stations

from station H2 as coastal stations, whereas the remaining stations were treated as open sea stations. This is in reference to the spectral shape of the diffuse attenuation coefficient K_d as described in Kratzer et al. (2008), which was significantly different for the inner stations of Himmerfjärden (H3–H5). This means that the inner bay is bio-optically different to the outer bay, partially because of the increasing concentrations of inorganic suspended particulate matter (Kratzer & Tett 2009) towards the head of the bay, as well as the increase in CDOM concentration. This was also reflected in the results shown from this study with relatively high concentrations of chlorophyll, TSM and CDOM in the inner bay. Because of the difference in number of observations (n) for each processor this table needs to be read with caution. However, we always used the sea-truthing data as a standard for comparison.

With ICOL, all the processors yielded quite good results as regards the retrieval of spectral reflectance in the open sea. With FUB, errors were rather low in the blue (Table 2) but were underestimated in the red (−34% MNB and 37% RMS). For MEGS the reflectance in the red was underestimated by about −20% MNB and 23% RMS, whereas the reflectance in the other channels was well predicted, even without any ICOL processing. The C2R underestimated the red with about −27% MNB and 29% RMS, and at 412 nm it overestimated the reflectance with about 23% MNB and 29% RMS.

At the outer stations ICOL processing did not have a strong effect, as the effect of the processor diminishes progressively to a distance of 30 km from land (Figure 4b). As far as the level 2 in-water products are concerned, ICOL processing improved chlorophyll retrieval using MEGS from −74% to about 34% MNB, and TSM retrieval from −63% to about 22% MNB. ICOL and FUB processing gave even better results for both chlorophyll (25% MNB and 45% RMS) and TSM (−4% MNB and 36% RMS) in the open Baltic Sea.

As mentioned before, all processors predicted TSM rather well, but the best results were obtained using the standard processor with a low RMS and a low MNB (−12% MNB and 17% RMS), i.e. low off-set and scatter around the 1:1 line when plotting MERIS retrieved against measured data. The C2R had a very low MNB for TSM (1%), which means a very small off-set from the 1:1 line, but a rather large scattering around the 1:1 line (54% RMS). The FUB was intermediate with −16% MNB and 31% RMS.

Table 2. Statistical results of the different processing schemes, including Mean normalised bias (MNB) and Root Mean Square before and after ICOL processing

Open sea stations, non-ICOL processed						
	FUB (n = 11 [15])		C2R (n = 12 [15])		MEGS 7.4 (n = 10 [15])	
R_{rs} (λ) [nm]	MNB [%]	RMS [%]	MNB [%]	RMS [%]	MNB [%]	RMS [%]
411.9	−4.1	23.0	26.5	36.0	5.8	44.8
443	−18.6	23.5	−0.8	18.5	−6.4	23.3
490.2	−12.6	16.0	−10.3	18.8	−4.3	18.1
509.8	−14.9	17.1	−19.1	22.8	−5.4	16.4
560	−22.7	24.2	−22.3	24.4	−6.7	13.9
620.2	−36.0	37.3	−20.2	23.0	−19.8	22.9
670.9	−39.9	41.2	−31.7	33.3	−22.2	26.1
CHL	14.8	38.2	118.7	141.6	−73.8	74.5
TSM	−9.0	32.4	23.7	40.2	−62.7	63.9

Open sea stations, ICOL processed						
	FUB (n = 12 [15])		C2R (n = 14 [15])		MEGS 7.4 (n = 11 [15])	
R_{rs} (λ) [nm]	MNB [%]	RMS [%]	MNB [%]	RMS [%]	MNB [%]	RMS [%]
411.9	1.7	19.8	22.7	28.8	10.9	49.7
443	−14.4	20.6	−3.2	13.3	1.0	27.4
490.2	−9.2	17.7	−11.3	16.8	−1.2	19.5
509.8	−12.4	18.7	−18.7	21.9	−3.5	17.4
560	−20.9	24.4	−19.8	22.2	−6.4	13.7
620.2	−29.6	33.6	−15.3	19.3	−17.7	20.7
670.9	−33.8	36.8	−27.3	29.2	−19.9	23.2
CHL	24.6	45.9	133.4	152.3	34.2	69.4
TSM	−4.0	33.5	32.9	47.6	22.4	35.5
$K_d(490)$	53.0	55.7	74.7	77.2	63.1	65.4

Coastal stations, non-ICOL processed						
	FUB (n = 0 [7])		C2R (n = 4 [7])		MEGS 7.4 (n = 0 [7])	
R_{rs} (λ) [nm]	MNB [%]	RMS [%]	MNB [%]	RMS [%]	MNB [%]	RMS [%]
411.9			24.3	57.1		
443			−4.9	22.0		
490.2			−25.6	17.4		
509.8			−47.8	42.0		
560			−66.2	62.0		
620.2			−73.7	69.6		
670.9			−77.1	73.4		
CHL			−68.2	63.3		
TSM			−51.6	46.4		

Table 2. (*continued*)

	Coastal stations, ICOL processed					
	FUB (n = 6 [7])		C2R (n = 5 [7])		MEGS 7.4 (n = 4[7])	
R_{rs} (λ) [nm]	MNB [%]	RMS [%]	MNB [%]	RMS [%]	MNB [%]	RMS [%]
411.9	−12.2	29.9	21.0	42.8	128.4	141.0
443	−21.5	31.1	−5.5	22.4	40.1	50.9
490.2	−4.2	25.7	−14.6	16.4	10.8	15.6
509.8	−11.5	19.6	−26.9	28.0	−4.3	9.0
560	−22.4	23.9	−35.9	37.3	−7.9	9.1
620.2	−26.1	29.3	−31.0	37.1	−22.7	23.9
670.9	−26.4	28.8	−37.4	42.4	−25.5	28.6
CHL	90.8	114.4	32.6	50.2	18.9	28.1
TSM	−15.5	30.5	1.2	54.2	−12.0	17.1
K_d (490)	11.5	15.0	16.0	34.1	0.4	10.3

Before ICOL processing only the C2R delivered valid pixels for the coastal areas. However, the reflectance in the higher channels (green, orange and red) was substantially overestimated (see Table 2), and the spectral signature appeared to be somewhat atypical (Figure 4a). The ICOL processor much improved spectral retrieval. This is true not only for the C2R, but for all three processors. Over the whole spectrum, the FUB processor gave the lowest errors for the inner bay. MEGS has high errors in the blue part of the spectrum.

$K_d(490)$ was also predicted rather well in the inner bay by all three processors after ICOL processing: best of all by the standard processor with 0.4% MNB and 10.3% RMS, followed by FUB with 12% MNB and 15% RMS. C2R was the least precise and accurate with 16% MNB and 34% RMS.

Chlorophyll was over-predicted in the inner bay with 91% MNB and 114% RMS with FUB and ICOL processing. However, the standard processor MEGS 7.4.1 gave fairly good results for chlorophyll after ICOL processing, with 19% MNB and 28% RMS. The C2R was intermediate, with 33% MNB and 50% RMS.

7. Discussion

Remote sensing methods have become the most cost-effective method for collecting environmental data at a range of spatial scales that are impractical with in situ methods (Andréfouët et al. 2009). Since remote methods supply information about important water quality parameters (such as concentrations of chlorophyll, suspended matter and CDOM absorption), coastal processes can be studied synoptically. In combination with the relatively low concentrations of suspended matter, the high CDOM concentration in the Baltic Sea (Kowalczuk et al. 2005, Kratzer & Tett 2009) leads to a relatively low reflectance, which results in a low signal to noise ratio, implying a clear challenge for the discipline; remote sensing in the Baltic Sea is by no means a trivial matter.

This paper, however, demonstrates a clear improvement in the MERIS level 2 products reflectance, chlorophyll and TSM when the ICOL processor is applied.

The pixels included in the ICOL processing showed a significantly better fit with the sea-truth data. For MEGS and FUB the ICOL processor improved the number of valid pixels in the coastal zone substantially and also the spectral shape of the retrieved reflectance. Before ICOL processing, there was a higher frequency of flagging when both processors were used, which basically indicates failure of the atmospheric correction. With the C2R atmospheric correction negative reflectances are not possible, which partially goes to explain why using ICOL does not add valid pixels when C2R is used.

The results in this study are comparable to those given in Kratzer et al. (2008), where we evaluated the retrieval of chlorophyll, TSM and CDOM for one FR scene on 19 August 2002 by comparing the % difference of transect data extracted from a MERIS scene (FUB processor) with the trendline of measured data along four transects on 9, 12, 15 and 22 August 2002. This trendline made it possible to add a spatial dimension in the comparison of match-ups. This was required as we only had a limited number of real match-ups. So, instead of comparing individual match-ups, we compared the satellite retrieved data (i.e. a transect extracted from MERIS data) to average sea-truthing data over the same month (i.e. the spatial trendline of the optical data measured during the month of July). This seemed a viable method, as we showed in Kratzer & Tett (2009) that the optical in-water parameters can be described by a polynomial decline when moving from the head of Himmerfjärden (source) to the Landsort Deep (sink). We therefore concluded that by adding a spatial dimension to the evaluation of match-ups, we could improve our way of calculating the error in satellite data.

Although we used completely different methods to estimate the error of the satellite data, we still obtained very similar results. In Kratzer et al. (2008), using FUB we overestimated chlorophyll by 91% in the coastal areas and underestimated TSM by -16%. CDOM was underestimated by approximately -37% in coastal areas, and -74% in the open Baltic Sea (note that these estimates were derived without ICOL processing). In the open Baltic Sea we estimated an error of −35% for chlorophyll, which was now improved in this study to 25% after ICOL processing.

The MNB in TSM retrieval in the coastal zone for the data in this study was −15.5% using FUB, and −12% using MEGS after ICOL processing. ICOL processed MEGS data also gave a rather good retrieval of chlorophyll in the coastal areas (MNB of 19% and RMS of 28%). In the open Baltic Sea the retrieval of chlorophyll using MEGS gave a MNB of 34% and RMS of 70%, which may have been due to the substantial heterogeneity caused by the cyanobacterial blooms. The improvement in the statistics for chlorophyll and TSM retrieval in this study compared to our previous study (Kratzer et al. 2008) may be due not only to the adjacency correction, but also to the greater number of match-ups (i.e. several MERIS scenes matching measured data).

Table 2 shows that our $K_{\mathrm{d}}(490)$ product derived from a local algorithm applied to ICOL processed data gave good results in Himmerfjärden in combination with FUB and MEGS processing. However, in the open Baltic Sea, retrieval was not as reliable, presumably because of the considerable patchiness caused by the surface accumulations of cyanobacteria. In order to validate the MERIS data, one needs to measure optical properties during the time of MERIS overpasses. In view of the high frequency of cloud cover in the Baltic Sea area, this is a logistical challenge. Our sea-truthing campaign was successful in the sense that the weather was good with mostly clear skies and relatively calm waters, as well as favourable sampling conditions. An important point that needs to be made in the context of sea-truthing in the Baltic proper in summer is that filamentous cyanobacteria always bloom in summer during good weather conditions, a fact reflected in our phytoplankton samples. Good weather conditions, however, are also a prerequisite for the acquisition of ocean colour data. This means that we cannot expect a homogeneous water body (either in the horizontal or in the vertical) during fine weather in summer. Owing to the biological variability in the area we have to accept a certain degree of heterogeneity in the extracted pixels (normally 3x3) coinciding with our sea-truth measurements, which basically means that we cannot apply case 1 standards to the definition of a valid match-up. This should be taken into consideration when including the Baltic Sea in a calibration/validation data set.

8. Conclusions

Figure 1 shows that MERIS substantially increases the number of water pixels retrieved for Himmerfjärden when moving from reduced to full resolution. This demonstrates a clear improvement of coastal remote sensing using MERIS FR data. The results from ICOL testing shows that we can substantially improve level 2 reflectance retrieval after correcting for the adjacency effect. By tackling some of the main issues of coastal remote sensing, i.e. spatial resolution as well as adjacency to land, coastal remote sensing as driven by the ESA MERIS project is developing in the right direction.

We presented our results during the MERIS validation team meeting in the Algarve in March 2009, where ESA decided to further fund the development of the ICOL processor. ICOL 2 will shortly be released; it is faster than the first version, and can also be applied to Landsat TM data. Also, ESA will make the next version of MEGS publically available (ODESA, MEGS 8), which means that we will be able to process our match-up scenes ourselves from ICOL processed level 1 to level 2. The third reprocessing of MERIS level 2 data is currently under way and is expected to be finished by September 2010. It includes a re-worked algorithm for atmospheric correction (updating of atmospheric tables and a new bright pixel atmospheric correction), which in the current standard processor (IPF 5.05) is a source of error for estimating in-water properties from MERIS data, especially in the blue part of the spectrum. Our data was submitted to MERMAID, the new MERIS validation database established by ESA. The MERIS data quality group therefore has access to our data set and can test the new atmospheric correction tables of the new processor on MERIS data in the Baltic Sea.

Future work should focus on improving atmospheric correction algorithms over optically complex waters and on further extending the range of optical variables used for processor calibration and training so as to cover the ranges typical for Baltic Sea waters. The development of MERIS processors is moving forward very quickly, so the results presented here are just a snapshot of a highly dynamic and interdisciplinary field of research.

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