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VALIDATION OF MERIS WATER PRODUCTS FOR BELGIAN COASTAL WATERS: 2002-2003

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ABSTRACT

This paper describes the validation of MERIS products for Belgian coastal waters for the period 2002-2003. The MERIS Level 2 water products are compared with sea-borne measurements if match-up conditions are satisfied. A qualitative assessment of MERIS imagery was made to provide recommendations to improve image quality as in our previous report. This shows that undetected cloud contaminated pixels can severely deteriorate image quality. Patches of non-positive water-leaving reflectance at blue bands are also found for both case 1 and case 2S waters, and water constituent retrieval may be unrealistic for those patches. Furthermore, a quantitative comparison for the match-up data is made focussing on a comparison of water-leaving reflectance. Compared with last year's MERIS processing ('200210' version), the latest MERIS processing ('200308' version) gives better results for the spectral shape of water-leaving reflectance in the blue and green bands, but differences in the absolute magnitude of reflectance are found. No apparent bias of MERIS reflectance with respect to the seaborne reflectance is found from the scatter plot of all the spectral reflectance data of 2002 and 2003. However, the relative difference is larger for blue bands and NIR bands. Differences in reflectance at visible bands could not be related to differences in either the imposed NIR band ratio of water reflectance or aerosol optical thickness with respect to our match-up data. This should be further investigated to improve the atmospheric correction procedure.

1. INTRODUCTION

Since the launch of the Medium Resolution Imaging Spectrometer (MERIS) on 1.3.2002, a number of seaborne cruises have been undertaken in Belgian waters in order to obtain match-up data for MERIS water product validation. The validation site located in Belgian coastal waters was described in the 2002 validation report **[1].** In brief, this area can be characterised as eutrophic coastal water with water depth less than 40m. It is usually turbid owing to the shallow bottom depth and strong tidal current and frequent strong wind events. In this area, chlorophyll ranges from 0.1 to 50 mg/m3, suspended particulate matter from 0.1 to 500 g/m3 and yellow substance (CDOM and tripton) absorption from 0.1 to 5.0 /m [2]. The highly turbid nature of this test site makes it particularly useful for validation of turbid water 'case 2S' atmospheric correction algorithms [3].

The 2002-2003 seaborne measurements providing match-ups with MERIS images were used to validate the following MERIS products:

- Water-leaving reflectance ($\rho_w(\lambda)$)
- Algae pigment index 2 (Algal2 or Chl2)
- Total suspended matter (TSM)
- Aerosol optical thickness (AOT)

Validation of the water-leaving reflectance spectra, $\rho_w(\lambda)$, has priority in this study since they are the input parameters for retrieval of water constituents. There are several different types of algorithms which use water-leaving reflectance (or normalised water-leaving radiance) as input: multi-variable inversion algorithms including the neural network technique **[4]** and semi-analytical algorithms **[5]** that use the full spectra available or single-variable retrieval algorithms **[6]** which use only a few bands. Since each algorithm has its own sensitivity to input reflectance error, it is valuable to assess the quality of MERIS reflectance. It remains challenging for the ocean-colour community to obtain high quality water-leaving reflectance from satellites over turbid case 2 waters although much progress has been made. Validation of Algal2 and TSM would be meaningful only after water-leaving reflectance is validated. Aerosol optical properties such as AOT and the Angstrom exponent (or equivalently, aerosol epsilon parameter) can be used for investigating problems that may be found in the water-leaving reflectance validation.

In last year's validation report for Belgian waters **[1]**, several problems were identified as degrading the image quality from the match-up imagery. An apparent discrepancy in spectral slope over blue-green bands was reported between

MERIS reflectance and seaborne reflectance, although agreement in green to near infrared (NIR) bands was impressive. Continuing from the report, the image quality of match-up scenes is analysed. Specifically, the effects of cloud contamination, negative water-leaving reflectance and discontinuities on image quality due to switching of atmospheric correction algorithms are described. For the water-leaving reflectance validation, the latest processing is compared with the October 2002 processing. Note that the October 2002 processing gave clear discrepancy in spectral slope of MERIS reflectance over blue-green wavelengths with respect to the seaborne reflectance measurements in Belgian coastal waters. Algal2 and TSM validation results are discussed in connection with reflectance spectra comparison. An overall comparison of the MERIS reflectance with the seaborne measurements is given by merging spectral reflectance from all match-ups. In order to identify the cause of differences in visible bands, the ratio of NIR water reflectances and AOT is discussed.

2. OVERVIEW OF MEASUREMENTS

Validation measurements have been made during a series of seaborne cruises in Belgian and UK coastal waters from the oceanographic Research Vessels Belgica (51m), Zeeleeuw (56m) and Tuimelaar (7m). Table 1 summarises these cruises and the corresponding MERIS imagery. In this context only « match-up » MERIS imagery acquired within one hour, or preferably 30 minutes, of seaborne measurements has been considered in order to minimise uncertainties associated with temporal variability of marine and atmospheric properties.

Table 1. Summary of MERIS Validation cruises undertaken in 2002 and 2003 and corresponding MERIS match-up possibilities.

Month	Days at sea	Optimal match-up images	Sub-optimal match-up images
March, 2002	5	0	1 ?
April, 2002	8	2 ?	1 ?
June, 2002	4	0	1 ?
July, 2002	5	2	2
October, 2002	1	0	0
SUBTOTAL, 2002	23	2-4	2-5
March, 2003	2	0	0
April, 2003	4	2	0
June, 2003	7	1	0
July, 2003	4	0	1
August, 2003	2	0	1
September, 2003	5	0	0
SUBTOTAL, 2003	24	3	2
TOTAL	47	5-7	4-7

3. MEASUREMENT METHODS

Details of the measurement methods for seaborne water-leaving reflectance, Algal2, TSM and AOT are given in **[1]** and **[7],** based on the MERIS validation protocols **[8].** In brief, seaborne measurements perfomed at each station included:

- upwelling and sky radiances, and downwelling irradiance measured with a set of three TRIOS hyperspectral radiometers which allow the calculation of the water-leaving reflectance, $\rho_w(\lambda)$
- upwelling and direct sun radiances measured with the SIMBADA radiometer which allow calculation of the water-leaving reflectance and AOT
- HPLC measurements of filtered water samples to define the chlorophyll *a* concentration
- Gravimetric measurements of filtered water samples to define the amount of total suspended matter

We note that for 2002 measurements the SIMDADA data has been reprocessed giving some differences with data reported in 2002 **[1].** For the TriOS processing a minor update has been made for estimation of the air-sea interface reflection coefficient, ρ_{as}, as a function of wind speed, W, in m/s given in equation (2) of **[1].** This is now taken as:

$$\rho_{as} = 0.0256 + 0.00039 * W + 0.000034 * W^2 .$$

4. RESULTS - MERIS IMAGERY

4.1 Overview of match-up imagery

A summary of 2002 match-up imagery can be found in **[1].** This gave essentially two match-up scenes with concurrent seaborne measurements. In 2003, there were 24 cruise days of which 13 days correspond to MERIS overpasses as seen in Table 2. The 13 potential match-up scenes are summarised in Table 2 with weather conditions observed from the ship and from the MERIS level 1B RGB images. After removal of cloudy scenes we have 5 clear scenes. All the 2003 level 2 images were processed by the latest MERIS processing version, termed '200308'-version

Table 2. Summary of potential match-up scenes in 2003 and corresponding atmospheric conditions.

Date	L1 data	L2 data	Atmospheric Conditions
03.3.2003	Received	Not received	Not good
22.4.2003	Received	Received	Good
23.4.2003	Received	Not received	Good
25.4.2003	Received	Not received	Not good
03.6.2003	Received	Not received	Not good
16.6.2003	Received	Received	Good
18.6.2003	Received	Not received	Not good
27.6.2003	Not received	Not received	Not good
07.7.2003	Received	Received	Not good
08.7.2003	Received	Received	Not good
10.7.2003	Received	Received	Good
05.8.2003	Received	Received	Good
09.9.2003	Not received	Received	Not good

Taking the seaborne measurements with time difference less than about one hour from the MERIS overpass, a total of 10 stations for 6 MERIS scenes, as listed below, were obtained for match-up comparison.

Date of MERIS Scene	Station names of match-up comparison
-19. 07. 2002	130 (High glint flag raised)
-29. 07. 2002	130, 230, MC5
-22. 04. 2003	230, MC5
-16. 06. 2003	MC16
-10. 07. 2003	230, MC4 (High glint flag raised)
-05. 08. 2003	130 (High glint flag raised)

If the MERIS pixel corresponding to the in situ measurement is affected by sun glint, the corresponding seaborne data is not recommended to be used for match-up comparison, though it is considered important to investigate also glint affected pixels to increase the usable area of MERIS images in the future. So, finally, our best match-up measurements are six seaborne stations for three MERIS scenes (29.7.2002, 22.4.2003 and 16.6.2003).

All MERIS products presented here were processed with the latest processor version ('200308'). In addition, for the 2002 match-ups, the MERIS products processed with the previous processor version ('200210') are shown for comparison. The imagery has been processed up to level 2 for the European Space Agency by ACRI/Brockmann Consulting using calibration information from orbit 1858 and after correction for smile as described at the Envisat-MERIS Commissioning workshop on 10.9.2002. Analysis of the images have been performed at MUMM using the BEAM and IDL software to generate graphical images or to pick up match-ups. Georeferencing was checked at several points along the Belgian coast and found accurate to within one pixel for reduced resolution (1.2km) data.

4.2 Qualitative assessment of imagery

Figures 3 to 5 show MERIS imagery corresponding to the match-ups of 29.7.2002, 22.4.2003 and 16.6.2003, respectively. Each figure includes six panels: upper left is a RGB composite of the level 1B image using bands 7 (665nm), 5 (560nm) and 2 (443nm); upper right is AOT at 865nm; middle left is water-leaving reflectance at 443nm; middle right is algal1 with case2S flag masked (black for case2S flag raised); lower left is algal2; lower right is total suspended matter. All images shown have been projected with nearest neighbour re-sampling so that one pixel corresponds to approximately 1.2kmx1.2km square, giving image resolution similar to the original reduced resolution (RR) image in scan coordinates. Pixels flagged as clouds are shown in white except for level 1B RGB composite (although white pixels in RGB are probably cloud pixels). Images are not masked by the corresponding PCD flags which are, at present, of unknown quality. A vector coastline as well as latitude/longitude grid lines are overlaid in red. The stations where in situ measurements were made are shown on the images in the upper left panel as white crosses, with the station names.

-Effect of cloud (contamination) on level 2 products

According to the MERIS processing flow, each pixel is classified to one of three types: land, water or cloud. Over the ocean, water algorithms are applied to the pixels which are classified as water to assign water properties to those pixels. Problems occur for pixels affected by thin clouds or broken clouds because water algorithms may fail. Those pixels produce a noisy pattern in level 2 water products such as algal2, yellow substance (YS) and TSM, as was also noticed in the 2002 validation report **[1]**. Such pixels can be easily identified since AOT is very high, e.g. pixels marked as 'cloud' in top-right panels in Fig. 3 to 5. It is not clear whether level 2 flag 'PCD_1_13' is raised systematically at those pixels. If the flag 'PCD_1_13' is used to screen out those pixels, other pixels with reflectance at some bands negative or affected by sun glint will be lost as well. Several ways to deal with this problem can be envisaged: to use another flag bit or to use the most significant bit of the digits of reflectance data as flag for this cloud contamination, or to set a dummy value (e.g. null) for reflectance values.

-Non-positive water-leaving reflectance in some bands

Large areas of non-positive water-leaving reflectance at 443nm can be seen in the image of 29.07.2002, in the central southern North Sea and in Dutch coastal waters (Fig. 3, light grey pixels, marked as 'NEGATIVE REFLECTANCE'). Water-leaving reflectance at blue bands can be very low when phytoplankton (or CDOM) concentration is high and TSM concentration is low, as seen in some coastal waters. However, this does not seem to be the case here. Although there are no seaborne measurements of water-leaving reflectance for the problem area, a qualitative analysis of the image can help to understand whether the problem is related to an atmospheric correction problem or not. The AOT shown in Fig. 3 is low and looks normal for those pixels. However, the aerosol epsilon factor (see Fig. 1) is as high as 1.2 in the central southern North Sea and increases to 1.3 to the north of the Scheldt Estuary, closely coinciding with the negative reflectance area. Moreover the area of negative reflectance increases as wavelength decreases from band 4 to 1. Therefore one potential cause of this anomaly is the selection of aerosols that have too high aerosol epsilon (equivalently Angstrom exponent). A similar problem can also be seen in the Channel in the image of 16.06.2003 (see Fig. 5). The negative reflectance has a significant effect on in-water products such as Algal1, Algal2, YS and TSM. The standard algorithms cannot compute water constituents reasonably for those negative pixels. Further investigation of parameters in the atmospheric correction algorithm such as aerosol reflectance spectra is recommended.

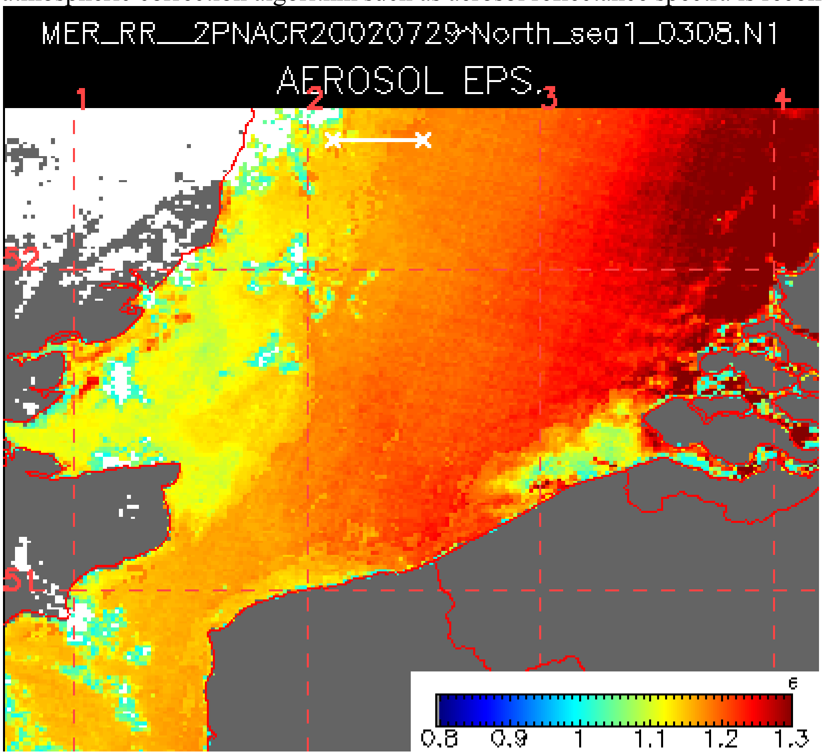

Figure 1. Aerosol epsilon factor for the 29.07.2002 image.

-Discontinuity arising from switching atmospheric correction algorithms

Atmospheric correction for case1 waters has been well established, in general. However for atmospheric correction in turbid waters, the water-leaving reflectance in the NIR must be estimated **[9, 10].** For MERIS the approach of switching on/off a case2S NIR correction has been adopted for waters of highly varying turbidity. This has the drawback that such switching can generate unrealistic fronts or noisy patterns. Such a front is shown as 'Case2S boundary' in the 29.07.2002 image (Fig. 3). It is possible that, in reality, a sharp reflectance front may occur. However, this front is sharper at blue bands than green-red or NIR bands, which seems wrong considering that the case2S boundary is determined by TSM estimation which is estimated by longer wavelength. The front coincides with a jump in the aerosol epsilon, which can be seen in both the image (Fig. 1) and the line data along a line crossing the front (Fig. 2). Such a discontinuity is also seen in the algal2 image in the case of the 29.07.2002 image. One solution for this problem could be to reduce the TSM threshold for case2S flagging or to process the entire image with the case2S atmospheric correction provided that NIR reflectance estimation works reasonably for case 1 waters.

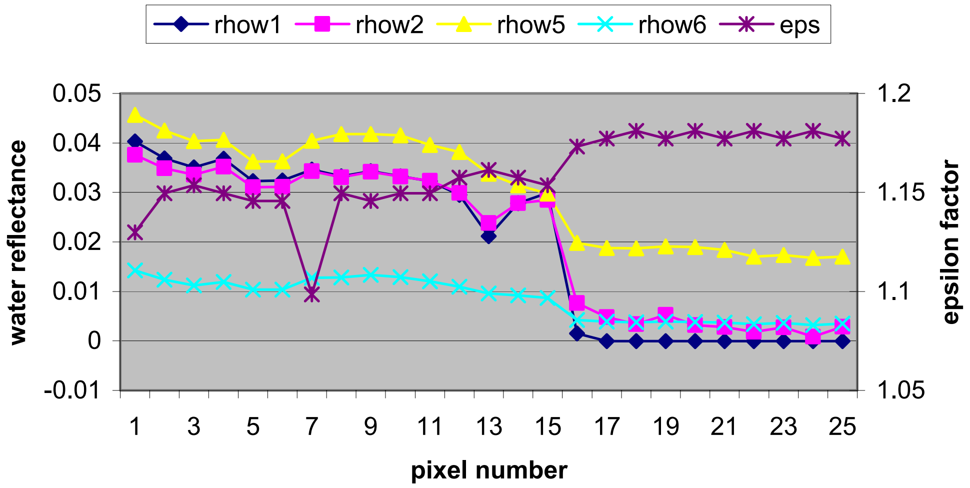

Figure 2. MERIS water reflectance and epsilon factor along a line of longitude from 2.11 to 2.50°E and latitude 52.4°N of the 29.07.2002 image. The line is shown as a white line in Fig. 1 and the left middle panel of Fig. 3. Rhow1, rhow2, rhow5 and rhow6 are water-leaving reflectance at bands 1, 2, 5 and 6, respectively and eps is epsilon factor. Case2S flag was raised for pixels 1 to 15.

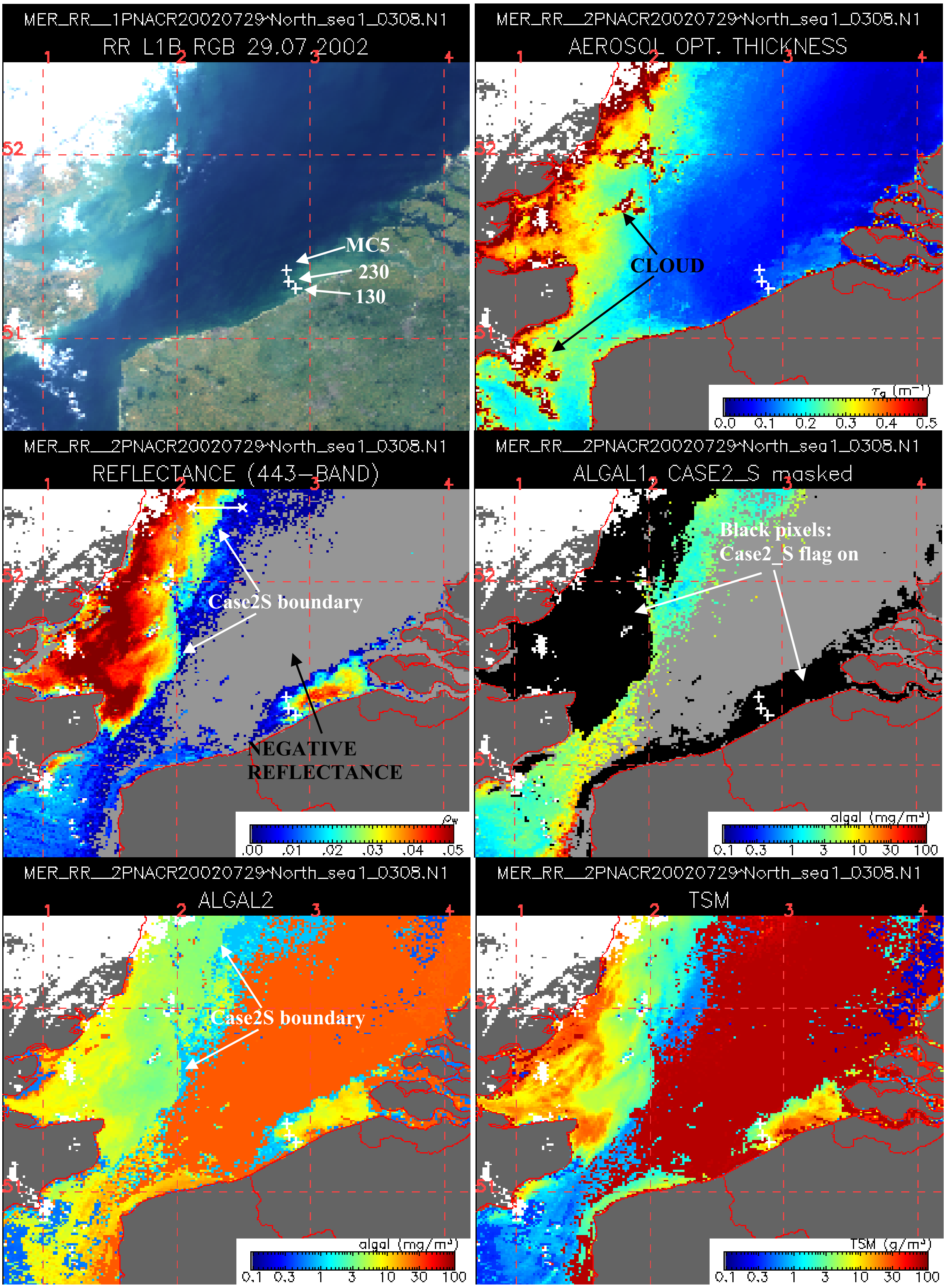

Figure 3. MERIS imagery for the Southern North Sea on 29.7.2002: Level 1B composite, AOT, water-leaving reflectance at 443nm, Algal1 with case 2S flag masked, Algal2, total suspended matter (see text for further details).

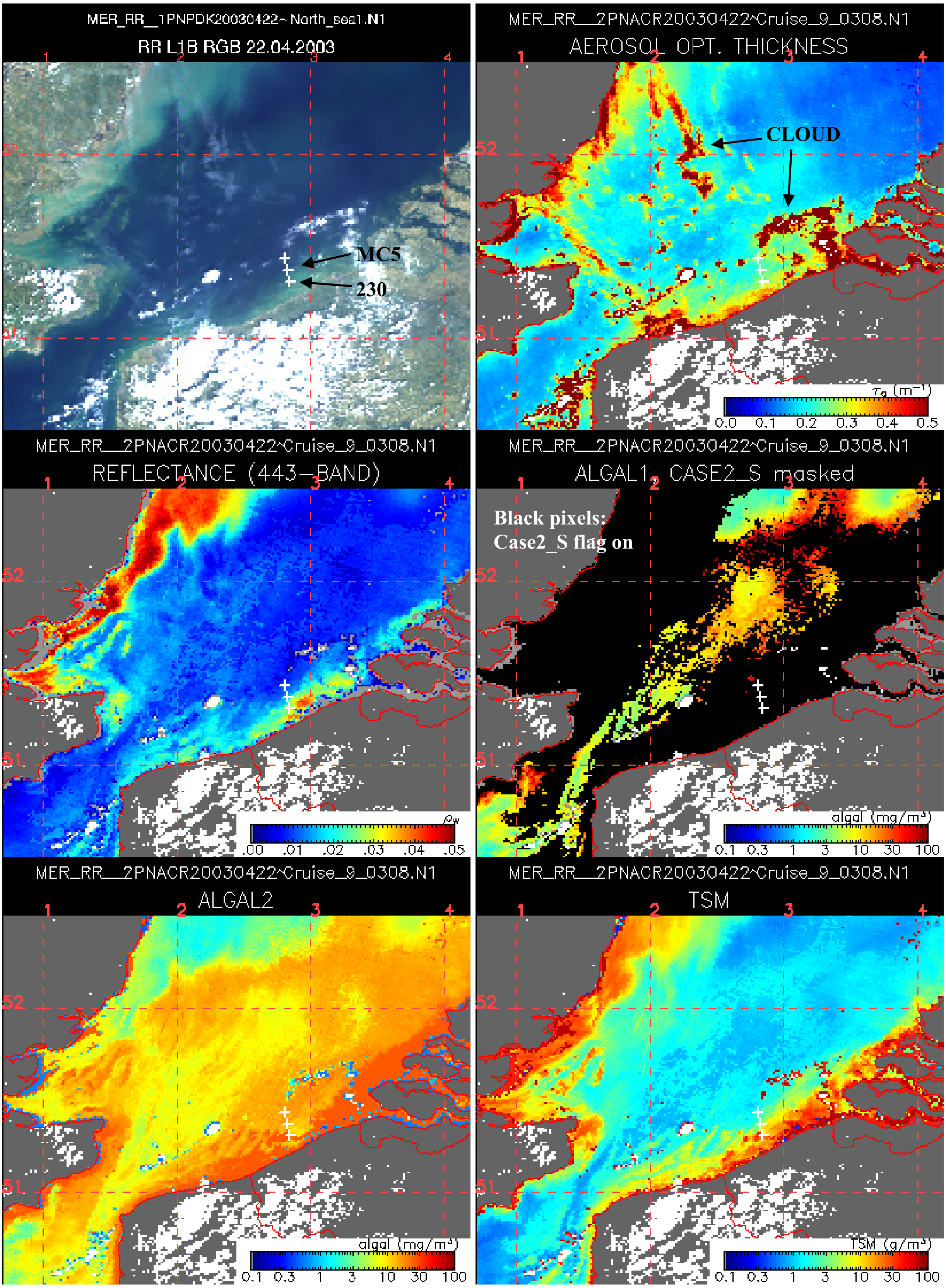

Figure 4. MERIS imagery for the Southern North Sea on 22.4.2003: Level 1B composite, AOT, water-leaving reflectance at 443nm, Algal1 with case 2S flag masked, Algal2, total suspended matter (see text for further details).

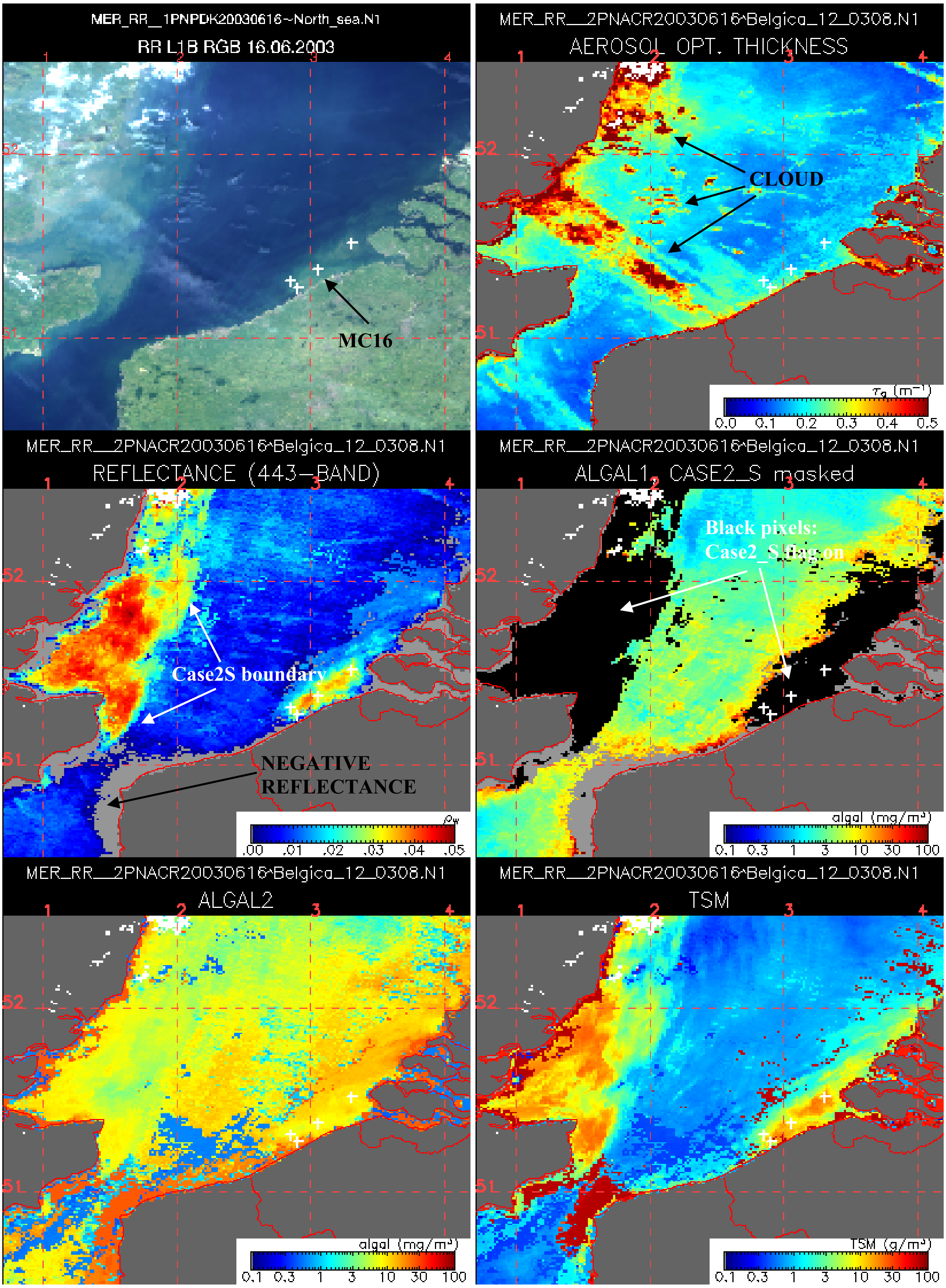

Figure 5. MERIS imagery for the Southern North Sea on 16.6.2003: Level 1B composite, AOT, water-leaving reflectance at 443nm, Algal1 with case 2S flag masked, Algal2, total suspended matter (see text for further details).

4.3 Match-up data of 2002 and 2003

- 29.7.2002 match-up

Radiometric measurements and water sampling were made at three stations: 130 (51° 16.25'N, 2° 54.30'E), 230 (51° 18.50'N, 2° 51.00'E) and MC5 (51° 20.38'N, 2° 50.38'E). These stations are indicated as crosses in Fig. 3 in a transect extending 20km offshore from Oostende. The 29.7.2002 measurements are compared with the values of the MERIS products in Fig. 6 and Table 3.

For the nearest neighbour pixels corresponding to in-situ measurements, the Algal1 confidence flag and science flags of case2_S and medium glint are raised for all three stations. This indicates that the Algal1 product is not reliable in the three stations, which is reasonable considering that these sites are in turbid case 2 waters. Turbid water atmospheric correction was applied and glint effect is moderate and corrected. Besides those common flags, the confidence flag for YS/TSM was raised at stations 130 and MC5.

The MERIS processing was updated several times in 2003. Compared with last year's processing version ('200210'), the latest version ('200308') brought several important changes in turbid water atmospheric correction including new implementation of atmospheric correction over bright waters, new coastal aerosol models with a stronger spectral slope included, a coastal flag based on bathymetry included in Case2S atmospheric correction (influencing aerosol type selection) and aerosol climatology enabled to switch-off dust-like aerosols north of 51°N [Email from Data Distribution Operator of 12.08.2003]. MUMM received the different processing versions for 2002 match-ups. Fig. 6 illustrates the differences between the two MERIS processing versions. The data of version '200210' are on left column and the data of '200308' on right column. There are significant differences between the two products in spectral slope and magnitude of water-leaving reflectance. For the spectral slope in blue-green bands, the '200308' processing gives a better comparison with the measurements than the '200210' processing. This might indicate that a more appropriate aerosol model was selected. On the other hand, no consistent direction of change can be seen for the magnitude of water-leaving reflectance between the two processors. For stations 130 and MC5, some over-correction of atmospheric effect can be seen. At these stations, the MERIS water-leaving reflectance at 412nm is very low or slightly negative (note that MERIS L2 products put 0 for negative reflectance). Consequently for these match-ups, Algal2 and TSM are not reliable in the '200308' processing. In fact, the '200210' processing gives a better comparison for these match-ups. For station 130, the MERIS Algal2 and TSM are 2.39 μg/l and 4.42 mg/m^3 whereas seaborne measurements give 5.33 μg/l and 15.07 mg/m^3, respectively. For station MC5 where the value of water-leaving reflectance at 412nm is zero, the MERIS Algal2 and TSM is 0.947 μg/l and 67.1 mg/m^3 whereas seaborne measurements give 2.82 μg/l (see the note below the Table 3 regarding this value) and 5.67 mg/m^3, respectively. Further improvement in either the atmospheric correction algorithm or the in-water algorithm for Algal2 and TSM is suggested at this point. For the data of station 230 where reflectance comparison is excellent, the MERIS Algal2 (8.81 μg/l) and TSM (5.70 mg/m^3) agree well with the seaborne measurements (8.29 μg/l and 8.67 mg/m^3 for Algal2 and TSM respectively).

- the 2003 match-ups

For the 2003 match-ups, concurrent measurements using the two independent systems, TriOS and SIMBADA are available. TriOS reflectance is shown as red dashed curves in Fig. 7. These concurrent measurements are important in establishing confidence in the seaborne measurements, since the two radiometers measure reflectance in a quite different way. For our match-up data, the two measurements coincide within about 20% over visible wavelengths except for 560 nm at station MC16, 16.06.2003. This gives us confidence in the in-situ radiometric measurements.

Measurements match-ups were made at three stations for the 22.4.2003 image: station 230(51° 18.49'N, 2° 50.89'E), station MC5 (51° 22.19'N, 2° 49.67'E) and station 330 (51° 25.87'N, 2° 48.40'E). These stations are indicated as white crosses in Fig. 4. The data from station 330 is not a match-up because of the time difference between the seaborne measurement and the satellite overpass. For the two match-up stations, confidence flags for Algal1, YS/TSM, Algal2, and science flags for case2_S, case2_anom, medium glint were raised. Figure 7 shows that MERIS reflectance for these stations is higher than seaborne reflectance over the whole spectral range although a slightly larger difference is observed at 412nm. The SIMBADA and TriOS measurements agree very well for these match-ups. The differences are thought to be related to atmospheric correction. This will be discussed further in the next section. The standard deviation of 3x3 pixels is smaller at station MC5 than at station 230. This implies the spatial variability of reflectance is larger near-shore, presumably because of suspended matter variability, assuming that the atmosphere is homogeneous at this spatial scale. The station MC16 of 16.6.2003 is located at (51° 22.27'N, 3° 3.49'E) and is shown as a cross in Fig. 5. The level 2 flags raised at the match-up pixel are confidence flags for Algal1, and science flags for case2_S, case2_anom. Comparison of MERIS reflectance and TriOS reflectance shows agreement within 10 % except at wavelengths 412nm and 443nm.

For the three match-ups of 2003, MERIS Algal2 and TSM differ by 2 or 3 times from the in-situ data. The difference in Algal2 and TSM seems larger than expected considering agreement in reflectance spectra, although any conclusion from a few match-ups is uncertain.

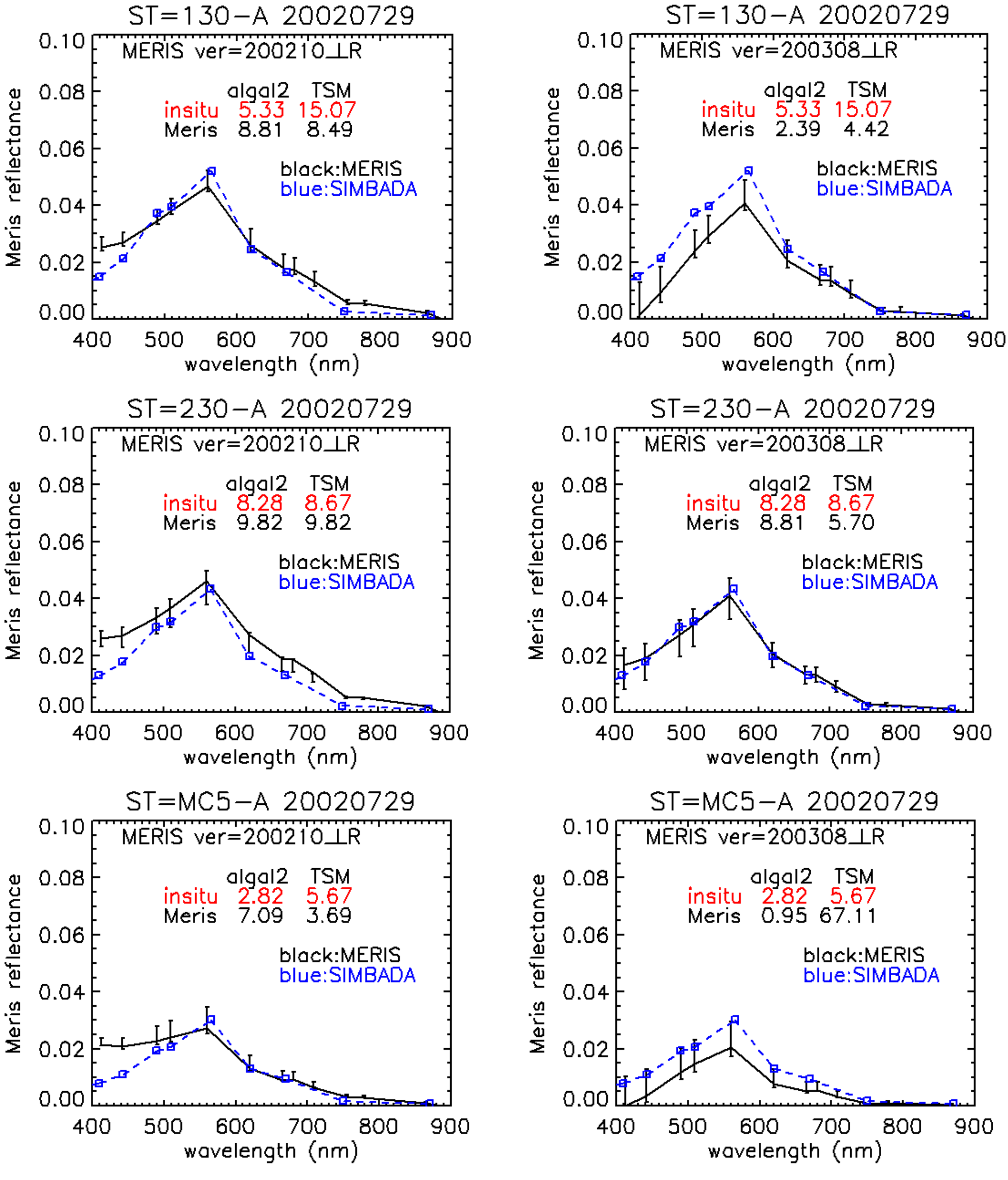

Figure 6. Comparison of MERIS water-leaving reflectance with seaborne measurements for three match-ups of 29.7.2002. Stations 130, 230 and MC5 are shown in upper, middle and lower row, respectively. Two different MERIS versions are shown: ‘200210’ (left column) and ‘200308’ (right column). The MERIS reflectance is shown as black solid lines with error bars indicating the standard deviation of the surrounding 3x3 pixel block. The SIMBADA measurements are shown as blue dashed lines with square symbols. Comparison of Algal2 and TSM are also shown. (See text for details)

Table 3. Match-up comparisons for stations 130, 230 and MC5 of 29.07.2002

Station 130, 29.07.2002	MERIS [standard deviation]	In situ
Time (UTC)	10:30	09:35
Reflectance(412nm)	0.0015 [0.0075]	0.0155
Reflectance(443nm)	0.0093 [0.0061]	0.0213
Reflectance(560nm)	0.0407 [0.0053]	0.0509
Reflectance(665nm)	0.0136 [0.0036]	0.0173
Reflectance(778nm)	0.0027 [0.0009]	0.0024
Reflectance(865nm)	0.0011 [0.0004]	0.0015
Algal pigment 2 (μg/l)	2.39 [2.38]	5.328
Total suspended matter (mg/m^3)	4.42 [6.31]	15.07
Aerosol optical thickness at 865nm	0.082 [0.012]	0.147

Station 230, 29.07.2002	MERIS [standard deviation]	In situ
Time (UTC)	10:30	10:07
Reflectance(412nm)	0.0166 [0.0071]	0.0132
Reflectance(443nm)	0.0188 [0.0063]	0.0176
Reflectance(560nm)	0.0411 [0.0072]	0.0422
Reflectance(665nm)	0.0134 [0.0030]	0.0137
Reflectance(778nm)	0.0027 [0.0006]	0.0019
Reflectance(865nm)	0.0011 [0.0002]	0.0011
Algal pigment 2 (μg/l)	8.81 [1.07]	8.29
Total suspended matter (mg/m^3)	5.70 [1.76]	8.67
Aerosol optical thickness at 865nm	0.088 [0.012]	0.139

Station MC5, 29.7.2002	MERIS [standard deviation]	In situ
Time (UTC)	10:30	11:35
Reflectance(412nm)	0.0000 [0.0063]	0.0082
Reflectance(443nm)	0.0034 [0.0057]	0.0109
Reflectance(560nm)	0.0204 [0.0061]	0.0293
Reflectance(665nm)	0.0051 [0.0020]	0.0098
Reflectance(778nm)	0.0009 [0.0004]	0.0014
Reflectance(865nm)	0.0004 [0.0002]	0.0007
Algal pigment 2 (μg/l)	0.947 [1.09]	2.818*
Total suspended matter (mg/m^3)	67.1 [280]	5.67
Aerosol optical thickness at 865nm	0.069 [0.011]	0.144

The in situ aerosol optical thickness has been retrieved from SIMBADA measurements.

The in situ reflectance values shown here are SIMBADA measurements which are linearly interpolated at MERIS wavelengths. SIMBADA measures reflectance at wavelengths 350, 380, 410, 443, 490, 510, 565, 620, 670, 750 and 870nm.

*For this sample, this value is doubtful as a representative value. Another sample (by a GF/C filter, which does not correspond to the MAVT protocol) taken at 3m depth gave 7.53m μg/l.

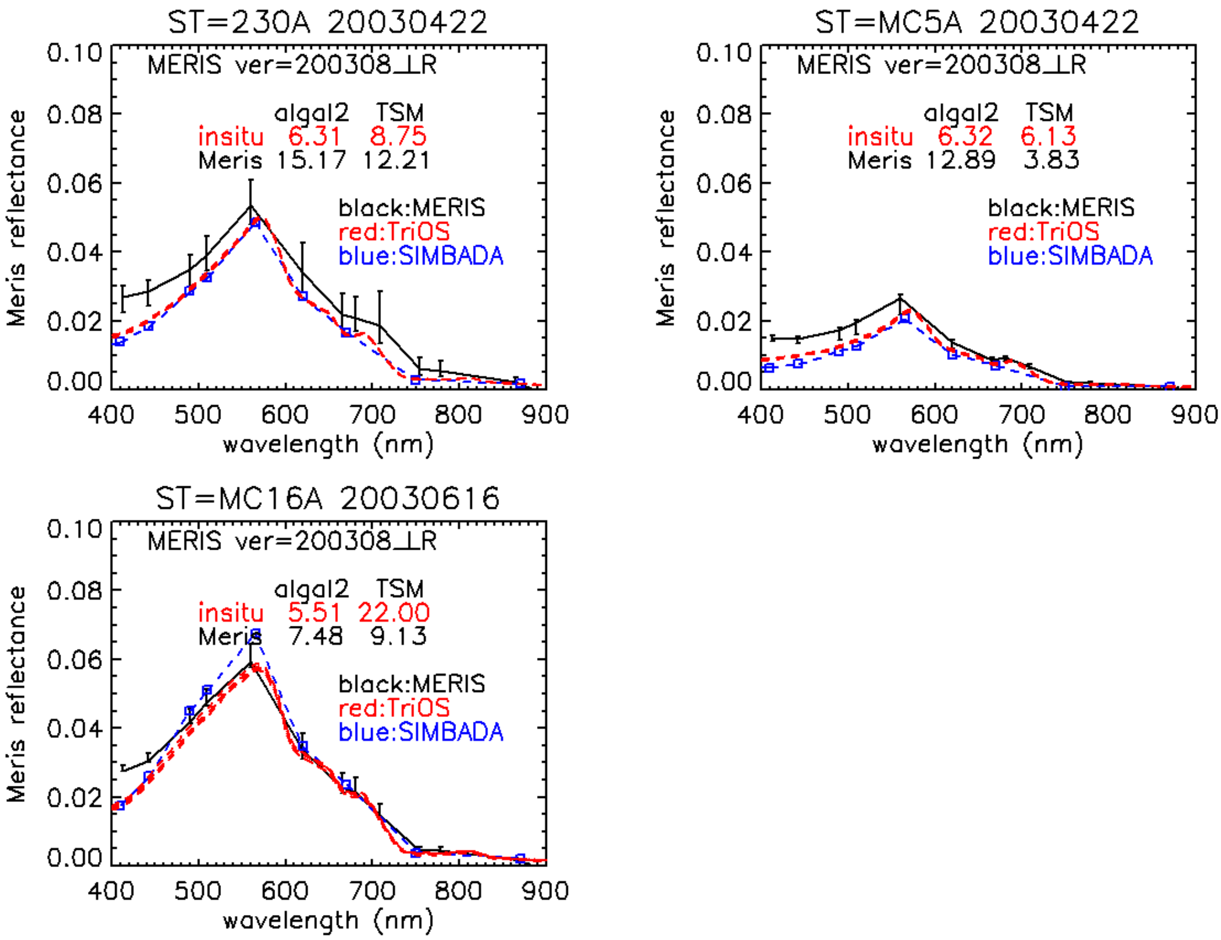

Figure 7. Same as Fig. 6, but for the match-up data of 22.4.2003 and 16.6.2003. The upper two panels show the data of station 230 (left) and station MC5 (right) of 22.4.2003. The lower panel shows the data of station MC16 measured on 16.6.2003. The MERIS processing version is '200308'. The five best TriOS scans are shown as red dashed lines.

Table 4. Match-up comparisons for stations 230 and MC5 of 22.04.2003 (upper) and MC16 of 16.06.2003

Station 230, 22.4.2003	MERIS [standard deviation]	In situ (SIMBADA, TRIOS)
Time (UTC)	10:39	10:53
Reflectance(412nm)	0.0268 [0.0037]	0.0142, 0.0165
Reflectance(443nm)	0.0287 [0.0037]	0.0183, 0.0202
Reflectance(560nm)	0.0536 [0.0064]	0.0470, 0.0477
Reflectance(665nm)	0.0217 [0.0051]	0.0177, 0.0170
Reflectance(778nm)	0.0056 [0.0023]	0.0026, 0.0028
Reflectance(865nm)	0.0023 [0.0010]	0.0017, 0.0017
Algal pigment 2 (μg/l)	15.17 [4.85]	6.31
Total suspended matter (mg/m^3)	12.21 [6.76]	8.75
Aerosol optical thickness at 865nm	0.277 [0.027]	0.216

Station MC5, 22.4.2003	MERIS [standard deviation]	In situ (SIMBADA, TRIOS)
Time (UTC)	10:39	11:45
Reflectance(412nm)	0.0151 [0.0008]	0.0064, 0.0090
Reflectance(443nm)	0.0148 [0.0010]	0.0074, 0.0099
Reflectance(560nm)	0.0267 [0.0029]	0.0199, 0.0214
Reflectance(665nm)	0.0088 [0.0009]	0.0073, 0.0075

Reflectance(778nm)	0.0020 [0.0002]	0.0009, 0.0014
Reflectance(865nm)	0.0008 [0.0001]	0.0009, 0.0009
Algal pigment 2 (µg/l)	12.89 [0.81]	6.33
Total suspended matter (mg/m^3)	3.83 [0.65]	6.13
Aerosol optical thickness at 865nm	0.239[0.008]	0.216

Station MC16, 16.6.2003	MERIS [standard deviation]	In situ (SIMBADA, TRIOS)
Time (UTC)	10:10	10:18
Reflectance(412nm)	0.0274 [0.0009]	0.0182, 0.0184
Reflectance(443nm)	0.0304 [0.0011]	0.0260, 0.0249
Reflectance(560nm)	0.0594 [0.0034]	0.0659, 0.0566
Reflectance(665nm)	0.0228 [0.0030]	0.0248, 0.0222
Reflectance(778nm)	0.0045 [0.0007]	0.0033, 0.0034
Reflectance(865nm)	0.0019 [0.0003]	0.0022, 0.0019
Algal pigment 2 (µg/l)	7.09 [0.40]	5.51
Total suspended matter (mg/m^3)	9.13 [1.09]	22.0
Aerosol optical thickness at 865nm	0.170 [0.022]	0.175

The in situ aerosol optical thickness has been retrieved from SIMBADA measurements.
The in situ reflectance values shown here are SIMBADA measurements which are linearly interpolated at MERIS wavelengths. SIMBADA measures reflectance at wavelengths 350, 380, 410, 443, 490, 510, 565, 620, 670, 750 and 870nm.

5. DISCUSSION

In order to see the overall comparison, MERIS water-leaving reflectance data are plotted against seaborne (SIMBADA and TriOS if available) measurements, putting together all bands from the six match-up stations in Fig. 8. The first six bands are plotted on the left and the other bands on the right. The regression line is close to the one-to-one line, meaning that MERIS reflectance has no systematic bias compared with the measurements. However, since the number of data may not be large enough to be confident of this result, it is hoped that this analysis will be extended to a larger dataset in the future. What is clearly seen is a larger relative difference in the blue and NIR bands than the intermediate bands. The blue band reflectance can be less accurate because the aerosol radiance correction is extrapolated from the NIR bands, which are far from the blue, and atmospheric correction for Rayleigh effect involves greater relative errors. The NIR reflectance is not expected to be highly accurate due to the weakness of water reflectance and difficulty in separating the satellite signal into water reflectance and aerosol reflectance.

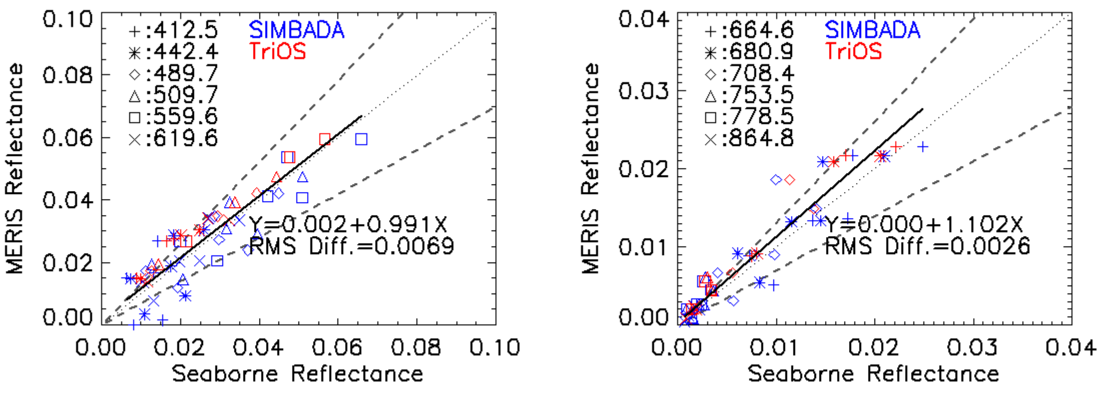

Figure 8. Scatter plots of MERIS reflectance against seaborne reflectance. Left for 412nm to 619nm bands and right for 664nm to 864 nm bands. Different symbols indicate different bands in each plot. The SIMBADA reflectance is shown as blue symbols and TriOS reflectance as red symbols. The dashed lines indicate ±30 % deviation from the 1:1 line.

In the previous section, we showed some differences between MERIS and seaborne measurements. The question now arises of whether the difference in water reflectance is related to atmospheric parameters such as AOT and epsilon parameter (NIR aerosol reflectance ratio).

For atmospheric correction, the path radiance and the surface reflected radiance are subtracted from the top-of-the-atmosphere radiance. In case of turbid waters, the NIR radiance from the water is also corrected before this. Surface reflected radiance should be well corrected for the match-up stations discussed here as the sea-surface conditions were good (wind speed less than 5m/s) and cloud coverage was low. The Rayleigh radiance, in general, can be estimated with high accuracy. Therefore, the main uncertainty is thought to be aerosol radiance (including Rayleigh-aerosol interaction). Usually two parameters, i.e. AOT and epsilon (alternatively, angstrom exponent) are used to characterise the aerosol optical properties. It is worth noting that aerosol absorption in the blue may not be indicated by these two parameters. Apart from this point, it seems that the match-up spectra difference should be related to the two aerosol products. Unfortunately the comparison of the aerosol epsilon product does not give good results **[11].** In case2S atmospheric correction, the imposed ratio of water reflectance at 778nm and 865nm influences the aerosol epsilon parameter. Thus, the higher the water-leaving reflectance ratio used, the lower the resulting epsilon parameter, and vice versa.
In Table 5, AOT and NIR reflectance ratios, $\rho_w(778)/\rho_w(865)$, are summarised for all match-ups. In the last two columns, match-up comparison of visible reflectance of 412 to 708nm is indicated. Spectral slope was in general good agreement, as stated earlier, but the absolute value is not. It is expected that water reflectance (in green-red bands) is overestimated if AOT is underestimated and vice versa. The 29.7.2002 data actually show the opposite: low water reflectance corresponds to low AOT. There is no obvious explanation for this at this moment.
Also the MERIS blue-green reflectance is expected to be underestimated if epsilon is overestimated (i.e. the MERIS NIR water reflectance ratio is overestimated). This is neither the case with our match-ups: the MERIS NIR water reflectance ratio is always higher than seaborne measurements. Note that both SIMDADA and TriOS show NIR ratios smaller than 2.0 while MERIS shows values higher than 2.3. This ratio of MERIS NIR reflectance seems too high compared with the ATBD **[10]** or previous work based on approximation by the pure water absorption ratio **[9].** This should be further studied and clarified in the future.

Table 5. Comparison of AOT, NIR reflectance ratio and visible-band (412 - 708nm) reflectance for match-up data

Date	Station	AOT		$\rho_w(778)/\rho_w(865)$		Visible-band reflectance: agreement in in-situ/MERIS	
		SIMBADA	MERIS	SIMBADA(TriOS)	MERIS	Slope	Magnitude
29.7.2002	130	0.147	0.082	1.62	2.32	Good	Low
29.7.2002	230	0.139	0.088	1.75	2.32	Good	OK
29.7.2002	MC5	0.144	0.069	1.91	2.36	Good	Low
22.4.2003	230	0.216	0.277	1.48 (1.69)	2.33	Good	High
22.4.2003	MC5	0.216	0.239	1.04 (1.62)	2.39	Good	High
06.6.2003	MC16	0.174	0.170	1.51 (1.84)	2.31	OK	OK

Slope: agreement of the spectral slope of water-leaving reflectance in the visible bands
Magnitude: MERIS reflectance of visible bands with respect to in situ reflectance

In order to assess the glint effect, figure 9 shows a scatter plot similar to Fig. 8 but for match-ups with the high-glint flag raised. Those stations are 130 of 19.7.2002, 230 and MC4 of 10.7.2003, and 130 of 05.8.2003. Except for the high-glint flag, all other conditions such as cloud coverage and wind speed are good. MERIS reflectance at bands 1 and 2 are shifted upward on the left panel and RMS differences are slightly higher in these match-ups than the best match-ups shown in Fig. 8. Since a significant part of MERIS scenes are affected by glint, some improvement and validation of glint correction would greatly increase the usability of MERIS data.

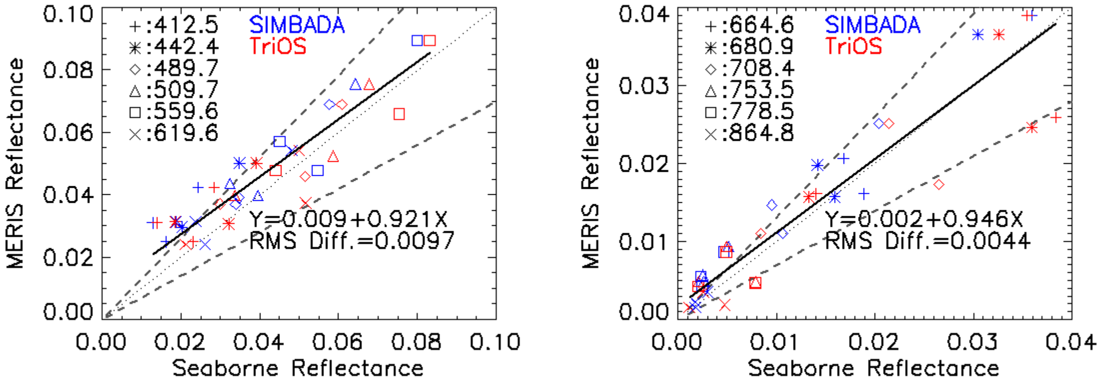

Figure 9. Scatter plots of MERIS reflectance against seaborne reflectance for the match-ups with high glint raised. Left for 412nm to 619nm bands and right for 664nm to 864 nm bands. Different symbols indicate different bands in each plot. The SIMBADA reflectance is shown as blue symbols and TriOS reflectance as red symbols. The dashed lines indicate ±30 % deviation from the 1:1 line.

6. CONCLUSIONS AND RECOMMENDATIONS

Three MERIS images of 29.07.2002, 22.04.2003 and 16.06.2003 for the Southern North Sea have been investigated with six corresponding match-up seaborne measurements in Belgian waters.

From the visual inspection of the images, a few problems have been identified:

- Many (partially) cloudy pixels have been classified as water pixels. The resulting images of water products look, thus, noisy and of poor quality. These pixels could be identified by an AOT threshold test or similar test in the atmospheric correction steps. If the PCD_1_13 flag is used for screening out these pixels, other pixels where this flag is raised for other reasons such as negative reflectance or high glint will be lost. A few suggestions can be made as candidate solutions including: to define another flag for this, to use the most significant bit of the reflectance digits for this flag, or to set null values for reflectance for the pixels.
- Patches of negative water-leaving reflectance in bands 1 and 2 have also been found in case 1 waters and, to a lesser extent, in case 2 waters. These can be related with an apparent overestimation of the epsilon (or Angstrom exponent). This results in unrealistic values of water parameters retrieved using the full spectra of water reflectance.
- Artificial fronts at the boundaries of case1 and case2S atmospheric correction were found. Such fronts in water parameters (clear in water-leaving reflectance at 412nm and 443nm, and Algal 2 in the case of the 29.07.2002 image) were associated with aerosol epsilon change, implying that these fronts are enhanced by switching of the atmospheric correction scheme. One solution for this problem, as recommended in the 2002 validation report **[1]**, could be to reduce the TSM threshold for case2S flagging or to process the entire image with case2S atmospheric correction provided that the NIR reflectance estimation works well for case 1 waters.

Concurrent measurements by the SIMBADA and TriOS radiometers are in agreement within about 20% difference over the 412 to 680nm range, which gives confidence in the seaborne reflectance data. MERIS reflectance agreed with seaborne reflectance with root-mean-square difference 0.007 in band 1 to 6 and 0.003 in band 7 and longer. This agreement is encouraging considering the difficulty in atmospheric correction over turbid waters. However, in relative terms, blue bands and red-NIR bands are less accurate than green bands. The difference in the visible part of spectrum could not be related to the difference in AOT or the ratio of NIR reflectance ($\rho_w(778)/\rho_w(865)$). In fact, the NIR ratio is clearly higher for MERIS products than for seaborne measurements.

On the basis of the limited data available and the restricted range of concentrations it is difficult to draw clear conclusions regarding the Algal2 and TSM products, though it is notable that no obvious problems have been detected unless water reflectance at blue bands is very small or negative.

It was found that MERIS water-leaving reflectance is slightly degraded in the case that the high-glint flag is raised. Further improvement and validation of the sun glint correction algorithm is recommended to increase the data usability, since a significant part of MERIS scenes is affected by sun glint.

7. ACKNOWLEDGEMENTS

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