OPTICAL REMOTE SENSING IN SUPPORT OF EUTROPHICATION MONITORING IN THE SOUTHERN NORTH SEA

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ABSTRACT

Spring mean and maximum chlorophyll *a* (chl *a*) concentrations are main factors to determine the eutrophication status of the Belgian waters as agreed within OSPAR in 2002. Other important assessment parameters to measure the degree of nutrient enrichment - the amounts of inorganic phosphate and nitrogen in winter - appeared to be above thresholds for most measurements performed in the period 1974-2002. As the standard *in situ* monitoring programme does not give a clear picture of the temporal and spatial distribution of chl *a*, it is logical to complement these measurements with optical remote sensing. However, chlorophyll concentrations derived from sensors such as SeaWiFS are unreliable in the Case 2 waters of this region because of high particulate and dissolved yellow substance absorption. Another important limitation of ocean colour sensors is the amount of useful images due to cloud cover. The combination of data from different ocean colour sensors in order to enable a better temporal coverage might be hampered by the different chlorophyll retrieval algorithms used. This study compares different global chl *a* algorithms (MODIS, SeaWiFS, MERIS) as well as a turbid water algorithm for the Southern North Sea. This is done by running the different algorithms on *in situ* reflectance spectra collected at 107 stations in the period 2001-2002 over the Southern North Sea and comparing them with *in situ* chl *a* concentrations, as well as by running the algorithms on a MERIS image of the 29th of July 2002. Based on this validation the accuracy of these products and their suitability for eutrophication monitoring in the Southern North Sea are assessed.

Keywords: ocean colour, chlorophyll a, eutrophication, North Sea.

INTRODUCTION

Eutrophication and OSPAR

It is relatively recent that anthropogenic eutrophication is perceived as a potential threat for the Southern North Sea. Increased runoff and discharge of nitrogen and phosphate from land since the fifties (1) have caused higher concentrations of these elements in rivers and coastal waters, reaching a maximum in the late seventies and early eighties (2). While consistent data sets on nutrient concentrations for the period 1950-2003 are not available to prove these trends, estimations and extrapolations of known nutrient concentrations allow the nutrient enrichment to be estimated.

The anthropogenic fraction of the total nutrient input in the Southern North Sea is estimated to be 30 % for phosphate and 40 % for nitrogen in 1985. In 1990, it was estimated that riverine inputs of phosphate and nitrogen were still 1.5 to 10 times and 3.5 to 12 times the natural range, respectively (2). The fact that the winter concentration of phosphorus decreased in the past decades, like proven for the period 1974-2002 in Belgian waters (3), suggests that phosphorus concentrations can be significantly influenced by human activities.

The high nutrient inflow through river discharge alters the N:P:Si (nitrogen:phosphorus:silicate) ratio in coastal waters, which can have an impact on phytoplankton species composition and therefore on the rest of the food web. The extent of the impact of anthropogenic eutrophication on phytoplankton concentrations is not known, since consistent and long time series of parameters - such as Chl *a* concentration - from the period before increased anthropogenic nutrient inflow are

lacking. Chl *a* concentrations for the period 1975-1991 in the Southern North Sea did not show a clear trend (2). In the Dutch Marsdiep area an increase in mean annual chl *a* levels has been observed since the mid-seventies (4), while the duration of the *Phaeocystis* blooms seems to have increased (5).

The North Sea states have decided, in the absence of good scientific information, to apply a precautionary principle and limit or if possible reduce this unnatural change of the coastal ecosystem. In the frame of the OSPAR convention, a set of parameters to determine the eutrophication status of different regions in the North Sea was established (Table 1). Classification in problem, potential problem or non-problem areas is determined by one or more parameters of Categories I and II and/or one or more parameters of Categories III and IV. For Belgian waters, parameters of Categories I and II were used, since the other categories were not applicable. The degree of nutrient enrichment is measured by the amount of inorganic phosphate and/or nitrogen in winter (DIN and DIP) and the direct effects of nutrient enrichment by maximum and mean chl *a* concentrations. Since most DIN and/or DIP measurements appear to be above thresholds in the period 1995-2000, the maximum and mean chl *a* concentrations and subsequent distribution patterns have been crucial in the classification of the Belgian waters (6).

Table 1: OSPAR Common Assessment Criteria for determination of Eutrophication Status

OSPAR Assessment parameters		
Category I	**Degree of Nutrient Enrichment**	
	1	Riverine total N and total P inputs and direct discharges (RID)
		Elevated inputs and/or increased trends
		(compared with previous years)
	2	Winter DIN- and/or DIP concentrations
		Elevated level(s) (concentration >50 % above salinity related and/or region specific background conc.)
	3	Increased winter N/P ratio (Redfield N/P = 16)
		Elevated cf. Redfield (>25)
Category II	**Direct Effects of Nutrient Enrichment (during growing season)**	
	1	Maximum and mean chl *a* concentration
		Elevated level (defined as concentration > 50 % above spatial (offshore) / historical background conc.)
	2	Region/area specific phytoplankton indicator species
		Elevated levels (and increased duration)
	3	Macrophytes including macroalgae (region specific)
		Shift from long-lived to short-lived nuisance species (e.g. *Ulva*)
Category III	**Indirect Effects of Nutrient Enrichment (during growing season)**	
	1	Degree of oxygen deficiency
		Decreased levels (< 2 mg/l: acute toxicity; 2 - 6 mg/l: deficiency)
	2	Changes/kills in Zoobenthos and fish kills
		Kills (in relation to oxygen deficiency and/or toxic algae) Long term changes in zoobenthos biomass and species composition
	3	Organic Carbon/Organic Matter Elevated levels (in relation to III.1) (relevant in sedimentation areas)
Category IV	**Other Possible Effects of Nutrient Enrichment (during growing season)**	
	1	Algal toxins (DSP/PSP mussel infection events)
		Incidence (related to II.2)

Ocean colour sensors

The availability of ocean colour data via remote sensing increased dramatically in 1996 and there are now eight sensors available for which a well-documented chlorophyll product exists: MOS-IRS, SeaWiFS, MODIS-Terra, OSMI, MERIS, MODIS-Aqua, ADEOS-GLI, and POLDER-2 (in chronological order of launching). The use of these standard chlorophyll products for eutrophication monitoring in the Southern North Sea is not straightforward as they are based on algorithms designed for use at global scale and particularly for open ocean waters. The algorithms are likely to be less accurate at regional scales than those developed for particular regions or bio-optical conditions (7).

Chlorophyll concentrations obtained from SeaWiFS and MODIS are based on a blue/green ratio (e.g.(8)) that allows the chl *a* absorption peak at 440 ~ 443 nm to be detected. This ratio is valid in Case 1 waters, but is not suitable for the waters of the Southern North Sea that are mainly Case 2. The higher amounts of suspended matter and especially of yellow substance can make it impossible to detect the contribution of chl *a* absorption in the blue range reflectance (Figure 1). An alternative is using a red/near infrared (NIR) ratio to single out the chl *a* absorption peak at 675 nm. This method works well if the water is turbid enough to emit a high reflectance signal in the NIR (9). Figure 1 illustrates the red bands available for some ocean colour sensors. MERIS has a NIR band at 709 nm that is better suited for use of a band ratio than for example the closest NIR band of MODIS (748 nm).
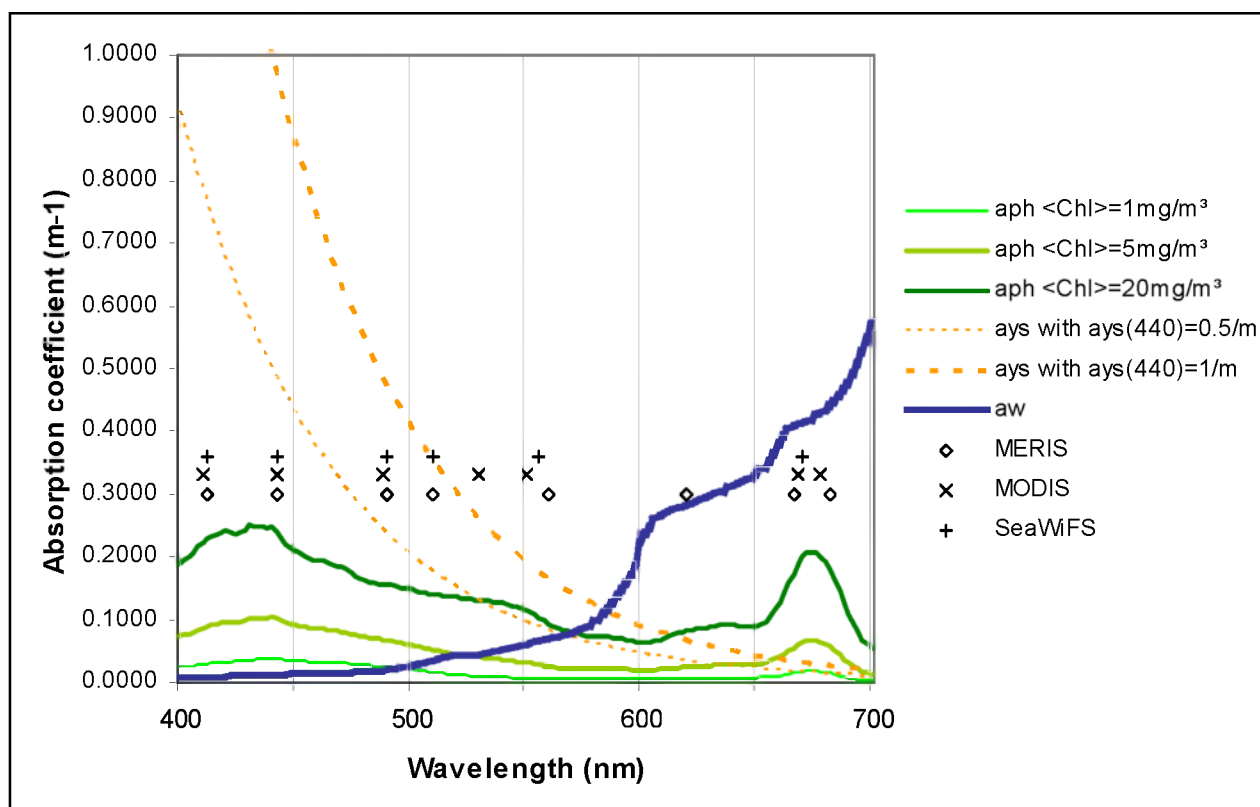

Figure 1: Absorption spectra for phytoplankton (aph) with chl a concentrations of 1 mg/m³, 5 mg/m³ and 20 mg/m³ based on (10,11), yellow substance (ays) with yellow substance absorption coefficients of 0.5 m⁻¹ and 1 m⁻¹ at 440 nm based on (12), and water (aw) based on (13). MERIS, MODIS, and SeaWiFS bands are indicated.

Another limitation to using ocean colour derived chlorophyll maps for the Southern North Sea is the limited number of useful images due to frequent cloud cover over the study area. As an example we consider the period October 1997 – December 2003 for which 267 cloud-free SeaWiFS images are available. This represents 6.2% of the potential number of images taking into account that SeaWiFS overpasses the study area approximately 1.9 times/day during daylight. A multi-sensor approach would allow for better temporal coverage - especially in detecting phytoplankton blooms -

but is hampered by the fact that all chlorophyll products are based on a different chl *a* retrieval al-gorithm, giving an inconsistent dataset.

The aim of this study is to compare different global chl *a* algorithms, as well as a turbid water algo-rithm for the Southern North Sea. This is done a) by running the algorithms on 107 *in situ* radiomet-ric spectra collected during the period 2001-2002 and comparing them with the *in situ* chl *a* con-centrations and, b) by running the algorithms on a MERIS image of the 29th of July 2002. The re-sults should give an indication of the differences between the chl *a* products and of the most ap-propriate algorithm for the Southern North Sea.

IN SITU DATA

All 107 *in situ* data samples were taken in the Case 2 waters of the Southern North Sea (Figure 2). Measurements were performed by the Management Unit of the North Sea Mathematical Models, Belgium (MUMM) from March to September for the years 2001 and 2002 under varying weather conditions.
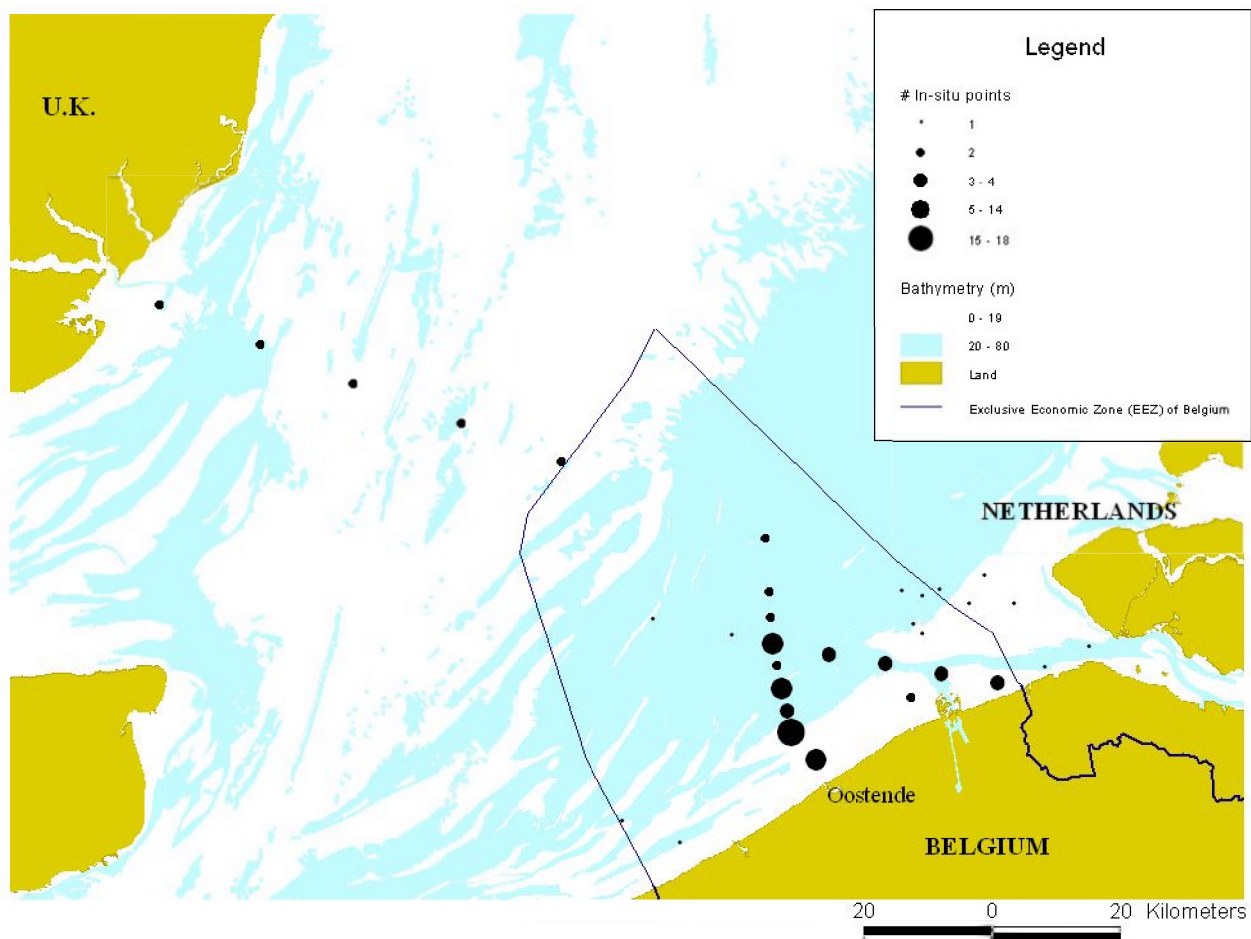

Figure 2: Position of 107 in situ measurements: radiometric spectra and chl a concentration

Radiometric data

The radiometric data set consists of above-water reflectance, ρ_w, as defined by:

$$\rho_w = \pi \frac{L_u^+ - \rho_{as}L_{sky}}{E_d^+}$$

$\rho_w(\lambda)$ is calculated from simultaneous above-water measurements of downwelling irradiance $E_d(\lambda)$, radiance from the water surface $L_u(\lambda)$, and sky radiance $L_{sky}(\lambda)$. This method corresponds to "Method 1" of (14). The air-sea interface reflection coefficient ρ_{as} is estimated as a function of wind speed W (m/s) derived from (15):

$$\rho_{as} = 0.026 + 0.0001\,W + 0.00006\,W^2$$

Measurements are performed with three TriOS RAMSES hyperspectral spectroradiometers, two measuring radiance (sea and sky) and one measuring downwelling irradiance. The instruments are mounted on a steel frame similar to that of (16). As shown in Figure 3, zenith angles of the radiance sensors are 40° (14). The frame is fixed to the prow of the ship, facing forwards to minimise ship shadow and reflection. The ship is manoeuvred on station to point the radiance sensors at a relative azimuth angle of 135° with respect to the sun. Simultaneous measurements with the three radiometers are taken every 10 s for about 10 minutes. The sensors measure the wavelength range 350-950 nm at a sampling interval of approximately 3.3 nm and spectral width of about 10 nm. Data are acquired with the MSDA software (v1.94 in 2001-2002) using the file recorder function and radiometrically calibrated using nominal calibration constants. Calibrated data for $E_d(\lambda)$, $L_u(\lambda)$ and $L_{sky}(\lambda)$ are interpolated to 2.5 nm intervals and exported to Excel for further processing. The sensors are calibrated in a MERIS Validation Team laboratory on a yearly basis after which the definitive spectra can be obtained.

A small number of bad reflectance spectra was removed from the data set resulting in a data set of 107 points. The rejected spectra contained negative values for at least one of the bands used in one of the algorithms, in practice usually the red and NIR bands. These rejected measurements were acquired during very windy conditions (wind speeds 9 – 19 m/s) resulting in a high correction factor for air-sea interface reflection or when the sun was completely covered by clouds and sky radiance was high in comparison to the radiance from the water surface. While the air-sea interface correction currently used could possibly be improved for such conditions, it is clear that the above-water reflectance measurement technique will not perform well for very high wave conditions.

Figure 3: Frame with 3 TriOS-RAMSES hyperspectral spectroradiometers installed on R/V Belgica

Chl *a* concentrations

The *in situ* chl *a* data set contains 107 values in the range 0.2 – 33.2 mg/m³ (Figure 4). Concentrations were measured with the high performance liquid chromatography (HPLC) method in the MUMM laboratory of Oostende. The original sampling method followed the MUMM protocol (17) designed to take chl *a* samples in the turbid Belgian coastal waters. In the period 2001-2002, the REVAMP protocol (18) was added to allow a better comparison with satellite data and international *in situ* data. The most important differences between the two protocols are the sampling depth, 3 m for the MUMM protocol and 0.5 m for the REVAMP protocol, and the type of filter that are GF/C

and GF/F, respectively. For this study, the REVAMP protocol was chosen when available. All samples were taken within the top 2 m of the surface and 60% of the filtrations were done with GF/C filters.
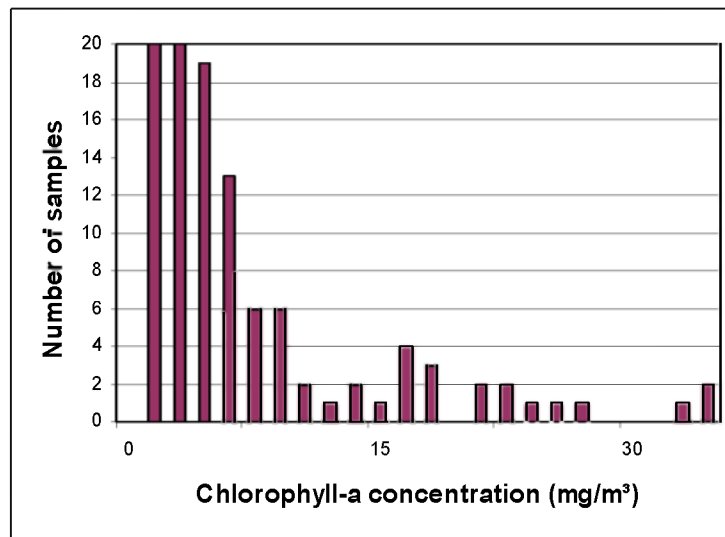

Figure 4: Frequency distribution of chl a concentration in Management Unit of the North Sea Mathematical Models (MUMM) 2001-2002 dataset

RESULTS

The performance of a global empirical chlorophyll algorithm (SeaWiFS OC4v4), a global Case 2 empirical chlorophyll algorithm (MODIS default), a global Case 2 neural network algorithm (MERIS), and a turbid water algorithm (called GR03) are evaluated. All these algorithms result in the concentration of chl *a*, excluding phaeopigment concentration.

MODIS default

The default, two-wavelength empirical algorithm to determine Case 2 chl *a* concentration (19) was used:

$$[Chla] = 10.0^{c_0 + c_1 \log \frac{R_{rs}(488)}{R_{rs}(551)} + c_2 \left[\log \frac{R_{rs}(488)}{R_{rs}(551)} \right]^2 + c_3 \left[\log \frac{R_{rs}(488)}{R_{rs}(551)} \right]^3}$$

(1)

with c_0, c_1, c_2 and c_3 empirically derived constants and R_{rs} the remote sensing reflectance

$(= \frac{\rho_w}{\pi})$.

The constants were derived for different bio-optical domains, i.e. for unpackaged-pigment domains, packaged-pigment domains, and transitional or global-average domains (19). The term "packaged" refers to low ratios of photoprotective pigments to chlorophyll and high self-shading, while "unpackaged" refers to high ratios and low self-shading. In the same study, nitrate-depletion temperatures indicate that the Southern North Sea is a transitional to packaged domain in winter and an unpackaged domain in summer[1]. The algorithm was therefore tested with constants determined for unpackaged-pigment domains, packaged-pigment domains, and for transitional or global domains.

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[1] the numerical filter applicable to satellite-derived data and designed to discriminate between the unpackaged- and packaged-pigment domains could not be used for the eutrophic waters of the Southern North Sea where the condition $R_{rs}(443)/R_{rs}(550) > 3$ is not applicable.

The MODIS specific Carder model – which is a four-wavelength semi-analytical model – was not applied as it cannot perform properly in waters with high concentrations of CDOM and chlorophyll. It is designed to return values only when modelled $a_{ph}(675)$ is less than 0.03 m^{-1}, which is equivalent to a chl a concentration of 1.5-2.0 mg/m^3 (19).

SeaWiFS: OC4v4

The Ocean Chlorophyll 4 maximum band ratio algorithm v. 4 (OC4v4) (20) was used:

$$[Chla] = 10.0^{\left(0.366 - 3.067 R_{4S} + 1.930 R_{4S}^2 + 0.649 R_{4S}^3 - 1.532 R_{4S}^4\right)}$$

with
$$R_{4S} = \log\left[Max\left(\frac{R_{rs}(443)}{R_{rs}(555)}, \frac{R_{rs}(490)}{R_{rs}(555)}, \frac{R_{rs}(510)}{R_{rs}(555)}\right)\right].$$

Gons adapted: GR03

A chl a retrieval algorithm was developed for turbid inland waters with chl a concentrations in the range 3-185 mg/m^3 by Gons (21). The algorithm was calibrated from the spectral subsurface irradiance reflectance (R^{0-}) determined from above-water shipboard measurements with a hand-held spectroradiometer PR650 with zenith 33°-78° (42° considered as optimal) and azimuthal angle relative to sun of 90°. The measurements were performed in inland waters of different regions of the world and North Sea coastal waters.

The algorithm was later adapted for the bands from MERIS satellite imagery and recalibrated with the original data set; it is termed hereafter GRR02 (22):

$$[Chla] = \frac{1}{a^*(664)}\left[\frac{R^{0-}(704)}{R^{0-}(664)}\left(a_W(704) + b_b\right) - a_W(664) - b_b^p\right]$$

with $a^*(664)$ a mean chl a specific absorption coefficient at 664 nm (0.0146 m^2/mg), $a_W(\lambda)$ the absorption coefficient of water at different wavelengths and p an empirical constant close to unity.

The backscatter b_b is estimated as:
$$b_b = \frac{R^{0-}(776) \cdot a_W(776)}{C - R^{0-}(776)}$$

with C a constant depending on incident light that is assumed to be 0.082Q (Q deduced from sun/sky conditions) for isotropic radiance. This algorithm was validated for various inland and coastal waters which resulted in a standard error of 9.2 mg/m^3 for 91 validation samples in the chl a concentration range 1-181 mg/m^3 (22).

For this study, the GRR02 algorithm was slightly adapted as follows:

1. Conversion from R^{0-} to ρ_W^{0+}

R^{0-} was converted to MERIS reflectance ρ_W (23):

$$\rho_W^{0+} = \frac{\pi \Re R^{0-}}{Q}$$

with the geometrical factor $\Re(\theta)$ representing all the air-sea interface effects. $\Re(\theta)$ was taken here equal to 0.53, though it could be refined to be function of wind speed and of internal reflectance of R^{0-} (24).

2. Adaptation to new MERIS bands

As the GRR02 algorithm was derived in the pre-launch period of MERIS based on nominal wavelengths, it was necessary to adapt it to the final wavelengths. Absorption coefficients of water were adapted to the MERIS bands 664.3 nm, 708.1 nm, and 778.2 nm. The data of (13) were used for

the water absorption coefficients and as they are determined with steps of 1 nm, the values for 664, 708, and 778 nm were used.

The resulting and newly adapted algorithm was called GR03:

$$[Chla] = \frac{1}{a^*(664.3)}\left[\frac{\rho^{0+}(708.1)}{\rho^{0+}(664.3)}\,(a_W(708) + b_b) - a_W(664) - b_b^p\right] \tag{2}$$

with the backscatter b_b defined as: $b_b = \dfrac{\rho^{0+}(778.2)\cdot a_W(778)}{0.173 - \rho^{0+}(778.2)}$

MERIS

The MERIS neural network algorithm designed for Case 2 waters (25) was only considered in the comparison of the algorithms for a MERIS image of 29 July 2002. The algal pigment Chl 2 as defined in the MERIS validation protocols (26) was used:

$$[Chla] = 26.212\cdot(a_{pig}(442))^{0.77135}$$

where a_{pig} is a model retrieval of the absorption of the bleachable fraction of the material which does not pass the filter during the filtration of all water particles, i.e. the difference between the absorption of the filter pad before and after bleaching. This optical definition provides an estimation of the chl a concentration as determined by the HPLC method.

RESULTS

Comparison with *in situ* reflectance data

The algorithms were run on the *in situ* reflectance spectra and compared with the *in situ* chl a concentrations. Results are shown in the scatter plots of Figure 5, using both linear and log-log scale. The scatter plot for the MODIS algorithm with constants derived for unpackaged pigment domains are not plotted, as they were very similar to results with the constants for a transitional or global-average (MODIS global) domain. Statistical results of the regression measured chl a vs. computed chl a are listed in Table 2. Invalid values (negative chl a values returned by the GR03 algorithm) were eliminated prior to plotting and statistical analysis.

Table 2: Statistical results of algorithm evaluations

Algorithm	Valid points	Regression with original values			Regression in log-log scale		
		R²	Intercept	Slope	R²	Intercept	Slope
GR03	96	0.779	0.735	0.829	0.415	0.113	0.701
GR03 with p	100	0.779	1.103	0.851	0.376	0.235	0.619
MODIS packaged	107	0.294	6.560	0.253	0.404	0.741	0.240
MODIS unpackaged	107	0.294	4.139	0.160	0.404	0.541	0.240
MODIS global	107	0.294	4.567	0.181	0.404	0.581	0.245
OC4v4	107	0.451	3.752	0.167	0.509	0.521	0.238

The correlation between algorithm results and in situ data is limited with regression coefficients of 0.4 to 0.5 in the log-log scale. However, GR03 seems to perform well when observing the data on a linear scale. This is explained by the fact that linear regressions are dominated by the highest value points. Indeed, both figures and statistics indicate that the GR03 algorithm allows a reasonable detection of high chl a concentrations, in contrast to the OC4v4 and the MODIS algorithms. This is consistent with the original concept of the model that was designed for turbid inland waters. However, GR03 shows poor performance for low chl a values, especially in the range <7 mg/m³.

This may be explained by the fact that the absorption of water and yellow substance are relatively larger compared to chl *a* absorption in the red and near infrared wavelengths (see Figure 1). A systematic overestimation of chl *a* in this lower concentration range as in (22) was not observed.
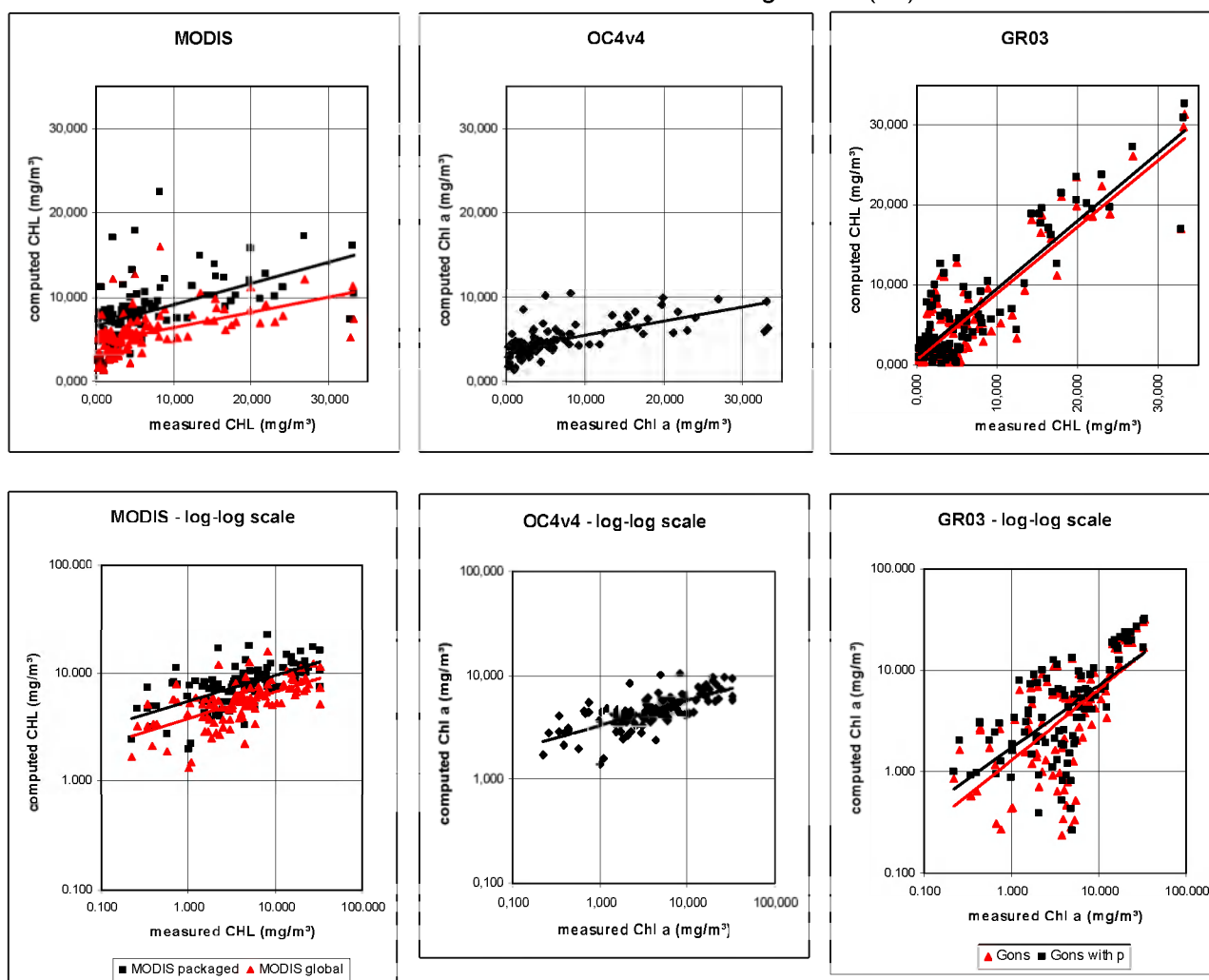

Figure 5: Comparison of in situ data with modelled chl a values

The OC4v4 and MODIS algorithms seem to allow better detection of chl *a* concentrations <7 mg/m^3 compared to GR03, although there is a tendency to overestimate chl *a* values <5 mg/m^3. One can notice that OC4v4 and to a lesser extent the MODIS algorithm always result in chlorophyll concentrations ranging from 2 to 10 mg/m^3, even for algal blooms with concentrations of up to 30 mg/m^3. The slope of 0.24 (log-log scale) illustrates this.

In addition it is noted that

- the use of the exponent p in GR03 which is purely empirical and does not correspond to a theoretical basis does not improve results for this data set. On the contrary, it can easily be left out of algorithm (2),

- the use of constants designed for the unpackaged-pigment, packaged-pigment or transitional or global domain in the MODIS algorithm (1) does not give a difference in the statistical results.

Threshold mapping algal blooms

One of the OSPAR criteria to determine the eutrophication status of an area is the maximum chl a concentration (Table 1). The use of the algorithms for detecting high chlorophyll events was tested with this respect. Using the same data set, a threshold mapping was applied with a chl *a* concen-

tration of 10 mg/m^3, a value based on time series of chl a concentration data collected for station 330 about 20 km offshore Oostende (27). The results in Table 3 confirm the strong capability of GR03 to detect high chl a concentrations and indicate that an OSPAR threshold mapping based on satellite data is very realistic.

Table 3: Detection rate of algal blooms by algorithms (in % of 22 events of algal blooms). Algal bloom is defined as an event with in situ chl a concentration >10 mg/m^3.

% detection by:	Algal Bloom
GR03	95.5
OC4v4	9.1
MODIS	31.8

Sunny and non-sunny *in situ* reflectance data

To investigate whether chl a retrieval is degraded here by inaccuracies in the reflectance measurements, the data set was split up into 'sunny' and 'non-sunny' measurements with 'sunny' defined as a clear sun or a variable sun with cloud cover less than 50%. Results for the sunny subset appeared to be much better compared to the non-sunny subset (Table 4, Figure 6). The differences could be explained by uncertainties involved in processing i.e. with regard to the air-sea interface correction or by the fact that calibration of the tested algorithms was performed with mainly sunny measurements, which can be different from calibration with all weather data. The latter is not the case for the GR03 algorithm, which was calibrated with all weather data.

Table 4: Statistical results of algorithm evaluations for the data set split up into 'sunny' (indicated in yellow) and 'non-sunny' measurements

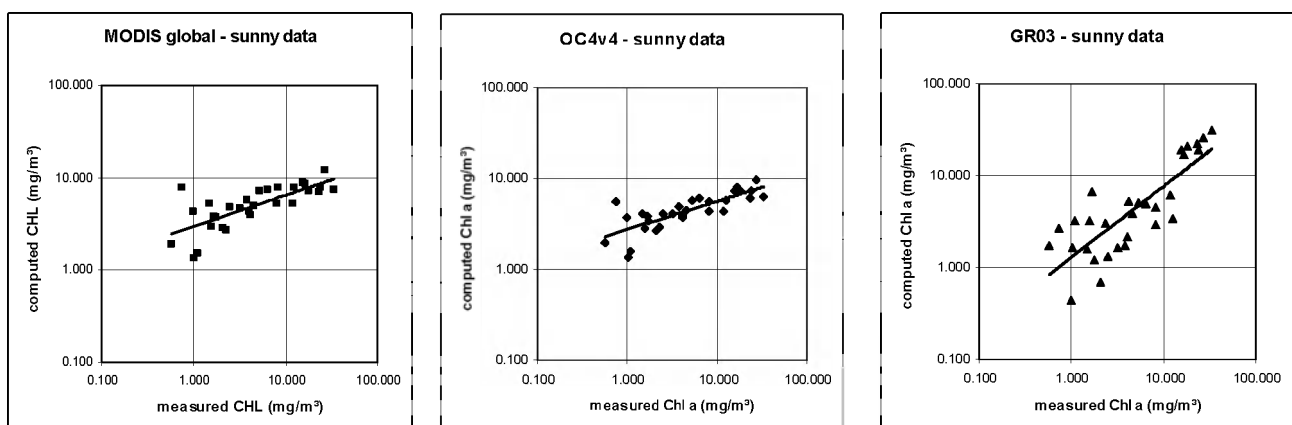| Algorithm	Valid points	Regression with original values			Regression in log-log scale		
		R²	Intercept	Slope	R²	Intercept	Slope
GR03	30	0.895	- 0.043	0.916	0.662	0.115	0.771
GR03	66	0.687	0.234	0.813	0.347	0.124	0.660
MODIS global	30	0.515	3.893	0.201	0.554	0.473	0.338
MODIS global	77	0.231	4.793	0.176	0.370	0.615	0.216
OC4v4	30	0.604	3.397	0.171	0.626	0.441	0.310
OC4v4	77	0.400	3.860	0.170	0.484	0.546	0.214

Figure 6: Comparison of 'sunny' in situ data with modelled chl a values

Comparison with satellite reflectance data

All algorithms were run on a MERIS Level 2 image of 29 July 2002, 10:30 UTC, and compared with the standard MERIS chl a product for Case 2 waters (25), referred to as Algal2. Figure 7 illustrates how different the results are for the four algorithms, which are all well documented and tested. It is not possible to state clearly which product is closest to reality because of the low amount of *in situ* validation measurements that can be taken within half an hour before/after the satellite pass. An additional problem of satellite product validation is that (mostly) single point data are compared with a pixel covering approximately 1 km x 1 km. However, for illustrational purposes, Table 5 shows the results for the three validation points sampled on the 29th of July.
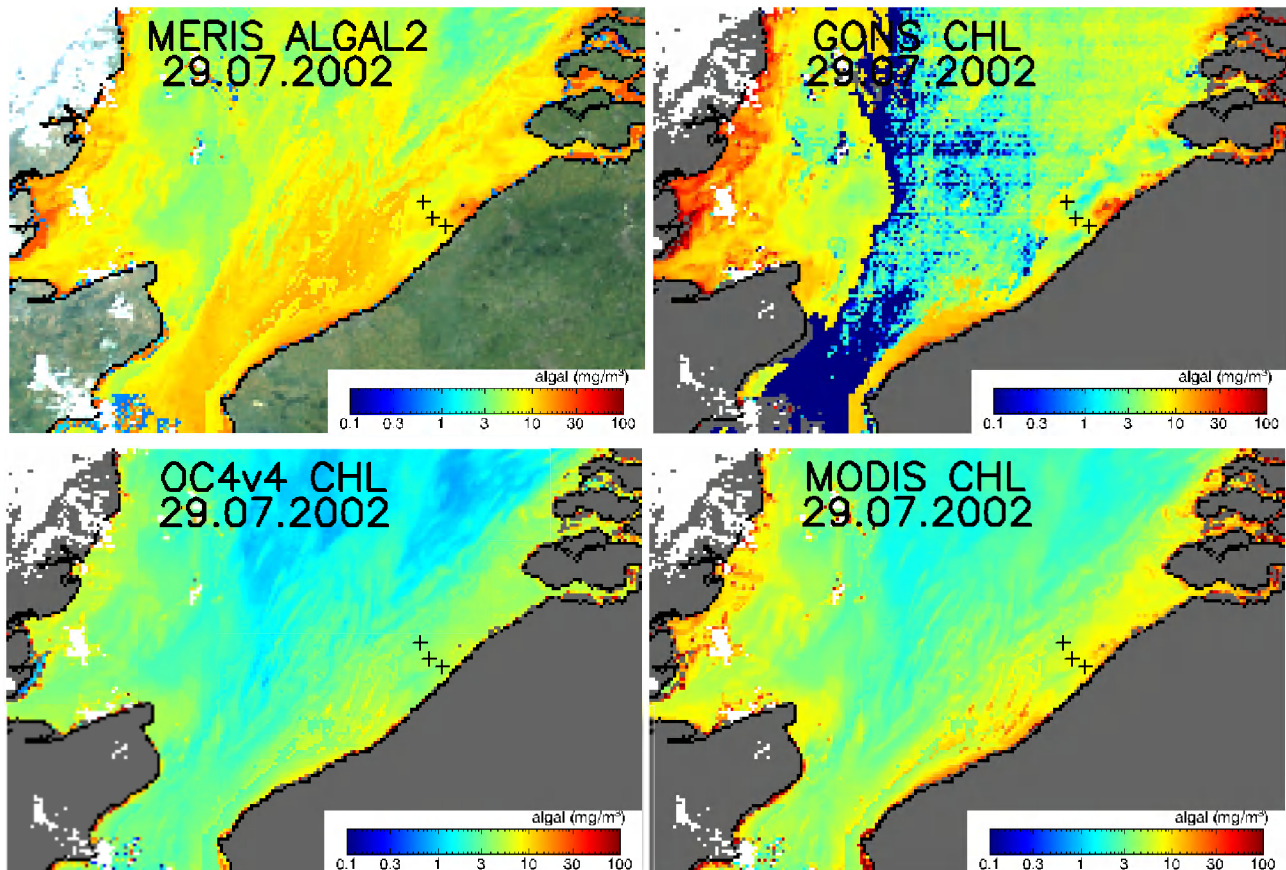

Figure 7: Comparison of chl a retrieval algorithms run on a MERIS image of 29 July 2002 (the GR03 algorithm is represented by 'GONS')

Table 5: In situ chl a values of 29 July versus predicted values by the algorithms. The stations correspond to the crosses on Figure 7 with 130 closest to the coastline and MC5 the furthest offshore.

chl a Concentration (mg/m³)	Station 130-A 9:35 UTC	Station 230-A 10:07 UTC	Station MC5 11:00 UTC
In situ measurement (surface)	5.33	8.28	2.82 (7.53 at -3 m)
MERIS ALGAL2	8.01	9.82	7.09
GR03 (GONS)	6.90	7.23	6.59
OC4v4	4.06	4.56	3.12
MODIS	6.80	7.80	4.51

The GR03 product shows a front with extremely low chl a concentrations. This front is an artifact of MERIS Level 2 processing and coincides with the border between Case 1 and Case 2 atmospheric correction algorithms as indicated by the MERIS flags. The Case 1 atmospheric correction as-

sumes the water leaving radiances to be zero in the NIR (28) and as the GR03 algorithm uses reflectances at 708 and 778 nm, this results in very low chl a values.

The noisy pattern in the GR03 product gives an indication of an input error (noise) of the red and/or near infrared bands. This shows that even if the GR03 algorithm performs well for *in situ* reflectances of turbid waters, practical problems may be encountered when using satellite reflectance because of the low signal/noise ratio of atmospherically corrected water leaving reflectances in the bands used.

The MERIS Algal2 product shows higher chl a values in Case 1 water in comparison with the other algorithms. The MERIS chl a product for Case 1 waters, referred to as Algal 1 (not displayed in Figure 7), yields a result similar to the MODIS and OC4v4 algorithms.

CONCLUSIONS AND FUTURE PERSPECTIVES

The results confirm the difficulty to produce chl a maps for Case 2 waters. Three different algorithms - two empirical, global algorithms (SeaWiFS OC4v4 and MODIS default Case 2) and a turbid water algorithm (called GR03) - performed rather poorly when run on 107 *in situ* reflectances of the Southern North Sea. The modelled results were compared with the *in situ* chl a concentrations that varied from 0.2-33.2 mg/m^3. The r^2 coefficient in the log-log regression varied from 0.4 to 0.5. A positive note is the potential of the GR03 algorithm for estimation of chlorophyll values in the higher concentration range, i.e. >10 mg/m^3. This was the only algorithm with a slope close to 1 (0.7 in the log-log regression), while the r^2 coefficient in the linear regression equalled 0.8. The fact that the GR03 model can easily detect high chl a concentrations allows it to be used in an OSPAR threshold mapping for maximum chl a concentrations. Twenty-one of the twenty-two 'algal blooms' of the data set - defined as events with chl a concentration >10 mg/m^3 - were detected.

The evaluation results depend on the quality of the *in situ* data to a high degree, as was demonstrated by the differences between 'sunny' and 'non-sunny' measurements. Evaluation of the 30 data points collected during sunny weather conditions resulted in a r^2 coefficient of 0.6 to 0.7 in the log-log regression. A strict standard procedure was followed for all 107 measurements, however, some refinements can be made, i.e. a more thorough quality procedure needs to be developed for filtering *in situ* reflectance data to reduce scatter and tighten regression. During development of this procedure, the different characteristics of sunny and non-sunny measurements will be checked, i.e. with regard to the correction for air-sea reflection.

Further adaptation of the GR03 algorithm might be worthwhile. Recalibration with the TriOS data may be considered, as this data was collected for a different region and under less varying conditions than the PR-650 data. Adding the estimation of yellow substance and suspended matter absorption in the 664 nm wavelength (as in (29)) to the GR03 algorithm can be tested.

These steps, together with an expansion of the database with 2003 measurements, will allow an upgrade of the algorithm evaluation.

The comparison of the three algorithms and the MERIS neural network algorithm on the same MERIS image was interesting to demonstrate the significant differences between the chlorophyll products. It also indicated the problem of a low signal/noise ratio for red and NIR bands used in the GR03 algorithm. However, validation over such big areas remains a problem. Additional comparisons of standard chlorophyll products acquired on the same day are necessary to assess a multi-sensor approach for covering cloud-free periods to the maximum and not miss phytoplankton blooms.

The study demonstrates that global chlorophyll products such as the ones of SeaWiFS and MODIS are not accurate enough for the Southern North Sea. The turbid water algorithm GR03 shows promising results for high chlorophyll concentrations and especially for detecting maximum chlorophyll concentration in the framework of the OSPAR assessment parameters (Table 1). Further validation and possibly refinement of the algorithm is advised, before it can be used reliably for eutrophication monitoring in the Southern North Sea. It is clear that *in situ* data collection remains very important as the most reliable data source for eutrophication managers at present, though suf-

fers from severe problems of spatio-temporal sparseness e.g. (27). Satellite chlorophyll maps and field measurements are definitely complementary methods of assessing maximum and mean chl a concentrations of the Southern North Sea.

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