Bio-Optical Measurements in Atlantic Open Ocean Waters for Satellite Validation

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ABSTRACT

Bio-optical measurements were performed on several transatlantic ship cruises to validate satellite derived biogeochemical properties such as chlorophyll-a (chl-a) concentration. Within this study a comparison between remote sensing reflectance determined from hyperspectral above and below water radiometric measurements was performed. The radiometric data were collected with TriOS-RAMSES radiometers in open ocean waters. The remote sensing reflectance were used to validate MERIS, MODIS and SeaWiFS remote sensing reflectance data. In the near future, apparent and inherent optical properties will be determined from below water measurements and used to validate existing definitions of biogeochemical provinces in the Atlantic Ocean and draw empirical relationships.

INTRODUCTION

Water constituents affect the optical properties of the water body and determine the spectral composition of the backscattered light. Ocean color satellite sensors are constructed to record this light in different wavelength bands. Mostly, phytoplankton is the dominant light absorbing part of water constituents in open ocean waters and thus, information about phytoplankton can be retrieved from satellite ocean color measurements. Ocean color measurements from satellite instruments like the Medium Resolution Imaging Spectrometer (MERIS), the Moderate Resolution Imaging Spectrometer (MODIS) or the Sea Viewing Wide Field of View Sensor (SeaWiFS) operated by European Space Agency (ESA) and National Aeronautics and Space Administration (NASA), respectively, are nowadays essential sources of climatological and environmental modeling. They permit monitoring and observation of biogeochemical properties in the upper layer of the ocean on a global scale by providing continuous data sets.

The remote sensing reflectance, R_{RS}, (radiation emerging from the ocean surface) is determined by applying an atmospheric correction to the measured spectral radiances at the top of the atmosphere. By means of particular algorithms, biogeochemical properties can be derived. Recently, several studies investigating the relationship between inherent optical properties, such as chl-a concentration, and apparent optical properties, such as reflectance, were obtained [e.g. Tedetti et al. (2010), Stramski (2008)]. Many of these studies consider in-situ data sets from a specific region. In the current study optical and biological data sets from several transatlantic cruises are taken into account and thus a large variety of biogeochemical provinces is addressed. Such provinces can be defined by differences in phytoplankton community structure and distribution, physical properties of the water body, or simply climatological regimes. A review of how different ocean regions can be defined is given in Ducklow (2003).

MATERIAL AND METHOD

Optical Instruments

For in-situ data acquisition RAMSES hyperspectral radiometers, constructed by TriOS GmbH (Germany) were used. Two types of RAMSES sensors were employed: RAMSES ARC VIS and RAMSES ACC-2 VIS, measuring hyperspectral radiance and irradiance, respectively. Both, ARC VIS and ACC-2 VIS cover a wavelength range from 320 nm to 950 nm with one sample every 3.3 nm and a spectral accuracy of 0.3 nm. The radiance measuring ARC VIS sensor has a field of view of 7°. A cosine collector was fixed in front of the irradiance sensor ACC-2 VIS to collect the light. The in-situ data were collected with two sets of hyperspectral RAMSES radiometers. In order to determine the water leaving R_{RS} above the sea surface, the downwelling irradiance E_d^+, upwelling radiance L_u^+ and sky radiance L_s^+ were measured. While E_d^+ was measured vertically into the sky, L_u^+ and L_s^+ sensors were oriented in the same azimuthal plane measuring in angles of 40° nadir and zenith, respectively. The radiance sensors were ideally oriented in an azimuthal angle of 135° relative to the sun. Sampling intervals were set to 10 s. All data were mostly collected around noon time to secure a high sun zenith angle and when the ship was stationary to avoid white caps in the sensors' fields of view. The second set of RAMSES radiometers was used to measure optical profiles in the water column down to a maximum depth of 200 m. The underwater data still requires analysis.

Measurement Sites

Optical measurements were carried out during several ship cruises with the German research vessel RV Polarstern (Table 1). A spatial overview of the stations where optical measurements were taken is given in Figure 1.

Table 1: Overview: Ship cruises

#	Cruise name	Ship	From	To	Start	End
1	ANT24-1	Polarstern	Bremerhaven	Cape Town	2007/10/26	2007/11/26
2	ANT24-4	Polarstern	Punta Arenas	Bremerhaven	2008/04/18	2008/05/20
3	ANT25-1	Polarstern	Bremerhaven	Cape Town	2008/11/03	2008/12/03

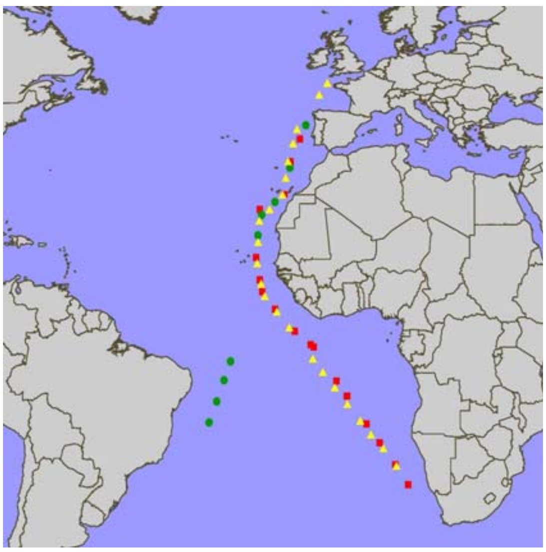

Figure 1: Map with measurement sites during different cruises: red squares for ANT 24-1, green dots for ANT 24-4 and yellow triangles for ANT 25-1

Analysis

As a first step quality checks were applied to the in-situ data. Only nearly clear sky conditions with wind speed < 10 m/s were taken into account. Additionally, the incoming solar light was forced to satisfy the criteria:

- minimum incoming light: $E_d^{\downarrow}(480nm) > 20 \frac{mW}{m^2 nm}$(described in Wernand (2002)),

- not influenced by dusk or dawn: $\frac{E_d^{\downarrow}(470nm)}{E_d^{\downarrow}(680nm)} > 1$(described in Wernand (2002))

The corresponding pitch and roll-data measured by ship‘s sensor must not exceed values larger than 5°.

After the quality check all RAMSES measurements were assembled to measurement batches of constant incoming solar radiation for every day. All measurements from one batch were averaged.

Satellite measurements which coincided in space (in a range of 3 times 3 satellite pixel) and time (within one day) with the ground-truth data were considered. The corresponding measurements for all three pixels were checked for quality flags, negative or too low measurements and cloud or high glint contaminated measurements. Data from pixels with clouds and glint effects were excluded. The remaining data points were averaged.

The water leaving remote sensing reflectance was then calculated from RAMSES measurements by: $\rho_W^{\uparrow} = \pi \frac{L_u^{\uparrow} - \rho_{as} L_s^{\downarrow}}{E_d^{\downarrow}}$, where the air-sea interaction coefficient, ρ_{as}, which depends on salinity, water temperature and wind speed, was calculated following Doerffer (2008). To be consistent with the MERIS reflectance product, MODIS and SeaWiFS measurements were multiplied with π: $\rho_W^{\uparrow} = \pi \cdot R_{RS}$.

These data were used to validate MERIS, MODIS and SeaWiFS remote sensing measurements. Additionally, the chl-a Level-2 products from all three satellite instruments were validated with in-situ chl-a measurements obtained from water samples taken during the cruises.

RESULTS

Reflectance Comparisons

Due to strong quality requirements, the amount of data suitable for the comparison of the satellite reflectance with ground-based above-water RAMSES reflectance was limited. SeaWiFS did not provide any suitable data for the reflectance validation. MERIS and MODIS contributed to the comparison with four and six collocations, respectively. Since several RAMSES batches (of constant Ed) were possible for every collocation, finally a total of 20 and 31 collocated batches were available for MERIS and MODIS, respectively.

Figure 2 shows the scatterplot of MERIS and MODIS remote sensing reflectance compared with RAMSES in-situ remote sensing reflectance. MERIS data correlated well with in-situ data (correlation coefficient $r^2 = 0.92$ and slope $m = 0.95$). MODIS provided an even better correlation ($r^2 = 0.95$) but its values are generally larger than the in-situ values ($m = 1.56$).

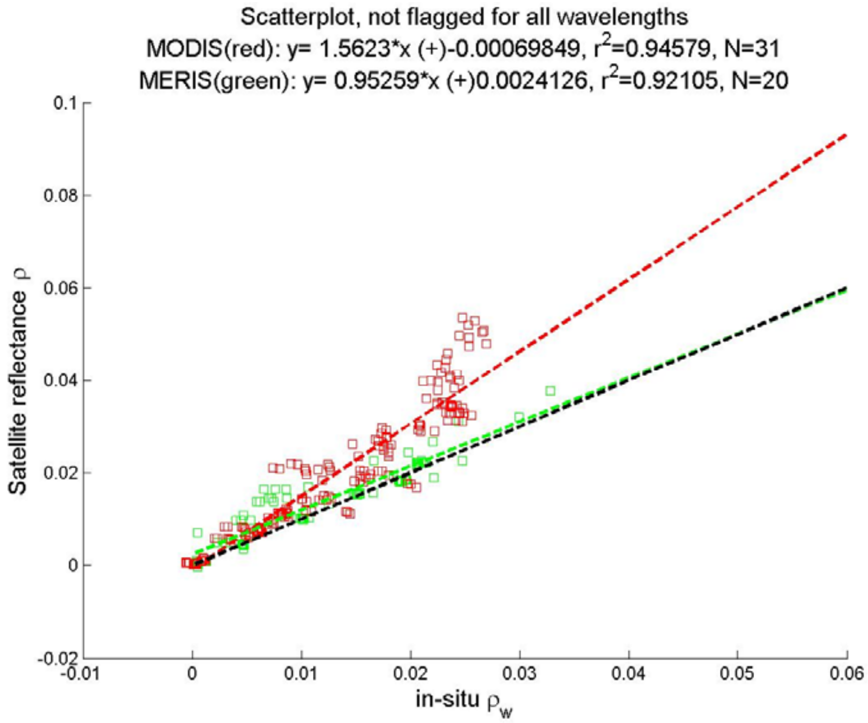

Figure 2: Comparison of reflectance, ρ, of satellite instruments MERIS and MODIS (not flagged data) to collocated in-situ remote sensing reflectance measurements, ρ_w, at all wavelength bands. The dashed black line is the angular bisector (1:1-line). MERIS and MODIS regression lines (green and red dashed) are printed and the corresponding values, together with correlation coefficient and number of considered batches are given in the title.

Wavelength separated analysis showed that most of the MODIS values were too high regarding the corresponding in-situ remote sensing reflectance. The best match was obtained at 531 nm. The wavelength band around 412 nm showed the poorest agreement. MERIS, on the other hand, generally showed regression lines with a slope smaller than one. At all wavelength bands MERIS data showed better results than MODIS data as the regression line for all single wavelength bands traverses the 1:1-line near the centroid of the data points. For the MERIS-in-situ comparison, the best result was obtained for the 443 nm wavelength band.

Satellite Level-2 Product Chl-A Validation

Figure 3 shows the comparison of the Level-2 product chl-a with the in-situ measured chl-a concentrations for all “not bad” flagged satellite data. This “not bad” classification contains medium glint flagged pixels, that are corrected in MODIS and SeaWiFS algorithms and those collocations with only very few flagged pixels. This results in more data and thus the significance of the statistical analysis could be increased. The “not bad” classification lead to two SeaWiFS collocations available for this comparison. Nevertheless a statistical analysis was not possible for SeaWiFS and the regression line was not plotted in Figure 3. Results show that MERIS fits the in-situ data slightly better than MODIS and both show good comparisons.

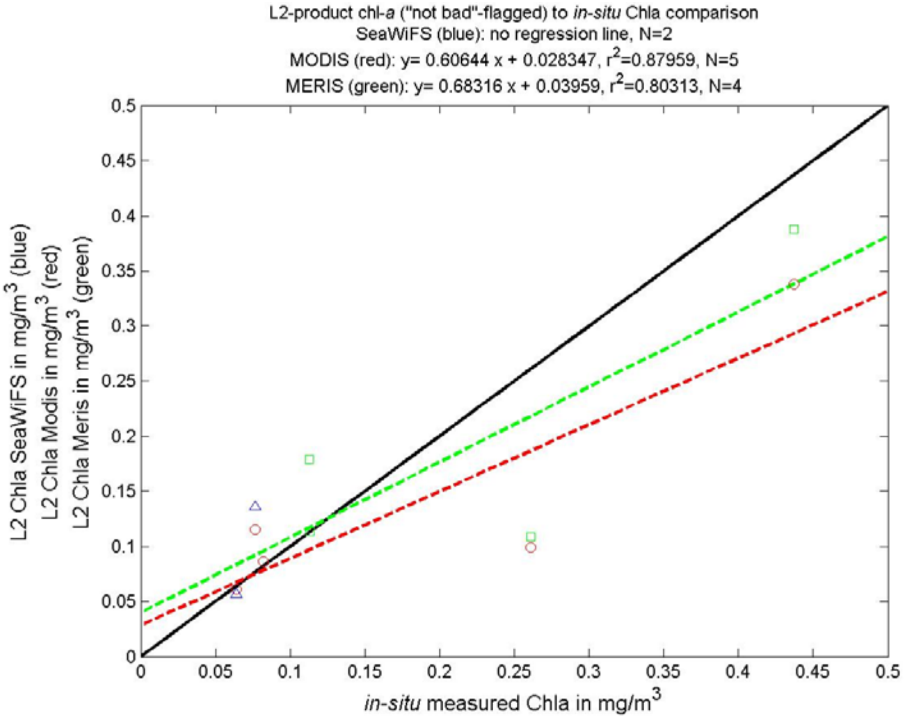

Figure 3: Comparison of Level-2 chl-a products with in-situ measured chl-a concentrations for all "not bad" flagged data including e.g. (corrected) medium glint flagged pixels. The dashed black line is the angular bisector (1:1-line). MERIS and MODIS regression lines (green and red dashed) are printed and the corresponding values, together with correlation coefficient and number of considered batches are given in the title. SeaWiFS regression line is not drawn due to only two data points.

DISCUSSION

Due to the small number of data points the significance of the correlation with the in-situ data is limited. Nevertheless, the validation of MERIS is clearly positive. MODIS shows slightly too high values, especially in the lower wavelengths. A reason for such effects could be a failing atmospheric correction [Theis et al. (2008), Antoine et al. (2008), Bailey and Werdell (2006) and Park et al. (2006)]. The atmospheric correction strongly relies on the correct assessment of absorbing aerosols in the atmosphere. An incorrect estimation of the aerosol amount and distribution will affect the retrieval of water leaving radiance. This effect is more severe for the shorter wavelengths than for larger. Thus, a large noise in shorter wavelengths indicates errors by atmospheric correction [Antoine et al. (2008)]. Such large differences in the first wavelength bands, especially 412 nm, occur quite often and are reasonable under this perspective.

Table 2 summarizes statistical values from this current work and three other studies (Antoine et al. (2008), Bailey and Werdell (2006) and Park et al. (2006)) for remote sensing reflectance and chl-a comparisons. Antoine et al. (2008) obtained better correlations for SeaWiFS and MODIS and slightly weaker for MERIS. This might be due to a different measurement site, since Antoine et al. (2008) considered ground-based measurements from the Mediterranean Sea and this current study deals with data from the Atlantic Ocean. Park et al. (2006) revealed very satisfying regressions for MERIS chl-a comparison due to large range of chl-a concentrations in the Belgian case 2 waters. Thus, results are not entirely comparable with the open ocean chl-a concentrations from this study. On the other hand, the present study yields equivalent results of the chl-a and remote sensing reflectance comparison to results from other studies and projects like Antoine et al. (2008) and Bailey and Werdell (2006).

Table 2: Resulting statistical values slope m, intercept n, correlation coefficient r2 and number of collocations N from reflectance and chl-a comparisons from current study ("no bad" and "not flagged" category), Antoine et al. (2008), Bailey and Werdell (2006) and Park et al.(2006). Note that Bailey and Werdell (2006) validated SeaWiFS data only and Park et al. (2006) took in-situ data in Belgian case 2 waters to validate MERIS data.

		reflectance comparison				chl-*a* comparison			
	study	m	n	r^2	N	m	n	r^2	N
SeaWiFS	current "not bad"	1.61	<0.01	0.98	6	6.34	0.35	1	2
	Antoine et al. (2008)	0.94	<0.01	0.89	888	0.45	-0.66	0.51	44
	Bailey and Werdell (2006)	only wavelength separated analysis				0.9	-	0.83	271
MODIS	current "not bad"	1.88	<0.01	0.92	86	0.61	0.03	0.88	5
	current "not flagged"	1.56	<0.01	0.95	31				
	Antoine et al. (2008)	0.93	<0.01	0.91	666	0.77	-0.24	0.82	31
MERIS	current "not bad"	0.9	<0.01	0.82	70	0.68	0.04	0.8	4
	current "not flagged"	0.95	<0.01	0.92	20				
	Antoine et al. (2008)	1.16	<0.01	0.88	400	0.58	-0.48	0.87	15
	Park et al. (2006)	only wavelength separated analysis				0.98	0.1	0.81	14

OUTLOOK

The analysis of all below water optical data is still in progress. In order to validate biogeochemical provinces in the Atlantic Ocean following Longhurst (1998), remote sensing reflectance retrieved from both above and below water optical measurements and calculated apparent optical properties (e.g., diffuse attenuation coefficient $K_d = -\frac{d}{dz}\ln E_d$ and irradiance reflectance $R^- = \frac{E_u^-}{E_d^-}$) will be examined. Moreover, comparisons to biological data including pigment concentration and distribution as well as inherent properties like absorption coefficients and fluorescence measurements will be conducted and empirical relationships will be drawn. The biooptical and pigment data will be investigated by cluster techniques to look for the imprint of the biogeochemical provinces.

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