VARIABILITY OF BIO-OPTICAL PARAMETERS OF THE SE BALTIC SEA COASTAL WATERS BASED ON *IN SITU* AND SATELLITE DATA

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ABSTRACT

In our study we present validation activities associated with satellite MERIS image processing aimed at estimating chlorophyll *a* (chl *a*), coloured dissolved organic matter (CDOM) and total suspended matter (TSM) in the Lithuanian Baltic Sea coastal waters. Eight MERIS full-resolution Level 1b images, acquired during late spring and summer 2010, were processed using five, neural network-based processors for optically Case 2 coastal and inland waters: FUB, C2R, Eutrophic, Boreal, and standard MERIS Level 2. Results showed that the FUB processor provided the most accurate estimates of the concentration of chl *a* and TSM. *In situ* CDOM absorption was most accurately estimated using the Boreal processor.

SE Baltic Sea at the Lithuanian coast is connected to the hypereutrophic Curonian Lagoon. The outflow region remains oligohaline with temporary and irregular salinity fluctuations from 0 to 7(8) PSU mainly driven by wind. Over the salinity gradient we observed patchy distribution of optically active constituents that may cause the changes of optical water properties. In order to understand the impact of the lagoon waters outflow to the coastal region on the validation results, during the summer 2012 inherent and apparent optical properties were measured and remote sensing reflectance was analysed over the investigation region.

1. INTRODUCTION

SE Baltic Sea at the Lithuanian coast is hydrodynamically unique environment due to its connection to the hypereutrophic Curonian Lagoon. The outflow region remains oligohaline with temporary and irregular salinity fluctuations from 0 to 7(8) PSU mainly driven by wind [1]. Over the salinity gradient we observed patchy distribution of phytoplankton and optically active constituents [2] that may cause the changes of optical water properties over the salinity gradient. Moreover, the large freshwater content is strongly associated with nutrient input from the densely populated and intensively cultivated catchment areas and the atmosphere [3]. The excess of the nutrients is one of the major causes of eutrophication processes occurring in the sea. The turbid fresh water plumes with river-borne nutrients and pollution in the Baltic Sea can be detected by three optical water components: coloured dissolved organic matter [4], total suspended matter [5] and chlorophyll *a* [6].

In recent years, the major ecological issue in the Baltic Sea is eutrophication and the worsening of water quality [7]. This has driven the most recent environmental objectives of government bodies such as the Helsinki Commission (HELCOM) and the European Commission (EC) that issued both the Water Framework Directive (2000/60/EC) and the Marine Strategy Framework Directive (2008/56/EC). Traditional field sampling methods cannot produce consistent datasets to monitor the spatial and temporal changes of water quality over large areas, whereas satellite-based remote sensing techniques are a key source of data for monitoring the ecological status of the ecosystems at global, regional, and local scales [8]. Chl *a*, CDOM, and TSM, are known as optically active components and can be derived by satellite remote-sensing techniques [9]. However, validation of satellite-based estimates of water quality parameters is a key issue for the implementation of remote sensing techniques to long-term water quality monitoring.

Validation activities has been started in 2009 over the Curonian Lagoon waters, when first time chl *a* and CDOM derived from MERIS full resolution data were compared with *in situ* measurements [10]. For CDOM mapping, the C2R processor was considered appropriate. For the chl *a* map, the procedure based on R_{rs} band-ratio in the red/near-infrared wavelengths, developed using *in situ* data and then applied to 6S-corrected satellite data, provided appropriate results ($R^2 = 0.94$). Later, the relationship between *in situ* measured chl *a* and band-ratio $R_{rs}708/R_{rs}664$ applied for MERIS was improved by Bresciani et al. [11] and Žilius et al. [12]. Giardino et al. [10] highlighted the importance of atmospheric correction in NIR spectral region and how the failure may influence chl *a* retrieval from satellite data over the eutrophic waters. Moreover, the precise investigation of *in situ* inherent and apparent optical

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properties allows improvement of regional bio-optical algorithms and ensures better retrieval of water quality parameters. Therefore the aim of this work is to focus on the validation of satellite-based water quality parameters in the SE Baltic Sea coast, which were derived from MERIS data by applying the different processors and investigate the variability of bio-optical parameters in three different water masses of the Lithuanian Baltic Sea coast.

2. MATERIAL AND METHODS

Study area. Lithuanian coast located at SE Baltic Sea is exposed to any wind westerly direction, with a wind fetch exceeding 200 km [13]. The permanent influence of SW and SE winds, waves, and water currents produces a hydrodynamically active environment. Surface salinity is in the range of 7 to 8 PSU, whereas near the mouth of the Curonian Lagoon salinity decreases to values, which approximate those of freshwater systems, and the salinity gradient can extend for tens of kilometres out into the sea [14]. The Curonian Lagoon is the largest European lagoon connection to the waters of the Baltic Sea via the Klaipeda Strait. The northern part of the lagoon is typically defined as a transitional riverine-like system, while the southern part is lacustrine and characterised by a relatively closed water circulation with lower current velocities [15], where wind is the main driving factor. The wind-driven brackish water inflows from the Baltic Sea can cause irregular rapid salinity fluctuations in the range of 0-8 PSU in the northern part of the lagoon. Brackish water may sometimes reach the central part of the lagoon [1]. However, this phenomena is very rare as the water level of the lagoon is on average almost 15 cm higher than the Baltic Sea water level [16]. Therefore, the Curonian Lagoon is still considered as a freshwater basin with an average annual salinity of 2.6 PSU at the entrance to the sea down to 1.2 PSU in the northern part and 0.1 PSU in the central part [1]. Hypereutrophic Curonian Lagoon waters with estimated chl *a* concentration above 400 mg m^{-3} [11] and Secchi disk depth varying from 0.3 to 2.2 m [17] strongly affects the plume area in the Lithuanian coast [2].

***In situ* measurements.** During one field campaign conducted on 29-30 July 2012 in the Lithuanian Baltic Sea (6 stations) and in the Curonian Lagoon (6 stations) *in situ* remote sensing reflectance (R_{rs}) measures were performed with Water Insight Spectrometer (WISP-3) (Fig. 1). Vertical profiles of backscattering were performed with the backscatter meter HydroScat-6 manufactured by Hobilabs. The HydroScat software, HydroSoft, was used for real-time data acquisition of down- and up-cast profiles. The backscattering coefficient $b_b(m^{-1})$ was calculated according to equation (1) [18]. Work with HydroScat data is still on-going therefore the results will not be presented in this paper.

$$b_b(\lambda) = 2\pi \int_{\pi/2}^{\pi} \beta(\theta,\lambda) \sin\theta \mathrm{d}\theta \qquad (1)$$

Water transparency was measured using standard 30 cm white Secchi disk. Water samples for pigment and non-algal particle (NAP) absorption measurements were filtered through glass fibre GF/F filters. The determination of absorption coefficients were based on [19] and [20]. The absorption of particles retained onto the filters was measured with the spectrophotometer using the filter pad technique [21, 22]. Absorption by NAP was measured after the bleaching with acetone 90% solution.

Water samples for chl *a* measurement were filtered through glass fibre GF/F filters with a nominal pore size 0.7 µm and extracted into 90% acetone. Photosynthetic pigments were measured spectrophotometrically and estimated according Lorentzen [23]. CDOM was measured spectrophotometrically after filtration through 47 mm diameter 0.22 µm membrane filters. The CDOM absorption coefficient at 440 nm (g_{440}) was derived according to Kirk [24]. TSM was assessed gravimetrically using the method proposed by Strickland and Parsons [25]. Species composition was determined using the inverted microscope technique [26].

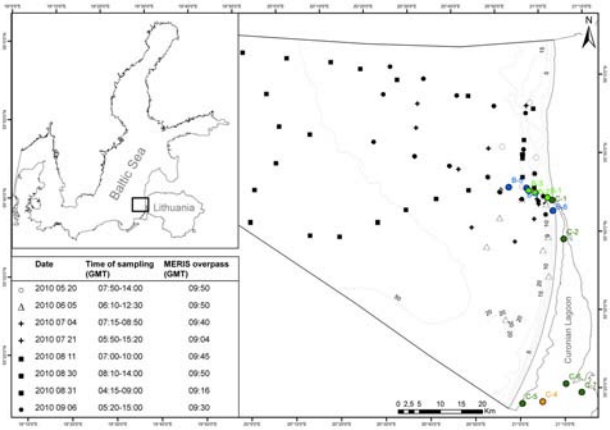

Figure 1. Study area and sampling locations during validation activities in 2010 and bio-optical measurements (blue circles correspond to coastal waters, light green– plume waters, dark green – lagoon waters, orange – scum) in 29-30 July in 2012 over the Lithuanian part of the Baltic Sea and the Curonian Lagoon.

Satellite data. Simultaneously with the dates of the field campaigns in 2010 (Fig. 1), MERIS full resolution (FR, 300 m) cloud free images were acquired. The Level 1b images firstly were corrected to account for the difference between actual and nominal wavelengths of the solar irradiance in each channel with the Smile tool (1.2.101 version) of the BEAM VISAT (4.8.1) software provided by Brockmann Consult/ESA, in order to perform an irradiance correction for all bands. Later, the MERIS images were processed using four different plug-in optical processors (Case-2-Regional, Boreal, Eutrophic and FUB) of the BEAM VISAT software in order to retrieve the water quality parameters chl *a*, CDOM and TSM. The fourth processor was developed by the German Institute for Coastal Research (GKSS) and Brockmann Consult and Freie Universität Berlin (FUB, 1.2.4 version). Finally, we also obtained standard MERIS Level 2 products for the validation analysis (more details in Vaičiūtė et al. [27].

3. RESUTS AND DISCUSION

Validation of MERIS data. In previous investigation done by Vaičiūtė et al. [27] it was shown, that he best fit between *in situ* and estimated chl *a* was found for the standard Level 2 and FUB processor (Tab.1). Comparison between C2R and *in situ* chl *a* explained a relatively small amount of variation in the data (R^2 = 10%–30%) and produced relatively high MAE (10 to 12 mg m^{-3}). Moreover, results showed an acceptable agreement only for the values of chl *a* lower than 10 mg m^{-3}, whereas above this value the satellite derived estimates were not accurate. The best fit between *in situ* CDOM and the satellite-derived values was found for the Boreal processor, while best fit between in situ and estimated TSM was found for the FUB processor (Tab 1.).

Table 1. Relationships between in situ measured and satellite-derived optically active components (OAC) by different algorithms. a – slope of the regression line, b – intercept point of the regression line, R^2 – determination coefficient, RMSE – root mean square error, N – number of investigations left after screening of valid pixel. Statistically significant relationships are indicated in asterisks, Vaičiūtė et al., [2].

	FUB	C2R	Eutrophic	Boreal	Level 2
	Chlorophyll *a*				
a	3.26	9.05	6.93	15.22	1.00
b	0.96	0.04	0.03	0.13	0.73
R^2	0.69*	0.10*	0.18*	0.28*	0.87*
RMSE	14.44	21.50	22.07	19.90	3.46
N	56	67	67	67	28
	CDOM				
a	0.06	0.01	0.18	0.22	0.19
b	0.64	0.40	0.32	0.33	0.11
R^2	0.53*	0.64*	0.51*	0.69*	0.08
RMSE	0.31	0.38	0.34	0.30	0.50
N	56	67	67	67	28
	TSM				
a	2.86	0.48	0.48	0.64	0.42
b	0.83	0.29	0.39	0.17	0.47
R^2	0.87*	0.53*	0.55*	0.37*	0.57*
RMSE	4.25	5.43	4.78	6.17	3.78
N	56	67	67	67	28

Variability in bio-optical parameters. Tab. 2 shows that highest concentrations of optically active components (OAC) was determined in the stations located in the Curonian Lagoon with an extreme values during cyanobacteria scum, without foam formation in station C-4 (chl *a* = 7134 mg m^{-3}, CDOM = 4.6 m^{-1}, TSM = 630 g m^{-3}, data are not included in the Tab. 2). In the stations where salinity was typical for coastal waters (6.7±0.1 PSU) chl *a* and TSM concentration was approximately thirty, while CDOM – tree times lower than in the lagoon.

Table 2. Average value of water quality parameters (chl a, CDOM, TSM and Secchi depth) estimated in situ, the value measured in the station C-4 (with scum) was not included in the calculation of the average.

	Chl *a*, mg m^{-3}	CDOM, m^{-1}	TSM, g m^{-3}	SD, m	Salinity, PSU
Coastal	5.8±0.6	0.8±0.6	1.2±0.4	3.0±0.3	6.7±0.1
Plume	46.9±19.7	1.8±0.4	12.2±4.1	1.1±0.8	4.3±1.8
Lagoon	168.8±197.9	2.8±0.2	29.7±21.3	0.7±0.3	0.5±0.6

Stations with a reduced salinity (4.3±1.8) show clear transition between coastal brackish and oligohaline lagoon waters (Tab. 2). Measured water transparency (SD) showed opposite tendencies being highest (3.0±0.3 m) in the coastal waters and lowest (0.7±0.3 m) in the lagoon.

Absorption coefficient due to phytoplankton is different by its magnitude in tree types of water masses caused by different biomass and structure of phytoplankton (Fig. 2). In the absorption spectra of the lagoon waters is well evident the peak of chl *a* near 680 nm and the peak at 620 nm due to phycocyanins.

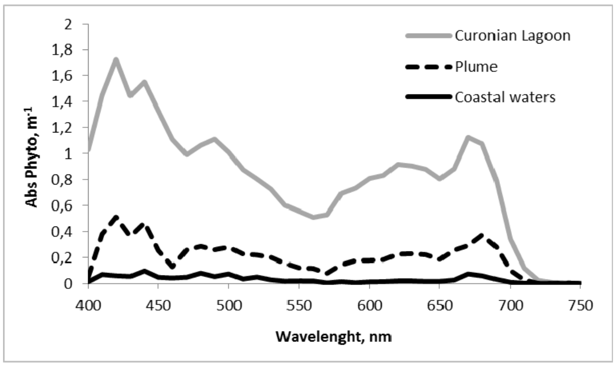

Figure 2. Averaged phytoplankton absorption coefficients in the coastal waters, plume area and in the Curonian Lagoon.

Fig. 3 shows clear differences of absorption by NAP, especially in shorter wavelength (400-500 nm). The area of the plume is more influenced by non-algal particle while the lagoon - by phytoplankton (including cyanobacteria mainly *Aphanizomenon flos-aquae* with presence of *Microcystis* spp.).

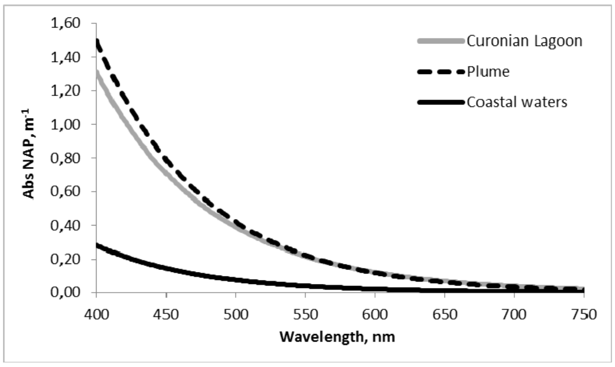

Figure 3. Averaged absorption by non-algal particles coefficients (NAP) in the coastal waters, plume area and in the Curonian Lagoon.

Higher absorption by CDOM in shorter wavelength (400-500 nm) was observed over the lagoon waters mainly originated from the inflow of Nemunas River and degradation of phytoplankton. Over the plume area and coastal waters CDOM absorption was lower (Fig. 4).

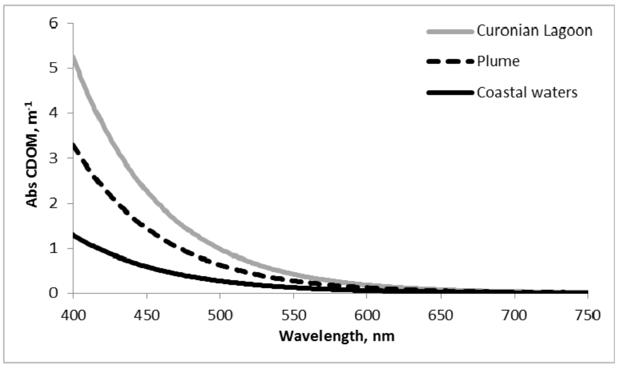

Figure 4. Averaged absorption coefficents due to CDOM in the coastal waters, plume area and in the Curonian Lagoon.

In situ measured Remote Sensing Reflectance (R_{rs}) differs over the different water masses, while the greatest difference is visible in the NIR spectral region (Fig. 5). High peak in NIR was measured at the station located in the Curonian Lagoon and characterized by high values of all optically active components. Extremely different spectral signature was measured during a scum event in station C-4 where concentration of chl *a* exceeded 7000 mg m^{-3} and it is described in Bresciani et al. [28]. In the coastal waters of the Baltic Sea, where concentrations of optically active components are ten times lower, spectral signatures have a completely different behaviour. Bresciani et al. [28] showed that the spectral signatures in the lagoon are mostly determined by the presence of cyanobacteria and TSM.

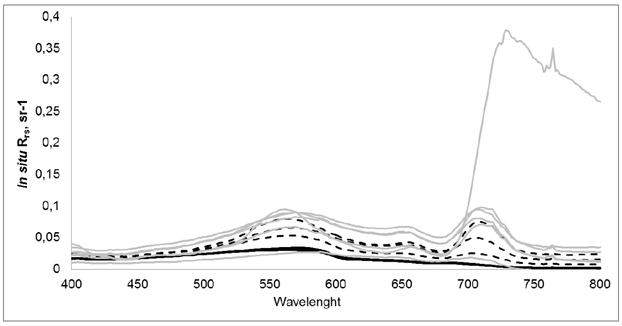

Figure 5. In situ measured remote sensing reflectance (R_{rs}) in the coastal waters (black solid line), plume area (black dashed line) and in the Curonian Lagoon (grey solid line).

Finally, according to MERIS images of 2005-2011 after application of Boreal processor in order to derive CDOM absorption, plume area formed by the outflow of the Lagoon (Nemunas River) waters was mapped [2]. The spread of the plume was mainly directed to the north, although with less frequency it occurred in the whole area of territorial sea and even up to 40 km from the shore line, covering 728±397 km^2 (Fig.6).

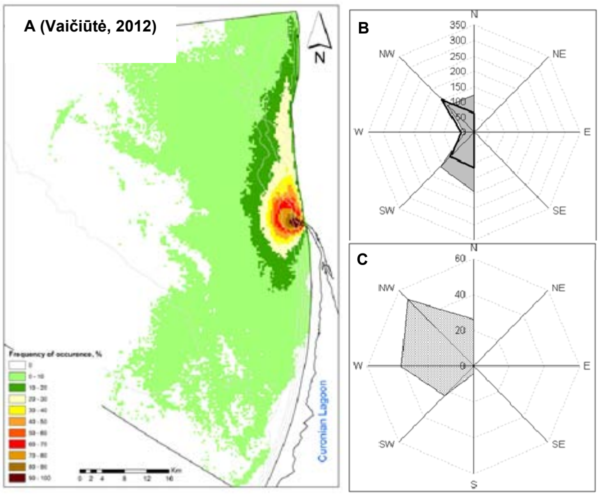

Figure 6. Spatial distribution of the plume area based on CDOM values derived from MERIS data after application of Boreal processor (A), mean (grey area) and standard deviation (black solid line) of the plume size, km² (B) and its frequency at the given directions (C) during the intensive vegetation period of 2005–2011.

4. CONCLUSIONS

The FUB and standard Level 2 processors were the most relevant to derive chlorophyll *a* concentration in the Lithuanian Baltic Sea coastal waters, the Boreal processor – CDOM absorption, the FUB processor – the concentration of TSM. Satellite remote sensing can be applied in order to assess water quality, investigate ecological processes and sub- and mesoscale coastal dynamics including coastal plume.

Waters of the lagoon strongly influence the entire coastal area and therefore it differs by the bio-optical properties due to different concentrations of in-water substances. According to MERIS 2005-2011 data, plume area is mainly directed to the north, although with less frequency it occurred in the whole area of territorial sea and even up to 40 km from the shore line, covering 728±397 km^2.

According to *in situ* radiometric measurements the spectral signatures of different water masses have a different behaviour and magnitude in the NIR spectral region.

This extreme variability of the optical properties is evident and should be investigated with future images Sentinel 3. Moreover the delineation and quantification of the areal zone plume and scum can be performed with Sentinel 2.

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