On the synergistic use of SAR and optical imagery to monitor cyanobacteria blooms: the Curonian Lagoon case study

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Abstract
Multi-sensor satellite data are used to assess cyanobacteria blooms in the Curonian Lagoon. The exploitation of SAR, in combination with optical data, is investigated to take full advantage from the all-weather, night/day SAR imaging capability. A dataset of images has been analyzed to: 1) study the effect of cyanobacteria on microwave signals; 2) assess the daily evolution of cyanobacteria bloom from multi-sensors data; and 3) evaluate the dependence of dynamics of blooms on winds. The results show a significant correlation (R² > 0.8, p<0.001) between the X- and C-band Normalized Radar Cross Section (NRCS) attenuation and the NIR-Red band ratio Index, with the latter considered as a proxy for the presence of cyanobacteria blooms. A combined use of microwave and optical observations can improve the detection of cyanobacteria blooms and their dependency on wind action.

Keywords: Cyanobacteria blooms, wind, ASAR, COSMO-SkyMED, MERIS, MODIS.

Introduction
In recent decades the increasing occurrence of algal blooms generated by cyanobacteria [e.g. Sellner et al., 2003; Hudnell, 2008] required the intensification of water quality monitoring and the integration of different research techniques. Cyanobacteria blooms can constitute a serious risk for human health and aquatic organisms survival [Codd et al., 2005; Backer et al., 2008] since some species may produce toxins (cyanotoxins), which can also compromise the sustainability of an aquatic ecosystem [Havens, 2008] and hamper associated economic activities [Dodds et al., 2009]. In addition to the negative impact of cyanobacteria on the ecology of the ecosystem and on its biogeochemical conditions, a reduced touristic presence and the application of more complex water purification practices represent a consistent economic loss [Mur et al., 1999]. Cyanobacteria are characterized by a large structural variability as well as by a good capacity to adapt to environmental conditions; for instance, they can consistently modify
their capability to exploit the incident radiation [Chorus, 2001; MacIntyre et al., 2002] and can migrate within the water column by adjusting their buoyancy [Reynolds, 1994]. Furthermore, cyanobacteria exhibit extremely high growing rates [Ressom et al., 1994] and their development is greatly influenced by weather and climatic conditions [Sukenik et al., 2009]. In particular, several studies pointed out the role of wind speed as crucial factor in the formation of cyanobacteria blooms [Kutser et al. 2009; Bresciani et al., 2013a]. Continuous measuring systems (e.g. fluorometric probes) can be associated with limnological measurements to collect as much information as possible about bloom events dynamics. However, cyanobacteria blooms are so variable in time and space [e.g. Sondergaard et al., 1990; Lucas et al., 2006; Wu and Kong, 2009] that samples collected from point-like stations cannot provide comprehensive information to fully understand their development features in the water body. The capability of optical remote sensing techniques to gather synoptic water quality data with suitable temporal and spatial resolutions has been increasing since many years [e.g. Dekker et al., 2001; Bresciani et al., 2011; Massi et al., 2011; Matthews et al., 2011]. Unfortunately, optical satellite acquisitions are usually performed in the morning under clear sky conditions, hence limiting the possibility to investigate the phenomena during the day. As microwave imaging can be operated all-weather and day/night, the aim of this study is to assess, through the integration of optical and radar imagery, the dynamics of cyanobacteria blooms in the Curonian Lagoon, the largest lagoon in Europe (1560 km²). Located between Lithuania and the Russian Federation, the Curonian Lagoon is featured by hypertrophic water conditions, which support impressive cyanobacteria bloom events characterized by serious water quality deterioration. Cyanobacteria blooms can extend for several kilometers over the lagoon’s area by forming dense surface cyanobacteria aggregations [Olenina and Olenin, 2002; Gasiūnaitė et al., 2008]. Giardino et al. [2010] and Bresciani et al. [2012] have recently demonstrated the feasibility to retrieve chlorophyll-a (Chl-a) concentrations in the Curonian Lagoon from MEdium Resolution Imaging Spectrometer-Full Resolution (MERIS) data. Therefore, these seminal studies were used to assess the capability of Moderate Resolution Imaging Spectroradiometer (MODIS) to detect cyanobacteria. Besides, the capability of cyanobacteria blooms to smooth the water surface roughness can be used to assess their detection on Synthetic Aperture Radar (SAR) as dark patches and relate the observed NRCS attenuation (Normalized Radar Cross Section) with respect to the expected wind vector-dependent backscatter strength. For this purpose, X band (9.6 GHz) COSMO-SkyMED (CSK) and C band (5.5 GHz) ASAR (Advanced Synthetic Aperture Radar) images acquired almost in coincidence with in situ measurements and MERIS images have been considered. The paper is organized as follows. First, the results obtained by comparison of synchronous ASAR and MERIS images [Bresciani et al., 2013a] will be summarized; then optical (i.e., MERIS, MODIS) and microwave (i.e., ASAR and CSK) images will be combined with the purpose to analyze the daily variations of cyanobacteria bloom and to evaluate the wind-dependent dynamics of bloom events.

Material and methods

Study area
The Curonian Lagoon (Fig. 1) is the largest (1584 km²) European coastal lagoon and it is split between Lithuania (26% of the lagoon area) and the region of Kaliningrad (Russian
The lagoon is located in the South-East Baltic Sea and is separated from the open sea by the narrow (0.5-3 km wide) Curonian spit.

![Figure 1 - Study area.](image)

The hydrology of the lagoon is strictly related to the discharge from the catchment area of the Nemunas River (22.1 km\(^3\)/year), therefore it is mainly a freshwater, terrestrial runoff-dominated system [Ferrarin et al., 2008]. In the northern part the lagoon is connected to the South-East Baltic Sea through the artificially deepened Klaipeda strait and remains oligohaline with temporary and irregular salinity fluctuations from 0 to 7(8) PSU (Practical Salinity Units), caused by wind-driven inflows of brackish water. The lagoon water circulation mainly is determined by winds and Nemunas River discharge [Ferrarin et al., 2008; Gasiūnaitė et al., 2008]. However, in autumn during the westerly wind-driven storms and in summer, when the water level difference between the lagoon and sea is minimal, the inflows of brackish water may cause temporary changes of the circulation regime in the northern part of the lagoon [Žaromskis, 1996; Davulienė and Trinkūnas, 2004].

Western winds are prevalent with fewer occurrences of southern winds [Dailidienė et al., 2011; Kelpšaitė et al., 2011]. Due to its shallowness (mean depth 3.8 m) the Curonian Lagoon is well mixed with enhanced turbidity (Secchi disk depth varies from 0.3 to 2.2 m) and the vertical water temperature stratification is weak. Water temperature dynamics is typical for shallow temperate lagoons with annual amplitude up to 25-29°C [Žaromskis, 1996].

Eutrophication is the main problem in the Curonian Lagoon which yields repeated algal blooms caused by diatoms in spring and cyanobacteria being more abundant in summer time [Olenina, 1998; Pilkaitytė and Razinkovas, 2007]. One of the main species causing drastic
summer blooms is nitrogen fixing, potentially toxic cyanobacteria *Aphanizomenon flos-aquae*. The biomass of *A. flos-aquae* mainly is at intensive or hyper-bloom level, reaching nearly 150 mg/l, while in small sheltered inlets it may be nearly 2000 mg/l [Olenina, 1998; Jaanus et al., 2011] and form nuisance scum on the water surface [Bresciani et al., 2013b]. Jaanus et al. [2011] recorded that *A. flos-aquae* was replaced by cyanobacteria *Planktothrix agardhii* in 2000s. However, in situ surveys conducted by the authors revealed that over the recent years *A. flos-aquae* was again dominant and caused drastic blooms. According to more recent investigations [Gasiūnaitė et al., 2008], the lagoon can be characterized as a hypertrophic system whose quality is controlled mostly by factors such as the water temperature regime, nutrient load caused by rivers and wind-wave driven resuspension, reduced water exchange with the Baltic Sea and high residence time [Ferrarin et al., 2008; Dailidienė et al., 2011].

**Field and satellite data**

*In situ* data were collected during a field campaign conducted on 29-30 July 2012 for a total of 9 investigated stations, distributed in the Lithuanian part of the lagoon. In correspondence of each station, water samples were collected near surface and filtered *in situ* for subsequent laboratory analysis. Chl-a concentrations were determined according to Lorenzen [1967]. At the same stations, remote sensing reflectance (Rrs) values in the spectral range 400-800 nm were acquired by simultaneous measurements of downwelling irradiance, sky radiance and water leaving radiance performed with a WISP-3 spectroradiometer [Hommersom et al., 2012]. Rrs values show the typical shape with drops and peak in the red and NIR (near-infra-red) regions caused by Chl-a photosynthetic activity [Giardino et al., 2010; Bresciani et al., 2012; Bresciani et al., 2013a]. Radiometric measurements performed in correspondence of surface aggregation show high reflectance spectra in the NIR region, in agreement with data collected in previous campaigns [Giardino et al., 2010; Bresciani et al., 2012; Bresciani et al., 2013a]. Satellite optical images gathered by MERIS and MODIS instrument were selected for this study. Two cloud free MERIS-FR (MEdium Resolution Imaging Spectrometer-Full Resolution) images were acquired on 24 July and on 4 August, 2011. MERIS, which is a pushbroom scanner recording electromagnetic solar radiation with 15 bands between 390 and 1040 nm aboard of Envisat satellite, acquired data around 9:30 UTC. The two MERIS-FR images (nominal pixel size of 300 m at nadir) were corrected for the difference between actual and nominal wavelengths for the solar irradiance using SMILE in the BEAM software (Basic ERS & Envisat (A)ATSR and MERIS) [Fomferra and Brockmann, 2006], while adjacency effect was removed using the ICOL (Improved Contrast between Ocean and Land) processor [Santer and Schmechtig, 2000; Santer et al., 2007]. MODIS is an instrument on board Terra and Aqua sun synchronous satellites. Their orbits (descending for Terra and ascending for Aqua) are crossing the equator in the morning and in the afternoon respectively, catching the Curonian Lagoon between 9:00 and 12:30 UTC. Nine level 1B products (i.e. calibrated radiances) at 1 km of spatial resolution have been processed in order to select among the 13 bands (from 412 to 870 nm) most suitable to assess water quality and in particular to retrieve spectral properties of cyanobacteria. MERIS and MODIS images were all corrected for atmospheric distortions using the 6S code (Second Simulation of a Satellite Signal in the Solar Spectrum) [Vermote et al., 1997;
Aerosol optical thickness (AOT) values at 550 nm were derived from AERONET (NASA, 2012) stations nearest to the study area: Minsk (53N, 27E) and Gustav Dalen (58N, 17E). At the same time prevalent wind direction during the time of satellite acquisitions was taken in account to select the most appropriate aerosol type and AOT values. The 6S-corrected data were validated by checking if, for the whole images, the reflectance values of spectrally invariant surfaces (e.g., urbanized areas) were constant (not shown).

A set of SST (Sea Surface Temperature) MODIS products (MOD 28) were also gathered (from http://oceancolor.gsfc.nasa.gov website) as ancillary data to be used in the interpretation of spatial and temporal cyanobacteria distribution.

Radar images used for this study were acquired by the X-band Synthetic Aperture Radar (SAR) onboard the Italian Space Agency Satellite constellation COSMO-SkyMED (CSK) and by the C-band Advanced SAR (ASAR) onboard the European Space Agency Envisat satellite. In particular, the dataset was composed by:

- 1 CSK-1 image acquired by the first satellite of the constellation on 3 August 2012 at 16:55 UTC in HIMAGE mode with a pixel size of 2.5 m and HH polarization;
- 1 CSK-4 image acquired by the forth satellite of the constellation on 30 July 2012 at 16:55 UTC in HIMAGE mode with a pixel size of 2.5 m and HH polarization;
- 1 CSK-2 image acquired by the second satellite of the constellation on 24 July 2012 at 16:58 UTC in HIMAGE mode with a pixel size of 2.5 m and HH polarization;
- 2 images acquired by the Advanced SAR (ASAR) in Wide Swath (WS) mode on 24 July 2011 at 09:15 UTC and on 4 August 2011 at 09:11 UTC with pixel size of 75 m and VV polarization.

First, the NRCS was estimated after range spreading losses, antenna gain pattern and processing gains removal by using the NEST (Next ESA SAR Toolbox) package provided by ESA (European Space Agency). The radiometrically corrected images were geocoded and a pixel aggregation was carried out consisting in calculating the average value of the pixels in a window corresponding to the pixel size degraded to about 300 m.

Table 1 shows the dataset of in-field and satellite data, with indication of acquisition time in order to illustrate match-ups among data and evaluate how data can be integrated to monitor water quality within a day. On 12 April 2012, after 10 years of service, Envisat stopped sending data to ESA Ground Segment, therefore MERIS data for 2012 were not available. The table also illustrates the lack of optical data due to cloud-cover.

Table 1 - Summary of data used in this study with indication of acquisition time in UTC (‘na’ stays for not available).

|                | 24 July 2011 | 3 Aug. 2011 | 4 Aug. 2011 | 30 July 2012 | 3 Aug. 2012 | 4 Aug. 2012 |
|----------------|--------------|-------------|-------------|--------------|-------------|-------------|
| Field          | na           | na          | na          | 09:30        | na          | na          |
|                |              |             |             | 16:00        |             |             |
| CSK            | 16:58        | na          | na          | 16:55        | 16:55       | na          |
| ASAR Envisat   | 09:15        | na          | 09:11       | na           | na          | na          |
| MODIS Terra/Aqua| 09:05/10:40  | 09:40/11:30 | 10:35       | cloud        | 09:50/11:40 | 10:35/12:25 |
| MERIS Envisat  | 09:15        | na*         | 09:11       | stopped      | stopped     | stopped     |

* = not used because not synchronous to the ASAR acquisition
### Image processing

#### Optical data

In order to identify the presence and the amount of cyanobacteria in the Curonian Lagoon, different indices based on NIR-Red band ratios (hereafter called NIR-R index) were applied to Rrs values extracted from MERIS and MODIS images [Gitelson et al., 2008]. The implementation of those indices is based on the work of Giardino et al. [2010] and Bresciani et al. [2013a] who developed a semi-empirical model to relate the ratio of MERIS Rrs values between 665 and 709 nm to Chl-a concentrations in the Curonian Lagoon. This model was thence used to convert Rrs MERIS data acquired on 24 July and 4 August 2011 into Chl-a concentrations. With respect to MODIS, the index was developed using the ratio of Rrs in bands 667 and 748 nm, which are the wavelengths closer to the MERIS bands. The MODIS-derived NIR-R index was compared with the two synchronous MERIS-derived Chl-a concentrations. Figure 2 illustrates the fit between MODIS-derived NIR-R index and MERIS Chl-a concentrations, with Chl-a ranging from 0 to up to 200 mg/m$^3$ with interval of 50 mg/m$^3$. The good agreement ($R^2>0.9$, $p<0.001$) found allowed us using the MODIS-derived index as a proxy of Chl-a concentrations, thence of cyanobacteria blooms. In particular, MODIS data can be used to overcome the MERIS stopped functionality for 2012; a further advantage of MODIS is the opportunity to have more than one acquisition per day with advantage to get more information on cyanobacteria dynamics.

![Figure 2 - Comparison between MERIS-derived Chl-a concentrations and the NIR-R index derived from Rrs MODIS data for detecting cyanobacteria blooms.](image)

#### SAR data

Microwave response of water surfaces is strongly influenced by the wind vector which affects its surface roughness. Therefore, the effect of wind on the measured NRCS was
determined to extract the contribution of cyanobacteria dispersed in the water column from the SAR NRCS.

For the C-band, the geophysical model function (GMF) relating the wind vector and the corresponding NRCS is provided by the semi-empirical backscatter models belonging to the C-band MODels (CMOD) family [Stoffelen and Anderson, 1997; Quilfen et al., 1998; Hersbach et al., 2007]. They are based on the following functional dependence:

\[
\sigma_0^{VV,C}(U_{10},\theta,\phi) = b_0(U_{10},\theta)[1 + b_1(U_{10},\theta)\cos\phi + b_2(U_{10},\theta)\cos2\phi]^n \quad [1]
\]

where \(\sigma_0^{VV,C}\) is the C-band VV polarization SAR NRCS, \(U_{10},\phi\) is the neutral 10 m wind speed and direction and \(\theta\) is the incidence angle of the radar beam. The exponent \(n\) is equal to 1.6 for the CMOD-5n model, which was selected for this study [Hersbach, 2008]. Finally, parameters \(b_i\)’s were statistically determined after comparison with wind data from the ECMWF atmospheric model.

A wind speed variability of about 10% can produce an uncertainty associated to GMF of about 10%. This is true except for winds lower than 3 m/s, where the GMF uncertainty monotonically decreases down [Portabella and Stoffelen, 2006].

The increasing availability of X-band SAR data gathered by the sensors on-board COSMO-SkyMED and TerraSAR-X, stimulated the development of new empirical geophysical models called XMOD [Nirchio and Venafra, 2010; Li et al., 2011; Ren et al., 2012]. In this work the linear XMOD was used [Ren et al., 2012], with the following GMF expression:

\[
\sigma_0^{VV,X}(U_{10},\theta,\phi) = x_0 + x_1 U_{10} - x_2 \sin\theta + x_3 \cos2\phi + x_4 U_{10}\cos2\phi \quad [2]
\]

where \(\sigma_0^{VV,X}\) is the X-band, VV polarized SAR NRCS. The variables \(x_i\)’s were statistically determined by using the ECMWF atmospheric model predictions as tuning dataset.

The CSK images used in this work were acquired in HH polarization so that, as for the C-band, a Polarization Ratio (PR) model should be adopted to express \(\sigma_{HH,X}\) from \(\sigma_{VV,X}\) values:

\[
P(\theta) = \frac{\sigma_0^{VV,X}}{\sigma_0^{HH,X}} = \frac{(1 + 2\tan^2\theta)^2}{(1 + \alpha \tan^2\theta)^2} \quad [3]
\]

with \(\alpha = 1.729\) for incidence angles in the range 20°-50° [Ren et al., 2012].

In this study, the mesoscale (10 km) wind predictions provided by the HIgh-Resolution Limited Area Model (HIRLAM, for a detailed description see http://hirlam.org) were used along with Equations [1], [2] and [3] to estimate the expected NRCS solely due to wind contribution and in the absence of cyanobacteria bloom on the water surface.

Given wind speed and direction, a reduced NRCS value with respect to clean water is
expected in presence of algal blooms. Since the algal bloom contribution to NRCS can be considered to be independent of the wind-induced NRCS, the attenuation model can be stated as follows:

\[ \Delta \sigma_0 = \sigma_0^{\text{SAR}} - \sigma_0^{\text{WIND}} \quad [4] \]

where \( \sigma_0^{\text{SAR}} \) is the NRCS measured on the SAR image and \( \sigma_0^{\text{WIND}} \) is the modeled wind-induced NRCS.

Results and discussion

Microwave data
The capability of ASAR in detecting cyanobacteria bloom was recently proved in [Bresciani et al., 2013a] where a dataset of 23 ASAR (C-band) images was analyzed to study the relationship between the attenuation of the NRCS and the presence of cyanobacteria bloom in terms of Chl-a concentration measurements directly retrieved on simultaneous MERIS images using the algorithm. The ASAR observations of cyanobacteria blooms were performed under different wind conditions ranging from quasi calm (<2 m/s) up to about 10 m/s and Chl-a concentrations exceeding 350 mg/m^3. C-band microwave data were feasible to detect cyanobacteria blooms in the range 2-6 m/s of wind speeds for which the algae layer was found to appreciably alter the water surface roughness. Indeed, calm wind conditions are not able to roughen the water surface, thus inhibiting any backscatter return from the water surface and therefore limiting retrieval/detection of cyanobacteria blooms; in turn, water column turbulence induced by moderate to high wind speeds may disperse the algae layer within the water body, thus reducing the algae accumulation on the surface. In addition, starting from values of Chl-a concentrations of about 50 mg/m^3 and up to about 150 mg/m^3, a linear increase of the NRCS attenuation (in dB) was observed. Although favorable ambient conditions for ASAR cyanobacteria blooms detection occurred only in the 18% of the analyzed cases, the combined exploitation of SAR and optical data can be envisaged to take full advantage from the all-weather, night/day SAR imaging capability. In this study the capability of X-band microwave data to detect cyanobacteria blooms was assessed by considering the CSK SAR image gathered on 30 July 2012 at 16:55 UTC. On the same day, nine stations in correspondence of intense cyanobacteria blooms were sampled in the northern part of the Curonian lagoon, within the Lithuanian political boundaries, and optically characterized by gathering Rrs data with the WISP-3 instrument [Hommersom et al., 2012]. The data set was collected in the first part of the day, approximately from 09:30 to 16:00 UTC. From in situ optical data, the NIR-R index was applied to derive a proxy of the Chl-a concentration [Gitelson, 2008]. The X-band NRCS attenuation (dB) corresponding to the location of the nine stations was estimated over the CSK SAR image. Due to the low wind speed (about 4 m/s), the drag effect on the algae blooms was only partially considered computing the CSK attenuation as mean value on a 2250 m x 2250 m window centered on each sampling station’s location. Although some changes on the cyanobacteria layer had occurred meantime the SAR overpass, the measured optical characteristics were assumed as representative of the algae composition at SAR time acquisition. A preliminary analysis
showed the expected trend of increasing X-band NRCS attenuation (dB) for increasing values of NIR-R index (Fig. 3) with a $R^2=0.82$ and $p<0.001$. However, the heuristic meaning of these results should be pointed out since a more rigorous approach has to be undertaken to establish the exact, quantitative relationship between X-band NRCS attenuation and Chl-a concentrations.

![Graph showing the dependence of X-band NRCS attenuation on NIR-R Index](image)

**Figure 3 - Dependence of the X-band NRCS attenuation as a function of NIR-R Index derived from *in situ* measurements.**

**Multi-sensor observations**

A subset of dates (i.e. 24 July 2011, 3-4 August 2011 and 3-4 August 2012) corresponding to highest number of synchronous multi-sensor overpasses, were selected in order to compare optical and microwave data with the aim to follow the evolution of cyanobacteria distribution inside the Curonian Lagoon.

MERIS and MODIS Rrs data were converted into the NIR-R index to get a proxy of cyanobacteria concentration. In case of ASAR and CSK data, the C-band and X-band NRCS attenuations ($\Delta\sigma_0$) were used. In order to sum up those parameters, a series of maps (Figs. 4, 5, 7) were generated by considering the averaged values ($\mu_G, \mu_S$) and corresponding standard deviations ($\sigma_G, \sigma_S$) of the NIR-R index, and $\Delta\sigma_0$ respectively.

Image pixels were clustered into three classes, each represented by a different color:

1. The blue color code corresponds to the pixels having a value of NIR-R Index lower than $\mu_G - \sigma_G$ (for optical images) and $\Delta\sigma_0$ higher than $\mu_S + \sigma_S$ (for radar images);
2. The red color code corresponds to the pixels having a value of NIR-R Index higher than $\mu_G + \sigma_G$ (for optical images) and $\Delta\sigma_0$ lower than $\mu_S - \sigma_S$ (for radar images);
3. The cyan color code otherwise.
In Figure 4 the results obtained for 24 July 2011 have been shown. The maps derived from MODIS and MERIS data, which were acquired 10 minutes apart, show the same pattern with differences only related to their slightly different pixel size. The observed spatial distribution could be explained by analyzing wind conditions. The average wind speed recorded during the early morning of 24 July 2011 was about 6 m/s, with prevailing South to North direction (Fig. 4). As the NIR-R Index is mostly in the range between $\mu_G-\sigma_G$ and $\mu_G+\sigma_G$, it is reasonable to assume that the wind induced mixing of the water column hampered the cyanobacteria cells to exploit their buoyancy capability to reach the water surface [Walsby et al., 2001]. Accordingly, accumulations of cyanobacteria (values higher than $\mu_G+\sigma_G$ on Figure 4 maps a, b, d) can be observed behind the Curonian Spit as it acts as a natural barrier that shields the area from the wind action. The relatively strong wind during the morning also determined a pepper-and-salt texture in the ASAR image (map c), which was acquired synchronously with MERIS. As indicated in Bresciani et al. [2013a], the radar attenuation signal is not able to discriminate cyanobacteria concentration when wind speed is higher or close to 6 m/s because of the wind capability to prevent the accumulation of cyanobacteria near the water surface. During the afternoon wind direction veered to N/NW and wind speed decreased to about 4 m/s. Finally, the CSK NRCS attenuation anomalies detected in the South-Eastern part of the lagoon (Fig. 4 map e) are in agreement with the water circulation patterns predicted for comparable wind regimes by Davulienė and Trinkūnas [2004].

MODIS, MERIS and ASAR images acquired on 3 and 4 August 2011 show similar patterns, with the central part of the lagoon characterized by red pixels (Fig. 5).
Blue pixels are mainly restricted to the southern and northern zones, the latter being the area with brackish waters, and in the region around the inflow of Nemunas river, where higher water mixing is occurring. These conditions not support cyanobacteria proliferation [Bresciani et al., 2013b]. The spatial distribution of classes recurring in all the five maps can be explained by stable moderate wind speed conditions (2-4 m/s). On 3 August 2011, the mean SST value measured all over the lagoon was of 21.5°C (±2°C), while on 4 August 2011 SST increased to 23.3°C (±2°C). Changes in water temperatures and wind direction can contribute to explain the variations in red patches extension (increase of 8%) and spatial distribution.

On 4 August 2011 both MERIS and ASAR sensors simultaneously acquired the area. In this case it is possible to provide a quantitative comparison between the estimated C-band NRCS attenuation and NIR-R index computed for the MERIS image. In order to accomplish this task a Region of Interest (ROI) has been selected being aware to discard pixels where NRCS can be influenced by other causes (land contamination, bathymetry, inlets, etc.).

The data points selected were then binned into 0.2 NIR-R Index interval and then shown in Figure 6. A good correlation between optical and microwave measures is obtained ($R^2 = 0.92$, $p$-value = 8.5×10^{-4}$), confirming the results found in case of X-band NRCS attenuation and the in situ NIR-R Index comparison. In addition, due to the presence of a more intense cyanobacteria scum, this case allows to observe the relation between SAR and optical data for high NIR-R Index values [3 – 5], with the corresponding NRCS which ranges from -11 to -8.5.
Figure 6 - Dependence of the C-band NRCS attenuation as a function of NIR-R Index derived from ASAR and MERIS images acquired on 4 August 2011.

Figure 7 - 3 and 4 August 2012 MODIS (a-b-d-e) maps of NIR-R index classification. (c) CSK NRCS attenuation classification image. The graph reports the temporal trend of wind speed and propagation direction during 6:00 UTC of the 3rd August 2012 and 15:00 UTC of the 4 August 2012 as predicted by HIRLAM model.
Meteorological conditions during 3 and 4 August 2012 were highly variable, both regarding wind conditions (speed and direction) and cloud cover as well. Looking at the maps in Figure 7 it is visible how clouds are moving and alternatively covering some parts of the lagoon, mainly in the southern part (Fig. 7). This condition strongly affects the growing and buoyancy capability of cyanobacteria, because cloud cover makes light intensity and water surface temperature consistently varying in the time. Solar radiation and temperature are two driving factors in the growing and proliferation of cyanobacteria cells [Bresciani et al., 2013a], particularly when wind is too low (about 2 m/s) to actively contribute in the cyanobacteria distribution, as it is our case. During the morning of 3 August 2012, the highest values of the index (i.e. \( \mu_G + \sigma_G \)) can be observed in the central-southern and central-northern part of the lagoon (Fig. 7, maps a-b). This spatial distribution is also noticed when considering the MODIS SST.

SST data (not shown) replicates the spatial pattern of maps a-b in Figure 7, showing mean values of 23.5°C in correspondence of index values \( \mu_G + \sigma_G \), and mean values of 20°C in correspondence of index values \( \mu_G - \sigma_G \). This observation supports the hypothesis that when wind action is not prevalent, solar radiations, and consequently temperature, are very important factors affecting cyanobacteria dynamics. The last three maps (Fig. 7 maps c-d-e) show common increased wind speeds (up to 6 m/s) and changed wind direction (East, South-East). SAR and MODIS images show index anomalies in the south-western point, while the central part of the lagoon is no longer interested by anomalous index values.

Conclusions

The waters of Curonian lagoon are heavily affected by cyanobacteria blooms. The high level of toxicity and the ability to change very quickly both in time and space deserve the urgent need to develop methods for comprehensive monitoring of such algae manifestations. Remote sensing techniques based on the exploitation of optical satellite sensors have demonstrated their capability of effective monitoring and characterization of the properties of cyanobacteria blooms. However, the potential of optical imaging is restricted to sun illuminated, clear sky conditions. As SAR sensors offer all-weather, day/night imaging capability, in this study was investigated the possibility to combine optical data with C-band and X-band SAR imagery to improve monitoring of cyanobacteria blooms. A set of images acquired between 2011 and 2012 by MERIS, MODIS, COSMO-SkyMED X-band SAR and Envisat C-band ASAR sensors was analyzed.

To characterize the cyanobacteria abundance, a proxy of Chl-a based on band-ratio indexes was extracted from available optical imagery and checked against its feasibility with MERIS-derived Chl-a concentration.

With respect to microwave data, the normalized radar cross section (NRCS) attenuation from selected X-band COSMO-SkyMED SAR images was compared with in situ optical measurements. Preliminary results confirmed the expected increase of the X-band NRCS attenuation with Chl-a concentration which was found using Envisat ASAR C-band NRCS data for high values of Chl-a (>50 mg/m³) and wind speed between 2 and 6 m/s [Bresciani et al., 2013a]. At the present stage of development, this study represents a first approach to combine microwave and optical observations aimed to provide suitable information on significant daily variation of cyanobacteria blooms. Although this preliminary conclusions need to be assessed by more rigorous, extensive quantitative comparisons between NRCS attenuation and Chl-a concentrations, the use of SAR data appears as a promising tool for the
identification of areas affected by cyanobacteria scums in conjugation with the optical data.

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