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Multitemporal analysis of algal blooms with MERIS images in a deep meromictic lake

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Abstract

MERIS images (2003-2011) were used to detect algal bloom events in Lake Idro (Northern Italy) applying a semi-empirical algorithm. From the study of an intense phenomenon occurred in late summer 2010, a retrospective analysis of similar events during late summer/early autumn period was performed. High intra- and inter-annual variability was observed and three additional bloom events were identified on 2003, 2005 and 2008. Hydrological and weather parameters were examined at different temporal intervals (August-October, September-October and monthly from August to October) to investigate the regulating factors of bloom incidence. Rather low temperatures and the persistence of clouds seem to facilitate starting and maintenance of blooms.

Keywords: Remote sensing, water quality, meteorological conditions, algal blooms, semi-empirical algorithm.

Introduction

Algal blooms, including cyanobacteria, are typical phenomena occurring in aquatic environments under periods of increased nutrient availability [Anderson et al., 2002; Glibert et al., 2005]. In oligotrophic and mesotrophic lakes spring and autumn overturn periods coincide with a mass transfer of key algal nutrients from the hypolimnion to the photic zone. Meromictic lakes do not mix surface and deep water due to permanent stratification of the water masses, and nutrients generally accumulate in high concentrations in the bottom water layers, adjacent to sediments. Here, understanding of the mechanisms regulating algal blooms is particularly intriguing as such phenomena are much less predictable in their timing and spatial dynamics. Furthermore, traditional sampling activities, according to the Water Framework Directive [Directive, 2000], are generally performed, for small lakes, on a single station, usually coinciding with the point of maximum lake depth, that is chosen as representative of the average conditions of the entire water body [Tonolli, 1964]. This sampling protocol do not have an high frequency that allow to catch sudden and temporary phenomena (a few days) as blooms. The strength of remote sensing techniques lies in their ability to provide both spatial and temporal views of surface

water quality parameters that is typically not possible from in situ measurements [Giardino et al., 2010]. Lake Idro is a meromictic deep basin which *whole lake* management was almost exclusively addressed to electricity production and irrigation and, to a minor extent, for touristic purposes. Productive-oriented management has resulted in dramatic drops and rises of water levels (up to 7 m, representing about 20% of the epilimnion) with cascading implications for the lake processes and functions. In the past only a few sampling campaigns aiming at the evaluation of the lake trophic status were realized; these research activities were mostly sporadic and irregular [Barbanti et al., 1994]. Only recently (2010-2012) Lake Idro water quality was monitored on a monthly basis. In one occasion water sampling coincided with an algal bloom occurring over the whole lake surface [Bresciani et al., 2011a].

In order to obtain information about the past occurrence of such phenomena in Lake Idro, remote sensing techniques offer an interesting option; they have, in fact, the important advantage to make retrospective analyses possible when past images are available [e.g., Olmanson et al., 2008; Hadjimitsis et al., 2010; Hu et al., 2010; Lazzara et al., 2010]. This represents undoubtedly an advantage when information gathered with traditional sampling approaches are missing.

Among water quality features of the euphotic zone, remote sensing techniques allow to characterize surface water temperatures, total suspended matter, yellow substances concentration, water transparency, chlorophyll-a and algal bloom events occurrence [e.g., Lindell et al., 1999; Kutser et al., 2005; Bresciani et al., 2009; Matarrese et al., 2011].

Bresciani et al. [2011a] analyzed the algal bloom event occurred in Lake Idro between the end of the summer and the beginning of the autumn 2010, integrating radiometric and limnological in situ measures with the goal of obtaining useful information about the features of the different algal groups forming the bloom (Cyanobacteria: *Microcystis* spp., *Planktothrix* spp., *Pseudanabena* cf. *limnetica*, *Aphanocapsa* sp., *Aphanizomenon* cf. *gracile*; Chrysophyte: *Dinobryon sociale* var. *stipitatum* and Bacillariophyceae: *Fragilaria ulna* var. *acus*). Algal presence and development actually cause a significant loss of water transparency, alter temporarily the transfer of energy along the trophic chains and negatively impact lake's recreational and touristic value. *In situ* measures allowed the implementation of a semi-empirical algorithm, based on the characteristic spectral response by photosynthetic pigments around 590 nm [Gregora and Maršálek, 2005; Sparks et al., 2009], to derive a specific index able to detect algal bloom events occurrence. This index was applied to ENVISAT-MERIS (MEDIum Resolution Imaging Spectrometer) images and the availability of multiple acquisitions during spring and autumn periods enabled the observation of temporal and spatial dynamics relative to the 2010 bloom event. From these encouraging results the present work has the objective of applying the same algorithm to historic MERIS images for the period 2003-2011 focusing our analysis on late summer and early autumn (during the August-October period) in order to detect the past occurrence of events similar to the 2010 algal bloom.

Semi quantitative index cannot provide exhaustive information about water quality in Lake Idro, but, since the phytoplankton component is of crucial importance to determine the trophic status of lake waters [Jeppesen et al., 2003; Carvalho et al., 2008], its definition is an important factor to be integrated with other information [Carvalho et al., 2008; Bresciani et al., 2011b]. For a better comprehension of different factors interacting with algal growth events, the index has been correlated with water levels and inflow tributary (River Chiese) amounts and with meteorological local conditions, as we expected that in a meromictic lake these aspects can influence algal bloom phenomena [Giardino et al., 2010; Thorne and Fenner, 2011; Salmaso and Cerasino, 2012].

Study area

Lake Idro is a meromictic southern deep alpine lake located in the Northern part of Italy at an altitude of 368 m a.s.l. across the provinces of Brescia and Trento (between Lombardy and Trentino-Alto Adige Regions) (Fig. 1).

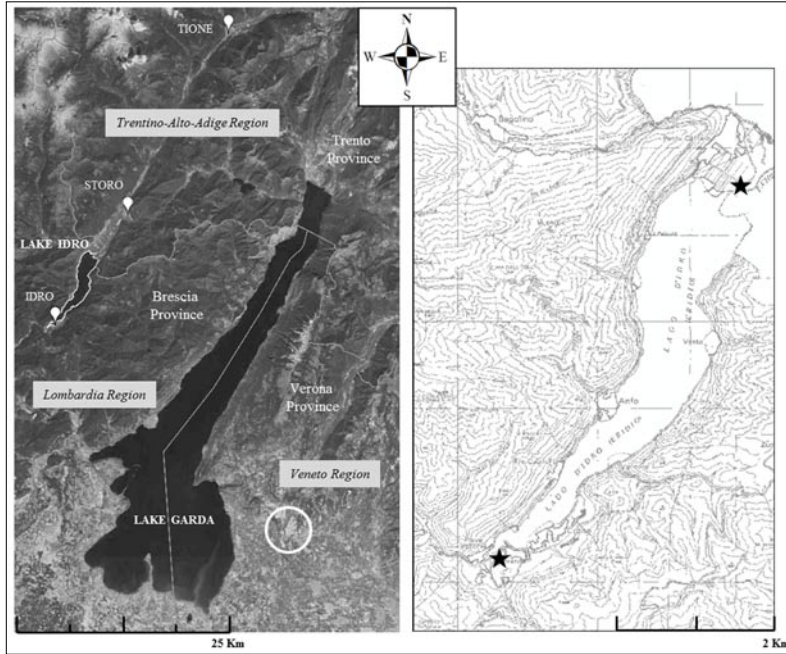


Figure 1 - Lake map with the localization of the local weather stations (TIONE, STORO, IDRO) and the sampling points used for the monitoring of water level fluctuations and inflow and outflow rates (stars). The white circle indicates the urbanized area used for validation of atmospheric correction.

The lake surface is equal to 11.03 km², with a maximum length of 9.4 km, a maximum depth of about 124 m and a volume approximately of 8.5x10⁸ m³. According to its trophic status the lake is meso-eutrophic and belongs to the meromictic type of circulation. Currently, the upper mixed water zone (the oxic layer) varies between 40 m and 50 m of depth, approximately 50-60% of the entire lake volume is permanently stratified and oxygen-free [D. Nizzoli, data not published].

This basin plays an important role in the economy of the local population essentially in terms of tourism and recreation; however, it is also the first Italian natural lake completely converted into a hydroelectric reservoir in 1929. Consequently, because of the huge drawdown and water level fluctuations imposed by hydropower exploitation, and the increase in pollutants delivery from its catchment since early 1970s, the basin underwent a progressive worsening of water quality and biotic component. The mid-term ecological consequence of these perturbations is the increase of the bottom layer of water (usually free of oxygen) moving from about a depth of 70-80 m (late 1960s) up to currently 40-50 m

[Garibaldi et al., 1997]. In the last ten years, a progressive steep reduction in the amplitude of artificial water level fluctuations, coupled with the accumulation of organic matter and nutrients in waters and surface sediments, enhanced a rapid and intense proliferation of littoral vegetation, but also recurrent algal blooms [R. Bolpagni, data not published].

Materials and methods

Thirty MERIS images ranging from 2003 to 2011, in addition to the six images already used in the previous study [Bresciani et al., 2011a] were analyzed in this work (Tab. 1).

Table 1 - MERIS images list, acquired between 2003 and 2011, with relative acquisition time and spatial resolution. In the table are also included all parameter values used as input for the atmospheric correction (Aerosol Optical Thickness = AOT, sun and sensor viewing angles).

data	hour (GMT)	Pixel size (m)	AOT (@550nm)	Sun zenith angles (deg)	Sun azimuth angles (deg)	View zenith angles (deg)	View azimuth angles (deg)
2003-08-19	10:00	341.5	0.10	37.10	146.13	11.35	286.30
2003-09-13	10:14	341.8	0.07	43.83	158.54	30.57	288.83
2003-09-26	10:06	330.9	0.06	48.96	158.98	19.56	287.31
2003-10-10	09:25	317.7	0.01	56.75	150.41	36.77	100.28
2004-08-22	10:03	341.7	0.07	37.90	148.30	15.55	286.80
2004-09-04	09:54	319.1	0.12	42.62	149.28	2.79	285.28
2004-09-17	09:46	304.5	0.07	47.59	150.40	10.32	103.78
2005-09-02	09:46	283.6	0.11	42.73	145.69	10.30	103.79
2005-09-24	09:55	281.6	0.10	49.21	154.99	2.71	285.29
2005-10-13	09:57	326.8	0.06	55.68	160.06	7.06	285.79
2005-10-16	10:03	295.2	0.10	56.41	162.21	15.49	286.80
2006-08-31	09:37	312.0	0.02	42.95	142.10	22.73	102.28
2006-09-12	10:00	281.1	0.10	44.62	153.44	11.39	286.29
2006-09-22	09:45	285.2	0.13	49.11	151.68	10.45	103.79
2006-10-11	09:48	320.4	0.03	55.45	157.15	6.12	104.29
2007-09-13	09:57	304.1	0.03	45.09	152.70	7.15	285.79
2007-09-23	09:43	279.4	0.05	49.59	151.02	14.43	103.30
2007-10-02	10:00	289.9	0.08	51.47	158.55	11.33	286.30
2007-10-15	09:51	317.2	0.01	56.57	158.66	1.67	104.80
2008-09-09	10:19	294.4	0.05	42.39	159.61	36.90	289.86
2008-09-16	10:00	286.9	0.03	46.15	154.68	11.35	286.30
2008-09-29	09:51	311	0.07	51.25	155.40	1.57	104.82
2008-10-09	09:38	294.4	0.10	55.78	153.53	22.74	102.29
2009-09-08	09:40	306.3	0.10	45.17	145.68	18.73	102.78
2009-09-23	10:08	285.2	0.02	47.92	159.22	23.51	287.82
2009-10-16	09:46	304.5	0.20	57.46	157.27	10.40	103.78
2010-08-26	10:16	299.2	0.15	37.83	154.54	33.77	289.34
2010-09-12	09:42	303.2	0.15	46.10	147.77	14.53	103.29
2010-09-15	09:48	288.1	0.05	46.57	150.48	6.04	104.29
2010-09-21	09:59	288.7	0.12	47.73	155.86	11.39	286.30
2010-09-28	09:39	301.2	0.10	51.66	151.50	18.73	102.78
2010-10-20	09:48	284.2	0.05	58.56	158.65	6.02	104.28
2011-09-13	09:48	370.4	0.08	48.65	160.85	19.98	287.25
2011-09-26	10:11	321.1	0.06	45.84	149.77	15.44	103.16
2011-10-05	09:42	295.8	0.05	53.81	153.81	24.88	101.99
2011-10-10	09:59	306.9	0.03	54.40	159.77	0.04	194.79

Images without any cloud cover and including the whole lake surface were selected during the period going from half of August to half of October, when bloom events are generally recorded [Garibaldi et al., 2003; Salmaso, 2010].

MERIS sensor, working from 2002 onboard of ENVISAT platform, was purposely built to study aquatic ecosystems; in fact, it presents an appropriate signal to noise ratio, high temporal acquisition frequency (important characteristic to monitor very dynamic environments such as waters) and suitable spectral bands (Tab. 2) for a correct detection of water optical properties.

Table 2 - Radiometric characteristics of MERIS sensor (expressed in nanometers = nm).

Band	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Center of band	413	443	490	510	560	620	665	681	709	754	761	779	865	885	900
Width of band	10	10	10	10	10	10	10	7.5	10	7.5	3.75	15	20	10	10

MERIS full resolution (FR) level 1B images were processed with the ESA Basic Envisat/ERS ATSR and MERIS (BEAMv. 4.2) toolbox [Fomferra and Brockmann, 2006; Bresciani et al., 2011a]. In particular, the smile correction was applied to the FR level 1B data, subsequently corrected for adjacency effects [Santer et al., 2007] by using the improved contrast between land and ocean (ICOL) plug-in.

Satellite radiances were converted into Remote sensing reflectance (Rrs) values by using the simulation of the 6S (Satellite Signal in the Solar Spectrum) code [Vermote et al., 1997; Kotchenova et al., 2006]. The 6S code was run by setting the aerosol type as continental, while the aerosol optical thickness at 550 nm was taken from measurements available from AERONET [NASA, 2012] in correspondence with the stations nearest to the study area (i.e., Ispra, Venice and Davos, about 130 km to the west, 140 km to the east and 100 km to the north, respectively).

The 6S-corrected data have been validated by checking if, for the whole images, the reflectance values of spectrally invariant surfaces (e.g. urbanized area characterized by industrial areas and marble quarries, 45°31'45"N and 10°49'00"E in Fig. 1, highlighted by a white circle) were constant. Total albedo values for all the MERIS 14 bands (except band 11, where atmospheric absorption is prevalent) turned out ranging from a minimum of 2.15 Wm⁻²sr⁻¹μm⁻¹ to a maximum of 2.49 Wm⁻²sr⁻¹μm⁻¹, with an average value of 2.31 Wm⁻²sr⁻¹μm⁻¹ and variance corresponding to 0.013. For every atmospherically corrected image and for every MERIS spectral band, no pixels with negative value or cloud pixels with value higher than 1 were registered, demonstrating that AOT values used were respectively not too high or too low.

In accordance with Bresciani et al. [2011a], the ratio MERIS band 6 (620 nm)/ MERIS band 5 (560 nm) was applied to Rrs values of atmospheric corrected images. Successively, a minimum threshold of 0.82 was used to identify the presence of algal bloom.

The spectral bands used to estimate the algal grow can be affected by a significant amount of total suspended matter (TSM) usually influenced by heavy precipitations. For this reason, TSM presence was also evaluated, observing its albedo in the near-infrared bands (10-12-13-14), typically increasing with TSM quantities [Ruddick et al., 2006; Wang and Lu, 2009]. Furthermore, this analysis can also be useful to determine possible disturbances due to cirrus presence [Pepe et al., 2005].

In order to detect any potential noise, in situ measures from 2010 were considered, when TSM values were on average equal to 1.2 mg l^{-1} (± 0.25), with correspondent albedo values of $0.017 \text{ Wm}^{-2}\text{s}^{-1}\mu\text{m}^{-1}$ (± 0.014).

Meteorological data (Fig. 2) were taken at Storo ($45^{\circ}49' \text{ N}$; $10^{\circ}32' \text{ E}$; 375 m a.s.l.), Idro ($45^{\circ}44' \text{ N}$; $10^{\circ}28' \text{ E}$; 371 m a.s.l.), and Tione weather stations ($46^{\circ}01' \text{ N}$; $10^{\circ}43' \text{ E}$; 539 m a.s.l.). Precipitation values were recorded at Storo from 01/01/2003 to 24/06/2008 and successively at Idro station; air temperature values were taken at Tione station for the period 01/01/2003 - 16/11/2005, while from 17/11/2005 to 24/06/2008 they were collected at Storo and afterwards at Idro station.

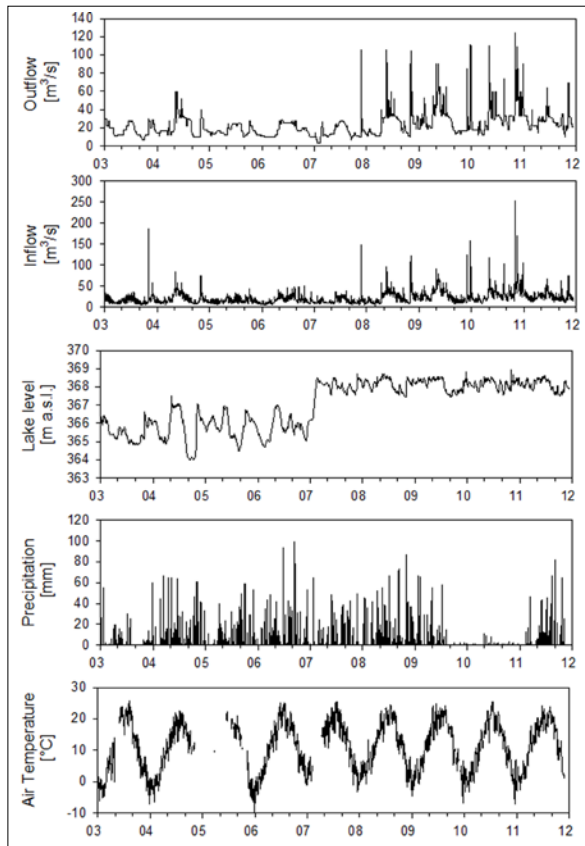


Figure 2 - Hydrological (Inflow, Outflow and Lake Water Level) and weather parameters (Precipitation and Air Temperature) evolution during the period 2003-2011.

In order to better understand the role of cloud cover presence in the bloom phenomenon, a temporal analysis of different satellite images was performed along the year period with most probability of bloom occurrence (August-October). Data from four different sensors (SeaWiifs, MODIS Terra, MODIS Aqua, MERIS) ranging from 9:00 a.m. to 2:00 p.m.

(depending on single satellite orbits) were examined for each day in the considered time range. It was possible to dispose of at least three images in a day. For each single day and for each single sensor, the cloud cover was classified as present, partially present and absent. Then, data from the different sensors were averaged to obtain a single value in a day. Student's t-test was performed in order to test differences in mean values of hydrological and weather parameters between bloom and non-bloom years at three different time scales of investigation: (a) three months periodicity (pooling data from August, September and October), (b) September-October period, and (c) using data of August, September and October separately [R Development Core Team, 2010]. The statistical analyses were performed on the mean parameter values in order to avoid temporal autocorrelation biases in accordance with [Helsel and Hirsch, 2002]. With respect to the October data, the present investigation was limited to the first ten days corresponding to the descending phase of the late-summer algae blooms in Lake Idro [Bresciani et al., 2011a].

Results and discussion

Figure 3 shows mean values (considering the whole lake surface) relative to the index $b6/b5$ (proxy of algal bloom events) derived from MERIS images along the study period (dates on the x-axis). It is possible to compare these values with the threshold value considered as the reference minimum number to detect one algal bloom event (dotted black line in Fig. 3). The consistent algal bloom event in 2010 is extremely visible in Figure 3.

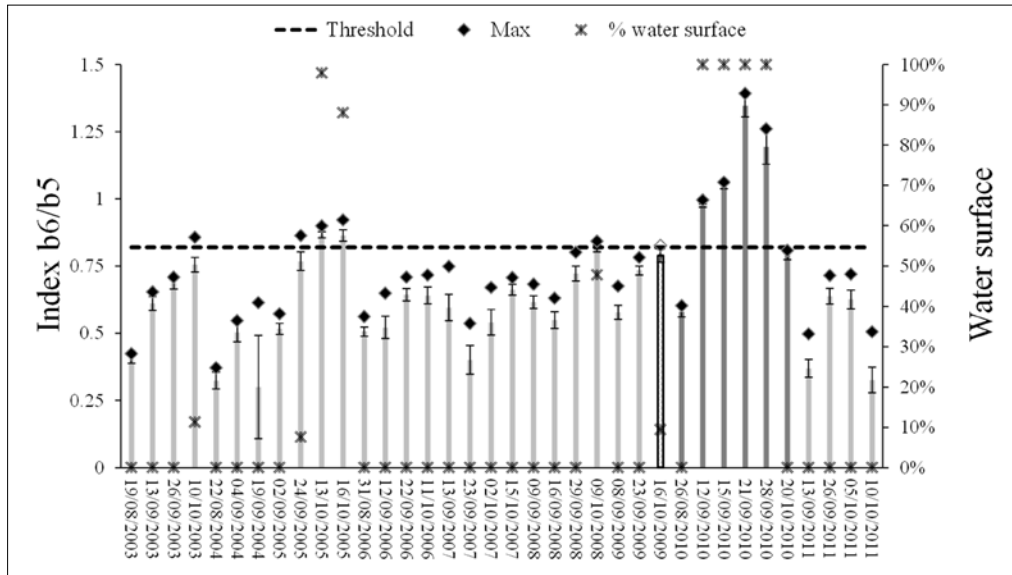


Figure 3 - Average index ($b6/b5$) values (grey bars) computed over the entire surface of Lake Idro (primary y-axis) as a function of the date of acquisition of the MERIS images (x-axis); the black diamond markers show the maximum punctual value of the index (estimated in correspondence of a single pixel). Stars represent the percentage of the lake surface (on the secondary y-axis) for which the pixel-based index values are above the threshold (horizontal black dotted line).

Besides, it is also clear that even during the rest of the years the considered index has an increasing trend in the period going from the end of the summer to the beginning of the autumn, suggesting that the transition summer-autumn is coupled with relevant changes within the lake epilimnion. These can be a consequence of drastic drops in available irradiance for pelagic primary producers, forcing vertical migration of algal groups generally confined in relatively deep water layers [Walsby et al., 2004]. Late summer is also the period of the collapse of macrophytic production, meaning that over the whole lake perimeter the littoral zone becomes probably a source of nutrients from decaying biomass and loses its buffer capacity against diffuse nutrients from the lake basin. Both events can affect nutrient availability and nutrient stoichiometry, and, as a consequence, be implied in the formation of algal blooms.

In 2004 it was not possible to detect water lake conditions after September 19th because of the persistent cloud cover preventing the satellite sensor observation. October 16th 2009 was also excluded because characterized by very high reflectance values in the near-infrared spectral region, potentially due to high TSM concentrations or to cirrus presence. The comparison between the average index values and the threshold index value (horizontal dotted line) shows that algal bloom events occurred not only during 2010, but also in 2003, 2005, 2008; even if only during 2005 on October 13th and 16th the phenomenon occupied the total lake surface (red stars). These observations highlight the large water quality variability in Lake Idro, displaying both intra- and inter- annual variations. Figure 4 shows some photographs acquired during the study period, which confirm the presence of algal bloom events.



Figure 4 - Algal bloom event pictures: a = 2003, b = 2008, and c = 2010.

From the whole weather data-set, together with water levels and water inflow/outflow rates, mean values (\pm standard deviation) for the three periods analyzed were extracted (Tab. 3).

These values can strongly influence growth and reproduction of macrophytes, an essential element in lacustrine balances conditioning even phytoplankton proliferation [Le Bagousee-Pinguet et al., 2012]. On the other hand, in very deep lacustrine ecosystems as Lake Idro (with mean depths greater than 15-20 m) metabolic pathways should be mainly controlled by phytoplankton, whereas macrophytes should limit their buffering effect on the littoral areas (up to 10 m of depth). The relative role of external loads, internal recycling, primary production by macrophytes and phytoplankton for the Lake Idro nutrient budget will add important information to the present picture and will allow to go deeper in the understanding of bloom formation [Nizzoli personal communication].

Overall, hydrological and weather parameter patterns comparison did not allow to detect

significant differences between bloom and non-bloom years with the exception of October temperatures (Tabs. 3 and 4).

Table 3 - Bloom (B) and non bloom (NB) years comparison: the table reports the mean values (\pm standard deviation) of water (LL = Lake level fluctuation, IF = Inflow and OF = Outflow rate) and weather parameters data (TE = Temperature, PR = Precipitation, and CC = Cloud covering rate) considering three different time scales of investigation: (A-O) August-October period, (S-O) September-October period, and using data referred to August (A), September (S), and October (O) months, separately; \S = rainfall totals *per period*⁻¹; \dagger = number of clear days *per period*⁻¹.

		A-O			S-O			A			S			O		
LL	B	366.7 \pm 1.5			366.6 \pm 1.4			366.4 \pm 1.6			366.5 \pm 1.4			366.9 \pm 1.2		
	NB	366.8 \pm 1.4			366.6 \pm 1.5			366.9 \pm 1.2			366.6 \pm 1.5			366.7 \pm 1.5		
IF	B	23.0 \pm 12.7			19.5 \pm 10.0			21.7 \pm 13.1			18.6 \pm 9.6			21.9 \pm 10.8		
	NB	19.2 \pm 8.3			16.0 \pm 7.9			22.0 \pm 7.0			16.4 \pm 8.5			14.6 \pm 5.7		
OF	B	23.3 \pm 10.1			17.5 \pm 3.6			22.5 \pm 10.8			16.9 \pm 7.7			19.2 \pm 9.5		
	NB	20.2 \pm 6.8			15.8 \pm 5.6			24.4 \pm 4.5			15.9 \pm 6.1			15.4 \pm 3.8		
TE	B	16.8 \pm 3.9			14.4 \pm 2.9			19.8 \pm 2.8			15.1 \pm 2.6			12.1 \pm 2.7		
	NB	17.6 \pm 3.1			16.1 \pm 2.6			19.6 \pm 2.5			16.6 \pm 2.6			14.8 \pm 2.2		
PR	B	2.9 \pm 9.5	795.4 \S		3.5 \pm 11.6	530 \S		2.2 \pm 5.2	265.4 \S		3.5 \pm 11.8	397.4 \S		3.4 \pm 11.1	132.6 \S	
	NB	4.0 \pm 11.3	1384.6 \S		3.1 \pm 11.6	594.2 \S		5.9 \pm 10.8	790.4 \S		3.3 \pm 12.6	464.4 \S		2.6 \pm 8.3	129.8 \S	
CC	B	0.6 \pm 0.4	64 (16) \dagger		0.7 \pm 0.4	29 (7) \dagger		0.5 \pm 0.4	35 (9) \dagger		0.6 \pm 0.4	23 (6) \dagger		0.7 \pm 0.4	6 (2) \dagger	
	NB	0.5 \pm 0.4	93 (19) \dagger		0.5 \pm 0.4	51 (13) \dagger		0.5 \pm 0.4	42 (8) \dagger		0.5 \pm 0.4	41 (8) \dagger		0.6 \pm 0.4	10 (2) \dagger	

Table 4 - Student's test results for the water (LL = Lake Level; IF = Inflow and OF = Outflow rate) and weather (TE = Temperature; PR = Precipitation; CC = Cloud cover) parameters referred to three different time-lag periods of analysis: a) three month periodicity (from August to October); b) considering September-October period; c) monthly periodicity considering August, September and October months separately. Levels of significance: '**' = 0.001; '**' = 0.01; '*' = 0.05; '.' = 0.1; 'n.s.' = 1.**

Investigation period	LL	IF	OF	TE	PR	CC
Three months	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
September – October	n.s.	n.s.	n.s.	.	n.s.	.
August	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
September	n.s.	n.s.	n.s.	n.s.	n.s.	.
October	n.s.	n.s.	n.s.	**	n.s.	n.s.

Effectively, in the first days of October higher temperatures were detected during the non bloom years (mean, 14.8 \pm 2.2 $^{\circ}$ C; range, 8.6~18.0 $^{\circ}$ C) compared to bloom ones (mean, 12.1 \pm 2.7 $^{\circ}$ C; range, 6.5~16.3 $^{\circ}$ C). A similar, but not significant, tendency was also observed for the temperature data of the September-October period, in which higher mean values occurred in non bloom years (mean, 16.1 \pm 2.6 $^{\circ}$ C; range, 8.6~22.3 $^{\circ}$ C) relative to bloom ones (mean, 14.4 \pm 2.9 $^{\circ}$ C; range, 6.5~21.9 $^{\circ}$ C). These results are consistent with the hypothesis that cold waters (air temperature-related) may stimulate the upward migration of cyanobacteria to the water surface [D'Alelio and Salmaso, 2011; Bonilla et al., 2012].

Likewise, both in September and September-October periods, a rather high number of non cloudy days was detected in non bloom years (equal to 13 and 8 days for September-October and September periods, respectively) compared to bloom ones (equal to 7 and 6 days for September-October and September periods, respectively) even though no statistical significance levels have been reached (Tab. 4). As already observed by Walsby et al. [2004] and by D'Alelio et al. [2011] large amounts of insolation during the day, typical of summer months, reduce the cyanobacteria buoyancy ability, determining their staying at high depths, while low irradiance typical of autumn months favors their migration to the water surface. Contemporaneously, during the August-October period in non bloom years total rainfall reached a mean value of 1385 mm against a mean of 795 mm in bloom years.

On the other hand, despite the August month's rainfalls contributed to about half of the total precipitations in the period investigated, no evidences suggested a direct link between rains and the onset and the persistence of algal blooms. Consequently, this evidence suggests that in the Lake Idro the diffuse input of nutrients from the basin is probably scarcely relevant if compared to point sources of pollutants or to internal recycling in leading algal proliferation. Trout aquaculture associated nutrient loads from the main lake tributary, phosphorus and nitrogen recycling from littoral (and deep) sediments and diffusing to the upper water layers could be relevant drivers of algal blooms in the Lake Idro [Salmaso et al., 2012].

In Lake Idro, these outcomes indicate that the stability/instability of water and weather parameters during the two months presiding the period of image acquisition (late September-early October) seemed to not have a univocal and dominant effect on the regulation of the onset of phytoplankton blooms. It has also to be noticed that a well stratified lake is less influenced by meteorological dynamics if compared with other lakes often recycling their waters. In Lake Idro the situation is therefore complicated by the constant water stratification and the consequent interpretation of bloom phenomena is an hard issue, because not only explainable by weather aspects.

In order to fully understand bloom events occurred in Lake Idro it would be necessary to evaluate the large-scale climatic fluctuations interesting the Mediterranean area, which can influence the phytoplankton developing in subalpine lakes, as highlighted by Salmaso [2012] and couple meteorological information with local nutrient dynamics.

Conclusions

This work confirmed the importance of remote sensed techniques to realize a multitemporal analysis about lake water quality, despite the limiting spatial resolution of satellite images with respect to the lake extension and the impossibility to have information about cloud covered periods, sometimes correspondent to greatly significant periods.

The performed analysis identified the algal bloom event of 2010 as the largest and unusual phenomenon occurred in Lake Idro in the last nine years, but it also proved that other high algal growth events occurred even in the past, although with less intensity. Our data suggest a possible role of temperatures and cloud cover in the genesis of algal blooms. For instance, these events can result from vertical migration of algal cells under low irradiance conditions. Furthermore, algal blooms can be triggered by littoral release of nutrients during the senescence period of the macrophytic biomass or by internal nutrient recycling. Overall, the complex phenomenon of onset of algal blooms requires further in-situ information to well explain the growing dynamics of phytoplankton.

In the future, the possibility to dispose of satellite images with better spatial and radiometric resolutions, such as the Sentinel sensors by ESA and PRISMA sensor by ASI, will improve the studies about algal bloom phenomena in Lake Idro, being useful for the comprehension of the specific ecologic dynamics.

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Bibliography

- Anderson D., Glibert P., Burkholder J. (2002) - *Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences*. Estuaries and Coasts, 25: 704-726. doi: <http://dx.doi.org/10.1007/BF02804901>.
- Barbanti L., Baudo R., Calderoni A., de Bernardi R., Galanti G., Giussani G., Mosello R. (1994) - *Valutazione della situazione limnologica del Lago d'Idro sulla base delle conoscenze bibliografiche ed alla luce degli usi preminenti delle acque*. C.N.R. Istituto Italiano di Idrobiologia, Report 01.94: 42.
- Bonilla S., Aubriot L., Soares M.C.S., González-Piana M., Fabre A., Huszar V.L.M., Lüring M., Antoniadis D., Padišák J., Kruk C. (2012) - *What drives the distribution of the bloom-forming cyanobacteria *Planktothrix agardhii* and *Cylindrospermopsis raciborskii*?* FEMS Microbiology Ecology, 79: 594-607. doi: <http://dx.doi.org/10.1111/j.1574-6941.2011.01242.x>.
- Bresciani M., Giardino C., Longhi D., Pinaridi M., Bartoli M., Vascellari M. (2009) - *Imaging spectrometry of productive inland waters. Application to the lakes of Mantua*. Italian Journal of Remote Sensing, 41: 147-156. doi: <http://dx.doi.org/10.5721/ItJRS20000941211>.
- Bresciani M., Giardino C., Bartoli M., Tavernini S., Bolpagni R., Nizzoli D. (2011a) - *Recognizing harmful algal bloom based on remote sensing reflectance band ratio*. Journal of Applied Remote Sensing, 5. doi: <http://dx.doi.org/10.1117/1.3630218>.
- Bresciani M., Stroppiana D., Odermatt D., Morabito G., Giardino C. (2011b) - *Assessing remotely sensed chlorophyll-a for the implementation of the Water Framework Directive in European perialpine lakes*. Science of the Total Environment, 409: 3083-3091. doi: <http://dx.doi.org/10.1016/j.scitotenv.2011.05.001>.
- Carvalho L., Solimini A., Phillips G., van den Berg M., Pietiläinen O.P., Lyche Solheim A., Poikane S., Mische U. (2008) - *Chlorophyll reference conditions for European intercalibration lake types*. Aquatic Ecology, 42: 203-11. doi: <http://dx.doi.org/10.1007/s10452-008-9189-4>.
- D'Alelio D., Salmaso N. (2011) - *Occurrence of an uncommon *Planktothrix* (*Cyanoprokaryota*, *Oscillatoriales*) in a deep lake south of the Alps*. Phycologia, 50

- (4): 379-383. doi: <http://dx.doi.org/10.2216/10-73.1>.
- D'Alelio D., Gandolfi A., Boscaini A., Flaim G., Tolotti M., Salmaso N. (2011) - *Planktothrix populations in subalpine lakes: selection for strains with strong gas vesicles as a function of lake depth, morphometry and circulation*. *Freshwater Biology*, 56 (8): 1481-1493. doi: <http://dx.doi.org/10.1111/j.1365-2427.2011.02584.x>.
- Directive. Directive 2000/60/EC of the European Parliament and of the council of 23 October 2000 establishing a framework for community action in the field of water policy. Off J Eur Communities 2000: L327:1-72.
- Fomferra N., Brockmann C. (2006) - *The BEAM project web page (Internet)*. Carsten Brockmann Consult, Hamburg, Germany. Available at: <http://www.brockmannconsult.de/beam/> (last accessed: 05/09/2012).
- Garibaldi L., Brizzio M.C., Galanti G., Varallo A., Mosello R. (1997) - *Idrochimica e fitoplancton del Lago d'Idro*. Documenta Ist. ital. Idrobiol., 61: 153-172, IT.
- Garibaldi L., Anzani A., Marieni A., Leoni B., Mosello R. (2003) - *Studies on the phytoplankton of the deep subalpine Lake Iseo*. *Journal of Limnology*, 62 (2): 177-189. doi: <http://dx.doi.org/10.4081/jlimnol.2003.177>.
- Giardino C., Bresciani M., Villa P., Martinelli A. (2010) - *Application of remote sensing in water resource management: the case study of lake Trasimeno, Italy*. *Water Resource Management*, 24: 3885-3899. doi: <http://dx.doi.org/10.1007/s11269-010-9639-3>.
- Glibert P.M., Anderson D.A., Gentien P., Graneli E., Sellner K.G. (2005) - *The global, complex phenomena of harmful algal blooms*. *Oceanography* 18 (2): 136-147. doi: <http://dx.doi.org/10.5670/oceanog.2005.49>.
- Gregora J., Maršálek B. (2005) - *A Simple In Vivo Fluorescence Method for the Selective Detection and Quantification of Freshwater Cyanobacteria and Eukaryotic Algae*. *Acta hydrochimica et hydrobiologica*, 33 (2): 142-148. doi: <http://dx.doi.org/10.1002/ahch.200400558>.
- Hadjimitsis D.G., Clayton C.R.I., Toullos L. (2010) - *A new method for assessing the trophic state of large dams in Cyprus using satellite remotely sensed data*. *Water and Environment Journal*, 24: 200-207. doi: <http://dx.doi.org/10.1111/j.1747-6593.2009.00176.x>.
- Helsel D.R., Hirsch R.M. (2002) - *Statistical methods in water resources*. U.S. Geological Survey Techniques of Water-Resources Investigations. 4 (A3): 510 p. (<http://water.usgs.gov/pubs/twri/twri4a3>).
- Hu C., Cannizzaro J., Carder K.L., Muller-Karger F.E., Hardy R. (2010) - *Remote detection of Trichodesmium blooms in optically complex coastal waters: Examples with MODIS full-spectral data*. *Remote Sensing of Environment*, 114: 2048-2058. doi: <http://dx.doi.org/10.1016/j.rse.2010.04.011>.
- Jeppesen E., Jensen J.P., Jensen C., Faafeng B., Hessen D.O., Søndergaard M., Lauridsen T., Brettum P., Christofersen K. (2003) - *The impact of nutrient state and lake depth on top-down control in the pelagic zone of lakes: a study of 466 lakes from the temperate zone to the Arctic*. *Ecosystems*, 6: 313-325. <http://dx.doi.org/10.1007/PL00021503>.
- Kotchenova S.Y., Vermote E.F., Matarrese R., Klemm F.J. (2006) - *Validation of a vector version of the 6S radiative transfer code for atmospheric correction of satellite data. Part I: Path radiance*. *Applied Optics*, 45 (26): 6762-6774. doi: <http://dx.doi.org/10.1364/AO.45.006762>.

- Kutser T., Pierson D., Kallio K., Reinart A., Sobek S. (2005) - *Mapping lake CDOM by satellite remote sensing*. Remote Sensing of Environment, 94: 535-540. doi: <http://dx.doi.org/10.1016/j.rse.2004.11.009>.
- Lazzara L., Marchese C., Massi L., Nuccio C., Maselli F., Santini C., Pieri M., Sorani V. (2010) - *Sub-regional patterns of primary production annual cycle in the Ligurian and North Tyrrhenian seas, from satellite data*. Italian Journal of Remote Sensing, 42 (2): 87-102. doi: <http://dx.doi.org/10.5721/ItJRS20104227>.
- Le Bagousee-Pinguet Y., Liancourt P., Gross N., Straile D. (2012) - *Indirect facilitation promotes macrophyte survival and growth in freshwater ecosystems threatened by eutrophication*. Journal of Ecology, 100: 530-538. doi: <http://dx.doi.org/10.1111/j.1365-2745.2011.01931.x>.
- Lindell T., Pierson D., Premazzi G., Zilioli E. (1999) - *Manual for monitoring European lakes using remote sensing techniques*. EUR Report n.18665 EN. Luxembourg: Office for Official Publications of the European Communities.
- Matarrese R., Chiaradia M.T., Tijani K., Morea A., Carlucci R. (2011) - *'Chlorophyll a' multi-temporal analysis in coastal waters with MODIS data*. Italian Journal of Remote Sensing, 43: 39-48. doi: <http://dx.doi.org/10.5721/ItJRS20114333>.
- NASA, AEROSOL ROBOTIC NETWORK (AERONET) (Internet) - Available at: <http://www.aeronet.gsfc.nasa.gov/> (last accessed: 05/09/2012).
- Olmanson L.G., Bauer M.E., Brezonik P.L. (2008) - *A 20-year Landsat water clarity census of Minnesota's 10,000 lakes*. Remote Sensing of Environment, 112: 4086-4097. doi: <http://dx.doi.org/10.1016/j.rse.2007.12.013>.
- Pepe M., Brivio P.A., Rampini A., Rota Nodari F., Boschetti M. (2005) - *Snow cover monitoring in Alpine regions using ENVISAT optical data*. International Journal of Remote Sensing, 26 (21): 4661-4667. doi: <http://dx.doi.org/10.1080/01431160500206635>.
- R Development Core Team (2010) - *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, AT.
- Ruddick K., De Cauwer V., Park Y-J., Moore G. (2006) - *Seaborne measurements of near infrared water leaving reflectance: The similarity spectrum for turbid waters*. Limnology & Oceanography, 51 (2): 1167-1179. doi: <http://dx.doi.org/10.4319/lo.2006.51.2.1167>.
- Salmaso N. (2010) - *Long-term phytoplankton community changes in a deep subalpine lake: responses to nutrient availability and climatic fluctuations*. Freshwater Biology, 55: 825-846. doi: <http://dx.doi.org/10.1111/j.1365-2427.2009.02325.x>.
- Salmaso N., Cerasino L. (2012) - *Long-term trends and fine year-to-year tuning of phytoplankton in large lakes are ruled by eutrophication and atmospheric modes of variability*. Hydrobiologia, 698 (1): 17-28. doi: <http://dx.doi.org/10.1007/s10750-012-1068-2>.
- Salmaso N., Buzzi F., Garibaldi L., Morabito G., Simona M. (2012) - *Effects of nutrient availability and temperature on phytoplankton development: a case study from large lakes south of the Alps*. Aquatic Sciences, 74: 555-570. doi: <http://dx.doi.org/10.1007/s00027-012-0248-5>.
- Salmaso N. (2012) - *Influence of atmospheric modes of variability on a deep lake south of the Alps*. Climate Research, 51: 125-133. doi: <http://dx.doi.org/10.3354/cr01063>.
- Santer R., Zagolski F., Gilson M. (2007) - *Uni. du Littoral, France, ICOL ATBD, Version 0.1*.

- Sparks W.B., Hough J., Germer T.A., Chen F., DasSarma S., DasSarma P., Robb F.T., Manset N., Kolokolova L., Reid N., Macchetto F.D., Martin W. (2009) - *Detection of circular polarization in light scattered from photosynthetic microbes*. Proceedings of the National Academy of Sciences, 106 (19): 7816-7821. doi: <http://dx.doi.org/10.1073/pnas.0810215106>.
- Thorne O., Fenner R.A. (2011) - *The impact of climate change on reservoir water quality and water treatment plant operations: a UK case study*. Water and Environment Journal, 25: 74-87. doi: <http://dx.doi.org/10.1111/j.1747-6593.2009.00194.x>.
- Tonolli V. (1964) - *Introduzione allo studio della Limnologia*. Edizioni dell'Istituto di Idrobiologia, Verbania-Pallanza, IT.
- Vermote E.F., Tanre D., Deize J.L., Herman M., Morcrette J.J. (1997) - *Second simulation of the satellite signal in the solar spectrum, 6S: An overview*. IEEE Transactions on Geoscience and Remote Sensing, 35: 675-686. doi: <http://dx.doi.org/10.1109/36.581987>.
- Walsby A.E., Ng G., Dunn C., Davis P.A. (2004) - *Comparison of the depth where Planktothrix rubescens stratifies and the depth where the daily insolation supports its neutral buoyancy*. New Phytologist, 162: 133-145. doi: <http://dx.doi.org/10.1111/j.1469-8137.2004.01020.x>.
- Wang J.J., Lu X.X. (2009) - *Retrieval of suspended sediment concentrations in large turbid rivers using Landsat ETM+: An example from the Yangtze River, China*. Earth Surface Processes and Landforms, 34 (8): 1082-1092. doi: <http://dx.doi.org/10.1002/esp.1795>.

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