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Short Communication

First assessment of MODIS satellite ocean color products (OC3 and nFLH) in the Inner Sea of Chiloé, northern Patagonia

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ABSTRACT. The use of remote sensing has allowed enormous progress in our understanding of biophysical processes worldwide. Despite their importance, the use of satellite bio-optical products is still limited due to optical complexity. In this study we assess the performance of the Moderate Resolution Imaging Spectroradiometer algorithm for chlorophyll-*a* (MODIS-OC3) and of normalized Fluorescence Line Height (nFLH), in inner waters of northern Chilean Patagonia (41°-45ºS). Satellite data were evaluated using a compilation of *in situ* chlorophyll-*a* data collected by the CIMAR-FIORDOS program during 2003-2012. During austral spring MODIS-OC3 showed a significant relationship with *in situ* measurements ($R^2 = 0.2$, $P = 0.03$, $F = 5.33$) in comparison with winter when the relationship was non-significant. In contrast, nFLH explained a significant fraction of observed variance of Chl-*a* during austral winter ($R^2 = 0.54$, $P = <0.01$, $F = 10.68$) and this relationship was not significant in spring. Our preliminary results offer an excellent chance to understand patterns of variability of the autotrophic biomass and physiological status in optically complex interior marine ecosystems.

Keywords: satellite validation, MODIS, fluorescence, chlorophyll-*a*, optical complex, northern Patagonia.

The study of phytoplankton through satellite remote sensing requires accurate estimates of the abundance and physiological status of autotrophic communities (Behrenfeld *et al*., 2008). However, complex optical conditions or time-varying patterns of autotrophic activity can greatly bias retrievals of chlorophyll-*a* (Chl-*a*) biomass using default algorithms (Vilas *et al*., 2011). In this way, conventional ocean color products are not fully operational in coastal and/or interior water (so called Case II waters), where substances from terrestrial origin change optical properties and introduce errors in Chl-*a* estimates (Gitelson *et al*., 2011).

Following high levels of organic matter (Iriarte *et al*., 2007; Silva & Astorga, 2010) and the significant input of freshwater runoff (León-Muñoz *et al*., 2013; Iriarte *et al*., 2016) to the Inner Sea of Chiloé (ISC), we consider this region as Case II waters. The ISC (41-45ºS, Fig. 1) is an extensive coastal region with a convoluted coastal topography marked by numerous fjords, inlets and islands and receives large freshwater discharges of fluvial and/or glacial origin bearing important loads of suspended organic and inorganic material (Dávila *et al*., 2002; Calvete & Sobarzo, 2011; Pantoja *et al*., 2011). One of the main features of envi-

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ronmental variability in the region is the marked seasonal cycle in Chl-*a* concentration and the associated changes in patterns of photosynthetic activity (Iriarte *et al*., 2007). These patterns have been difficult to quantify using satellite data at different spatial and temporal scales, a shortcoming that is further hindered by persistent cloud cover. Recent work in the region has helped to assess the relationships between oceanographic forcing and biological response in the ISC (Tello & Rodríguez-Benito, 2009; Lara *et al*., 2010, 2016). These studies have successfully used satellite data only as a *proxy* of autotrophic activity (biomass and primary production) observed *in situ*, underlining the potential of satellite-borne sensors in the region and providing support for our results showing that it is possible to identify cyclical patterns (*e.g*., interannual variability).

Errors in satellite Chl-*a* algorithm retrievals in Case II waters (*e.g*., MODIS-OC3; OC4 for SeaWIFS; O'Reilly *et al*., 1998) do not provide accurate Chl-*a* estimates in coastal environments (*e.g*., Gitelson *et al*., 2007) and hamper our understanding of the dynamics of bio-optical properties (*e.g*., Van Der Woerd & Pasterkamp, 2008; Ruddick *et al*., 2014). To improve the noise:error ratios associated with Chl-*a* retrievals, a new satellite product was developed following the SeaWiFS mission to better understand space-time patterns of Chl-*a* biomass and other phytoplankton properties. This product, called normalized Fluorescence Line Height (nFLH) is not affected by CDOM (colored dissolved organic matter) in the same way as Chl-*a* biomass estimates (Siegel *et al*., 2005; Szeto *et al*., 2011). In this way, the nFLH product stands as an improved indicator of physiological variability or phytoplankton biomass (Behrenfeld *et al*., 2009). In coastal waters, the precision of default Chl-*a* algorithms is deprecated due to the high concentration of CDOM and non-algal particles. In this cases (and inner waters), the use of sun-induced fluorescence tend to be a better option to estimate phytoplankton biomass (Huot *et al*., 2013).

Located at the northern tip of Chilean Patagonia, the ISC receives freshwater inflow from fluvial and/or glacial origin (Calvete & Sobarzo, 2011) and terrigenous sediment supply (Silva *et al*., 2011). The West Wind Drift (WWD) flow impinges on the continent near ~42ºS and drives a strong oceanic-atmospheric coupling in the region (Garreaud *et al*., 2013) that is manifested as a pronounced horizontal density gradient along ISC waters (Calvete & Sobarzo, 2011). Retrospective satellite Chl-*a* validation studies in the ISC are limited by the lack of matching *in situ* measurements for validation (*e.g*., Tello & Rodríguez-Benito, 2009; Lara *et al*., 2010, 2016). Here, to evaluate the performance of the standard MODIS Chl-*a* algorithm (MODIS-OC3), we address these limitations using satellite high-resolution Chl-*a* and nFLH estimates, together with a compilation of historic *in situ* Chl-*a*, and evaluate the nFLH algorithm as an estimator of photosynthetic biomass in the ISC ecosystem.

Oceanographic research cruises were conducted between 2003-2012 during austral winter (June, July and August, JJA, Fig. 1a) and spring (September, October and November, SON, Fig. 1b) as part of the CIMAR-FIORDOS program. Each seasonal cruise extended over the entire ISC region. Water samples were collected to measure Chl-*a* by filtering 250-500 mL of surface seawater on to glass fiber filters (0.7 µm size). Filters were immediately frozen (-20ºC) until later fluorometric analysis (Turner Design TD-700), using acetone (90% v/v) for the pigment extraction according to Parsons *et al*. (1984).

To characterize autotrophic biomass using remote sensing we used 10 years (2003-2012) of daily MODIS-OC3 high resolution (1 km) data. Satellite ocean color data were processed using NASA's software SeaDAS (SeaWIFs Data Analysis Systems) version 6.4, and following the recommendation for files with low processing level (Level-1A), and containing the information at its maximum spatial resolution (*e.g*., Saldías *et al*., 2012). To reduce the influence of additional light absorbing components, other than chlorophyll, we retrieved matching normalized Fluorescence Line Height data (Behrenfeld *et al*., 2009) derived using normalized water leaving radiance as described in Huot *et al*. (2013). Finally, to reduce the noise associated with clouds and land edges and potential low accuracy of a single pixel, a 3×3 pixels two-dimensional median filter was used so that each *in situ* measurement was centered in a nine pixel box (*e.g*., Bailey & Werdell, 2006). As the distribution of phytoplankton pigment biomass exhibits a log-normal distribution (Bricaud *et al*., 2002), we used a $\log_{10}$-transformed data for statistical analyses.

We obtained the highest fraction of matching MODIS satellite retrievals, and *in situ* observations, by averaging over a spatial window of 3×3 pixels compared to a "nearest-neighbor" approach. The low accuracy of a single pixel (Patt, 2002), and the increase of useful MODIS observations, when using a 3×3 window (Bailey & Werdell, 2006), enhances this approach for increasing/optimizing the number of match-ups. A greater number of match-ups were found during the spring months (137) than in winter (74) due to high cloud cover (Fig. 1). Histograms illustrating the frequency distribution of co-located $\log_{10}$-transformed *in situ* Chl-*a*, MODIS-OC3, and nFLH observations during the two seasons, are shown in Figure 2. During austral winter, MODIS-OC3 overestimated *in situ* Chl-*a*

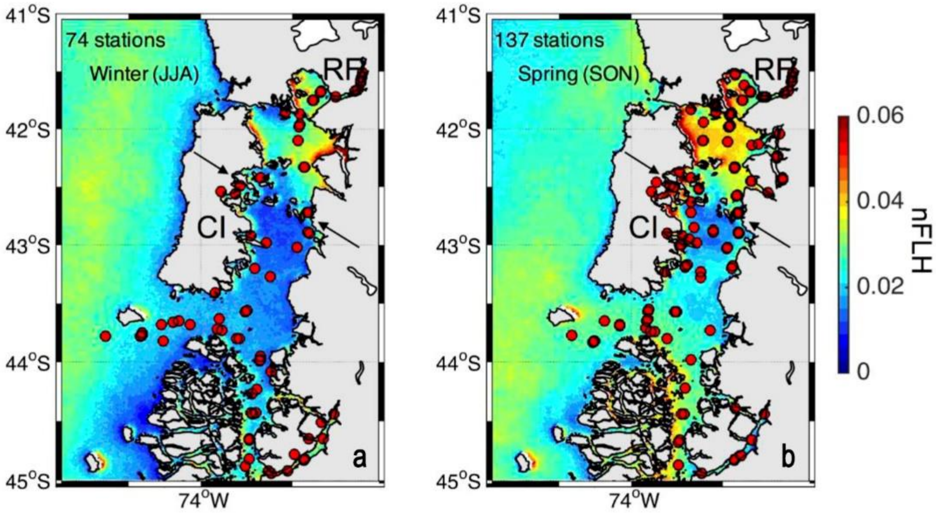

Figure 1. Study area off southern Chile showing the average climatology (2003-2012) of normalized Fluorescence Line Height (nFLH) for a) winter (JJA: June, July, August), and b) spring (SON: September, October, November). The position of in situ sampling stations of surface chlorophyll-*a* are shown as red dots. The black arrows denote the main axis of Desertores Islands. CI: Chiloé Island, RF: Reloncaví Fjord.

biomass at all Chl-*a* values, while in spring months MODIS-OC3 matched well *in situ* Chl-*a* (MODIS-OC3 $\leq$ 1.0 mg m^{-3}) towards MODIS-OC3 high values (>1.0 mg m^{-3}) (Figs. 2a-2b). Seasonal histograms of log$_{10}$-transformed nFLH and *in situ* Chl-*a* are similar during winter months, while in austral spring (high phytoplankton activity and biomass) nFLH underestimates the center of the distribution, with a better performance towards high values (Figs. 2c-2d).

A linear regression of *in situ* Chl-*a versus* MODIS-OC3 explained a low, non-significant percentage of variance during austral winter (R^2 = 0.06, *P* = 0.37, F = 0.80). During austral spring, *in situ* Chl-*a* showed a higher and significant relationship with MODIS-OC3, but accounted for a low fraction of the variance (R^2 = 0.2, *P* = 0.03, F = 5.33). The strength of the linear relationship (Fig. 3) may be influenced by the poor performance of the MODIS-OC3 algorithm in coastal waters where suspended particles bias estimates at the wavelengths used to estimate chlorophyll with this algorithm (Zhang *et al*., 2006).

Supporting the interpretation that fluorescence provides a better estimate of autotrophic biomass despite the impact of physiology (Beherenfeld *et al*., 2009; McKibben *et al*., 2012) a linear regression of *in situ* Chl-*a versus* nFLH explained a larger and significant fraction of variance during austral winter (R^2 = 0.54, *P* = <0.01, F = 10.68; Fig. 4). However, the relationship was not significant during spring months (R^2 = 0.04, *P* = 0.42, F = 0.67). The largest mismatches between satellite observations and *in situ* Chl-*a* are associated with areas of freshwater input, mainly in the region located north of the Desertores Islands. Several rivers (*e.g*., Puelo River, Reñihue River) provide a large amount of allochthonous substances (Silva *et al*., 2011). These materials of terrigenous origin may induce errors in the quantification of autotrophic biomass in the ISC during particularly seasons of high stream flow, particularly spring (Calvete & Sobarzo, 2011; León-Muñoz *et al*., 2013).

Our work corresponds to an initial investigation in the study of ecological processes of autotrophic communities through analysis of high-resolution satellite data. Due to the high cloud cover and the limited *in situ* information, it is important to consider the validation and calibration of satellite products that provide information of the spatiotemporal variability of autotrophic communities in an optically complex ecosystem. Besides, this information is relevant to the assessment of changes in ocean color, *e.g*., due to phytoplankton blooms anomalies (Hu *et al*., 2005). Our work, as Hu *et al*. (2005) and Behrenfeld *et al*. (2009), among others, highlights the importance of the nFLH from satellite to avoid interference from other components (*e.g*., CDOM, shallow bottom) because this product is centered at 667, 678 and 748 nm, which increases its correlation with measurements of *in situ* Chl-*a* (*e.g*., Hu *et al*., 2005; R^2 > 0.91, Florida, USA). Future research should be directed toward the correction of algorithms MODIS- OC3 and nFLH for a better understanding of ecological processes operating on the variability of phytoplankton biomass in the ISC. Long-term time series of ocean co-

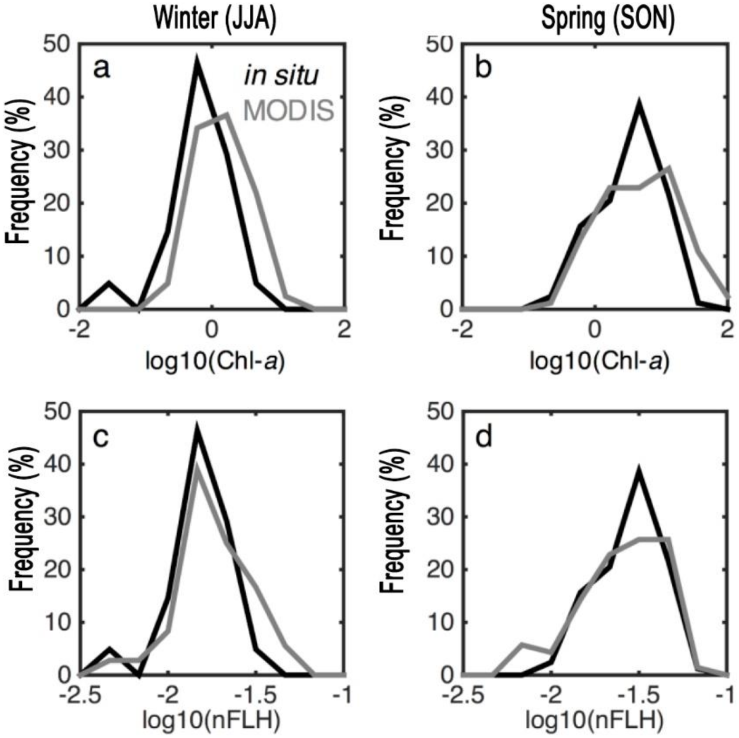

Figure 2. Histograms of match-ups data between Chl-*a* (black lines) and MODIS-OC3 in a) winter (JJA: June, July, August) and b) spring (SON: September, October, November). Histograms of match-ups data between Chl-*a* (black lines) an nFLH in c) winter and d) spring. Note that the histogram of Chl-*a* is repeated between seasonal panels for better comparison.

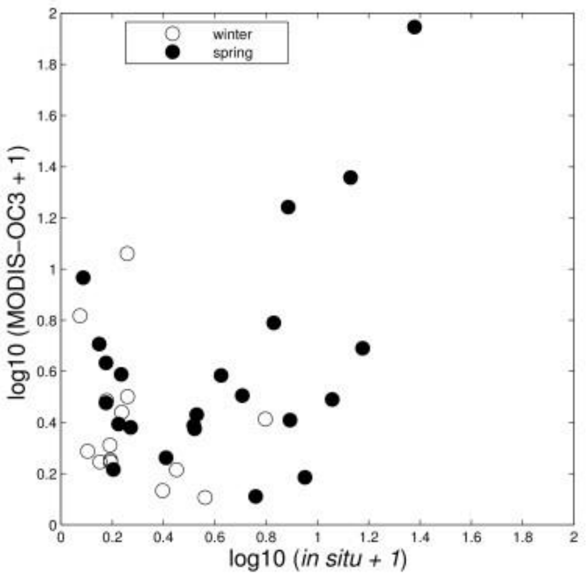

Figure 3. Scatterplots between *in situ* Chl-*a* and MODIS-OC3 data for the matching dates. Observations for winter and spring are with and black circles, respectively. Regression statistics are presented in the text.

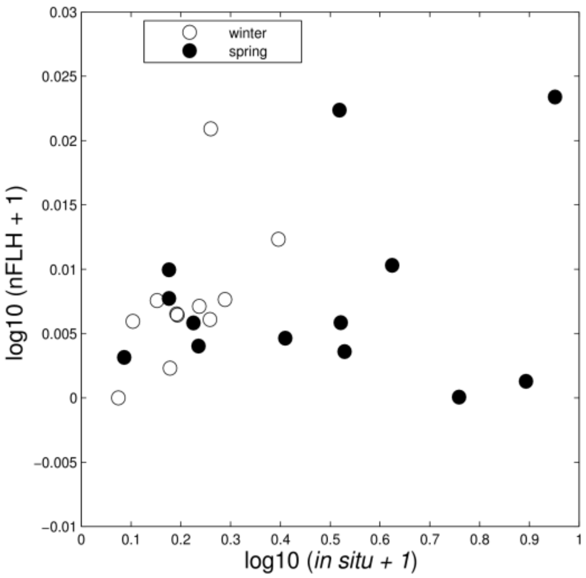

Figure 4. Scatterplots between *in situ* Chl-*a* and nFLH data for the matching dates. Observations for winter and spring are with and black circles, respectively. Regression statistics are presented in the text.

lor imagery will also provide a future assessment of the influence of climate variability on local oceanographic conditions (*e.g.*, Saldías *et al*., 2016).

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