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Remote sensing of coccolithophore blooms in selected oceanic regions using the PhytoDOAS method applied to hyper-spectral satellite data

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Abstract

In this study temporal variations of coccolithophore blooms are investigated using satellite data. Eight years, from 2003 to 2010, of data of SCIAMACHY, a hyper-spectral satellite sensor on-board ENVISAT, were processed by the PhytoDOAS method to monitor the biomass of coccolithophores in three selected regions. These regions are characterized by frequent occurrence of large coccolithophore blooms. The retrieval results, shown as monthly mean time-series, were compared to related satellite products, including the total surface phytoplankton, i.e., total chlorophyll-*a* (from GlobColour merged data) and the particulate inorganic carbon (from MODIS-Aqua). The inter-annual variations of the phytoplankton bloom cycles and their maximum monthly mean values have been compared in the three selected regions to the variations of the geophysical parameters: sea-surface temperature (SST), mixed-layer depth (MLD) and surface wind speed, which are known to affect phytoplankton dynamics. For each region the anomalies and linear trends of the monitored parameters over the period of this study have been computed. The patterns of total phytoplankton biomass and specific dynamics of coccolithophores chlorophyll-*a* in the selected regions are discussed in relation to other studies. The PhytoDOAS results are consistent with the two other ocean color products and support the reported dependencies of coccolithophore biomass dynamics to the compared geophysical variables. This suggests, that PhytoDOAS is a valid method for retrieving coccolithophore biomass and for monitoring its bloom developments in the global oceans. Future applications of time-series studies using the PhytoDOAS data set are proposed, also using the new upcoming generations of hyper-spectral satellite sensors with improved spatial resolution.

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different phytoplankton functional types (PFTs; see summary by Nair et al., 2008) with improved algorithms and new retrieval methods has recently been in the focus of research (Ackleson et al., 1994; Brown and Yoder, 1994a; Tyrrell et al., 1999; Gordon et al., 2001; Subramaniam et al., 2002; Sathyendranath et al., 2004; Alvain et al., 2005).
5 The development of PFT-based retrieval methods will also improve the estimates of the total phytoplankton biomass and deepen the understanding of the oceanic biogeochemical cycles. Based on this demand, the PhytoDOAS method was established to discriminate major phytoplankton groups based on their specific absorption footprints on the backscattered radiation from the ocean (Bracher et al., 2009).

10 PhytoDOAS is an extension of Differential Optical Absorption Spectroscopy, DOAS (Perner and Platt, 1979; Platt, 1994) into the aquatic medium. By applying the PhytoDOAS method to hyper-spectral satellite data, provided by the SCIAMACHY sensor (on-board ENVISAT), the global distributions of two main phytoplankton groups, diatoms and cyanobacteria, have been derived. By improving the method through
15 *multi-target fitting*, two more PFTs, *coccos* and dinoflagellates have been distinguished recently (Sadeghi et al., 2011). To test this improvement, SCIAMACHY data from 2005 have been globally processed using the improved PhytoDOAS method. The successful retrieval of *coccos* was proven by comparisons with the global distribution of PIC, provided by MODIS-Aqua level-3 products and comparison with the *coccos* modeled data
20 obtained from NASA Ocean Biochemical Model, NOBM (Gregg et al., 2003; Gregg and Casey, 2007). In addition, two sample *coccos* blooms, detected by satellite imagery, were identified by applying the improved PhytoDOAS to the SCIAMACHY data: one located around New Zealand, reported in December 2009 as a RGB image by MODIS (Sadeghi et al., 2011); and the other one in the North Atlantic in August 2004.

25 1.3 Objectives

The main interest of this study was to apply the PhytoDOAS method for quantitative remote sensing of *coccos* using satellite data. Due to the crucial role of *coccos* in the global biogeochemical cycles, this satellite-based method can be used for monitoring

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temporal and spatial variations of *coccos* on a global scale, which in turn can be used (as a phenomenal study of phytoplankton dynamics) for studying the impacts of a varying climate on marine phytoplankton (Winder and Cloern, 2010). To show this capacity, *coccos* blooms in selected regions were monitored over eight years and their
5 inter-annual variations were investigated along with the temporal variations of certain geophysical parameters. On the other hand, PhytoDOAS takes the following factors into account, which are often not considered in current biooptical methods based on band-ratio algorithms: the phytoplankton absorption spectra, the existence of multiple PFTs and the light penetration depth in the water. Therefore, the above specific
10 capacities of the method are investigated by this study. More specifically, concerning *coccos* retrieval, while other phytoplankton pigments cause a decrease in backscatter radiance mostly in the blue part (and slightly in the green), *coccos*, due to their calcite plates, affect the solar irradiance uniformly in both the blue and the green (Gordon et al., 1988). Furthermore, as *coccos* blooms cause flattening of the reflectance spectrum, the standard ratio pigment algorithms (Gordon and Morel, 1983) will not provide
15 correct pigment retrievals within the blooms (Balch et al., 1989; Balch, 2004); while, by retrieving the differential absorption features, the PhytoDOAS method has the potential to obtain results on PFT chl-*a* in high *coccos* regions, when hyper-spectral variations are still visible. In this sense, retrieving *coccos* blooms provides a reliable application
20 to test the improved PhytoDOAS method.

2 Study setup

2.1 Initial tests and selection of regions

Regarding the fact that the whole *coccos* group can not be observed through in-situ measurements, the direct comparison of the retrieved *coccos* with the in-situ data is too
25 difficult. More precisely, with analyzing water samples by microscopy or with the Continuous Plankton Recorder (CPR) only the larger cells (> 5 and $> 10 \mu\text{m}$, respectively) can

be identified. From HPLC and flow-cytometric analysis only the groups of haptophytes or nano-eukaryotes, respectively (to both coccolithophores belong to), can be identified. In addition, there is a significant difficulty associated with the collocation of the in-situ point measurements to the large SCIAMACHY ground pixels of 30 km by 60 km. Therefore, so far, the PhytoDOAS *coccos* results, instead of validation, were compared to the global distribution of PIC obtained from the MODIS-Aqua level-3 products (this was after the preliminary comparisons with the NOBM *coccos* modeled data). The reason behind is, since the concentration PIC is proportional to the suspended *coccoliths* in surface waters, it is regarded as the main indicator of *coccos* Balch et al. (2005). Very good agreements were observed in patterns of *coccos* and PIC on a monthly and seasonal basis (Sadeghi et al., 2011). Moreover, *coccos* chl-*a* results were compared to the total chl-*a* (provided by GlobColour merged data), as the maximum limit of observed chl-*a* for *coccos*. Figure 1 illustrates a sample comparison of these three products for August 2005, showing consistent patterns between *coccos* (upper panel) and PIC (middle panel), followed by partially similar patterns of the total chl-*a* (lower panel).

To monitor the development of *coccos* blooms, regions of high occurrence were selected based on the following procedure: first, a global distribution of *coccos*, mapped by Brown and Yoder (1994a) and Brown (1995) was considered; secondly, eight years of global distribution of PIC, from MODIS-Aqua level-3 monthly products was monitored; and finally *coccos* field studies were analyzed (Brown and Podesta, 1997; Balch et al., 1991; Holligan et al., 1993; Garcia et al., 2011; Raitsos et al., 2006; Painter et al., 2010; Burns, 1977; Tilburg et al., 2002). Based on these pre-investigations, three regions have been selected (Fig. 2), located in the North Atlantic (south of Iceland), the South-West Atlantic (north of the Falkland Islands), and the South-West Pacific (southwest of New Zealand, surrounded by the Tasman Sea). For simplicity the regions were labeled as: *nAtl*, *sAtl* and *sPac*, respectively. The regions were been selected to be $10^{\circ} \times 10^{\circ}$ areas, which regarding their latitudinal distributions means almost the same area for *sAtl* and *sPac* and smaller for *nAtl*. As shown in Fig. 2 on a background of the

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MODIS-Aqua PIC product, two regions (*sAtl* and *sPac*) are located in the *Great Calcite Belt* (Balch et al., 2011), which is a great latitudinal belt of elevated PIC concentrations, containing over one-third of all global PIC. The *Great Calcite Belt* is located all the way around the Southern Ocean near the sub-Antarctic front and polar front (between about 30° S and 60° S). To retrieve *coccos* dynamics in selected regions, the PhytoDOAS method according to Sadeghi et al. (2011) was applied to SCIAMACHY data (from January 2003 to December 2010) for each region. Absorption spectrum of *Emiliana huxleyi* (*E. huxleyi*) was used for the *coccos* target, because *E. huxleyi* is generally the dominant species in this group. The principles of this improved PhytoDOAS method as well as all needed reference spectra, were explained in details in Bracher et al. (2009); Sadeghi et al. (2011).

2.2 Satellite and modeled data

Satellite data used for the PhytoDOAS method must be spectrally highly resolved. This requirement is met using the data collected by SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartography), a sensor on-board ENVISAT (ENVIRONMENTAL SATellite of European Space Agency, ESA) launched in 2002. This sensor covers a wide wavelength range (from 240 to 2380 nm in 8 channels) with a relatively high spectral resolution, ranged from 0.2 to 1.5 nm (Bovensmann et al., 1999). In this study, nadir-viewing SCIAMACHY data in specific wavelength ranges of UV and visible were used, for which the spectral resolution is ranging from 0.24 to 0.48 nm. These data, used to built up the measured *optical-depth*, include backscattered radiation from oceanic surfaces (case-I waters), with a spatial resolution of about $30 \times 60 \text{ km}^2$, and solar radiation measured at the top of the atmosphere in the same wavelength range. Within PhytoDOAS, SCIAMACHY data were exploited at two wavelength ranges: First, the absorption spectra of the target PFTs were fitted using the visible data within the fit-window of 429 to 521 nm; secondly, part of SCIAMACHY UV data (from 340 to 385 nm) was used to estimate the *light-penetration depth* through retrieving the spectral signature of vibrational Raman scattering of water molecules (Vountas

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the time-series of the PhytoDOAS *coccos* are some missing points, due to the post-processing of the retrieved data; i.e., the fit-quality filter (χ^2) and the average-quality condition (number of pixels per month).

Due to these gaps the *coccos* time-series, compared to the time-series of the other parameters, depict more artifact features, which must be distinguished from their natural irregularities. The main reason for this anomaly is that SCIAMACHY (primarily designed for atmospheric missions), compared to usual ocean color sensors, e.g., MODIS-Aqua, SeaWiFS and MERIS, has a very coarse spatial resolution. The characteristic of having large ground pixels makes its surface UV-visible data very sensitive to cloud contaminations, as compared to other sensors with high spatial resolutions. Therefore, the time-series of PIC, provided by MODIS-Aqua, and the time-series of total chl-*a*, obtained from GlobColour merged data, show very few gaps. However, there are still enough data points in the *coccos* time-series, for comparing *coccos* temporal variations with the other parameters.

In the time-series of the *nAtl* region (Fig. 3) all parameters show a clear annual cycle; however, for some of the parameters (not for SST and MLD) the inter-annual cyclical periods of high intensities are deviating from one year to another; e.g., from 2008 to 2009 for *coccos* and PIC the period between the maxima is reduced to 10 months, while it is 11–14 for all other years (e.g. 2007 to 2008). However, for GlobColour total chl-*a* the intervals between successive maxima for the periods 2008/2009 and 2007/2008 are about 13 and 10 months, respectively. It can also be seen that the timing of the maximum conc. of *coccos*, PIC and total chl-*a* are positively correlated. These maxima are negatively correlated with the MLD, as they should be, because the rate of *coccos* growth increases rapidly with shoaling of MLD (Raitsos et al., 2006). More precisely, all three phytoplankton-based time-series in Fig. 3 imply that the phytoplankton prosperity is associated with a rapidly decreasing MLD, and reaches its maximum when MLD begins its period of constant minimum. The North Atlantic is generally characterized by an extremely deep winter mixed layer, which causes very low phytoplankton activity in wintertime, which can be seen as well in Fig. 3. The

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phytoplankton and PIC maxima coincide with the high positive gradient of SST, i.e. SST peaks always appear delayed to the phytoplankton peaks, which is in accordance with the results of Raitsos et al. (2006). Theoretically, it is expected that the maxima of the three phytoplankton-based time-series follow in a sequence as the time elapses: total chl-*a* followed by *coccos* and finally PIC, as *coccos* start growing when the necessary nutrients for the growth or the survival of other species are scarce (Margalef, 1978; Holligan et al., 1983). On the other hand, the PIC concentration is expected to be proportional to the amount of *coccoliths*, which can be either attached to the living *coccos* or detached from them and suspended in the water, even after the disappearance of the *coccos*. However, this sequence could not be reproduced in our time-series, except for the year 2008. In fact, the peaks of total chl-*a* and PIC appear more or less at the same time, while *coccos* peaks often follow the two former peaks with a slight delay. This systematic behavior might be originated from the large monthly time interval used for averaging the retrieved products and setting up the *coccos* time-series (the lower subplots in Figs. 3–5); one-month period is probably larger than the real, rather weekly, temporal rhythm of phytoplankton dynamics.

While the SST, the MLD, and also the PIC conc. show clear annual cycles in the regions of *sAtl* and *sPac* (Figs. 4 and 5), the annual patterns for *coccos* and total phytoplankton chl-*a* are much more irregular than in the *nAtl*. This can be explained by the very dynamic wind-speed patterns observed in *sAtl* and *sPac*. As surface wind-stress forces the vertical motion in the water column (in addition to the horizontal motions as surface waves), it is affecting the stratification and the nutrient regime. As the *coccos* are only a group of the phytoplankton it is expected that total chl-*a* would vary more smoothly than this specific PFT. Moreover, there are several other possible reasons for the irregular phytoplankton and PIC conc. in the *sAtl* region:

- The general circulation in the *sAtl* is influenced by the collision of two main currents: the Malvinas (Falklands) current, transporting northwards sub-Antarctic cold and fresh waters and the Brazil current, carrying southwards subtropical saline and warm waters (Gordon, 1989; Spadone and Provost, 2009). The

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Brazil/Falklands confluence is an energetic and complex region of interaction and mixing of water masses (Brandini et al., 2000; Oliveira et al., 2009).

- The *sAtl* is located at the eastern part of the Patagonian shelf, which is regarded as one of the richest areas of primary production (Bianchi et al., 2005, 2009; Schloss et al., 2007), and features recurring large *coccos* blooms (Longhurst, 1995; Painter et al., 2010). The Patagonian shelf, between 38° S and 51° S, is located southwest of the confluence zone and therefore is affected by that. Apart from that, according to hydrography observations and satellite imagery (Saraceno et al., 2004; Bianchi et al., 2005; Romero et al., 2006), there are two other factors affecting the hydrography of the Patagonian shelf: the *shelf break front*, which is a transition between the Malvinas current and shelf waters, existing in both winter and summer seasons (being stronger in the summer months) and the energetic *tidal fronts*, with pronounced seasonal variability, causing the vertical stratification of water masses (Sabatini et al., 2004; Bianchi et al., 2005).
 - The non-cyclic aerosol-load and dust transport from the Patagonian desert into the South Atlantic Ocean (atmospheric and riverine), affecting the phytoplankton productivity of the Patagonian shelf by changing the nutrient regime (Erickson et al., 2003).
 - The South-Atlantic Anomaly (SAA) of the Earth's magnetic field affects most of satellite measurements over parts of South-America and South-Atlantic. Although the SAA region lies roughly between latitudes 5° S and 40° S, its precise shape, size and strength varies with the seasons (<http://sacs.aeronomie.be/info/saa.php>). Hence, our *sAtl* region, residing between 40° S and 50° S, could be partly affected by SAA.
- The high variations and anomalies seen in the *sPac* time-series, can be attributed to its location, which is surrounded by the Tasman Sea. The Tasman Sea is one of the fastest warming areas in the Southern Hemisphere ocean (Neuheimer et al., 2011;

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Ridgway, 2007), because of both, globally rising SST and specific local effects, such as the characteristic of the warm poleward waters of the East Australian Current (EAC) (Cai et al., 2005; Ridgway, 2007). Moreover, large eddies occurring in the Tasman Sea have a great contribution to the vertical mixing within the upper ocean. This increased mixing effectively counteracts the winter stratification and results in a varying *chl-a* seasonal cycle (Tilburg et al., 2002). In this sense, the seasonal cycle of *chl-a* in *sPac* should be pronounced, similar to the North Atlantic, which has very strong mixing. Whereas the seasonality in the time-series of GlobColour total *chl-a* for *sPac* is rather weak (less pronounced than in *coccos*). This observation suggests a demand for a regional improvement of the *chl-a* algorithms from ocean-color sensors, at least for the South-West Pacific.

In *sPac*, higher *chl-a* for *coccos* than for the total phytoplankton is observed. Further investigations showed why the PhytoDOAS *coccos* method is overestimating the coccolithophore *chl-a* (Fig. 5): studies by Burns (1977) and Rhodes et al. (1995) showed that in the Tasman Sea and also around New Zealand (i.e., in *sPac*) the dominant *coccos* species is varying between *E. huxleyi* and *Gephyrocapsa oceanica* (*G. oceanica*). Whereas, in this study the PhytoDOAS retrieval of *coccos* was based on the specific absorption spectrum of *E. huxleyi*. Figure 6 illustrates the specific absorption spectra of these two *coccos* species, *G. oceanica* and *E. huxleyi*, which were measured on cultures obtained from the isolation of these species from natural samples in different regions. As illustrated in Fig. 6, the specific absorption values of *G. oceanica* are much lower than the values of *E. huxleyi*. The reason is that the former species has, compared to *E. huxleyi*, much more *chl-a* pigment contents per cell. Hence, retrieving *G. oceanica* from a *E. huxleyi* specific absorption spectrum results in an overestimation of *chl-a* content. However, the similar absorption patterns of these two species ensures that the retrieval process can identify them as *coccos* target. All together, these samples show the spatial variations in phytoplankton absorption within the same phytoplankton group. This feature and the different photo-acclimation, also changing the specific phytoplankton absorption, can affect the result of the PhytoDOAS retrieval.

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3.4 Climatology analysis

Figure 11 illustrates the climatology curves for the corresponding six parameters in the three selected regions. Each data-point here depicts the mean value of a certain month over eight years' data of the respective time series. In *nAtl*, the *coccos* reached their maximum in August, whereas in *sAtl* and *sPac* two maxima were reached annually, a smaller one in austral spring (between September and October) and a higher one in austral summer (between February and March). The occurrences of two *coccos* blooms annually in the Southern Hemisphere has been reported before (Balch et al., 2011). In *sPac* these maxima were not as pronounced, showing another weak maximum in May. This may be caused by the effect of large eddies existing in the Tasman Sea. However, the *coccos* maximum in austral spring in *sPac* was also observed by studying SeaWiFS data (Tilburg et al., 2002).

The GlobColour total chl-*a* showed an annual peak spreading over spring and summer, with two weak shoulders in *nAtl* (higher in June and a smaller in August), one wide peak in *sAtl* from October to January and only a minor peak in *sPac* from October to February. These results in *nAtl* and *sAtl* suggest that the *coccos* are the dominant phytoplankton group succeeding the main bloom in late summer, which again supports the argument that *coccos* are favored when nutrients are depleted. However, the almost flat curve of GlobColour total chl-*a* in *sPac* is not consistent with SeaWiFS results presented in Tilburg et al. (2002) for the Tasman Sea. MODIS-Aqua PIC showed five months (May to September) of enhanced conc. in *nAtl* with two pronounced shoulders in June and August, coinciding temporally with the maxima of GlobColour total chl-*a*, while only the latter peak was coinciding with the *coccos* annual maximum. This may indicate that either during the first total chl-*a* peak (in June) *coccos* were contributing significantly to the biomass and the PhytoDOAS algorithm is underestimating the *coccos* chl-*a*, or the PIC algorithm is partly incorrect in this region. The PIC climatology curves in *sAtl* and *sPac* varied quite smoothly (similar to each other), with a peak in December/January, which is more pronounced in *sAtl*. The patterns of PIC climatology

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in these regions followed the GlobColour total chl-*a* between March and October. The climatology curves of MLD, SST and wind-speed clearly supported the expected geophysical conditions for the formation of *coccos* blooms.

4 Conclusions

We studied the developments of coccolithophore and total phytoplankton blooms and PIC conc. in three selected regions have been studied from January 2003 to December 2010 with satellite data. The time series results of these three phytoplankton-based products reveal the seasonal bloom cycles in a regular order with fairly good accordance to each other. In the *nAtl* region one *coccos* maximum was regularly observed in the summer, while in the *sAtl* and *sPac* regions two maxima in austral spring and summer occurred. The maxima for total chl-*a* and PIC conc. were during the same time period, but in both hemispheric regions only appeared once per year over a longer time period (4–5 months). The results show that the *coccos* blooms generally dominate the total phytoplankton maxima in late summer (August/September in *nAtl* and February/March in two other regions). In the *nAtl* and *sAtl* regions the maximum concentrations are comparable for all three parameters, while they are much lower (70–50%) in the *sPac* regions. Comparisons to time series of geophysical parameters clearly show that the phytoplankton growth is related to shallow MLDs, low wind-speed, and high and sharp-rising SSTs. Overall, the accordance of the three ocean color data products was better in *nAtl*, as compared to *sAtl* and *sPac*. The major environmental factors affecting the Patagonian shelf and the Tasman Sea have been briefly mentioned, in order to address the possible causes of turbulent and mixing effects in *sAtl* and *sPac*, respectively. The specific regional characteristics in *sAtl* and *sPac*, probably cause effects in smaller time scales than a month. However, our time series study had to be limited to the monthly resolution because of the coarse spatial resolution and limited global coverage of the available hyper-spectral satellite data used for the PhytoDOAS *coccos* retrieval. Applying the PhytoDOAS method to upcoming hyper-spectral satellite

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sensors, e.g., the Sentinel-5-Precursor (planned to launch in 2014) with $7 \times 7 \text{ km}^2$ pixel size and global coverage within two days, will allow the weekly-based monitoring of such phytoplankton blooms dynamics.

The outcome of the study proves that the PhytoDOAS *coccos* data show valuable results, even though there are still sources of uncertainties in the retrieval, to be accounted for, e.g., the spatial variations in the absorption spectra. It should be noted that this product is based on a new method, mostly independent from biological a priori data, as opposed to the standard ocean color products. This retrieval method can be reliably used for remote identification of *coccos* and tracking its bloom developments in the global ocean. For better analysis and interpretation of the results, more investigations on the geophysical parameters ruling the regional climate, as well as on local biological conditions will be done for each region. For instance, due to the importance of light for the formation of *coccos* blooms (Nanninga and Tyrrell, 1996), the variation in solar radiation must be included (e.g., regional time series of water leaving radiance at 555 nm, as referred by Raitsos et al. (2006)). The regional variations of nutrient regime, especially phosphate and nitrate, using appropriate modeled data is the other supplementary work to do. Regional adaptations of the PhytoDOAS *coccos* retrieval are planned in order to account for the spatial variations in specific absorptions with respect to the dominating *coccos* species. In general, to avoid the uncertainties associated with the spatial variations in phytoplankton absorption, an alternative approach would be to establish a multi-regional PhytoDOAS retrieval, using different sets of PFTs' absorption spectra, representing the main regions. For this purpose, the biogeographical provinces presented by Longhurst (1998) could provide a good criterion for dividing the world oceans into the regions. The PhytoDOAS *coccos* data will be validated with available in-situ measurements (e.g., Continuous Plankton Recorder or specific *coccos* cell counts). The data shall also be compared to chl-*a* conc. of haptophytes inferred from HPLC pigment analysis. However, in-situ data also have to be treated with care as they either only consider the large *coccos* via microscopic techniques or, as for the HPLC derived information, also other haptophyte species besides *coccos*; moreover,

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matching the in-situ point measurements to the large satellite ground pixels is always a challenging task. Time-series studies for other regions of particular interest (e.g., Bering Sea) are planned in order to assess the overall global picture of *coccos* distributions.

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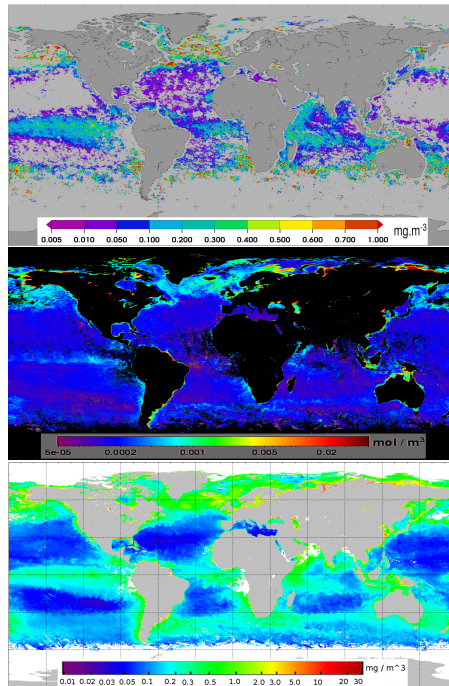


Fig. 1. A sample comparison of three monthly mean products, all obtained in August 2005: the PhytoDOAS *coccos* chl-a (upper panel) retrieved from SCIAMACHY data, the PIC concentration (middle panel) from the MODIS-Aqua level-3 products, and the total chl-a (lower panel) from the GlobColour level-3 merged data.

11755

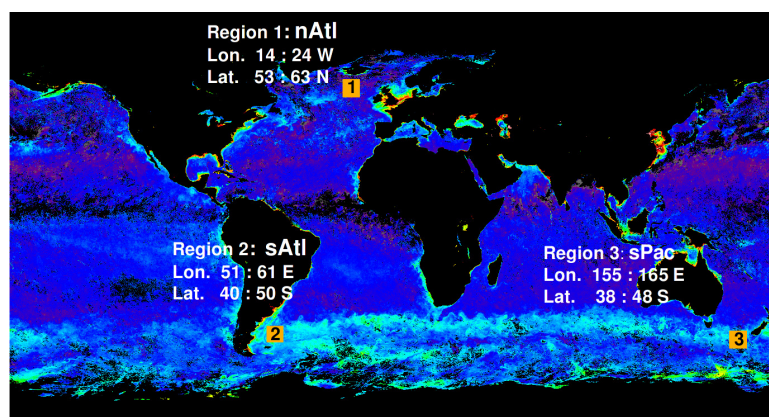


Fig. 2. Selected regions for monitoring the development of *coccos* blooms in this study. Each region has the geographical size of $10^\circ \times 10^\circ$; regions 1, 2 and 3 have been named as *nAtl*, *sAtl* and *sPac*, respectively. The background image shows the PIC monthly-mean conc. in March 2005 from the MODIS-Aqua level-3 products, demonstrating the *Great Calcite Belt* as a bright greenish band above the sub-Antarctic regions.

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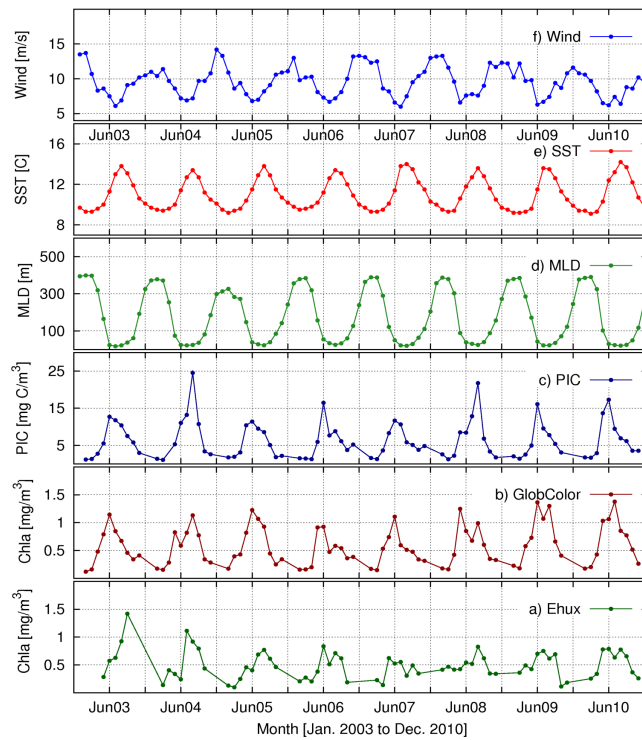


Fig. 3. Time series of six parameters monitored in *nAtl* from January 2003 to December 2010: **(a)** *coccos* [*Ehux*] chl-*a* conc. retrieved by PhytoDOAS; **(b)** GlobColour total chl-*a*; **(c)** MODIS-Aqua PIC conc.; **(d)** MLD from Ocean Productivity; **(e)** SST from AVHRR; and **(f)** surface wind-speed from AMSR-E.

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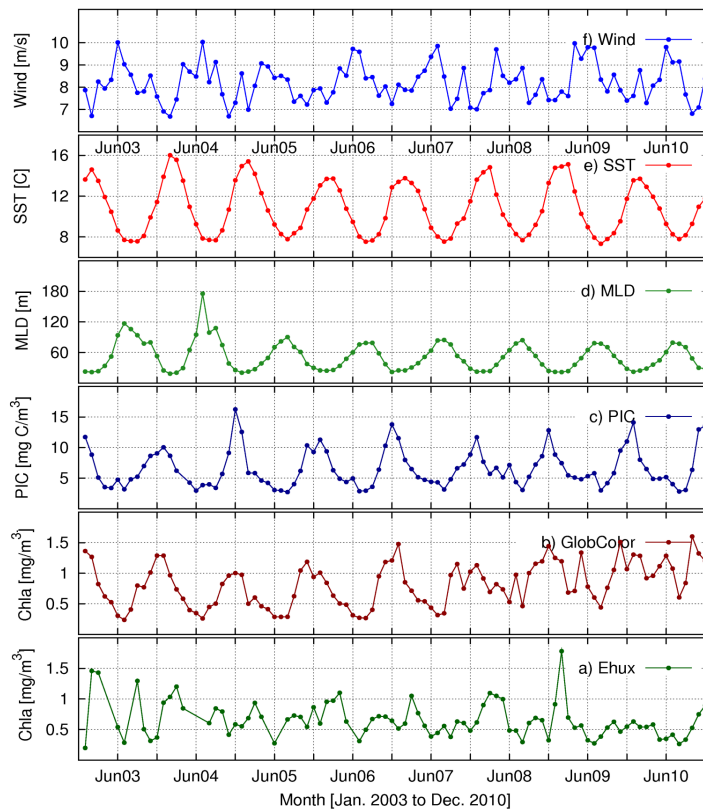


Fig. 4. Time series as described in Fig. 3, but for the *sAtl* region.

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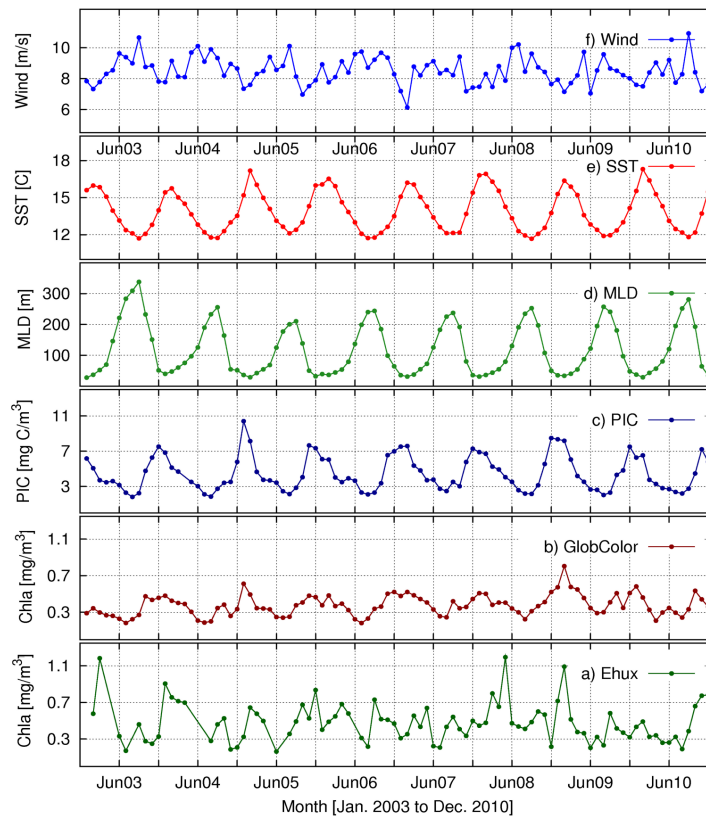


Fig. 5. Time series as described in Fig. 3, but for the *sPac* region.

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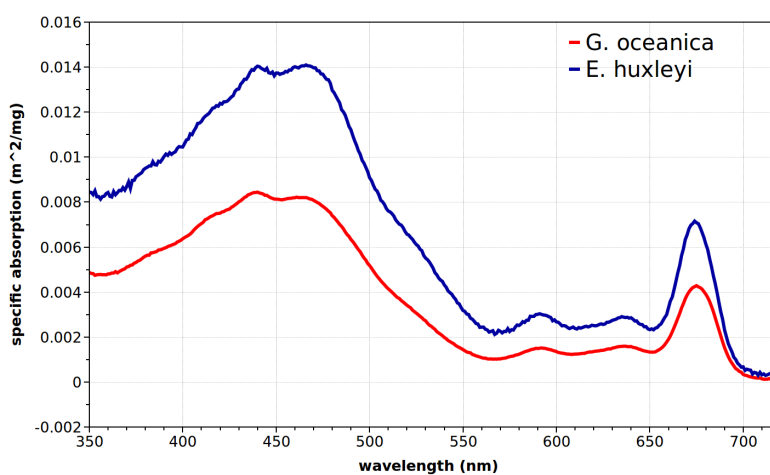


Fig. 6. Specific absorption spectra of two different *coccos* species obtained from cultures: *G. oceanica* (red), isolated from the North Atlantic near the Portuguese coast; and *E. huxleyi*, isolated from the Tasman Sea in the South-West Pacific.

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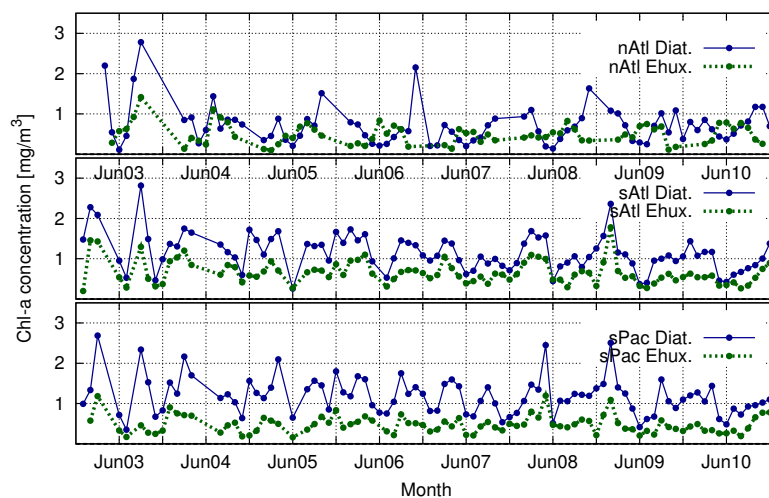


Fig. 9. Times series of the PhytoDOAS diatoms (blue solid lines) and *coccos* (green dashed lines) chl-a in the three selected regions: *nAtl* (lower panel), *sAtl* (middle panel) and *sPac* (upper panel).

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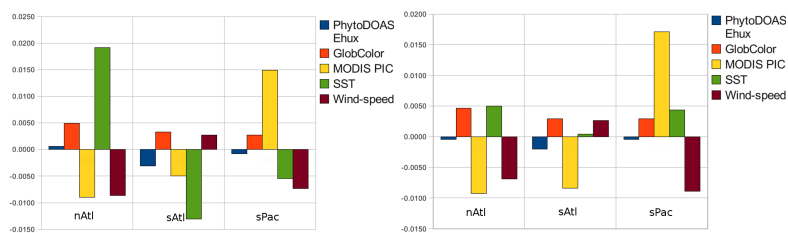


Fig. 10. Linear trends of five monitored parameters over eight years data (2003 to 2010) in three selected regions: *nAtl* (left), *sAtl* (middle) and *sPac* (right). The left panels show the values of the *simple trends*, while the right panels show the values of the *anomaly trends*. In both cases only the regional spring and summer months were considered, which means: April to September for *nAtl* and September to March for *sAtl* and *sPac*. The chart does not include the MLD trends, due to their different ranges, being much higher in order of magnitude.

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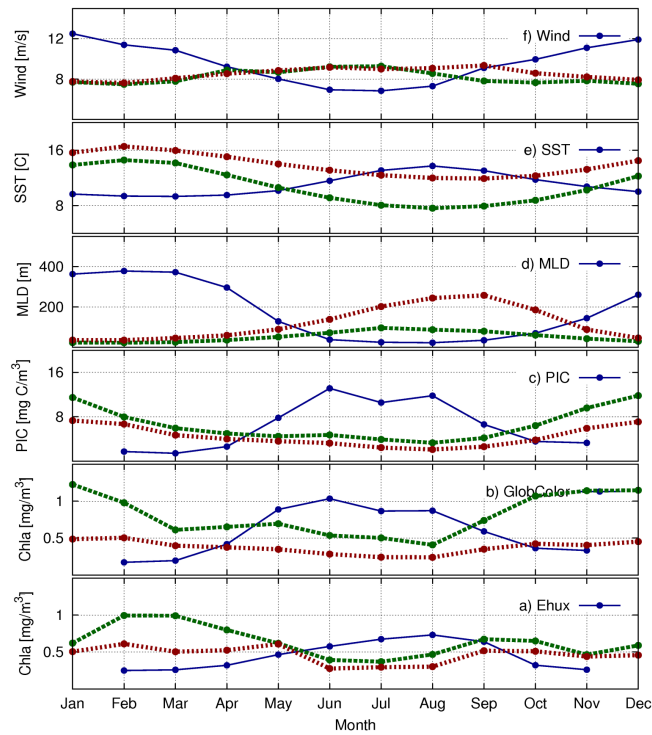


Fig. 11. Climatology curves of all monitored parameters in three selected regions. Each subplot contains the climatologies of a certain parameter in three regions, which are denoted as follows: *nAtl* (blue line), *sAtl* (green dashed-line) and *sPac* (red dashed-line). The subplots have been arranged in the same order as before: **(a)** *coccos* chl-*a* conc.; **(b)** GlobColour total chl-*a*; **(c)** PIC conc.; **(d)** MLD **(e)** SST, and **(f)** surface wind-speed.