Variation of the chlorophyll *a* related to sea surface temperature, wind and geostrophic currents in the Cape Verde region using satellite data

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Abstract

We present a comparative analysis of satellite derived climatologies in the Cape Verde region (CV). In order to establish chlorophyll *a* variability, in relation to other oceanographic phenomena, a set of, relatively long (from five to eight years), time series of chlorophyll *a*, sea surface temperature, wind and geostrophic currents, were ensembled for the Eastern Central Atlantic (ECA). We studied seasonal and inter-annual variability of phytoplankton concentration, in relation to the rest of the variables, with a special focus in CV. We compared the situation within the archipelago with those of the surrounding marine environments, such as the North West African Upwelling (NWAU), North Atlantic Subtropical Gyre (NASTG), North Equatorial Counter Current (NECC) and Guinea Dome (GD). At the seasonal scale, CV region behaves partly as the surrounding areas, nevertheless, some autochthonous features were also found. The maximum peak of the pigment having a positive correlation with temperature is found at the end of the year for all the points in the archipelago; a less remarkable rise with negative correlation is also detected in February for points CV2 and CV4. This is behavior that none of the surrounding environments have shown. This enrichment was found to be preceded by a drastic drop in wind intensity (SW Monsoon) during summer months. The inter-annual analysis shows a tendency for decreasing of the chlorophyll *a* concentration.

1. Background

Cape Verde is located in the eastern side of the NASTG between the longitudes 14º 50'-17º 20' W and the latitudes 22º 40'- 25º30'N. The CV presents diverse hydrographical conditions as a consequence of the some oceanic currents confluence and the proximity of the coastal upwelling, although the islands are mostly located into the inter-gyre region. The Canary Current (CC) and the North Equatorial Current (NEC) are the main surface currents influencing the archipelago; however, the southern side of the islands is seasonally influenced by the NECC due to the movement of the Inter-Tropical Convergence Zone (ITCZ) which produces changes of the wind regime in the survey area [Menezes, 2003; Fernandes *et al*. 2004]. A significant frontal zone takes place near the archipelago [at 20º N according to Arhan *et al*., 1994], mixing both SACW and NACW and has been widely studied [Zenk *et al*., 1991; Pérez-Rodriguez *et al*., 2001; Vangriesheim *et al*., 2003]. This study is focused on the chlorophyll variability along the CV. Nutrient limitation is the factor identified to explain the short spreading of the high chlorophyll signal northward of the eastern recirculation region (10º N-19º N), whereas lower values in the south are due to the weakening of the wind stress and the influence of seasonal warm water from the NECC [Lathuilière *et al*., 2008]. High chlorophyll values are also observed near GD; some authors have noticed that these increases are due to nutrient ascent caused by mesoscale structures [Yentsch, 1974; Kawase and Sarmiento, 1985; Pelegrí *et al*., 2006]. The goals of this study are: i) the estimation of the seasonal and inter-annual variability of the chlorophyll at the different local conditions depicted in the survey region, and ii) to search the variation patterns as a consequence of the temperature and wind changes.

2. Data and Method

To study local spatial and temporal variability, satellite derived time series were used. Chlorophyll *a* time series was taken from the operationally derived from SeaWiFS sensor using standard NASA's *state of the art* algorithms, in the form of 8 day averages, with an approximated geometric resolution of 9x9 Km NASA OCEAN COLOR. An equivalent sea surface temperature dataset was obtained from NOAA and NASA pathfinder project dataset (version 4), giving about 18 Km resolution images and representing 7 days averages of the parameter. These are derived from the successive AVHRR sensors using best estimates of SST, providing that given advanced atmospheric and radiometric corrections are applied (Arbelo *et al*., 2005). Wind data were taken from level 2 processed QUIKSCAT archives [Triñañes *et al*., 2006]; geostrophic currents derived from multi-mission altimetry were also used as processed by AVISO group. The aforementioned data don't share the same spatial structure, due to the features of the altimetric sampling diamond like pattern. Data obtained from ten-days orbits are needed to complete an equivalent (spatial and temporal resolution) operational product which is updated every three days, giving a measure of mean geostrophic velocity vectors. The span of the available time series differs among sensors; for instance temperature series traces back to the eighties while satellite derived winds are available only since 1999. All data were merged onto a common reference framework using SIMOM software developed for multi-parametric and multi-resolution data fusion [Perez-Marrero *et al*., 2005]. From the conjunction of datasets, time series were obtained from designated points, performing at them a detailed analysis. Seasonal standardized anomalies were obtained using objective analysis methods, inter-annual variability was also calculated for the yearly and monthly binned time series. Detailed correlation analysis was performed among the time series at different temporal scales between all locations. In order to compare the conditions of the archipelago with those of the surrounding areas, four points were chosen to be representative of the main hydrographical regimes found in the subtropical and subequatorial Atlantic waters that encompass Cape Verde. NWAU, NASTG, NECC and GD are the ones that directly influence over the archipelago. Five analogous sites were selected (Figure 1) around the islands for the characterization of the Cape Verde waters.

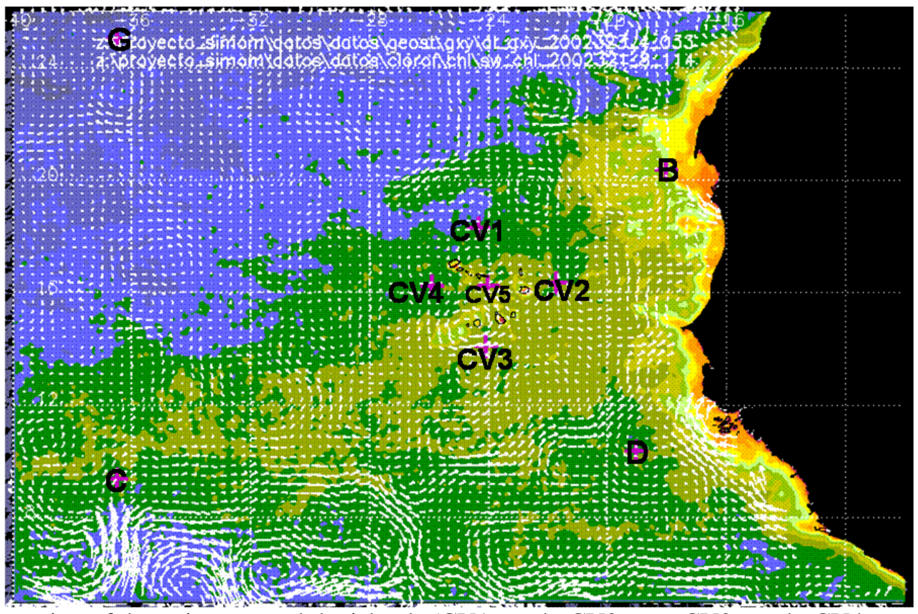

Figure 1. Location of the points around the islands (CV1-north, CV2-east, CV3-south, CV4-west and CV5-center) and the reference points (B – NWAU, G - NASTG, D - GD and C - NECC).

3. Results and Discussions

3.1.Seasonal variability

The absolute maxima and minima are found at the reference sites, that is, B 3.3 mg m-3 and G 0.04 mg m-3, respectively, and are resembled to the values presented by Lathuilière *et al*. (2008). Seasonal chlorophyll *a* distribution is quite similar in the five points around the islands. They show a large increase during October and November, and then a less pronounced rise during February in CV2 and CV4. Higher concentration values are found during the warming period at the end of the year, in the points located at the southeast of the islands (CV2 1.043 mg m-3 and CV3 0.96 mg m-3). The lower values found at the SE are associated to the weakening of wind velocities during the summer time; this is the general behavior, except in CV5 where a local wind regime seems influenced by the islands themselves. This general pattern of wind decreasing while water temperature increases is consistent with the monsoon seasonality and the general wind circulation in the area, making the ITCZ to oscillate from its southernmost point in winter to its northernmost during summer [Gabric *et al*., 1993; Helmke *et al*., 2005; Pelegrí *et al*., 2006; Lathuilière *et al*., 2008].

Interesting correlation coefficients between temperature and chlorophyll concentration are found; these are especially high when the latter is lagged one or two months from the first, suggesting that seasonal warming is affecting this pigment increase. We believe that the phytoplankton enrichment which occurs at the end of the year could be due to the arrival of waters from upwelling systems that are present in the area; as an example the cyclonic gyre of the GD, as can be seen in animations of satellite images of geostrophic currents. Yentsch (1974, cited in Pelegrí *et al*., 2006) remarks the importance of geostrophic circulation to alter the vertical distribution of isopycneals and hence nutrients, through a dominant mechanism that reinserts nutrients into the euphotic zone. Phytoplanktonic material also arrives accompanying warm, rain-influenced waters from the south during summer monsoon and northern displacement of ITCZ [Pelegrí *et al*., 2006; Lathuilière *et al*., 2008]. The latter generates the northwards flowing Mauritanian Current (MC) transporting warm, nutrient enriched waters from the equatorial zone.

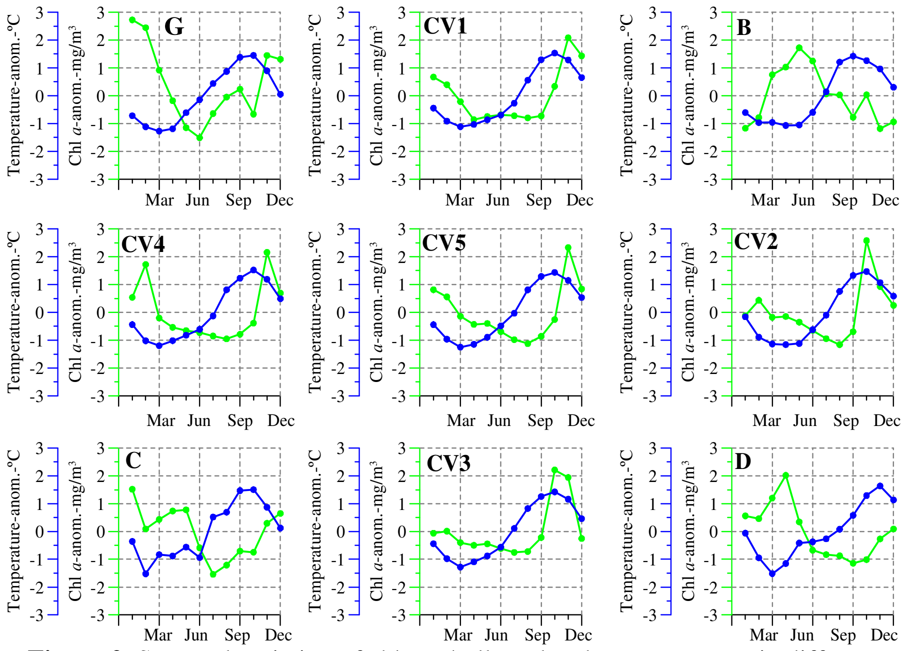

Figure 2. Seasonal variation of chlorophyll *a* related to temperature in different points.

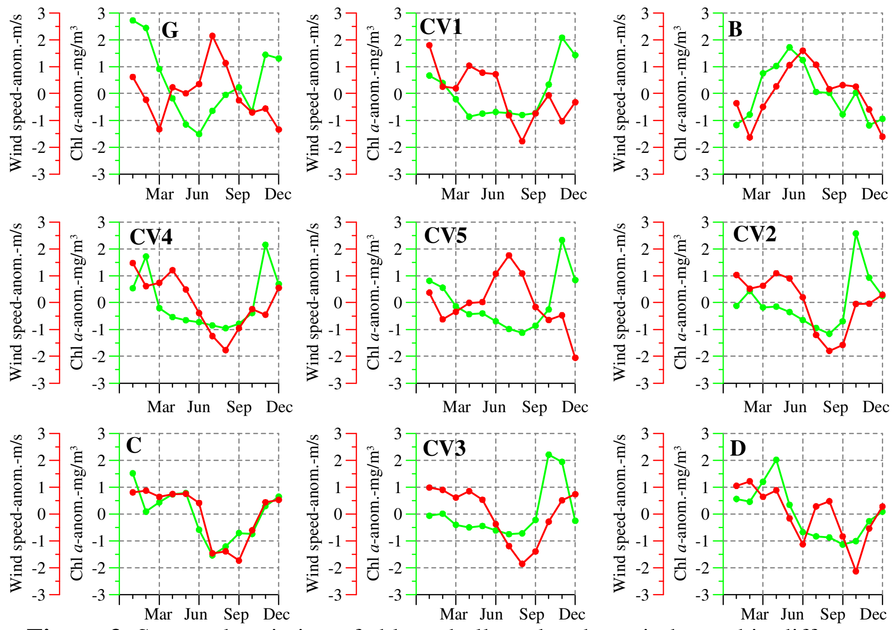

Figure 3. Seasonal variation of chlorophyll *a* related to wind speed in different points.

The MC is a northern branch of the NECC [Fernandes *et al*. 2004] and can be observed with satellite images as a relatively intense northward flux near Cape Verde (Dakar), restricted only to October and November. We believe that this pigment distribution could still be influenced by the formation of mesoscale structures in the south of the islands; they could be a consequence of the Canaries Current passing by the archipelago. This phenomenon has been widely described for the Canary Islands archipelago (Hernández-Guerra *et al*., 1993; Aristeguí *et al*., 1994, 1997; Molina *et al*., 1996; Barton *et al*., 1998, 2000; Pacheco and Hernández-Guerra, 1999; Marrero-Díaz *et al*., 2001; Basterretxea *et al*., 2002). Spatial correlation among the different locations is very high in temperature time series, with significance levels of 99.9% in all cases (Table 1).

	B	G	D	C	CV1	CV2	CV3	CV4	
CV1	-0,702	0,648	0,012	0,404					Chlorophyll *a*
CV2	-0,245	0,163	-0,028	0,161	0,575				
CV3	-0,381	0,160	-0,237	0,032	0,646	0,898			
CV4	-0,642	0,768	0,209	0,451	0,869	0,444	0,500		
CV5	-0,588	0,685	0,233	0,581	0,940	0,486	0,578	0,931	
CV1	0,954	0,924	0,919	0,921					Temperature
CV2	0,970	0,932	0,890	0,924	0,987				
CV3	0,980	0,967	0,894	0,944	0,985	0,989			
CV4	0,974	0,954	0,902	0,940	0,993	0,989	0,996		
CV5	0,978	0,962	0,901	0,933	0,989	0,992	0,998	0,997	
CV1	0,073	-0,111	0,223	0,707					Wind speed
CV2	-0,226	-0,414	0,276	0,945	0,848				
CV3	-0,500	-0,522	0,373	0,942	0,698	0,943			
CV4	-0,387	-0,438	0,426	0,857	0,854	0,936	0,926		
CV5	0,746	0,888	0,037	-0,428	-0,074	-0,390	-0,569	-0,473	

Table 1. Seasonal correlations of each parameter using the Pearson's coefficient among the different points.

Regarding chlorophyll time series, significance levels are also high (90-99.9%) within Cape Verde points, with the exception of the correlations between CV2 with CV4 and CV5. The most significative correlations (99.9%), allows for the distinction of two groups, the first includes CV1, CV4 and CV5, corresponding to the north western and central areas, while the second, in the south eastern part represented by CV2 and CV3. There are interesting correlations, negative between B and CV1, CV4 and CV5 and positive between G and the same points in the central and NW areas presenting levels of 95 to 9%. This phenomenon of variability appears to be in concordance with the variability in nutrient inputs that have been related to the seasonality of wind forcing and large scale circulation in this region as proposed by Lathuilière *et al*. (2008). Note that with the exception of the positive correlation, with 95% of significance, between C and CV5, C and D do not present significative correlations with any of the points of the islands; this may indicate that there is no exclusive influence of the oceanographic phenomena related to NECC and GD over chlorophyll cycle in the archipelago. Nevertheless, a well defined seasonal cycle is found for CCNE, located around 5ºN during winter, reaching 10ºN in summer [Mittelstaedt, 1991; Stramma *et al*., 2005], This oscillation influences over the cyclonic circulation of GD, which is a permanent and quasi stationary feature associated to NEC, NECC y a North Equatorial Undercurrent (Siedler *et at*., 1992). Correlations of seasonal wind distributions among the locations situated around the islands are quite significant, with the exception of CV5 that exhibits non significant, negative correlations. This fact may be attributed to the influence of the islands themselves. Time lagged correlations of temperature and wind velocities with respect to chlorophyll are shown in table 2.

	Chl-Temp	Chl-Temp(+1)	Chl-Temp(+2)	Chl-Temp(-1)	Chl-Temp(-2)	Chl-Wind	Chl-Wind(+1)	Chl-Wind(+2)	Chl-Wind(-1)	Chl-Wind(-2)
CV1	0,418	0,790	0,923	-0,072	-0,523	-0,073	-0,136	-0,466	0,263	0,639
CV2	0,363	0,592	0,617	0,023	-0,280	0,327	-0,217	-0,671	0,414	0,472
CV3	0,564	0,682	0,622	0,261	-0,153	0,181	-0,332	-0,757	0,458	0,555
CV4	0,039	0,458	0,733	-0,370	-0,670	0,347	0,313	-0,163	0,626	0,819
CV5	0,111	0,521	0,769	-0,330	-0,702	-0,567	-0,644	-0,467	0,641	0,995
B	-0,488	-0,735	-0,803	-0,135	0,301	0,677	0,224	-0,166	0,880	0,657
G	-0,289	0,165	0,610	-0,626	-0,801	-0,287	-0,271	-0,306	-0,599	-0,385
D	-0,624	-0,379	0,052	-0,694	-0,699	0,656	0,496	0,328	0,417	0,074
C	-0,494	-0,121	0,241	-0,880	-0,801	0,841	0,529	0,125	0,831	0,476

Table 2. Seasonal correlations of chlorophyll *a* (Chl) with temperature (Temp) and wind speed (Wind) using the Pearson's coefficient, with lags of up to two months in different points. (+1) 1 month latter; (+2) 2 months latter; (- 1) 1 month before; (- 2) 2 months before.

In that sense, the positive correlations between temperature and chlorophyll in the points around the islands, increase if temperature distribution is delayed by two months, this supports that seasonal cycle of temperature precedes that of chlorophyll, and hence could be related to ITCZ oscillation, the Monsoon period and the onset of CM [Fernandes *et al*. 2004; Menezes, 2003; Lathuilière *et al*., 2008]. When compared against the wind, a different behavior is found, the largest correlations show up if the cycle is moved forward by two months, but for CV2 and CV3, significant correlations are reached only if cycles are delayed by two months, this demonstrates mesoscale variability of this parameter within large scale circulation [Lathuilière *et al*., 2008].

3.2.Inter-annual variability

The trend analysis of the complete series shows a generalized decrease in chlorophyll concentration in the area, a similar behavior has been described for other regions in the last decades, like Galiza in the northern limit of the NE Atlantic upwelling system [Bode *et al*., 2008, *in press*], the Mediterranean [Barale et al., 2008], and the northern part of the CC CC (32ºN-44ºN) [Morales *et al*., 2008], pointing to reasons related to biomass, phytoplankton composition, nutrient limitation and water warming. To study the level of coupling with the rest of the parameters, data series were synchronized for the period between 2000 and 2004, calculating anomalies distributions and correlations among the chlorophyll and the rest of the parameters. As can be seen in table 3, no significant correlation was found when using annual mean values in the analysis.

	B	G	D	C	CV1	CV2	CV3	CV4	CV5
Chl-Temp	0,005	-0,446	0,483	0,050	-0,612	-0,322	-0,273	-0,214	-0,033
Chl-Wind	0,608	-0,052	0,162	0,326	0,438	0,414	-0,005	0,723	0,326

Table 3. Inter-annual correlations of chlorophyll *a* (Chl) with temperature (Temp) and wind speed (Wind) annual averages, using the Pearson's coefficient, in different points.

Nevertheless, if inter annual variability is studied by sub year periods, significant correlations between chlorophyll and temperature are observed for the first term of the year in locations G and C, also between wind velocity and chlorophyll in CV1 and CV4, during the second term, and specially between chlorophyll and temperature during the last term (table 4).

	B	G	D	C	CV1	CV2	CV3	CV4	CV5
Chl-Temp	-0,522	0,243	0,453	0,814	0,883	-0,742	-0,498	0,822	0,531
Chl-Wind	0,224	0,422	-0,898	0,777	0,433	0,030	-0,628	-0,154	-0,274

Table 4. Inter-annual correlations of chlorophyll a (Chl) with temperature (Temp) and wind speed (Wind) of the averages of four month's period (September-December), using the Pearson's coefficient, in different points.

High values of correlation significance among the locations in the case of temperature (Table 5) show the uniformity in the seasonal distribution for this parameter. Regarding chlorophyll distribution, positive and significative correlations are observed between B and CV2, G and CV4, C and CV4, C and CV5 and CV4 and CV5, respectively. In the case of wind distributions correlations were significant among all locations, with the exception of point CV5, in the middle of the archipelago, that presents a completely different cycle due to the influence of the islands. Although, significance level of 95% is found between B and CV5.

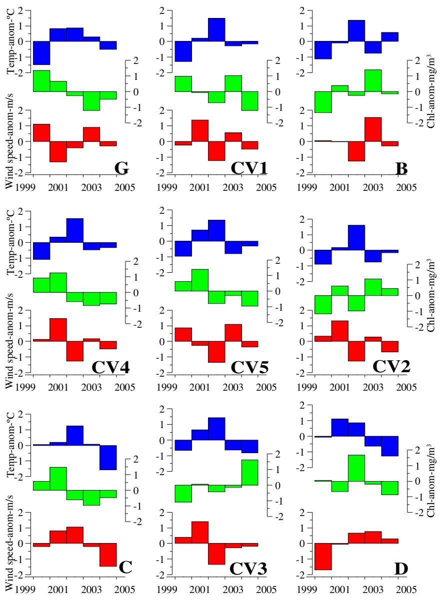

Figure 4. Inter-annual variation of the parameters in different points.

	B	G	D	C	CV1	CV2	CV3	CV4	
CV1	0,107	0,206	-0,061	0,124					chlorophyll *a*
CV2	0,865	-0,601	-0,672	-0,097	0,020				
CV3	0,296	-0,488	-0,553	-0,226	-0,711	0,574			
CV4	-0,423	0,896	-0,235	0,967	0,324	-0,235	-0,441		
CV5	-0,088	0,692	-0,324	0,906	0,491	0,050	-0,443	0,935	
CV1	0,887	0,841	0,492	0,511					temperature
CV2	0,909	0,680	0,572	0,539	0,952				
CV3	0,660	0,749	0,857	0,772	0,860	0,906			
CV4	0,857	0,814	0,621	0,600	0,985	0,978	0,933		
CV5	0,817	0,780	0,726	0,544	0,918	0,951	0,952	0,963	
CV1	0,619	-0,227	-0,064	0,122					wind speed
CV2	0,547	-0,098	-0,372	0,146	0,947				
CV3	0,321	-0,264	-0,473	-0,007	0,856	0,931			
CV4	0,489	-0,240	-0,288	0,122	0,967	0,986	0,955		
CV5	0,877	0,736	-0,412	-0,374	0,476	0,560	0,392	0,456	

Table 5. Inter-annual correlations (annual averages) of each parameter using the Pearson's coefficient among different points.

4. Conclusions

Chlorophyll seasonal distribution in all locations around Cape Verde is rather similar, nevertheless, they are different in chlorophyll concentration values, showing maxima in CV2 (1.043 mg m-3) and CV3 (0.96 mg m-3) in October. Seasonal cycle can be divided into three periods: a first, not very pronounced, peak only for CV2 and CV4, low values of pigment between March and September, and finally the absolute maxima in October (CV2 and CV3) and November (CV1, CV2 and CV3). Because of the different correlations between cape-verdian and reference locations, we can say that the seasonal chlorophyll distribution is influenced by a synergy of factors that vary connected to the general oscillation of physical parameters in the Sub Tropical North Atlantic. Hence a clear groping is formed among CV1, CV4 and CV5 (central and north western areas), and another group formed by CV2 and CV3, for the south eastern area.

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