Afr. J. mar. Sci. 25 : 363-372 - 2003

CLIMATOLOGY AND VARIABILITY OF SEA SURFACE TEMPERATURE AND SURFACE CHLOROPHYLL IN THE BENGUELA AND AGULHAS REGIONS AS OBSERVED BY SATELLITE IMAGERY

H. Demarcq[*,†] R. Barlow[†] and F. A. Shillington[‡]

[*,]IRD, Institut de Recherches pour le développement, France
[†]Marine and Coastal Management, Private Bag x, Roggebaai, 8012
[‡]Department of Oceanography, University of Cape Town, Rondebosch 7701

A climatology of satellite-derived sea surface semperature (SST) and surface chlorophyll a concentration (SCC), and their associated variability at time scales from weeks to years, was constructed for the Benguela and Agulhas regions. Global area coverage (GAC) data at 4.5 km spatial resolution from both AVHRR and SeaWiFS sensors were used to assemble the climatology, from weekly and 5-day time-series respectively. The SST data series spanned 18 years (1982-1999), whereas the SCC data covered the period September 1997 to April 2002. The dominant pattern in the annual SST is the cold upwelled water on the western continental shelf of South Africa and Namibia. SST was high at the Angola/Benguela front (15-17°S) and Agulhas plateau, the northern and southern extremities of the upwelling system respectively. Monthly variability is the strongest for SST in the Benguela region, except for the upwelling areas north of Cape Town and north of Lüderitz (<1°C), and for the Agulhas current area. The western Agulhas Bank chowned a clear seasonal pattern of warm surface water in summer and cool surface water in winter (amplitude of 2.5°C). A band of high SCC (>5-10 $mg{\cdot}m^{-3}$) was apparent close to the coast from the Angola/Benguela frontal zone to Cape Town. However, there was a well marked relative minimum at Lüderitz. On the South Coast, the highest SCC values (>3 $mg{\cdot}m^{-3}$) were between Cape Agulhas and Port Elizabeth, in the form of a plume that moves offshore. In contrast to SST, SCC variability mainly occurs at a intra-monthly scale with patchy distributions of high values north of the Angola/Benguela front in summer and in the upwelling areas in winter. The SCC in the Agulhas Bank region is much more variable at any time step.

The Benguela ecosystem in the south-eastern Atlantic Ocean extends from southern Angola (17°S) to the southern tip of Africa near Cape Town (34°S), and is bounded at both extremities by the warm water of the Angola Current in the north and the Agulhas Current in the south (Shannon and Nelson 1996, Shillington 1998). The system is dominated by coastal upwellings, driven by alongshore wind flow, resulting in cold temperatures and high productivity (Bakun 1996). Sea surface temperature (SST) and surface chlorophyll a concentration (SCC) are two major variables that are easily derived from spaceborne sensors, and can provide valuable information on physical and biological phenomena in the upper ocean. A detailed knowledge of the seasonal distribution and variability of SST and SCC is therefore useful for both climate and fisheries research in the region. Reliable information about the mesoscale spatial and seasonal variability of SST and SCC has only been possible since the advent of satellite remote sensing. Knowledge of these variables provides insight into the dynamic of coastal upwellings and the response of phytoplankton production. This coupling is of prime importance in the highly productive Benguela ecosystem, and its effect on the fluctuating fisheries (Boyer et al. 2000).

The primary goal of this study is to present an atlas of the spatial and temporal variability of SST and SCC in the Benguela ecosystem, and to describe the main patterns of the seasonal variability. SCC climatology for this region has been lacking during the past decade, and despite improvements in quality, the global SST climatologies (Reynolds and Smith 1995, Smith and Reynolds 1998, Xue et al. 2002) are of too coarse a spatial resolution (1 degree of latitude and longitude) for effective studies of coastal processes. The joint use of SCC and SST allows a more comprehensive observation of the surface environment. The area covered by these climatological series is adjacent to the three African countries of Angola, Namibia and South Africa, extending from 12°-40°S and 6°-29°E, and encompasses the whole Benguela upwelling region, as well as the southern coast of South Africa from Cape Town to Port Elizabeth (Fig.1).

DATA AND METHODS

The SST and SCC from the global area coverage (GAC) datasets (both at the 4.5 km resolution) were made available by NOAA (National Oceanic and Atmospheric Administration) and NASA (National Atmospheric and Space Administration) respectively. The original data were respectively acquired from the AVHRR and the SeaWiFS sensors, on board the NOAA satellite series and the OrbView-2 satellite respectively. The 4.5 km resolution is obtained from an inboard sampling of the initial 1.1 km resolution images, that makes possible an almost global coverage of the earth surface, including areas not covered by any receiving station. This resolution matches the large-scale extent of the study, and is high enough to describe the spatial and temporal variability of the observed surface mesoscale patterns. The SST dataset was constructed and used in the ENVIFISH European Union funded project (Shillington and Nykjær 2002) and was derived into weekly and monthly composites.

SST data were processed using the method described in Kidwell (1995) and slightly modified by Nykjær *et al* (1996). The final product consists of weekly averages of SST, from 1982 to 1999. In order to use the best data possible, and to keep the same overlap with the SCC dataset, the 18 year (1982-1999) climatology was preferable to a 5 year period as was the case for the SCC. The clearer variability of the SST, which is a less persistent variable than the SCC, also confirmed the appropriateness of this choice.

The SeaWiFS GAC database extends from the first available data of the SeaWiFS mission (September 1997) to April 2002. The original “chlorophyll” GAC level 2 data product was used to build the SCC composites directly from the version 3 of the SeaWiFS algorithms (O'Reilly *et al.* 2000) using the SeaDAS software package (Baith *et al.* 2001).
A daily spatial compositing of the standard chlorophyll a product was formed by merging the data from different orbits (between 2 and 3 over the Benguela region). Because of the loss of data specific to the original GAC product at the extremities of the swaths, there is no data overlap from two successive orbits when compositing at a daily scale. The aberrant values frequently encountered near cloudy areas were removed by using an empirical gradient detection-procedure over a 3x3 pixel window, where values associated with a gradient greater than an adequate threshold have been removed.
Both fortnightly and monthly climatologies were constructed but since there was very little difference between the two, a monthly climatology was chosen. Weekly SST and 5-day SCC composites were constructed initially from daily images, by using a simple arithmetic average. This procedure reduced the amount of cloud cover interference. The GAC SST dataset was directly

available as weekly and monthly composites from the European ENVIFISH project (Shillington and Nykjær 2002).

The 5-day SCC composites were constructed similarly from daily images, where the effect of cloud cover was reduced by using a temporal Gaussian weighted average over a 2-day window.

Monthly and yearly SST and SCC averages were calculated respectively from all the weekly and 5-day composites. The variability associated with every time interval (5-day, week, month and year), was expressed as the standard deviation (SD) for the SST and as the coefficient of variation (CV; standard deviation divided by the average) for the SCC. This last choice was necessary because, in contrast to the SST, the usual range of the SCC values was very large (from 0.01 to 10 $mg{\cdot}m^{-3}$). The spatial patterns using the SD alone did not adequately reflect the actual temporal variability. For the variability study, three time scales have been calculated: the yearly, monthly, and weekly or 5-day (for SST and SCC respectively). The average monthly variability (representing the seasonal cycle) was calculated from the climatological time series composed of 12 monthly images, from which both yearly and short-term components were absent. Finally, the shorter-term variability was deduced from the initial weekly or 5-day composites from which both yearly and monthly components were removed. The sum of the three *variances* (for the three time intervals considered) was equal to the total variance of the raw data.

RESULTS AND DISCUSSION

Annual climatology

The annual averages and main variability patterns of both SST and chlorophyll a are spatially explored using images (Fig. 1) and specifically quantified using averaged values in selected areas (Fig. 2). The major feature depicted in the 18-year average SST (Fig. 1a) is the strong local cooling associated with the presence of persistent coastal upwelling activity (average SST < 16.7°C) from Walvis Bay to Cape Town. To the north and south of these areas, an intermediate upwelling area (average SST between 17-18°C) can be identified. Three major upwelling areas are observed: from Walvis Bay to 28°S, around Hondeklip Bay, and from north of Cape Columbine to the Cape peninsula. The SST of the coastal part of these areas is between 14-16°C (Fig 2a) while the Cunene area (15°N) and the Central Agulhas Bank are over 18°C.

The most intense SST gradient was observed from the 6°E meridian to the coast at Lüderitz, where the temperature decreased by 6.6°C (19.8-13.2°C) approaching the upwelling area from the west. This is the most intense upwelling area in the Benguela system and, according to Bakun (1996), perhaps in the world ocean. The two upwelling areas south of Lüderitz have less intense offshore gradients of 6 and 5°C respectively.

Figure 1a shows the warm signature of the Agulhas Current (Lutjeharms 1996) adjacent to the 200 m isobath, from 29°E to the southern tip of the Agulhas Bank (37°S/21°E). The Agulhas retroflection and return current is strongly influenced by the Agulhas plateau (east of 25°E), which causes a northward meander. The cold subtropical front lies west of the Agulhas retroflection .

There is considerable spatial differences of the SST variability along the Benguela ecosystem (Fig. 1b). The Lüderitz and Cape Columbine areas have relatively “stable” seasonal SST SDs between 1.3 and 1.4°C (by far the lowest of the region) whereas the intermediate and less intense upwelling area of Hondeklip is more variable (SD >1.8). The most variable areas are at the two coastal boundaries of the upwelling system, the Angola-Benguela Front (15-18°S) and the Agulhas Bank (19-23°E), with SD >2.5°C (Fig. 1b and 2a). SST in the core of the Agulhas Current appears to be moderately variable, whereas its northern boundary regularly meanders onto the Agulhas Bank, with an SST SD of 2.0 °C. The subtropical area south of 39°S exhibited the highest SD of >3°C.

For most of the areas, the SST variability is essentially seasonal.

The 5-year average SCC (Fig. 1c) shows a strong and regular increase from 0.1 mg·m^{-3} in the offshore oligotrophic area to >10 mg·m^{-3} near the coasts, almost continuously along the shelf from Cape Town to northern Namibia. A notable exception is the Lüderitz area, characterized by the strongest winds (Strub et al 1998) and Ekman transport (Bakun and Nelson 1991) of the region, inducing a high mixing rate in the surface layer, which might cause light limitation of the phytoplankton growth, due to deepening of the surface-mixed layer, and despite the high level of nutrient enrichment of this area. From Walvis Bay up to 19°S (and to a lesser degree up to 16°S), where cooling by upwelling is less intense than farther south (Fig. 1a and 2a), the SCC seems to be greater than would be suggested by the upwelling intensity alone. There also appears to be significant productivity on the Agulhas Bank as indicated in Fig 1c and Fig 2b (SCC of around 2-3 mg·m^{-3}).

The SCC SD (Fig. not shown) is strongly correlated with SCC but because of its wide range of variation, its CV is more useful than the SD to investigate the variability of this parameter. To explore SCC variability at the same temporal scales as the SST, the CVs were computed for 5-day, monthly (Fig. 1e) and yearly time intervals. Total Chl a CV (including all three temporal scales) is shown in Figure 1d. The highest coefficients were observed at the boundaries of the system, especially north of Walvis Bay and in the coastal area of the central and eastern Agulhas Bank (CV >2), while the smaller variations occurs in the main upwelling areas. These results are synthesized in Figure 2b. The Agulhas Current area shows a clear pattern of high SCC variability due to the coastal upwelling activity, and well separated from the Agulhas Bank, suggesting a separate source of enrichment from the continental slope, most likely associated with movement of the Agulhas Current on and off the shelf edge (Lutjeharms et. al. 1989). The yearly SCC CV (not shown) is the lowest source of variability (highest coastal values about 0.2) and is also spatially homogeneous, specially in the upwelling areas. The monthly CVs are also weak at most of the upwelling areas (about 0.3), except north of 17°S (north of the Angola-Benguela frontal area), in the coastal area of the central Agulhas Bank (about 0.5) and the upwelling boundaries between Cape Agulhas (20°E) and Cape Columbine (Fig. 1e). The higher chlorophyll variability of the boundaries of the Benguela ecosystem is also linked to higher variability patterns in the SST (Fig. 1b). A positive correlation exists in the Benguela region between SST and SCC as well as between their variability, at very large spatial and temporal scales. Different relationships certainly occurs at shorter time scales (<1 week) but they can not be investigated from our data.
The high SCC variability observed in the extreme northern part of the Benguela region has to be considered with caution because is it associated with low values of SCC that are less accurately determined with remote sensing techniques on account of heavy cloud cover in this region.

Monthly climatology

A monthly seasonal climatology of the SST (Fig. 3) and associated SD (Fig. 4) was processed using every weekly composites from 1982 to 1999. Figure 7a and 7b shows some of the main patterns of this seasonality for the 6 areas used in Figure 2. As the annual SST variance (not shown) is generally <10% of the total variance and is spatially very uniform, the monthly SDs essentially represents the short-term (intra-monthly) variability. Despite the spatial averaging effect of the climatology (72 composite images for one climatic month), many SST frontal features remains. It is the case of the main upwelling fronts from Walvis Bay to the cape peninsula, and the northern borders of the Agulhas current, including the almost permanent signature of a branch moving northward along the western Agulhas plateau.

As previously shown, the SST seasonality (Fig. 3) is strong except for two major upwelling areas: Lüderitz and the St Helena Bay-Cape Columbine area. The Lüderitz upwelling is very intense and almost permanent while the second one is maximum in summer (Boyd 1994), in phase opposition with the solar radiation, resulting in very reduced seasonal SST differences, of about 1°C (around 16°C), as shown by the average coastal SST (Fig.7a). It appears that SST seasonality is essentially forced by the incoming solar radiation, for most of the areas. It is the case of the Central Agulhas Bank area, protected from any direct upwelling cooling and where the seasonal SST amplitude reaches 6° C, due to high stratification in summer and deep water-column mixing in winter (Boyd and Shillington 1994). The variability at the seaward edge of the Agulhas Bank (occurring between October and April) is most likely attributable to the Agulhas Current shear eddies along the continental slope.

The major spatial patterns of SST variability occurs in the Angola-Benguela frontal area (Fig.4), specially from January to April between 15 and 20 °S and from May to June north of 18°S. The "Cunene" area of Figure 7b shows the pronounced seasonality of this variability, due to the meridional movements of a narrow zonal front (Shannon and Nelson 1996). All the other areas shows a lower seasonality of the variability, with a maximum always occurring in summer, between December and March. The SST variability in the main coastal upwelling areas (from Walvis Bay to Cape Town) is moderate from May to November (<1°C), but higher from December to April with local maxima >2°C in February-March. There is a secondary maximum of variability in December, from Lüderitz to the eastern Agulhas Bank (Fig. 4), also visible in the 3 corresponding areas of Figure 7b. This seasonal inversion is due either to the contribution of exceptional and intense events in the climatology, as the warming of summer 1999-2000 (Roy et al. 2000) or to more subtle seasonal changes of the Southern Benguela. Two other coastal patterns of high SST variability are apparent: on the eastern Agulhas Bank from February to April, associated to a coastal and slope upwelling well visible from SST during the same period (Fig. 3). The Agulhas Current presents high short-term SDs all over the year (with a minimum in winter) associated with spatial variations of its coastal boundary.

The monthly climatology of SCC (Fig. 5 and 7c) depicts weak seasonal differences in surface chlorophyll a. Notable exceptions are the coastal area of the central Agulhas Bank, with higher concentrations from April to June, and in the Walvis Bay area, with consistently high coastal values, with a maximum in June-July. The St Helena Bay area is the richest of the southern Benguela and presents an almost inverse seasonality, with a pronounced minimum in July. In between, almost no seasonality occurs at Lüderitz where SCC at the coast is generally lower than in the surrounding areas (Fig. 5 and 7c), and associated to a moderate offshore extent of the phytoplankton biomass. The Angola-Benguela frontal area shows a weak seasonality of the SCC values (the "Cunene" area of Fig. 7c) but also pronounced spatial variations in both latitude and offshore extention (Fig. 5), extreme positions occurring in March and August.

The short-term variability of the SCC (Fig. 6) was computed from January to December from the 5-day averages. Some isolated high values of CV (as those commonly observed west of 10°E in the northern Benguela region from November to April) may be associated to high and very infrequent values of SCC and for these reason, have to be considered with care. Patterns of high SCC variability are observed between Cape Columbine and the western Agulhas Bank in summer (December-April). They seems to be linked to similar patterns in SST variability (specially from February to April) but appears further offshore than the SST ones. This observation agrees with the general coupling between the apparition of newly superficial upwelled water close to the coast and the observation of chlorophyll-rich surface water, that takes place later on in time and space and consequently further offshore. SCC variability along the West Coast (16-33° S) is high in winter (specially in July), in contrast to the SST variability that is very low (Fig. 4). This contrast may be due to such influences as shorter term SST variability related to upwelling pulses (1-5 days), external forcing of wind induced turbulence, or other limiting factors that could play an important role in enhancing primary productivity in winter.

Except for the central Agulhas Bank and the tropical part of the region, the seasonal variability of the SCC in the main upwelling areas is low does not seems to be primarily related to the seasonality of the upwelling enrichments. Other factors have to be considered, as the variability of the photosynthetic active radiation, the depth of the mixing layer, the iron limitation, and their importance have to be tested in both northern and southern Benguela ecosystems, that are different in many respects.

A joint climatology of SST and SCC at a fine spatial resolution is of special interest in the well contrasted Benguela region and offer a synoptic view of major oceanic and coastal processes. According the high number of observation used, the spatio-temporal patterns described have a high statistical validity and some spatial or temporal patterns rise pertinent questions in term of biophysical processes. SST variability is by far dominated by its seasonal term, while SCC is essentially dominated by the weekly variability. Nevertheless, higher variability frenquencies exists for both variables and are important to consider for primary production efficiency. The data used for these climatologies will also help in defining a regional tuned primary production model suitable for resources management purposes (Carr, 2002).

Remote sensing allows a fine description of the main patterns of their variability at various time step, that would be incompatible with *in situ* measurements techniques. Furthermore, many new sensors are now operating in ocean color and it is potentially important to estimate their capabilities according what is now widely accessible from remote sensing, where the amount of quality data is exponentially increasing. Numerous oceanographic data continuously collected in the region has now to be combined to offer more comprehensive views of a 3 dimensional ocean. Hydrodynamic models, coupled biological NPZD ones and ecosystemic model are running in the southern Benguela region and remote sensing observations are key data for their calibration or complementary inputs. Satellite wind data have also to be used in conjunction of these climatology, as they represent the main forcing of most of the processes described here.

ACKNOWLEDGEMENTS

The AVHRR SST dataset was made available by the Joint Research Centre (JRC) of the European Commission as a development of a scientific collaboration agreement between NASA and JRC. The SeaWiFS project provided the SeaWiFS GAC data, from a contract between NASA and Orbimage. We thank Ms Weeks (OceanSpace) for obtaining part of the GAC data from NASA. FAS thanks NRF for research funding. This is a contribution to the joint South African-French programme IDYLE, which involves the IRD (Institut de Recherche pour le Développement), Marine and Coastal Management, the University of Cape Town and OceanSpace. We thank the reviewers for comments that improved the manuscripts.

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Figure captions

Figure 1. Annual average (a) and monthly standard deviation (b) for SST computed from monthly composites (1982-1999). Annual average (c) and total coefficient of variation (d) of SCC computed from 5-day weighted composites from September 1997 to April 2002. Monthly coefficient of variation of SCC (e) computed from monthly composites.

Figure 2. Annual average of SST (a) and Chlorophyll *a* (b) and total standard deviation (error bars) for 6 characteristic coastal areas from Angola to the Agulhas Bank.

Figure 3. Monthly climatology of the SST (1982-1999) in the Benguela from the weekly GAC ENVIFISH database. SST is increasing from light blue (12°C) to red (24°C).

Figure 4. Monthly variation of the average weekly standard deviation of SST, for the period 1982-1999.

Figure 5. Monthly climatology of chlorophyll *a* (concentration) for the period September 1997 to April 2002.

Figure 6. Monthly variability of the chlorophyll *a* coefficient of variation for the period September 1997 to April 2002.

Figure 7. Monthly variability of SST (a) and Chlorophyll *a* (c) and their variability (a and d), for the same coastal areas than Figure 2.

Notes about last changes to the manuscript:

- Many part have been rewriten and the english revisited everywhere.
- 2 figures (Fig. 2 and 7, black&white graphs) are added to summarize and quantify mant points raised in the discussion
- Other figures redone according specifications (except figure 1, the color figures are split in 2 parts to be separated into 2 facing pages)
- 2 references added, 1 removed
- Results and discussion have been merged and the SST and SCC have been discussed together rather than separately, but a split has been made between **Annual climatology** and **Monthly climatology**
- the term “region” has been replaced by “areas”. “region” is only refers to the Benguela region.
- Conclusion is rewriten and shortened