Seasonal and interannual changes in Intense Benguela Upwelling (1982–1999)

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Abstract − Monthly maps of remotely sensed sea surface temperatures derived from NOAA/AVHRR thermal images are used to describe changes in 'Intense Benguela Upwelling' during 1982–1999. The coastal area under investigation lies between 9–34° S and 8–20° E and the total area of cold water between the coast and the course of the 13 °C isotherm is considered to be an index of intense, active upwelling. It exhibits a decreasing trend over the study period of 18 years and some evidence for a quasi-cycle of about 27 months. Seasonal cycles are discussed for the total cold water area as well as for its mean alongshore and offshore extents. The main season of cold surface water was found to occur between July and September during the austral winter. It peaks in August with a mean area of about 30×10^3 km^2 and relaxes drastically during the rest of the year. The underlying process of intense coastal upwelling is regionally trapped in two coastal zones. These are centred around 26 and 29° S and reach a mean offshore extension of 210 and 130 km, respectively, to form giant upwelling filaments. The area of cold water drastically shrinks, roughly by a factor of two, during weak upwelling years but significantly expands by a factor of about 1.5 during strong years. Associated sea level changes along the south-west African coast were derived from measurements at four coastal stations between 23 and 34° S during 1982–1987. The first principal component describes about 63 % of the total sea level variance. The lowest sea levels were found in the prominent Lüderitz cell near 26° S. On both the annual and interannual time scale, decreasing cold water areas are accompanied by increasing sea levels and vice versa. Mean seasonal cycles reveal that variations in the total cold water area lag behind those in the sea level along the entire south-west African coast by about 1 month. © 2001 Ifremer/CNRS/IRD/Éditions scientifiques et médicales Elsevier SAS

Résumé − Modifications saisonnières et interannuelles de l'upwelling intense de Benguela. Des cartes mensuelles de température de surface de la mer, obtenues par satellite à partir du capteur NOAA/AVHRR, sont utilisées pour décrire l'épisode intense de la remontée d'eau de Benguela entre 1982 et 1999. La région côtière étudiée s'étend de 9 à 34° S et de 8 à 20° E ; la totalité de la tâche d'eau froide entre la côte et l'isotherme 13 °C est considérée comme le signe d'un upwelling intense. Cet indice décroît durant la période de 18 années et un cycle de 27 mois apparaît. Les cycles saisonniers sont discutés pour l'ensemble de la région « froide ». La saison principale de remontée se situe entre juillet et septembre, durant l'hiver austral. Elle atteint son maximum en août avec une aire moyenne concernée de 30×10^3 km^2 et l'upwelling est particulièrement faible tout le reste de l'année. Deux foyers de remontée existent le long de la côte. Ils sont centrés sur 26° et 29° S et s'étendent au large respectivement jusqu'à 210 et 130 km en formant des filaments géants. L'aire de remontée se réduit de moitié durant les années de faible upwelling et s'étend d'une fois et demi les années d'upwelling intense. Des changements de niveau marin sont associés à ces phénomènes comme le prouvent les mesures effectuées à quatre stations côtières entre 23° et 24° S de 1982 à 1987. La composante principale décrit 63 % de la variance du niveau marin. Les niveaux les plus bas se rencontrent dans la cellule de Lüderitz près de 26° S. Aussi bien à l'échelle annuelle qu'à l'échelle interannuelle, les aires d'eau froide décroissantes sont liées à une montée du niveau

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marin et vice versa. Les cycles saisonniers moyens montrent que les variations de la surface totale d'eau froide sont décalées d'environ un mois par rapport à celles du niveau marin tout le long de la côte SW d'Afrique.

Benguela Current / coastal upwelling / remote sensing / sea surface temperature / Benguela Niño

Courant de Benguela / upwelling côtier / télédétection / température de surface de la mer / Niño de Benguela

1. INTRODUCTION

The area along the south-west African west coast is one of the most important fishery grounds in the world. Its meteorological, hydrographic investigation possesses a certain tradition (cf. Defant, 1936; Boss, 1941; Currie, 1953). Both the equatorial low air pressure belt along the Intertropical Convergence Zone and the south-west African low establish pressure gradients with respect to the South Atlantic Anticyclone with a high pressure belt at about 26° S, 10° W, (Schell, 1970). Consequently, the south-east trade wind (SET) dominates along the Namibian and South African coasts. Its equatorward alongshore component is the driving force for coastal upwelling processes in the Benguela Current, which can be considered to be the eastern branch of the basin scale gyre circulation (*figure 1*). Reviews by Shannon (1985) and Shannon and Nelson (1996) discuss associated spatial and temporal scales in more detail.

In contrast to other regimes of subtropical coastal upwelling with a poleward 'cold boundary' and an equatorward 'warm boundary', the Benguela regime is embedded meridionally between two warm water regions (Boyd and Agenbag, 1985). Intrusions of relatively warm near-surface water originate from the Agulhas Current in the Indian ocean, (Lutjeharms and Stockton, 1987). The warm water enters the South Atlantic to form mixed water types in coastal areas off south-west Africa. Garzoli and Gordon (1996) reported that the typical 13 Sv (1 Sv = 10^6 $m^3 \cdot s^{-1}$) volume transport of the Benguela Current is composed of 50 % South Atlantic central water, 25 % Indian ocean water and the rest could be a blend of Agulhas water and tropical Atlantic water. The result is a near-surface frontal system, which separates the cold upwelled water in the north from the warm water in the south. This frontal zone dominates surface and near surface layers to form the southern border of the Benguela upwelling (Lutjeharms, 1996). According to Defant (1936), the frontal position varies seasonally between 28° S (July) and about 34° S (January). Therefore, the

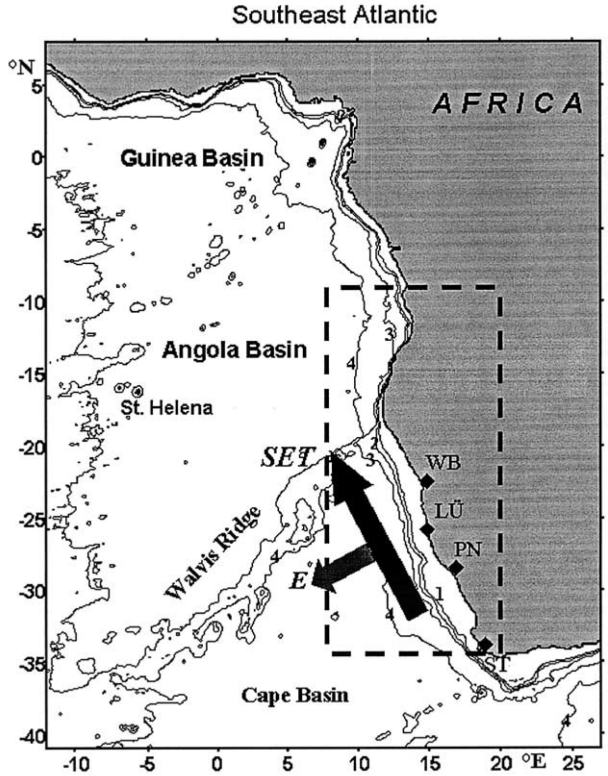

Figure 1. Area of investigation between 9–34 °S and 8–20 °E; the approximate bottom topography is shown (km) as well as the mean direction of the south-east trade wind (SET) and its Ekman offshore transport (E); tidal gauges recorded sea levels at Walvis Bay (WB), Lüderitz (LÜ), Port Nolloth (PN), and Simonstown (ST).

coastal belt of cold water stretches from this southern border to about 15–16° S, where the northern border of the upwelling regime is formed by the Angola-Benguela frontal zone (Kostianoy and Lutjeharms, 1999). The Angola-Benguela frontal zone separates warm equatorial water in the north from cold upwelling water in the south. Within surface and near-surface layers, this front is dynamically linked to the clockwise rotating gyre of the Angola Dome (Yamagata and Iizuka, 1995). Its climatic centre is located at about 12° S, 4–5 °E. For instance, the case study of Lass et al. (2000) suggests that motions along the southern flank of this gyre turn into poleward currents which feed, at least sometimes, up to 7 Sv subtropical water into the Benguela Current regime. To the north of about 17° S, the southward spreading equatorial water is commonly accompanied by an exceptionally relaxed SET. On the interannual time scale, a relaxation of the SET is commonly accompanied by intrusions of equatorial water into the northern Benguela regime (e.g. Shannon et al., 1986; Boyd, 1987). During such events cold upwelled water is replaced by warm, saline water during the main upwelling season to produce ‘weak upwelling years’, which have been referred to as ‘Benguela Niños’ in the literature. They frequently act as ‘fish killing years’ due to reduced feeding conditions in the nursery grounds of commercially exploited fish species (Boyd et al., 1992). These events are usually accompanied by eruptions of hydrogen sulphide from bottom mud layers which affect the entire water column over the continental shelf and drastically reduce the oxygen content in coastal zones (Chapman and Shannon, 1985). Because of their effect on the ecosystem, Benguela Niños are undoubtedly one of the most important phenomena observed in the Benguela system. At present little is known about the trigger mechanism for such events. There is, however, no question that both strength and direction of the SET play crucial roles in the development of extreme upwelling years. This is clear from investigations by Walker (1987) and Taunton-Clark and Shannon (1988). These authors studied the variability of the Benguela regime by means of monthly ship data in four time windows, 1906–1914, 1921–1939, 1946–1985 and 1961–1984. Warm events could be identified from elevated SST during 1909, 1923, 1934, 1937, 1949, 1963, 1974, and 1984. Significant cold events occurred during the years 1907, 1929, 1946, 1955, 1969, and 1982.

The limited base of direct measurements previously available mainly allowed for the description of SST variations along shipping routes. By comparison the large set of satellite derived data available for this investigation allows a more comprehensive study of the entire upwelling zone and also enables us to extend the above mentioned series of extreme upwelling years from the 1980s to the late 1990s. Nevertheless, this study should not be viewed as a climatological work because causative mechanisms of ocean-atmosphere interactions will not be dealt with. It should rather be seen as an attempt to describe annual- and interannual changes in the Benguela upwelling regime by means of an absolute quantity. One such, well-defined quantitative indicator could be the total area of ‘Intense Benguela Upwelling (IBU)’ and a time series of this indicator is expected to be suitable for comparing the oceanic response to changes in forcing conditions during this and subsequent studies. Therefore, this study focuses on the following two questions: (1) which years of strong (cold) and weak (warm) upwelling years during the 1980s and 1990s would extend the mentioned series of extreme upwelling years and (2) can it be confirmed that there are regionally fixed centres of IBU and how do they behave during extreme upwelling years?

2. DATA BASE

The analysis was based on remotely sensed sea surface temperatures (SST) in the form of monthly maps. This means that temporal fluctuations can only be resolved for periods longer than 2 months. The data set was derived from the Global Area Coverage (GAC) format SST images obtained from the Advanced Very High Resolution Radiometer (AVHRR) on board of the National Oceanic & Atmospheric Administration (NOAA) satellites. The SST maps were provided by the project ‘Cloud and Ocean Remote Sensing around Africa (CORSA)’ of the Space Applications Institute (SAI) of the European Joint Research Centre (JRC) in Ispra, Italy. This series covers 216 months (18 years) between January 1982 and December 1999 and its spatial resolution is 4.5×4.5 km^2 at the equator to decrease with the cosine of latitude. The production of such monthly SST maps smoothes out high frequency structures in space and in time. Therefore, we compared two 4-year series of monthly SST computed from daily- and 5-d composite maps and obtained a squared correlation coefficient of 0.95 between them. Consequently, we accept that methodical discrepancies have no major effect on the interpretation of monthly SST fields but absolute values for areas of cold surface water should nevertheless be viewed with some caution due to uncertainties in the underlying processing procedure. We refer to McClain et al. (1983) and Cole and Villacastin (2000) for more methodical details.

To study changes in the Benguela upwelling regime, a rectangular sub-area was selected between 9–34° S and 8–20° E (*figure 1*). This sub-region approximately covers the coastal zone from Luanda in the north to Cape Town in the south. In contrast to other approaches (cf. Nykjaer and van Camp, 1994; Demarcq and Citeau, 1995), we computed the area between a selected isotherm and the coast line and constructed a time series of monthly values of the total area occupied by cold coastal water. This approach follows the working hypothesis that globally acting processes of the atmosphere should be responsible for weak or strong winds and that their spatial scales exceed those of the coastal upwelling. Therefore, this treatment considers the entire cold water belt as a dynamical unit and essentially ignores meso-scale structures, which may be caused by the regional reaction of the coastal current system on changed forcing conditions to form transient upwelling features. We intend using this index in subsequent investigations to relate changes in the coastal upwelling to those in biological productivity, which exert an influence on interannual variations of commercially important fish species.

Water mass analysis of Hagen et al. (1981) and Lutjeharms and Valentine (1987) suggests that the SST 13 °C isotherm can be used to describe the offshore boundary of intense upwelling processes. This isotherm only intersects the sea surface in nearshore zones during the upwelling season, (Boyd and Agenbag, 1985). An actual example is shown in *figure 2*. This vertical temperature transect was obtained on a line of hydrographic stations normal to the shore line at about 25° S in October 2000. Water masses with temperatures smaller than 13 °C originate from layers beneath the seasonal thermocline. This internal boundary layer separates relatively warm water (T > 16 °C) of near surface layers from the cold water (T ≤ 13 °C) of subsurface layers. It intersects the sea surface over the steep continental slope to form a cold water belt extending several tens of kilometres from the coast. The 13 °C water has thermohaline properties of the South Atlantic central water with a salinity of about 35.1 (Currie, 1953).

In using this 13 °C criterion to elucidate areas of Intense Benguela Upwelling (IBU), we carried out the following three processing steps. At first, the total area of IBU was obtained by summation of all pixels between the 13 °C isotherm and the coast line correcting for the latitudinal change in pixel size. Thus, the total area of IBU was estimated independently of regionally occurring upwelling filaments. Second, the alongshore extension of IBU was determined as the distance between the northernmost and southernmost 13 °C pixel. This quantity describes the total alongshore extent of cold coastal water. Division of the total area by that alongshore extension provided the regionally averaged offshore extent. Finally, the area of investigation was subdivided by slices of one degree latitude to elucidate meridionally patterned structures in the IBU.

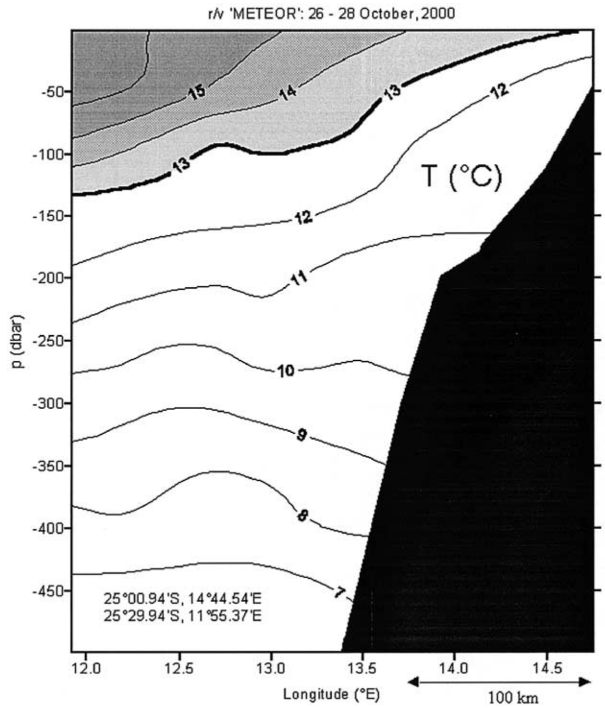

Figure 2. Vertical temperature transect recorded by r/v *Meteor* between 25–26° S and 11–15° E in October 2000; water layers warmer than 13 °C are coloured; note that the 13 °C isotherm intersects the sea surface close to the coast over the continental shelf.

Changes in the area of the coastal cold water belt can be related to fluctuations in the sea level via the Ekman offshore transport. Available sea level records were extensively described by Brundrit (1995). Access to the data sets was provided by the Permanent Service of Mean Sea Level (PSMSL) via the World Wide Web (www). To describe sea level conditions along the Namibian and South African west coasts we selected monthly values between 1982 and 1987 for the four coastal stations Walvis Bay (WB, 22.95° S), Lüderitz (LÜ, 26.633° S), Port Nolloth (PN, 29.25° S), and Simonstown (ST, 34.183° S) (*figure 1*). The time series from the stations were merged using the method of principal components described by von Storch et al. (1995).

3. RESULTS

3.1. The cold water belt

The time series of monthly areas of IBU is plotted in *figure 3a*. Its total mean points to 10 543 km^2. The plot indicates not only a decreasing trend but also drastic fluctuations. Annual peak values in the area of IBU only fall below the level of (mean + sigma) during weak upwelling years: 1984, 1993, 1996, 1997 and 1999. However, they exceed the level of (mean + 3sigma) during strong upwelling years: 1982, 1985, 1990 and 1992. Here, sigma is the standard deviation. It is evident that the total area of IBU during 'strong years' exceeds that of 'weak years' by a factor of about three. Pronounced upwelling years are also marked by longer lasting upwelling seasons (*figure 3b*). The main upwelling season occurs during the austral winter-spring. It usually starts in June and terminates in October to be greatly reduced during the austral summer-autumn (December–May). When the IBU is weakly developed, the upwelling season only lasts 1 month (1984) or completely disappears (1993, 1996, 1997, 1999) to start 1 or 2 months later. Without any doubt, changes in the strength of the seasonal cycle characterise the IBU on the interannual time scale. The power spectrum of the IBU series (not shown) exhibits the seasonal cycle but also a slight accumulation of 'energy' in the period range between 26 and 28 months. This effect is also visually detectable in the peak values of *figure 3a*. Unfortunately 216 months is much too short for a serious analysis of upwelling fluctuations with periods of several years.

Positions of the northernmost and southernmost boundary of IBU reflect the alongshore extent of upwelling favourable forcing fields. It reaches a maximum – 1 680 km – in September during the upwelling season. This value closely agrees with the climatic distance between the southern and northern boundaries of the SET during the main upwelling season. The mean seasonal cycle in the alongshore extent of the IBU is compared with those of weak and strong upwelling years in *figure 4*. These plots imply that there must be a coastal strip where such exceptional cold water occurs during the whole year and that this strip's alongshore distance must be smaller than about 500 km. Normally the cold water belt monotonically expands from February to September and shrinks during the rest of the year. A similar seasonal cycle could be detected for weak upwelling years, but of course at a lower level. By contrast, strong years exhibit two cold water seasons. The first one occurs between March and April at a relatively low level while the other occurs in August. The latter arrives 1 month earlier than usual. However, there is no doubt that upwelling during the autumn season contributes to the alongshore expansion of upwelled cold water during exceptional upwelling years.

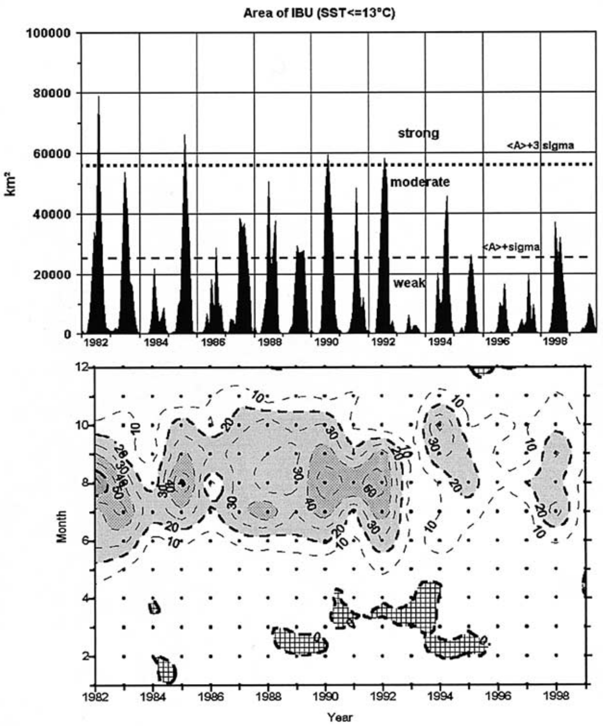

Figure 3. Areas with SSTs cooler or equal to 13 °C indicating Intense Benguela Upwelling (IBU): monthly time series; the area of IBU exceeds the mean value <A> plus three times the standard deviation (3sigma) during strong but it fluctuates beneath (<A> + sigma) during weak upwelling years, corresponding contour plot for 18 years (1982–1999); the extent of the IBU larger than 20×10^3 km^2 is coloured while times of no IBU are hatched. (The comparison of this IBU series with those of other satellites suggests that values of the year 1992 could be somewhat underestimated.)

Dividing the total mean of the IBU by its averaged alongshore extent yields 10 km as the mean offshore extent of the cold water belt. This value reflects the scale of the first baroclinic radius of deformation within the vertically well mixed near shore upwelling zone. It can be expected that increasing alongshore extensions of the IBU would coincide with increasing offshore distances and vice versa. The results show that this expectation is justified for alongshore extents which significantly ex

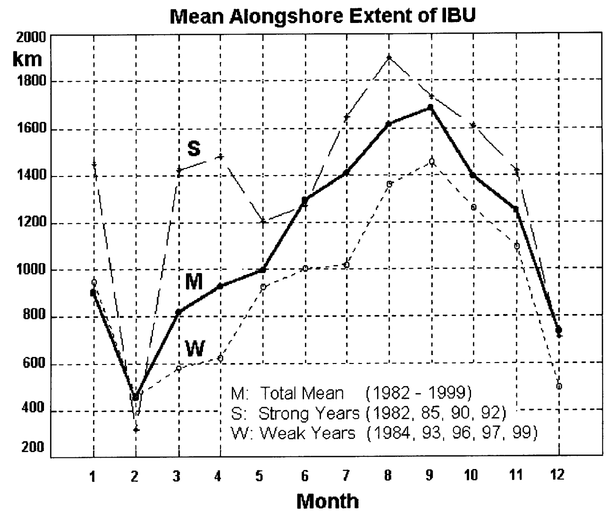

Figure 4. Mean seasonal cycle (M) in the alongshore extent of the IBU (km) and averaged cycles for weak (W) and strong (S) upwelling years.

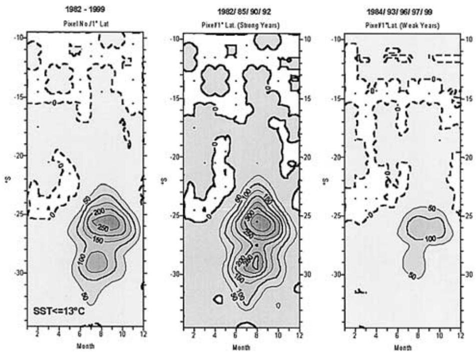

Figure 5. The mean seasonal cycle in the IBU plotted versus the latitude; contours are given by pixel numbers for SSTs equal or lower than 13 °C for the total mean (left hand panel), strong upwelling years (middle panel), and weak upwelling years (right hand panel); latitudes and periods with no IBU are white; note that the IBU is regionally fixed in two cells around 26 and 29° S and the seasonal cycle of the southern cell precedes that of the northern cell by about 1 month.

ceed a critical value of about 500 km. However, offshore extents increase with decreasing alongshore extents when the values of the latter fall below this critical value. Data points in this category probably describe outbreaks of cold water, caused by single upwelling events. Daily and weekly SST maps show that such features sporadically occur within the entire belt of IBU. They form transitory upwelling filaments, which cause localised expansion of the upwelling signal to relatively large distances offshore.

3.2. Permanent upwelling cells

The IBU area is dominated by two permanent upwelling cells. The largest is located near latitude 26° S, just off Lüderitz Bay. This is seen in *figure 5*. To elucidate seasonal cycles of the IBU as a function of latitude cold water pixels were accumulated for slices of one degree in latitude and plotted as contours. The left hand panel shows the entire time series while the middle and the right hand panels describe strong and weak years, respectively. The diagram indicates the presence of cold surface water with SST ≤ 13 °C over most of the area between 15 and 34° S throughout the year. The exception being the region 20 to 25° S where such water was often not present during the mid-summer to early-winter part of the year. The situation is similar during strong upwelling years. Two upwelling centres dominate the IBU from May/June until October/November. The Lüderitz cell influences the whole area between 24 and 28° S while the Namaqua cell dominates the zone between 28 and 30° S. The mean upwelling season of the southern cell (29° S) commonly starts 1 month earlier than that of the northern cell (26° S) but it starts about 1 month later and terminates 1 month earlier during weak years.

Both IBU centres synchronously reflect the above mentioned effects of extreme upwelling years. *Figure 6* demonstrates characteristic zonal extents for the two cells. The ratio between offshore extent of the northern cell to that of the southern cell is 1.7 during average conditions, 1.5 during strong years and 2.4 during weak years. This implies that, in terms of biological production, the importance of the Lüderitz cell probably increases with decreasing upwelling intensity. In general, the cold water belt of IBU extends from about 22 to 34° S but the northern limit migrates northwards to about 18° S during moderate and strong upwelling years. Due to the regional importance of the two IBU cells, their mean seasonal cycles are compared for strong and weak upwelling years in *figure 7*. It is noted that the time lag of 1 month in reaching peak values is more typical for strong upwelling years and that the maximum cold water area of the southern cell in such years reaches about 75 % of the northern cell area. During weak upwelling years, the IBU areas only reach 25 % of the values which characterise strong years and in contrast to the IBU of the southern cell, which has a single peak in August, the northern cell exhibits also a second peak in October.

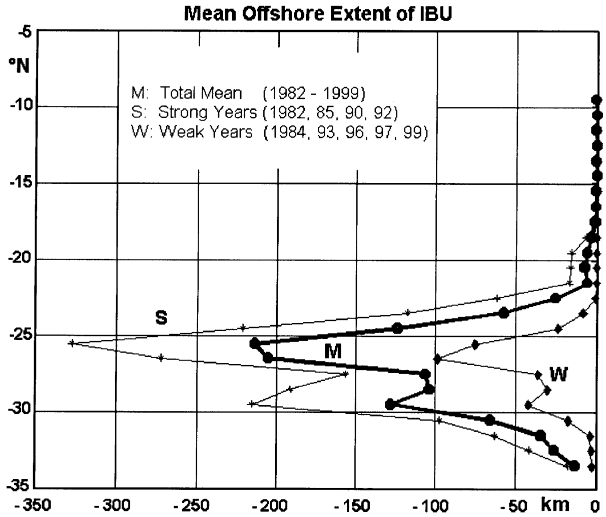

Figure 6. Mean offshore extent (M) of IBU (km) versus the latitude and corresponding averages characterising weak (W) and strong (S) upwelling years within the upwelling cells at 26 and 29° S.

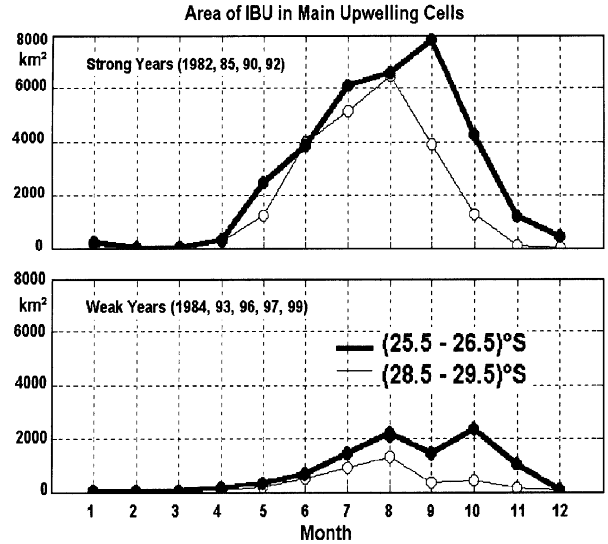

Figure 7. Mean seasonal cycles of both identified IBU cells in between 25.5–26.5 and 28.5–29.5 °S for strong (upper panel) and weak upwelling years (lower panel).

Thus, strong and weak upwelling years affect the cells in a similar manner but the total area of the IBU is somewhat larger in the northern cell. Comparing the IBU series for the zones between 25.5 and 26.5° S and between 28.5 and 29.5° S (not shown), it seems to be that the relatively weak southern cell is more sensitive to interannual variations than the dominating northern cell. In the south, there is also a tendency to develop double peaks in the upwelling seasons of the 1990s. More randomly distributed double peaks mark the upwelling season in the northern cell.

3.3. Sea level changes

Interannual changes in strength and direction of the SET give rise to positive (negative) sea level anomalies through reduced (enhanced) Ekman offshore transports along the whole Namibian and South African west coast. Tidal gauge records of sufficient quality were only available from four stations for 6 years (1982–1987) within the study period. These 6 years include three extreme upwelling years: weak upwelling in 1984 and strongly developed upwelling in 1982 and 1985 (*figure 3a*). The tidal gauges are located at Walvis Bay (~23° S), Lüderitz (~27° S), Port Nolloth (~29° S), and Simonstown (~34° S) (*figure 1*). There is a clear depression in the alongshore distribution of averaged sea level in vicinity of Lüderitz which confirms the regionally fixed northern upwelling cell near 26° S. From this point, mean sea levels increase southwards as well as northwards. By contrast, the standard deviations show a minimum near Port Nolloth and increase in both directions with larger values towards the equator. The variance in sea level data was decomposed in principal components to describe the sea level variability by its first empirical mode, which represents 62.7 % of the total variance. The time series of coefficients was normalised to the absolute peak value and thereafter z-transformed (mean = 0, sigma = 1). The same procedure was applied to the IBU series in order to compare them on the same numerical level (*figure 8*). As expected the curves show an inverse relationship where sea level depressions more or less coincide with peaks in the IBU area. It is seen that during strong upwelling years, the IBU area peak lags behind the sea level minimum by about 2 months. After removal of persistence between neighbouring data points by introduction of the statistical degree of freedom, the cross-correlation between the two series shows a mean time lag of 1 month at the 95 % confidence level – a value visually confirmed by the averaged seasonal cycles. It seems that this time lag more or less disappears during moderate and/or weak IBU years. Usually, the lowest sea level along the whole coast line occurs in July and is lagged by the total area of IBU in August. The interannual variability is strongest

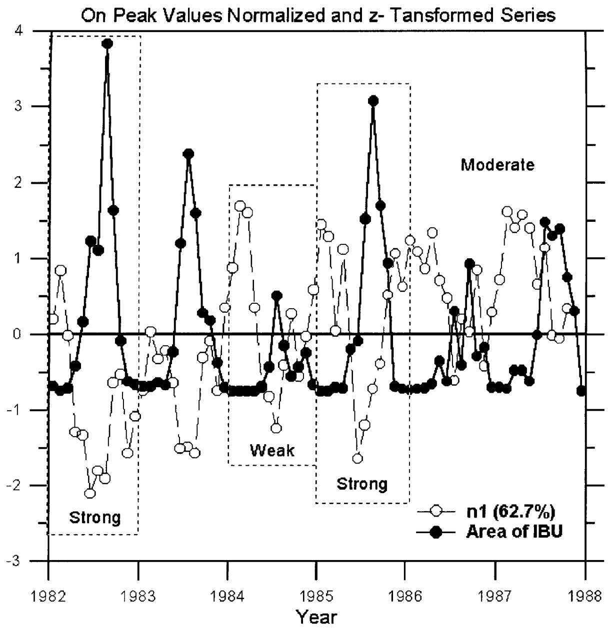

Figure 8. On peak values normalised and z-transformed time series (mean = 0, sigma = 1) of the area of IBU (bold line) in comparison with that of the first principal component (n1) of sea level variations between Walvis Bay in the north and Simonstown in the south (broken line); the latter describes about 63 % of the total variance; strong, weak and moderate upwelling years are indicated; note that low sea levels only lead enhanced areas of the IBU by about 1 up to 2 months during strong and moderate years.

during the IBU season. It is evident that there was a slight tendency for sea levels to increase and total areas of IBU to decrease between 1982 and 1987. Thereafter, the decreasing tendency in IBU of the upwelling season continued until 1999 (*figure 3a*). Strong upwelling years, such as 1985, only interrupted this trend for the duration of one upwelling season.

Taking into account the distance of 409 km between Walvis Bay (~23° S) and Lüderitz (~27° S), the averaged seasonal cycle of the sea level gradients between these two locations exhibits a positive sign during the whole year (not shown). The minimum gradient (about $0.6{\times}10^{-7}$) occurs in September when upwelling, and hence alongshore expansion of the northern cell is greatest (*figure 4*). The corresponding maximum of about $1.7{\times}10^{-7}$ occurs in March. In other words, there is about a factor three difference between the non-upwelling and the upwelling seasons. This factor increases to a value of about four in the coastal zone between Lüderitz and Port Nolloth (~29° S). The alongshore distance between these two stations is about 290 km and includes the Namaqua upwelling. The mean seasonal cycle for this stretch of coastline shows a minimum of about $-3{\times}10^{-7}$ in July and a maximum of about $-0.7{\times}10^{-7}$ in December. The sea level gradient between Port Nolloth and Lüderitz is thus always negative. This tendency continues southward into the coastal belt between Port Nolloth and Simonstown (~34° S); these two stations being about 548 km apart. Alongshore gradients in this coastal section fluctuate between values of about $-0.4{\times}10^{-7}$ in July and October and $-1.3{\times}10^{-7}$ in January and December with no seasonal cycle.

Both important IBU cells are located to the north of Port Nolloth. Therefore, when we focus our attention on the effect of anomalous upwelling years on the sea level, we only consider the Walvis Bay to Lüderitz and Lüderitz to Port Nolloth zones. In these zones, as already discussed, alongshore gradients in sea level are reduced by a factor of two to three during the main upwelling season. In order to study effects of anomalous upwelling years, we computed monthly anomalies of sea level gradients by removing the mean seasonal cycle. We then compared the 1984 anomalies (a weak upwelling year) with the 1985 anomalies (a strong upwelling year) in *figure 9*. It is seen that in the Walvis Bay to Lüderitz zone (upper panel) positive anomalies in alongshore gradients lasted about 5 months in 1985 due to the intensified upwelling season. Considering this year of relatively strong coastal upwelling, it seems to be that the curve of anomalies in sea level gradients across the northern cell is mirrored by that across the southern cell (lower panel). Such a mirror in the curves of anomalies across the two upwelling cells is not seen during the Benguela Niño of 1984. The poleward spreading of warm equatorial water, which was accompanied by increasing sea levels between Walvis Bay and Port Nolloth, generated inverse gradient anomalies across the two upwelling centres during the upwelling season.

In summary, we may conclude that the northern upwelling cell near 26° S plays a crucial role in the whole Benguela Current regime not only during strong but also during weak upwelling years while the southern cell near 29° S reacts more intensively to extreme upwelling years. The IBU only occurs within these two regionally fixed cells and is associated with enhanced cold water areas and by reduced sea levels. Years of strong IBU are associated with longer lasting upwelling seasons and positive anomalies in alongshore sea level gradients

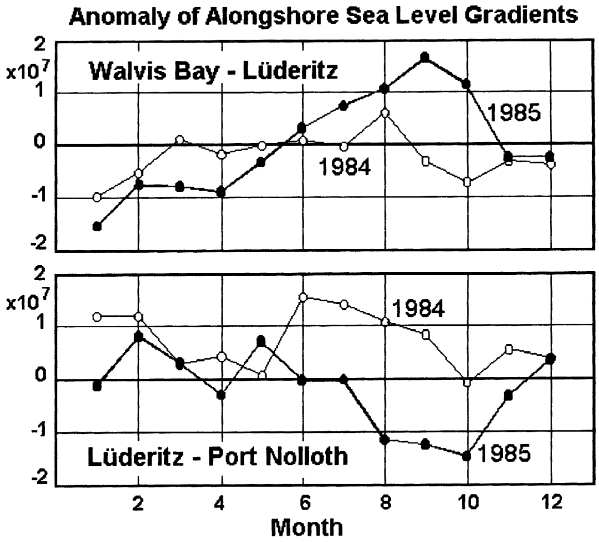

Figure 9. Monthly anomalies in alongshore gradients of sea level for two adjacent years of weak (1984) and strong (1985) upwelling between Walvis Bay and Lüderitz across the northern upwelling cell and between Lüderitz and Port Nolloth across the southern upwelling cell.

across the northern cell and negative anomalies across the southern cell. The inverse situation describes Benguela Niños with a drastically reduced upwelling season.

4. DISCUSSION

The main driving force of the Benguela upwelling is the alongshore component of the wind stress with a climatic value of about $0.04\ N \cdot m^{-2}$. This value causes a mean offshore volume transport per unit length of about $0.7\ m^2 \cdot s^{-1}$. It will be balanced by a sea level gradient of the order of 10^{-7} over the main upwelling centre (26° S). This follows from simple vorticity balance calculations based on wind-driven offshore motions and geostrophically adjusted alongshore currents. The resulting offshore extent of cold upwelled water reaches about 100 km (Lutjeharms and Meeuwis, 1987). The width of that cold water belt mainly depends on the scale of the cyclonic wind-stress curl (Bakun and Nelson, 1991). According to Nelson and Hutchings (1983), this distance increases by a factor of two or three in regionally fixed upwelling cells, especially between 23 and 32° S. However, active, intense upwelling processes are confined to coastal zones with a mean offshore distance of several tens of kilometres, cf. Hagen et al. (1981) and Boyd and Agenbag (1985). This comparatively small offshore scale corresponds to that of the dynamically controlled baroclinic radius of deformation within the vertically homogeneous coastal belt, (Fennel, 1992). The ratio between the Ekman offshore transport and deformation radius indicates that the characteristic upwelling velocity should be about $2 \times 10^{-5}\ m \cdot s^{-1}$. Water mass analyses show that the upwelled water originates from layers at the base of the seasonal pycnocline at a distance of a few hundreds of kilometres offshore. This pycnocline vertically separates relatively warm near surface water from cold water of intermediate layers below 100 m depth. Thus, water parcels need about 2 months to ascend to the sea surface within the coastal zone which suggests that a time series based on monthly averages would sufficiently resolve the main upwelling signal.

Therefore, monthly maps of the sea surface temperature (SST) were used to describe the seasonal cycle and interannual variations in Intense Benguela Upwelling (IBU) along the Namibian and South African west coast for the period between 1982 and 1999. The area of investigation covers the rectangular sub-region in between 9–34° S and 8–20° E. It is assumed that, independently of cooling processes at the sea surface during the winter season, intense upwelling generates SST of less or equal to 13 °C. The total area between this isotherm and the coast line as well as its alongshore and offshore extent were considered suitable quantities for characterising both spatial and temporal changes in the Benguela upwelling. This study has shown that the area of water colder than 13 °C – the IBU – is at a maximum during the austral winter/spring and minimum during the austral summer/autumn. This might be construed to imply that the IBU is essentially reflecting the seasonal cooling cycle and not upwelling. We contend that this is not the case for two reasons. First, there is some observational evidence that the 13 °C isotherm will only intersect the sea surface during active upwelling. And, second, we have shown that the IBU lags behind the sea level minimum by about 2 months – a lag which is in agreement with the one reported by Verstraete and Picaut (1983) for the Gulf of Guinea and also with our own theoretical calculations of the Benguela upwelling dynamics. If, on the other hand, the observed IBU cycle was purely a consequence of seasonal cooling, then there should be no lag.

The monthly IBU series exhibit a quasi cycle with a period of about 27 months. After removal of the mean seasonal cycle, resulting anomalies show a clear correspondence with the 28-month averaged cycle of the Quasi Biennial Oscillation (QBO). This atmospheric phenomenon describes rhythmic changes in zonal winds of the equatorial stratosphere (Naujokat, 1986). For instance, Maruyama and Tsuneoka (1988) reported a longer westerly QBO during the Pacific El Niño years 1965, 1968, 1976, 1979, 1982/83, 1986/87 and 1991/92. That could be an indication that the global equatorial wind system of the upper atmosphere influences the forcing regime of the SET in a similar manner. Unfortunately, the time series of 18 years is much too short for a detailed frequency analysis.

Between the climatic northern and southern boundaries of the south-east trade wind (SET), the IBU is concentrated in two regionally fixed upwelling centres located at about 26 and 29° S. The offshore extent of the northern cell reaches 220 km while that of the southern cell is roughly smaller by a factor of two. The latter cell is more sensitive to interannual changes in the SET than the northern cell. Its offshore extent varies by a factor of about six between weak and strong upwelling years while that of the northern cell varies by a factor of about three. Due to the importance of the northern cell to the whole Benguela upwelling regime, the factor of three also determines the ratio between weak and strong IBU for the entire Namibian and South African west coast.

In combination, the two cells at 26 and 29° S effectively split the Benguela upwelling region into northern and southern regimes (cf. Agenbag and Shannon, 1988), with the result that sea levels increase equatorwards as well as polewards from these latitudes. This implies that all other regionally fixed filaments within the Benguela upwelling (as discussed by e.g. Lutjeharms and Meeuwis, 1987) should be associated with SST higher than those of the IBU and/or time scales shorter than about 2 months.

Having dealt with the second of the two questions posed as research objectives we turn back to address the first: which years of strong (cold) and weak (warm) upwelling years during the 1980s and 1990s would extend the mentioned series of extreme upwelling years? Generally, there was a decreasing trend in the total area of IBU during the period 1982–1999. However, pronounced coastal upwelling occurred in 1982, 1985, 1990, and 1992. These years were characterised by upwelling seasons being 2 to 3 months longer than the average. Benguela Niño-like events occurred during the years 1984, 1993, 1996, 1997 and 1999. In this case, the upwelling season was usually 2 months shorter than average. Thus, the previously reported series of extreme upwelling years (cf. Walker, 1987; Taunton-Clark and Shannon, 1988) can be extended to 1999. Within the extended series, a total of twelve ‘warm years’ and nine ‘cold years’ can be identified between 1907 and 1999. The mean gap between all consecutive extreme years was about 11 years for Benguela Niños, which occurred between 1909 and 1963, but it only was about 5 years between 1974 and 1999. The corresponding mean gap was about 16 years between adjacent strong upwelling years in the period 1907–1955 but it was only about 6 years between 1969 and 1992. Therefore in the case of both warm and cold Benguela events, the mean gap between successive events decreased by a factor of about two during the recent past. This could be a consequence of increased observational density or of a climatically triggered ‘regime shift’. If we disregard the former possibility then it seems to be that the frequency of extreme warm and cold upwelling years switched from the decadal scale to the interannual scale during the late 1960s and early 1970s. The switch could be regionally or globally forced. From the literature it is clear that there are three different types of warm water intrusions which lead to the development of a Benguela Niño.

First, equatorial surface and subsurface water from the equatorial Atlantic Ocean, particularly from the Gulf of Guinea and around the Angola Dome, spread southwards along the south-west African coast. Both strength and duration of the regular upwelling season is reduced dramatically (Servain et al., 1985). Such ‘remote forcing’ from equatorial regions influences the entire northern Benguela region. According to Horel et al. (1986), the relaxation of zonal winds in the western equatorial Atlantic triggered the 1984 warm event in the northern Benguela when huge quantities of warm, saline equatorial water replaced the cold upwelling water. As the volume of warm waters in the upper layers increased the sea level was raised significantly. This led to increased hydrostatic pressure which displaced the pycnocline downwards. As a result local upwelling favourable winds were not able to pump nutrient rich water into the euphotic zone.

The second type of warm intrusion can involve an influx of water from the south. Walker (1986) reported such an event to have occurred in April 1984.

Third, a similar effect can result from shoreward intrusions of oceanic water due to regionally relaxed Ekman offshore transport. Such situations were observed in the early 1970s by O'Toole (1980).

Although all three types of warm water intrusions are accompanied by elevated sea levels near the coast, the type of intrusion can be identified from the associated anomalies in alongshore gradients. The 'equatorial type' of 1984 completely removed sea level gradients between Walvis Bay (~23° S) and Lüderitz (~26° S) and positive anomalies occurred between Lüderitz and Port Nolloth (~29° S). Opposite conditions with comparable consequences must be expected for the 'Agulhas-type' in the southern Benguela. In the case of an 'offshore-type' intrusion, all anomalies in alongshore sea level gradients are expected to be drastically reduced. All three types of intrusion however develop in reaction to spatial and temporal changes in the forcing mechanisms and all three types lead to a reduction of the area of IBU which, in turn, leads to a reduction of biological production and commercial fish catches such as was discussed by Boyd (1987) for annual landings of Cape Horse mackerel.

We may finally conclude that the 'IBU area' based on the 13 °C criterion, developed during this study, may be employed as a robust parameter useful for monitoring variations in the Benguela upwelling regime and which proved to be a particularly effective tool for the characterisation of both weak and strong upwelling years in a compact manner.

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REFERENCES

Agenbag, J.J., Shannon, L.V., 1988. A suggested physical explanation for the existence of a biological boundary at 24°30'S in the Benguela system. S. Afr. J. Mar. Sci. 6, 119–132.

Bakun, A., Nelson, C.S., 1991. The seasonal cycle of wind-stress curl in subtropical eastern boundary current regions. J. Phys. Oceanogr. 21, 1815–1834.

Boss, G., 1941. Niederschlagsmenge und Salzgehalt des Nebelwassers an der Küste Deutsch- Südwestafrikas. Biolklimatische Beiblätter 1, 1–48.

Boyd, A.J., 1987. The intrusion of saline tropical water onto the Namibian shelf (1973–1974; 1979–1987). Trop. Ocean-Atmos. Newsl. 40, 8–11.

Boyd, A.J., Agenbag, J.J., 1985. Seasonal trends in the longshore distribution of surface temperatures off Southwestern Africa 18–34° S, and their relation to subsurface conditions and currents in the area 21–24°S. In: Bas, C., Margalef, R., Rubies, P. (Eds.), International Symposium on the Most Important Upwelling Areas off Western Africa (Cape Blanco and Benguela). Instituto de Investigaciones Pesqueras, Barcelona, pp. 119–148.

Boyd, A.J., Taunton-Clark, J., Oberholster, G.P.J., 1992. Spatial features of the near-surface and midwater circulation patterns off western and southern South Africa and their role in the life histories of various commercially fished species. S. Afr. J. Mar. Sci. 12, 189–206.

Brundrit, G.B., 1995. Trends of southern African sea level: statistical analysis and interpretation. S. Afr. J. Mar. Sci. 16, 9–17.

Chapman, P., Shannon, L.V., 1985. The Benguela ecosystem Part II. Chemistry and related processes. Oceanogr. Mar. Biol. Ann. Rev. 23, 183–251.

Cole, J., Villacastin, C., 2000. Sea surface temperature variability in the northern Benguela upwelling system, and implications for fisheries research. Int. J. Remote Sensing 21, 1597–1617.

Currie, R., 1953. Upwelling in the Benguela Current. Nature 171, 497–500.

Defant, A., 1936. Das Kaltwasserauftriebsgebiet vor der Küste Südafrikas, Länderkundliche Studien, Festschrift W. Krebs, Stuttgart, pp. 52–66.

Demarcq, H., Citeau, J., 1995. Sea surface temperature retrieval in tropical area with Meteosat: the case of the Senegalese coastal upwelling. Int. J. Remote Sensing 16, 1371–1395.

Fennel, W., 1992. Responses of a coastal ocean. Trends Phys. Oceanogr. 1, 163–179.

Garzoli, S.L., Gordon, A.L., 1996. Origins and variability of the Benguela Current. J. Geophys. Res. 101, 897–906.

Hagen, E., Schemainda, R., Michelchen, N., Postel, L., Schulz, S., Below, M., 1981. Zur küstensenkrechten Struktur des Kaltwasserauftriebs vor der Küste Namibias. Geod. Geoph. Veröff. 36, 1–99.

Horel, J.D., Kousky, V.E., Kagano, M.T., 1986. Atmospheric conditions in the Atlantic sector during 1983 and 1984. Nature 310, 248–251.

Kostianoy, A.G., Lutjeharms, J.R.E., 1999. Atmospheric effects in the Angola-Benguela frontal zone. J. Geophys. Res. 104, 20963–20970.

Lass, H.U., Schmidt, M., Mohrholz, V., Nausch, G., 2000. Hydrographic and current measurements in the area of the Angola-Benguela Front. J. Phys. Oceanogr. 30, 2589–2609.

Lutjeharms, J.R.E., 1996. The exchange of water between the South Indian and the South Atlantic Ocean. In: Wefer, G., Berger, H., Siedler, G., Webb, D.J. (Eds.), The South Atlantic. Springer Verlag, Berlin, Heidelberg, New York, pp. 125–162.

Lutjeharms, J.R.E., Meeuwis, J.M., 1987. The extent and variability of south-east Atlantic upwelling. S. Afr. J. Mar. Sci. 5, 51–62.

Lutjeharms, J.R.E., Stockton, P.L., 1987. Kinematics of the upwelling front off southern Africa, Afr. J. Mar. Sci. 5, 35–49.

Lutjeharms, J.R.E., Valentine, H.R., 1987. Water types and volumetric considerations of the South-East Atlantic upwelling regime. S. Afr. J. Mar. Sci. 5, 63–71.

Maruyama, J.S., Tsuneoka, Y., 1988. Anomalously short duration of the easterly wind phase of the QBO at 50 hPa and its relationship to an El Niño event. J. Met. Soc. Jpn. 66, 629–634.

McClain, E.P., Pichel, W.G., Walton, C.C., Ahmad, Z., Sutton, J., 1983. Multi-channel improvements to satellite-derived global sea surface temperatures. Adv. Space Res. 2, 43–47.

Naujokat, B., 1986. An update of the observed Quasi-Biennial Oscillation of the stratospheric winds over the tropics. J. Atmos. Sci. 43, 1873–1877.

Nelson, G., Hutchings, L., 1983. The Benguela upwelling area. Prog. Oceanogr. 12, 333–356.

Nykjaer, L., van Camp, L., 1994. Seasonal and interannual variability of coastal upwelling along northwest Africa and Portugal from 1981 to 1991. J. Geophys. Res. 99, 14197–14207.

O'Toole, M.J., 1980. Seasonal distribution of temperature and salinity in the surface waters off South West Africa 1972–1974. Rep. Sea Fisheries Institute of South Africa, Cape Town.

Schell, I.I., 1970. Variability and persistence in the Benguela Current and upwelling off southwest Africa. J. Geophys. Res. 75, 5225–5241.

Servain, J., Picaut, J., Busalacchi, A.J., 1985. Interannual and seasonal variability of the tropical Atlantic Ocean depicted by sixteen years of sea-surface temperature and wind stress. In: Nihoul, J.C.J. (Ed.), Coupled Ocean-Atmosphere Models. Elsevier Science Publishers, Amsterdam, pp. 211–237.

Shannon, L.V., 1985. The Benguela ecosystem part I. Evolution of the Benguela, physical features and processes. Oceanogr. Mar. Biol. Ann. Rev. 23, 105–182.

Shannon, L.V., Nelson, G., 1996. The Benguela: large scale features and processes and system variability. In: Wefer, G., Berger, H., Siedler, G., Webb, D.J. (Eds.), The South Atlantic. Springer Verlag, Berlin, Heidelberg, New York, pp. 163–210.

Shannon, L.V., Boyd, A.J., Brundrit, G.B., Taunton-Clark, J., 1986. On the existence of an El Niño-type phenomenon in the Benguela system. J. Mar. Res. 44, 495–520.

Taunton-Clark, J., Shannon, L.V., 1988. Annual and interannual variability in the South-East Atlantic during the 20th century. S. Afr. J. Mar. Sci. 6, 97–106.

Verstraete, J.M., Picaut, J., 1983. Variations du niveau de la mer de la température de surface et des hauteurs dynamiques le long de la cote nord du Golfe de Guinée. Océanogr. Trop. 18, 139–162.

von Storch, H., Bürger, G., Schnur, R., Storch von, J.S., 1995. Principal oscillation patterns: a review. J. Clim. 8, 377–400.

Walker, N.D., 1986. Satellite observations of the Agulhas Current and episodic upwelling south of Africa. Deep-Sea Res. 33, 1083–1106.

Walker, N.D., 1987. Interannual sea surface temperature variability and associated atmospheric forcing within the Benguela system. S. Afr. J. Mar. Sci. 5, 121–132.

Yamagata, T., Iizuka, S., 1995. Simulation of the tropical thermal domes in the Atlantic. J. Phys. Oceanogr. 25, 2129–2140.