Benguela Dynamics
Pillar, S. C., Moloney, C. L., Payne, A. I. L. and F. A. Shillington (Eds). *S. Afr. J. mar. Sci. 19: 143–157*
1998

TEMPORAL AND SPATIAL PATTERNING OF SEA SURFACE TEMPERATURE IN THE NORTHERN BENGUELA UPWELLING SYSTEM: POSSIBLE ENVIRONMENTAL INDICATORS OF CLUPEOID PRODUCTION

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The physical dynamics of the northern Benguela upwelling system between July 1981 and August 1987 were investigated by applying standardized Principal Components Analysis to a time-series of 235 mean, weekly sea surface temperature satellite images of the region. The first three principal components accounted for 87% of the total variance in the standardized input images and were the only components retained for interpretation. Principal Component I (PC I) represents the mean spatial structure of the system in terms of relative SST gradients, PC II represents the balance in dominance between inshore-offshore v. longshore SST gradients and PC III highlights patterns associated with the warming of the central Namibian region (19–23°S) in conjunction with the maintenance of cooler conditions to the north and/or south. These results are interpreted within the context of previous findings on the behaviour of the system, and their relevance to clupeoid recruitment is discussed. Strong negative loadings on PC II indicated conditions which would promote the longshore "retention" of clupeoid eggs and larvae and "concentration" of planktonic food across thermoclines and thermal fronts, whereas strong positive loadings on PC III indicated conditions which would promote onshore retention and concentration. Conditions promoting onshore retention would, on occasion, have also been reflected by positive loadings on PC II whenever there was a uniform contraction of the offshore upwelling front, as a result of reduced, but similar, levels of upwelling along the entire coast.

Research on how environmental conditions can affect the reproductive success of fish stocks has typically involved searching for correlations between physical parameters and various aspects of stocks reproductive cycles, such as spawning intensity, larval survival and year-class strength. This approach has been successful in uncovering general trends. For instance, in eastern boundary currents, variation in upwelling activity, surface circulation and the vertical structure of the water column have all been found to influence the recruitment success of clupeoids. Key processes are thought to include: enrichment of the food chain, via the upwelling of nutrient-rich water; retention of eggs and larvae, via reductions in upwelling activity and intrusions of warmer water masses; and the concentration of food particles across thermal fronts and thermoclines for the feeding larvae (Lasker 1978, Bakun 1993, Parrish *et al*. 1983, Cury and Roy 1989).

Nonetheless, there remains a general inability to predict clupeoid recruitment success reliably on a yearly basis from knowledge of environmental conditions. One reason suggested to explain this is that little attention has been paid to the importance of scale in many correlation studies (Taggart and Frank 1990). A particular problem is that fisheries and environmental parameters are often measured, sampled and compared with each other at different spatial scales, and/or averaged across inappropriate temporal scales.

In studies that have found good long-term relationships between single environmental parameters and recruitment, the environmental parameter has often been averaged over relatively long intervals of time and/or measured from areas that are different in size or location from the distribution of the fish stock (e.g. Cury and Roy 1989, Lluch-Belda *et al*. 1989, Shannon *et al*. 1988). Whereas this approach may reveal general relationships, and provide insight into the impact of remote forcing on stocks, it also masks variations in local environmental conditions and consequently is unlikely to provide a sufficiently sound basis for recruitment prediction. Ultimately, it is local conditions, irrespective of how they relate to larger scale processes, which will determine spawning activity and the survival of the early life-history stages.

Historically, there have been enormous constraints on where and when environmental and fisheries data could be collected. Data have been limited to observations from "ships of opportunity", coastal observations, and the frequency with which research ships could be deployed. In coastal upwelling systems, high resolution monitoring is needed in order to capture their biological and physical variability fully.

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Manuscript received: November 1996

The advent of maritime remote sensing in 1978 (Sherman 1985) marked a new era in the monitoring of the marine environment, and has offered a solution to this problem of scale. Time-series of satellite-derived sea surface temperature (SST) and ocean colour images have recently become available from organizations such as the National Aeronautics and Space Administration (NASA) and the European Joint Research Centre (JRC). These datasets offer the potential to resolve the relationship between recruitment and environmental conditions better, first by allowing for the construction of environmental indices across a wide range of temporal and spatial scales, and second by opening up the possibility of exploring the behaviour of marine systems according to changes in their spatial structure through time.

The purpose of the present study is to evaluate the use of standardized Principal Components Analysis (PCA) on a time-series of mean weekly sea surface temperature (SST) images of the northern Benguela. PCA has been most commonly applied to remotely sensed data as a method of data compression in multi-channel sets of satellite images (Lillesand and Kiefer 1987), and it has also been used as an objective method of investigating patterns of spatio-temporal change in time-series of satellite images. Examples include the evaluation of changes in vegetation across Africa (Eastman and Fulk 1993), the behaviour of the Californian Current off Baja California, using SST images (Gallaudet and Simpson 1994), and the behaviour of the coastal upwelling system off Mauritania, also using SST images (Hernández-Guerra and Nykjaer 1997, Maus 1997).

SST images potentially contain a lot of information on the functioning of eastern boundary systems, as regards upwelling activity, intrusion of warm water masses and the presence of mesoscale features (e.g. filaments, eddies and fronts). Insofar as PCA can be used to classify and quantify system variability, according to the evolution of spatial structure through time, it is hoped that it may help to identify and track environmental features thought to be important in influencing the recruitment success of the northern Benguela's sardine *Sardinops sagax* and anchovy *Engraulis capensis* stocks.

MATERIAL AND METHODS

CORSA data and software

Weekly SST images of the northern Benguela were extracted from the Cloud and Ocean Remote Sensing around Africa (CORSA) dataset, held at the European Joint Research Centre (JRC) at Ispra in Italy. The dataset consists of weekly, monthly and annual SST composites for the area 45°S–45°N; 30°W–51°E, from July 1981–December 1990. Data were processed in the Marine Environment Unit at the JRC from Global Area Coverage (GAC) Advanced Very High Resolution Radiometer (AVHRR) data, under a data-sharing agreement with NASA (C. Villacastin, Space Applications Institute, Italy, pers. comm.). The CORSA SSTs for the northern Benguela have been validated successfully (e.g. Cole 1997) with the Comprehensive Ocean Atmosphere Data Set (COADS, Woodruff *et al*. 1987, Roy and Mendelssohn 1998). PCA was performed using ERDAS Imagine™.

It should be noted that, although weekly SST images used in the present analysis clearly show the main macroscale features of the system, the averaging procedure inevitably means that there is some blurring of event-scale (3–10 days) and mesoscale features.

Data preparation

The study window within which the analysis was performed is illustrated in Figure 1. A total of 235 weekly composites from July 1981 to August 1987 were retained for analysis, and 60 (20%) were discarded because of excess cloud cover (it would not have been possible to include the entire time-series as a result of ERDAS Imagine™ having an upper limit of 255 "images" on which it can perform PCA.) Composites were discarded if there was >30% cloud contamination within the entire study region, and/or >60% cloud contamination within any of the following latitudinal subdivisions of this area: 16–18, 18–21, 21–24 and 24–26°S. Areas of cloud contamination in the "chosen composites" were replaced by the distance-weighted average of SSTs in the surrounding non-cloud contaminated pixels.

All pixel values outside of the study window were set to zero and, for the purposes of the analysis, were ignored. For each composite, the SST values within the study window were standardized according to the mean spatial SST and spatial standard deviation of the particular composite in question. Given that there was a wide range in levels of spatial SST variability among the weekly composites, and that PCA works on the variance structure of the input dataset, standardization was judged to be an important step in order to avoid the analysis being unduly biased towards those composites that had higher levels of spatial SST variability.

Lastly, the standardized composites were concatenated into a $t \times n$ matrix $\mathbf{X}$, where t is the number of time-steps (235) and n is the number of pixels within the study window (about 12 500).

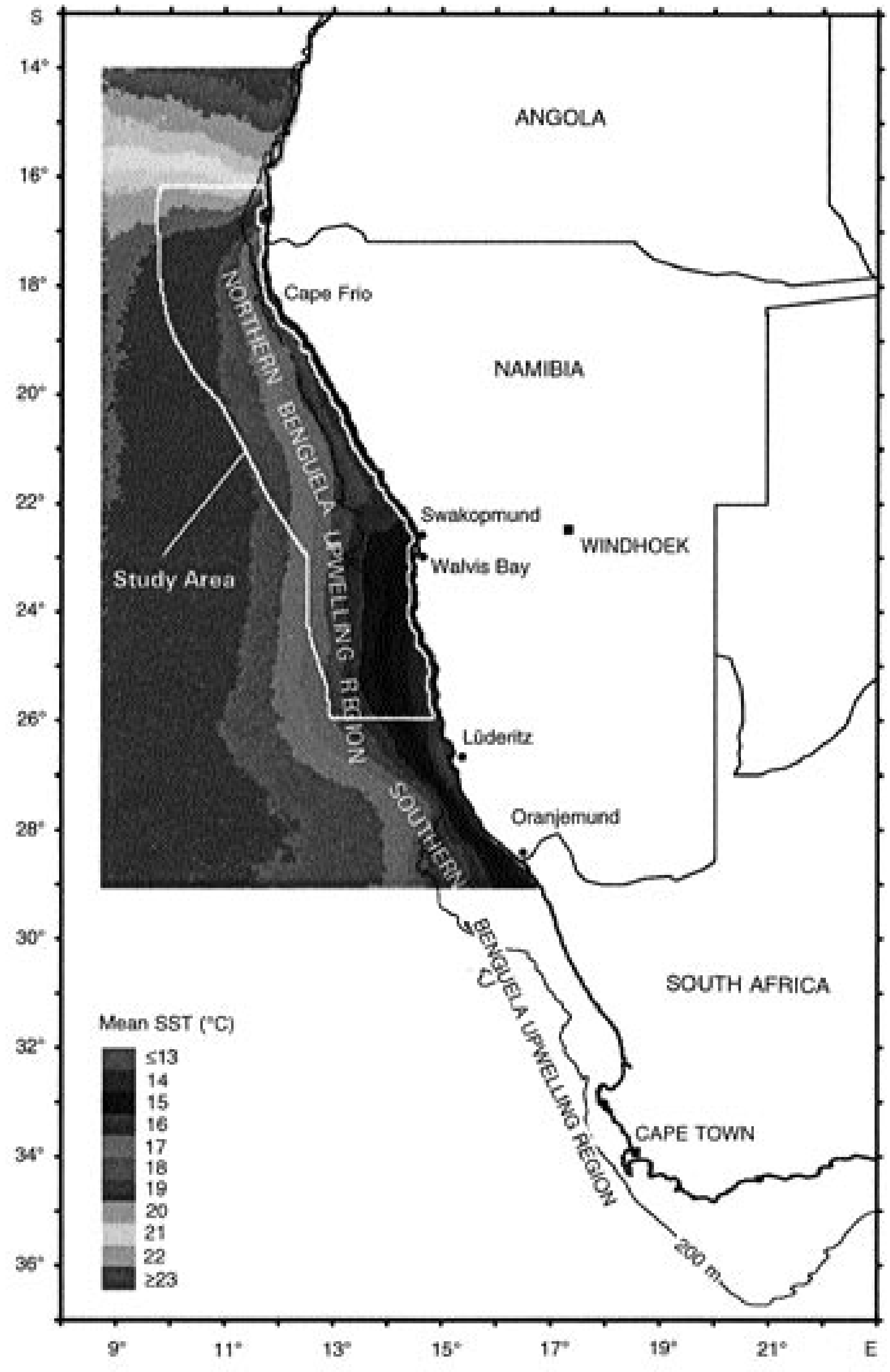

Fig. 1: The west coast of southern Africa showing the Benguela upwelling system, with mean SSTs in the northern Benguela from 1981 to 1990. The study window for PCA is indicated

Table I: Eigenvalues and the percentage of total variance in the standardized input accounted for by the first 10 principal components

Principal component	Eigenvalues	% of total variance
I	187.41	79.25
II	12.32	5.21
III	5.59	2.36
IV	3.04	1.28
V	2.12	0.90
VI	1.57	0.66
VII	1.26	0.53
VIII	1.13	0.48
IX	0.83	0.35
X	0.76	0.32

Principal components analysis

In applying PCA to a time-series of images, each image should be thought of as a separate dimension and each pixel as a separate sample. Output is both spatial and temporal. Principal component images are the spatial output, such that each successive component represents a spatial pattern of residual variance which is uncorrelated with previous components. Temporal output is in the form of "loadings", which indicate the degree of similarity between each standardized image in the time-series and the spatial pattern in each principal component image.

Given that the application of PCA to time-series of satellite images is a fairly recent development, the four main stages involved in this procedure is outlined below. Some of the notation is similar to that used by Gallaudet and Simpson (1994).

CALCULATION OF THE COVARIANCE MATRIX

A $t \times t$ covariance matrix $\mathbf{R}$ is calculated from the input matrix $\mathbf{X}$ and its inverse ($\mathbf{X}^{-1}$) using the formula

$$\mathbf{R} = [1/(tn - 1)]\, \mathbf{XX}^{-1} \quad .$$

Calculating a correlation matrix from unstandardized input would also produce the same matrix $\mathbf{R}$.

CALCULATION OF EIGENVECTORS (EIGENMATRIX) AND EIGENVALUES

Each principal component is "described" by an eigenvalue and an eigenvector. The eigenvalues represent the variance in the input matrix $\mathbf{X}$ accounted for by each component, whereas the eigenvectors describe the "direction" that each principal component takes in the t-dimensional space. The "eigenmatrix" is composed of successive eigenvectors (column vectors) lined up next to each other. Both the eigenvalues and the eigenmatrix are found by solving the equation

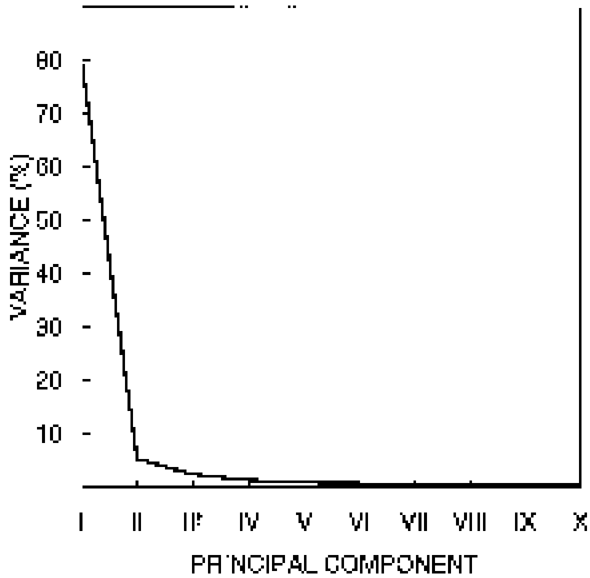

Fig. 2: Percentage variance accounted for by each of the first 10 principal components

$$\mathbf{ERE}^{T} = \mathbf{V} \quad ,$$

where $\mathbf{E}$ is the $t \times t$ eigenmatrix, $\mathbf{V}$ is the $t \times t$ matrix of eigenvalues (in which all the non-diagonal elements are zero), and $\mathbf{E}^{T}$ is the transpose of $\mathbf{E}$.

By convention, the eigenvalues in $\mathbf{V}$ are ordered according to decreasing magnitude. The first eigenvalue represents the fraction of variance accounted for by the first principal component, and similarly for successive components. The eigenvectors in the eigenmatrix are ordered according to the magnitude of their associated eigenvalues, with the first eigenvector describing the first principal component.

The eigenvectors are all orthogonal and the variability accounted for by each component is uncorrelated to the other components. Each successive principal component accounts for the maximum proportion of residual variability in the input dataset not accounted for by previous components.

CALCULATION OF THE PRINCIPAL COMPONENT IMAGES

Principal component images are the spatial output from PCA. The first component represents the spatial

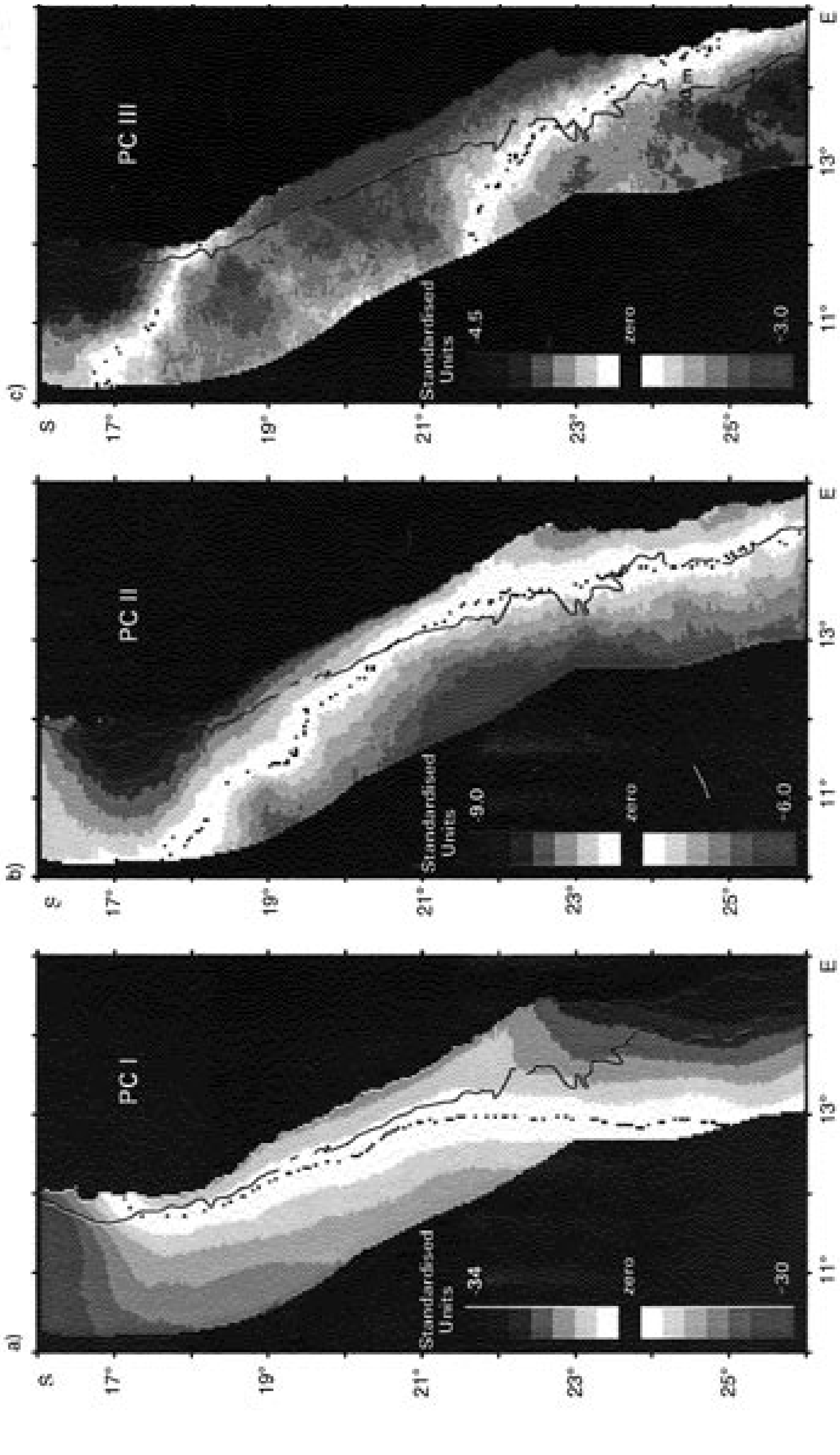

Fig. 3: Principal Components I, II and III

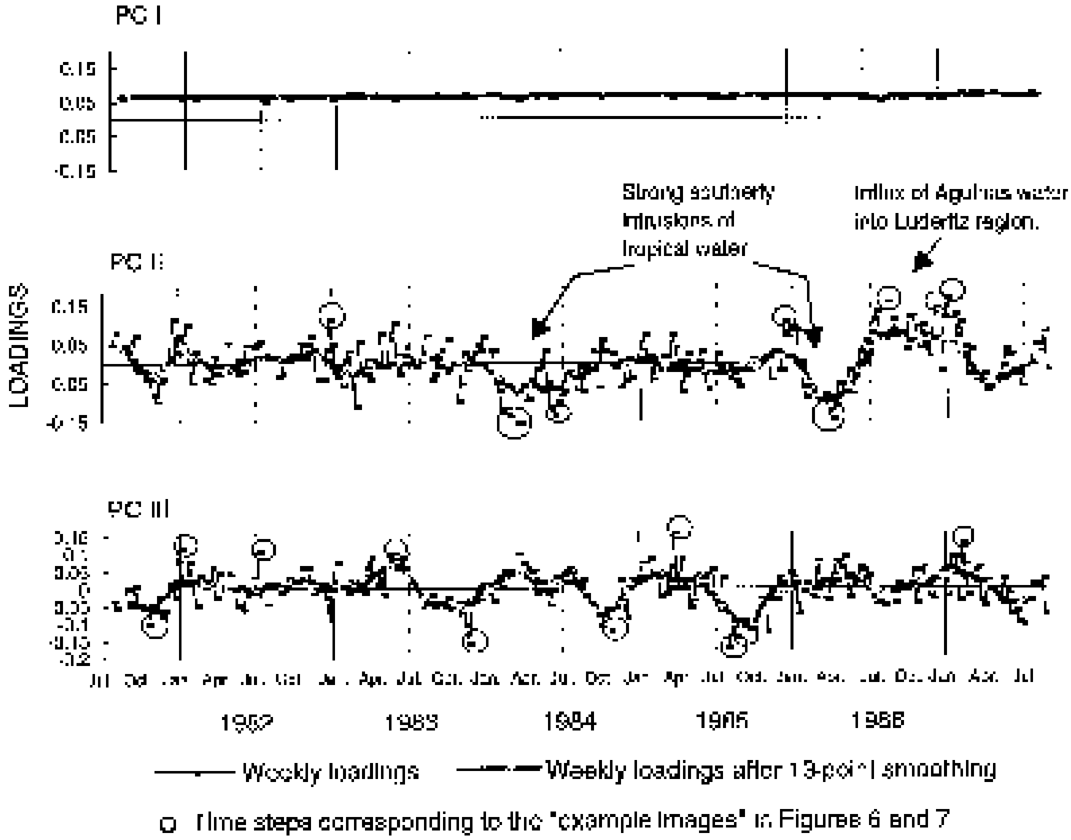

Fig. 4: Weekly and 13-point smoothed loadings on Principal Components PC I, PC II and PC III. Missing data points in the weekly loadings are the result of SST images being excluded from the Principal Components Analysis as a result of too much cloud contamination

pattern that accounts for most of the variability in **X**, the second component represents the spatial pattern of as much as possible of the residual variability in **X** that is uncorrelated with the first component, and so on for successive components. Calculation of the component images is achieved by linearly recombining the input matrix **X** with the inverse of the eigenmatrix **E**, using the formula

$$\mathbf{Y} = \mathbf{E}^{-1}\,\mathbf{X} \qquad ,$$

where **Y** is the $t \times t$ output matrix of principal component images, in which the pixel values of the i^{th} principal component are found along row i. The units in the output images (i.e. in **Y**) are the same as the input units, namely standardized units.

DERIVATION OF LOADINGS

The "loadings" are the temporal output from the analysis, and they indicate the similarity between successive time-steps (i.e. successive rows in **X**) and the pattern represented by the component image. Loadings may be positive or negative, according to whether the input images show similar or inverse spatial patterns to those described by the component image. The loading values for each component are derived from the successive elements in their respective eigenvectors. For example, the first element in the eigenvector associated with the first principal component is the loading of the first image in the time-series on this component.

Interpretation and presentation of results

In order to decide how many components should be kept for interpretation, two different rules are often used (Chatfield and Collins 1980). The first is to retain only those components with eigenvalues ≥1.

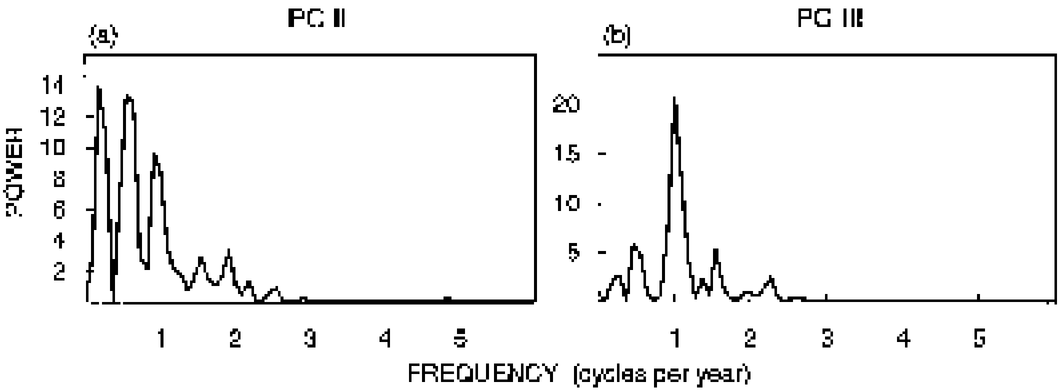

Fig. 5: Power spectra of the smoothed loadings on (a) PC II and (b) PC III

The second involves looking at the pattern of eigenvalues and including only those components that occur above a natural breakpoint, where the additional variance explained by successive components becomes very much reduced (sometimes referred to as the "scree test"). The latter rule is the one used in this analysis.

Each component was interpreted according to both its spatial and temporal output. Component images were evaluated in terms of the residual patterns of spatial SST variability they represented. In order to relate the components and their loadings back to SST patterns in the original (i.e. unstandardized composites), a total of 45 composites was inspected per principal component. This was done by observing the similarities among, and differences between, the following groups: composites that corresponded to the highest 15 loadings, those which corresponded to the lowest 15 loadings, and a selection of 15 composites that corresponded to zero loadings. Interpretation of the individual components was augmented by examining the smoothed curves and power spectra for evidence of seasonal and interannual trends, and noting whether these in any way corresponded with known aspects of the system's behaviour.

RESULTS

The first three principal components (PCs) were retained for interpretation. Between them, they accounted for some 87% of the total variance in the standardized input dataset (Table I). The other components were discarded on the basis that, individually, they account for very little additional variance beyond that already explained by the first three (Table I, Fig. 2). The images of these first three components and their temporal loadings are illustrated in Figures 3 and 4.

Principal Component I

PC I accounted for 79.25% of the total variance. It represents the average spatial SST structure of the system, as deduced by the similarity between the patterns in Figure 3a and the patterning of mean SSTs in Figure 1, and by the lack of any substantial fluctuations in its temporal loadings (Fig. 4a). As such, it conforms to previous observations on the nature of the first principal component. In other words, when all the dimensions (i.e. time steps) are positively correlated, then PC I is in effect an average, and, when the input is standardized, the dimensions all have similar loadings on this component (Chatfield and Collins 1980). In view of these results, it was considered unnecessary to perform spectral analysis on the loading values.

Principal Component II

PC II accounted for 5.21% of the total variance. The spatial output (Fig. 3b) shows a pattern of negative coastal values in the north, grading into positive values moving south and away from the coast. The highest values are offshore between 21 and 24°S, where there are two fairly distinct "hotspots"; one 21–22°S and the other 23–24°S. In addition, there is a third, less pronounced, "hotspot" offshore at approximately 19°S. Except for the region north of 17°S, the general orientation of the gradients between areas with different standardized values is inshore-offshore.

The loadings in Figure 4b are highly variable. Nonetheless, the presence of a seasonal cycle is discernible from the smoothed plot, and is confirmed by the seasonal peak (i.e. at one cycle per year) in its power spectrum (Fig. 5a). In general, the highest annual smoothed loadings are during summer (November–January), whereas the lowest are between late summer and early winter (February–May). These seasonal trends are particularly well developed between the period 1984 and 1987.

Interannual trends, however, are of greater relative importance, as deduced by two dominant spectral peaks at frequencies of fewer than one cycle per year (Fig. 5a). Examination of the smoothed loadings shows that 1984 and 1986 have the lowest loadings, whereas 1986 and 1987 have the highest. The former corresponds to the strong southerly intrusions of warm Angolan water in the north during 1984 and 1986 (Boyd *et al*. 1987) and the latter coincides with the northerly influx of Agulhas Current water in the south during the late winter/spring of 1986 (Shannon and Agenbag 1987, Shannon *et al*. 1990).

Principal Component III

PC III accounted for 2.36% of total variance. In the component image, both the northern and southern ends of the system have negative values, with positive values in between. The lowest values are adjacent to the coast in the north, and between 17 and 19°S there is a region with relatively strong gradients from negative to positive. The highest values are adjacent to the coast between 19 and 23°S. In addition, there are two distinct "hotspots" offshore of the 200 m depth contour, one 18–19°S and the other 19°30′–21°S.

The loadings for PC II are highly variable. Nonetheless, the smoothed plot in Figure 4c and its power spectrum in Figure 5b indicate a dominant seasonal signal. Indeed, for all the years except 1986, the highest annual loadings tend to occur during the first six months of the year (Fig. 4c), whereas the lowest loadings are generally during late winter/spring (August–November).

DISCUSSION

Interpretation of results

PRINCIPAL COMPONENT I

PC I represents the average spatial structure of the system in terms of its relative SST gradients. The lowest relative SSTs were in the Lüderitz region (24–28°S) and the highest ones in the north, where the northern Benguela upwelling system meets the warm, tropical Angolan waters. The relatively uniform temporal loadings indicate that the spatial mean was stable in time. This is similar to the results from other standardized PCAs (e.g. Eastman and Fulk 1993, Maus 1997).

PRINCIPAL COMPONENT II

PC II reflects the spatial variability in relative SST conditions between inshore coastal waters, especially in the north, and offshore waters, particularly south of 21°S. Figure 3b shows that loadings will be high when, relative to the south-west, coastal SSTs in the north are lower than usual, and likewise when relative to coastal waters in the north, offshore SSTs south of 21°S are higher than usual, and vice versa for low loadings. Zero loadings will result from the balance of SSTs between these different areas being roughly average. In addition, the orientation of the gradients in Figure 3b could suggest high loadings when the dominant SST gradients are in the inshore-offshore direction, low loadings when the dominant gradients are in the longshore direction, and zero loadings when there is a mix of inshore-offshore and longshore gradients, as represented by the mean structure in PC I.

Figure 6 (weekly composited data) illustrates how high loadings correspond to a dominant pattern of inshore-offshore SST gradients throughout the study region and upwelling in the north. In contrast, low loadings correspond to a dominant pattern of longshore SST gradients, with warm water in the north and cool water in the south. Composites corresponding to zero loadings (not shown) were midway between either extreme.

In terms of the hydrology, relatively consistent inshore-offshore SST gradients within the study region indicate enhanced coastal upwelling activity in the north with respect to the Lüderitz upwelling region, and vice versa. Conversely, appreciable longshore gradients in SST indicate warming in the northern half of the system and the maintenance of some upwelling in the south. Potential causes of warming in the northern and central parts of the region include surface and subsurface southward intrusions of Angolan water, shoreward intrusions of oceanic water, reduced upwelling combined with solar heating of the surface layers, or a combination of these processes (e.g. Boyd and Agenbag 1985, Boyd *et al*. 1987). The temporal characteristics of the loadings and the results from previous investigations into the physical dynamics of the region provide further confirmation for these interpretations.

Charts of long-term average SSTs by month and by degree of latitude from shipping data (Boyd 1987, Boyd *et al*. 1987) verify that the lowest longshore gradients in SST, and therefore the most regular inshore-offshore SST gradients, would be expected during early to midsummer, consistent with the period when annual loadings tend to be highest (November and January, Fig. 4b). As regards interannual trends,

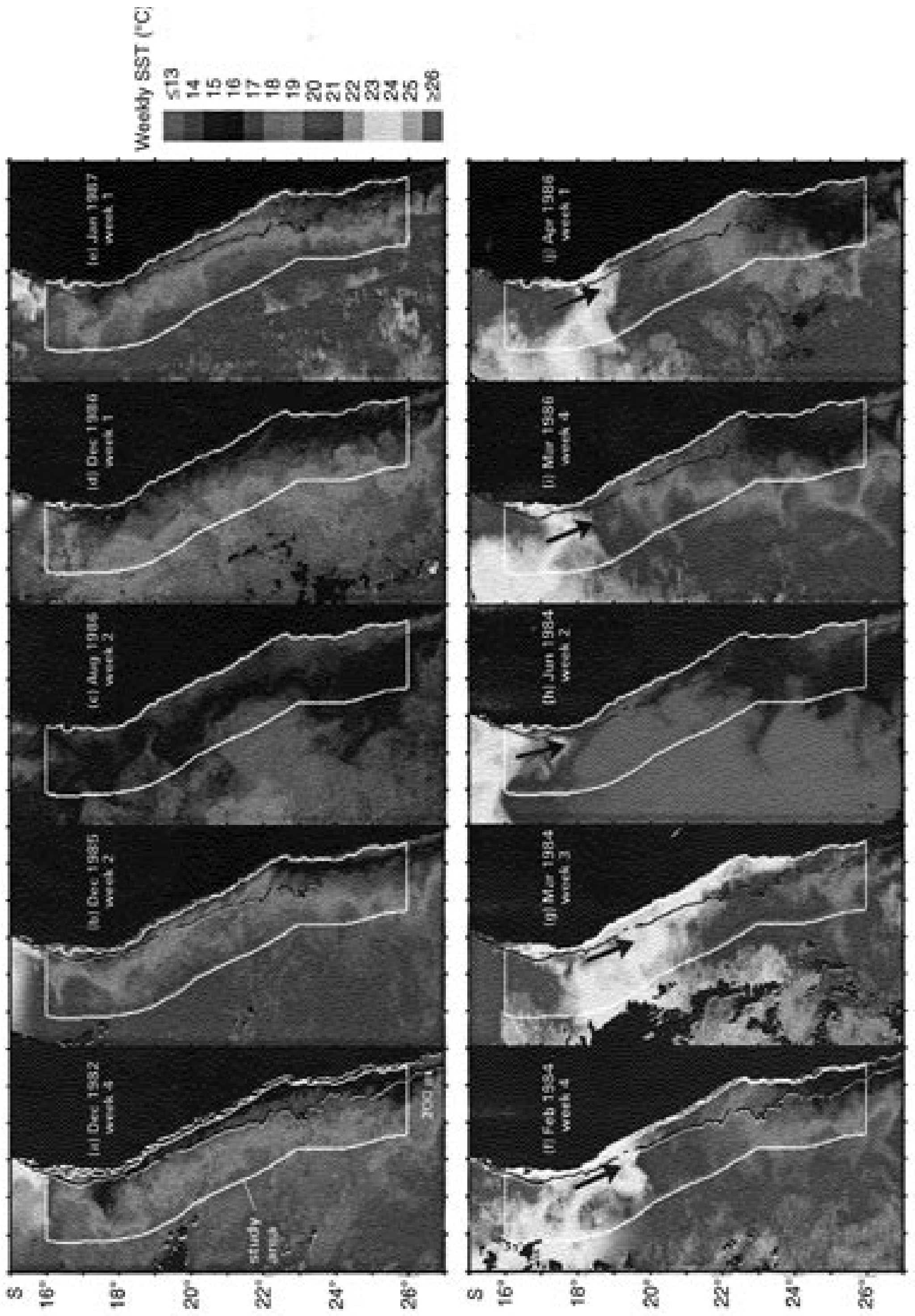

Fig. 6: Weekly SST composites which correspond to (a−e) positive and (f−j) negative loadings on PC II, as shown in Figure 4. The arrows in composites f−j indicate the southerly flow of surface water likely to be associated with these thermal patterns, and represent a potential mechanism for the retention of clupeoid eggs and larvae

the unusually high loadings during late winter/spring in 1986 coincide with a strong influx of warmer water, originating from the Agulhas Current, into South-West African coastal waters. The effect of this warmer water on coastal hydrology was felt as far north as Lüderitz, where it suppressed the normally vigorous winter upwelling (Shannon and Agenbag 1987). In terms of SST patterns, the presence of warmer water off Lüderitz would cause higher-than-usual loadings on PC II, because of its effect in reducing longshore gradients and therefore, by association, enhancing the consistency of inshore-offshore gradients throughout the region.

Seasonally, loadings tend to be lowest between late summer and early winter (Fig. 4b). This coincides with observations indicating that intrusions of warm, saline Angolan water are most common and that longshore gradients are strongest during late summer/autumn (e.g. Boyd *et al*. 1987, O'Toole 1980, Lutjeharms and Meeuwis 1987). As regards interannual trends, the strong intrusions of Angolan water experienced during the Benguela *El Niño* of 1984 and again in 1986 (Shannon *et al*. 1986, Boyd *et al*. 1987) are reflected in the very low loadings during the early part of those years. In contrast, late summer/autumn loadings during the cooler years of 1982, 1983 and 1985 were not as low.

PRINCIPAL COMPONENT III

The residual pattern of SST variance highlighted by PC III (Fig. 3c) is that of relatively warmer water in the middle of the study region (18–23°S) sandwiched by cooler water in the north and south. High loadings are expected when conditions in the central region are warmer, relative to the north-east and the south, than usual. The opposite is expected for low loadings. Figure 7 illustrates how composites corresponding to high loadings clearly show higher SSTs in the central region relative to the north, and also to the south. Conversely, composites with low loadings show the reverse, especially for cooler water between 18 and 23°S relative to the waters north of 18°S.

Elevated SSTs between 18 and 23°S, as reflected by high loadings, could be attributable to a combination of reduced coastal upwelling, solar heating of the surface layers, and shoreward intrusions of oceanic water in association with a shoreward contraction of the offshore upwelling front. Although warming in this central region must usually coincide with the maintenance of relatively vigorous upwelling activity north of 18°S for loadings to be high, there is the odd exception. For example, during the third week of March 1984 (see Fig. 6g), there was a high loading on PC III, in spite of the marked absence of any relatively colder coastal water in the north. However, in that instance, the area south of 19°S corresponded very closely to the pattern in Figure 3c, with relatively warm water lying inshore of cooler water between 21–25°S.

There is limited information in the literature with which to compare temporal trends in the loadings. Nonetheless, from temperature and salinity survey data between the period 1972 and 1974, O'Toole (1980) observed greatest onshore movement of oceanic water between 19 and 22°S during summer, consistent with the peaks in annual loadings found in the present study between January and March in 1982, 1985 and 1987. This does not imply that there was no onshore movement of oceanic water in those months during the other years of study. However, if this was the case, it would have involved the suppression of the northern upwelling cells and therefore would not necessarily be reflected by high loadings on PC III.

To some degree PC II and PC III have both been interpreted according to trends in surface advection, as deduced from the spatial patterning of SSTs and as verified with supporting evidence in the literature. However, without comparison to surface current flow measurements, it is not possible to determine fully the extent to which various SST patterns reflect, for instance, the onshore or longshore flow of warmer waters versus other factors, such as solar heating or levels of upwelling activity. Unfortunatley, during the period covered by this study there was no routine monitoring of current flows in the region.

MESOSCALE FEATURES

Although PC II and PC III primarily account for the macroscale dynamics of the region, distinct mesoscale features are visible as "hotspots" in Figure 3a, c. It is possible that the offshore "hotspots" at 19–20°S and 21–24°S point to eddies being a common feature of these areas. Circumstantial evidence is provided by dynamic topography maps from Stander (1964), Boyd (1987) and Salat *et al*. (1992), which indicate the presence of eddies at one or other of these locations.

Relevance to recruitment

PC II and PC III highlight dynamic features of the northern Benguela, which may have important roles in influencing the recruitment success of small pelagic fish there. In particular, the loadings on these components directly reflect the presence or absence of conditions likely to promote retention of egg and larvae within the system. Strong, negative loadings on PC II indicate the likelihood of longshore "retention"

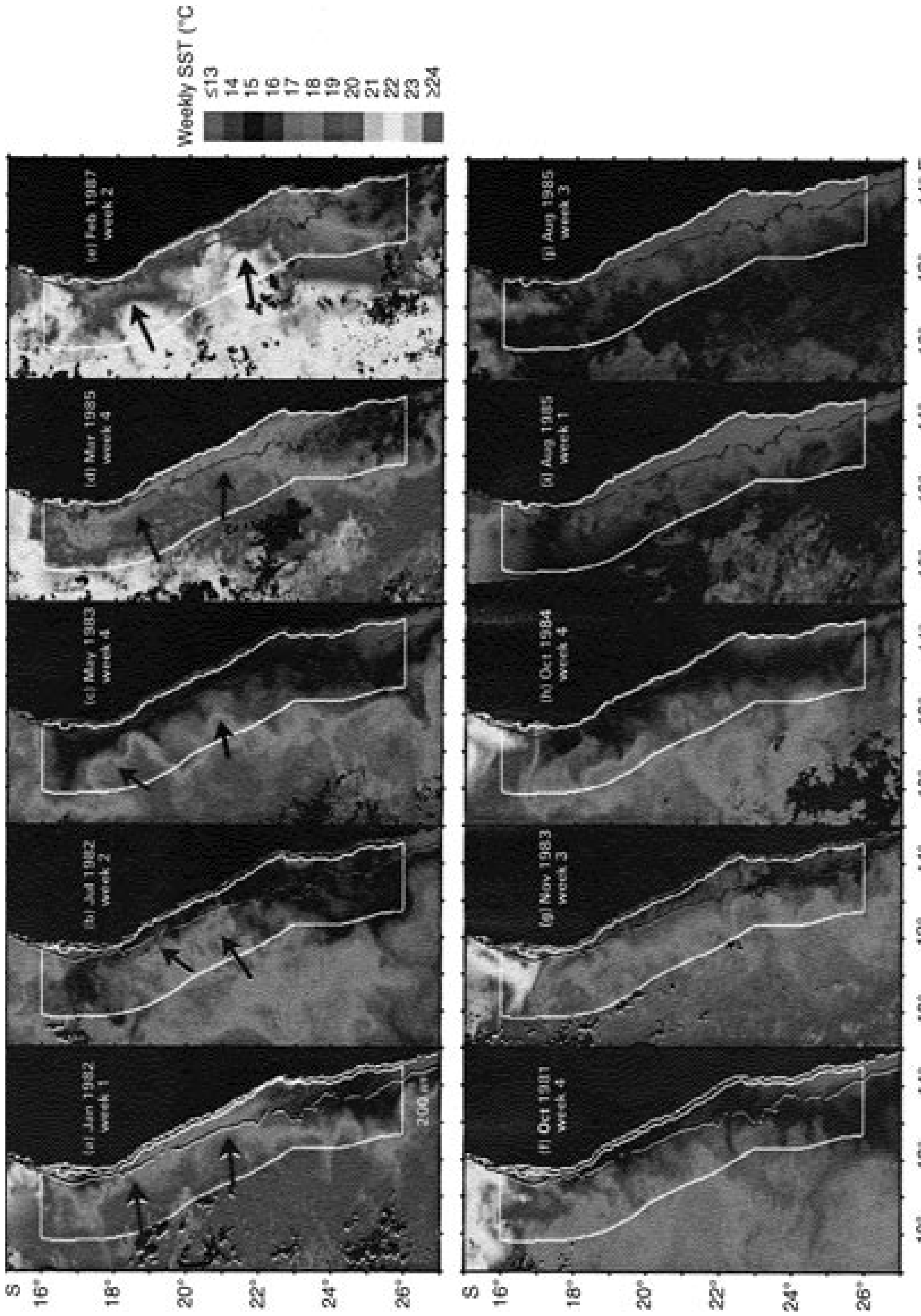

Fig. 7: Weekly SST composites which correspond to (a–e) positive and (f–j) negative loadings on PC III, as shown in Figure 4. The arrows in composites a–e indicate the onshore flow of surface water likely to be associated with these thermal patterns, and represent a potential mechanism for the retention of clupeoid eggs and larvae

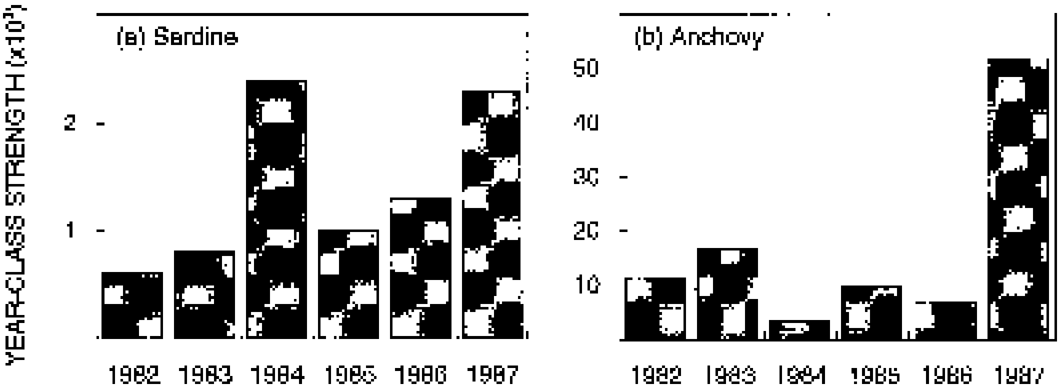

Fig. 8: Recruitment success in (a) sardine and (b) anchovy in Namibian waters between 1982 and 1987, measured by the number of 0-year-old recruits. Data derived from vitual population analysis (after Le Clus *et al.* 1988)

as a result of a combination of reduced upwelling activity in the north and southward intrusions of warm water. High positive loadings on PC III indicate the possibility of inshore-offshore retention from a combination of reduced upwelling activity off central Namibia (relative to the north and south) and onshore intrusions of surface oceanic water.

The loadings on PC II could therefore act as an index of longshore retention, and the loadings on PC III as an index of onshore retention. However, an important exception to this concept will arise whenever there is a fairly uniform shoreward contraction of the offshore upwelling front as a result of reduced, but nonetheless similar, levels of upwelling activity along the entire coast. These conditions could also promote retention and would be reflected by positive loadings on PC II whenever inshore SSTs were greater than around 17°C (see Fig. 6b, e). In order to account for these exceptions, an additional measure of onshore retention could be constructed by weighting the positive loadings on PC II according to synoptic temperature conditions along the coast (Cole 1997, Cole in press).

The loadings on these two components may also indirectly reflect the presence/absence of thermal fronts and thermoclines, across which planktonic food for the larvae and juveniles may be concentrated. Off central and northern Namibia, the presence of both these features is related to the same processes which enhance retention, namely reduced upwelling and intrusions of warmer water masses (Boyd 1987).

As regards "enrichment", the loadings on PC II and PC III reveal the relative difference in levels of upwelling between different parts of the system. Caution must be exercised in interpretation of PCs for deriving estimates of enrichment, according to gross levels of upwelling activity, because the standardization procedure in effect gives each input composite the same mean SST. Standardization can also exaggerate or diminish the relative strength of the thermal gradients, according to the range of SSTs found in each composite, therefore preventing the derivation of an upwelling index based upon the strength and orientation of SST gradients as detected by PCA.

Because the loadings on PC II and PC III provide reasonably direct measures of retention and indirect measures of concentration, some relationship may be expected between these loadings and the reproductive success of the region's clupeoid stocks. Some trends in Namibian sardine and anchovy recruitment during the years covered by this analysis are shown in Figure 8. For sardine, there was poor recruitment during 1982 and 1983, intermediate recruitment during 1985 and 1986 and good recruitment during 1984 and 1987. The pattern was different for anchovy, with generally poor recruitment from 1982 to 1986 and good recruitment during 1987. Moreover, the fact that density-dependent regulations would have been minimal between 1982 and 1987, because of the small size of the adult populations (Le Clus *et al.* 1988), suggests that the effects of density-independent (i.e. environmental) recruitment regulation then would be prominent. For a quantitive evaluation of the relationship between the surface dynamics of the northern Benguela, as revealed by SST images, and clupeoid recruitment, refer to Cole (in press).

For sardine, some general trends emerge from the smoothed loadings shown in Figure 4 for the main reproductive season, i.e. October-March (Crawford *et al*. 1987, Le Clus 1990). During 1982 and 1983, when recruitment was poor, the smoothed loadings on PC II and PC III during the reproductive season never deviated far from zero, suggesting a general absence of conditions suitable for promoting retention and concentration.

In contrast, during 1985 and 1986, when there were intermediate levels of recruitment, there were either negative loadings on PC II or positive loadings on PC III during the main reproductive season. In 1985, the loadings on PC III were generally high from January to March, indicating good levels of onshore retention and concentration, whereas the loadings on PC II fluctuated around zero. During 1986, the situation was reversed, with the smoothed loadings on PC III remaining close to zero and very negative loadings on PC II from January to March, indicating good levels of longshore retention and concentration.

The two years of good recruitment (1984 and 1987) again show different trends in terms of their loadings relative to the other four years, and they are also different from each other. During 1984, the loadings on PC II were negative between January and March and for the same period tended to be positive for PC III. Therefore, conditions could be expected to have been excellent for both longshore and onshore retention and concentration during that time.

During 1987, there were positive loadings on both PC II and PC III during the course of the main reproductive season. On their own, the positive loadings on PC III indicate the presence of good conditions for onshore retention and concentration. The positive loadings on PC II are more difficult to interpret. Whenever high loadings on PC II were associated with reduced and fairly uniform levels of upwelling activity along the coast (as opposed to enhanced and fairly uniform levels of upwelling activity), these too would also indicate good onshore retention and concentration, as discussed above. Unfortunately, given that the loadings themselves give little indication of overall levels of upwelling activity (i.e. enrichment), it is not possible to determine whether these positive loadings on PC II do in fact reflect conditions that might promote retention. However, given that the composite illustrated in Figure 6e falls within this period, there is a good chance that at least some of the weeks with positive loadings on PC II during this reproductive season had good levels of onshore retention and concentration.

Overall, the pattern appears to be that higher levels of sardine recruitment are associated with higher levels of retention and, by proxy, concentration. The situation is somewhat different for anchovy. Apart from the good recruitment during 1987, anchovy appear to share little in common with the trends observed for sardine. For anchovy, there are likely to be other important factors. Sardine stocks seem to flourish under warm conditions, whereas anchovy stocks appear healthiest during cooler conditions (e.g. Sharp and McLain 1993, Cushing 1996, Cole in press). Given that intrusions of warmer water play an important role in promoting retention in the region, a positive relationship between water temperature and levels of retention is likely. Conversely, given that the upwelling of cool water brings nutrients to the surface, there is likely to be an inverse relationship between levels of enrichment and water temperature. Following the hypothesis that anchovy benefit from cool conditions and sardine from warm conditions, anchovy recruitment in the region could be limited by enrichment, whereas sardine recruitment could be limited more by levels of retention and concentration.

Such an effect would account for the poor anchovy recruitment during 1984 and 1986, when the upwelling of cool, nutrient-rich water along much of the Namibian coast was inhibited by strong surface and subsurface intrusions of warm tropical water from Angola (Shannon *et al*. 1986, Boyd *et al*. 1987). Le Clus *et al*. (1987) showed that, during January and late February/early March 1986, anchovy spawning was much reduced compared to 1985, when cooler conditions prevailed. During 1984, low nutrient concentrations and poor feeding conditions were believed to be responsible for heavily reduced spawning, poor survival of larvae and poor recruitment (Le Clus 1985, Boyd *et al*. 1985).

Low SSTs alone would not explain the remarkably strong anchovy recruitment during 1987. Although inshore SSTs were low during the 1986/87 reproductive season, this would not account for the strong recruitment, given that inshore SSTs were no lower then than during the 1981/82 and 1982/83 reproductive seasons (Cole 1997, Cole in press).

Shannon and Agenbag (1987) proposed that the unusually high recruitment in the northern Benguela may have resulted from the advection of anchovy larvae from the southern Benguela. They related this to the influx of Agulhas Current water along the southwest coast of Africa and the suppression of the Lüderitz upwelling cell during the latter half of 1986. However, this theory could not be adequately substantiated because of a lack of information on the distribution of eggs and larvae at the time of the proposed Agulhas Current intrusion (Le Clus *et al.* 1988). The fact that there were simultaneously high levels of enrichment (indicated by the low inshore SSTs) and good retention and concentration (reflected by the loadings on PC II and PC III) during the 1986/87 reproductive seasons may provide an alternative explanation for the high recruitment.

From the foregoing, it appears that standardized PCA of weekly SST images provides a useful means whereby environmental conditions can be related to fluctuations in clupeoid recruitment success. The main drawback of the technique is its inability to measure enrichment according to gross levels of upwelling activity. Nevertheless, for empirical investigations into the relationship between recruitment success and environmental conditions, this drawback could in future be remedied by combining the loading values with coastal sea surface temperatures (e.g. Cole in press).

CONCLUSIONS

- Standardized PCA is a suitable technique for quantifying the physical dynamics of the northern Benguela upwelling system according to the evolution of its spatial structure through time, particularly for detecting differential levels of upwelling activity within the region and the intrusion of warmer water masses. The first three components accounted for 87% of the total variance in the input dataset, and were interpreted in terms of what is already known of the oceanography of the northern Benguela
- PC I accounted for the mean thermal spatial structure of the region. PC II and PC III both identified and quantified aspects of the system's behaviour that may directly influence the retention of clupeoid eggs and larvae, and which may indirectly result in the formation of strong thermal fronts and thermoclines across which planktonic food may be concentrated for first-feeding larvae. The loadings on PC II measured the relative orientation of SST gradients from primarily inshore-offshore gradients to longshore gradients, clearly isolating thermal patterns associated with intrusions of warmer water from both the north and the south. The loadings on PC III measured the difference in SSTs off central Namibia relative to the north and south, and clearly detected warming in the central region as a result of reduced upwelling, solar warming and onshore intrusions of oceanic water.

ACKNOWLEDGEMENTS

We are grateful to the following individuals and institutions: Dr J. Maus (formerly University of Warwick, U.K.) for discussions on the application and interpretation of PCA; Drs K. Koranteng (formerly University of Warwick) and A. J. Boyd (Sea Fisheries, Cape Town) for valuable comments on the manuscript; Messrs J. Marshall (Plymouth Marine Laboratory), R. Klaus (GEOS, U.K.) and P. McCormack (University of Warwick) for technical assistance; and Dr L. Nykjaer and Mr C. Villacastin (Space Application Institute, Italy) for making available the CORSA dataset. This work forms part of a Ph.D. completed by the senior author, which was funded by the Biotechnology and Biological Sciences Research Council, U.K. With regards to the content of other parts of the thesis, we would also like to acknowledge the support of many scientists from the Namibian National Marine Research and Information Centre in Swakopmund and Sea Fisheries in Cape Town, South Africa.

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