EARTH Interactions

Physical Oceanographic Influences on Central Benguela Fish Catch

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ABSTRACT: Ocean and atmosphere reanalysis fields are used to study environmental conditions and their relation to commercial fish catch in the central Benguela upwelling zone, using both targeted and objective techniques. Composite maps and sections indicate a 10%–20% weakening of southeasterly winds, a 0.5°C warming of sea temperatures over the shelf, and changes in currents and subsurface upwelling associated with higher fish catch. During periods of high fish catch, recirculating gyres form that may aid the retention of eggs and larvae. Offshore winds contribute to poleward Ekman transport in a 50-m-deep layer within 100 km of the coast.

In addition to composite analysis, the natural variability is studied by principal component analysis of wind stress, sea level, temperature, salinity, currents, and vertical motion in the period 1970–2007. Comparison of interannual time scores and fisheries data indicate that anomalous poleward winds and warmer temperatures in the Lüderitz plume, driven by an atmospheric trough in the South Atlantic, are associated with higher catch rates.

KEYWORDS: Marine environment; Benguela; Fisheries

1. Introduction

Pelagic fish populations in upwelling systems exhibit multiyear fluctuations in abundance (Crawford 1987; Shackleton 1987; Shannon et al. 1988; Schwartzlose et al. 1999; Baumgartner et al. 1992) associated with natural environmental forcing

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and changes in fishing effort and management (Bakun 1996; Cury et al. 2000; Boyer et al. 2001). Pelagic fish such as sardine and anchovy integrate physical–chemical influences over their lifespan but are more sensitive to environmental conditions at certain phases of development. Specific year classes can affect the pelagic fishery over the following 2–3 years. Bakun (Bakun 1996) suggested that nutrient enrichment and plankton concentration were important at stages of rapid growth and that larval retention and recruitment pathways were significant at other stages. Bursts of upwelling lift nutrients into the euphotic zone for plankton enrichment, whereas quiescent periods under solar heating enable concentration of plankton in stable layers for feeding. Retention of eggs and larvae over the shelf is important to prevent advective losses into the low nutrient zone offshore. In this regard, wind-induced Ekman transport and subsurface currents that conspire to retain eggs and larvae over the shelf with minimal export are beneficial. Although these concepts aid our understanding of physical influences on upwelling ecosystems, direct measurements are rare. Monthly ½°-resolution ocean reanalysis products that make use of numerical model assimilation of in situ measurements and satellite-estimated winds, temperatures, and sea surface height are available (Carton et al. 2000; Carton and Giese 2008) to provide new insights into the hydrography and dynamics of shelf zones.

There are three zones in the Benguela: northern, having winter upwelling influenced by the intrusion of tropical waters north of 20°S (Gammelsrød et al. 1998); central, with continual upwelling (the focus here); and southern, south of 32°S, with summer upwelling and an Agulhas boundary (Hutchings et al. 2009). The central Benguela exhibits perennial upwelling of cool, fresh, nutrient-rich water (Nelson and Hutchings 1983; Boyd et al. 1985; Shannon 1985; Jury 1988; Shannon and Nelson 1996; Shillington 1998). The upwelling is driven by equatorward winds that follow the coast (Nicholson 2010), causing offshore Ekman transport in a 20–30-m mixed layer. The most persistent upwelling occurs at Lüderitz, at 27°S (Shannon 1985; Lutjeharms and Meeuwis 1987). Other upwelling cells are located at Cape Columbine, at 33°S, and Hondeklip Bay, at 30°S (Shannon 1985; Jury 1988), as reflected in the ocean climatology fields (cf. Figure 1). There are intermittent seasonal upwelling cells at the southern and northern boundaries of the Benguela system (Cape Peninsula, at 34°S, and Cape Frio, at 16°S), beyond which lie the warm Agulhas and Angola Currents characterized by higher temperature and salinity, lower chlorophyll (Boyd et al. 1987; Shannon et al. 1987; Thomas et al. 2001; Hardman-Mountford et al. 2004), and weaker winds (Shannon and Nelson 1996).

Pelagic fish such as sardine spawn over the shelf during austral spring and summer (September–February in the Benguela; Matthews 1964; O'Toole 1977; Le Clus 1990; Kreiner et al. 2001). The planktonic larval stage lasts about 3 months (Shannon 1998), after which the fish are able to swim and forage. Environmental conditions influence mortality rates according to Hardman-Mountford et al. (Hardman-Mountford et al. 2004), through processes controlling food supply and cross-shore advection. In the central Benguela region, chlorophyll levels are quite high and may exceed what is required by the fishery at times. There is an optimal range (Cury and Roy 1989) that contributes to increased abundance and commercial catch rates. Thus, weak upwelling that favors larval retention and juvenile recruitment is hypothesized to promote a more sustainable resource. Strong upwelling (during spawning) will export eggs and larvae and inhibit plankton

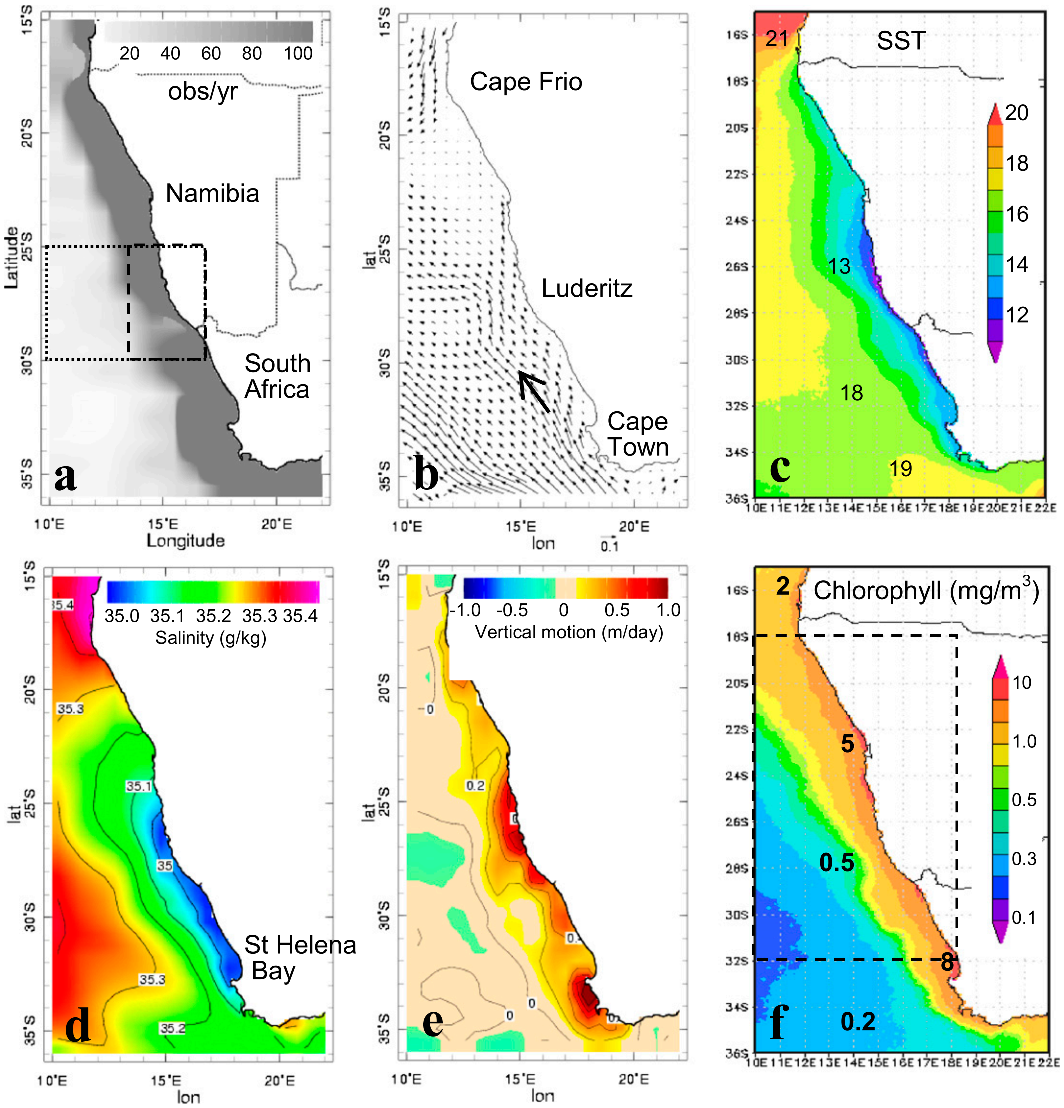

Figure 1. (a) Observation density for profiles to 200 m with box for data extraction and sections, (b) 0–200-m currents, (c) SST, (d) 0–200-m salinity, (e) 0–500-m vertical motion, and (f) chlorophyll. Here, (b),(d),(e) are SODA2.4 reanalysis 30-yr climatology and (c),(f) are MODIS and SeaWiFS 10-yr climatology. The dashed box in (f) refers to area of fish catch.

aggregation (Parrish et al. 1982; Cury and Roy 1989), whereas an absence of upwelling for a few seasons could negatively impact enrichment, but in the central Benguela this is rare.

In this paper, patterns in meteorological and oceanographic fields are investigated to understand how the marine environment off the southwest coast of Africa affects the fishery. Weather maps and ocean sections for multiyear periods of high and low catch are studied for signals that relate to the integrative effects of fish catch in the central Benguela area, 18°–32°S and 10°–18°E (Figure 1f). The key question to be addressed is the following: What environmental influences are most important to fish catch in the central Benguela? The scope of research here excludes mechanisms linking ocean dynamics/primary production and fishery spawning/population and the dependency of catch rates on changes in fishing methods/management strategies.

2. Data and methods

The commercial fish catch reported annually to the Food and Agriculture Organization (FAO) by South Africa and Namibia for various species in territorial and offshore waters since 1970 provides a basis for this research. The sector considered here extends seaward ~200 km and extends from 18° to 32°S (Figure 1f), encompassing one of the largest upwelling plumes in the world, Lüderitz. The main species of commercial significance are pelagic sardine and anchovy. Although demersal fish (mainly hake) are reported to be <10% by weight, they are a valuable part of the fishery. Fréon et al. (Fréon et al. 2005) indicate that sardine are caught in water depths of ±100 m, which is found about 100 km offshore in the central Benguela. Anchovies are caught nearer the coast, whereas hake are fished at shelf edge in approximately 300-m depth. Up to 1990 the species- and area-specific reporting were quite inconsistent, with catch datasets exhibiting sudden switches between species, areas, and countries. To avoid problems with consistency in these data, the aggregate marine fish catch that includes all species (~85% pelagic, mainly sardine; Boyer et al. 2001) is the index used. Combining data from two countries creates a meaningful index, because they share a similar environment and species composition but have differing management strategies. The evolving spectral character of fish catch is analyzed via wavelet transform using the Royal Netherlands Meteorological Office (KNMI) Climate Explorer website (http://climexp.knmi.nl/).

The monthly oceanographic and meteorological fields contain local space–time variability, which, for comparison with catch data, are averaged into annual increments. The targeted approach relies on the catch index being able to "point out" periods when the physical environment is biologically favorable. To provide a measure of shelf productivity, phytoplankton concentration estimates from Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) ocean color in the period 1998–2007 are obtained from the National Aeronautics and Space Administration (NASA) Giovanni website and the seasonal cycle is calculated. The meteorological scenario is studied via National Centers for Environmental Prediction (NCEP) reanalysis products (Kalnay et al. 1996) that include National Oceanic and Atmospheric Administration (NOAA) satellite data (Smith and Reynolds 2004). The atmospheric data resolution is monthly at ~200-km horizontal resolution and ~1-km vertical resolution. Regional maps of geopotential height and winds at 200 hPa (12 km) are analyzed. Oceanographic fields are provided by monthly Simple Ocean Data Assimilation version 2.4 (SODA2.4; Carton and Giese 2008) comprising European Centre for Medium-Range Weather Forecasts (ECMWF) wind stress, sea surface height, temperature, salinity, currents, and vertical motion at 50-km horizontal resolution and ~30-m vertical resolution. Both reanalysis products are based on a four-dimensional numerical model assimilation of all available in situ and remotely sensed data, and they include atmospheric profilers, scatterometer wind stress, drifters and Argo profilers, infrared surface temperature, and microwave altimetric sea height. All Marine and Coastal Management research ship cruise data that are recorded at the South Africa Data Center for Oceanography and Global Ocean Data Assimilation System (GODAS) are brought into the high-resolution SODA2.4 fields to create good hydrographic coverage over the Benguela shelf as illustrated in Figure 1a. In addition, there is a busy shipping lane along the shelf edge with a long history of good wind and sea temperature observations. Intercomparison of SODA2.4 and observed sea temperatures in the central Benguela over the period 1958–2007 indicate close agreement with $r^2 = 42\%$ and little bias in cool or warm months.

To select years for inclusion in composite analysis, the South Africa (north of 32°S) and Namibia fish catch (south of 18°S) are combined into a single index (cf. Figure 3a) and ranked over the period 1970–2005. Given that annual area-averaged catch data are used, the composites are formed using annual blocks of data. Because catch tends to vary in multiyear spells and the composite technique requires equal number of cases in each group, the high years are 1973–75, 1987–88, 1992–93, and 2002–04 and the low years are 1977, 1980, 1982, 1984–86, 1989–1991, and 1996. The mean catch for high years is 1.38 MT yr^{-1}, and the low catch mean is 0.82 MT yr^{-1}, a 51% difference. Intermediate years were excluded from this analysis. The composite reanalysis fields are calculated, and the low catch years are subtracted from the high years to produce differences. Meteorological influences are described as maps over a wide area (0°–40°S, 10°W–25°E), whereas oceanographic influences are analyzed as depth sections over the shelf off Lüderitz (25°–30°S, 10°–17°E; cf. Figure 1a). Contrasts may be small or incoherent, so the interpretations focus on areas where differences with respect to fish catch exceed ±one standard deviation.

As an alternative to targeted composite methods, a principal component analysis (PCA) is made of the SODA2.4 ocean reanalysis fields via the International Research Institute for Climate Prediction (IRI) Climate Library website (http://iridl.ldeo.columbia.edu). This involves an eigenvector decomposition of the covariance matrix within a single input field, so that the natural year-to-year variability is reduced to modes with spatial clusters and temporal scores. PCA is done for temperature T averaged to 200 m, salinity S averaged to 200 m, currents U, V averaged to 200 m, vertical motion W averaged to 500 m, sea level (SL), and ECMWF wind stress X, Y. Prior to PCA, the 38-yr time series at each grid point is detrended and standardized. The first three modes are retained, and their time scores are cross-correlated with Benguela fish catch. Those modes with pairwise significance are subjected to multivariate linear regression. A stepwise technique is used, which drops the less influential modes, retaining the more important. For statistical evaluation, the annual time series have 35 degrees of freedom, such that $r > 0.28$ achieves 90% confidence. As the predictors are standardized, their coefficients indicate relative influence in the model.

3. Results

3.1. Climatology, seasonal cycle, and catch

SODA2.4 currents averaged to a depth of 200 m (Figure 1b) exhibit an equatorward current along the shelf edge near Cape Town with a shoreward perturbation near 27°S. Analysis of a section over latitudes 31°–33°S (not shown) indicates the equatorward current resembles a jet of 0.1 m s^{-1} extending to 200-m depth in the longitudes 15°–17°E. Many coarse-resolution models such as NOAA–GODAS do not resolve the jet. Off central Namibia there is a broad zone of weak currents, and near Cape Frio the poleward Angola Current is seen in SODA2.4 reanalysis. Moderate Resolution Imaging Spectroradiometer (MODIS) satellite infrared SST climatology (Figure 1c) reveals the upwelling zone extending 2° offshore from 22° to 32°S, with coolest waters ($<$13°C) near Lüderitz at 26°S. The 0–200-m salinity has a narrow zone of freshwater ($<$35 m) along the coast from 25° to 32°S (Figure 1d), coincident with uplift (Figure 1e). Hence, the SODA2.4 reanalysis at 0.5° adequately captures the coastal upwelling zone where most fish are caught (Fréon et al. 2005), similar to that of higher-resolution regional models (Veitch et al. 2010). There are distinct cells of upwelling $>$ 1 m day^{-1} in the southern Benguela and also off Lüderitz, collocated with high 0–200-m nitrate concentrations (Garcia et al. 2005). The SeaWiFS chlorophyll content parallels the SST pattern (Figure 1f): high values remain inside the 17°C isotherm. Peak values of 5 and 8 mg m^{-3} are found along the sheltered coasts of Swakopmund and St. Helena Bay, respectively. Such high productivity is unique to the Benguela upwelling system (Roy et al. 2001; Romero et al. 2002). The SODA2.4 climatology portrays many well-known features (Jury 1988), such as the inshore zone of fresh upwelled water and a shelf edge jet, and lends confidence to the analysis.

The seasonal cycle over the central Benguela shelf is illustrated in Figures 2a,b. Chlorophyll rises to a peak in October–November of $>$3 mg m^{-3}, as equatorward winds strengthen to 8 m s^{-1}. Winds slacken a bit and then rise again to 8 m s^{-1} in February, before starting a gradual decline that corresponds with chlorophyll. Minimum productivity levels are reached from May to July, although values remain $>$2 mg m^{-3}. The mixed layer is deepest in September, being $>$30 m at the onset of the upwelling season, and then declines to $<$20 m from December to April. MODIS shelf-averaged SST follows the solar cycle, rising from 15° to 18°C from August to January. Kreiner et al. (Kreiner et al. 2001) show that pelagic fish condition tends to follow SST, but the amplitude of change is low in the central Benguela, in keeping with the perennial nature of upwelling. The mean cycle of chlorophyll for 1998–2007 is analyzed as an *x–t* Hovmöller plot in Figure 2c. It shows a general offshore decline in chlorophyll from values of $>$5 mg m^{-3} in the coastal zone to $<$2 mg m^{-3} near the shelf edge at ~15°E. Some seasonality is evident in the rapid spread of phytoplankton over the shelf in September each year, followed by a gradual shoreward contraction from November to May. Preliminary analysis suggests that anomalies of chlorophyll and catch are inversely related over the 10-yr period of overlapping data.

The Benguela annual fish catch time series is illustrated in Figure 3a. Numerous multiyear spells of high and low catch are evident. The series has little trend despite suggestions that the fishery is in decline (Beckley and van der Lingen 1999; Boyer et al. 2001). High and low catches occur in 2–3-yr epochs, with a significant cycle of 5–6 years in the 1980s and 1990s, as identified by wavelet analysis (Figure 3b), attributable to bursts in anchovy catch and strong year classes at those intervals. The 1970s and early 1980s exhibit a downtrend followed by abrupt increases in 1987, 1992, and 2002. The species composition (Figure 3c) reveals the pelagic nature of the fishery: 80% sardine and anchovy.

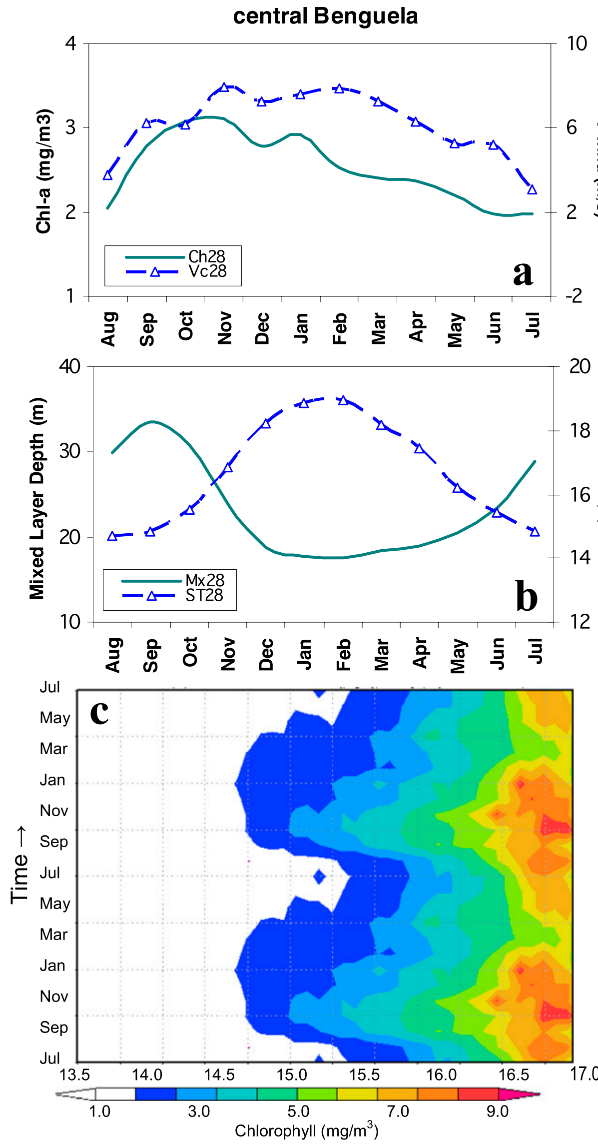

Figure 2. Central Benguela seasonal cycle of (a) chlorophyll and meridional winds and (b) mixed layer depth and SST. (c) Hovmöller *x–t* analysis of 2x mean seasonal cycle of chlorophyll averaged in 26°–30°S (box in Figure 1a).

Intercomparison of South African and Namibian sectors reveals a similarity of species composition.

3.2. Composite weather maps and ocean sections

The weather patterns with respect to periods of high and low catch are analyzed as composite difference maps in Figure 4. There is a broad region of anomalous northwesterly wind stress over the central Benguela (Figure 4a), representing a

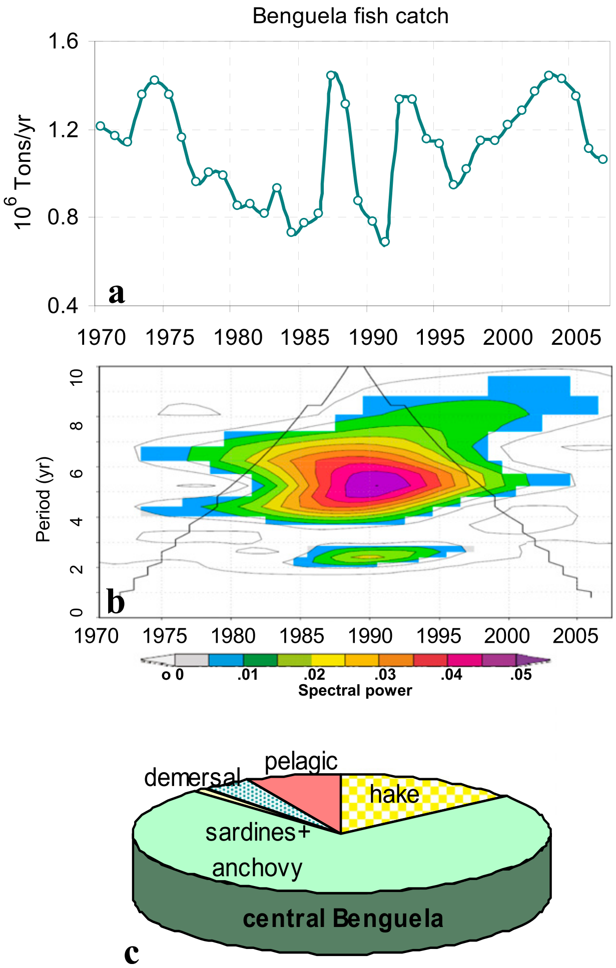

Figure 3. (a) Benguela fish catch time series for area in Figure 1f. (b) Wavelet spectra of fish catch, with shaded power (p < 0.2 masked) and cone of validity. (c) Mean species composition pie chart.

10%–20% decrease of upwelling favorable wind. There is an anomalous heat flux of -6 W m^{-2} over the area 10°–30°S, 10°W–15°E that warms the sea, contributing to increased sea surface height. Along the Benguela coast from 15° to 35°S, there is a band of anomalous offshore winds that induce poleward Ekman transport, which could reduce dispersion of passive biota from the upwelling zone. These easterly winds join northwesterly wind anomalies over the shelf edge. An investigation of this wind pattern suggests it is robust and not dominated by a few events. The offshore winds may serve to flatten waves, making fishing operations more efficient. The upper (200 hPa) wind and geopotential height patterns (Figures 4b,c) exhibit a trough of lower pressure (<-10 m) located near 40°S, 0° similar to that found in Jury (Jury 1997) and Jury et al. (Jury et al. 2000). Sweeping out of this trough are anomalous westerly winds of 2–3 m s^{-1} that affect the Benguela. The South Atlantic anticyclone is displaced northward and weakened by the westerly trough.

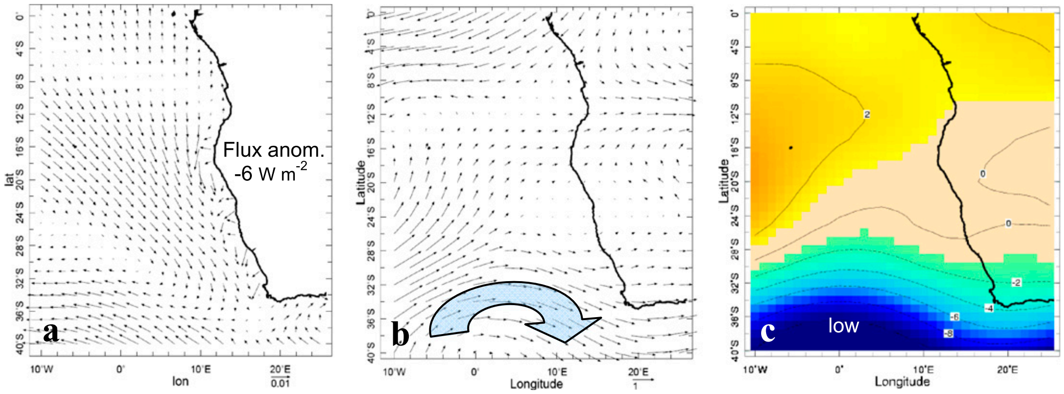

Figure 4. High minus low fish catch differences for atmospheric parameters (a) surface wind stress, (b) upper 200-hPa wind, and (c) upper geopotential height. Arrow in (b) highlights the standing westerly trough. Areas with differences < 0.5σ are statistically insignificant and have small vectors or neutral shading here and in Figure 5.

Oceanographic features over the Benguela shelf are presented in Figure 5 as composite sections in respect of high minus low catch. The *T*/*S* hydrographic structure is anomalous warm and salty in the 50–200-m layer from 11° to 15°E (Figures 5a,b). The *U*–*W* current pattern (Figure 5c) indicates strengthened

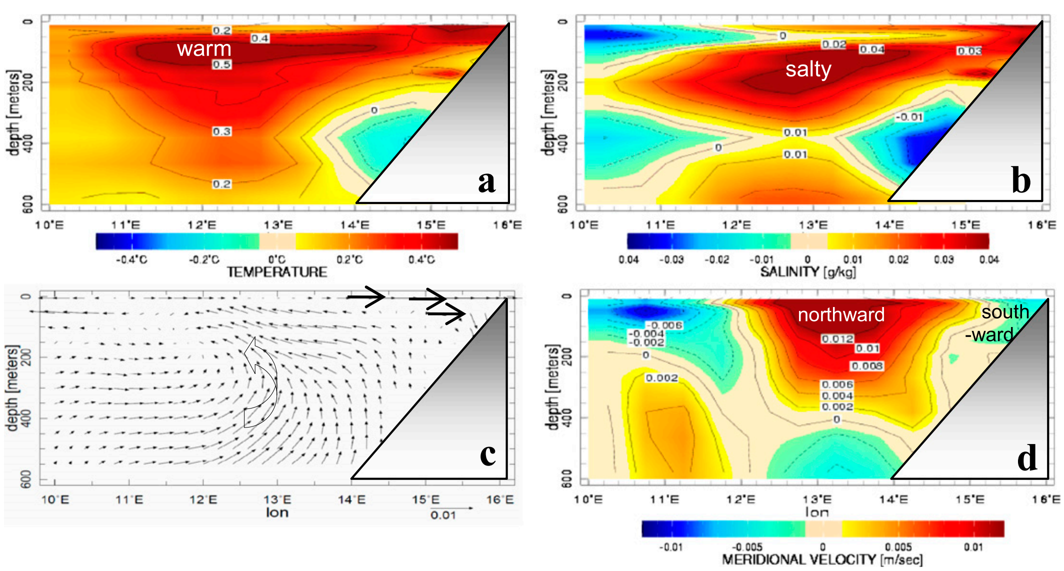

Figure 5. High minus low fish catch differences for depth sections within the rectangle in Figure 1a: (a) temperature, (b) salinity, (c) *U*–*W* currents with vertical motion exaggerated, and (d) *V* currents with shelf edge represented. Schematic arrows in (c) highlight key features.

Table 1. Variables, variances resolved by PCA, and pairwise correlation with catch. Variables in boldface are included in multivariate model; correlations in boldface are significant above 90% confidence.

Variable	Variance	R → fish
U1	0.108	−0.02
U2	0.087	0.06
U3	0.082	0.14
V1	0.108	**−0.25**
V2	0.107	−0.04
V3	0.091	**−0.22**
W1	0.082	−0.03
W2	0.075	0.15
W3	0.073	**0.22**
T1	0.197	−0.13
T2	0.138	**0.52**
T3	0.114	0.16
S1	0.224	**0.24**
S2	0.155	**−0.24**
S3	0.113	**0.31**
X1	0.551	**0.33**
X2	0.219	0.08
X3	0.151	−0.01
Y1	0.563	**0.26**
Y2	0.212	−0.20
Y3	0.104	**−0.32**
SL1	0.189	**−0.48**
SL2	0.127	−0.07
SL3	0.116	0.04

subsurface upwelling off the shelf edge (13°E), coincidently where hake are caught, below the warm inshore layer. To the west, there is onshore (offshore) flow below (above) 300 m and thus zonal overturning. In the surface layer, there is onshore transport that sinks near the coast, coincidently where anchovies are caught. Equatorward flow on the shelf edge (Figure 5d) is a response to warmer temperature and higher sea level farther offshore. The current patterns (not shown) feature counterrotating gyres on either side of the equatorward flow axis, which offer recirculating pathways for retention of passive biota.

3.3. PCA and relationships

Although the composite analysis distinguishes the environmental conditions affecting fish catch, it is necessary to support the interpretations using an objective analysis that is not specifically targeted on the fisheries. Following PCA, the natural modes of variability were calculated and time scores were cross-correlated with fish catch. Table 1 lists the variance explained by each mode and their pairwise correlation with fish catch. Ranking the pairwise correlation values, it is found that (detrended) temperature and sea level modes T2 and SL1 achieve 95% confidence. In multivariate regression, four modes provide input: Benguela fish catch = −2.73(Y3) + 1.74(SL1) + 1.55(T2) − 0.93(X1), where the coefficient signifies level of influence. The Y3 meridional wind pattern that has the highest influence

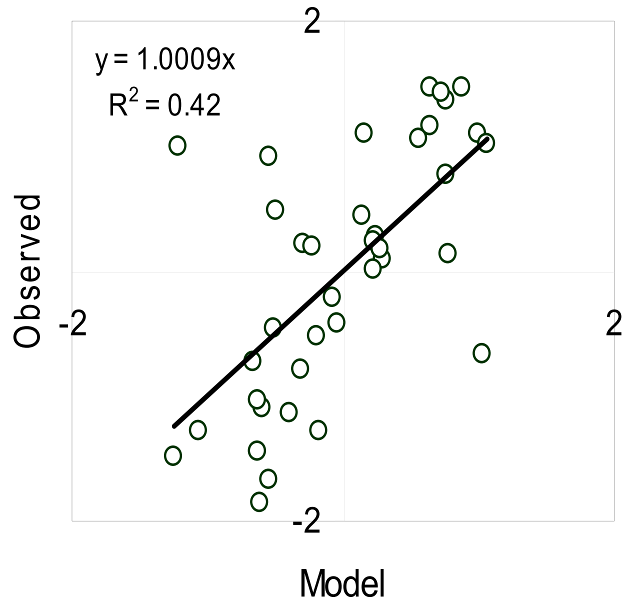

Figure 6. Multivariate regression of four PC time scores onto Benguela fish catch departures.

suggests that a poleward wind anomaly improves fish catch. The sea level (SL1) and temperature (T2) patterns both refer to an anomalous warming of the Lüderitz plume (22°–30°S, 10°–17°E). The zonal wind pattern (X1) is such that offshore coastal winds favor higher fish catch. The linear multivariate regression of environmental PCA modes accounts for 42% of catch variance (Figure 6), which exceeds 99% confidence.

4. Discussion and summary

Environmental influences on central Benguela fish catch have been analyzed using annual reanalysis data: contrasting periods of high and low catch in composite weather maps and ocean sections. The effects of the marine environment on fish catch are not necessarily deterministic, so this analysis isolates the key forcings and offers brief insights on the underlying processes. As pointed out earlier, the central Benguela is unique with year-round productivity. The composite differences in respect of high catch show a 10%–20% weakening of southeasterly winds that leads to a 0.5°C warming of sea temperatures to a depth of 200 m in the Lüderitz plume (cf. Figure 4). Equatorward currents strengthen at the shelf edge, below which there are rising motions that are insufficient to overcome surface warming by reduced evaporation (cf. Figure 5). Gyres over the shelf offer recirculation pathways to aid retention as suggested by Cole and McGlade (Cole and McGlade 1998) and Cole (Cole 1999). Offshore winds near the coast may flatten the waves and contribute to poleward Ekman transport in the surface layer, limiting the dispersion of passive biota. Weak downwelling near the coast (cf. Figure 5c) keeps chlorophyll levels near 2 mg m^{-3}, optimal for the central Benguela fishery.

Hutchings et al. (Hutchings et al. 1998) and van der Lingen et al. (van der Lingen et al. 2006) describe the patterns of spawning and recruitment in the southern Benguela and the environmental conditions favoring higher success rates, 16°–19°C with reduced mixing and currents. Here in the central Benguela it is also found that warming and weakening of wind mixing and ocean currents favors stratification, higher productivity, and increased fish catch. Jacox and Edwards (Jacox and Edwards 2011) found similar results in the coastal upwelling zones of California, Peru, and Morocco.

The identification of oceanographic features by PCA reduced a noisy environment to modes whose interannual time scores could be compared with fish catch. It was determined that anomalous poleward (Y3) and onshore winds (X1) and higher sea levels (SL1) and warmer temperatures (T2) in the Lüderitz plume were linked with higher fish catch, supporting the results of the composite analysis and corroborating that certain modes of natural variability have biological consequences (42% of catch variance). Because the ocean reanalysis fields incorporate in situ hydrographic and meteorological observations and satellite information on the surface temperature, sea surface height, and currents, it provides a unique view of the Benguela system at a level of detail that resolves the coastal upwelling cells. With the early years (1970s) sparsely observed, our approach was to aggregate data in the satellite era with older records via composite and PCA analysis, thereby improving confidence in the results. The results presented here suggest that Angola or Agulhas intrusions (Boyd et al. 1987) are less influential to central Benguela fish catch. Rather, it is the interannual meteorological forcing of the Lüderitz plume by a trough in the South Atlantic (Figures 4b,c) that is consequential. Such a pattern arises through climate teleconnections alluded to in earlier studies (Jury et al. 2000; Jury 2006; Richter et al. 2010; Rouault et al. 2010) that cause equatorward shifts of the South Atlantic anticyclone so that winds diminish and catch increases. Further work could be done by comparing FAO catch series with detailed acoustic biomass and recruitment surveys by Marine and Coastal Management and by analysis of submonthly chlorophyll and related physical/chemical variables to understand the high-frequency forcing of enrichment events as in Veitch et al. (Veitch et al. 2010).

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References

Bakun, A., 1996: Patterns in the ocean: Ocean processes and marine population dynamics. NOAA/California Sea Grant College System Rep., 323 pp.

Baumgartner, T. R., A. Soutar, and V. Ferreira-Bartrina, 1992: Reconstruction of the history of Pacific sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara Basin, California. History of Pacific sardine and northern anchovy populations, CCOFI Rep., Vol. 33, 22–40.

Beckley, L. E., and C. D. van der Lingen, 1999: Biology, fishery and management of sardines (Sardinops sagax) in southern African waters. *Mar. Freshw. Res.,* **50,** 955–978.

Boyd, A. J., J. D. Hewitson, I. Kruger, and F. Le Clus, 1985: Temperature and salinity trends off Namibia from 1982 to 1984, and their relation to the spawning success of pelagic fish. International Commission for the Southeast Atlantic Fisheries Collection of Scientific Papers, Vol. 12, 53–58.

——, J. Salat, and M. Masó, 1987: The seasonal intrusion of relatively saline water on the shelf off northern and central Namibia. *S. Afr. J. Mar. Sci.,* **5,** 107–120.

Boyer, D. C., H. J. Boyer, I. Fossen, and A. Kreiner, 2001: Changes in abundance of the northern Benguela sardine stock during the decade 1990 to 2000, including a discussion of the relative importance of fishing and the environment. *S. Afr. J. Mar. Sci.,* **23,** 67–84.

Carton, J. A., and B. S. Giese, 2008: A reanalysis of ocean climate using Simple Ocean Data Assimilation (SODA). *Mon. Wea. Rev.,* **136,** 2999–3017.

——, G. Chepurin, X. Cao, and B. S. Giese, 2000: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950–95. Part I: Methodology. *J. Phys. Oceanogr.,* **30,** 294–309.

Cole, J. F. T., 1999: Environmental conditions, satellite imagery, and clupeoid recruitment in the northern Benguela upwelling system. *Fish. Oceanogr.,* **8,** 25–38.

——, and J. McGlade, 1998: Temporal and spatial patterning of sea surface temperature in the northern Benguela upwelling system: Possible environmental indicators of clupeoid production. *S. Afr. J. Mar. Sci.,* **19,** 143–158.

Crawford, R. J. M., 1987: Food and population variability in five regions supporting large stocks of anchovy, sardine and horse mackerel. *S. Afr. J. Mar. Sci.,* **5,** 735–757.

Cury, P., and C. Roy, 1989: Optimal environmental window and pelagic fish recruitment success in upwelling areas. *Can. J. Fish. Aquat. Sci.,* **46,** 670–680.

——, A. Bakun, R. J. M. Crawford, A. Jarre, R. A. Quinones, L. J. Shannon, and H. M. Verheye, 2000: Small pelagics in upwelling systems: Patterns of interaction and structural change in 'wasp-waist' ecosystems. *ICES J. Mar. Sci.,* **57,** 603–618.

Fréon, P., L. Drapeau, J. H. M. David, A. F. Moreno, R. W. Leslie, W. H. Oosthuizen, L. J. Shannon, and C. D. van der Lingen, 2005: Spatialized ecosystem indicators in the southern Benguela. *ICES J. Mar. Sci.,* **62,** 459–468.

Gammelsrød, T., C. H. Bartholomae, D. C. Boyer, V. L. L. Filipe, and M. J. O'Toole, 1998: Intrusion of warm surface water along the Angolan–Namibian coast in February–March 1995: The 1995 Benguela Niño. *S. Afr. J. Mar. Sci.,* **19,** 41–56.

Garcia, H. E., R. A. Locarnini, T. P. Boyer, and J. I. Antonov, 2005: *Nutrients (Phosphate, Nitrate, Silicate).* Vol. 4, *World Ocean Atlas 2005,* NOAA Atlas NESDIS 64, 396 pp.

Hardman-Mountford, N. J., A. J. Richardson, J. J. Agenbag, E. Hagen, L. Nykjaer, F. A. Shillington, and C. Villacaslin, 2004: Ocean climate of the south east Atlantic observed from satellite data and wind models. *Prog. Oceanogr.,* **59,** 181–221, doi:10.1016/j.pocean.2003.10.001.

Hutchings, L., and Coauthors, 1998: Multiple factors affecting South African anchovy recruitment in the spawning, transport and nursery areas. *S. Afr. J. Mar. Sci.,* **19,** 211–225.

——, M. R. Roberts, and H. M. Verheye, 2009: Marine environmental monitoring programmes in South Africa: A review. *S. Afr. J. Sci.,* **105,** 94–102.

Jacox, M. G., and C. A. Edwards, 2011: Effects of stratification and shelf slope on nutrient supply in coastal upwelling regions. *J. Geophys. Res.,* **116,** C03019, doi:10.1029/2010JC006547.

Jury, M. R., 1988: The spatial distribution of wind driven upwelling off the west coast of Africa, 29-34S. *Cont. Shelf Res.,* **8,** 1257–1271.

——, 1997: Southeast Atlantic warm events: Composite evolution and consequences for southern African climate. *S. Afr. J. Mar. Sci.,* **17,** 21–28.

——, 2006: Tropical south-east Atlantic response to ENSO as an ecosystem indicator for the southern Benguela. *Afr. J. Mar. Sci.,* **28,** 41–50.

——, H. Mulenga, and H. Rautenbach, 2000: Tropical Atlantic variability and Indo-Pacific ENSO: Statistical analysis and numerical simulation. *Global Atmos. Ocean Syst.,* **7,** 107–124.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kreiner, A., C. D. van der Lingen, and P. Fréon, 2001: A comparison of condition factor and gonadosomatic index of sardine Sardinops sagax stocks in the northern and southern Benguela upwelling ecosystems, 1984–1999. *S. Afr. J. Mar. Sci.,* **23,** 123–124.

Le Clus, F., 1990: Impact and implications of large-scale environmental anomalies on the spatial distribution of spawning of the Namibian pilchard and anchovy populations. *S. Afr. J. Mar. Sci.,* **9,** 141–159.

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

Matthews, J. P., 1964: The pilchard of South West Africa (Sardinops ocellata): Sexual development, condition factor and reproduction 1957–1960. Administration of South West Africa Marine Research Laboratory Investigational Rep. 10, 96 pp.

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

Nicholson, S., 2010: A low-level jet along the Benguela coast, an integral part of the Benguela current ecosystem. *Climatic Change,* **99,** 613–624.

O'Toole, M. J., 1977: Investigations in some important fish larvae in the south east Atlantic in relation to the hydrological environment. Ph.D. thesis, University of Cape Town, 274 pp.

Parrish, R. H., A. Bakun, D. M. Husby, and C. S. Nelson, 1982: Comparative climatology of selected environmental processes in relation to eastern boundary current pelagic fish reproduction. *Proc. Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources,* San Jose, Costa Rica, Food and Agriculture Organization of the United Nations, 731–777.

Richter, I., S. K. Behera, Y. Masumoto, B. Taguchi, N. Komori, and T. Yamagata, 2010: On the triggering of Benguela Niños: Remote equatorial versus local influences. *Geophys. Res. Lett.,* **37,** L20604, doi:10.1029/2010GL044461.

Romero, O., B. Boeckela, B. Donnera, G. Lavikb, G. Fischera, and G. Wefer, 2002: Seasonal productivity dynamics in the pelagic central Benguela system inferred from the flux of carbonate and silicate organisms. *J. Mar. Syst.,* **37,** 259–278.

Rouault, M., B. Pohl, and P. Penven, 2010: Coastal oceanic climate change and variability from 1982 to 2009 around South Africa. *Afr. J. Mar. Sci.,* **32,** 237–246.

Roy, C., S. Weeks, M. Rouault, G. Nelson, R. Barlow, and C. van der Lingen, 2001: Extreme oceanographic events recorded in the southern Benguela during the 1999–2000 summer season. *S. Afr. J. Sci.,* **97,** 465.

Schwartzlose, R. A., and Coauthors, 1999: Worldwide large-scale fluctuations of sardine and anchovy populations. *S. Afr. J. Mar. Sci.,* **21,** 289–347.

Shackleton, L. Y., 1987: A comparative study of fossil fish scales from three upwelling regions. *S. Afr. J. Mar. Sci.,* **5,** 79–84.

Shannon, L. J., 1998: Modelling environmental effects on the early life history of the South African anchovy and sardine: A comparative approach. *S. Afr. J. Mar. Sci.,* **19,** 291–304.

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

——, and G. Nelson, 1996: The Benguela: Large scale features and processes and system variability. *The South Atlantic: Present and Past Circulation,* G. Wefer et al., Eds., Springer-Verlag, 163–210.

——, J. J. Agenbag, and M. E. L. Buys, 1987: Large- and mesoscale features of the Angola-Benguela front. *S. Afr. J. Mar. Sci.,* **5,** 11–34.

——, R. J. M. Crawford, G. B. Brundrit, and L. G. Underhill, 1988: Response of fish populations in the Benguela ecosystem to environmental change. *ICES J. Mar. Sci.,* **45,** 5–12.

Shillington, F. A., 1998: The Benguela upwelling system off southwestern Africa. *The Sea: The Global Coastal Ocean,* A. R. Robinson and K. H. Brink, Eds., *Regional Studies and Syntheses,* Vol. 11, Wiley, 583–604.

Smith, T. M., and R. W. Reynolds, 2004: Improved extended reconstruction of SST (1854–1997). *J. Climate,* **17,** 2466–2477.

Thomas, A. C., M. E. Carr, and P.-T. Strub, 2001: Chlorophyll variability in eastern boundary currents. *Geophys. Res. Lett.,* **28,** 3421–3424.

van der Lingen, C. D., L. J. Shannon, P. Cury, A. Kreiner, C. L. Moloney, J. P. Roux, and F. Vaz-Velho, 2006: Resource and ecosystem variability, including regime shifts, in the Benguela Current system. *Benguela: Predicting a Large Marine Ecosystem,* L. V. Shannon et al., Eds., Vol. 14, Large Marine Ecosystems, Elsevier, 147–185.

Veitch, J. A., P. Penven, and F. A. Shillington, 2010: Modelling equilibrium dynamics of the Benguela Current system. *J. Phys. Oceanogr.,* **40,** 1942–1964.