Research Article

Environmental Forcing of Red Tides in the Southern Benguela

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The Southern Benguela cape upwelling plumes have inshore wind shadows prone to red tides in late summer. Their intensity and coverage are estimated by satellite fluorescence measurements in the period 1997–2012 and qualified by in situ reports. High satellite fluorescence cases are identified at daily to seasonal time scales, and characteristics of the upper ocean and lower atmosphere are studied using third generation reanalyses. A dominant feature is easterly winds over the Cape Peninsula (34°S, 18°E) induced by a ridging anticyclone-coastal low weather pattern. Over Cape Columbine (33°S), there is a wind shadow with cyclonic wind and current shear. Composite atmospheric profiles reveal a 4°C temperature inversion near 500 m that traps a coastal wind jet >6 m/s below 200 m. The composite shelf oceanography shows a relic upwelling plume below 10 m overtopped by warmer water near the coast, providing the thermal stratification needed for biotic aggregation. Data from the IPSL5 coupled climate model over the period 1980–2080 indicates that environmental conditions favoring red tides may become more frequent.

1. Introduction

The Southern Benguela (31.5–34°S, 17.5–18.5°E) is a zone of summer upwelling and equatorward flow [1–4]. The upwelling intensifies next to two capes at 34°S and 33°S [4–7]. In the north of each cape, there is wind shadow and corresponding band of warm surface water [8, 9]. Cyclonic wind shear produces a clockwise circulation in the leeward bay [9–12] where high chlorophyll content promotes dinoflagellate blooms or “red tides” [13]. In situ surveys have found that red tides form in ~5 × 20 km patches and accumulate over a few days [14–16], mainly in February to April season.

The upwelling is pulsed by passing weather systems and amplified by coastal low pressure cells [17–19]. As they transit the Southern Benguela, equatorward flow becomes shallow and sheared by the topography. Wind shadow zones grow offshore and stratified conditions lasting many days contribute to red tides [20–24], which appear rapidly at high concentrations suggesting that local growth is boosted by confluent circulations [16, 25, 26]. The decay of red tides leads to low oxygen water and marine life mortalities with economic consequences [27].

Most red tides exhibit spectral radiance in the fluorescence band ±683 nm. These can be measured near the surface by satellite remote sensing [28, 29]. The sea wide-field sensor (SeaWiFS) collected data from 1997 to 2010 in spectral bands from 412 to 865 nm. Since 2002, the moderate resolution imaging spectroradiometer (MODIS) provides decoupled 8-day 9 km resolution imagery in 405–877 nm spectral bands that enable a fluorescence line height (FLH) calculation [30]. MODIS FLH is found to be consistent with in situ observations of red tide [31–33] as a radiometric index of relative harmful phytoplankton biomass. The European MERIS satellite also has spectral bands across the fluorescence peak capable of detecting red tides and cyanobacteria blooms [34], even in coastal turbid waters [35]. FLH is sensitive to phytoplankton nutrient status, growth rates, species, and size through variations in quantum yield. In addition to fluorescence proxies, satellite measured chlorophyll (CHL) indicates high biomass dinoflagellate blooms and sea surface temperature (SST) helps in establishing the background conditions that contribute to the formation of red tides during wind-driven coastal upwelling relaxation. Satellite altimetry can

resolve the background circulation in conjunction with ocean model assimilation of in situ observations.

Multiple environmental factors can be evaluated by regression of variables onto an FLH index. Additional FLH proxies may be generated from the National Aeronautics and Space Administration (NASA) ocean biogeochemical model (NOBM). The NOBM physical [36] and chemical submodels [37] assimilate satellite data in parallel with environmental observations. The model calculates budgets and interactions between phytoplankton, nutrients, minerals and zooplankton, and consequent dissolved organic material and detritus. The NOBM employs a sophisticated Kalman ensemble filter. Its use in the coastal zone is limited by a 100 km resolution, so application here is made in the broader upwelling zone north of Cape Columbine.

Ocean-atmosphere reanalysis products are employed here to study the environmental forcing of red tides in the Southern Benguela in February–April season in 1997–2012. This is a challenge given the coastal pulsed nature of upwelling [38–41]. The paper addresses the following research questions. What are the temporal and spatial characteristics of satellite fluorescence that indicate red tides? What are the environmental influences on red tides at event to seasonal time scales? Are conditions favoring red tides more likely in future?

Methods are employed to bring out the environmental forcing of red tides at time scales from daily local weather to interannual ocean influence. The spatial scale includes the two shelf zones leeward of the Cape Peninsula and Cape Columbine upwelling plumes, where red tides are most frequently observed. The study does not attempt to “predict” red tides but to understand the multivariate environmental forcing. Model fitting is done only to extend the MODIS record back to SeaWiFS and to establish a daily index corresponding with red tides.

2. Data and Methods

The primary index to estimate red tide intensity and coverage in the Southern Benguela is the MODIS fluorescence line height (FLH) 9 km 8-day data from July 2002 to December 2012 obtained from NASA. A SeaWiFS FLH proxy is calculated by multivariate regression of radiance data in the period of overlap with MODIS, extending the record back to September 1997. Time series are averaged over the Southern Benguela shelf zone: 34–31.5°S, 17.5–18.5°E (Figure 1(e)), to indicate red tides within the two cape upwelling shadows. In situ red tide reports from the Fisheries Service (MCM) were used to qualify the satellite estimates, and cases were screened accordingly. In addition to FLH data, satellite chlorophyll (CHL) is analyzed given its relationship to winds and currents in coastal upwelling zones [42, 43]. A proxy for FLH at daily time scale is an arithmetic average of NOBM chlorophytes and cyanobacteria. For comparison with oceanographic sets, the SeaWiFS-MODIS FLH is binned into months. Thus, we have FLH or FLH proxies at three time scales (daily, 8-day, monthly) to investigate the shelf-scale environmental forcing

TABLE 1: FLH cases for inclusion in composites screened by in situ reports.

High daily	High 8 days	High month	Low month
27 February 2000	29 March 2000	April 2002	February 1998
7 March 2002	15 April 2000	February 2006	March 1998
20 February 2005	18 February 2005	March 2006	February 1999
18 March 2007	26 February 2005	March 2007	March 2001
23 March 2008	21 March 2008	April 2007	February 2003
21 April 2009	7 April 2009	March 2008	March 2003
24 March 2012	29 March 2012	April 2008	April 2005

of red tides in the period 1997–2012. FLH case studies (qualified by in situ reports) are listed in Table 1.

Global atmospheric and oceanography datasets with 30–50 km resolution are used to understand the shelf dynamics. Monthly wind stress, surface and upper wind, wind vorticity, sea level air pressure (SLP), surface temperature (Ts), latent heat flux (evaporation), specific humidity, and precipitable water are obtained from the coupled forecast system (hereafter, CFS [44]). Daily atmospheric data are obtained from the National Center for Environmental Prediction (NCEP) operational assimilation system and time- and space-averaged to match FLH for temporal analysis. Oceanographic fields are provided by Simple Ocean Data Assimilation version 2.1.6 (SODA, [45]) and include subsurface (1–100 m) temperature, salinity, currents and vertical motion, sea surface height, and European Community Medium-Range Weather Forecasts (ECMWF) wind stress. Monthly ocean data assimilation is performed within the Geophysical Fluid Dynamics Lab Modular Ocean Model version 4 [46]. Coastal upwelling and mesoscale winds are studied using daily 25 km NOAA SST data [47], 25 km J-OFURO reanalysis [48], satellite scatterometer measurements from QuikSCAT and ASCAT, and 4 km Meteosat infrared imagery. Atmospheric mixed layer profiles are studied by composite averaging of daily aircraft (AMDAR), radiosonde, and NCEP wind and temperature profiles near Cape Town Airport for high (daily) FLH cases. In general, data from “first generation” reanalyses (at 200 km resolution) are unsuitable for shelf-scale analysis and use here.

The environmental forcing of red tides is evaluated by multivariate regression of candidate predictors onto FLH in the form of (a) mean annual cycle, (b) monthly, (c) 8-day, and (d) daily data. This is done by backward stepwise removal of less influential variables, until an optimal multivariate algorithm is found. These time scales represent a progression from the “climate envelope” to the “local weather” which induces red tides in the coastal zone. Oceanographic and atmospheric structures are analyzed as depth or height sections over the Southern Benguela shelf (34–31.5°S, 17°–19°E), based on composites of the seven highest FLH months in February to April season minus the seven lowest FLH months (hereafter “high minus low”). Red tide events in the 8-day FLH record are studied by composite-averaging maps of SLP, SST, winds, latent heat flux, and MODIS FLH imagery. FLH index-to-field correlations are calculated for monthly surface

FIGURE 1: Mean annual cycle averaged over the Southern Benguela 1997–2012 for the following: (a) 8-day SeaWiFS-MODIS chlorophyll and fluorescence; (b) monthly MODIS SST and SODA 1–100 m temperature; (c) ECMWF meridional wind stress and SODA 1–100 m salinity; (d) coupled forecast system (CFS) air-sea latent heat flux and lowest 2.5% absolute vorticity $\times 10^{-5} \text{ s}^{-1}$; (e) day-time land surface temperatures for high (daily) FLH cases with coastal topography and place names. Box is the averaging area for all analyses: 34–31.5°S, 17.5–18.5°E; dot is regional airport.

temperature, wind stress, latent heat flux, meridional upper wind, and sea level air pressure both within and around the Southern Benguela in February to April season. Pairwise correlations are analyzed between FLH and monthly environmental variables averaged over 34–31.5°S, 17.5–18.5°E, except the s-n SLP index: 10–20°E, 35–45°S minus 15–25°S. Statistical significance is evaluated according to the degrees of freedom as limited by record length, temporal resolution/averaging, and persistence.

Given the peculiar sea level air pressure (SLP) pattern found in the FLH index-to-field correlations, data from the French Institut Pierre Simon Laplace (IPSL) version 5 coupled general circulation model used for climate change projections [49] is evaluated over the period 1980–2080. Principal component clusters are calculated for February to April SLP and air temperature (T_a). The leading mode of the IPSL5 simulated SLP resembles the FLH correlation pattern, so its trend and variance are analyzed. The IPSL5 is selected from a long list of models in the Intergovernmental Panel on Climate Change (IPCC) Intercomparison Project (CMIP5) because it exhibits low differences between simulated and observed conditions in the Benguela upwelling zone [50]. The IPSL5 model is described by Dufresne et al. [51] and has a dynamic coupling and feedback scheme that accurately simulates past climate. Its horizontal resolution is ~100 km and representative of large scale environmental forcing, but not shelf—or event—scale processes.

3. Results

3.1. Annual Cycle. The mean annual cycle is studied based on red tide index area-averaged 8-day FLH and CHL values (Figure 1(a)). Both variables show a gradual rising trend from December to April, following an initial surge in November. CHL drops precipitously in April while FLH remains high then. Both annual cycles bottom out in July as coastal upwelling declines. It can be noted that river inflows are near zero from January to April, and thus “mistaken” turbidity events are unlikely. The annual cycle of SST is at a maximum in January while subsurface temperatures are at a minimum in March (Figure 1(b)). The larger difference represents stratification dT/dz necessary for biotic aggregation. Subsurface salinity is inversely related to SST with a minimum in January and a maximum in July. Meridional wind stress has a large annual cycle with equatorward values peaking from December to February, then falling rapidly in March to negative values in June (Figure 1(c)). Latent heat flux is at a minimum over the shelf from February to April, and its lowest 2.5% of cases falls almost to zero in February. Similarly wind vorticity is most cyclonic from February to April, when standing clockwise rotors prevail over the coast. Wind vorticity rises rapidly (anticyclonic) after May (Figure 1(d)) to inhibit upwelling and red tides. Figure 1(e) provides a map view of the Southern Benguela and its topography. Day-time land surface temperatures in high (daily) FLH cases exhibit values $>40^\circ\text{C}$ in wind shadow zones. Pairwise correlations of environmental variables with the annual cycle of FLH (Table 2) are high for latent heat flux (–0.95),

TABLE 2: Pairwise cross-correlations of monthly data.

Annual	FLH	Anomaly	FLH
Algae	0.38	Algae	0.12
Phyto	0.40	Phyto	0.11
MLD	–0.88	MLD	–0.03
V curr	0.35	V curr	0.07
U curr	–0.42	U curr	–0.04
W-50	0.14	W-50	0.17
Temp	–0.92	Temp	–0.06
Salt	–0.80	Salt	0.02
SSH	–0.13	SSH	–0.09
tau X	–0.71	tau X ec	–0.39
tau Y	0.41	tau Y ec	0.27
dST/dz	0.71	dST/dz	–0.23
m SST	0.59	m SST	–0.27
oi SST	0.62	oi SST	–0.35
Vort.	–0.69	Vort.	–0.24
Qe sea	–0.95	Tair	0.16
Qe 2.5%	–0.74	S salt	0.16
		tau X cf	–0.38
	90% confidence (bold)	tau Y cf	0.33
	r > 0.80 annual cycle	W 700	0.10
	r > 0.30 anomaly series	Qe sea	–0.28

TABLE 3: Multiple regression statistics: mean annual cycle of monthly FLH.

Adj. R sq.	0.974			
Std. error	0.001			
Obs.	12.0			
ANOVA	df	SS	MS	F
Regression	3.0	0.000	0.000	138.2
Residual	8.0	0.000	0.000	
Total	11.0	0.000		
Variables	Coeff.	Std. error	t stat	P value
Intercept	2.666	0.434	6.1	0.000
Temp.	–0.014	0.001	–10.4	0.000
Salt	–0.069	0.013	–5.5	0.001
tau Y	–0.032	0.004	–7.3	0.000

subsurface temperature (–0.92), and mixed layer depth (–0.88). Multivariate regression onto the annual cycle of monthly FLH fits 97% of variance with negative coefficients for subsurface temperature and salinity and meridional wind stress (Table 3) with ~3 degrees of freedom.

3.2. Characteristics of High Fluorescence Spells. The environmental forcing of red tides in early 2002 is studied using daily FLH proxy and daily NCEP data. Multivariate regression (Table 4, Figure 2(a)) yields negative coefficients for U wind (–1.06), V wind (–0.44), SST (–0.49), south-north SLP (–0.67), and mixed layer depth (–0.79) and a positive coef-

FIGURE 2: (a) Scatterplot of environmental model versus daily NOBM FLH proxy (cf. Table 4). (b) January to May 2002 time series of daily normalized departures of CFS meridional wind, NOAA SST, and NOBM mixed layer depth. (c) CFS zonal wind, precipitable water, and south minus north sea level air pressure index. (d) CFS meridional wind cross-section averaged 34–31.5°S, Feb–Apr 2002, indicating depth of equatorward flow in km. (e) SeaWiFS FLH proxy (10^{-2}), 6–13 March 2002, and ECMWF wind stress anomalies (March 2002, max = 0.08 Nm^{-2}). Arrows in (b) highlight upwelling relaxation.

ficient for atmospheric precipitable water (+0.28). The multivariate environmental algorithm explains 52% of FLH variance (Table 4) with >50 degrees of freedom. Analyzing the normalized time series, frequent upwelling relaxations are noted (Figure 2(b)): SSTs peaked three times, meridional winds reversed, and the mixed layer was shallow. Zonal winds were persistently westward in February coincident with a positive s-n SLP index (Figure 2(c)) indicating a “ridged

anticyclone-west coast trough” weather pattern. Precipitable water was high at the end of February 2002, due to an influx of tropical air. Meridional (equatorward) winds remained shallow during this period (Figure 2(d)) and thus sheared by the coastal topography. Wind stress anomalies along the coast were offshore and poleward, and satellite measured fluorescence was high in the shelf zone leeward of the two upwelling plumes (Figure 2(e)). Pitcher et al. [9] summarize in situ

FIGURE 3: (a) Meteosat 4 km infrared image and CFS wind vorticity (contours, 10^{-5} s^{-1}) for high FLH case of 18 March 2007; (b) MODIS FLH (10^{-2}) for 14–21 March 2007 and wind streamlines. Scatterometer wind maps (color flags, m/s) for (c) 20 March 2007 and (d) 24 March 2012 with CFS atmospheric mixed layer height (m) labeled at key points.

reports of repeated red tides, low oxygen water, and ecological mortalities in St. Helena Bay in early 2002.

Spatial features of high (daily) FLH events are studied. Wind and surface temperature maps on 18 March 2007 and MODIS FLH in the period from 14 to 21 March are given in Figures 3(a) and 3(b). Southeasterly winds prevailed off the Cape Peninsula and there was a wind shadow in St. Helena Bay. Cyclonic wind vorticity west of the two capes was $\sim -2 \times 10^{-5} \text{ s}^{-1}$. Meteosat infrared temperatures exhibited a wide zone of coastal upwelling $< 12^\circ \text{C}$ and land temperatures above 22°C . The MODIS 8-day FLH map of 14–21 March 2007 (Figure 3(b)) suggested red tides along the coast of St. Helena

Bay and seaward of the upwelling plumes at 31.3°S and 33.1°S . Scatterometer wind maps for two different high FLH cases are given in Figures 3(c) and 3(d). They exhibit a wind shadow with wind speeds $< 7 \text{ m/s}$ inshore and boundary layer height $\sim 200 \text{ m}$, contrasting with $> 15 \text{ m/s}$ winds in the south and boundary layer height $\sim 1 \text{ km}$. On 24 March 2012, there was a long shear line NW of the Cape Peninsula, initiated by friction of the Hottentots Holland Mountains and reinforced by negative sensible heat fluxes (-20 W m^{-2}) over the upwelling zone. In St. Helena Bay, the winds curled cyclonically, and poleward wind flow was observed along the Namaqua Coast. The surface temperature and wind patterns in two further

FIGURE 4: Meteosat 4 km infrared images for two high FLH cases: (a) 7 March 2002 and (b) 24 March 2012, all at 20:00 LST. (c, d) Scatterometer 25 km gridded wind speed (shaded, m/s) and CFS wind stress vectors for the same cases.

high FLH cases are analyzed in Figures 4(a)–4(d). All share similar features: the upwelling zone was wider and further south than usual. SSTs were $<13^{\circ}\text{C}$ off the cape at 34°S and $\sim 16^{\circ}\text{C}$ in St. Helena Bay. Land surface temperatures (at 20:00 LST) were well above 22°C and the satellite imagery was cloud-free due to offshore wind flow. Scatterometer winds were $>12\text{ m/s}$ in the south, and there was a broad wind shadow $<4\text{ m/s}$ to the north where stress vectors turned clockwise.

The 8-day FLH time series (Figure 5(a)) that is the basis for most analyses is filled with high and low spells embedded in a background seasonal rhythm. Multiple regression of surface weather variables yields an algorithm fitting 28% of variance with negative influences from PAR, zonal wind, and SST and with positive influences from meridional wind and

humidity (Table 5). A higher fit could be possible with subsurface ocean variables, but these are not available at multiday time scales. Fitting continuous data provides insights into the seasonal forcing of red tide. However, peak events tend to occur in February–April, wherein seven cases (Table 1, cf. [52]) are used to calculate daily and 8-day composite maps of environmental conditions. Within each high FLH spell, there is a ridging anticyclone-coastal low event that stands out. The composite SLP map sequence (Figure 5(b)) reveals an anticyclone moving eastward along 40°S , reaching 20°E on day-0 and 33°E on day+1, while a coastal low event shifts from 28°S to 32°S . An important feature for red tides is the repetition of this weather sequence and development of a west coast trough to the north of an anticyclone belt.

FIGURE 5: (a) Time series of 8-day SeaWiFS/MODIS fluorescence (area as in Figure 2(e)) with circles to identify the 7 high FLH cases confirmed by in situ reports. (b) Composite high day-0 (left) and day+1 sea level air pressure maps. (c) Composite high day-0 SST anomaly. (d) Example of MODIS FLH (10^{-2}) and ECMWF wind stress anomalies (max = 0.08 Nm^{-2}) in February-March 2005.

FIGURE 6: Composite (a) wind direction, (b) wind speed (m/s), (c) dew point, and (d) temperature (C) profiles with height (m) for high daily FLH cases from NCEP model assimilation, AMDAR aircraft, and radiosonde near Cape Town.

The composite SST anomaly map for high FLH cases (Figure 5(c)) has a cold anomaly between the two capes that represents a broadening of the upwelling zone. There is a warm anomaly offshore, so the thermal gradient is strengthened. The MODIS satellite FLH composite in February-March 2005 (Figure 5(d)) exhibits high values along the Namaqua and St. Helena Bay coasts and in a meridional axis west of Cape Columbine. Low FLH values are noted in the Cape Peninsula upwelling plume. Wind stress anomalies

during February-March 2005 were poleward in the vicinity of Cape Columbine.

3.3. Structure of High Fluorescence Spells. The coastal environment accompanying red tides in the Southern Benguela is studied. Past research has identified that ocean stratification is important, but what about the atmosphere? In Figure 6, composite atmospheric profiles from NCEP model assimilation,

FIGURE 7: Composite 7 high minus 7 low FLH months averaged 17.5–18.5°E from SODA for the following: (a) wind stress and sea height, (b) currents and salinity, and (c) temperature and vertical motion differences, to study alongshore gradients.

TABLE 4: Multiple regression statistics: daily FLH index, Nov. 01–Jul. 02.

Adj. R sq.	0.52			
Std. error	2.27			
Obs.	273.0			
ANOVA	df	SS	MS	F
Regression	6.0	1558.2	259.7	50.2
Residual	266.0	1375.1	5.17	
Total	272.0	2933.3		
Std. variables	Coeff.	Std. error	t stat	P value
Intercept	4.512	0.172	26.2	0.000
U wind	-1.061	0.107	-9.9	0.000
V wind	-0.443	0.086	-5.1	0.000
SST	-0.495	0.054	-9.1	0.000
s-n SLP	-0.671	0.077	-8.7	0.000
M.L. depth	-0.790	0.060	-13.2	0.000
Prec. water	0.280	0.054	5.1	0.000

TABLE 5: Multiple regression statistics: 8-day FLH index, Sep. 97–Dec. 12.

Adj. R sq.	0.28			
Std. error	0.01			
Obs.	704.0			
ANOVA	df	SS	MS	F
Regression	5.0	0.02	0.00	54.78
Residual	698.0	0.04	0.00	
Total	703.0	0.06		
Variables	Coeff.	Std. error	t stat	P value
Intercept	0.05	0.00	12.93	0.000
PAR	-0.0002	0.00	-5.27	0.000
U ncep	-0.0009	0.00	-3.94	0.000
V ncep	0.0013	0.00	5.04	0.000
Humidity	0.0036	0.00	10.19	0.000
SST	-0.0026	0.00	-6.77	0.000

AMDAR aircraft, and radiosonde near Cape Town are analyzed for high daily FLH cases. Winds directions tend to be

southerly to varying degrees and shift to easterly with height, as expected from the Ekman spiral effect of surface friction. Model and radiosonde wind direction profiles are smoother

FIGURE 8: Composite 7 high minus 7 low FLH months averaged 34–31.5°S from SODA for the following: (a) temperature, (b) salinity, (c) currents: meridional differences shaded, zonal overturning vectors max = 0.02 m/s, and (d) wind stress and sea height differences, to study cross-shelf gradients.

than aircraft. Wind speeds exhibit a near-surface coastal jet of varying thickness, with strongest winds from 100 to 200 m in aircraft and radiosonde profiles, and somewhat deeper in the model representation. Dew point temperatures are 10–15°C and decrease with height consistent with dry easterly downslope flow, locally known as “berg winds.” Temperature inversions are found in all profiles, indicative of stable atmospheric conditions that inhibit turbulent momentum transfer at the top of the mixed layer. The increase is $\sim 4^\circ\text{C}$ from 10 m to 500 m in aircraft and radiosonde profiles and weaker in the model analysis. With surface air temperatures near 18°C and coastal SST below 15°C, an inversion exists over the upwelling zone which helps to maintain the wind shadow.

Composite ocean structure for seven high minus low FLH months (cf. Table 1) is illustrated in Figures 7(a)–7(c) along coast axis. A key feature is the negative ECMWF meridional wind stress difference indicating a wind shadow over Cape Columbine (33.2–32.7°S). Zonal wind stress is neutral in the south but westward (–) over the Namaqua coast (32.3–31.5°S), indicating berg winds. Sea surface height shows a positive difference in the wind shadow and a negative slope to the north. Composite SODA currents are onshore- and poleward-directed to the south, suggesting a “pulling” action on shelf waters. Salinity differences are positive in the south with a slope toward neutral conditions elsewhere. SODA subsurface temperature differences are neutral in the south and exhibit a

FIGURE 9: Correlation maps using February–April FLH index with CFS reanalysis: (a) surface temperature T_s , (b) meridional wind stress τ_Y , (c) latent heat flux Q_e , (d) 200 mb meridional wind V_{200} , and (e) sea level air pressure SLP. Values of $|r| > 0.40$ significant at 90% confidence in the period 1998–2010.

gradient toward cold conditions north of Cape Columbine: a broadening of the upwelling zone there. Vertical motion differences are the inverse: negative (downwelling) in the south and neutral elsewhere.

Composite ocean structure for high minus low FLH months is analyzed as cross-shelf sections in Figures 8(a)–8(d). These help to identify the “climate envelope,” within which the red tides events are formed. The temperature–salinity sections identify subsurface cold (-0.7°C) fresh differences on the shelf edge (18.0°E) denoting a relic upwelling

plume, while warm differences are located offshore. Most significantly, the SODA reanalysis detects the warm salty surface layer at the coast (18.6°E). The current differences reveal several features consistent with in situ surveys during red tide [53]. A zonal downwelling circulation is found, with poleward flow differences (-0.03 m/s) in the upper layer from 17.8 to 18.4°E . The cross-shelf structure of wind stress differences is most negative at 18.2°E . The V-shape indicates shear lines that separate active upwelling and quiescent zones. The sea surface height is elevated on the coast due to onshore transport and

FIGURE 10: (a) February–April principal component scores for SLP1 (38%) and T_a2 (11%) based on IPSL simulation and (b, c) their loading patterns. Linear trend for SLP1 refers to increasing ridging high, coastal trough pattern, contributing to warm easterly winds over the Southern Benguela.

supports surface poleward currents. It is suggested that the ability of 50 km resolution ocean reanalysis products to represent many known features underlying red tides in the Southern Benguela means that operational forecasts of conditions suitable for red tide are within reach.

3.4. Environmental Influences on Seasonal Fluorescence. FLH index-to-field correlations are analyzed for the February–April season in Figures 9(a)–9(e). This analysis promotes an understanding of the interannual forcing of red tides. The CFS correlation maps exhibit a pattern of increased upwelling and equatorward wind flow in respect of high FLH seasons. Surface temperature correlations are negative in the upwelling zone ($r < -0.4$) and positive inland. Wind stress correlations are positive and upwelling favorable, but negative correlations with latent heat flux suggest light winds between the two capes. Further inland there are positive correlations

referring to increased moisture flux. Taking a wider perspective (Figure 9(d)), the FLH index-to-field correlations are positive (equatorward) for meridional upper winds and refer to an anticyclonic ridge in the midlatitude jet stream. The sea level air pressure map is most important (Figure 9(e)). It exhibits south-high/north-low values: a ridged anticyclone-west coast trough weather pattern. Thus, the climate “envelope” contains event-like features that could enable forecasts at long lead times.

Coupled model simulations that form part of the IPCC CMIP5 assessment are available for analysis here. Use is made of the IPSL5 model outputs for SLP and T_a with an rcp 4.5 W/m² scenario, considering the principal component time scores and loading patterns (Figures 10(a)–10(c)). The leading SLP mode is the ridged anticyclone-west coast trough pattern explaining 38% of variance in February to April season over the period 1980–2080. The IPSL5 model, which

represents the Benguela upwelling zone better than most, predicts a poleward shift of subtropical anticyclones as CO₂ rises. With more easterly winds, the west coast trough deepens. The SLP1 loading pattern of IPSL5 (Figure 10(b)) resembles the FLH-SLP map (Figure 9(e)). The upward trend of its time score (18% of variance, Figure 10(a)) suggests that the frequency of red tide events could grow in the Southern Benguela, as the wind shadow widens. Concurrently, the easterly winds raise air temperatures over the upwelling zone (Figure 10(c)), giving rise to stronger inversions that promote cyclonic wind shear. These changes are underway, drawing the fisheries southward along the coast [54].

4. Summarizing Discussion

This exploration of environmental influences on red tide initially considered a wide variety of spatial and temporal scales and satellite proxies. Following statistical tests, the 8-day fluorescence line height averaged 34–31.5°S, 17.5–18.5°E appeared to be the best indicator and yields the most in situ confirmations. Local ship and aerial surveys have found that red tides form in ~5 × 20 km patches and accumulate over a few days [14–16], mainly in February to April season. Efforts to detect and predict red tides have focused on local observations and nested models over multiday events. Here, 30–50 km monthly reanalysis fields have identified the key environmental forcing. The large scale weather is comprised of ridging anticyclone and west coast trough which generates sustained easterly winds over the Cape Peninsula and cold upwelling plumes that extend >100 km seaward (Figures 3(b) and 4(a)–4(c)). As the weather evolves into a quiescent phase, there is poleward Ekman transport and inshore warming. The composite SLP anomaly south of Cape Town reaches +9 mb during high FLH cases. The climate “envelope” contains repeated red tide weather events (compare Figures 5(b) and 9(e)) involving a retreat of the circumpolar westerlies and an atmospheric ridge south of Cape Town (Figure 9(d)). These features can be forecast by global models at seasonal lead times.

The windward cape-leeward bay geography creates upwelling shadows where increased residence time builds phytoplankton biomass and harmful dinoflagellate blooms [55–59]. Alongshore winds and currents accelerated by the cape sweep clockwise into the leeward bay (Figure 3(f)). The upwelling shadow promotes onshore poleward currents (Figure 8(c)) and thermal stability (Figures 8(a) and 8(b)) which transports and concentrates red tides near the coast. As they dissipate and decay, anoxic water stresses the marine life. The economic consequences of red tides could be mitigated through improved forecasts of its environmental forcing as outlined here. Further progress can be made by employing higher resolution daily products such as the 8 km HYCOM-NCODA model assimilation from <http://apdrc.soest.hawaii.edu/las8>.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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