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Regime-shifts in the southern Benguela shelf and inshore region

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ABSTRACT

Over the past two decades, several species have undergone distributional shifts in the southern Benguela. The commercially-important West Coast rock lobster *Jasus lalandii* is one of these, and its shift in distribution has had profound effects on the rest of the ecosystem along the south-west coast. Reasons for these shifts are not fully understood, but are probably linked to changes in environmental conditions. We applied a sequential *t*-test algorithm for analyzing regime shifts (STARS) to physical (wind and upwelling) and biological (rock-lobster catch and growth, Bank Cormorant abundance) data for the southern Benguela inshore region and performed sensitivity tests on each of the variables. Regime shifts were defined as 'robust' or 'possible' if they were detected for ⩾70% or ⩾60% of the sensitivity tests respectively. To corroborate the shifts detected by STARS, we then applied two additional methods: change point analysis and the Chow breakpoint test. The STARS method outperformed the other two methods because it could handle shorter time series and detect shifts towards the end of the time series, but most of the significant shifts detected by STARS were also detected by one or both of the other methods. A significant shift in Cape Point winter winds occurred in 1983, an El Niño year. However, measurement methodology changed during the same period and this is discussed in relation to the shift. A decline in rock-lobster growth rate occurred in the mid 1980s, and significant increases in upwelling variability and mean summer winds were detected in the early-to-mid 1990s – the same period in which rock lobster abundance underwent an eastward shift, declining on the west coast and increasing on the south-west coast. Bank Cormorants underwent respective declines and increases in the mid-to-late 1990s on the west and south-west coasts following the shift in lobsters. Further shifts in mean wind and upwelling were detected in the 2000s. These results are a step towards developing ecosystem indicators for the region, which can be monitored with the intended use of providing an early warning system for long-term, ecosystem-scale changes.

1. Introduction

Over the past two decades regime shifts have become a major component of marine research, largely because time series data have been collected for sufficient duration to allow identification of such shifts (deYoung et al., 2004). Whilst various definitions of a regime shift exist, we define it here as a sudden shift from one relatively stable ecosystem state to another, whereby various trophic levels are affected and the time-frame for the change to occur is relatively short in comparison with the contrasting regimes (deYoung et al., 2004; Cury and Shannon, 2004; Jarre et al., 2006). Regime shifts in marine ecosystems are often thought to be driven mainly by abiotic processes – e.g. changes in ocean and atmospheric climates (Polovina, 2005), although other key drivers include biotic processes, changes in structural habitat and fishing (e.g. Scheffer and Carpenter, 2003; Daskalov et al., 2007). All of these drivers can be either natural, anthropogenic or a combination of both (deYoung et al., 2008). Regime shifts have been reported in marine ecosystems worldwide (e.g. Francis and Hare, 1994; Anderson and Piatt, 1999; McGowan et al., 2003; Cury and Shannon, 2004; Alheit and Ñiquen, 2004) and various statistical techniques have been developed to try and identify them (e.g. Easterling and Peterson, 1995; Lanzante, 1996; Perreault et al., 2000; Elsner et al., 2000; Lund and Reeves, 2002; Ducré-Robitaille et al., 2003; Mauget, 2003; Rodionov, 2004), and by using several techniques, the robustness of detecting a shift is strengthened (Mantua, 2004). Some well known examples of regime shifts that have been tested using statistical techniques include the North Pacific (Hare and Mantua, 2000), North Sea (Beaugrand, 2004) and Bering Sea (Rodionov and Overland, 2005).

The detection of regime shifts, along with the development of models and ecosystem indicators, help to quantify ecosystem states. Indicators are defined as variables or indices that provide

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information on (i) the state of an ecosystem, (ii) the extent and intensity of exploitation within an ecosystem and (iii) ecosystem management progress in relation to specified objectives (Garcia et al., 2000; Jennings, 2005). Fisheries scientists have developed numerous ecosystem indicators (e.g. Shin et al., 2005; Cury et al., 2005; Vandermeulen, 1998; Rochet and Trenkel, 2003; Shin and Shannon, 2010; Shin et al., 2010) and frameworks for their selection and evaluation are already in place internationally (Livingston et al., 2005; Rice and Rochet, 2005; Rochet and Rice, 2005; Piet et al., 2008) and under development for the Benguela (Shannon et al., 2010). In the Benguela region, the detection of regime shifts and development of ecosystem indicators has largely been limited to the offshore pelagic and demersal fisheries and associated offshore ecosystems (e.g. Shannon and Cury, 2003; Drapeau et al., 2004; Moloney et al., 2005; Howard et al., 2007), including possible implications for fisheries management (King and MacFarlane, 2006; Smith and Jarre, 2011).

The southern Benguela upwelling system supports a wide variety of commercially-exploited fish species and, like all upwelling systems, exhibits substantial variability in both oceanographic and biological components. Over the past two decades, a number of these species have undergone distributional shifts. In the offshore ecosystem, the distribution of two important pelagic species – the Sardine *Sardinops sagax* and Anchovy *Engraulis encrasicolis* – underwent an eastward shift during the late 1990s (van der Lingen et al., 2002; Fairweather et al., 2006b). The implications of this shift are significant – both socio-economically (Fairweather et al., 2006a) and ecologically (e.g. Crawford et al., 2008b, 2008c). Roy et al. (2007) linked the eastward shift in anchovy spawners to a cooling of waters along the inner shelf of the Agulhas bank on the south coast, east of Cape Agulhas. Similarly, Rouault et al. (2009, 2010) report cooling of inshore waters along the south coast since the 1980s and Howard et al. (2007) identified two major ecosystem changes in the southern Benguela offshore system, one of which occurred due to environmental forcing, during the late 1990s/early 2000s.

Distributional shifts have also taken place in the benthic inshore coastal zone (defined here as approximately 0–100 m depth). The West Coast rock lobster *Jasus lalandii*, one of South Africa's most economically important marine species, occurs from approximately Walvis Bay in Namibia (23°S) down to Port St John's in the Eastern Cape, South Africa (31°S) (Heydorn, 1969). However, the South African commercial rock-lobster fishery, which dates back to the late 19th century (Melville-Smith and van Sittert, 2005), has historically been based on the west coast where lobster population densities were greatest (Heydorn, 1969). A significant decline in commercial lobster catch occurred during the mid-1960s, most likely due to a combination of overfishing and changes in ecosystem productivity (Melville-Smith and van Sittert, 2005). During the 1980s lobster catches stabilized, but declined further in the early 1990s, linked to a decline in somatic growth rates (Melville-Smith and van Sittert, 2005), and exacerbated by increased lobster-walkouts (Cockcroft, 2001).

While *J. lalandii* was decreasing along the west coast during the late 1980s/early 1990s, a substantial increase in their abundance took place along the south-west coast in an area known as 'East of Cape Hangklip' (or 'EOCH') (Cockcroft et al., 2008), with serious consequences for the rest of the ecosystem (Mayfield and Branch, 2000; Blamey et al., 2010, in press; Blamey and Branch, 2012). Other inshore species have also shifted eastwards: kelp beds comprising mostly *Ecklonia maxima* have increased in the north-western region of False Bay since the 1980s (Mead, 2011; Griffiths and Mead, 2011) and kelp biomass has increased at least sevenfold EOCH (Blamey et al., 2010). More recently, a population of *E. maxima* was recorded for the first time *ca.* 60 km *east* of Cape Agulhas at De Hoop Nature Reserve in 2008 (Bolton et al., 2012). The intertidal warm-water Brown mussel *Perna perna* has also shifted, undergoing a range retraction along the south-west coast (Mead, 2011; Griffiths and Mead, 2011).

In this paper, we collate physical and biological data for the southern Benguela inshore region and apply a suite of statistical techniques with the aim of detecting possible regime shifts. Firstly, we use a sequential *t*-test algorithm for analyzing regime shifts (STARS) that was developed by Rodionov (2004) for the Pacific Decadal Oscillation and North Pacific ecosystems and since applied in other marine ecosystems (Rodionov and Overland, 2005; Litzow, 2006; Howard et al., 2007; Atkinson, 2010). Secondly, we apply two additional statistical methods to these data in an attempt to corroborate the shifts identified by STARS. Lastly, we relate identified shifts back to the biology of the southern Benguela inshore system.

2. Methods

2.1. Data

Four sets of oceanographic data and three sets of biological data were analysed using three different methods: (1) the sequential *t*-test algorithm for analyzing regime shifts (STARS), (2) change point analysis and (3) the Chow breakpoint test. Howard et al. (2007) have applied the STARS method to two of these data sets (upwelling and sea surface temperature anomalies). In our study, we analyse the remaining five data sets using STARS, and then apply the additional methods to all seven data sets.

2.1.1. Cape Point wind runs

Wind data at Cape Point (Fig. 1) for 1960–2010 are presented in the form of North/South and East/West wind runs for winter (April–September) and summer (October–March). Wind runs are the monthly accumulation of the wind speed, multiplied by the duration of the wind. This provides an index that better reflects the effect of the wind on the marine environment, rather than wind speed alone.

2.1.2. Wind anomalies

Based on the wind data from Cape Point, monthly wind deviations were calculated by subtracting the long-term (1960–2010) monthly mean from the mean monthly windrun. These monthly wind deviations were then summed from October year y to September year $y + 1$, to give an annual North/South and East/West total wind deviation.

2.1.3. Upwelling indices based on geostrophic winds

Monthly upwelling indices ($\mathrm{cm\,day^{-1}}$) representing coastal upwelling are provided for Hondeklip Bay, Cape Columbine, Cape Point, Cape Hangklip and Cape Agulhas (Fig. 1) for the period 1981–2010. These indices were calculated using geostrophic wind data, derived from monthly sea level pressure (according to Ekman's theory for wind-induced mass transport). Calculations were performed online at http://las.pfeg.noaa.gov/las6_5/servlets/dataset. Geostrophic time series extend further back in time than Scatterometer-derived wind data and Agenbag (2011) demonstrate good correlation between geostrophic and scatterometer winds for the region, so we used upwelling indices based only on the geostrophic data. Analyses were performed on both monthly and mean annual summer (October–March) upwelling, as summer is where upwelling in concentrated (Nelson and Hutchings, 1983).

2.1.4. Upwelling and inshore sea surface temperature (SST) anomalies at 30°S and 32°S

Upwelling and inshore sea surface temperature (SST) anomalies spanning the period 1910–2006 for the south-west and west coasts

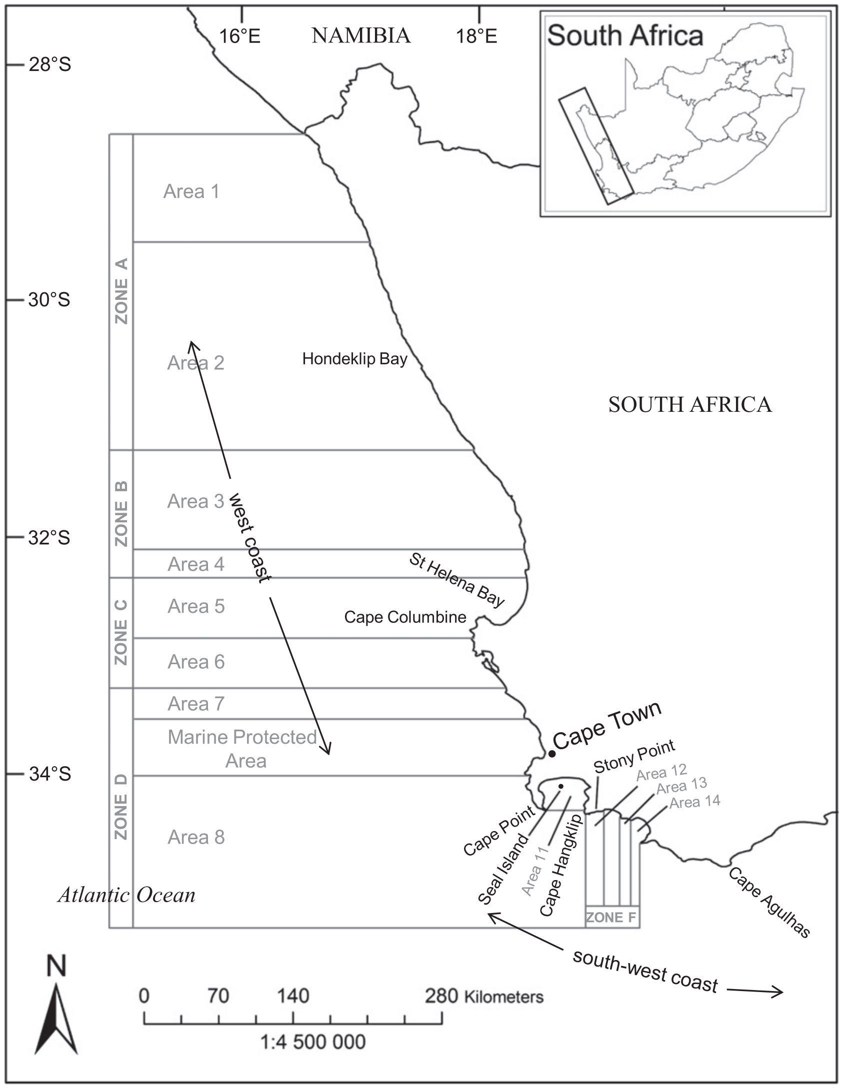

Fig. 1. Map of the southern Benguela region showing sites where data were collected along the west and south-west coasts and the West Coast rock lobster fishing zones A–D, F and areas 1–8 and 11–14.

of South Africa were extracted from the extended reconstruction of SST data set (Smith and Reynolds, 2004), and were processed and made available by Dr. Claude Roy (Institut de Recherche pour le Développement, France). Only the summer data were used: further details appear in Howard et al. (2007).

2.1.5. Lobster commercial catch data

The West Coast rock lobster fishing grounds are divided into fishing zones and areas (Fig. 1), for which a zonal Total Allowable Catch (TAC) is calculated based on the total TAC which is set using an Operational Management Procedure (Johnston and Butterworth, 2005). Commercial catch data exist for 1910–2008. However, only data for 1978–2008 were analysed for the following reasons: (1) Catch methods and equipment have evolved over the 20th century, so catches over the entire time period are likely incomparable; (2) even though catch methods have continued to evolve since 1978, the major gear change occurred in the 1960s when winch-hauled traps replaced hand-hauled hoopnets (Schoeman et al., 2002), (3) the period analysed is comparable to that for which Bank Cormorant *Phalacrocorax neglectus* data are available (1978–2006); and (4) we were particularly interested in biological shifts in the southern Benguela inshore system that are known to have occurred between 1980 and 2010.

A commercial fishery recently developed on the south-west coast (East of Cape Hangklip), but the time series for the catch data there is too brief for including so catch data solely from Area 8 (Fig. 1) have been used as a proxy for this area. Catch data representing the west coast comprise data from fishing Areas 3–6 (Fig. 1). Analyses were carried out on catch data that were expressed as a percentage contribution of the west and south-west coasts to the total rock lobster catch, in line with Fig. 2 in Cockcroft et al. (2008).

2.1.6. Lobster growth rates

Somatic growth-rate estimates (1968–2009) for pre-moult 70 mm carapace length (CL) male rock lobsters were calculated using a moult probability model and tag-recapture data for the period 1978–2008 (Department of Agriculture, Forestry and Fisheries, unpublished data). Growth rates representing the south-west coast are from Areas 8–14 and those representing the west coast are an average of Areas 3–4 and Areas 5–6 (Fig. 1).

2.1.7. Bank Cormorant breeding pairs

Jasus lalandii is an important prey item to the Bank Cormorant *P. neglectus* (Hockey et al., 2005) and trends in *P. neglectus* breeding pairs are consistent with the eastward shift in rock lobster

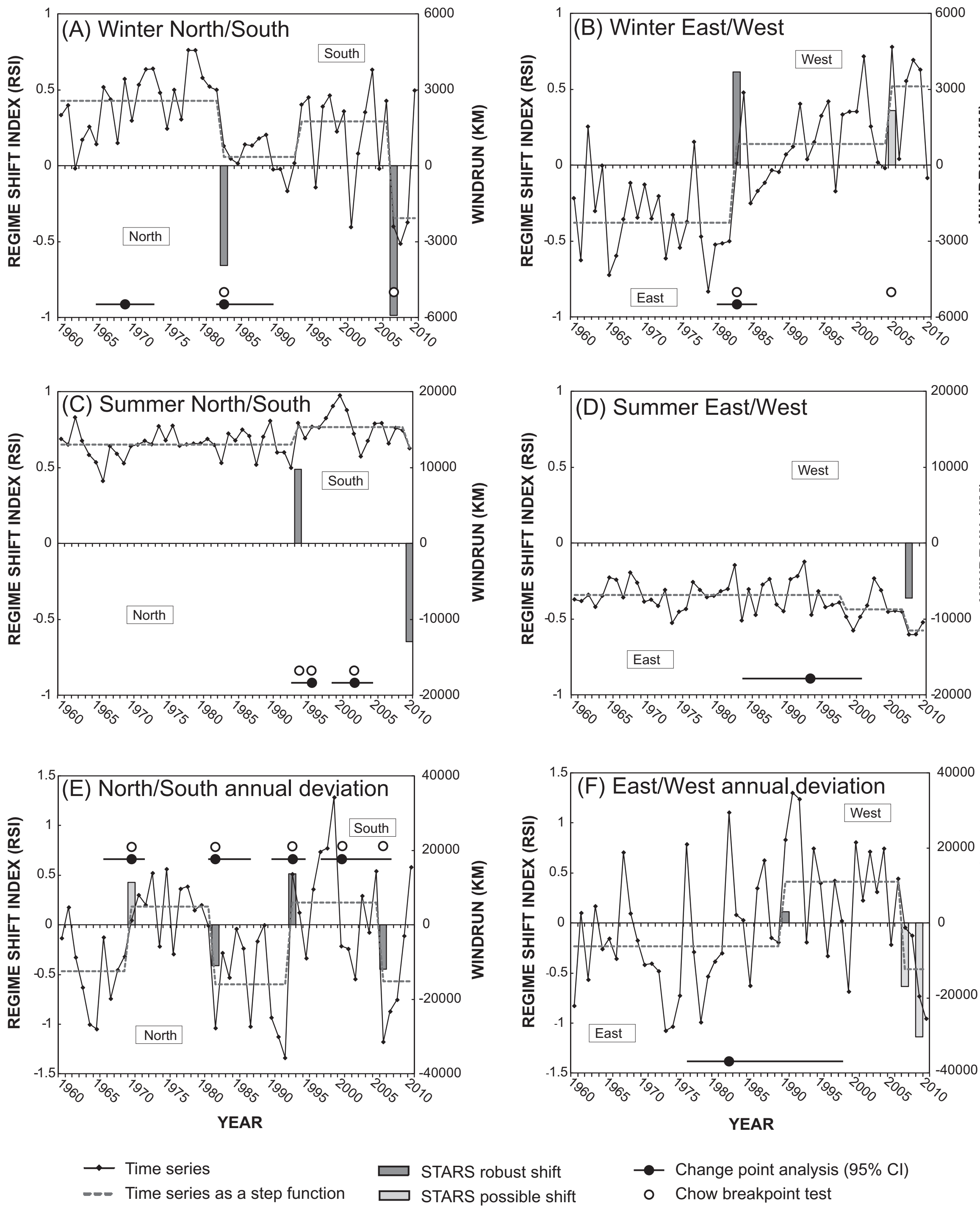

Fig. 2. STARS analyses for the Cape Point windruns: (A) mean winter North/South, (B) mean winter East/West, (C) mean summer North/South and (D) mean summer East/West; and for the (E) North/South and (F) East/West annual deviations (a summation of the monthly annual windruns minus the monthly long-term mean). The time series and weighted mean windrun are shown by the black solid and grey broken lines respectively; the magnitude of the regime shift (RSI) is shown by the grey bars, distinguished as either robust or possible; and the change point analysis (±95% confidence intervals) and Chow test shifts are indicated by the solid and open circles respectively.

(Crawford et al., 2008a). Data on *P. neglectus* breeding pairs for 1978–2006 are taken from Crawford et al. (2008a). West coast data are from islands within lobster fishing Areas 3–6 and south-west coast data are from Seal Island and Stony Point (Fig. 1).

2.2. STARS analysis

Data were analysed using a sequential *t*-test algorithm for analyzing regime shifts (STARS), as detailed by Rodionov (2004) and summarized in Howard et al. (2007). STARS tests the null hypothesis (H_0: a regime shift does not exist) for each data observation. There are three possible outcomes to each test: (1) Reject H_0, (2) cannot reject H_0 or (3) continue with the test. The algorithm comprises seven steps, after which the test continues to loop through the remaining data, comparing each observation to the mean of the current regime using a Student's *t*-test. If the current observation is significantly different to the mean of the current regime, then the observation is marked as a possible shift. Further observations are tested in the same way, either confirming the change as a shift, or considering it an outlier.

2.2.1. Autocorrelation

Time series data often show serial correlation, and most methods used to detect regime shifts (including the STARS analysis) are unable to differentiate between an actual regime shift and a 'red noise' (autocorrelation) signal (Rudnick and Davis, 2003). The STARS method assumes independence of data points within the given time series (i.e. no autocorrelation). However, Rodionov (2006) developed a method called 'prewhitening', which removes potential autocorrelation from the data series prior to running a STARS analysis. Red noise is modelled by the first order autoregressive model (AR1) in which an estimate of AR1 is required. Two methods are available to estimate AR1: the MPK (Mariott-Pope and Kendall) method and the IP4 (Inverse Proportionality with 4 corrections) method, both of which are described in Rodionov (2006). The two methods produce very similar results and only in certain instances (small subsample size) does the IP4 method significantly outperform the MPK method (Rodionov, 2006). For this reason, the IP4 method was used in our analyses.

2.2.2. Shifts in the variance

A method for detecting shifts in variance has been developed, and is similar to that of the STARS analysis, except that it uses an *F*-test instead of a *t*-test. The method is still in an experimental phase (see Bering Climate website www.beringclimate.noaa.gov) but we employed it to assess variability in upwelling, and refer to it as the "Rodionov method".

2.2.3. Sensitivity analyses

Seventeen variables were analysed using the STARS analysis: North/South windrun (winter, summer and anomaly), East/West windrun (winter, summer and anomaly), mean annual upwelling (five sites), lobster commercial catch (west and south-west coasts), lobster growth rates (west and south-west coasts), and Bank Cormorant breeding pairs (west and south-west coasts). Variability was analysed using the Rodionov method and applied to upwelling only, as there was no pattern in the variability of other variables. Each variable was analysed using a 'straight' and 'prewhitened' method and sensitivity analyses were performed using eight different parameter inputs (Appendix 1 Tables A1–A11, A13–A18) for each of the variables, except upwelling variability which used six parameter inputs (Appendix 1 Table A12). Based on these sensitivity analyses, a regime shift was defined as 'robust' if it occurred in the same year for 70% of the parameter settings for 'straight' and 'prewhitened' analyses, or 'possible' if it occurred in the same year for at least 60% of the parameter settings.

Three parameters were tested for sensitivity and are defined below:

2.2.4. Cut-off length (l)

The minimum duration of a regime shift for which the magnitude of that regime shift remains intact is defined as the cut-off length (l, in years). An increase or decrease in *l* will respectively increase or decrease the time-scale of regimes to be detected. If regimes are longer than *l*, they will be detected. However, those that are shorter than *l* have a reduced probability of detection, but may still be detected as long as the shift is of sufficient magnitude (Rodionov, 2004).

Three different cut-off lengths ($l = 7$, $l = 10$ and $l = 13$) were used to test the sensitivity of results obtained from STARS analyses. Regime shifts are known to be associated with decadal-scale oceanic variability and so an initial cut-off length of 10 was chosen. In line with the study by Howard et al. (2007), cut-off lengths of 7 years and 13 years were chosen for sensitivity analyses. Equivalent cut-off lengths of $l = 84$, 120 and 156 months were chosen for the Rodionov method, which was applied to upwelling variability.

2.2.5. Huber weight parameter (H)

The Huber weight parameter treats outliers (values greater than *H* standard deviations) by controlling the weight assigned to them and can therefore affect the average value of the regime shift, as detailed in Huber (1964), Howard et al. (2007) and Overland et al. (2008), as well as the Bering Climate website www.beringclimate.noaa.gov. By default the Huber parameter is set at $H = 1$ and sensitivity analyses were performed using $H = 3$ and 6. The Huber parameter does not apply to the *F*-test analysis employed to detect a shift in variance.

2.2.6. Significance level (α)

The significance level (α) is the level at which the Student's *t*-test (or *F*-test in the case of variance) finds a significant difference between the mean values (or variances) of two regimes. The lower this level, the larger the magnitude of the regime shift necessary for its detection. Analyses were carried out using a significance level of 0.10 and then at 0.05 for sensitivity analyses.

2.3. Change point analysis

Changes in time series data can be detected using a combination of cumulative sum (CUSUM) charts and bootstrapping, and to apply this approach we employed Change Point Analysis software (Taylor, 2000).

Using the original data, the cumulative sums (S_i) were calculated by adding the difference between the current observed value x_i and the mean $\overline{X}$, to the previous cumulative sum S_{i-1} as follows:

$$S_i = S_{i-1} + (x_i - \overline{X}) \tag{1}$$

where the first cumulative sum $S_0 = 0$ and the mean $\overline{X} = \frac{\sum_{i=1}^{n}}{n}$.

These calculated cumulative sums were then plotted to construct a CUSUM chart. The difference (S_{diff}) between the largest and smallest cumulative sum was calculated:

$$S_{diff} = S_{max} - S_{min} \tag{2}$$

Random data sets of *n* data points were then generated from the original data by randomly re-ordering the *n* data points, and bootstrap CUSUM values S_0^0 *to* S_n^0 were calculated and plotted. For each bootstrap data set, the bootstrap difference (S_{diff}^0) was calculated using the largest and smallest bootstrap cumulative sums (see equation 2). The bootstrap difference (S_{diff}^0) was then compared to the original difference (S_{diff}).

The bootstrap samples represent random re-orderings of the data and mimic the original CUSUM chart if no change has occurred. By performing a large number of bootstraps, one can estimate how much S_{diff}^0 would vary if no change occurred. This was then compared to S_{diff} calculated from the original data which, should be consistent with that estimated by bootstrapping if no change occurred.

A 95% confidence level was required for a significant change to be detected and so a confidence level (expressed as a percentage) was calculated as follows:

$$Confidence\ level = 100 * \frac{X}{N} \tag{3}$$

where *X* is the number of times $S_{diff}^0 < S_{diff}$ *N* is the number of bootstraps.

Change point analysis required that the data have an independent error structure. This assumption was tested using the Change Point Analysis software prior to running the analysis and if violated, then the mean of consecutive pairs of data were used instead.

This analysis was applied to the same variables to which STARS was applied, as well as to the upwelling and SST anomalies that were analysed by Howard et al. (2007).

2.4. Autoregressive intergrated moving average (ARIMA) models and Chow breakpoint test

The use of modelling methods such as ARIMA allows decomposition of time series into their trend, seasonality and irregular component (Enders, 2004) and detection of structural breaks or changes in the mean of time series that may correspond with long-term changes in the marine ecosystem or regime shifts. This method has been used to identify when regime shifts have occurred in other marine ecosystems (Mantua, 2004; Francis and Hare, 1994; Farley and Quinn, 1998). Each variable's time series was modelled using autoregressive and moving average terms. An autoregressive model takes into account the observations preceding it. A moving average process can be explained as random events that produce an immediate effect that dissipates after a short period (Farley and Quinn, 1998). However there is often a lack of independence between successive observations in marine time series and this serial correlation violates the standard assumption of regression theory and must therefore be removed before ARIMA models can be fitted. The time series is said to be stationary when the autocorrelation is removed and non-stationary when it is present in the data. When the series is non-stationary, an integrated ARMA model is used. These are known as autoregressive integrated moving average models (ARIMA). This uses methods such as differencing and detrending to remove the autocorrelation from the series. Trends in variance can be removed by transforming the data whereas trends in the mean can be removed by taking successive differences of the data.

These ARIMA models consist of an *AR* term, a differencing term and an *MA* term, and are written as ARIMA (p, d, q) where p is the order of the *AR* term, d is the level of differencing used and q is the order of the *MA* term. There are several notations to describe them. Following Enders (2004), the autoregressive model of order p is defined as an $AR(p)$ term:

$$X_t = c + \sum_{i=1}^{p} \phi_i X_{t-i} + \varepsilon_t \tag{4}$$

where $\phi_i, \ldots, \phi_p$ are parameters of the model, c is a constant and $_t$ is an error term with zero mean and variance =σ^2.

The moving average model of order q is defined as a $MA(q)$ term:

$$X_t = \varepsilon_t + \sum_{i=1}^{q} \theta_i \varepsilon_{t-i} \tag{5}$$

where $\theta_i, \ldots, \theta_q$ are model parameters and ε_t, ε_{t-i} are error terms

Put together they form the mixed ARMA (p, q) model:

$$X_t = \varepsilon_t + \sum_{i=1}^{p} \phi_i X_{t-i} + \sum_{i=1}^{q} \theta_i \varepsilon_{t-i} \tag{6}$$

The ARMA model is altered for an ARIMA model:

$$(1 - \sum_{i=1}^{p} \phi_i L^i)(1 - L)^d X_t = (1 + \sum_{i=1}^{q} \theta_i L^i)\varepsilon_t \tag{7}$$

where d is a positive integer that controls the level of differencing. The differencing factor removes the unit root from a series, resulting in a stationary process. For a full account of ARIMA modelling theory see Enders (2004).

2.4.1. Model development

Box and Jenkins (1976) developed a three-step process for applying ARIMA models to time series data, which we employed in our analysis using the EViews 7.0 software.

The first step involves model identification; it is determined whether there is a need to transform the data or to use differencing to render the time series stationary. The augmented Dickey Fuller test was used to detect for the presence of a unit root, which indicates a trend in the mean of the time series (Enders, 2004). If a unit root was present, then successive differences of the data were taken until the series was stationary. Plots of the autocorrelation and partial autocorrelation were then examined to determine the order of *AR* and *MA* components to be fitted.

The second step requires estimating parameters for the possible models selected. This is carried out by the software using a non-linear estimation procedure. Standard errors are computed and any parameter that is not significantly different from zero is discarded and the estimation repeated.

The third step is model diagnostic checking, which involves assessing the adequacy and assumptions of the model fit. There are several criteria that need to be met for a model to be selected. The residuals must form a white noise series, i.e., no further correlation within the residuals after the model is fitted. Examination of the diagnostic correlograms and the Durbin–Watson test statistic were used to test for the presence of autocorrelation. The adjusted R^2 value, which indicates the amount of variance accounted for by the model, should be as close to one as possible. In model selection there is a trade-off between reducing the sum of squares of residuals, which can be reduced by including a greater number of parameters, or having a parsimonious model with few parameters as this keeps the degrees of freedom larger and requires fewer parameters to be estimated. The Akaike Information Criterion (*AIC*) and Bayesian Information Criterion (*BIC*) values are used to find the balance in this trade off. As the fit of the model improves, both *AIC* and *BIC* values will approach $-\infty$. Therefore the *AIC* and *BIC* values should be as low as possible. A bias corrected *AIC* term was found by Wong and Li (1998) to outperform *AIC* and *BIC* for small sample sizes in fitting ARMA models. Therefore the *AIC* term was corrected for small samples where appropriate and the model with the smallest AIC_c term was the model chosen.

$$AIC_c = AIC + \frac{2k(k+1)}{n-k-1} \tag{8}$$

where k is the number of parameters in the model and n is sample size.

2.4.2. Breakpoint detection

To identify break points or shifts in the time series, the Chow breakpoint test was used. This test requires an *a priori* hypothesis of a year or years when shifts may have occurred. The dates when shifts were detected by the STARS and change point analyses were used as these *a priori* dates. The time series is divided into two or more subsamples (depending on the number of breaks entered) and an equation fitted to each subsample. The test then detects if there are significant differences between the estimated equations. The Chow test compares the sum of squared residuals obtained by fitting a single equation to the entire sample with the sum of squared residuals obtained when separate equations are fitted to each subsample of the data. Small sample sizes can affect the efficacy of this test and often make it difficult to verify breaks. However, based on the data available, breaks found in the STARS and change point analyses were compared to those detected with this method.

3. Results

We analysed oceanographic and biological data using three different methods: (1) STARS, (2) change point analysis and (3) the Chow breakpoint test. Results from these analyses are presented below, while those detailing sensitivity analyses for the STARS method are given in Appendix 1 Tables A1–A18 and the

ARMA/ARIMA model selection results (required for the application of the Chow test) are given in Appendix 2 Tables A1–A3.

3.1. Cape Point windruns

Cape Point windrun data showed a steady increase in winter southerly winds during the 1960s and 1970s, followed by a significant decline during the 1980s (Fig. 2A). After 1992, winds fluctuated between the south and north. STARS analyses detected regime shifts in the winter North/South wind runs for 1983, 1994, 2005 and 2007 at the 10% significance level and in 1983 and 2007 at the 5% significance level (Appendix 1 Table A1). However, only the 1983 and 2007 shifts were robust, with the former also being detected by the change point analysis and the Chow test and the latter by the Chow test (Fig. 2A). The change point analysis also detected a shift in 1969, but neither of the other methods confirmed this (Fig. 2A). The East/West wind component was dominated by easterlies up until the early 1980s, after which they became predominantly westerlies (Fig. 2B). A robust regime shift in the winter East/West wind run was detected by STARS in 1983 at both the 10% and 5% significance levels, for both straight and prewhitened data and other sensitivity tests, and a possible shift was detected in 2005 (Fig. 2B, Appendix 1 Table A2). The shift in 1983 was also detected using the change point analysis (with reasonable confidence intervals) and the Chow test, but the shift in 2005 was only detected by one of the two other methods (Chow test) and only when tested with 1983 (Fig. 2B, Appendix 2 Table A3). All three methods indicated increased north-westerly winds in the early 1980s and two out of three methods suggested a further increase in these winds in the 2000s.

Summer months were dominated by southerly and easterly winds during 1960–2010, with both these winds showing an increase from the late 1980s/early 1990s (Fig. 2C and D). All three methods detected increased summer southerly winds during the mid 1990s, with STARS detecting a robust shift in 1994, the change point analysis in 1996 and the Chow test in both 1994 and 1996 (Fig. 2C, Appendix 1 Table A3). Only the change point analysis and Chow test detected a negative shift in southerly winds in the early 2000s, while STARS detected this in 2010 (Fig. 2C, Appendix 1 Table A3). However, 2010 was the end year and indications of shifts at the end of a time series are likely to be unreliable. In contrast, shifts in East/West summer winds were not very convincing: the STARS and change point analysis detected vastly different shifts (2008 vs. 1994) and the Chow breakpoint test did not detect any shifts (Fig. 2D).

3.2. Wind anomalies

During the 1960s, there was a northerly annual deviation in winds, changing to more of a southerly anomaly during the 1970s and back to a substantial northerly anomaly in the 1980s and early 1990s (Fig. 2E). This then fluctuated in the late-1990s and 2000s. East/West annual deviation data show that up until the mid-to-late 1980s, there were predominantly more easterly anomalies. However, from the late-1980s onwards, this changed to predominantly westerly wind anomalies (Fig. 2F).

Regime shifts in the North/South deviation were detected for 1970, 1982, 1993, 2006 and 2010 at the 10% significance level (Appendix 1 Table A5), of which 1982, 1993 and 2006 were robust to sensitivity analyses (straight analyses only) and 1970 was marked a possible shift (Fig. 2E, Appendix 1 Table A5). The shifts in 1970, 1982 and 1993 were also detected using the change point analysis and Chow test, and the 2006 shift was detected using the Chow test but not the change point analysis (Fig. 2E, Appendix 2 Table A3). Regime shifts in the East/West deviation were detected for 1982, 1986, 1990, 2007, 2008 and 2009. The shift in 1990 was considered robust at both significant levels but only using prewhitened analyses (Appendix 1 Table A6). The shifts in 2007 (prewhitened) and 2009 (straight) were considered possible shifts (Appendix 1 Table A6, Fig. 2F). However, none of these shifts were detected by the other two methods. The change point analysis detected a shift only in 1983 (with extremely wide confidence intervals) and the Chow breakpoint test failed to detect any shifts (Fig. 2F, Appendix 2 Table A3).

3.3. Upwelling indices based on geostrophic winds

Annual summer upwelling rates (cm day^{-1}) for the period 1981–2010 were obtained from geostrophic wind data for five sites along the west and south-west coasts. Mean annual upwelling appeared to decrease in the early 1980s, however this was detected only at Cape Columbine and Cape Hangklip, and only with the change point analysis (Fig. 3). A positive shift in upwelling was detected in the mid-to-late 1990s at all sites except Hondeklip Bay, suggesting an increase in mean upwelling during this period. All three methods detected this shift at Cape Point and Cape Hangklip, and two of the three methods at Cape Columbine and Cape Agulhas (Fig. 3A–E, Appendix 1 Tables A7–A11). Although Hondeklip Bay appeared to be an oddity, the change point analysis and Chow test did detect an increase in mean upwelling in the early 1990s, but STARS failed to detect any such increase (Fig. 3A). A negative shift in mean upwelling was then detected in the early 2000s for all sites using at least two of the three methods (Fig. 3A–E). Cape Agulhas was the only site where this shift was detected using all three methods, and for which the STARS shift was robust (Fig. 3E).

Monthly upwelling rates (cm day^{-1}) at all five sites were relatively constant during the 1980s, becoming increasingly variable in the 1990s and early 2000s (Fig. 4A–E). This signal was delayed at Cape Point (Fig. 4C), only showing an increase in upwelling and variability in the mid-to-late 1990s. Following the Rodionov method, either a robust or possible significant shift in upwelling variation was found in the late 1980s/early 1990s for all sites (Fig. 4A–E, Appendix 1 Table A12), except for Cape Point which only showed a robust significant increase in upwelling variability in 1995 (Fig. 4C). A second, also positive, shift in upwelling variability was detected at all sites post-2000 (except at Cape Point): Hondeklip Bay in 2001, Cape Hangklip and Cape Agulhas in 2007 and Cape Columbine in 2009.

It therefore appears that upwelling increased on the south-west coast in the early-to-mid 1990s, along with increased variability. Upwelling variability increased again on the south-west coast during the second half of the 2000s, although around a slightly reduced mean, which nevertheless, was still greater than in the period before the mid-1990s. The results for mean upwelling on the west coast are inconclusive, but increased upwelling is indicated both for Hondeklip Bay and Cape Columbine since 2005, under continued high variability.

3.4. Upwelling anomalies at 30°S and 32°S

Howard et al. (2007) applied STARS to upwelling data from 30°S and 32°S, to which we then applied the change point analysis and Chow test. Using the STARS method, Howard et al. (2007) detected possible shifts in the 30°S upwelling data during the 1950s, 1990s and 2000s. However, in our analyses, both the change point analysis and Chow test failed to detect any of these shifts, and instead detected a significant break in 1922. However, associated confidence intervals and *p*-values placed little confidence in this break (Table 1). In the 32°S data, STARS detected a robust negative shift in the early 1970s and possible shifts in the 1960s and early-to-mid 2000s. Of these, the 1970s shift was also detected using the other two methods and the 1960s shift using the Chow test only (Table 1).

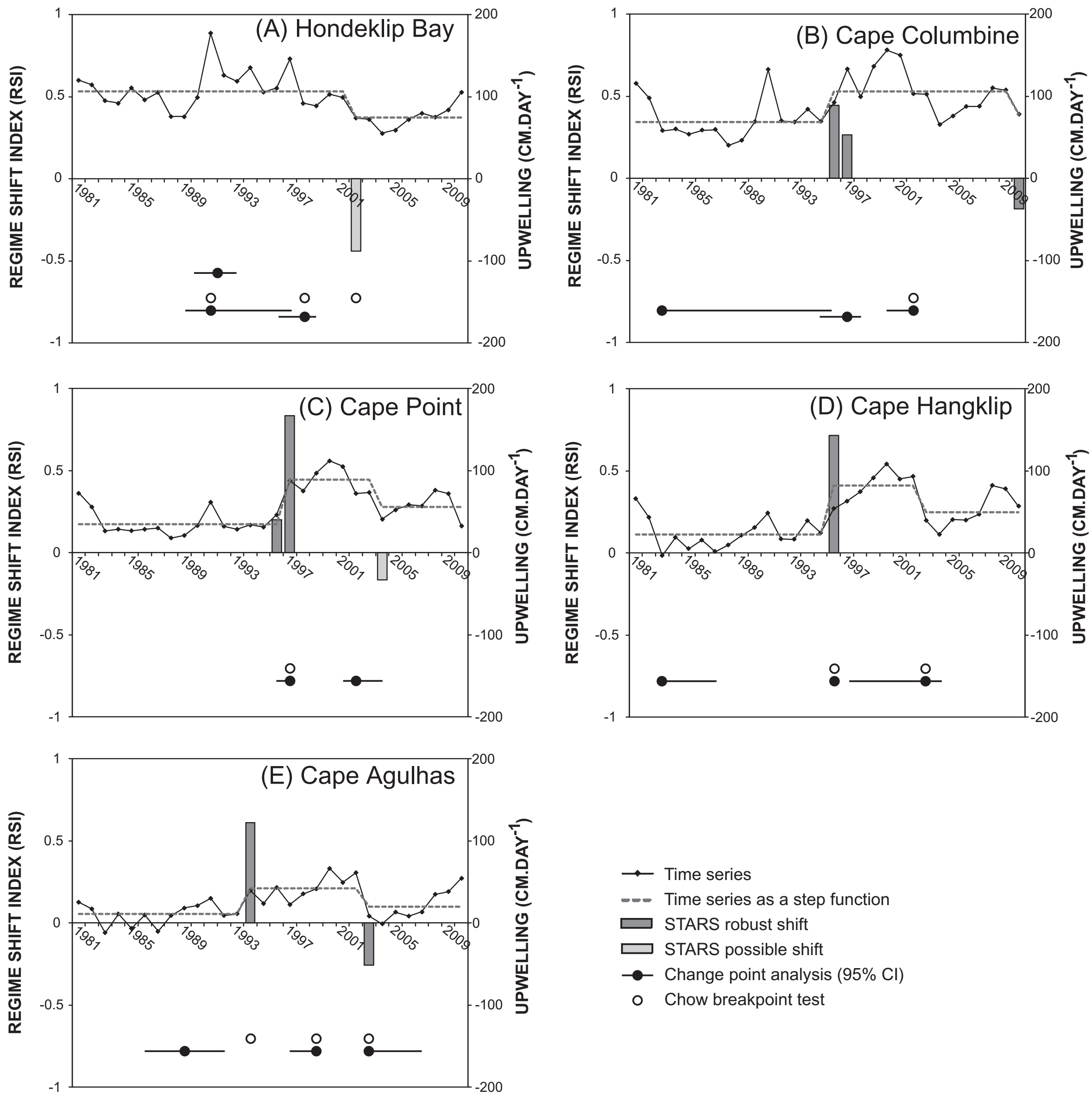

Fig. 3. STARS analyses for mean annual summer upwelling for (A) Hondeklip Bay, (B) Cape Columbine, (C) Cape Point, (D) Cape Hangklip and (E) Cape Agulhas. The time series and weighted mean upwelling are shown by the black solid and grey broken lines respectively; the magnitude of the regime shift (RSI) is shown by the grey bars, distinguished as either robust or possible; and the change point analysis (±95% confidence intervals) and Chow test shifts are indicated by the solid and open circles respectively.

3.5. Inshore SST anomalies at 30°S and 32°S

Inshore SST data from 30°S and 32°S were analysed by Howard et al. (2007) using STARS. We applied the change point analysis and Chow test and found that all three methods detected an increase in SST at 30°S in the late 1956/57 and in 1991/92, and two of the methods detected shifts in the early 1970s and mid 1980s (Table 1). The 32°S data showed a significant increase in SST during the mid 1950s (detected by all three methods) and in the early 2000s (detected by two of the methods) (Table 1).

3.6. Lobster commercial catch

In the late 1970s/early 1980s, approximately 60% of the total rock-lobster commercial catch came from Areas 3–6 on the west coast. This declined to less than 10% in the 2000s, with a substantial decline occurring in the late 1980s and again in the mid-to-late 1990s (Fig. 5A). The percentage contribution of the south-west coast (Area 8) to the overall lobster catch (Areas 1–8) remained below 20% until the late 1980s, but by 2008 this had increased to over 60% (Fig. 5B). STARS analyses detected a negative shift in the percentage contribution of lobster catch for the west coast in 1989, and this shift was considered robust under straight analyses and possible under prewhitened analyses (Fig. 5A, Appendix 1 Table A13). A further negative shift was detected in the mid-1990s but was not considered possible or robust. The change point analysis did not detect a shift in the late 1980s, but did detect a decline in catch contribution in 1994. The Chow test detected declines in both 1989 and 1994 (Fig. 5A). On the south-west coast, all three methods detected a positive shift in lobster catch contribution in 1990, and two of the three methods detected a further positive shift in 2006 (Fig. 5B, Appendix 1 Table A14).

3.7. Lobster growth rate

Estimated somatic growth rates were slightly greater for rock lobsters on the west coast than those on the south-west coast, but both followed the same declining trend (Fig. 5C and D). All

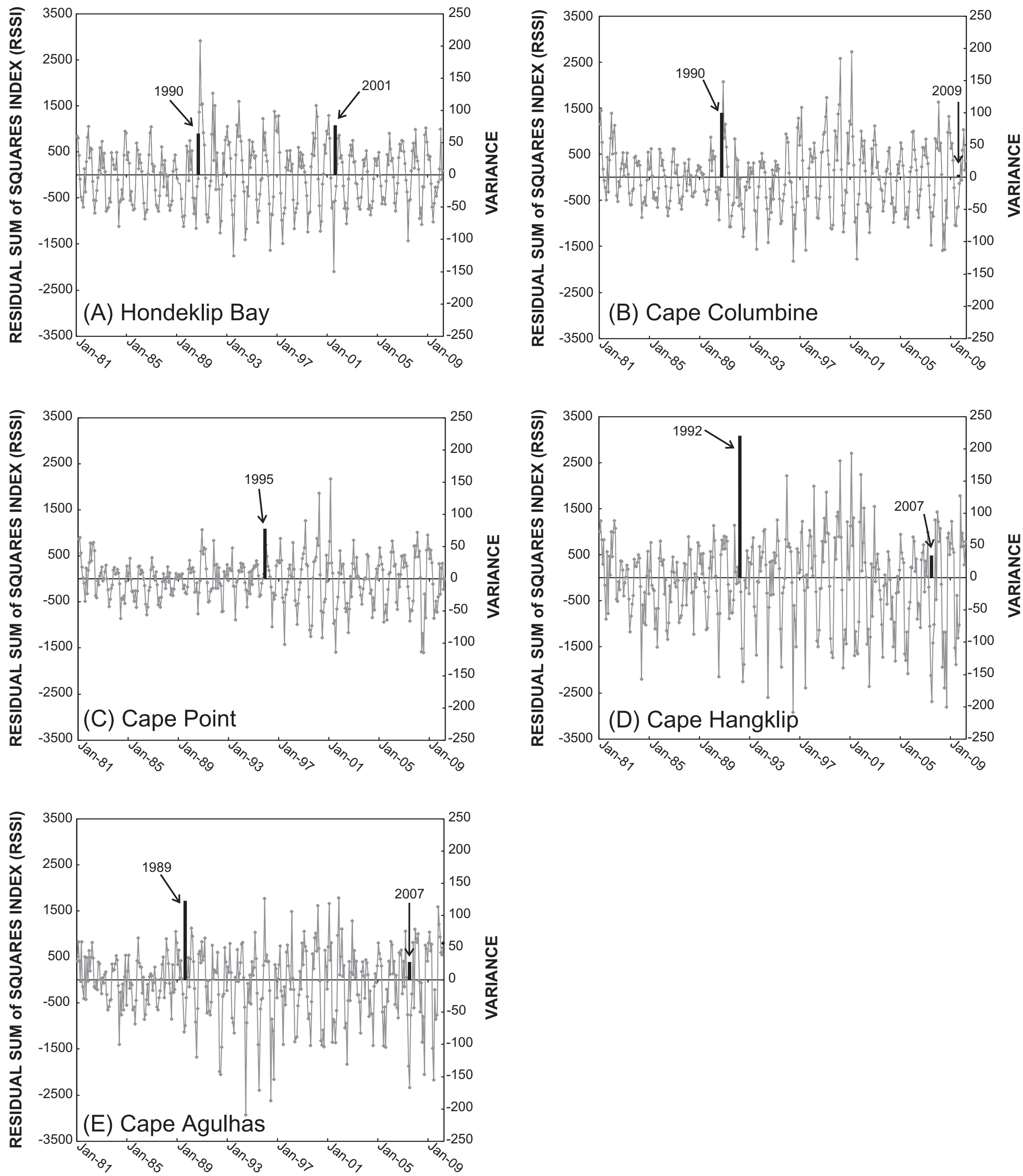

Fig. 4. Rodionov method (*F*-test) showing the variation in upwelling cycles (grey line) for the period 1981–2010, and the magnitude of the regime shift in the variance (RSSI, black bars) for (A) Hondeklip Bay, (B) Cape Columbine, (C) Cape Point, (D) Cape Hangklip and (E) Cape Agulhas.

three methods detected a negative shift in the mid 1970s for both the west and south-west coasts (Fig. 5C and D). However, this shift was not considered significant (possible/robust) by STARS. A further negative shift was detected by all three methods in 1986 for both coasts, but was only considered 'possible' by STARS as only 65% of the sensitivity tests detected this shift (Fig. 5C and D, Appendix 1 Tables A15–A16).

3.8. Bank Cormorant breeding pairs

On the west coast, the number of Bank Cormorant breeding pairs fluctuated between the late 1970s and mid-1990s, always remaining at or above 200. However, from the mid-1990s onwards, their numbers declined and in 2006 only 85 pairs were recorded (Fig. 5E). During the period in which breeding pairs on the west coast were declining, they began increasing on the south-west coast (Fig. 5F). STARS and the change point analysis detected a negative shift in breeding pairs on the west coast in 1995 (Fig. 5E, Appendix 1 Table A17). A further negative shift was detected in the 2000s, with the change point analysis detecting this shift in 2003 and STARS in 2006. However the 2006 shift detected by STARS was not considered reliable as this was the end year of the breeding-pair time series. Positive robust shifts in breeding pairs on the south-west coast were identified in 1998 by all three methods and in 2002 by two of the three methods (Fig. 5F, Appendix 1 Table A18).

Table 1
Summary of the 'shifts' detected when applying (1) STARS, (2) change point analysis and (3) the Chow breakpoint test to upwelling and sea surface temperature at 30°S and 32°S. STARS analyses were performed by Howard et al. (2007). Only significant (robust/possible) shifts were reported.

Variable	Statistical Method			
	STARS		Change Point Analysis	Chow Breakpoint Test
	Robust shift	Possible shift	Change Point (*95% CI*)	Break (*F-statistic, p value*)
Upwelling 30°S	–	1951, 1956, 1991, 1998, 2004/2005	1922 *(1917, 1930)*	1922 *(2.5, 0.0494)*
Upwelling 32°S	1971/72	1964, 2000/2001, 2004/2005	1933 *(1920, 1968)*; 1973 *(1935, 1992)*	1964 *(11.6,<0.0001)*; 1971 *(6.9, 0.0017)*; 1973 *(5.7, 0.0045)*
SST 30°S	–	1956, 1971, 1985, 1991, 2004/2005	1912 *(1912, 1930)*; 1957 *(1938, 1965)*; 1992 *(1984, 1998)*	1956 *(4.5, 0.0140)*; 1957 *(6.5, 0.0023)*; 1971 *(3.8, 0.0253)*; 1985 *(4.1, 0.0198)*; 1991 *(4.9, 0.0099)*; 1992 *(7.0, 0.0015)*
SST 32°S	1956, 2000/2001	1950, 1991	1911 *(1911, 1911)*; 1957 *(1949, 1966)*	1956 *(5.6, 0.0126)*; 1957 *(5.9, 0.0040)*; 2000 *(3.2, 0.0451)*

3.9. STARS sensitivity analyses

The Huber parameter ($H = 1$, 3 and 6) had little or no effect on the detection of regime shifts. For this reason, this parameter was set at $H = 1$ in the results presented in this study. Cut-off lengths of $l = 7$, 10 and 13 years were tested and we found that in some instances a larger cut-off length resulted in less shifts being detected, but in general there was little effect on shift detection when changing the cut-off length. For this reason, we have only presented results using $l = 10$ years. Analyses were most sensitive to changes in the significance level, with more shifts generally being detected at the 10% level than at the 5% level. A detailed description of the sensitivity results can be found in Appendix 1.

4. Discussion

The sustainable management of fisheries is facilitated by a clear understanding of marine ecosystems and the abiotic, biotic and anthropogenic forces that act on them. Regime shift detection is an integral part of this, and over the years various methods have been developed to detect such shifts (see references in Introduction). The simultaneous application of several methods can help corroborate identified shifts (Mantua, 2004).

A number of species have undergone distributional shifts in the southern Benguela (Cockcroft et al., 2008; Crawford et al., 2008a; Fairweather et al., 2006b; Blamey et al., 2010) and although not fully understood, it is thought that these shifts are linked to changes in environmental conditions. In this study, we applied three statistical methods to environmental and biological data from the southern Benguela inshore region in an attempt to identify significant temporal shifts.

4.1. Statistical methods

The STARS method developed by Rodionov (2004) has a number of advantages over other regime shift detection methods: (1) It does not require an *a priori* hypothesis about the timing of the shifts; (2) it can process time series with multiple shifts; (3) it can detect both abrupt and gradual shifts, and (4) it can detect regime shifts towards the end of time series (Rodionov and Overland, 2005). A common problem with many methods used for regime shift detection is that they struggle to detect regime shifts towards the end of a time series. The STARS method has shown the ability to do this in both our analyses and others (Rodionov and Overland, 2005; Howard et al., 2007; Atkinson, 2010).

The Huber parameter had a negligible effect on the detection of regime shifts, as did the cut-off length – although a smaller cut-off length generally led to the detection of more shifts. The same was true for analyses carried out by Rodionov and Overland (2005) and Howard et al. (2007). The significance level had the greatest effect on regime-shift detection – particularly for the physical variables – where a significance level of 5% often resulted in fewer shift detections than at a 10% level. However, for the two biological variables, it had almost no effect.

Autocorrelation is problematic when analysing time series data. In the STARS method, the analysis of data using a prewhitened method enabled removal of the effect of autocorrelation. This however reduces the magnitude of the regime shifts detected (Rodionov, 2006). We found that the number of regime shifts detected under straight and prewhitened analyses were often similar, but there were cases when the prewhitening led to detection of fewer shifts, as was the case in Howard et al. (2007). Although the prewhitened method was capable of detecting regime shifts, the timing of these shifts was sometimes slightly different to those detected under straight analyses. In the ARMA method, the augmented Dickey Fuller test and diagnostic correlograms reported an absence of autocorrelation in the Cape Point wind data, and in the 30°S and 32°S upwelling and SST anomalies, suggesting that the 'straight' method may be sufficient when applying STARS to these data.

Both change point analysis and the Chow test (using ARMA/ARIMA models) have been developed to identify changes or 'breaks' in economic time-series data, in which data points are numerous. In particular, the fitting of ARMA models is effective for long time series and it is recommended that series with a minimum of 50 observations be used (Holden et al., 1990). Environmental and biological time series often have far fewer observations and many of the variables analysed in this study had 20–40 observations, with the exception of upwelling and SST anomalies at 30°S and 32°S. The Chow breakpoint test also lacks power with short time series. It also cannot detect shifts towards the end of time series because it requires that the number of observations be greater than the number of estimated parameters. Therefore, results using this method can merely give an indication of whether the shifts it detected are similar to those detected by other methods.

Mantua (2004) state that the type of method used in an analysis can influence the shift that is identified, and therefore it is advisable to use more than one type of method for shift detection. We used three different methods and found that a number of significant shifts detected using the STARS were also detected using at least one of the other methods, and in some cases both of the other methods (Figs. 2, 3 and 5), suggesting that STARS performed well and was reliable in many of the robust shifts it detected. It also performed better towards the end of the times series and could handle fewer observations. Consequently, our results suggest that the STARS method is superior to the other two methods.

4.2. Data limitations

Physical/environmental time-series data for the southern Benguela inshore region are inadequate, particularly along the

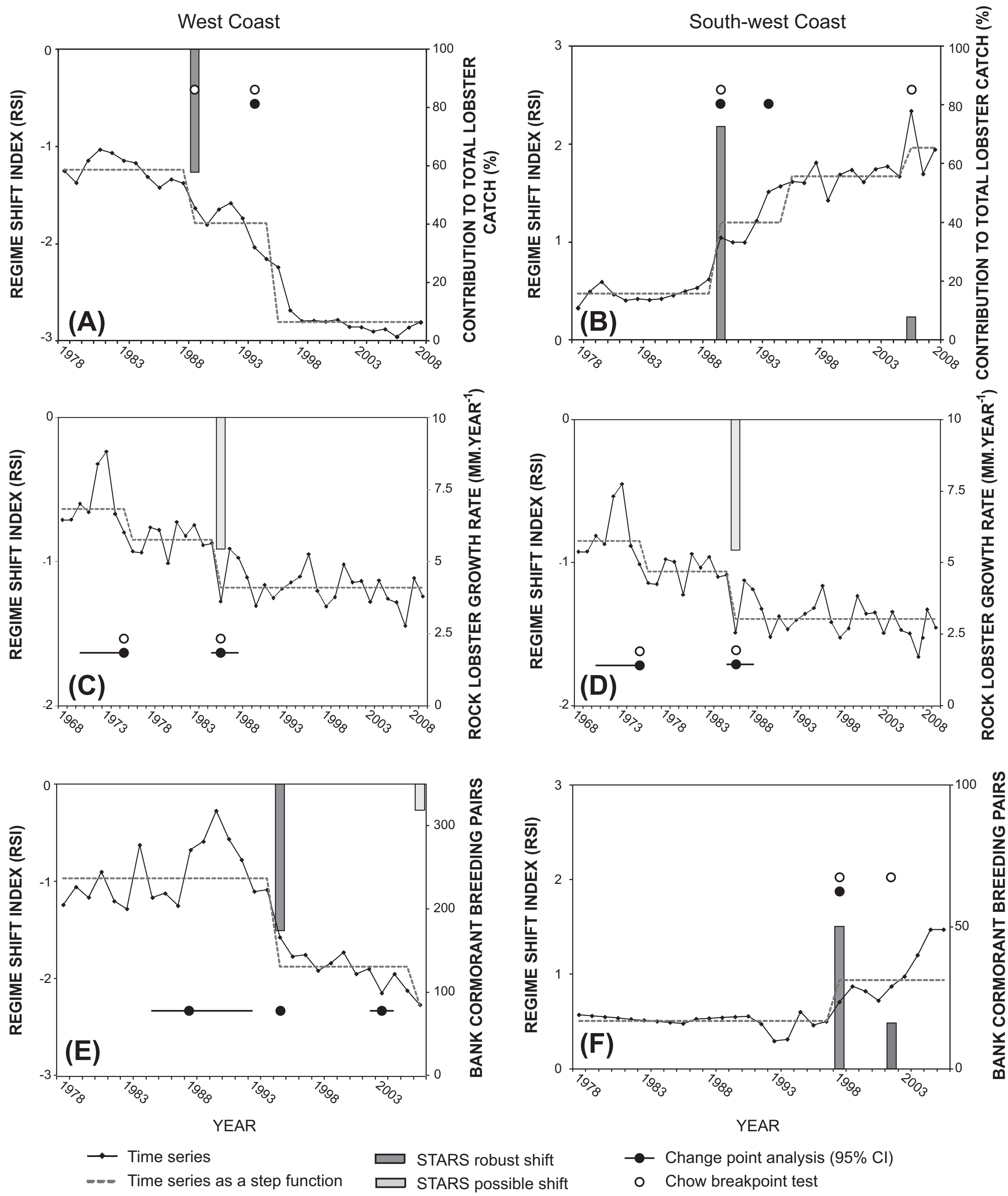

Fig. 5. STARS analyses showing regime shifts on the west and south-west coasts for (A and B) lobster commercial catch (% contribution of total catch), (C and D) lobster growth rates and (E and F) Bank Cormorant breeding pairs. The time series and weighted mean are shown by the black solid and grey broken lines respectively; the magnitude of the regime shift (RSI) is shown by the grey bars, distinguished as either robust or possible; and the change point analysis (±95% confidence intervals) and Chow test shifts are indicated by the solid and open circles respectively.

south-west coast. Either the data do not exist, or they do not extend far enough back in time. The low resolution of data and the close proximity of the inshore coastal zone to the land are also problematic. We identified four physical variables likely to affect the coastal inshore ecosystem and for which data exist:

(1) Oxygen data were collected from Cape Columbine for the period 1983–2010 from the GWB-2 station line. Unfortunately these data were not collected from a fixed point and although most were collected just off Cape Columbine, there are a few critical years during this period where data were collected 40–80 km further north in St Helena Bay. Given the patchiness of the southern Benguela environment, we cannot assume these data are comparable and for this reason the oxygen data were excluded from our analyses.

(2) Temperature data relating to the inshore region are difficult to obtain due to the high resolution required and the close proximity of the inshore coastal zone to the land. Temperature

data for the offshore region are unlikely to reflect those of the inshore region and therefore we did not include them in our analyses.

(3) Upwelling data based on geostrophic winds only extend as far back as 1981. There appears to have been a decline in upwelling at the beginning of the 1980s, but this remains inconclusive due to the lack of data prior to 1981. However, Johnson and Nelson (1999) calculated Ekman estimates of upwelling based on Cape Columbine wind data for the period 1957–1992 and showed that upwelling declined in the early 1980s, and only began to increase again in the early 1990s, in line with the signal from upwelling based on geostrophic winds that we employed. Shannon et al. (1992) reported a similar trend, in which Cape Columbine winds displayed a prolonged weakening throughout most of the 1980s.

(4) Wind data collected from Cape Point were available for the period 1960–2010. In 1983 wind measurements changed from estimates made by the lighthouse keeper to measurements taken by an automated weather station (Hutchings et al., 1984). Comparisons between the lighthouse and automatic data revealed that wind speeds had previously been overestimated and that northerly winds were frequently recorded as westerlies and therefore underestimated (Hutchings et al., 1988). Cape Columbine wind data were available for the period 1957–1993 and for the period 1995–2007. However, the actual measured data from the latter period were missing and were therefore re-constructed using Saldanha Bay wind data. Correlations (not shown) between measured winds (for both Cape Columbine and Cape Point lighthouses) and geostrophic winds were significant for the periods where the actual data were available, but not for the period (1995–2007) where the Cape Columbine data were re-constructed. For this reason, we decided not to use the Cape Columbine wind data.

Biological time-series data are also problematic. *Jasus lalandii* was identified as the only candidate inshore species with a distribution across both the west and south-west coasts that had long-term catch/abundance data. However, as with most long-term catch data, these data have been subject to changes in fishing methods and gear as well as changes in minimum size limits. While we tried to account for this by only using catch data for the period after the major gear change took place (Schoeman et al., 2002), we acknowledge that there may still be problems associated with using long-term catch data to indicate signals of change in abundance. Also, *J. lalandii* is a long-lived, slow growing species and the fishery targets several year classes (Pollock, 1986). Therefore, any change in availability of lobsters leading to changes in TAC, would probably have been delayed. Ideally it would be useful to have used either a shorter-lived, more responsive species or to have looked at long-term changes in lobster recruitment. However, such data are not available.

4.3. Relating environmental indices back to the biology

Our analyses revealed a strong environmental signal during the mid-1950s. Both the change point analysis and the Chow test detected a shift in SST at 30°S and 32°S in 1956/1957, corroborating the robust, positive shift that Howard et al. (2007) detected in the same year using STARS. They also detected a similar positive (but not robust) shift in upwelling at 30°S. This shift was not detected by the two additional methods we employed, suggesting that the upwelling signal is much weaker than that of inshore SST. A possible shift in upwelling at 32°S was detected using STARS in the mid 1960s (Howard et al., 2007), and also by the Chow test that we employed in this study. Again, this upwelling signal was weak and neither of them could be supported using upwelling indices based on geostrophic winds, as they do not extend far enough back in time. It is possible that this upwelling signal at 30°S and 32°S is confounded. Firstly, these upwelling data were calculated using the difference between the inshore and offshore SST (Howard et al., 2007) and are therefore not based solely on changes in the inshore. Secondly, Rouault et al. (2009, 2010) have shown that the Agulhas current (offshore) has warmed over the last three decades, thereby increasing the difference between inshore and offshore SST, although, this does not necessarily imply a change in the inshore SST or an increase in actual upwelling. Howard et al. (2007) discuss these environmental shifts and relate them back to the pelagic ecosystem. They also detected a positive, robust shift in upwelling at 32°S in the early 1970s using the STARS method. Both the change point analysis and Chow test supported this shift. However, this shift was not detected in upwelling data from 30°S.

A significant decline in winter southerly winds and a significant shift from winter easterlies to westerlies was detected in 1983. Cape Point wind anomalies also indicate a decline in southerly winds during the 1980s. However, as mentioned above, the authenticity of this 1983 shift is difficult to determine because in addition to it being a major El Niño year, wind measurement methodology changed (Hutchings et al., 1984). Despite this, for several reasons we argue that an authentic shift in wind patterns did occur during the early 1980s, albeit exaggerated by the change in measurement methodology. Firstly, if a change in measurement methodology was solely responsible for the detection of a shift in winter winds in 1983, then one would expect to see a similar shift detected in the summer data, but this was not the case. Secondly, a number of cold-water upwelling areas experienced warmer waters during the 1982/1983 ENSO event (Philander, 1983). Walker et al. (1984) and Shannon et al. (1986) have linked the southern Benguela warm event, in part, to abnormalities in summer winds as opposed to an intrusion of warm water from the north, as seen in the Pacific. Thirdly, Shannon et al. (1992) report fairly random North/South monthly wind deviations up until the mid 1970s at Cape Columbine. Then, between the mid 1970s and early 1980s more southerly winds were recorded, switching to more northerly winds in 1982/1983 which then persisted, beyond the ENSO event, until the end of the 1980s. Cape Columbine wind measurement methodology was only changed in the mid 1980s (Hutchings et al., 1984) and again in 1995 (L. Hutchings, Department of Environmental Affairs, pers. comm). Lastly, Schumann (1992) reports a 30° shift in the principal wind axis at Cape Town and Port Elizabeth during the 1982/1983 El Niño, and Shannon et al. (1992) argue that this would have increased the influence of westerly winds, resulting in reduced upwelling during the 1980s. Although we did not detect any shifts in summer winds for the Cape Point time series, upwelling appeared to have declined in the early 1980s and Shannon et al. (1992) report a prolonged weakening of winds at Cape Columbine for most of the 1980s. The anomalous westerly and northerly winds in the 1980s that we detected in our analyses support this, as do the actual upwelling indices (based on geostrophic winds) for various sites along the west and south-west coasts.

Reduced upwelling during this period could have resulted in increased stratification and consequently increased low oxygen events. This may explain the two major lobster-walkouts that occurred during the 1980s (1986 and 1989, see Fig. 6), both of which were attributed to an inshore movement of low-oxygen bottom water during calm conditions (Cockcroft et al., 1999; Cockcroft, 2001). Reduced upwelling and low oxygen events could also impact puerulus settlement and therefore future recruitment to the fishery. The pueruli settle in shallow water (impacted by low oxygen) (Pollock, 1973) and their onshore movement from where they moult from phyllosoma to pueruli is believed to be aided by water

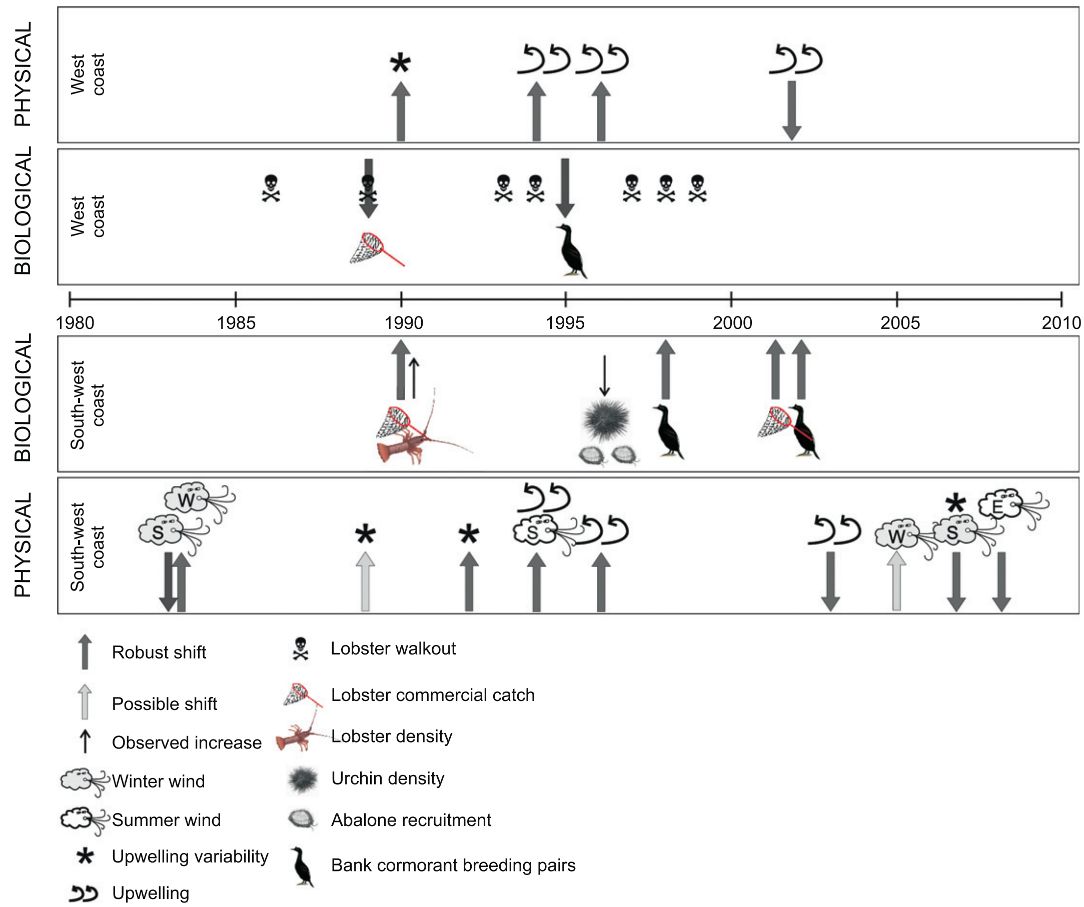

Fig. 6. Summary of the physical and biological regime shifts that have occurred in the southern Benguela inshore system for the period 1980–2010. Observed biological changes (for which there are no adequate time series data) are also included. Upward arrows indicate a positive shift (or increase) and downward arrows indicate a negative shift (or decrease).

movement (due to wind, currents and/or upwelling). However, dissolved oxygen time series data from the St Helena Bay/Cape Columbine area were considered unreliable for inclusion in this study.

During the early 1990s, upwelling variability appeared to increase and the Rodionov method identified positive robust shifts in upwelling variability between 1989 and 1992 for all sites except Cape Point, where the shift was delayed and identified only in 1995. This period coincides with negative and positive regime shifts in commercial lobster catch for the west and south-west coasts respectively (Fig. 6), as well as observed increases in lobster abundance for the south-west coast (Cockcroft et al., 2008), followed by a substantial decline in urchins and juvenile abalone (Fig. 6, Tarr et al., 1996; Mayfield and Branch, 2000; Blamey et al., 2010). An increase in upwelling variability may result in increased instability within the ecosystem. Our study revealed an increase in mean upwelling in the mid 1990s with all three methods detecting positive shifts at Cape Point and Cape Hangklip and two of the methods detecting positive shifts at Cape Columbine and Cape Agulhas. This increase in upwelling was supported by an increase in summer southerly winds at Cape Point with a positive shift being detected by all three methods in the mid 1990s. During the same period, Rouault et al. (2010) report major cooling events on the west and south coasts, which they link to stronger upwelling-favourable winds (southerly and south-easterly). During the 1990s, five major lobster walkouts occurred (Fig. 6), three of which were especially severe, further stressing the already depleted lobster stock (Cockcroft, 2001). In contrast to the 1980s walkouts, all five of these events were closely linked with dense dinoflagellate blooms associated with increased upwelling and quiescent periods (Cockcroft, 2001), which our findings support.

The Bank Cormorant *P. neglectus* feeds predominantly on rock lobsters (Hockey et al., 2005) and appears to have shifted its distribution. Crawford et al. (2008a) link the declines in *P. neglectus* breeding colonies on the west coast, and their increase on the south-west coast to respective decreases and increases in rock-lobster abundance in these areas. Our results corroborate this: a robust negative shift in breeding pairs was detected in 1995 on the west coast using the STARS and change point analysis. This negative shift in breeding pairs follows (1) a decline in lobster commercial catch that was detected in 1989 and in 1994, and (2) two lobster mass mortalities that occurred in 1993 and 1994 (Fig. 6). Along the south-west coast, a positive shift in breeding pairs was detected in 1998 following an increase in lobster catch there in 1990 and a reported increase in lobster density during the early 1990s (Tarr et al., 1996; Blamey et al., 2010).

A second increase in lobster commercial catch on the south-west coast was detected in 2001, but was most likely a direct result of an increased TAC rather than an increase in lobster abundance. However, Bank Cormorant breeding pairs also experienced a second positive shift in 2002 on the south-west coast as a result of increased lobster abundance there.

During the 2000s, negative shifts in mean upwelling, upwelling variability, southerly and easterly winds occurred between 2004 and 2008, as well as a possible positive shift in winter westerly winds (Fig. 6). These signals were not as strong as those in the 1980s/1990s, and were often detected by only two of the three methods employed.

The identified environmental shifts in the early-to-mid 1990s and again in the mid 2000s correspond temporally to shifts identified in other parts of the Benguela ecosystem. Boyer et al. (2001) reported a collapse in the Namibian (northern Benguela) sardine stock in the mid 1990s leading to a possible regime shift. An eastward shift in two of the southern Benguela pelagic species began in the mid-1990s. In 1996, almost all of the anchovy biomass was located east of Cape Agulhas (van der Lingen et al., 2002) and by the early-to-mid 2000s, sardine biomass was also greatest east of Cape Agulhas (Coetzee et al., 2008). Howard et al. (2007) identified two shifts in the southern Benguela offshore system, one of which occurred in the early 2000s most likely due to environmental forcing. Atkinson (2010) identified two shifts in demersal fish assemblages: one in the early-to-mid 1990s and another in the mid 2000s, but the second one is possibly confounded by gear modifications (Atkinson et al., 2011).

4.4. Summary

During a period of increased globalization and climatic variability, the sustainability of fisheries will require deft management and reducing uncertainty in ecosystem dynamics is paramount. The identification of regime shifts is an integral part of this process. STARS analyses identified robust shifts in the physical environment during the early 1980s (wind) and in the early-to-mid 1990s (increased southerly winds and upwelling). The two other statistical methods we employed corroborated these findings. During the 2000s, both southerly winds and mean upwelling appear to have declined, although they remained at a level greater than that in the late 1980s/early 1990s.

During the period when upwelling and southerly winds increased in the 1990s, the lobster resource shifted its distribution south-east, causing knock-on effects through the rest of the inshore ecosystem (Mayfield and Branch, 2000; Blamey et al., 2010). Urchins, a preferred prey of rock lobsters, virtually disappeared following the increase in lobsters (Tarr et al., 1996; Mayfield and Branch, 2000). The paucity of urchins has had serious consequences for the abalone population, given that in this area juvenile abalone shelter beneath urchin spines where they receive protection from predators (Day and Branch, 2000, 2002). These ecological effects combined with the overfishing of abalone populations due to poaching, have almost certainly resulted in a localized population collapse with the possibility of recruitment failure in some areas (Blamey and Branch, 2012; Blamey et al., in press). This has had enormous economic repercussions for the abalone industry. Once the most lucrative fishery in South Africa, abalone fishing quotas were severely reduced in the 1990s, followed by the closure of the recreational fishery in 2003 and a temporary closure of the commercial fishery in 2008 (Hauck, 2009). In an attempt to compensate for the drastically reduced fishing permits, a small-scale commercial rock-lobster fishery was initiated EOCH in 2003 (Cockcroft et al., 2008). The continued demand for abalone in South Africa is now largely met by abalone mariculture industries that were established in the 1990s (Troell et al., 2006). Given that kelp *E. maxima* is the major food source for cultured abalone, the development of the abalone mariculture industry has expanded kelp harvesting (Troell et al., 2006). In addition to the ecological implications of the eastward shift of lobsters, there have also been significant socio-economic consequences (Hauck and Sweijd, 1999). In particular, the legal fishery on abalone has been reduced. Although this was largely due to illegal fishing, the direct and indirect effects of the lobster 'invasion' have aggravated the situation, prolonging the possible recovery of the abalone resource (Blamey et al., in press).

Given that these changes took place within a relatively short period of time and have altered inshore trophic levels (particularly on the south-west coast) in a manner that persists, it is almost certain that a regime shift has taken place in the southern Benguela inshore region. Our study provides a first step towards identifying ecosystem indicators that can be monitored with the intended use of developing an early warning system for possible future shifts in the southern Benguela inshore region.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pocean.2012.07.001.

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