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FORECASTS OF RECRUITMENT IN SOUTH AFRICAN ANCHOVY FROM SARP FIELD DATA USING A SIMPLE DETERMINISTIC EXPERT SYSTEM

S. J. PAINTING and J. L. KORRÛBEL†*

A rule-based deterministic model is used to forecast recruitment of anchovy *Engraulis capensis* in the southern Benguela from field measurements of biological and environmental variables collected during two consecutive years. Field data were obtained on a monthly basis during the anchovy spawning season as part of the South African Sardine and Anchovy Recruitment Programme (SARP). A total of six indicator variables was considered for the analysis: distance offshore of the 16°C isotherm; southerly wind stress; anchovy egg abundance; incidence of oocyte atresia in adult females; an index of fish starvation; and oil : meal ratios obtained from commercial data (which were used as an index of fish condition). In the model, data for each variable were assessed against a threshold value. "Active" variables were assumed to contribute towards below-average recruitment by being either above or below their threshold values, as defined by the rules. The model was not based on the SARP field data, which were used to test the model. Predicted results from the expert system compared favourably with final estimates of recruitment strength for both 1994 and 1995 (years of below average recruitment), indicating that field measurements of biological and environmental variables may be used in a structured manner to obtain forecasts of anchovy recruitment to the fishery.

Anchovy *Engraulis capensis,* sardine *Sardinops sagax* and round herring *Etrumeus whiteheadi* are the major components of the pelagic fishery in the southern Benguela upwelling system, which encompasses the west coast of South Africa and the western Agulhas Bank at the southernmost extremity. Commercial catches since the 1970s have, until recently, been dominated by anchovy. The species is relatively short-lived (≈ 3 years) and the fishery is largely dependent upon juvenile fish (approx. 6 months old), which are spawned during a distinct season. As a result, the fishery is seasonal and highly sensitive to interannual variations in recruitment, both of which impose a number of problems in the management of the resource. The most important management tool is the setting of the Total Allowable Catch (*TAC*) for each fishing season (January – September/October), which needs to be done at the start of the season (January), before recruitment strength is known.

Prior to 1983, the anchovy fishery was managed by adopting a constant catch strategy, which allowed for catches of approximately 300 000 tons per year (Crawford *et al*. 1987). In 1983, a new Sea Fisheries (SF) vessel, the F.R.S. *Africana*, with hydro-acoustic capacity was commissioned, and since then hydroacoustic surveys have been conducted annually during the anchovy spawning season (in November) and during the subsequent recruitment period (in May/June, Hampton 1987, 1992). Quantitative assessment of the resources has permitted development of a management procedure for anchovy based on survey estimates of stock sizes of spawners and recruits. By the early 1990s, the management procedures incorporated a strategy of constant escapement (Butterworth and Bergh 1993, Butterworth *et al*. 1993). An important assumption in the setting of the *TAC* was that recruitment in any given year was equal to the observed median recruitment. Survey results of spawner biomass in November were therefore used to determine an initial *TAC* for the following season. This was revised after the midyear survey in which actual recruitment was estimated (see Butterworth *et al*. 1993).

Simulation studies by Cochrane and Starfield (1992) indicated that a valuable increase in mean annual yield could be achieved if recruitment variability could be correctly predicted at the start of the fishing season. Conservative estimates indicated a 16% increase in mean annual catch if forecasts could differentiate between "below-median" or "median or above" recruitment. Using field data collected during November surveys from 1985 to 1992, Cochrane and Hutchings (1995) developed a conceptual model of the factors influencing anchovy recruitment, and investigated 10 biological and environmental indicators that could be used to make such forecasts. Fluctuations in anchovy recruitment were shown to be associated with fluctuations in five of the indicators, *viz.* copepod biomass and production on the anchovy spawning grounds, the incidence of oocyte atresia in adult female anchovy,

* Sea Fisheries, Private Bag X2, Rogge Bay 8012, South Africa. Email: painting@sfri2.wcape.gov.za
† Formerly Marine Biology Research Institute, Department of Zoology, University of Cape Town; now Department of Mathematics and Applied Mathematics, University of Natal, Private Bag X01, Scottsville 3209, Pietermaritzburg, South Africa.
Email: korrubelj@science.unp.ac.za

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the incidence of southerly winds at Cape Point, and the distance offshore of the 16°C isotherm at Cape Columbine. The authors proposed three scenarios under which recruitment in the forthcoming season was "likely" to be "below average".

This approach was investigated further by Korrûbel (1995, see also Korrûbel *et al*. 1998), who developed a rule-based expert system to predict below-average recruitment of anchovy in the southern Benguela on the basis of environmental and biological information collected during the November surveys. After investigating a number of variables, and a process of rule calibration, Korrûbel (1995) was able to obtain correct predictions of below-average recruitment for all years in the recruitment time-series from 1985 to 1994.

An important assumption in the management procedure for anchovy is that results of a survey conducted in one month, November, are representative of spawning processes taking place for the duration of the spawning season (August – March, Shelton and Hutchings 1990, Melo 1994a, b). Monthly sampling during the Cape Egg and Larva Programme (CELP, Shelton and Hutchings 1990) showed considerable variability between months. From histological studies, it is clear that anchovy in the southern Benguela are serial spawners, which may produce a new batch of eggs every 7–11 days, depending upon environmental conditions (Melo 1994a, b). Events taking place on the spawning grounds during November may therefore not be representative of events over the whole spawning season. Forecasts of anchovy recruitment from multiple cruises may produce a different result from the forecast made from a single survey.

The extent of within-season variability in anchovy spawning and environmental conditions on the Agulhas Bank was investigated during recent studies which formed part of the Sardine and Anchovy Recruitment Programme (SARP, Painting 1993, Painting *et al.* in press a, b). The overall objectives of SARP were to investigate within-season variability in the spawning success of anchovy and sardine in response to environmental factors, and to quantify the potential impact of this variability on recruitment. Intensive surveys were conducted on a monthly basis during the spawning season in 1993/94 (SARP I) and 1994/95 (SARP II) to determine variations in fish distribution, spawning success, and environmental factors such as sea surface temperatures, food availability and offshore and longshore transport (Fowler and Boyd 1998, Richardson *et al.* 1998, Painting *et al.* in press a, b). The longer-term goal of SARP, which is addressed in this study, was to develop the ability to predict the spawning and recruitment success of anchovy and sardine from year to year.

The objectives of this study were:

(i) to determine whether it was possible to forecast the observed anchovy recruitment in 1994 and 1995 from monthly field data obtained during the preceding spawning seasons using the deterministic expert system of Korrûbel (1995);

(ii) to compare the prediction based on data from a single annual survey (as in Korrûbel 1995) with the prediction resulting from the SARP cruises conducted at regular intervals throughout the spawning season; and

(iii) to use the SARP field data as an independent test of the expert system, as the SARP data were not used in the original construction of the model.

Furthermore, this study should permit identification of a number of key variables which are useful indicators of recruitment strength and which can be monitored easily. This has been one of the important goals of intensive environmental research that has been carried out in the southern Benguela since 1988.

DESCRIPTION OF THE MODEL

The expert system developed by Korrûbel (1995) incorporates a set of rules linking anchovy recruitment to selected biological and environmental variables. The model is used to simulate a variety of "IF (condition) – THEN (conclusion)" scenarios and, for each of these scenarios, qualitatively forecast the occurrence of "below-average recruitment" (BAR), in a deterministic manner. The model, originally developed to forecast recruitment on the basis of an annual assessment of physical and biological factors during the middle of the spawning season (November, see Korrûbel *et al*. 1998), was used here to obtain separate forecasts from similar data obtained at approximately monthly intervals during two consecutive spawning seasons during SARP.

The software used to develop and run the expert system described here was "WinEXP – A small expert system for Windows", the MS-WINDOWS® version of a shell designed for developing simple expert systems on MS/PC-DOS® computers (see Adams 1985, Starfield *et al.* 1985 for a description of the early, DOS-based, version of the shell).

Methods, data and assumptions

The life cycle and migration behaviour of the anchovy in the southern Benguela is relatively well

Table I: Indicators used in the rule-based production model, and their threshold values

Variable	Threshold
Index of wind stress (southerly wind anomaly)	1 667 km cumulative southerly wind-run
Distance offshore of the 16°C isotherm	26 miles
% Starvation stations on the Agulhas Bank	30%
% Females with Alpha-oocyte atresia	10%
Daily egg production	300 eggs·m^{-2}
Monthly (commercial) oil : meal ratio	1.7% oil

understood (Crawford *et al*. 1980). The habitat of the species can be divided into relatively distinct spawning, transport and recruitment areas (Shelton and Hutchings 1990). The SARP survey grid was designed to include the spawning area on the western Agulhas Bank, the transport area off the Cape Peninsula, and the nearshore nursery area in St Helena Bay on the West Coast. Cruises were conducted approximately every 4–6 weeks to determine changes in fish distribution and reproductive condition, ichythyoplankton abundance, phyto- and zooplankton biomass, copepod production, and hydrography. Details of survey design and sampling procedures are given in Painting *et al.* (in press a, b).

In all, 14 SARP cruises were conducted over the spawning seasons of anchovy in 1993/94 (August – March) and 1994/95 (September – March). However, to make the results useful to the current management procedure, where initial forecasts of recruitment would be required at the start of the fishing season (January) for the setting of the annual *TAC*, only those SARP data from the first part of the spawning season (August/September up to and including December) were used here in the forecasting procedure.

Data for three of the six variables used in the study were obtained from field samples collected during the SARP cruises, *viz.* anchovy egg abundance, the incidence of oocyte atresia in adult female anchovy, and an index of fish starvation. Data for the remaining three variables (the distance offshore of the 16°C isotherm, southerly wind stress and oil content of the fish) were obtained for the same time periods as the SARP cruises, but from other sources (see below). SARP field data used as model input for this study are presented in Figures 1–6. The data are shown as individual values or as averages per month during the anchovy spawning seasons in 1993/94 and 1994/95.

DEVELOPMENT OF THRESHOLD VALUES

In general, two parameters of a probability distribution may be used to describe adequately many processes, *viz.* the mean and the variance. One measures the central position of the distribution and the other measures its breadth. However, many biological problems concern the extremes in the variables rather than their central tendencies, i.e. the relevant parameter is not the average, but the extreme (maximum or minimum, Gaines and Denny 1993). Quantitative thresholds (Table I) for the six indicator variables under examination were therefore determined from empirical data and theoretical considerations (Korrûbel 1995). Original threshold values determined for the annual assessments (Korrûbel 1995) were used in this study. Two of the variables (index of wind stress and oil : meal ratios) were adapted to accommodate the monthly nature of the SARP data. Field data were then assessed against these thresholds to determine whether or not the individual data points in the time-series of a particular variable could be considered "extreme" (i.e. having a negative impact on recruitment).

OFFSHORE POSITION OF THE 16°C ISOTHERM

Shelton and Hutchings (1990) showed that anchovy eggs on the West Coast were concentrated within the frontal zone between upwelled and oceanic water, and that the offshore position of the front varied depending on the frequency and intensity of upwelling. The average monthly offshore position of the 16°C isotherm on the West Coast provides a useful index of the frequency and intensity of upwelling each month (Painting *et al.* in press a). Furthermore, the distance offshore of the 16°C isotherm provides an index of the strength of the frontal jet and therefore serves as a proxy for transport success (Cochrane and Hutchings 1995).

The distance offshore of the 16°C isotherm was estimated from maps showing weekly means of sea surface temperature produced by the South African Weather Bureau (Painting *et al.* in press a). Estimates were obtained at latitude 33°S (Cape Columbine, Fig. 1a) and 34°S (Cape Point, Fig. 1b). Analysis of the data from 1984 to 1991 by Korrûbel (1995) showed considerable variability in the distance offshore of the 16°C isotherm at Cape Columbine, with

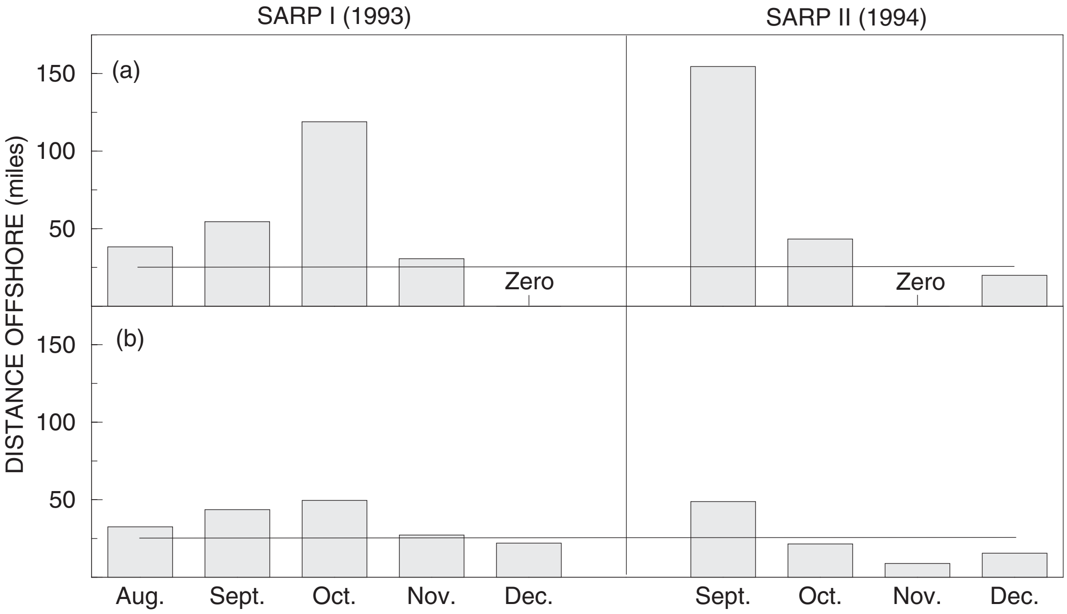

Fig. 1: Monthly changes in the distance offshore of the 16°C isotherm at (a) latitude 33°S and (b) latitude 34°S during SARP. Cruises were conducted during the anchovy spawning seasons of 1993/94 (SARP I) and 1994/95 (SARP II). The horizontal lines indicate the threshold value of 26 miles

values ranging between 14.3 and 33.5 miles offshore. The mean distance offshore, for the period 1984–1993, was 26 miles (Korrûbel 1995). This value was adopted as the threshold in the study by Korrûbel (1995) and was also used here. If the isotherm was positioned close to shore (<26 miles), it was assumed that upwelling had not been very active during that month. This implies that the Cape Columbine jet current is then relatively weak, resulting in reduced transport success of eggs and larvae to the nursery area, increasing the chances of observing a BAR event.

SOUTHERLY WIND STRESS

The "optimal environmental window" hypothesis for upwelling regions suggests that there is a relationship between wind and pelagic fish recruitment, i.e. optimum winds exist such that there is sufficient upwelling, enhanced food production or increased encounter rate between larvae and food particles, and offshore transport is not detrimental. Above or below optimum winds have a negative impact on recruitment (Cury and Roy 1989). In the southern Benguela, very strong southerly winds may result in increased upwelling and Ekman transport offshore, and consequently increased loss of eggs and larvae from the coastal upwelling system (Shannon *et al*. 1992).

To detect the likelihood of abnormally high losses of anchovy eggs and larvae through offshore transport on the west coast of South Africa, Korrûbel (1995) used north-south (N-S) wind-run anomalies measured at Cape Point from October through December each year, from 1984 to 1992. These were analysed for corresponding peaks and troughs in recruitment – in general, strong southerly wind-runs (the three-month cumulative sum of departures from the long-term mean) coincided with below average recruitment the following year. The threshold value used by Korrûbel (1995) was 5 000 km for the three-month period. To accommodate the monthly nature of the SARP dataset, the figure of 5 000 km was divided by three (months) to obtain a monthly threshold (1 667 km) for N-S wind-run anomalies.

During SARP, hourly estimates of wind speed and direction recorded at the Cape Point lighthouse were converted into monthly progressive vector diagrams (see Painting *et al*. in press a, b). Deviations of the N-S wind components from long-term monthly means (1960–1991) for each month, (SF unpublished data, see Painting *et al*. in press a), were used in this study (Fig. 2). If the cumulative monthly southerly wind-run was high (>1 667 km), it was assumed that a

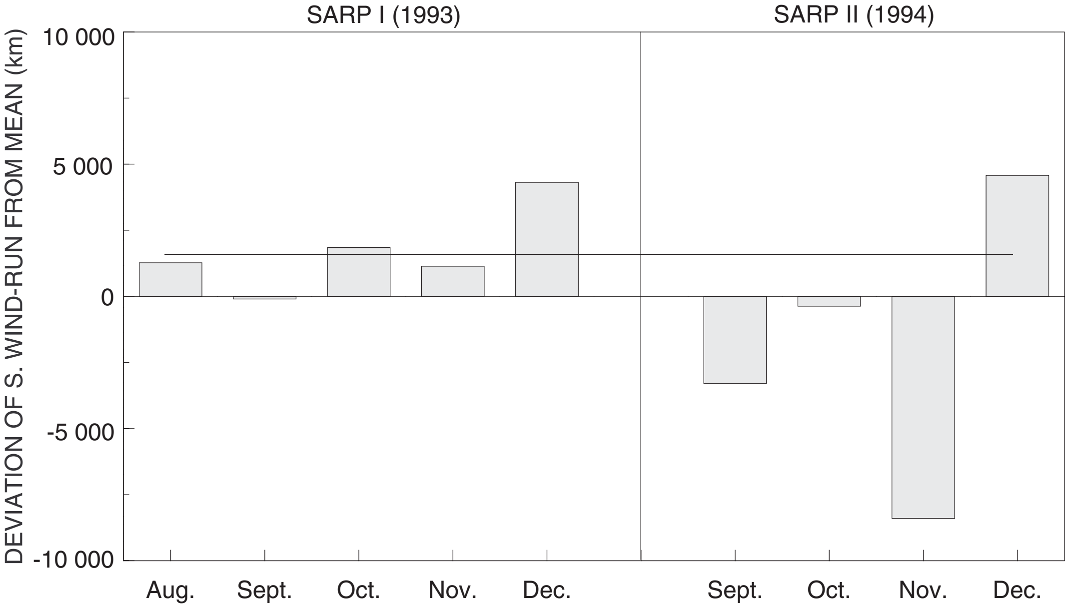

Fig. 2: Monthly deviations of N-S winds from long-term averages (1960–1991) during SARP I and II. The horizontal line indicates the threshold value of 1 667 km

large proportion of the spawning products would be lost to the offshore environment, therefore increasing the chances of observing a BAR event.

COMMERCIAL DATA ON OIL YIELD : FISH MEAL RATIOS

The oil content of pelagic fish, expressed as the oil : meal ratio, provides a general index of fish condition (Schülein *et al.* 1995). Korrûbel (1995) used catch and processing data from the commercial sector (see Stuttaford 1991, 1994) to calculate an oil-yield threshold for anchovy. These data were only available as total annual tonnages for all pelagic fish combined and included sardine, Cape horse mackerel *Trachurus trachurus capensis*, round herring and lanternfish *Lampanyctodes hectoris*. Lanternfish, in particular, have a very high oil content (Chief Directorate Marine Development 1986) and can represent up to 10% of the total pelagic catch. As a consequence, only data for the years where anchovy constituted 50% or more (65, 75 or 80% and more) of the total pelagic catch were considered for the calculation of the oil-yield threshold. Mean values (± 1 standard deviation) were compiled for each dataset. As low oil yields are assumed to indicate poor physical condition in the adult spawners (see Schülein *et al.* 1995), the lower bounds of the means were investigated. These values ranged from 18.5 to 20.6%, with a mean of 19.7%. A threshold of 20% was adopted by Korrûbel (1995). This figure was, however, an annual mean, and applied to the cumulative oil yield over the fishing season. In the current study, this annual value was divided by 12 (months) to obtain a monthly threshold value (1.7%) applicable to the SARP dataset.

Monthly oil-yield data were obtained from Gans Bay on the South Coast and all landing ports in the Western Cape and averaged for the purposes of this analysis (Fig. 3). If the oil : meal ratio was low (<1.7%), it was assumed that adult fish coming onto the spawning grounds were in poor condition (i.e. had poor energy reserves), resulting in reduced egg production and an increased probability of non-sustained egg production, therefore increasing the chances of observing a BAR event.

ANCHOVY EGG ABUNDANCE

Egg abundance (Fig. 4) was used here as a predictor of recruitment, on the assumption that this index is one step shorter in the causal chain than the classical stock-recruitment relationship. Korrûbel (1995) analysed the daily egg production time-series for the

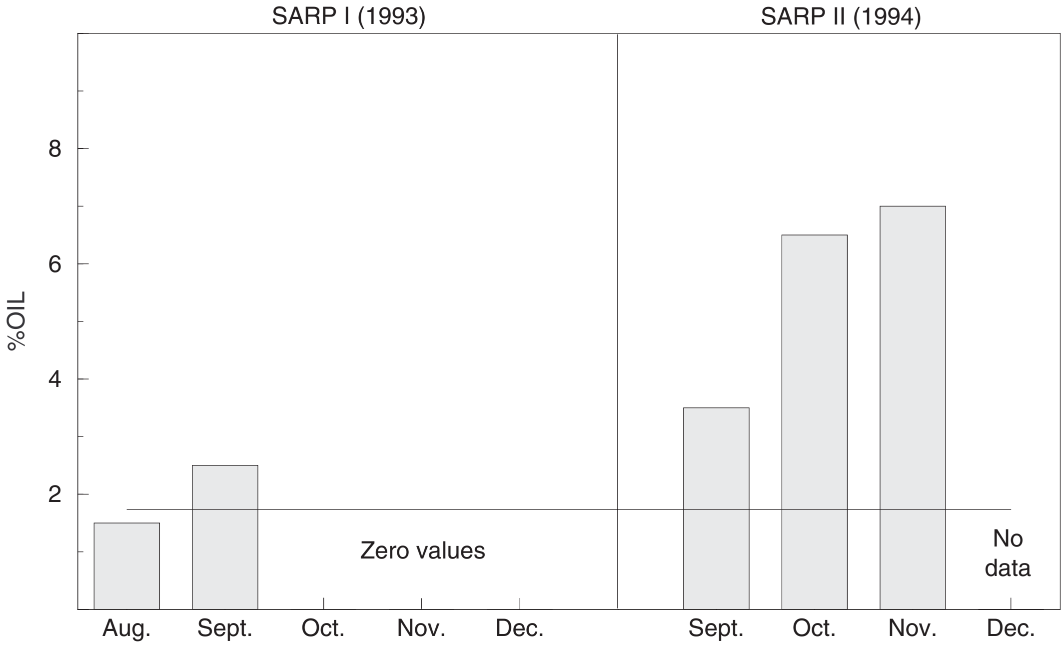

Fig. 3: Monthly data on the oil : meal ratio of pelagic fish obtained from commercial fisheries during SARP I and II. The horizontal line indicates the threshold value of 1.7%

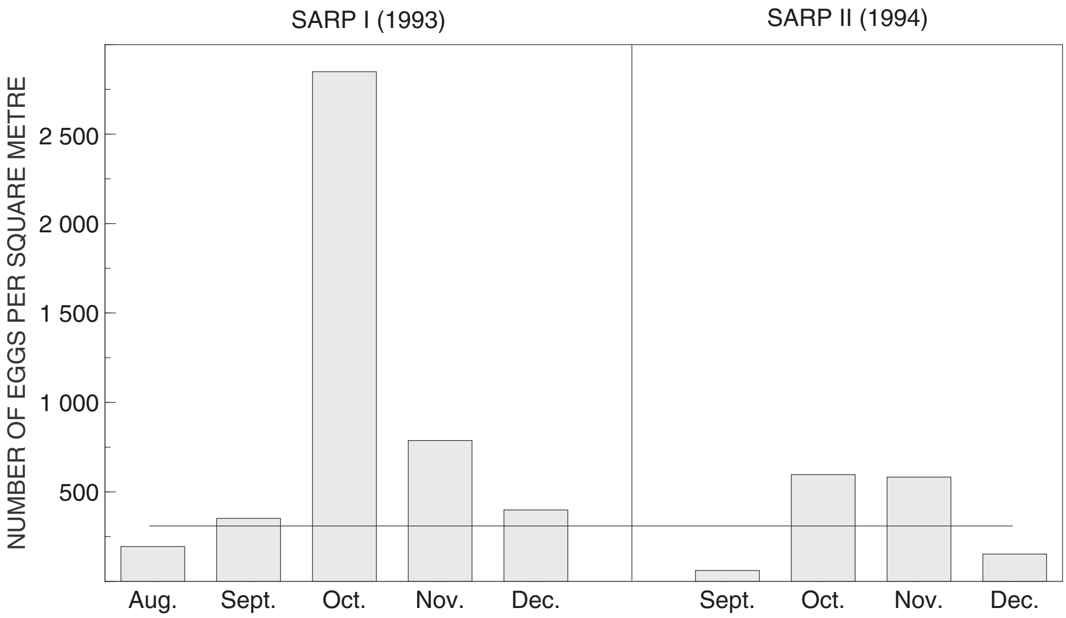

Fig. 4: Monthly average abundance of anchovy eggs on the western Agulhas Bank during SARP I and II (J. L. Fowler, University of Cape Town, unpublished data). The horizontal line indicates the threshold value of 300 eggs·m^{-2}

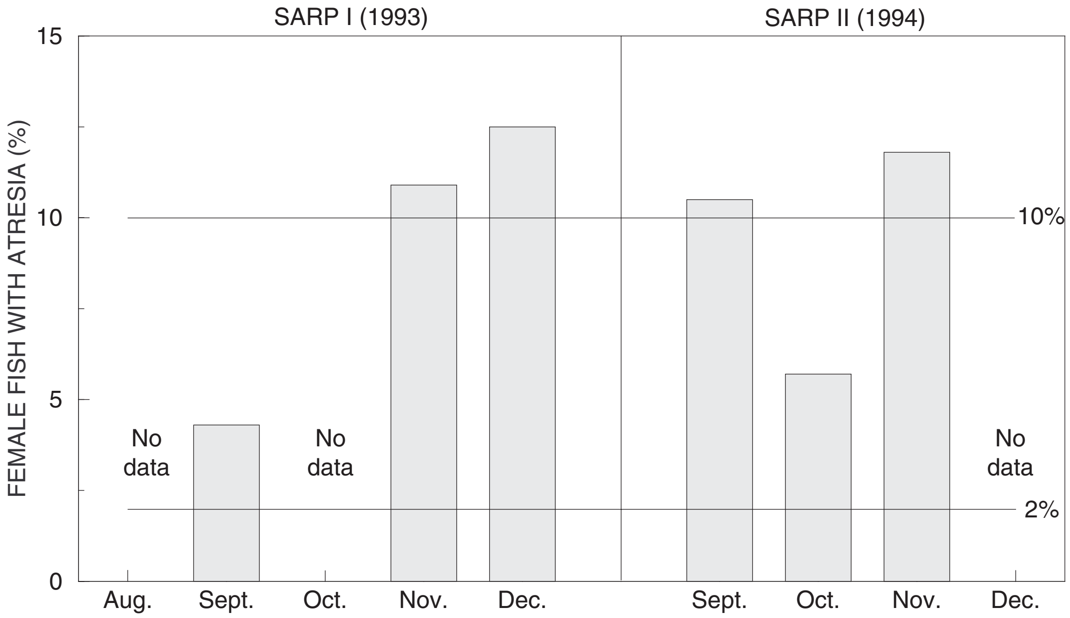

Fig. 5: Estimates of the percentage of adult anchovy females undergoing oocyte resorption during SARP I and II (Y. S. Melo, SF, unpublished data). The lower horizontal line indicates the expected upper limit of 2% (see text), whereas the upper horizontal line indicates the threshold value of 10% adopted for this study

period 1984–1993 for corresponding peaks and troughs in anchovy recruitment. The mean value of egg production was 381.5 eggs·m^{-2}. The data were extremely variable, however, and some years which exhibited above-average recruitment were preceded by below-average egg production. A threshold value of 300 eggs·m^{-2}, adopted by Korrûbel (1995), was used for the current study. A low abundance of anchovy eggs (<300 eggs·m^{-2}) implies that fewer eggs are available for subsequent development, so increasing the chances of observing a BAR event.

ALPHA OOCYTE ATRESIA IN FEMALE ANCHOVY

Levels of alpha oocyte atresia (resorption of gonad material) in female anchovy, estimated from histological studies of anchovy gonads (Fig. 5) were used as an index of reproductive condition. Previous studies (Hunter and Macewicz 1985) have shown that oocyte atresia is indicative of inadequate energy reserves for oocyte maturation. Korrûbel (1995) found evidence for a relationship ($r = -0.52$, $n = 9$, $p < 0.10$) between the percentage of female anchovy with alpha-stage oocyte atresia and recruitment the following year for the period 1985–1993. A low percentage of atresia (1–2%) in female fish is not uncommon. Values exceeding this should indicate that poor spawning, and possibly a subsequent drop in recruitment, is imminent (Y. C. Melo, SF, pers. comm.). During the spawning seasons of 1985–1987, <1% of the anchovy examined showed signs of atresia (Melo 1994b). However, during subsequent years, the percentage atresia exceeded 2%. Values for 1989–1993 ranged between 4 and 13%. The mean value (10%) was adopted as the threshold value by Korrûbel (1995) and was used in the current study. It was assumed that, if the level of atresia was high (>10%), there would be a reduced output of eggs by the spawning females, and an increased chance of observing BAR.

STARVATION INDICES

Estimates of the percentage of stations where fish are unable to obtain sufficient copepod food to meet their maintenance requirements provide an index of poor feeding conditions for pelagic fish, and indicate when the food environment may impact upon their reproductive condition (Peterson *et al*. 1992). These starvation indices have been obtained on all November spawner biomass surveys since 1988. Although the time-series is short, higher indices of starvation are associated with poor recruitment and there is a good

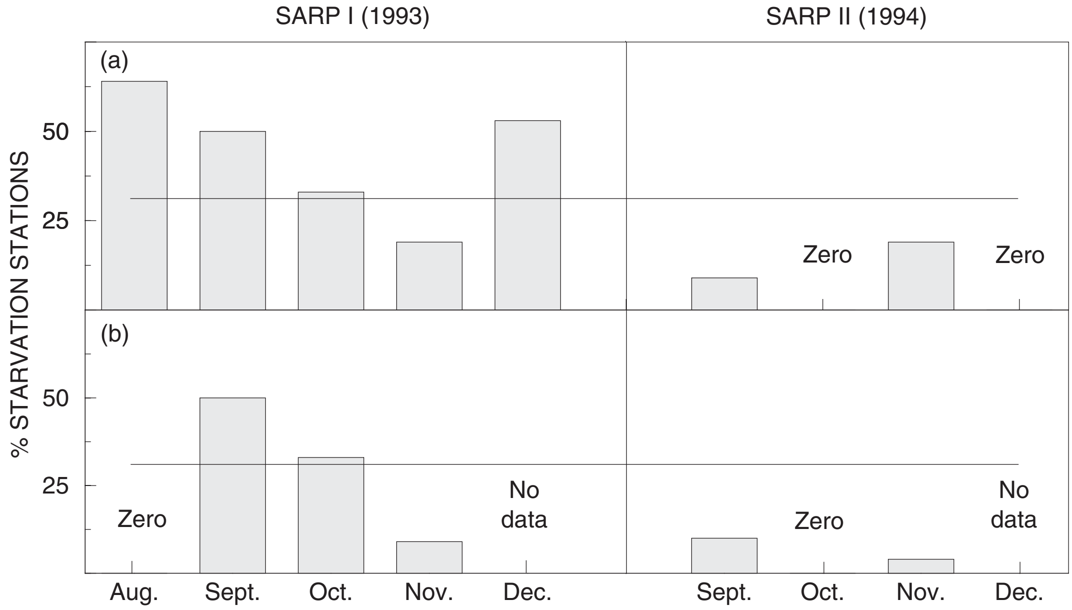

Fig. 6: Starvation indices for pelagic fish on the western Agulhas Bank during SARP – (a) all pelagics, i.e. anchovy, sardine and round herring, (b) anchovy only. The horizontal lines indicate the threshold value of 30% used in this study

correlation between the percentage of starvation stations on the spawning grounds and anchovy recruitment the following year ($r = -0.77$, $n = 6$, $p < 0.025$, Korrûbel 1995). The mean percentage of starvation stations for the period 1988–1993 was 22.1% (Korrûbel 1995). A value of 30% was adopted as a threshold value.

During SARP, starvation indices were derived from estimates of copepod biomass and fish density by assuming a P : B ratio of $0.2 \cdot day^{-1}$ for copepods and a fish maintenance ration of 2% of dry body mass$\cdot day^{-1}$ (see Painting *et al.* in press b). Indices were calculated for all pelagic fish species combined (anchovy, sardine and round herring, Fig. 6a), on the assumption that they compete for a common food resource, and for anchovy only (Fig. 6b), because they are the species of interest. If the percentage of starvation stations was high (>30%), a reduction in spawning ability and a reduced probability of sustained spawning were assumed, so increasing the chances of observing a BAR event.

FINAL ESTIMATES OF ANCHOVY RECRUITMENT STRENGTH IN 1994 AND 1995

Final estimates of anchovy recruitment strength in the southern Benguela indicate that recruitment was poor in both 1994 and 1995 (Fig. 7). The total number of recruits to the fishery during those two years was estimated to be 97 billion and 197 billion respectively, below the long-term (1984–1995) average of 302 billion fish (Fig. 7a, SF unpublished data). Corresponding biomass estimates for anchovy recruitment were 200 000 tons and 296 000 tons for 1994 and 1995 respectively, both of which were below the long-term (1985–1995) arithmetic average of 570 000 tons (Fig. 7b, SF, unpublished. data).

Forecasting procedures

Where possible, all six variables were used to obtain forecasts of anchovy recruitment. Where no data were available for *n* particular indicator(s), the system was reduced to a 6-*n* variable system, for that particular forecast. Forecasts were assigned through a simple numerical scheme (see Table II), as described in the Appendix. An "active" indicator was assumed to contribute towards below-average recruitment by being either above or below its threshold value as determined by the rules. For example, a threshold value of 10% was adopted for oocyte atresia in females. If the level of atresia during a given month exceeded 10%, then below-average recruitment (BAR) was in-

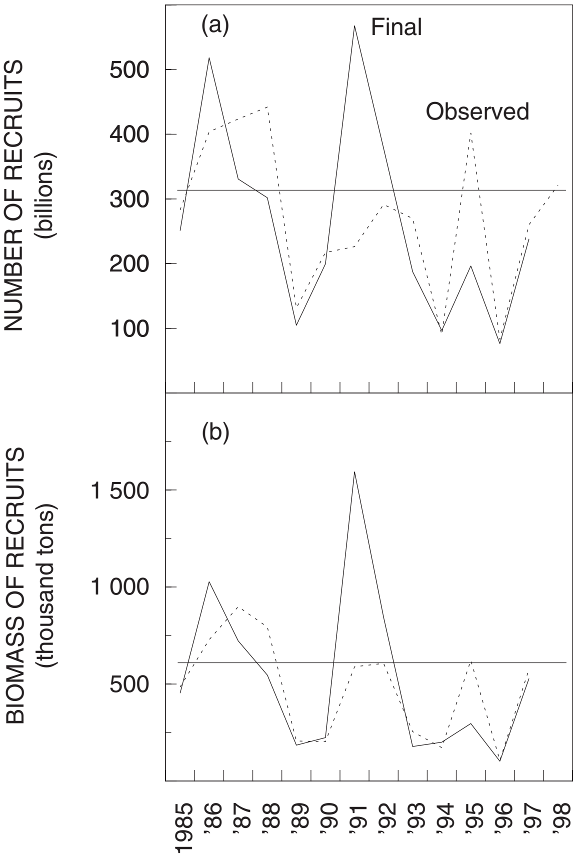

Fig. 7: Estimates of anchovy recruitment strength in the southern Benguela, Estimates in terms of (a) numbers and (b) biomass. Recruitment estimates are obtained in the middle of the year from hydro-acoustic surveys of anchovy recruits (i.e. "observed" recruitment), and are recalculated once the biomass of the spawner stock is known, using a simulation model of the population dynamics (i.e. "final" recruitment estimates, J. A. A. De Oliveira, SF, pers. comm). All recruitment estimates (except "observed" biomass) are back-calculated to the start of the year, and corrected for a 64% bias in field results. The horizontal lines indicate the long-term arithmetic means of the final recruitment: (a) 1984–1995: 302 billion fish (De Oliveira 1995) and (b) 1985–1995: 570 000 tons (SF, unpublished data)

dicated, and atresia was considered to be an "active" variable. If more than 33% of the variables were active, "likely" or "very likely" BAR was forecast. Of three possible categories of "BAR" forecast, those considered to be useful to management in the setting of initial quotas are only "likely" and "very likely". Forecasts of "possible" below average recruitment are considered to be unusable (see Korrûbel *et al.* 1998).

RESULTS

For the "base-case" expert system, the initial variable combination was chosen to include the position of the 16°C isotherm at 33°S (Fig. 1a) and the starvation index for all pelagic species (Fig. 6a), on the basis that: (a) processes at 33°S are more critical to anchovy recruitment success than at 34°S, because of the presence and behaviour of the Cape Columbine jet current at 33°S, and (b) the starvation index for all pelagic species combined is more realistic than that for anchovy only. Sensitivity analysis was performed on the base-case system by replacing these two datasets, individually and in tandem, resulting in a total of four expert systems.

Forecasts of anchovy recruitment from the base-case system

The decision table for the "base-case" system is presented in Table III and the monthly forecasts obtained from it are shown on Table IV. The precise procedure followed in generating these forecasts is shown in the Appendix.

For 1994, all the monthly forecasts fell in the below-average recruitment category (Table IV) and compared favourably with the final estimate of recruitment, which was below average (97 billion fish). Numerically, this would justify a final forecast of below-average recruitment for the impending 1994 season. Exclusion of the forecasts of "possible" below-average recruitment provided greater confidence in the overall forecast of below-average recruitment for 1994.

For the 1994/95 forecasts, the situation was not so clear. Three of the four forecasts fell into the below-average category, whereas one fell into the average/above-average recruitment category (Table IV). Unfortunately, 50% of the below-average forecasts were "possible" and therefore unusable, leaving only two usable forecasts – one for, and the other against recruitment failure. Formulating a final forecast could therefore not be fully justified, indicating that caution should be used. The final estimate of recruitment in 1995 (197 billion fish) was below average.

Sensitivity analysis

Forecasts of anchovy recruitment from different sets of field data were also obtained by swopping out datasets used in the base-case system above (see Table V). In the first manipulation, the starvation index for all pelagics was replaced with that for anchovy only, while keeping the remainder of the datasets the same. The decision table (Table V) was

Table II: Summary of the rules used for forecasting recruitment

If there are no active indicators, then "average/above-average recruitment" will be forecast

As soon as there are active indicators, however, a chance (however small) exists for "below-average recruitment", and as such,

(i) if the number of active indicators is one-third (33%) or less of the total number of indicators used in the forecast, "possible below-average recruitment" will be forecast

(ii) if the number of active indicators lies between one- and two-thirds (33 – 66%) of the total number of indicators used in the forecast, "likely below-average recruitment" will be forecast

(iii) if the number of active indicators is greater than two-thirds of the total number of indicators used in the forecast, "very likely below-average recruitment" will be forecast

similar to that for the base-case system (Table III). Differences during the December surveys were because no data were available on anchovy densities from the surveys. In August 1993, the starvation index was driven by sardine, which dominated the pelagic fish biomass. These differences aside, forecasts produced by the system were the same as those generated by the base-case system (see Table IV).

For the second manipulation, the starvation index for all pelagic fish was reinstated and the 33ºS isotherm dataset was replaced with that for 34ºS (Table V). Except for the forecast generated from the October 1994 data, the forecasts (Table VI) remained the same as those generated by the base-case system (Table IV). In October 1994, the position of the 16ºC isotherm was below the threshold level, therefore changing the status of that variable from non-impacting to impacting, resulting in a change in the forecast from "average/above average" recruitment, to "possible" below-average recruitment.

In the final manipulation, the starvation index for all pelagics and the 33°S isotherm datasets were replaced with starvation indices for anchovy only and the 34°S isotherm datasets (Table V). Forecasts were the same as those in Table VI and therefore similar to those generated by the base-case system (Table IV), except for the October 1994 forecast. In those two systems (Table VI) all the forecasts for 1995 (from 1994) fell in the below-average recruitment category. As above, this should justify a final forecast of below-average recruitment for the 1995 season. The majority (75%) of the forecasts were, however, unusable, leaving only a single usable forecast of "very likely" below-average recruitment.

It was clear, therefore, that it made no difference to the forecasts whether starvation indices were based on all pelagic species or on anchovy only. Differences between the forecasts were driven by the offshore position of the 16°C isotherm; using the higher latitude (34°S) to obtain the isotherm position gave a better forecast (with respect to the final estimate of recruitment) for October 1994.

Table III: "Base-case" decision table based on SARP results using a starvation index for all pelagic species combined and 16°C isotherm data from 33°S. An "active" variable (✓) contributes to below-average recruitment, whereas an "inactive" variable (×) does not. Forecasts based on this decision table are shown in Table IV

Year/month	% Starvation stations (All pelagics)	Oil yield	Atresia	Egg production	Southerly wind index	16°C isotherm (33°S)
1993						
August	✓	✓	–	✓	×	×
September	✓	×	×	×	×	×
October	✓	✓(Zero)(??)	–	×	✓	×
November	×	✓(Zero)(??)	✓	×	×	×
December	✓	✓(Zero)(??)	✓	×	✓	✓
1994						
September	×	×	✓	✓	×	×(??)
October	×	×	×	×	×	×(??)
November	×	×	✓	×	×	✓
December	×	–	–	✓	✓	✓

– = No data
Zero = Zero data value
?? = Possibly spurious data

Table IV: Forecasts of anchovy recruitment made from the "base-case" expert system (Table III). Only "LIKELY" and "VERY LIKELY" forecasts of below-average recruitment are usable (see text). Observed recruitment is for the following year

Year/month	Forecast of BAR	Observed recruitment
1993		
August	LIKELY	Below average
September	Possible	
October	LIKELY	
November	Possible	
December	VERY LIKELY	
1994		
September	Possible	Below average
October	A/AA	
November	Possible	
December	VERY LIKELY	

BAR = Below-average recruitment
A/AA = Average/above-average recruitment

DISCUSSION

Conventional empirical attempts to relate recruitment of pelagic fish to environmental factors have so far not been very successful. Although mathematical models may be used to investigate environmental variability (see Korrûbel 1992), rule-based systems may provide a more useful alternative for providing a structured approach to using environmental parameters to forecast recruitment. Rule-based systems are relatively easy to construct and they provide an easy way to furnish explanations (Hayes-Roth 1985). Furthermore, they are considered to be the best approach for formalizing and coding problem-solving expertise (Hayes-Roth *et al*. 1983), and are a useful approach for interpreting a broad range of variables. Notable success has been achieved in other studies predicting the effects of biotic and abiotic factors (see Starfield *et al*. 1989, Starfield 1990, Collopy and Armstrong 1992).

The approach adopted in this study indicates the usefulness of the expert system for synthesizing a broad range of biological and environmental variables that may affect recruitment success of anchovy in the southern Benguela. It is clear, however, that this approach needs further refinement in order to provide reliable forecasts of anchovy recruitment. Direct comparisons of forecasts of anchovy recruitment obtained in this study with final estimates of recruitment were difficult owing to the monthly nature of the results presented. Consistent forecasts of below average recruitment (as for 1994) justify a final forecast of BAR. Variable forecasts of anchovy recruitment for 1995 from monthly field data do not allow for an easily justifiable final forecast and indicate that caution should be exercised when using results from a single survey to forecast recruitment for the following season. Model results from three of the four months indicated that recruitment for 1995 would be below average. Model results from October indicated that recruitment would be average or above. If the spawner biomass survey had been conducted during October, it is likely that incorrect forecasts of anchovy recruitment would have been made for the following year.

Notwithstanding any of the above, the estimates of anchovy recruitment in 1995 raise a number of important issues. Although final estimates of recruitment (197 billion fish) indicated that recruitment in 1995 was below average, the recruitment estimate of 402 billion anchovy obtained during the midyear hydro-acoustic survey (Fig. 7a) indicated that recruitment in 1995 was in fact above average. The twofold difference between the observed and final estimates of recruitment could be largely attributable to the assumptions used in the calculation procedures used. In essence, the final estimates of recruitment are obtained from a simulation model of anchovy population dynamics, using the results of both the recruit and subsequent spawner biomass surveys, once they are available, and assuming a constant rate of natural mortality of $1.2 \cdot \text{year}^{-1}$. In 1995, the biomass of recruits during the midyear survey was high (622 000 tons). However, by the end of the year, the biomass of the spawner stock was low (432 000 tons, SF unpublished data). In the absence of data on higher-than-normal rates of natural mortality of anchovy recruits (e.g. as a result of predation or environmental anomalies), modelling procedures resulted in a final estimate of below-average recruitment for 1995. Hutchings *et al.* (1998) proposed high predation losses as a result of unusually high abundance of snoek *Thyrsites atun* in the latter half of 1995. Higher-than-normal rates of mortality of anchovy as a result of predation would have resulted in an underestimate of anchovy recruitment for 1995 by the modelling procedures used to provide the final estimates of anchovy recruitment strength in the southern Benguela.

Alternatively, the sudden decline in anchovy population size during the latter half of 1995 could have been a result of migration of juvenile and/or adult fish out of the region and into an area not covered by the survey. For example, during the November 1996 survey, only 20% of the anchovy stock was located in the traditional anchovy spawning area west of Cape Agulhas. The bulk of the stock was east of Cape Agulhas and appeared to extend past the eastern limit of the survey area (SF

Table V: Sensitivity tests – decision table based on SARP results using (top two panels) a starvation index for anchovy only and 16°C isotherm data from 33°S, (middle two panels) a starvation index for all pelagic species combined and 16°C isotherm data from 34°S, and (bottom two panels) a starvation index for anchovy only and 16°C isotherm data from 34°S. An "active" variable (✓) contributes to below-average recruitment, whereas an "inactive" variable (×) does not

Month	% Starvation stations	Oil yield	Atresia	Egg production	Southerly wind index	16°C Isotherm
			1993; anchovy only; 33°S			
August	×	✓	–	✓	×	×
September	✓	×	×	×	×	×
October	✓	✓(Zero)(??)	–	×	✓	×
November	×	✓(Zero)(??)	✓	×	×	×
December	–	✓(Zero)(??)	✓	×	✓	✓
			1994; anchovy only; 33°S			
September	×	×	✓	✓	×	×(??)
October	×	×	×	×	×	×(??)
November	×	×	✓	×	×	✓
December	–	–	–	✓	✓	✓
			1993; all pelagics; 34°S			
August	✓	✓	–	✓	×	×
September	✓	×	×	×	×	×
October	✓	✓(Zero)(??)	–	×	✓	×
November	×	✓(Zero)(??)	✓	×	×	×
December	✓	✓(Zero)(??)	✓	×	✓	✓
			1994; all pelagics; 34°S			
September	×	×	✓	✓	×	×(??)
October	×	×	×	×	×	✓
November	×	×	✓	×	×	✓
December	×	–	–	✓	✓	✓
			1993; anchovy only; 34°S			
August	×	✓	–	✓	×	×
September	✓	×	×	×	×	×
October	✓	✓(Zero)(??)	–	×	✓	×
November	×	✓(Zero)(??)	✓	×	×	×
December	–	✓(Zero)(??)	✓	×	✓	✓
			1994; anchovy only; 34°S			
September	×	×	✓	✓	×	×(??)
October	×	×	×	×	×	✓
November	×	×	✓	×	×	✓
December	–	–	–	✓	✓	✓

– = No data
Zero = Zero data value
?? = Possibly spurious data

unpublished data). The highest densities of fish on the eastern Agulhas Bank (between Cape Infanta and Plettenberg Bay) during November 1996 appeared to be in a filament of the Agulhas Current, indicating eastward current flow. This may have resulted in aggregation of fish farther east, far beyond the limits of the southern Benguela upwelling region. For a species adapted to an upwelling environment, future reproductive success on the warmer South and East coasts remains unclear.

Data limitations

Results of studies such as this are clearly dependent upon the assumptions and variables used in the model. For example, it was assumed that increased southerly wind stress results in increased offshore advection of fish eggs, which are then lost from the system. However, Cochrane and Hutchings (1995) also discuss an alternative hypothesis (Shannon 1985) that strong southerly winds in early summer (October – December)

Table VI: Forecasts of anchovy recruitment made from SARP results using isotherm data from 34°S and starvation indices for all pelagic fish and for anchovy only (see Table V). Forecasts based on Table V are shown on Table IV. Observed recruitment is shown for the following year

Month	Forecast of BAR	Observed recruitment
1993		
August	LIKELY	Below average
September	Possible	
October	LIKELY	
November	Possible	
December	VERY LIKELY	
1994		
September	Possible	Below average
October	Possible	
November	Possible	
December	VERY LIKELY	

BAR = Below-average recruitment

result in the development of the Cape Columbine jet, which moves eggs and larvae northwards and inshore to the nursery area, resulting in their retention in the system. Fowler and Boyd (1998) also suggest that, under certain conditions, eggs transported offshore from the Cape Peninsula region may be returned to the system farther north.

A number of problems were evident in the reliability of the data for the indicators under analysis. Consequently, data thought to be unreliable were flagged as possibly spurious in the decision tables (e.g. Table III). The main areas of concern were for the data on oil : meal ratios and estimates of the distance offshore of the 16°C isotherm. Owing to sampling and processing procedures adopted by the industry (Cochrane and Hutchings 1995), oil : meal ratios obtained from this source may not be reliable indicators of fish condition. As a result, zero values for oil : meal ratios in October, November and December of 1993 (Fig. 3) were considered spurious in the present study. Schülein *et al*. (1995), however, analysed annual oil cycles of pelagic fish and showed that oil : meal ratios declined during the spawning season, primarily as a result of the transfer of energy reserves for gonad development. This indicates that the values used here may be realistic.

The offshore position of the 16°C isotherm served as a very useful index for upwelling and transport success in this study. However, estimates of the isotherm position at a particular latitude may be affected by local variations in upwelling. Close inspection of the plots of sea surface temperature indicates that a more reliable proxy for upwelling will be obtained if the average isotherm position is estimated over a larger area.

Field data obtained during SARP cruises are also subject to a number of limitations. The starvation indices used here provide only a crude index of the food available to the fish. Richardson *et al*. (1998) used field measurements of copepod egg production and moulting rates to improve the precision in estimating the availability of food to fish. However, these measurements are prohibitively time-consuming and cannot be incorporated into routine monitoring studies easily. The incidence of gonad atresia in female anchovy during each of the SARP surveys was difficult to quantify for a number of reasons, including low densities of anchovy in the survey area (see Painting *et al.* in press b). With the exception of the November surveys, the atresia, results presented here are not statistically significant (Y. C. Melo, SF, pers. comm.). Average abundance of anchovy eggs was also difficult to quantify, largely because of spatial patchiness in egg distribution (see Painting *et al.* in press b). Coefficients of variation of the means (*CV*s) during each cruise were unacceptably high for calculation of statistically valid mean egg densities.

Evaluation of the expert system approach, and future studies

Although only six variables were selected for use in this study, it must be emphasized that fish production may be impacted by a suite of variables, which may vary from time to time (Cochrane and Hutchings 1995). Furthermore, at any given time these variables may act in isolation or together (Hutchings 1992). An expert system is particularly useful in this regard, because rules may be added easily with little disturbance to the system (Hayes-Roth 1985).

Analysis of the field data in this study was predominantly semi-quantitative and qualitative in nature, because the data were generally not suitable for use directly in the mathematical and statistical methods currently used for management purposes. Nevertheless, this approach provides real and valuable information that should be utilized to provide insights to the recruitment process (see Hilborn 1992).

Results of this study indicate that a number of key variables may be useful indicators of forthcoming recruitment strength. Of the six variables used, four were relatively difficult to monitor. Obtaining estimates of starvation indices, anchovy reproductive condition and egg abundance is time-consuming and labour-intensive, and there is considerable delay in producing the results needed for timeous forecasting. Although oil : meal ratios from commercial fisheries are useful indicators of fish condition, sampling and processing procedures impose limitations on their reliability (Schülein *et al*. 1995). Alternative approaches recently developed to obtain similar indices from individual fish during routine sampling of commercial catches and during research surveys (Cochrane and Hutchings 1995, Van der Lingen and Hutchings in prep.) may be useful in future studies.

The two variables which were relatively easy to monitor and which served as a useful proxy for upwelling were the position of the 16°C isotherm and southerly wind stress. The position of the 16°C isotherm appeared to be a driving variable in the recruitment process. Because of temporal variability in the offshore position of the 16°C isotherm at a particular latitude, this index is likely to be improved by estimating the average isotherm position over a larger area.

The expert system approach adopted in this study appears to be extremely useful for analysing field data on the biological and environmental factors affecting pelagic fish, and warrants further development. Future studies may be improved by weighting variables, or by refining the rules for defining below average recruitment. As a result of their successful bet-hedging strategies (Shelton 1987), anchovy may be able to maintain their population on the basis of only one month in which spawning and transport to the nursery grounds was successful. Additional refinements of the model will necessitate further testing against field data, and it is important that the relevant field studies are ongoing. Improved forecasting abilities from field data collected at frequent intervals during the spawning season will depend largely on the ability of future expert systems to synthesize the results from each sampling interval and to produce a single forecast that may be compared with the single final estimate of recruitment strength.

CONCLUSION

Results of this study indicate that field measurements of biological and environmental variables obtained during the anchovy spawning season may be used in a structured manner to obtain a forecast of anchovy recruitment to the fishery during the subsequent season. These forecasts may be extremely valuable in the management of the resource.

The deterministic rule-based expert system (Korrûbel 1995) used in this study produced forecasts of anchovy recruitment from field data obtained on a monthly basis during the preceding spawning season. Forecasts from the expert system compared favourably with final estimates of recruitment for 1994. In general, forecasts for 1995 also compared favourably with final estimates of recruitment. A forecast of average or above from one of the four months indicates that forecasts based on a single survey may be less reliable than forecasts based on a series of surveys. During the two SARP years analysed here, forecasts obtained from the November surveys compared favourably with the final estimates of recruitment.

The expert system included six environmental factors; *viz*. the distance offshore of the 16°C isotherm, southerly wind stress, anchovy egg abundance, percentage alpha-oocyte atresia, starvation index for pelagic fish, and commercial oil : meal ratio. Although these variables were identified as potential indicators of pelagic fish recruitment in an earlier study (Korrûbel 1995), this is the first attempt to use actual field data. The simplest approach was adopted here, with the use of unweighted variables. Future use of weighted deterministic and probabilistic models may yield further insights into the environmental and biological factors affecting recruitment.

Of the six variables selected for use in this study, the two which were easiest to monitor and which appeared to be useful indicators of the recruitment strength of anchovy during the forthcoming season were the offshore position of the 16°C isotherm and southerly wind stress. It is essential to future studies of anchovy recruitment success in the southern Benguela that monitoring of at least these two variables be continued.

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APPENDIX

Procedure followed when generating forecasts

The example illustrated here is that of the base-case system used to generate the forecasts seen in Table IV (based on the data in Table III) as per the rules in Table II. The procedure for generating the forecasts from Table V is similar.

Base-case 1993

August No data were available for atresia, so five indicators were used. Three of the five indicators were active (33%< x <66%), resulting in a forecast of LIKELY below-average recruitment.

September All data were available, so the full complement of six indicators was used. One of the six indicators was active (<33%), resulting in a forecast of POSSIBLE below-average recruitment.

October No data were available for atresia, so five indicators were used. Three of the five indicators were active (33%< x <66%), resulting in a forecast of LIKELY below-average recruitment.

November All data were available, so the full complement of indicators was used. Only two of the six indicators were active (<33%), resulting in a forecast of POSSIBLE below-average recruitment.

December All data were available. Five of the six indicators were active (>66%), resulting in a forecast of VERY LIKELY below-average recruitment.

Base-case 1994

September All data were available. Two of the six indicators were active (<33%), resulting in a forecast of POSSIBLE below-average recruitment.

October All data were available. None of the six indicators was active (0%), resulting in a forecast of ACERAGE/ABOVE AVERAGE recruitment.

November All data were available. Two of the six indicators were active (<33%) resulting in a forecast of POSSIBLE below-average recruitment.

December No data were available for oil yield or atresia, so four indicators were used. Three of the four indicators were active (>66%), resulting in a forecast of VERY LIKELY below-average recruitment.