Food, Transport and Anchovy Recruitment in the Southern Benguela Upwelling System of South Africa

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Abstract

Recruitment of the South African anchovy, *Engraulis capensis*, is related to two environmental indices. These are fish oil yields (measured as the oil-to-meal ratio from pelagic reduction factories) and south-easterly winds as measured at Cape Point lighthouse. The nature and appropriateness of these indices are discussed in terms of recent statistical studies on oil yields and modelling of advective processes on anchovy recruitment. The rationale for these relationships is that good oil yields are indicative of good food availability to the growing anchovy, whereas strong south-easterly winds yield poor (cool and turbulent) conditions for spawning and a greater risk of fish eggs and larvae being transported offshore into the deep ocean. In 1986 an intrusion of Agulhas water is believed to have upset both relationships, but they are still statistically significant over the entire time-period. Non-linear relationships between anchovy recruitment and south-easterly winds are also presented.

Résumé

Le recrutement de l'anchois d'Afrique du Sud, *Engraulis capensis*, est étudié en fonction de deux indices environnementaux : les rendements en huile de poisson (mesurés par le rapport entre l'huile et la farine de poisson dans les usines de réduction de poissons pélagiques) et les vents du sud-est à Cape Point Lighthouse. La nature et le caractère approprié de ces indices sont discutés à l'aide de récentes analyses statistiques sur les rendements en huile et la modélisation des processus d'advection et leur action sur le recrutement de l'anchois. Le raisonnement afférent à ces relations est que de bons rendements en huile indiquent une bonne disponibilité en nourriture pour la croissance des anchois, tandis que de forts vents du sud-est procurent des conditions défavorables (froides et turbulentes) et un risque plus grand pour les œufs et larves d'être transportés vers le large dans l'océan profond. En 1986, on pense qu'une intrusion des eaux provenant du courant des Aiguilles est susceptible d'avoir perturbé ces deux relations, mais elles restent cependant toujours significatives durant toute la période de temps considérée. Des relations non linéaires entre le recrutement de l'anchois et les vents du sud-est sont aussi présentées.

Introduction

This paper relates anchovy (*Engraulis capensis*) recruitment in the southern Benguela Upwelling System to the variables of food and transport. This is accomplished by providing evidence showing that these variables are indeed important to anchovy recruitment in the region, and by showing that the long-term indices taken to represent food availability and transport are appropriate. Thereafter, both linear and non-linear regressions between these indices and anchovy recruitment biomass and recruitment numbers are undertaken.

The Benguela Upwelling System is one of the world's four major eastern ocean upwelling systems (Parrish *et al.*, 1983) extending from southern Angola to south of Cape Town. It can be divided into a northern and southern region on either side of the Lüderitz upwelling cell (Fig. 1), on the basis of differences in meteorology and oceanography (Shannon, 1985) and largely separate fish stocks (Crawford *et al.*, 1987). The southern region differs from other systems in that it is bounded on its poleward margin by a warm water system caused by topography (the Agulhas Bank) and Agulhas Current leakage, and therefore is subject to both South Indian and South Atlantic influences (Shelton *et al.*, 1985). Meteorologically it shows strong teleconnections with El Niño/Southern Oscillation (ENSO) cycles (Taunton-Clark, in prep.). The northern region is more affected by the oceanic "Benguela Niño" phenomenon (Shannon *et al.*, 1986).

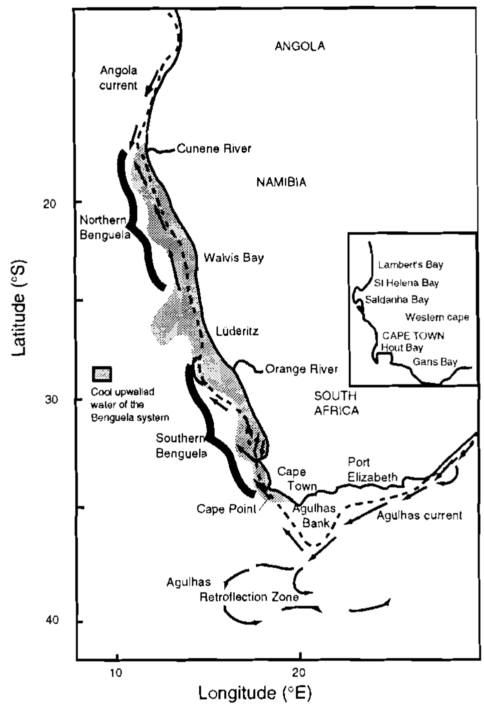


Fig. 1: The major currents off Southern Africa's west coast and the Benguela upwelling system showing the division into northern and southern regions, and the major fishing ports (adapted from Siegfried *et al.*, 1990).

The pelagic fishery in the south was dominated by anchovy from 1967 to 1993, following a period of dominance by sardine *Sardinops sagax* (Schülein *et al.*, 1995). Extensive multidisciplinary research into the recruitment processes of anchovy has been undertaken subsequent to direct acoustic surveys of the resource, which commenced in 1984, showing the stock to be both larger and more variable than previously thought (Hampton, 1987). In particular, the anchovy recruitment failure of 1989 was closely examined and postulated to be due largely to a lack of food for spawning adults during the peak spawning period in that year (Hutchings and Boyd, 1992). However, the study by the latter authors also identified larval transport and growth of recruits as potentially important variables. Bloomer *et al.* (1994) investigated the prediction of recruitment by means of a rule-based model and emphasized the role of turbulence and larval transport, as affected by winds in the spawning and transport regions respectively. Cochrane and Hutchings (1995) have recently re-examined a larger list of environmental variables influencing recruitment of the southern anchovy stock.

The pelagic fishery of the northern Benguela, centered at Walvis Bay, was initially dominated by catches of sardine for a quarter of a century until 1977. Anchovy, although caught since 1970, were only dominant from 1978 to 1984, apart from a single good recruitment in 1987. The life history of anchovy in the northern system is similar to that off Peru and California, in terms of upwelling providing food, but also bringing about losses of spawning products. In addition, the region is subject to strong interannual oceanic advection events called Benguela Niños (Stander and De Decker, 1969; Shannon *et al.*, 1986; Boyd *et al.*, 1987), which severely restricted productivity and led to an anchovy recruitment failure in 1984 (Boyd *et al.*, 1985).

Direct field evidence of a food limitation for anchovy in the Benguela system is hard to obtain and therefore various proxies for feeding, such as the oil content of pelagic fish from commercial landings, as well as oocyte atresia of spawners in the spawning season, have been used as surrogates. The former data set of oil yields covers both the northern and southern Benguela since 1951 (Fig. 2), and has recently undergone statistical analysis for seasonality, trend, anomalous years and coherence between ports (Schülein *et al.*, 1995). In the present study, we follow-up the work of Schülein *et al.* (1995) and use oil-to-fishmeal ratios of pelagic fish landings as an index of feeding.

The other variable which we address is transport, with the index used being restricted to the southern Benguela, namely south-easterly winds at Cape Point during the anchovy spawning season. However, the rationale for selecting transport as an important variable, and its apparent correspondence with south-easterly winds, is supported by extensive simulations done for this study using a computer model developed by Nelson and Shannon (1994). This model, fully described by Shannon (1995), utilizes four years of current measurements on the South African shelf (Boyd and Oberholster, 1994) to obtain a mean flowfield, and computes anchovy egg production based on seven years of spawner distributions. Batches of anchovy eggs are released and transport is simulated through the mean flowfield, upon which various perturbations are superimposed.

1. Environmental indices and data sources

1.1. Oil-to-meal ratios of pelagic fish in the northern and southern Benguela (Schülein *et al.*, 1995): an index of feeding

Oil-to-meal data are collected on a monthly basis from pelagic fish reduction factories at seven ports from Walvis Bay in Namibia to Gans Bay on the Cape south coast. The time-series for the four Western Cape ports (excluding Cape Town and Gans Bay- see Fig. 1) are also averaged into a single index (as shown in Fig. 2).

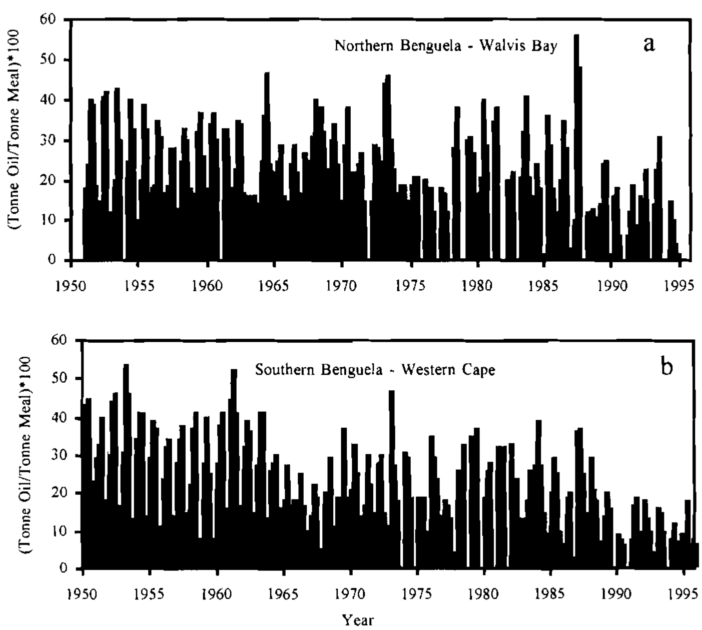


Fig. 2: Monthly oil-fishmeal ratios (tonne oil x 100/tonne meal) in the northern (a) and the southern Benguela systems (b) (after Schülein *et al.*, 1995).

The monthly data were fitted with a Fourier (sine/cosine) model to take into account seasonality (and the fact that data were not available for all months of the year), and either a long-term linear trend or year factors showing anomalous years (Fig. 3). The coherence between ports was investigated by correlating the residuals resulting from fitting autoregressive models to the year factors from the different ports.

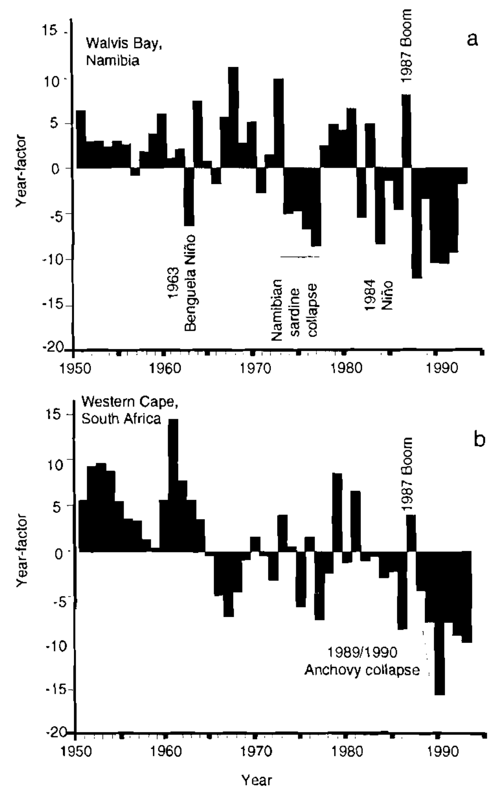


Fig. 3: Oil yield year-factors from the northern (a) and the southern Benguela systems (b), 1951-1993 (adapted from Schülein *et al.*, 1995).

Schülein *et al.* (1995) report a strong seasonal signal in oil-to-meal ratios, ranging from 37% of the amplitude at Walvis Bay to between 43 and 50% at the ports of the Western Cape. The peaks in the phases off the Western Cape show a high degree of coincidence moving southwards with the arrival of recruits in the catches (Hampton, 1987). The degree of coincidence of years of high and low oil yields in the Benguela system is of much interest in assessing the scale of spatial coherence of the phenomena, such as was done for sea surface temperature by Taunton-Clark and Shannon (1988). Coherence between Walvis Bay in the northern Benguela and the average for the western Cape ports over the period 1951 - 1993 is statistically significant (r=0,51). However, Gans Bay (on the Cape south coast and subject to Agulhas Bank hydrology) only showed weak coherence with the closely adjacent Benguela system ports (see Fig. 1), underscoring the different ecosystem forcing between it and the Benguela region. Northern/southern coherence values were not high, with the common variance explained being approximately 25%. This level of coherence is thought to be caused by the occurrence of both Benguela wide signals (e.g., 1987) as well as oceanic events such as Benguela Niños (Shannon *et al.*, 1986), which are mainly restricted to the northern region and are associated with reduced productivity (e.g., 1963 and 1984; Stander and De Decker, 1969; Boyd *et al.*, 1985).

Despite the evidence resting mainly on the studies of the Benguela Niño events in the north and the 1989 collapse in the south, Schülein *et al.* (1995) argue that the oil-to-fishmeal time-series is an index reflecting the successful feeding of the pelagic fish stocks and therefore the ecological health of the ecosystem.

1.2. Transport of anchovy eggs and larvae in the southern Benguela: does modelling suggest transport that affects recruitment?

In the southern region, the transport of anchovy eggs and larvae from their spawning ground on the Agulhas Bank to the Cape west coast nursery grounds is due to equatorward alongshore transport in a frontal jet system (Bang and Andrews, 1974; Crawford, 1980; Shelton and Hutchings, 1982; Boyd *et al.*, 1992; Hutchings and Boyd, 1992) (Fig. 4). This well-described process has recently been modelled using an averaged and interpolated Acoustic Doppler Current Profile (ADCP) flowfield for transport (Fig. 5). This flowfield was recently adjusted by minus 3° in current direction to counteract an incorrect offset for ADCP transducer alignment for part of the study period (when the offset was 2° instead of -2° or -3°). Currents incorporated were predominantly bottom-referenced, allowing simple correction. The biological processes incorporated in the model are listed in Appendix A. Runs with this model, including percentage-wise strengthening and reduction of the East/West orientated components of the (uncorrected) flowfield, suggested little variability in anchovy year-class strength attributable to variation in transport processes (Crawford *et al.*, 1995). This result was viewed with some sceptism on account of the importance attached to transport in the descriptive studies referred to above, and because there already exists some evidence of an inverse relation between anchovy recruitment and the strength of upwelling winds in the spawning region, although not the transport region (Bloomer *et al.*, 1994).

In 1994, the ENSO high phase coincided with strengthened SE (upwelling) winds after three years of below-average winds during its low phase (Fig. 6), and it coincided with the worst anchovy recruitment since measurements began in 1984 (and possibly in two decades). Environmental causes were sought and the advection model and its application were examined more critically. In the first instance, modifications to the flowfield were made to tune results to obtain a more realistic spatial distribution of recruitment and advective losses using the extensive 1991 spawner distribution. The 'weakness' of the original (uncorrected) flowfield was viewed as the complete absence of advective losses west of Cape Agulhas. Hence,

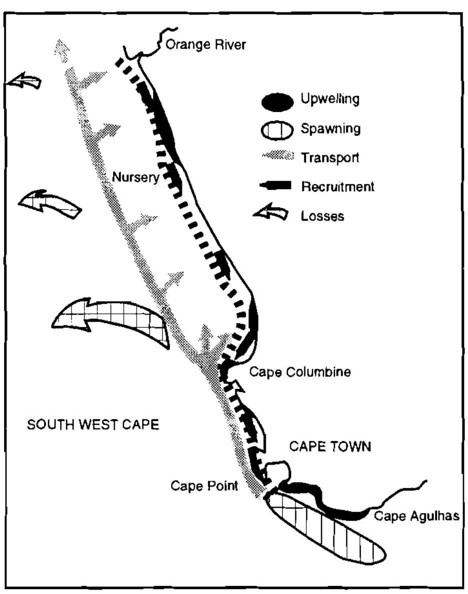


Fig. 4: The various life history stages of the anchovy *Engraulis capensis* in the southern Benguela (after Hutchings and Boyd, 1992).

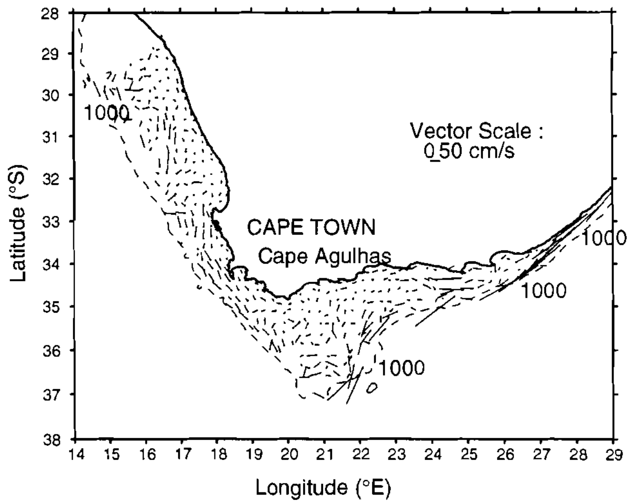


Fig. 5: Currents at 30 and 50 m depth for spring and summer, measured by Acoustic Doppler Current Profiler on *F.R.S. Africana* from November 1989 to March 1993 (during austral spring and summer), and upon which the flowfield in the model was based. Note that , in this figure, the vectors are 3° biased in a positive sense. The currents flow away from the dot.

mainly westward advection was added until greater spatial realism in the distribution of recruits and losses was considered to have been achieved. At the time, justification for this process was the fact that most of the ADCP flow field data had been collected during the El Niño years of 1990/91 - 1992/93, which show a greater amount of onshore (NW) winds than do non-El Niño years (Fig. 6). In addition, flow above the 30 - 50 m reference depths may well have been directed more offshore because of the direct influence of upwelling winds causing Ekman drift in the upper layer. The 3° (generally onshore) offset of the uncorrected field would also have played a small role. The development of a modified flowfield (relative to the uncorrected one), as described by Shannon (1995), was eventually accomplished by adding velocity components as shown in Figure 7. This done, the model was run using seven actual spawner distributions under the following flowfields: 1) the uncorrected flowfield, 2) the corrected flowfield and 3) the field based on additions to the uncorrected flowfield. Differences can be seen in Table 1. The results are similar for both the uncorrected and corrected flowfields (mean difference between the two recruitment values is 1.3%, although a paired t-test showed the difference to

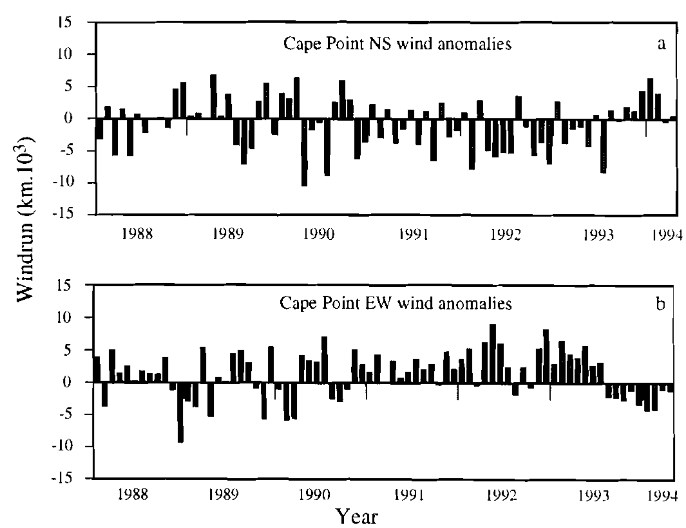


Fig. 6: Monthly N/S (a) and E/W (b) wind anomalies at Cape Point from January 1988 to April 1994. Positive anomalies indicate stronger winds from the south and west.

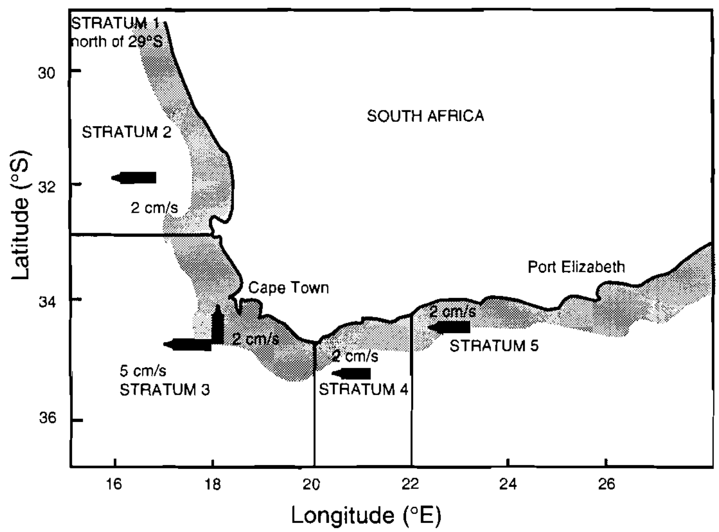


Fig. 7: Modifications to the uncorrected ADCP velocity field shown in Fig. 5 and used in the simulation of transport under non-El Niño conditions (during which higher advective losses could be expected).

be significant at the 5% level - the corrected field yielding slightly lower recruitment than the uncorrected field). The modified field resulted in markedly smaller or poorer recruitment but also substantially more variability in recruitment numbers, which now vary by a factor of two and indicate transport to be important variable in the recruitment process.

Spawning/ Recruitment	'Uncorrected' 'Reduced' advection scenario	'Corrected' 'Reduced' advection scenario	Modified advection scenario
1986/87	470	468	122
1987/88	475	461	179
1988/89	420	420	139
1989/90	469	465	135
1990/91	484	484	214
1991/92	441	431	200
1992/93	473	464	219
Seven years mean	462	456	173
Standard deviation of mean	23	23	40
Coefficient of variation (%)	5	5	23

Table 1: Summary of recruitment results (numbers x10^9) from application of anchovy model to various flowfields (see text).

1.3. Anchovy recruitment

Recruitment numbers and biomass were estimated from hydro-acoustic surveys (Hampton, 1992 and 'Pelagic Working Group documents of the Sea Fisheries Research Institute') conducted since 1984 between Cape Agulhas and the Orange River. The present study uses these survey estimates directly for correlation with the environmental indices, in contrast to Cochrane and Hutchings (1995) who used population model estimates of recruitment.

2. Linear correlation of anchovy recruitment with indices of transport and food

The recruitment numbers from acoustic surveys were found to vary by a factor of five and also relate inversely to the SE wind record (Fig. 8). Similar relationships had been proposed previously by various authors (e.g., Boyd (ms), Cochrane and Hutchings, 1995), but the statistical significance of this specific correlation was established by the 1994 data point (even when the 1986 outlier was included). This outlier corresponded to an intrusion of Agulhas Current water as far as southern Namibia (Shannon *et al.*, 1990) which, despite strong SE winds, could have restricted advective losses. If this point is excluded, the correlation is even more 'significant', as shown in Figure 9. The general division into two groups, namely poor recruitment and average-to-good recruitment, as well as the outlying good recruitment, can clearly be seen in this figure.

This result had a feedback effect on the way the advection model was viewed. Instead of searching for a single flowfield representative of average conditions, the possibility of the different flowfields shown in Table 1 pertaining to various years in a flip-flop scenario within the period 1987-1993, as shown schematically in Table 2, was now favoured. The latter table shows results using only the corrected and the modified ADCP flowfields. In particular 1989, but also 1990 and 1992 were years of high advective loss (Shannon *et al.*, in press), the former two coinciding with moderate to high SE winds, whereas 1987, 1988, 1991 and 1993 were years of low advective losses. This did not match the model completely, because high advective losses were also shown by the model following the extensive spawning of 1991/1992. Nevertheless, because of non-linear mortality, these losses did not reduce recruitment to the same extent as in 1988/1989 and 1989/1990.

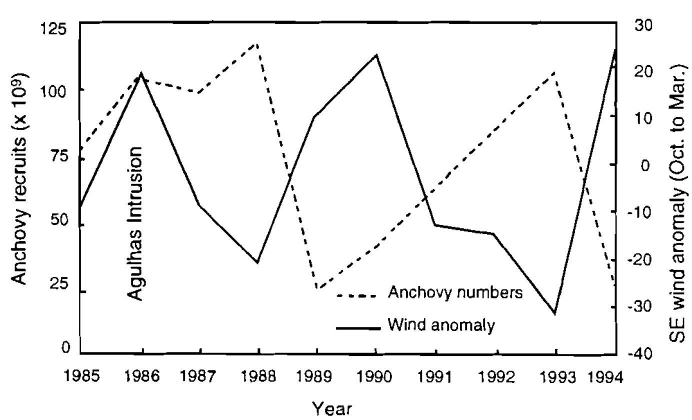


Fig. 8: Time-series of the numbers of anchovy recruits (billions) measured during winter hydro-acoustic surveys and the cumulative October to March SE wind anomaly measured at Cape Point, 1985-1994.

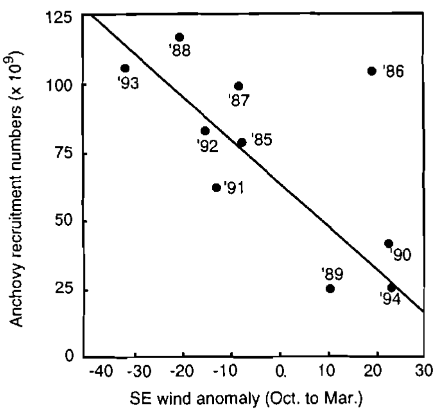


Fig. 9: Correlation between anchovy recruit numbers and the spring/summer SE wind anomaly at Cape Point. The line is drawn excluding the 1986 data point (see text), although the correlation coefficients are given for this point excluded ($r=-0.88$; $n=9$; $p<0,005$), as well as for it being included, ($r=0.65$; $n=10$; $p<0,05$).

Spawning/ Recruitment	(Corrected) 'Reduced' advection scenario (numbers x10^9)	Modified advection scenario	Observed trends (Figures 8 and 9)
1986/87	468*	122	Low SE wind - High recruitment
1987/88	461*	179	Low SE wind - High recruitment
1988/89	420	139*	High SE wind - Offshore spawning Low recruitment
1989/90	465	135*	High SE wind - Low recruitment
1990/91	484*	214	Low SE wind High number of recruits
1991/92	431*	200	Low SE wind - good spawning and recruitment on central Agulhas Bank
1992/93	464*	219	Very low SE wind - High number but low biomass of recruits

*: suggested flowfield domain

Table 2: Summary of recruitment results from application of the model to two different flowfields (see text) and comparison with observed wind and recruitment, and inferred flip-flop scenario.

The conclusion of the modelling and correlation exercises (Fig. 8 and 9, Table 2) is that advective losses could indeed have a significant influence on anchovy recruitment numbers in the southern Benguela during periods of strong SE winds coinciding with the global signal of ENSO high phase. Local SE winds appear implicated in the process, as shown in the regression in Figure 9 (excluding the 1986 data point), with the 1986 outlier showing the occasional strong affect of oceanic advection.

The food index, namely the oil-to-meal ratios for the Western Cape, was correlated against anchovy recruitment biomass, also from the acoustic surveys, from 1985 to 1994. This resulted in a significant relationship, even when only the first four months of the year are used (Fig. 10). The correlation (r=0.69, n=10, Fig. 11) also shows the potential for oil yields to be used as a mid-season predictor of total recruitment biomass. Annual data could also be used as a proxy for recruitment in longer-term studies, because linear regression of recruitment biomass against mean annual oil yields and "year-factors" yielded r values of 0.74 and 0.72 respectively, although these indices could not be used in any predictive sense. The pelagic fish catches from the Western Cape west coast ports largely exclude the spawning fish, which are mainly found on the Agulhas Bank, although some spawning sardine are caught, as well as adult red-eye and juvenile horse mackerel, particularly in the first few months of the year.

Fig. 10: Time-series of the biomass of anchovy recruits measured during winter hydro-acoustic surveys (thousand tonnes) and the oil-to-fishmeal ratio between January and April from western Cape ports (excluding Gans Bay).

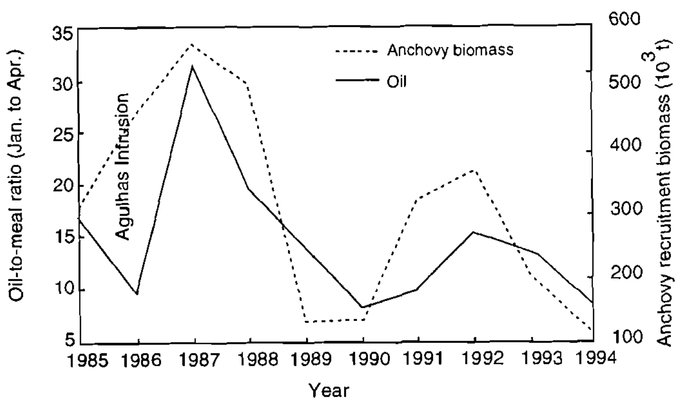
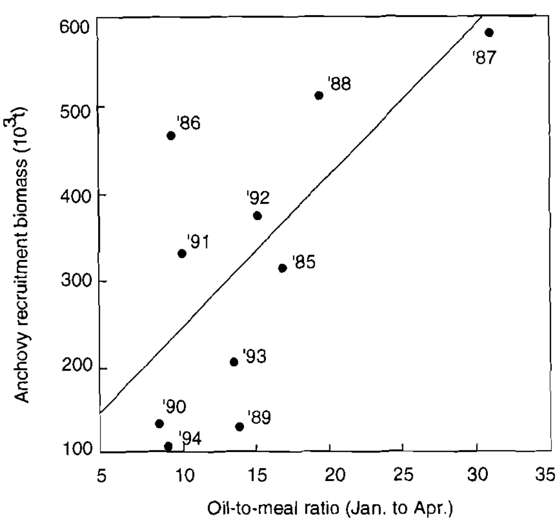


Fig. 11: Correlation (r=0.69; n=10; p<0.05) between the oil-to-fishmeal ratio from January to April and the biomass of anchovy recruits measured during winter hydroacoustic surveys (thousand tonnes).



3. Non-linear relationships

In terms of Optimal Environmental Window (OEW) models (Cury and Roy, 1989), the 1993 data point, with high numbers but an even lower biomass of recruits, is the only one that would appear to lie to the left of the dome. Recruitment in all other years falls either in the centre or to its right. This was tested using ACE methods (Cury *et al.*, 1995), with the anchovy biomass data being related to the wind index. The result is shown in Figure 12a. When numbers were considered, the transformation was basically linear for both variables, resulting in virtually the same negative relationship (Fig. 12b). However, an ACE regression of anchovy biomass against both wind and oil yield (not shown here) suggested that the positive relationship against oil-yield was dominant.

Additionally, in OEW models the factors of upwelling wind and food abundance are held to be positively correlated (i.e., more wind, more food). However, the wind and oil data presented here showed an insignificant inverse relationship when correlated linearly. This suggests that, in this southern Benguela model, the food and wind indices are not tightly coupled and that oil yield is acting more as a proxy for recruitment. Therefore, SE winds could possibly be the dominant independent factor, but both wind and food indices are nevertheless still subject to being overruled by oceanic advection in certain years such as 1986.

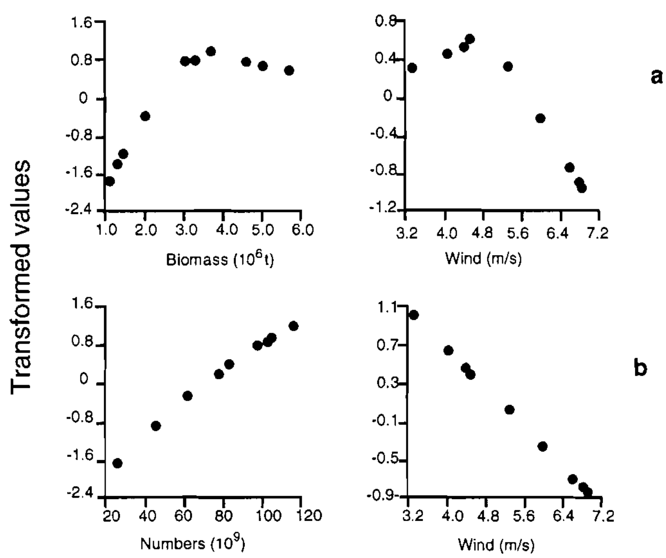


Fig. 12: Plot of the ACE transformation of anchovy recruit (a) biomass and (b) numbers and mean SE winds ($m.s^{-1}$) from October to March in the southern Benguela.

Discussion

The South African anchovy fishery relies mainly upon catching the annual recruitment run, and TACs are based upon hydroacoustic estimates of recruitment undertaken in the middle of the fishing season. (Hampton, 1992). However, advance knowledge of recruitment would be of great value (Cochrane and Starfield, 1992).

In relating environmental factors to fish recruitment there is often the problem of which came first, the index which correlates with recruitment or the rationale for choosing a suitable index. In this instance, we were fortunate, but also restricted, in having a single, long time-series of fish oil-to-meal ratios which could be used as a food index and an appropriate long term wind record which appears to tie in with transport. Rationale involved choice of the temporal and spatial averaging in producing the indices.

The approach we took here with regard to the oil data differs fundamentally from previous studies (e.g., Cochrane and Hutchings, 1995) which looked at the oil yields of the previous year as a potential predictor of the recruitment the next year. (Such studies argued that high oil yields operating through adults having sufficient lipid reserves would lead to successful spawning and thereafter to good feeding for juveniles). By choosing oil-yields from the pre-recruitment period (although from fish of commercial size), we delay any forecast but hopefully make the relationship more robust. Both approaches do have problems, however. In order to justify using oil-yields to indicate likely future spawning success, the fishery would have to target on these spawners to a far greater extent than the SA pelagic fishery does. On the other hand by using the oil data from largely before the beginning of the season to indicate recruitment (as done here) we implicitly suggest a common favourable environment for adults of various species and anchovy pre-recruits.

With regard to the wind index, the transport rationale is generally given an equal or lesser rating than wind-driven turbulence, as described by Lasker (1975, 1978). We do not exclude the possibly important effect of turbulence on recruitment, but rather show that advective losses arising from the position of spawners in the flowfield can, and perturbations of the surface flowfield attributable to winds could, lead to a good proportion of the observed recruitment variability. The recruitment of anchovy, and possibly other pelagic species, could be investigated in the future by using the model to simulate transport under different flowfield scenarios, which could arise as a result of a changing global climate. Future work could build upon the use of oil-yield data as a proxy for anchovy recruitment and investigate the relationship of this variable, as dependent upon SE winds, using a longer time-series.

Lastly, it should be mentioned that, although SE winds can be strongly implicated in the anchovy recruitment failure during 1994 (through transport and/or turbulence), additional factors have been proposed by some of our colleagues. These include the possibly poor condition of young spawners and the sharp divide between very cool upwelled and warm Agulhas water in the spawning area, leading to fish being relatively far offshore in a small region of favourable temperatures. This anomalous year merits a study in its own right, particularly because it was studied by means of eight consecutive monthly cruises throughout the spawning season as part of the South African Sardine and Anchovy Recruitment Prediction programme. This programme also addresses the sardine, the spawning biomass of which had, by late 1994, reached the same as that of anchovy for the first time in over 25 years. Whilst the increase in sardine, resulting from conservative management plus unknown environmental cues is to be welcomed, it may affect the relationship between oil-yield data and anchovy recruitment, if anchovy are no longer the main contributor to the pelagic reduction plants.

Acknowledgments

G. Nelson is acknowledged and thanked for constructing the anchovy transport model used in this study, and for his guidance in the project. We are grateful to L. Underhill for his statistical advice in the oil-yield project which forms part of this paper. The Benguela Ecology Programme is thanked for funding enabling A.J. Boyd to attend the First International CEOS meeting held in California in September 1994, and at which this paper was presented.

APPENDIX: MODELLING TRANSPORT OF CAPE ANCHOVY, *ENGRAULIS CAPENSIS*, OFF THE COAST OF SOUTH AFRICA

This model was developed by G. Nelson and L.J. Shannon of the Sea Fisheries Research Institute, Cape Town, in order to address the following questions:

(1)How does the interannual variation in spatial distribution of spawners influence recruitment and the spatial distribution of young-of-the-year anchovy?

(2)What are the effects of altered advection on anchovy recruitment?

The oceanic area around South Africa was divided into quarter-degree (latitude and longitude) blocks, to which spawner biomass and current data were allocated based on two data sets, namely Acoustic Doppler Current Profile (ADCP) data and November spawner biomass survey data. Each simulation involved selection of one of the historical spawner distributions between 1986 and 1992. Egg production in each block was then calculated from the spawner biomass measured there in that year, for each day within the spawning season (October - March). Egg production also depends on the fraction of females spawning each day of the spawning season, the number of eggs spawned per female per batch and the female ratio. Transport of reproductive products was simulated on an hourly time-scale from time of spawning until recruitment to the purse-seine fishery, assumed to take place after six months. Monte Carlo simulation of eddies and filaments and of smaller-scale diffusion was also included in the model. Numbers of anchovy were reduced by hourly mortality owing to factors other than advection. Batches crossing the offshore boundaries beyond where anchovy survive were considered to be lost to the system. Differential mortality, predation and swimming capability (of older juveniles) were omitted from this application of the model.

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