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SEASONAL AND INTERANNUAL VARIABILITY IN WIND FIELD AND COMMERCIAL CATCH RATES OF *AUSTROGLOSSUS PECTORALIS* (SOLEIDAE)

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The impact of deviations in the direction and strength of the wind field on the spatial, seasonal and interannual variability in catch rates of Agulhas sole *Austroglossus pectoralis* was investigated. Temporal variability in the wind cycle on the Agulhas Bank during the period 1981–1996 was deduced mainly from trends in the pressure gradient, measured from south of Cape Agulhas (35°S) to the region of westwind drift (40°S). Because interannual deviations in the catch rates differed between seasons, catch rates were assessed by season. Coastal catch rates of Agulhas sole between Cape Agulhas and Cape Infanta were high in autumn and winter, when offshore north-westerly winds prevailed, and low in spring and late summer, when onshore south-easterly winds dominated. There was often a secondary peak in catch rates in November–December, coincident with a midsummer change in the pressure gradient. Between the period 1982 and 1996, catch rates in autumn and early winter (April–July) were highest during years when the winter north-westerly winds were strongest ($r^2 = 0.62$, $p < 0.01$). Catch rates usually peaked in May–June. This pattern changed in some years, depending on the timing and rate of change to winter wind conditions. Seasonal and interannual fluctuations in catch rate are associated with deviations in the wind field, but the mechanism whereby this effect is mediated remains unknown.

The Agulhas sole *Austroglossus pectoralis* is a small, but commercially important, component of the inshore Agulhas Bank fisheries. The landed mass is only about 5% of the total inshore demersal trawl catch (75-mm mesh, Japp *et al*. 1994). During the period 1963–1996, the annual catch ranged between 445 and 1 040 tons (Botha 1977, Badenhorst and Sims 1982, Badenhorst 1985, Payne 1986, Table I). The annual catch has been limited by quotas since 1978, and recently, in the interest of industrial stability and because assessment results did not necessitate a substantial change, the Total Allowable Catch (*TAC*) has been maintained at 872 tons (Table I). Whenever the *TAC* was exceeded, the overcatch has been compensated for in the following year.

Catch rates of Agulhas sole vary with season, depth, sediment type and locality (Badenhorst and Smale 1991, Le Clus *et al.* 1994, 1996, Le Clus and Roberts 1995). Sole are more available on the trawling grounds at certain times of the year, resulting in greater variability in catch rates between months than between years (Badenhorst 1986, 1987, Table II). This creates difficulties for fishermen, who prefer to catch sole where and when concentrations are high enough for fishing to be economically viable. There were also periods when annual catch rates were higher than the immediately preceding and subsequent years (e.g. 1966–1967, 1975–1976, 1980–1982, 1989–1990, 1995–1996, see Table I), making interpretation of trends in stock abundance problematic. Therefore, a better understanding of environmental factors, such as wind, which may influence seasonal and annual changes in sole catch rates, should assist both managers and scientists in uncoupling short-term fluctuations in catch rates from real changes in abundance.

Wind may be a key determinant of ocean variability over a wide spectrum of time and space. Changes in longshore wind have been identified as important for barotropic processes on the shelf, for surface drift and Ekman transport, for stratification and generally for upwelling and frontal dynamics (Shannon *et al.* 1990). Studies of wind in relation to fish behaviour are few (Laevastu 1993), and only two studies have dealt with the effect of wind on catches of bottom fish (Harden Jones and Scholes 1980, Scholes 1982).

In this study, seasonal and interannual trends in catch rates of Agulhas sole and the associated variability in wind direction and strength were investigated. The specific aims were:

(i) to present the spatio-temporal variability in catches and catch rates;
(ii) to determine seasonal trends in catch rates in relation to wind direction;

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Table I: Annual catch, effort and catch rate (not standardized to the efficiency of a standard 400-ton vessel) and *TAC* in the Agulhas sole fishery on the Cape south coast (20–28°E) – peak catch rate for each period emboldened (updated after Badenhorst 1987)

Year	Catch (tons)	Effort ('000 h)	Unstandardized catch rate (kg·h^{-1})	*TAC*
1963	732	19	38.5*	
1964	690	–	–	
1965	841	24	34.7	
1966	575	15	**39.6**	
1967	520	12	**41.8**	
1968	445	13	34.6	
1969	642	20	32.9	
1970	663	22	29.7	
1971	877	25	35.0	
1972	1 044	37	28.0	
1973	961	73	13.2#	
1974	611	44	19.9	
1975	763	32	**23.7**	
1976	1 040	49	**21.4**	
1977	500	52	9.6	
1978	850	64	13.1	700
1979	899	49	18.2	700+150
1980	943	46	**20.3+**	900
1981	1 026	41	**25.3+**	900
1982	817	39	**20.8+**	930
1983	682	42	16.2	930+20
1984	857	53	16.2	930+20
1985	880	61	14.5	930+20
1986	796	54	14.8	930+20
1987	855	53	16.5	868
1988	839	50	16.8	868
1989	913	41	**22.2**	868
1990	808	39	**20.6**	834
1991	716	40	17.9	872
1992	704	38	18.4	872
1993	772	46	16.8	872
1994	938	52	17.9	872
1995	769	38	**20.8**	872
1996	909	45	**20.1**	872

* *Cpue* data for 1963–1972 were estimated from limited records and are not comparable to those for 1973–1996
\# *Cpue* data for 1973–1979 were estimated fom industry purchase records (Badenhorst and Sims 1982)
\+ *Cpue* data for 1980–1982 may be biased because the quality and return of drag sheet and landing data were poor, and allocation of target species was suspect

(iii) to assess interannual variability in catch rates in relation to deviations in direction and strength of the wind field.

THE DATA

The study area, catches and catch rates

The main trawling grounds for Agulhas sole are inshore on the central Agulhas Bank, between 20°40′ and 21°40′E (Fig. 1). Because there are no harbours along that coastline, most of the catches are landed at Mossel Bay (22°20′E) and, to a lesser extent, at Hermanus and Gans Bay (Fig. 1). The inshore trawling grounds are located mainly on deep, clayey silts (Fig. 1), but in some localities they extend to the adjacent sands, where the sediments sparsely cover the rocky sea bed (Le Clus *et al.* 1996). Although Agulhas sole are found as deep as 125 m, catch rates decline with depth, being greatest at depths <75 m (Le Clus and Roberts 1995). Within that depth range, juvenile (10–25 cm) and adult (25–55 cm) distributions over-lap (Le Clus *et al*. 1994). The coastal strip <50 m deep is generally narrow and rocky (Le Clus *et al*. 1996) and trawling is often hazardous, except in bays. However, in most of the bays, trawling at depths <50 m is prohibited to protect juveniles. Sole are therefore targeted mainly at depth between 50 and 75 m.

The spatial distribution of catches and catch rates of Agulhas sole during the period 1984–1995 is recorded by rectangular blocks of 20′ longitude by 20′ latitude (the formal, commercial catch-reporting grid). For the purpose of analysis, the nine coastal blocks between Cape Agulhas and Mossel Bay (Fig. 1) were subdivided into three regions, the western (Cape Agulhas–Cape Infanta, 20°–20°40′E), middle (Cape Infanta–Still Bay, 20°40′–21°40′E), and eastern regions (Gourits River–Mossel Bay, 21°40′–22°40′E). Some sole catches were also made in the three offshore blocks next to the coastal blocks (20°40′–21°40′E). Catches in other blocks on the central Agulhas Bank are usually small. Spatial catch rates included all catches for which effort data were available. Monthly catch rates were estimated from the sum of sole-directed catches divided by the sum of directed effort (Table II). Monthly catch rates (kg·h^{-1}) between 1982 and 1996 and spatial catch rates were standardized to the relative efficiency of a "standard" 400-ton vessel (Table II). Annual catch rates for that period (Table I) were not standardized in order to increase the length of the time-series used for stock assessment and for comparison with earlier years.

Monthly catch rates for 1982 and 1983 were included in the analysis to assess the effect of the major *El Niño*-Southern Oscillation (ENSO) event of 1982/83 (see Philander 1990). However, no spatial data were available for the period 1982–1983. In addition, prior to 1983, the quality and return of drag sheet and landing data were poor, and allocation of target species was suspect. Catch rates for the period 1963–1972 were estimated from the records of a limited number of boats, whereas those between 1973 and 1979 were estimated from industry purchase records. Therefore, the annual catch rates may not be directly comparable between those periods.

Table II: Catch rates (standardized to those of a 400-ton vessel) of Agulhas sole, 1982–1996

Year	Catch rate (kg·h^{-1})												
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	All months
1982	54.8	37.4	45.3	35.3	37.4	53.3	36.8	34.9	29.8	28.3	35.5	36.0	39.4
1983	43.4	46.5	38.7	30.0	33.0	26.2	27.3	25.0	26.9	38.5	28.1	27.9	30.7
1984	24.8	24.4	24.7	35.9	40.4	31.2	36.2	25.5	27.1	21.0	31.0	34.4	30.6
1985	28.8	26.9	31.5	23.4	29.3	33.8	27.3	25.8	21.7	23.5	24.3	26.2	27.2
1986	19.9	25.4	41.1	27.9	30.5	24.3	22.2	24.7	24.3	21.8	26.7	34.4	28.0
1987	27.9	30.4	28.0	32.7	37.3	34.9	34.9	27.1	30.7	25.3	32.9	28.6	30.6
1988	28.3	22.9	29.7	33.7	33.6	31.8	28.5	26.4	28.0	30.8	37.6	33.7	30.5
1989	44.9	45.8	49.2	38.7	37.3	40.1	46.3	31.1	35.0	27.5	42.2	44.9	42.1
1990	27.7	24.6	34.0	39.3	53.0	46.2	41.4	35.0	39.3	34.3	33.7	36.6	38.6
1991	26.4	30.2	26.1	23.5	36.8	40.4	40.2	33.9	25.0	27.1	28.7	45.1	33.7
1992	27.6	26.8	28.2	29.0	33.3	53.6	34.2	27.1	32.7	28.1	31.4	39.1	34.9
1993	35.1	28.4	21.0	27.1	27.6	48.0	34.6	27.2	30.1	26.3	31.4	33.7	31.9
1994	29.1	25.5	33.6	32.1	37.1	49.1	41.6	29.1	23.2	25.2	30.1	27.7	33.6
1995	25.8	44.3	45.4	47.2	32.7	53.0	39.1	26.6	26.6	29.5	25.8	29.8	39.4
1996	31.8	23.9	25.4	43.4	36.8	67.4	45.1	28.0	37.5	22.1	35.5	38.6	38.3

Wind field

Seasonality in the offshore-onshore winds in the western blocks are summarized in Figure 2. The wind direction and the speed for the period 1988–1990 were measured 84 m above sea level on two oil rigs (*Actinia* and *Omega*, see Fig. 1), between 21 and 22°E (Cape Infanta–Gourits River). The wind data for the period 1993–1995 were collected at a coastal station (Waenhuiskrans) midway between Cape Agulhas and Cape Infanta (Fig. 1). Between Cape Agulhas and Cape Infanta, true westerly (W) winds, as well as all winds with northerly components (ENE–WNW), were designated as offshore-flowing, whereas true easterly winds (E), as well as all winds with southerly components (WSW–ESE) were designated as onshore-flowing (Fig. 2).

Spatial coverage of wind direction and strength was obtained from Voluntary Observing Ships (VOS) for the area 34–39°S × 19–24°E. Filtered and standardized VOS data (Taunton-Clark 1994) were used to show the seasonality in the winds on the South Coast. East-west (VOS–EW) and north-south (VOS–NS) components of the wind were analysed separately (Fig. 3a, b). Wind run indices in kilometres were compiled, incorporating wind direction, strength and duration (Fig. 3 a, b), and were averaged for the years 1906–1985 (Table III). Unfortunately, the time-series of VOS wind data have been standardized for the period up to mid-1992 only (Taunton-Clark 1994).

The time-series of the Cape Agulhas Pressure Index (CAPI) was used to assess the wind anomalies for the period 1981–1996 (Agenbag 1996, Agenbag and Roberts 1996). The CAPI is calculated from the difference in daily sea level atmospheric pressure measured at 14:00 at two sites south of Cape Agulhas, 5° of latitude apart: P_1 (20°E, 35°S) and P_2 (20°E, 40°S). The second point (P_2) measures the pressure changes in the westerly wind belt passing south of South Africa. Pressure data were obtained from synoptic weather maps in the Daily Weather Bulletins of the South African Weather Bureau. The daily pressure gradient values between the two sites correlate with the mean daily easterly wind component recorded at a lighthouse west (18°E) of the sampling points (Agenbag 1996). The monthly averages of the pressure gradient (CAPI, hPa) were used as indices of change in the strength and direction of the wind field, with

Table III: Averaged wind-run data for the period 1906–1985, obtained fom Voluntary Observing Ships (VOS) between 34 and 39°S and 19 and 24°E (after Taunton-Clark 1994)

Month	East-west components (km)	North-south components (km)
January	–3.3	–16.3
February	+6.3	–16.5
March	+10.4	–12.1
April	–8.2	–9.5
May	–29.5	–2.6
June	–34.0	–1.0
July	–38.0	–3.8
August	–35.2	–8.7
September	–22.1	–10.7
October	–11.7	–13.6
November	–2.0	–14.8
December	–10.3	–15.3

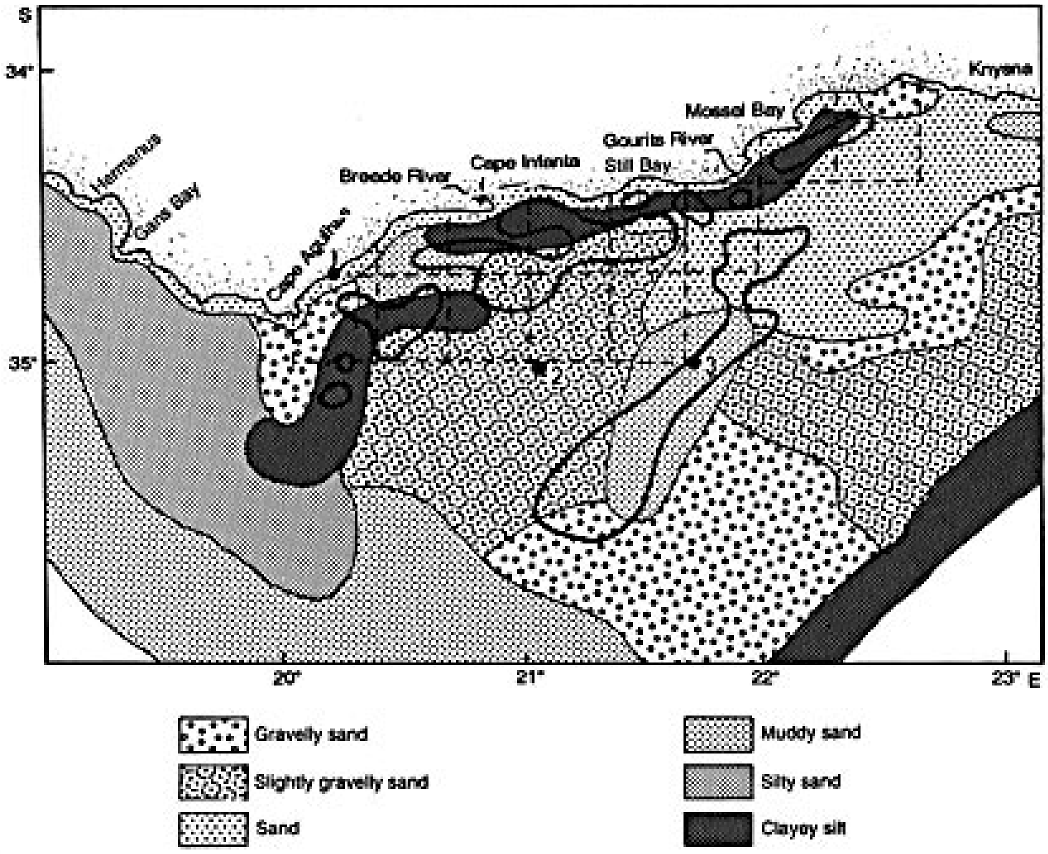

Fig.1: Map of the central Agulhas Bank, showing trawling grounds and reporting rectangles (20′ latitude × 20′ longitude) in relation to the distribution of sediment types (after Le Clus *et al.* 1996), and the positions of a coastal station (1 = Waenhuiskrans) and two oil rigs (2 = *Actinia*, 3 = *Omega*) where wind direction was measured

negative and positive values indicating westerly and easterly winds respectively (Fig. 3c).

RESULTS AND DISCUSSION

Wind field

Offshore winds (mostly west-north-westerly and north-westerly) peaked in winter (Fig. 2a, c) and onshore winds (mainly easterly, east-south-easterly and south-easterly) peaked in spring and summer (Fig. 2b, d). During some years, e.g. 1989 and 1995, there were higher incidences of offshore winds (mainly east-north-easterly) in summer (Fig. 2a, c). These seasonal trends were also apparent in the averaged (1906–1985) VOS data. The wind components on the Cape south coast changed from easterly in February–March to westerly from April onwards, peaking in July before declining towards early summer (Table III). The incidence of westerly winds declined in November, but peaked again in December. Southerly winds prevailed in late summer, declined in winter (May–July) and increased again in spring and early summer (Table III). The contour maps of east-west and north-south wind-runs (km) for the period 1963/64–1990/91 (Fig. 3a, b) depict the main seasonal switch in the wind regime in April and October and the variability between years. In summer (October–March), anomalous westerly components (windrun <0) persisted for several months during ENSO events (e.g. 1965/66 and 1982/83). The westerly anomaly in summer was particularly marked in November–

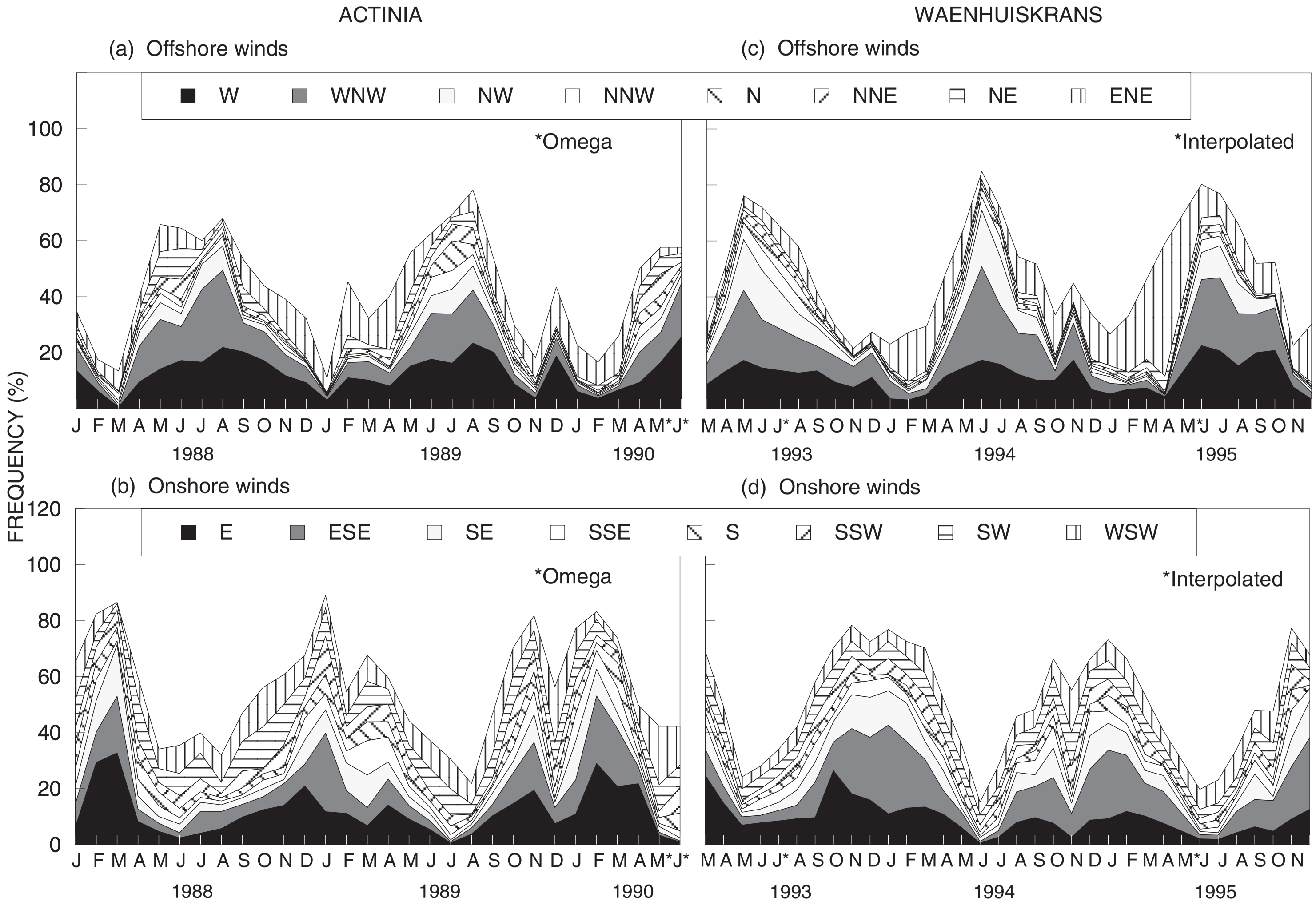

Fig. 2: Percentage frequency of (a) offshore and (b) onshore winds measured at two oil rigs (*Actinia* and *Omega*) at 84 m height for the period 1988–1990 (unpublished SOEKOR data), and (c) offshore and (d) onshore winds measured at a coastal station (Waenhuiskrans) between Cape Agulhas and Cape Infanta for the period 1993–1995 (after CSIR reports EMAS-D-95005, EMAS-C-95012, EMAS-D-96003

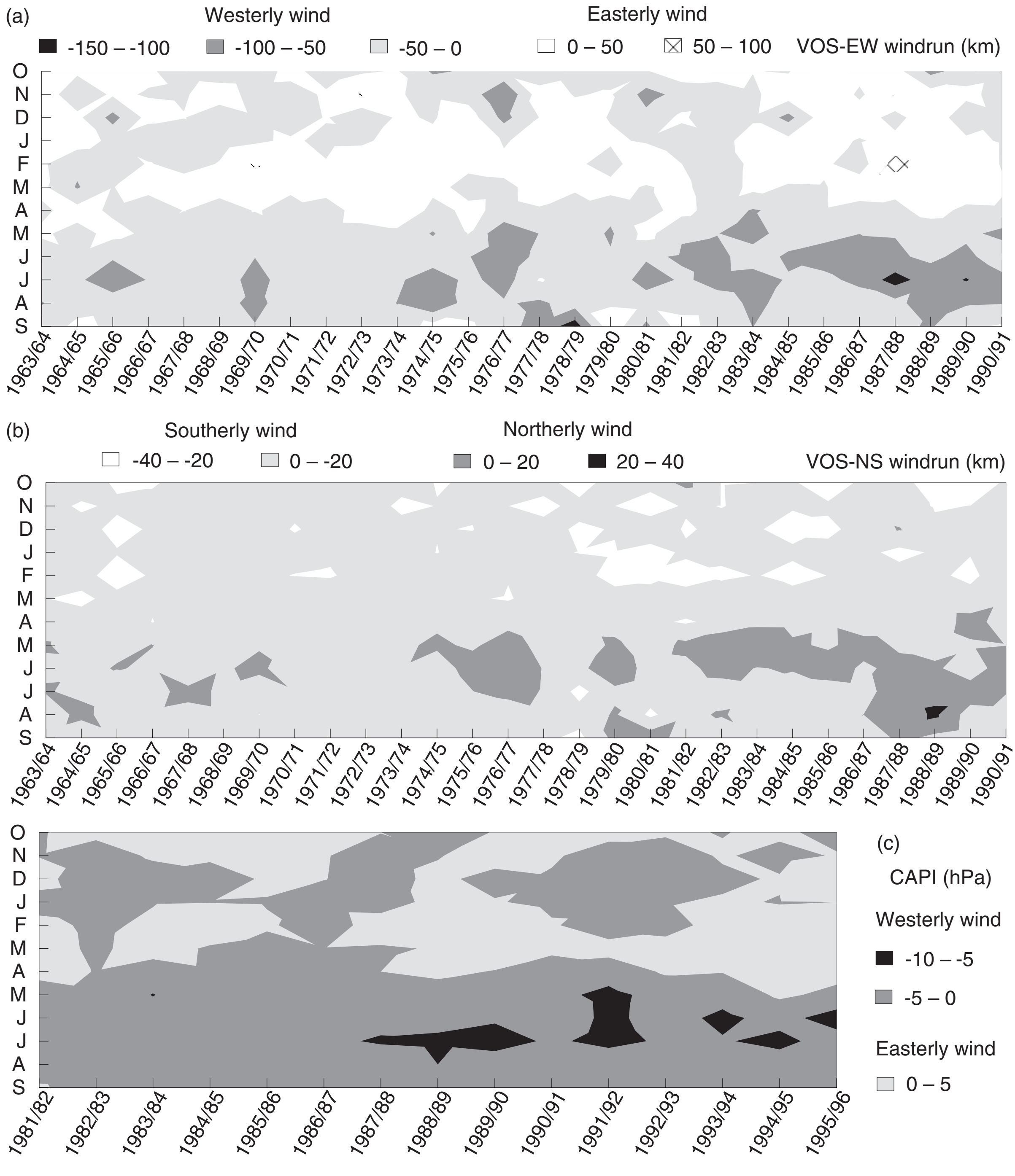

Fig. 3: Contour maps showing the main seasonal and interannual features of (a) the VOS-EW wind-run (km) for the period 1963–1991, (b) the VOS-NS wind-run for the period 1963–1991 and (c) the Cape Agulhas Pressure Index (CAPI) for the period 1981–1996

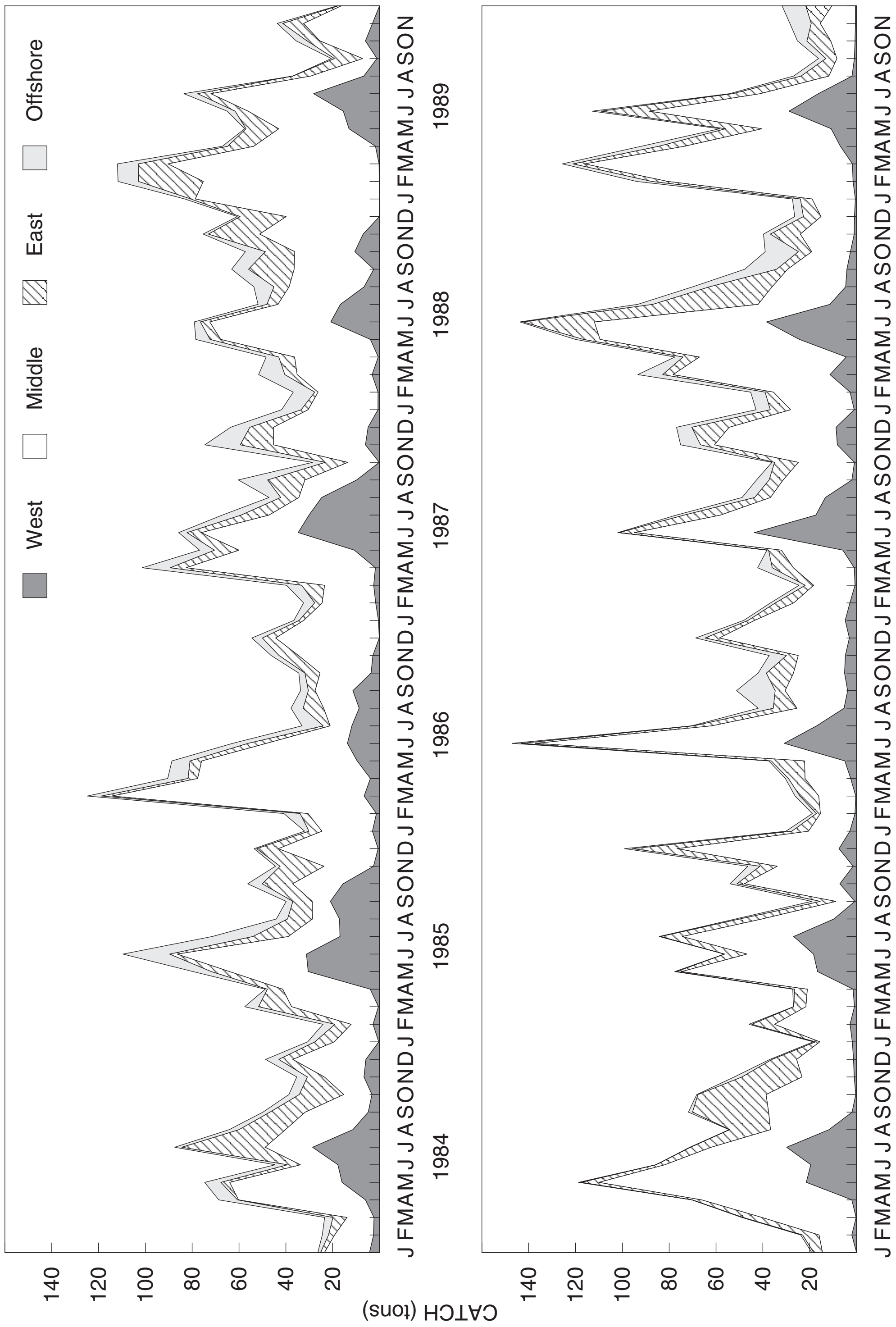

Fig. 4: Seasonal and interannual trends in commercial catches of Agulhas sole at four localities on the central Agulhas Bank for the period 1984–1995

December 1976 (Fig. 3a). By February 1977, exceptionally warm bottom temperatures (18°C) were recorded 100 km south of Cape Infanta at 100 m deep (Eagle and Orren 1985, Lutjeharms *et al.* 1996). In winter, the northerly and westerly wind components intensified after 1974/75, compared to previous years (Fig. 3a, b).

The contour map of the CAPIs resolved the broad trends of seasonal variability and interannual anomalies in the wind field on the Cape south coast for the period 1981–1996 (Fig. 3c). During normal years or cold (*La Niña*-Southern Oscillation) events, easterly winds (positive CAPI) dominated in spring and summer (October–March), sometimes with short periods of westerly winds (negative CAPI) in midsummer. However, during warm (ENSO) events (cf. Philander 1990, Agenbag 1996, Agenbag and Roberts 1996), summer winds were more westerly over a period of several months (e.g. 1982/83, 1991/92, 1992/93 and early and late in 1987, Fig. 3c). Westerly winds prevailed in autumn and winter (May–September), and from 1988 onwards the midwinter winds were stronger ($-10<\text{CAPI}<-5$ hPa) than previous years (Fig. 3c).

The changes in wind direction are associated with differences in the thermal stratification on the central Agulhas Bank. In summer, when south-easterly (onshore) winds prevail, the water column on the Agulhas Bank is highly stratified as a result of the intrusion of warm, subtropical Agulhas Current water (>18°C) at the surface and frequent upwelling of cold Indian Ocean Central water (8–10°C) along the eastern and south-eastern shelf edge (Swart 1983, Schumann and Beekman 1984, Eagle and Orren 1985, Chapman and Shannon 1987, Catzel 1989, Chapman and Largier 1989, Lutjeharms *et al.* 1996). In winter, when offshore north-westerly winds prevail, the thermal stratification breaks down to almost isothermal conditions (Eagle and Orren 1985). Variability in strength of thermal stratification in summer may be a potential modulator of the effect of the wind field on catches and catch rates of Agulhas sole.

Annual trends

Annual catch rates (unstandarized) prior to 1983 are not directly comparable to the post-1983 period (Table I), but catch rates for the periods 1963–1972, 1973–1979 and 1980–1996 are comparable. The lowest annual catch rates were recorded in 1977 (Table I), coincident with relatively high bottom temperatures following an intense westerly wind anomaly in November–December 1976 (Fig. 3a). No consistent annual environmental anomalies were apparent in the data (Fig. 3a, b) that could explain the several periods of high annual catch rates (Table I), but rainfall anomalies provide some clues. Tyson (1990) identified wet and dry cycles of summer rainfall, with an average periodicity of 11 years. During the 1962–1971 dry cycle, there were two years of high catch rates (1966 and 1967, Table I), bracketing the wettest year (October 1966–September 1967). High catch rates in 1975 and 1976 preceded the 1976/1977 warm event and bracketed the wettest year (1975/1976) in the 1971–1981 wet cycle (Tyson 1990). Annual catch rates were also high during the periods 1980–1982, 1989–1990 and 1995–1996 (Table I), associated with more persistent easterlies in summer (Fig. 3c) compared to the succeeding *El Niño* years. Despite persistent easterly winds in summer 1985/1986 (Fig. 3), annual catch rates were low (Tables I, II), coincident with an intrusion of warm Agulhas water into the southern Benguela (Shannon *et al.* 1990),which may have suppressed the effects of the stronger winds. To understand the variability in annual catch rates, fine-scale spatial and seasonal variability was investigated.

Spatial trends in catches and catch rates

The monthly catches of Agulhas sole showed different seasonal trends in the three coastal regions between Cape Agulhas and Mossel Bay (Fig. 4). Catches were highest in the middle blocks, with major peaks during autumn/winter and secondary peaks in summer. In anomalous years, the summer peak exceeded the autumn/winter peaks (e.g. 1989 and 1995). In the western blocks, monthly catches were low, peaking mainly from May to July, whereas in the eastern and offshore blocks, catches were generally low, with spring and summer peaks. Overall monthly catch rates are therefore biased by the catches and catch rates in the middle blocks.

Monthly catch rates also exhibited different seasonal trends in the three coastal regions (Fig. 5). Of note is the increase in catch rates in the western blocks in autumn/winter, especially in the post-1988 period. Prior to 1989, short-term increases in catch rates were small compared to those in subsequent years (Fig. 5). In the western blocks, catch rates were low (<20 $kg{\cdot}h^{-1}$) in spring and summer, and peaked (>40 $kg{\cdot}h^{-1}$) in autumn/winter (May–July). In the eastern blocks, catch rates were usually low, increasing in most years in spring and summer, and occasionally in winter (e.g. 1984, 1994). In the middle blocks at Cape Infanta, catch rates usually remained above 20 $kg{\cdot}h^{-1}$ throughout the year. When catch rates were high (>40 $kg{\cdot}h^{-1}$) in the coastal blocks between Cape Infanta and Still Bay (see Fig. 5), monthly catch rates overall peaked, usually in autumn/winter, but occasionally in summer

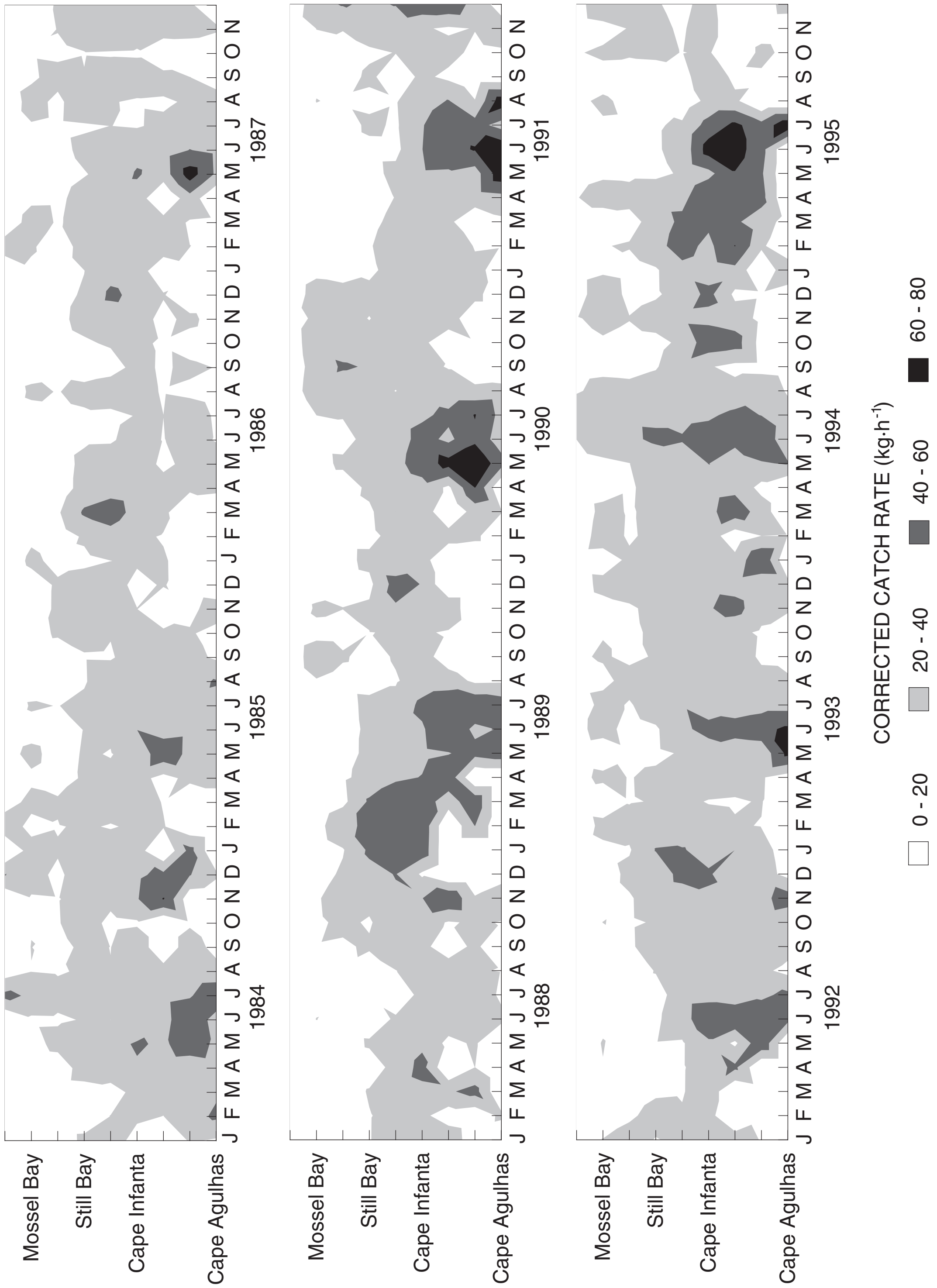

Fig. 5: Contour map of seasonal and interannual trends in corrected catch rates (kg·h^{-1}) of Agulhas sole at nine coastal blocks between Cape Agulhas and Mossel Bay for the period 1984–1995

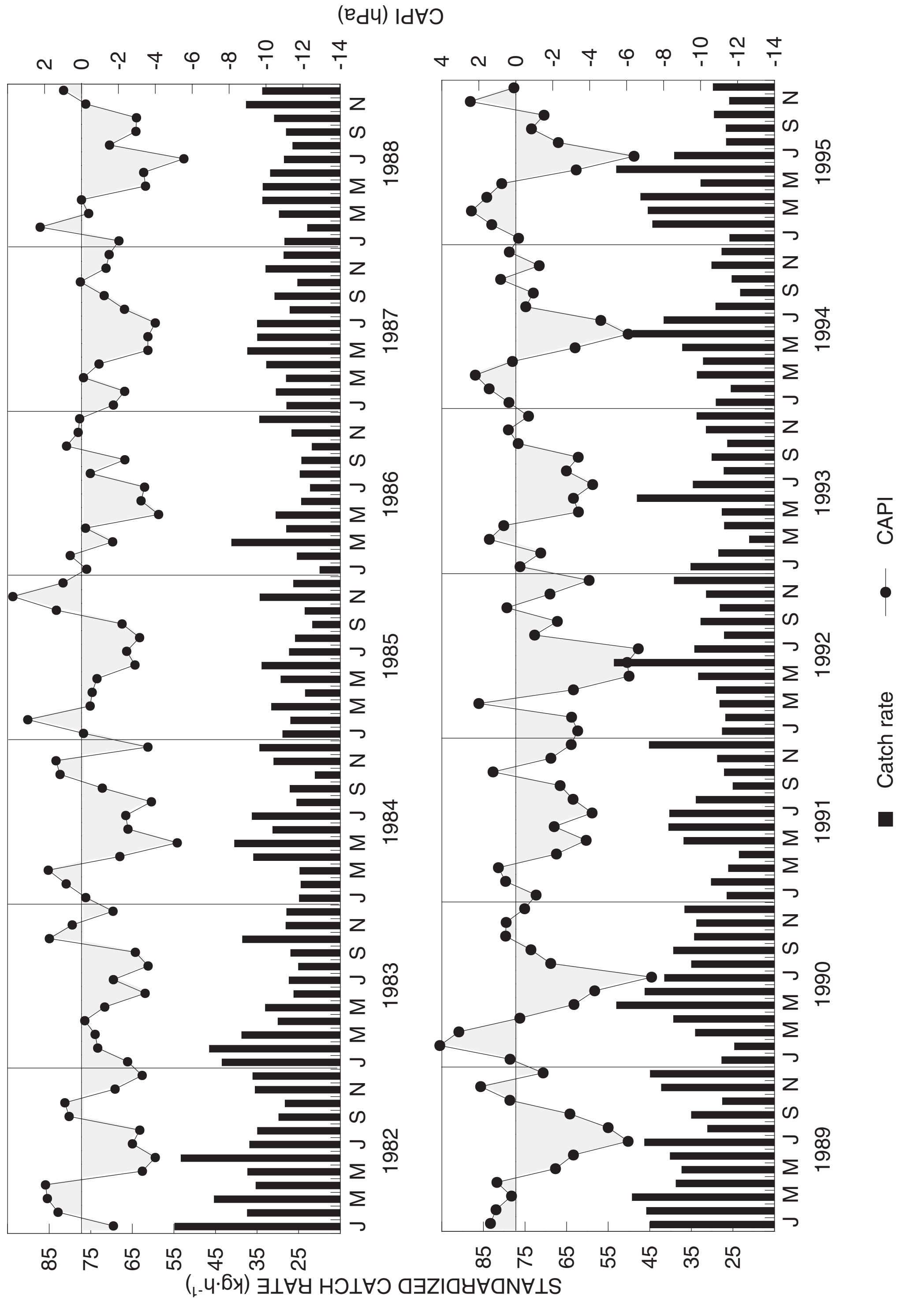

Fig. 6: Corrected monthly catch rates of Agulhas sole relative to trends in the Cape Agulhas Pressure Index (CAPI) for the period 1982–1995

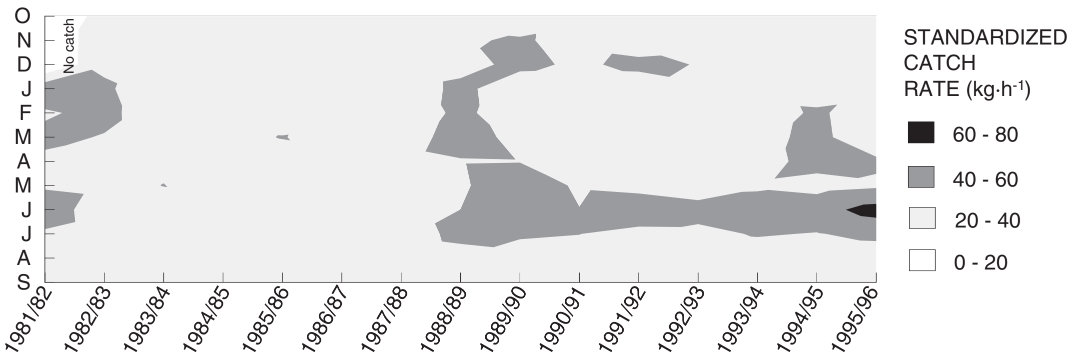

Fig. 7: Contour map showing the prominent seasonal and interannual features of the corrected monthly catch rates of Agulhas sole for the period 1981–1996

(Table II). When high catch rates persisted for several months between Cape Infanta and Still Bay (e.g. 1989, 1990, 1995, Fig. 5), the annual catch rate peaked (Table I, II).

Monthly catch rates v. trends in the wind field

Changes in monthly catch rates were assessed relative to seasonal and annual variability in the CAPI (Fig. 6). As variability in monthly catch rates are biased towards catches and catch rates between Cape Infanta and Still Bay, only certain aspects of the interaction between catch rates and wind effects could be addressed. Catch rates in winter and midsummer improved when the wind changed to more-westerly components (negative CAPI). Autumn-winter catch rates usually peaked in May or June, after a wind reversal from easterly to westerly persisted for at least two consecutive months. Peaks were also found in March 1986, April 1988 and July 1989, coincident with anomalies in the timing of the seasonal reversal in the wind direction (Fig. 6).

In years when the winter north-westerly winds were weak (e.g. 1983, 1985), or when the changeover from summer to winter winds was prolonged or the rate of change altered (e.g. 1986, 1988), catch rates in winter remained low (Fig. 6). Catch rates and the maximum westerly deviation of the wind in winter did not often peak in the same month. In such cases, the peak in catch rates was delayed, following some months after the changeover to winter winds (e.g. 1992–1994). The maximum deviation to westerly wind components was generally between April and July, with a secondary deviation in midsummer in most years. Higher peaks in catch rates in midsummer were found during larger-than-normal or prolonged westerly deviations of the CAPI during that period

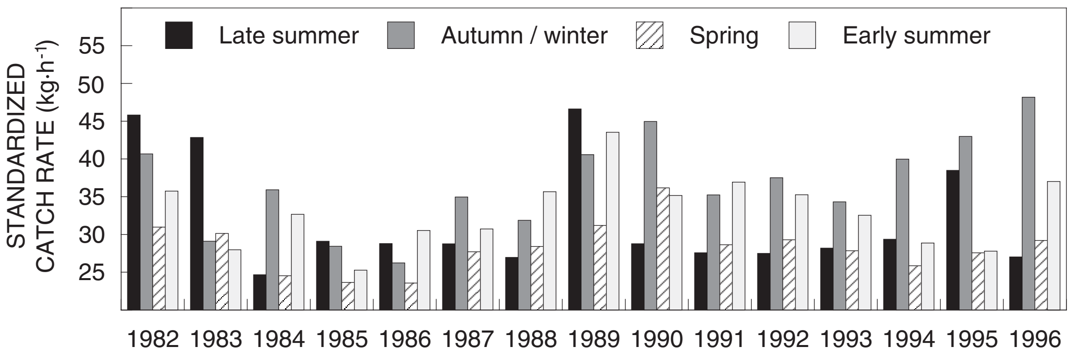

Fig. 8: Averaged corrected catch rates of Agulhas sole for late summer (January–March), autumn-winter (April–July), spring (August–October) and early summer (November–December)

(Fig. 6), such as the ENSO events, in 1982/83, 1991/92, 1992/93 (Agenbag 1996, Agenbag and Roberts 1996). Peaks in catch rates in midsummer were smaller when spikes of westerly winds were absent during that period (e.g. 1985/86) or weak (e.g. 1993/94) or delayed (e.g. 1986/87).

Two prominent interannual anomalies in monthly catch rates (Fig. 7) were compared to the CAPI trends (Fig. 3c). Above-average winter catch rates in the period 1989–1996 were associated with a period of strong north-westerly winds in winter (Fig. 6, CAPI<–5 hPa), whereas catch rates were lower between 1983 and 1988, when winter winds were weaker (0<CAPI>–5 hPa). However, the extended periods of high summer catch rates in 1982–83, 1989 and 1995 (Fig. 7) could not be explained by CAPI anomalies only. Different environmental conditions were associated with each of these anomalous years, but a common denominator could be the breakdown of the summer thermal stratification. In midsummer 1982/83, the CAPI resembled the pattern of winter westerly winds (Fig. 6). In 1989 and 1995, the higher catch rates were associated with a higher incidence of offshore north-easterly winds in summer (Fig. 2a, b) a relationship not shown by the CAPI. In midsummer 1988/89, there was strong, persistent upwelling, and inshore and sea surface temperatures at Knysna (23°E) resembled winter conditions (Schumann *et al.* 1995). This could indicate a deviation from the normal summer wind field that was not explained by the CAPI, except that the usual midsummer change in the wind field was not evident (Fig. 6).

Seasonal and interannual variability

To establish the seasonality in catch rates, some of the variability was removed by averaging the catch rates for late summer (January–March), autumn-winter (April–July), late-winter-spring (August–October) and early summer (November–December). The general seasonal pattern in catch rates is exemplified in the period 1991–1994, when catch rates were low in late summer, peaked in autumn-winter, declined in spring and peaked again in early summer (Fig. 8). The low catch rates in spring and late summer were associated with onshore south-easterly winds, whereas the higher catch rates in autumn-winter were associated with offshore north-westerly winds (Fig. 2, Table III). The increase in catch rates in early summer was often accompanied by a midsummer decrease to values that were more negative in the CAPI (Fig. 6).

Superimposed on the seasonal pattern, the inter-annual deviations in catch rate differed between seasons

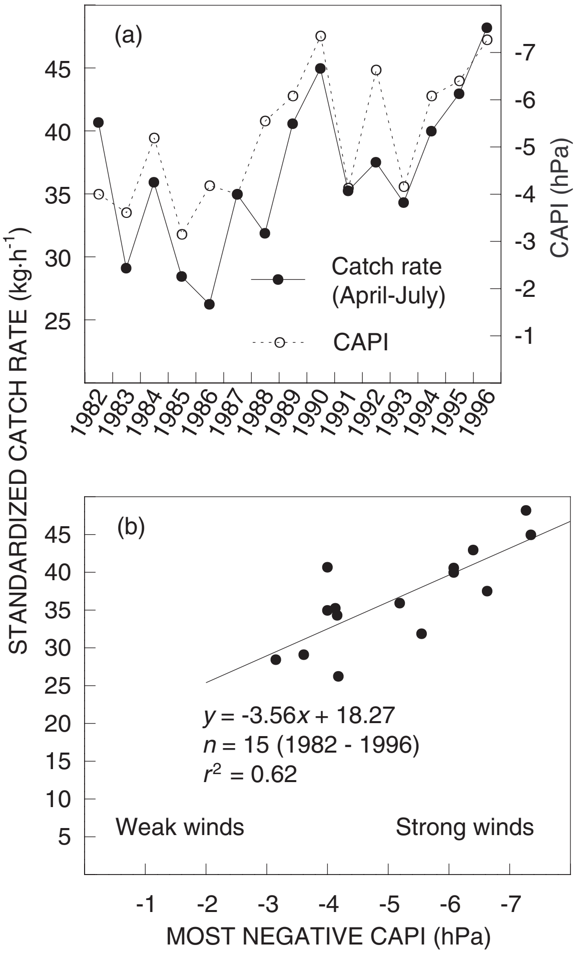

Fig. 9: (a) Annual trends in the averaged corrected catch rates of Agulhas sole for April–July and the minimum (most negative) deviation in winter of the Cape Agulhas Pressure Index (CAPI) for the period 1982–1996; (b) regression of the averaged corrected catch rates (kg·h^{-1}) for April–July against the minimum (most negative) deviation in winter of the Cape Agulhas Pressure Index (CAPI) for the period 1982–1996

(Fig. 8), rendering simple correlation between annual catch rates and environmental factors inappropriate. The relationship between averaged autumn-winter catch rates and the minimum (most negative) CAPI in winter (Fig. 9a) showed that the autumn-winter catch rates were significantly higher in years when winter north-westerly winds were strongest. (Fig. 9b, $r^2 = 0.62$, $p < 0.01$).

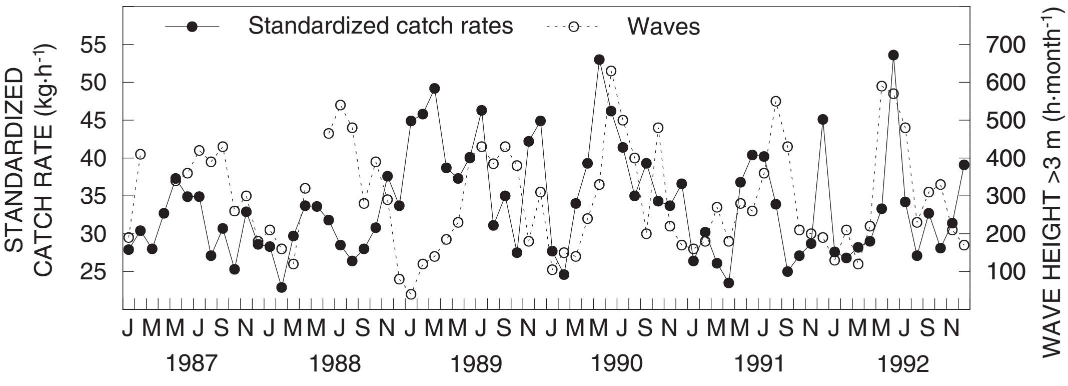

Fig. 10: Corrected monthly catch rates (kg·h^{-1}) of Agulhas sole and the frequency of wave height >3 m estimated from waverider data collected near the Gourits River in 30 m water depth (after CSIR report EMAS-C-93046)

Effect of wind on catches

Clearly, changes in wind patterns can have an effect on the catch rates of the Agulhas sole, but it is not clear how they are mediated. Surface wind, through its effect on wave action, could affect fishing operation and gear, so influencing catch rates (Laevastu 1993). Agulhas sole catch rates peak in winter when the frequency of waves higher than 3 m is greatest (Fig. 10), and catch rates are highest in years with strongest winds (Fig. 9). This implies that the lower catch rates in spring and summer are not attributable to the effect of wind and waves on fishing operations. Surface winds can influence fish behaviour through their effects on the ocean, mainly by wave action and associated turbulence and oscillatory movement within the water column, or by the generation of currents or changes in the mixed layer depth (Laevastu 1993). Potential responses of bottom-dwelling fish to unfavourable winds include burying themselves deep in the sea bed, moving into midwater or migrating to deeper water (Harden Jones and Scholes 1980). Agulhas sole may not be capable of burying themselves sufficiently deep to be unavailable to trawling. Laboratory observations show that they usually cover themselves with a thin layer of sand (F. Le C., pers. obs.), too shallow to avoid capture. Catch rates of Agulhas sole may decline if they move into bays where trawling is prohibited, into rocky areas where trawling is hazardous, or into deeper water away from the inshore trawling grounds. Catch rates may improve if they migrate towards the trawling grounds from shallow water, or from deeper water into the lee of the Cape Agulhas headland to avoid north-westerly gales. By migrating from shallow water to the trawling grounds, catch rates should increase in all the coastal blocks, a trend, however, not apparent in Figure 5. Migration to shelter from north-westerly gales provides a more plausible explanation for the sudden increases in catch rates in the westerly blocks in autumn and winter (Fig. 5).

Concluding remarks

It is the current authors' opinion that seasonal and interannual changes in wind pattern can affect catch rates of Agulhas sole. Further research is required to determine whether this relationship is causal or not, and to ascertain the mechanism whereby wind can induce such seasonal and spatial variability in catch rates or changes in availability of the resource. Electronic data-logging tags may provide some information on the seasonal movements of Agulhas sole in response to changes in wind direction and strength, so elucidating some of the questions raised by this study.

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