Effects of seasonal variations in meteorology and oceanography on the Brazilian sardine fishery

PATRICIA S. SUNYÉ AND JACQUES SERVAIN

Centre ORSTOM de Brest, BP 70, 29280 Plouzané, France. E-mail: psunye@ifremer.fr

ABSTRACT

Seasonal variations in meteorological and oceanographic processes in the South Brazil Bight were studied to assess their influence on the Brazilian sardine *Sardinella brasiliensis* fishery. According to its environmental characteristics, the South Brazil Bight was divided into three sectors. The northern and southern sectors were similar during the spring and summer, showing areas of coastal upwelling and low rainfall rates. The middle sector was characterized by the presence of low-salinity coastal waters in the inner shelf and by high rainfall. During autumn and winter, the middle and southern sectors were similar, both being under the influence of sub-Antarctic waters. Multiple regression analyses showed significant correlation between environmental data and catches, although at a lower level in the northern sector ($r^2 = 0.57$). In the middle and southern sectors, environmental data were highly correlated with the catches ($r^2 = 0.90$ and 0.84). The sardine landings in the middle sector are principally affected by meteorological parameters, and in the south by oceanographic ones. In the middle sector, an inverse correlation between landings and rainfall is shown, while in the south, landings are positively correlated with salinity and sea temperature. The conclusion is that the seasonal landings of the Brazilian sardine within the South Brazil Bight are influenced by the distribution of less saline waters, the coastal waters and sub-Antarctic waters.

Key words: fisheries oceanography, fishery, meteorological processes, oceanographic processes, *Sardinella brasiliensis*, South Brazil Bight

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INTRODUCTION

The South Brazil Bight (SBB) is a large urban, industrial and fishery area on the Brazilian coast, extending from Cabo Frio in the north (23°S) to Cabo de Santa Marta in the south (28°S), and covering an area of 150 000 km^2 (Fig. 1). The Brazilian sardine, *Sardinella brasiliensis*, is the most important marine resource of the SBB, constituting 25% of the total Brazilian marine landings in the 1980s (Valentini and Cardoso, 1991). Since 1980, the Brazilian Sardine Study Group (GPE) has analysed the fishery and the biological data for this species. The GPE suggested that the decline of the fishery in the mid 1980s was a direct response to increasing fishing effort, in association with climatic changes (IBAMA, 1994; Cergole, 1995).

Fish have a preference for some optimum combination of physical and biological conditions, therefore a knowledge of these optimum conditions is a necessary step towards the prediction of fish concentrations and their variability (Laevastu and Hayes, 1981). Information on the distribution of sardines in relation to oceanographic features along the Brazilian coast is scarce, and only the optimum temperature range (19–26°C) is known (Saccardo and Rossi-Wongtschowski, 1991). A latitudinal migration within the SBB, apparently not related to reproduction or food, was suggested by Vazzoler and Phan (1976), Rossi-Wongtschowski (1978) and Braga (1987). While these authors were not able to determine whether this migration was seasonal, they suggested that sardine movement inside the SBB could be related to oceanographic processes.

In the SBB, the circulation pattern is dominated by the southward flow of the Brazil Current along the continental slope. During the summer (November–March), South Atlantic Central Water intrudes onshore over the bottom of the shelf (Castro Filho *et al.*, 1987). This water mass reaches the surface only near Cabo Frio (Valentin *et al.*, 1987; Bakun and Parrish, 1990). Recent observations showed that during the winter (June–September), the northwards flow of the Malvinas Current reaches latitudes as far as 23°S in some years (Campos *et al.*, 1996). Thus, regional

Table 1. Coastal meteorological station data from the Brazilian Department of Meterology, except for the Cananéia coastal station which are from the University of São Paulo.

Station	Abbreviation	Latitude (°S)	Longitude (°W)	Period analysed
Cabo Frio	CF	22.59	42.02	1970–1987
Rio de Janeiro	R	22.55	43.10	1973–1990
Ilha Guaíba	I	23.00	44.02	1972–1990
Angra dos Reis	A	23.01	44.19	1961–1990
Ubatuba	U	23.30	45.07	1961–1990
Santos	S	23.56	45.20	1961–1990
Cananéia	C	25.00	47.55	1961–1990
Paranaguá	P	25.31	48.31	1961–1990
Florianópolis	F	27.35	48.34	1961–1990
Torres	T	29.20	49.44	1961–1990

variability within the SBB might be expected owing to the high heterogeneity of the local oceanography and climate.

The objective of this study is to analyse the seasonal variation in meteorological and oceanographic parameters in the SBB, and to discuss their possible effects on the Brazilian sardine fishery.

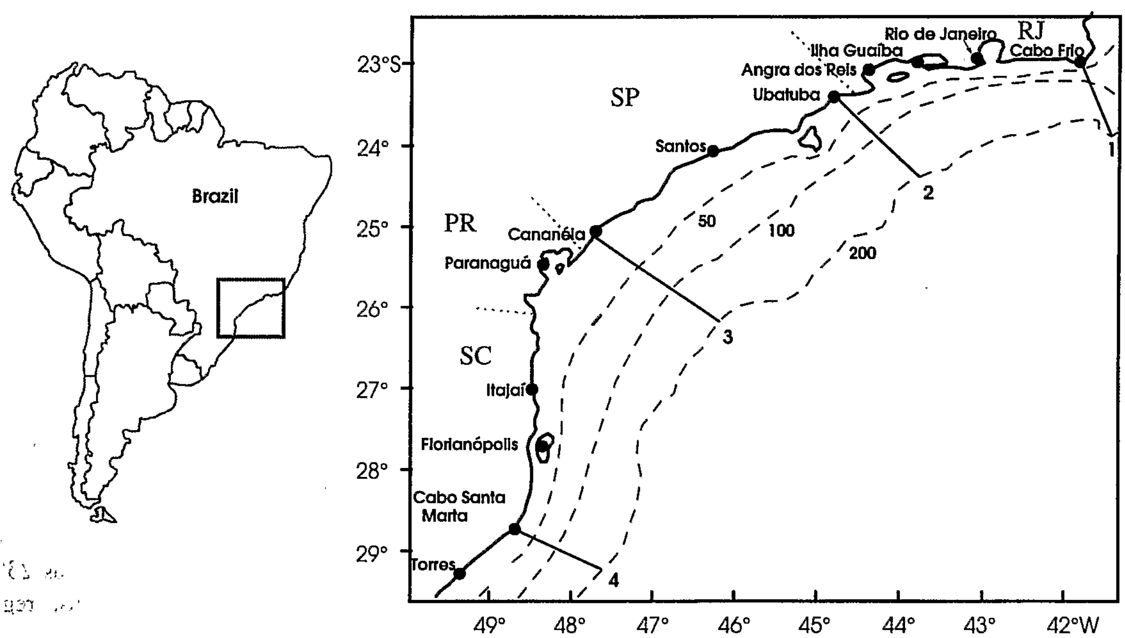
METHODS

Data sources

Sardine fishery statistics have been recorded since 1964 by the Brazilian Environmental Agency (IBAMA) in the three fishing states (Fig. 1): at Rio de Janeiro (RJ) in the north (principal fishing harbour at Rio de Janeiro); at São Paulo (SP) in the middle sector (principal fishing harbour at Santos); and at Santa Catarina (SC) in the south (principal fishing harbour at Itajaí). Landings are reported as tonnes landed per month in each state. Fishing is conducted close to the landing harbours, so geographical patterns may reflect true patterns of the stock itself.

Data on the long-term climatic environment were obtained from two sources. The meteorological data consisted of an 18–30 year climatological average for 10 coastal stations (Table 1 and Fig. 1), all of

Figure 1. Study area, showing the regional states, the positions of the coastal meteorological stations, the fishing harbours and the vertical hydrographic sections examined. PR, Paraná; RJ, Rio de Janeiro; SC, Santa Catarina; SP, São Paulo.



which data are published by the Brazilian Department of Meteorology (DNMET, 1992), except for those of Cananéia which were provided by the University of São Paulo (Laboratory of Marine Meteorology). The parameters analysed were: air temperature (°C), cloud cover (tenths), duration of sunshine (hours), total rainfall (mm), total evaporation (mm), rainfall minus evaporation (mm), relative humidity (%), and atmospheric pressure (hPa). Cloud cover data were not available from the Cananéia coastal station.

Temperature and salinity data for the shelf waters of the SBB were extracted from the water bottle data set at the surface, 10, 20, 30, 50, 75, 100, 125, 150, and 200 m depth from the National Oceanographic Data Centre, for the area between 22°30′S to 29°30′S and 41°W to 50°W (NODC, 1994). From 1911 to 1988 a total of 3565 observations were made, most of them (3326) from 1960 onwards, this giving, on average, around 600 observations for each two-monthly period of the calendar year.

Data analysis

For the fishery data, the percentile monthly landings in each area were averaged from 1980 to 1990. This period is characterized by similar fishing regulations, all years having fishing prohibited during January.

To identify zones with similar climatological patterns and monthly changes, similarity matrices between stations were produced using the Euclidean distance dissimilarity measure on normalized data, followed by non-metric multidimensional scaling ordination (MDS; Clarke and Warwick, 1994).

Water masses were identified using a temperature–salinity (TS) diagram according to Emilsson (1961) and Campos *et al.* (1996). The data were summarized from the surface to 50 m depth for the whole SBB, for the combined months of January/February and July/August. Density, as sigma-t, presented in the TS diagrams was calculated following UNESCO (1981). For sea temperature and salinity at each depth, the arithmetic means of the observations were calculated for each 0.25 × 0.25° rectangle in two-monthly periods. Rectangles with fewer than five observations were not included. The resulting grids were used to prepare the surface maps, which were smoothed using a two-by-two point, moving-average filter. Four vertical sections perpendicular to the coast (Fig. 1) were also analysed, by superimposing the contour maps of each depth (from the surface to 200 m depth), and extracting the vertical profiles in each section.

Sea surface temperature and salinity data were separated into three areas for analysis: (a) northern sector: 41–43°W/23–24°S; (b) middle sector: 44–46°W/23–24°S, 46–47°W/24–25°S, 47–48°30′W/25–26°S; (c) southern sector: 48–49°W/27–29°S. In the same way, the coastal stations were separated into three areas: the north, from Cabo Frio to Iguaba Grande; the middle sector, from Angra dos Reis to Paranaguá; and the south, from Florianópolis to Torres. Formal significance tests for differences of the meteorological and oceanographic data between the areas (north, middle and south) of the SBB in each three-monthly seasonal period were performed using a one-way analysis of similarity (ANOSIM, Clarke and Warwick, 1994).

Figure 2. Total Brazilian catch of sardine for the period 1980–1990, plotted as percentage in each area each month, with associated ± 1 standard deviation error bars. No data are available for January because fishing is prohibited in that month.

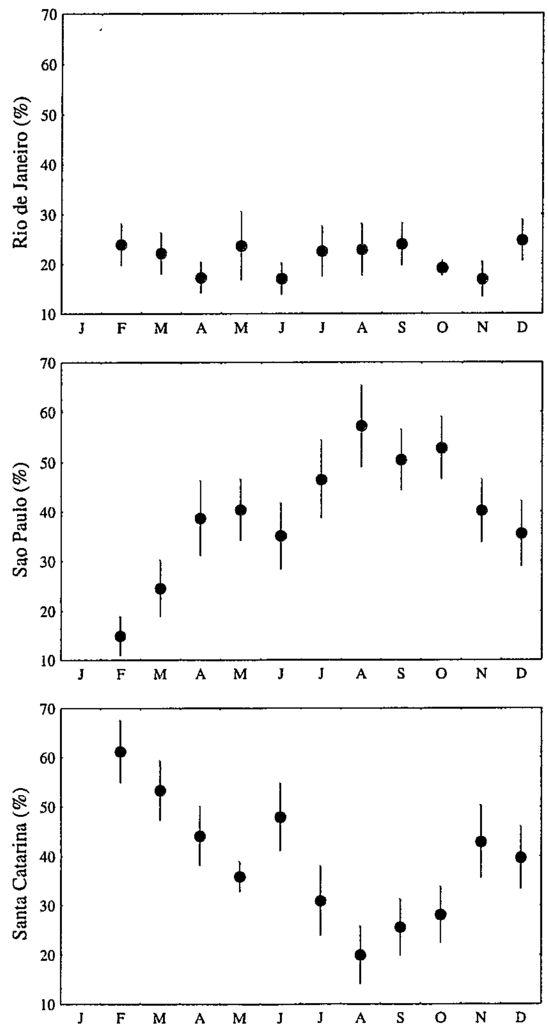
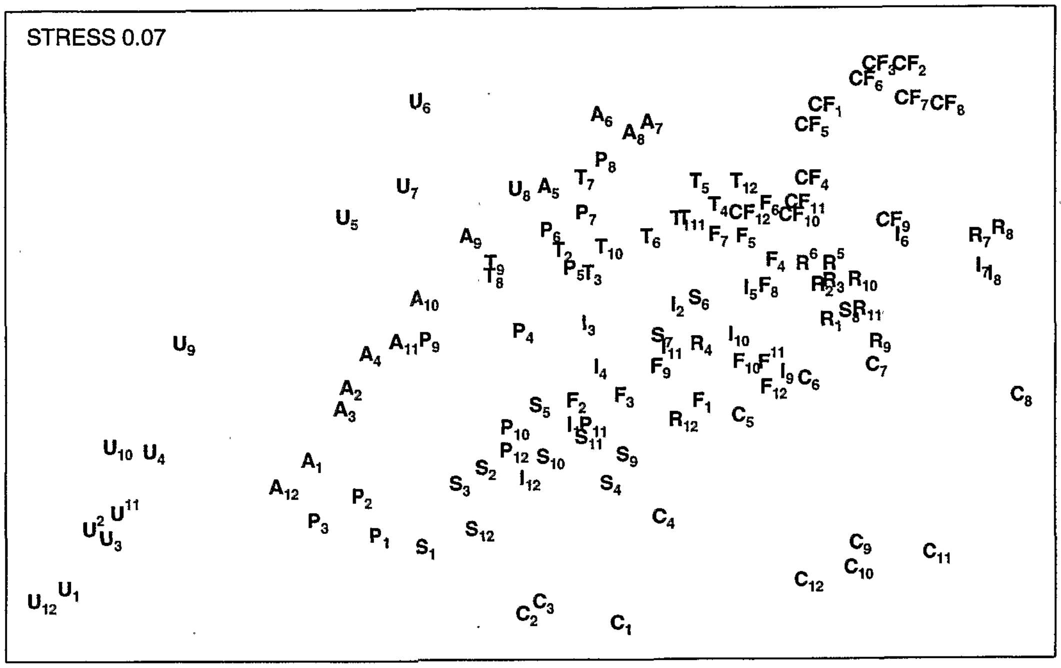


Figure 3. Non-metric MDS representation of the meteorological data from the 10 coastal stations indicated by the different letters (Table 1); the data for each month are shown by the subscript number, from 1 (January) to 12 (December).



The relationships between the sardine landings and the environmental parameters for each area were analysed by multi-regression analysis (MREG), using backwards selection with log-transformed data. The 'F-to-remove' values were determined in relation to the number of variables and observations (Davis, 1973). Prior to the MREG, a standard product-moment correlation analysis between all environmental parameters was carried out, and whenever a high correlation (more than 90%) was present, only one of the parameters was used in the MREG analysis.

RESULTS

Seasonal variability of sardine landings

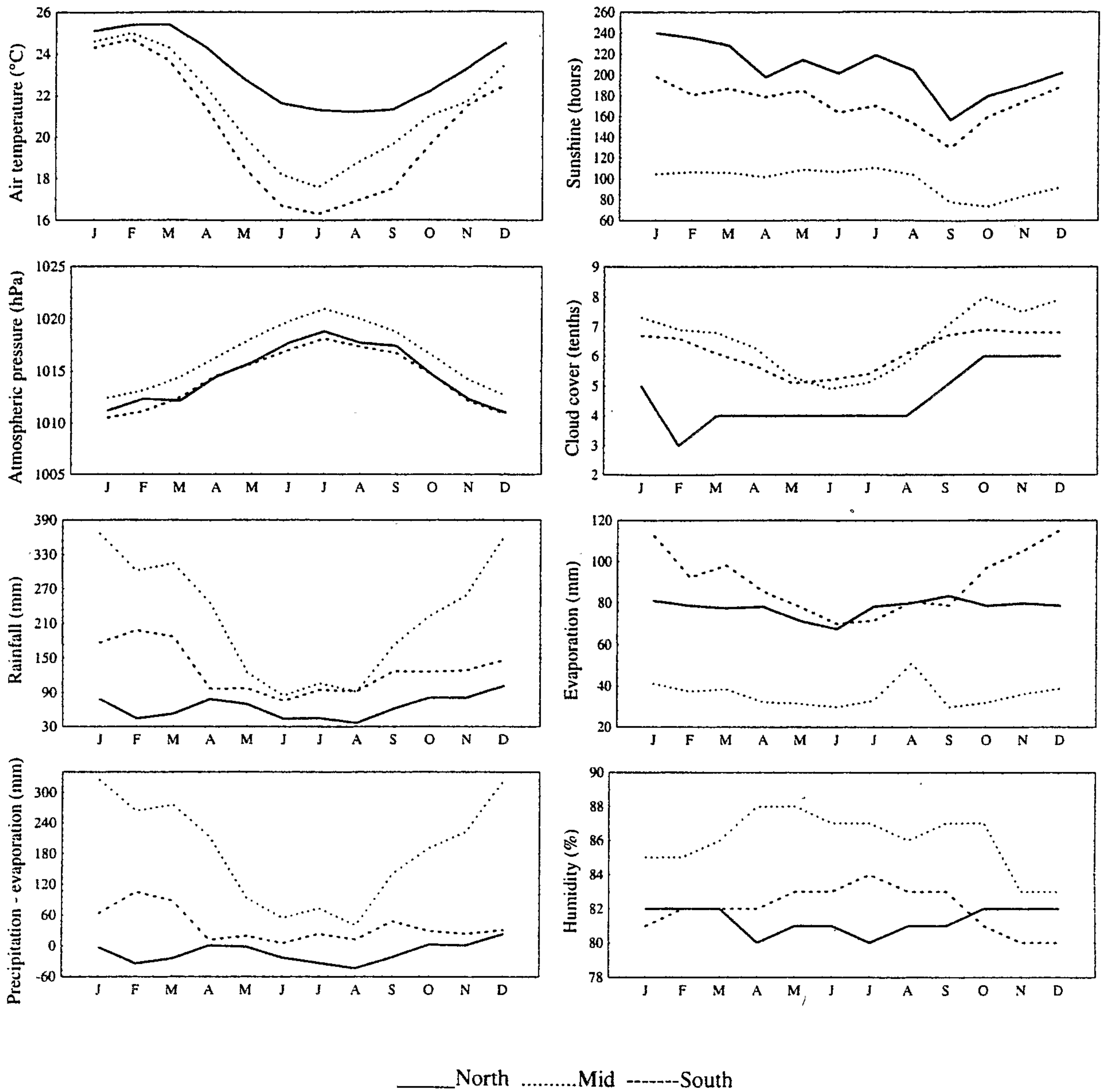
Although there is a high monthly variability in this fishery, a different seasonal pattern could be observed for each of the fishing areas (Fig. 2). Landings at Rio de Janeiro were low throughout the year, accounting for only 20% of the Brazilian catch. At São Paulo, landings were low during the summer, increasing in the winter to nearly 60% of the total Brazilian catch. Data for the Santa Catarina area, in the south of the SBB, showed an inverse pattern to São Paulo, with 60% of Brazilian landings in the summer being made in this area.

Meteorology

For the meteorological data, MDS analysis did not show any simple gradient of relationship corresponding to their geographical location (Fig. 3). Their arrangement in the plot indicates that Ubatuba and Angra dos Reis (represented by U and A on the left of the plot), Cananéia (C at the bottom right) and Cabo Frio (CF at the top right) represent the most distinctive areas of the SBB. The positions on the plot of Rio de Janeiro (R), Florianópolis (F) and Torres (T) towards the grouping of the Cabo Frio data suggest some similarity between the stations situated at the northern and southern limits of the SBB. The other stations, which are mostly in the more central area of the plot, indicate some similarity of conditions in the middle sector of the SBB. Seasonal variations in the meteorological data are also reflected in the MDS plot. Data for the summer months (November–March) are positioned more towards the lower left of the plot, whilst data for the winter months (June–August) are mainly located towards the upper right.

Considering the number of meteorological coastal stations, the univariate graphical representation of meteorological conditions (Fig. 4) was reduced to three sites, one at the northern limit of the SBB (Cabo Frio), one in the middle sector (Ubatuba) and one in the south (Florianópolis). Air temperature is the only

Figure 4. Monthly variation in air temperature, hours of sunshine, atmospheric pressure, cloud cover, rainfall, evaporation, rainfall minus evaporation, and humidity based on long-term climatological data at Cabo Frio (——), Ubatuba (···) and Florianópolis (----).

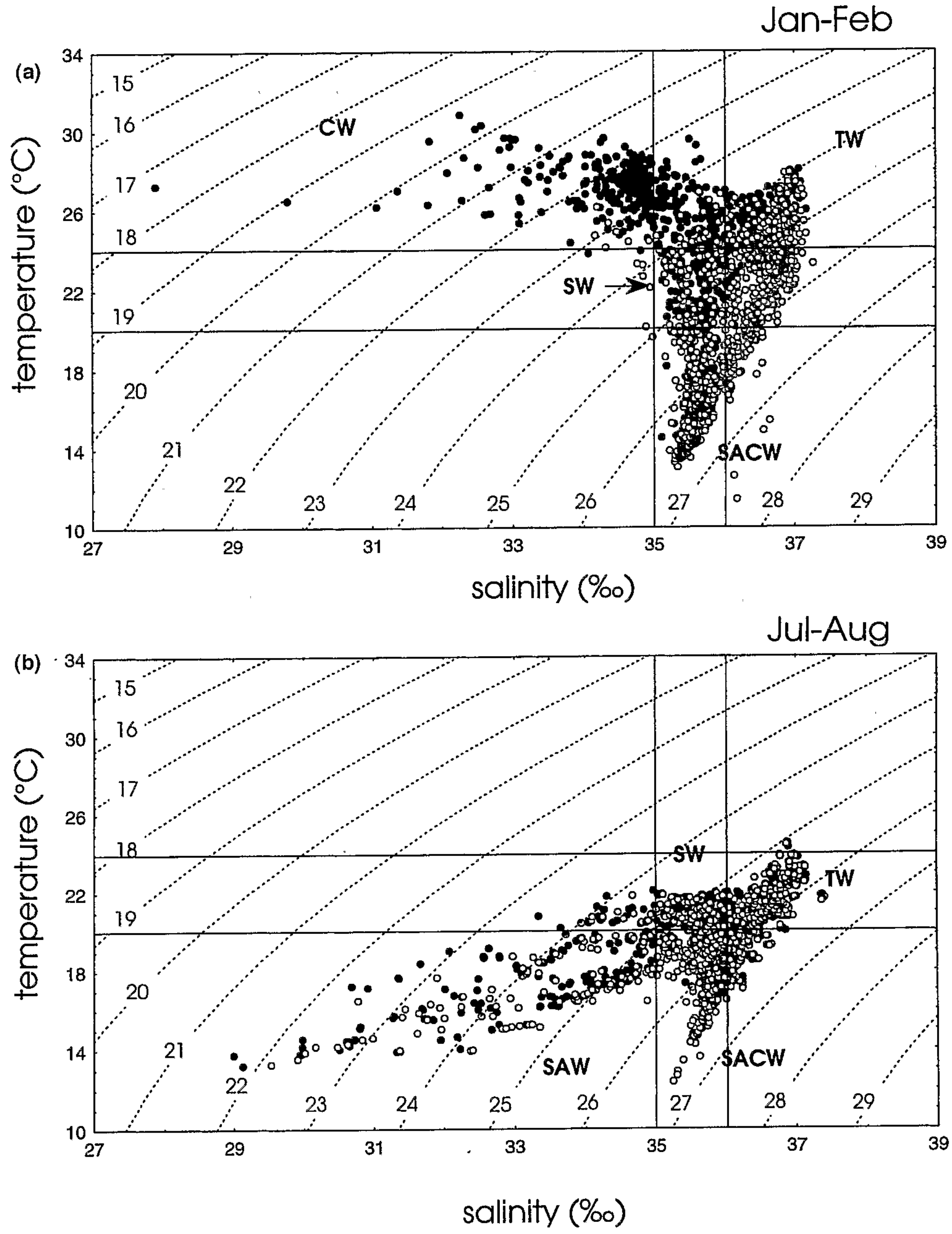


parameter that shows a clear latitudinal gradient, varying in the winter between 22°C in the north and 16°C in the south (Fig. 4). Otherwise, meteorological conditions tended to be more similar at the northern and southern limits of the SBB, characterized by the greatest duration of sunshine hours, weak-to-moderate rainfall, higher evaporation, lower humidity and lower cloud cover than in the middle sector.

Hydrography

The hydrography of the area is examined for the two extreme seasonal situations, these being for the warmest period, January–February (summer) and the coldest, July–August (winter), using data from the surface to 50 m depth. The summer TS plot (Fig. 5a) indicates the presence of four different water masses: Tropical Water (TW), associated with the

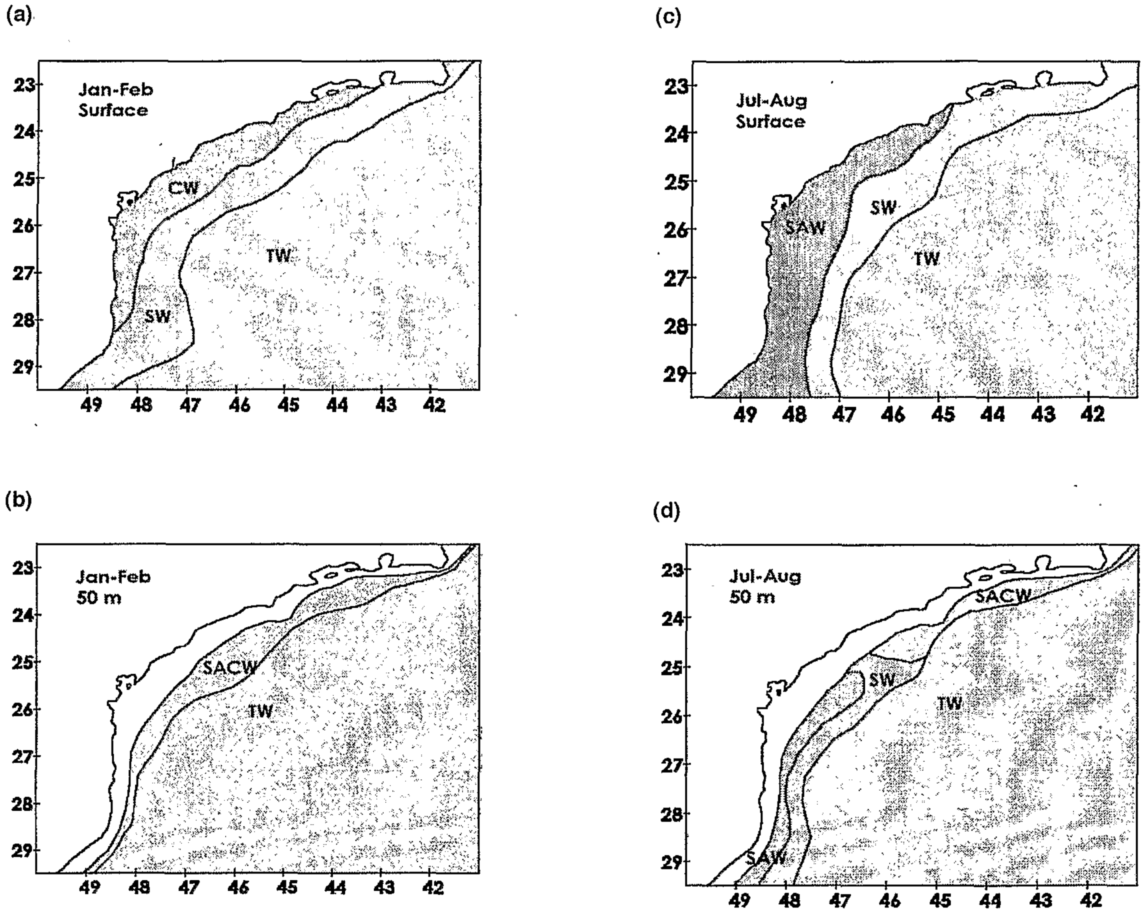
Figure 5. TS diagram for (a) summer (January–February) and (b) winter (July–August) for data extracted for the area between 22°30′S to 29°30′S and 41°W to 50°W, from the surface to 50 m depth. Filled circles refer to samples within the upper 10 m of the water column; open circles are for samples between 20 and 50 m depth. Contour lines refer to sigma-t density values. CW, Coastal Water; SACW, South Atlantic Central Water; SAW, Sub-Antarctic Waters; SW, Shelf Water; TW, Tropical Water.



Brazil Current; South Atlantic Central Water (SACW); Coastal Water (CW), predominantly in the upper 10 m of the water column and influenced by continental run-off; and Shelf Water (SW), this being a mixture between the three other water masses.

In winter, the amplitude of variation of temperature is smaller (Fig. 5b). The CW disappears and is replaced mainly by Sub-Antarctic Water (SAW), which is observed from the surface to 50 m depth.

Figure 6. Horizontal distribution of water masses over the SBB during the summer (January–February) at (a) the surface and (b) 50 m depth, and during the winter (July–August) at (c) the surface and (d) 50 m depth. CW, Coastal Water; SACW, South Atlantic Central Water; SAW, Sub-Antarctic Waters; SW, Shelf Water; TW, Tropical Water.



Distribution of water masses

During the summer (January–February), the influence of continental run-off over the inner shelf is observed in the area occupied by the CW, principally in the middle sector of the SBB (Fig. 6a) from the surface to 20 m depth (Fig. 7b,c). The outer shelf is dominated by SW. The TW, associated with the Brazil Current, is close to the coast only in the northern sector, remaining offshore and in a deeper position further south. While the SACW is not observed at the surface, there is localized surface cooling, both at the northern and southern limits of the SBB, associated with coastal upwelling. A strong subsurface upwelling (at around 20 m depth) occurs mainly in the northern part of the area, and at 50 m depth the SACW occurs over the bottom of the whole shelf, close to the coast (Fig. 7a). In the middle sector, the temperature difference between the surface and the cold SACW at 50 m depth is 10°C, resulting in strong thermal stratification of the water column.

During the autumn (not shown), the presence of CW on the shelf is less evident, probably owing to the reduction in rainfall in this season, consequently the continental shelf area is dominated by the SW. SACW is also detected at shallow depths (30 m) and with higher temperatures than in summer. In late autumn, the structure of the isotherms and isohalines on the shelf is strongly determined by the beginning of the northward flow of the cold, low-salinity SAW from the Argentinian shelf, particularly in the south of the SBB.

The northwards flow of the SAW intensifies during winter (Fig. 6c), reaching Ubatuba. The Brazil Current (TW) continues to flow southward over the continental slope (Fig. 7e,f), but at its southern limit, the TW is displaced offshore (Fig. 7g,h), probably

Figure 7. Vertical distribution of water masses in the SBB, during the summer (January–February) and winter (July–August). CW, Coastal Water; SACW, South Atlantic Central Water; SAW, Sub-Antarctic Waters; SW, Shelf Water; TW, Tropical Water. Depth in metres. The positions of the sections are shown in Fig. 1.

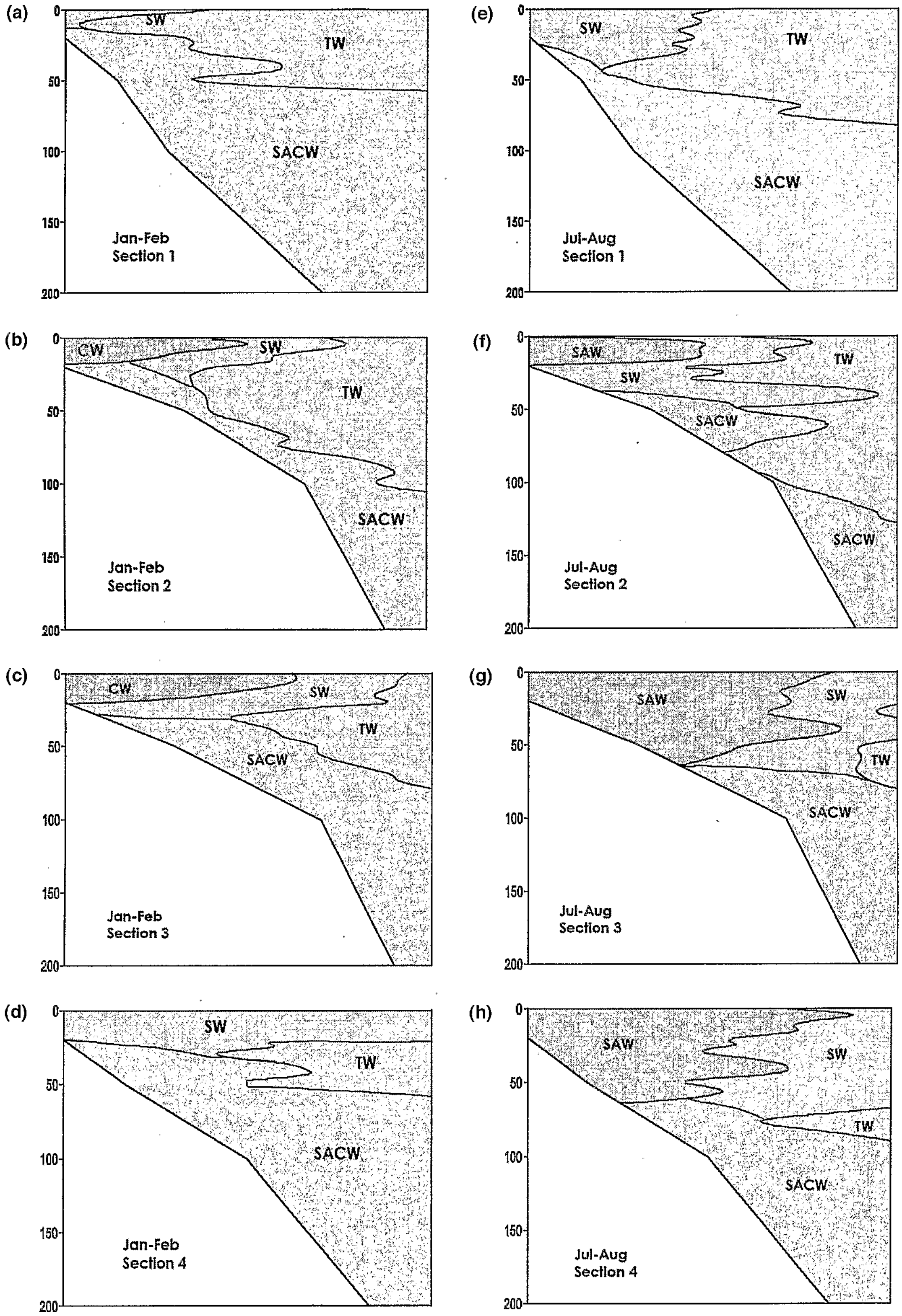


Table 2. *R*-statistic for one-way ANOSIM pairwise tests for significant differences in environmental data (meteorological and oceanographic) between the three areas of the South Brazil Bight in each seasonal period. Significant values are marked with an asterisk and non-significant values with ns.

	Summer		Autumn		Winter		Spring	
Areas compared	*R*	*P*	*R*	*P*	*R*	*P*	*R*	*P*
North × middle	0.75	0.00*	0.24	0.00*	0.43	0.00*	0.23	0.02*
North × south	0.17	0.08 ns	0.28	0.01*	0.83	0.00*	0.08	0.19 ns
Middle × south	0.49	0.00*	0.10	0.19 ns	0.13	0.14 ns	0.22	0.05*

Table 3. Multiple regression (MREG) models between the log-transformed monthly catches of the Brazilian sardine in the three fishing areas and various independent meteorological and oceanographic parameters. Humid, humidity; Cloud, cloud cover; Rain, rainfall; Sun, sunshine; Evap, evaporation; Sss, sea surface salinity; Sst, sea surface temperature. For all regressions, $n = 11$. The r^2 and *P* values are also shown. Significant values are marked with an asterisk.

Fishing areas	r^2	*P*	MREG model
Rio de Janeiro (RJ)	0.57	0.03*	RJ = 0.9 Humid − 0.8 Cloud − 0.7 Rain
São Paulo (SP)	0.90	0.00*	SP = −2.2 Rain + 2.0 Cloud + 1.3 Sun + 0.5 Humid
Santa Catarina (SC)	0.84	0.00*	SC = 1.1 Sss + 0.8 Sst − 0.5 Evap

pushed by the SAW. In late winter, this water mass begins to retreat to the south. In the north of the area, the coastal and inner shelf areas are completely occupied by the SW. SACW continues its intrusion along the bottom of the shelf, but is now restricted to the north of the area. In the middle sector and in the south, the SACW is found deeper, below the 50 m isobath.

The spring (not shown) is characterized by the end of the retreat of the SAW, and the transition to summer conditions.

Separation into three sectors

The results of the ANOSIM test on the meteorological and oceanographic data of the SBB (Table 2) indicate that differences between sectors are dependent on the season of the year. During spring and summer, the northern and southern sectors are similar, but both differ significantly from the middle sector. This confirms the pattern of distribution of water masses (predominance of CW only in the middle sector) and weather variability (principally rainfall, humidity and hours of sunshine) described earlier. Conversely, during autumn and winter, the middle and the southern sectors are similar to each other but different from the north. Such a pattern again shows a correspondence with the distribution of water masses and weather, SAW being restricted to the middle and southern sectors, with moderate rainfall and cloud cover and low air temperature.

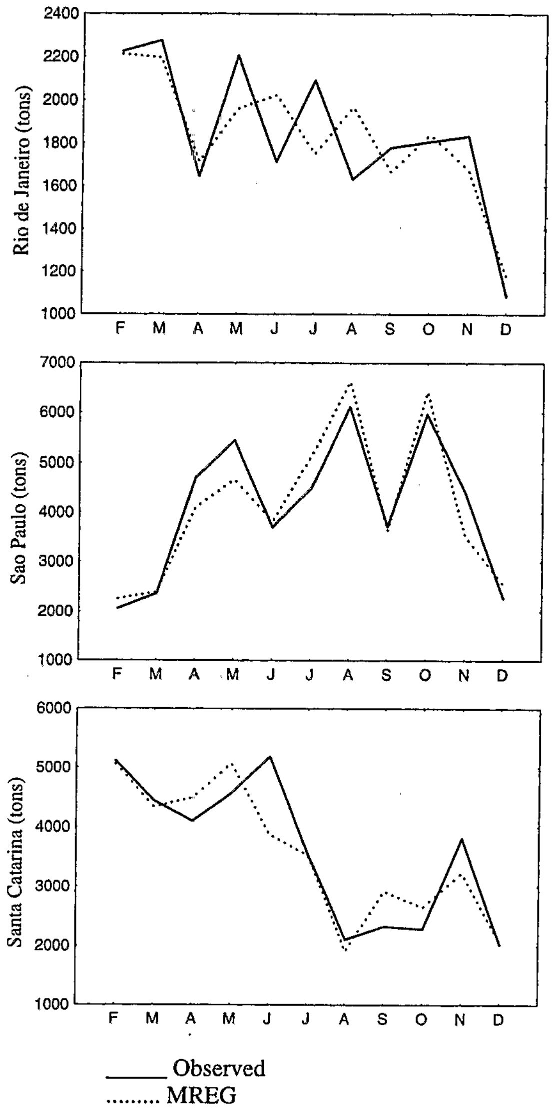
Relationship between sardine catch and environmental parameters

The results of the multiple regression analyses are shown in Table 3 and Fig. 8. The highest correlations between catches and environmental data were found for São Paulo and Santa Catarina, but all models were significant ($P < 0.05$). Catches at Rio de Janeiro were predicted ($r^2 = 0.57$) by a combination of three independent variables: humidity, cloud cover and rainfall. At São Paulo, the same combination of variables plus sunshine were responsible for the high correlation observed ($r^2 = 0.90$). No oceanographic data were required in the models, indicating that meteorological conditions were more important in the northern and middle sectors, especially those related to rainfall. At Santa Catarina, catches were predicted principally by oceanographic parameters, the combination of salinity, temperature and evaporation showing a strong correlation ($r^2 = 0.84$) with landings.

DISCUSSION

In the present analysis the seasonal variability in occurrence of sardine in the SBB was represented by landing data, which may not necessarily reflect stock abundance; however, several lines of evidence suggest that in this particular case, this may be a valid assumption. Firstly, the Brazilian sardine fishery is restricted to areas within the 60 m isobath, neither field records nor acoustic surveys having detected

Figure 8. Monthly catches of Brazilian sardine at Rio de Janeiro, São Paulo and Santa Catarina, and fits produced by the multiple regression models; (——) observed, (···) MREG fit.



S. brasiliensis in deeper water (Castello *et al.*, 1991; Saccardo and Rossi-Wongtschowski, 1991); therefore, the sardine population is probably available to the fishery within the SBB throughout the year. Secondly, the landing harbours have to be close to the fishing areas because of the lack of refrigeration systems in the fishing boats (Valentini and Cardoso, 1991). Thus it may be correct to conclude that differences between regions in the catch of the Brazilian sardine reflect the geographical pattern of abundance and/or availability of the pelagic fish.

It has previously been suggested that the SBB has a relatively homogeneous oceanographic structure (Castro Filho, 1990). However, the results of the present study showed a clear seasonal and spatial variability of the environmental parameters within the area. According to its meteorological and oceanographic characteristics, the SBB could be divided into three different sectors: a northern sector that corresponds to the stations from Cabo Frio to Ilha Guaiba; a middle sector between Angra dos Reis and Paranaguá; and a southern sector south of Florianópolis.

The meteorological and oceanographic structures of the northern sector differed from those of the middle sector during all seasons, and from the south during the autumn and winter. In the north, low seasonal variability in weather conditions is accompanied by a seasonal coastal upwelling near Cabo Frio. It is well known that some of the most productive regions with the largest pelagic fish populations are associated with coastal upwelling systems (Bakun, 1996). Interestingly, the sardine landings in the northern sector are the lowest of the SBB throughout the year. This particular upwelling system, in the vicinity of Cabo Frio, is characterized by its short-term instability, which leads to daily changes in the sea surface temperature of up to 10°C (Valentin, 1984). Moreover, in spite of the seasonal upwelling, the local primary productivity shows little seasonal variation (Gonzalez-Rodriguez, 1994). The relatively low productivity of this sector, compared with the remaining SBB (Gonzalez-Rodriguez *et al.*, 1992), together with the high environmental instability, may explain the low concentrations and small catches of sardine in this area. Weak seasonal variability in both climatic and fishery data determined the low correlation ($r^2 = 0.57$) in the multiple regression analysis.

The landings in the middle and the southern sectors account for almost 80% of the total sardine catch in the SBB, but with an inverse seasonal pattern. While 60% of the landings in the south are in the summer, during winter 60% are in the middle sector. The results of the ANOSIM analysis for both meteorological and oceanographic data revealed two distinct patterns: during the spring and summer, the middle and southern sectors differed significantly; while during the winter and autumn, these sectors showed the same environmental conditions.

Differences between the middle and southern sectors of the SBB in spring and summer are clearly related to continental run-off, which results in the low salinity and high temperatures of the middle sector coastal waters. Matsuura (1986) suggested that the CW is restricted to a narrow band adjacent to the coast and its influence on the water masses over the shelf is limited. In the present study, the CW occupied all of the inner shelf of the middle sector, whilst the southern area was dominated by the SW. Large-scale sea surface temperature maps also show a maximum temperature core over the middle sector of the SBB (Hastenrath and Lamb, 1977; Bakun and Parrish, 1990), confirming the importance of CW over the shelf. In the south of the SBB, a restricted and more productive coastal upwelling in the vicinity of Cabo Santa Marta in the summer has been reported previously (Odebrecht and Caruso, 1987), which is supported by the climatological data of the present study.

In the winter, the intrusion of the cold, low-salinity SAW is the most prominent oceanographic feature in both the middle and southern sectors. The widescale presence of this water mass in the SBB leads to a homogeneous environmental structure, as evidenced by the results of the ANOSIM analysis. The northernmost penetration of the SAW has previously been reported at 30°S (Ciotti *et al.*, 1995; Lima *et al.*, 1996), at 26°S (Brandini, 1990) and recently at 23°S (Campos *et al.*, 1996; Stevenson, 1996). These variations reflect a considerable interannual variation, possibly related to the position of the Brazil–Malvinas Confluence (Castello *et al.*, 1990). In the present study, the climatological data indicated that on average, this water mass reaches 24°S.

Species of the genus *Sardinella* are sensitive to changes in environmental conditions, which may control their seasonal movements (Binet, 1982, 1988, 1995; Longhurst and Wooster, 1990; Vakily and Pauly, 1995). It is also likely that movements of the Brazilian sardine inside the SBB are affected by meteorological and oceanographic processes, as evidenced in all sectors by the significant correlation of landings with environmental parameters. Both in the north, where the correlation is weak, and in the middle sector where the correlation is high, the landings seems to be more closely related to meteorological conditions than to the oceanography. The MREG models in these two areas included meteorological variables only, most notably related to rainfall. Conversely, in the southern sector the oceanographic variables, particularly salinity, accounted for most of the variability in the catch.

It is interesting to compare the ecological significance of the variables related to the landings in each area. In the south, landings were positively correlated with salinity, and in the northern and middle sector, negatively correlated with rainfall. This suggests that less saline waters, or meteorological parameters that lead to a reduction of the salinity in the coastal waters (such as rainfall, evaporation and sunshine), affect the distribution of Brazilian sardine inside the SBB. Similar results for the African species of *Sardinella* were found by Vakily and Pauly (1995) and Binet (1982). Less saline waters over the SBB were observed in two different water masses: in the CW during summer, which is highly influenced by the local climate, and in the SAW during winter. The CW and the SAW delineated boundaries between different water types, and these fronts are associated with high primary production (Brandini, 1990). In the SBB, Brazilian sardine abundance and availability are driven by two apparently independent processes. Longer time series would be required to determine the annual variation of these processes, and therefore their relative influence on the Brazilian sardine fishery.

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