PRODUCTION MODELS AS APPLIED TO SUB-STOCKS DEPENDING ON UPWELLING FLUCTUATIONS

by

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Resumen

La plataforma continental del oeste de Africa entre los 11°N y 24°N representa un área de pesca muy rica relacionada a afloramiento costero. En esta área se presentan dos poblaciones de sardinas (*Sardinella aurita* y *Sardinella maderensis*), cuyos adultos migran largas distancias dentro del área descrita. La explotación es intensiva y variada, pero debido a lo poco adecuado de las estadísticas de captura no es posible establecer modelos de producción para toda la población de cada especie.

Dos áreas principales de cría reciben importantes sub-stocks de individuos jóvenes, los que permanecen en dichas áreas hasta su primer desove. Una de las áreas de cría, localizada en la "Petite Côte" de Senegal, es explotada intensamente, disponiéndose de series de datos de captura y esfuerzo de pesca (de la pesquería semi-industrial y artesanal).

Se discuten dos hipótesis principales, una relacionada a la estabilidad de la tasa de explotación fuera de "Petite Côte" y la otra, que se relaciona a parte del reclutamiento. Bajo estas dos hipótesis, cada sub-stock correspondiente puede ser considerado separadamente. Los datos colectados sugieren que los rendimientos de la pesca están relacionados con el esfuerzo de pesca local, y con la intensidad del viento responsable del afloramiento costero. La interpretación del efecto del afloramiento sobre los rendimientos se conoce todavía en forma incompleta: hay probablemente una adición a la fertilización del ambiente, y es probable que haya un aumento de la disponibilidad de sardinas asociadas al aumento de la productividad.

Se han establecido diferentes modelos de producción en base a análisis de regresión linear múltiple, incluyendo rendimiento de la pesca, esfuerzo e intensidad de vientos, tales como:

$$\text{c.p.u.e.} = a \exp (a/f) + b\bar{V} + \varepsilon$$

Donde c.p.u.e. es la captura por unidad de esfuerzo para el año (n), f es el esfuerzo de pesca durante el mismo año, V es la intensidad promedio de los vientos durante los años (n) y (n-1), a, b y c son constantes, y ε es el residuo. Las hipótesis preliminares son confirmadas indirectamente y se discuten los resultados obtenidos.

Bajo las condiciones presentes de explotación, el máximo rendimiento sostenible de *Sardinella spp* en la "Petite Côte" debe fluctuar entre 56 000 y 90 000 toneladas métricas por año. La actual tasa de explotación está próxima a su óptimo y se teme que una disminución de la intensidad del afloramiento (por ejemplo causada por la velocidad del viento), y/o un aumento del esfuerzo de pesca pueda afectar seriamente los stocks.

Sin embargo, los datos actuales no permiten una evaluación precisa de la producción para condiciones extremas de intensidad de viento y esfuerzo de pesca mayores que los esfuerzos de pesca en las áreas costeras, a través de varios métodos:

- la extensión de las áreas de pesca que está actualmente limitada por el tipo de embarcación la localización de los lugares de desembarque,

- mantenimiento de un tipo de explotación flexible con la finalidad de poderlos ajustar rápidamente a las fluctuaciones de producción que pueden estar relacionados a la intensidad de los vientos, en relación a este último punto, la dualidad de la pesquería, artesanal y semi-industrial, tiene gran interés.

INTRODUCTION

The West African continental shelf, extended from 11°N to 24°N, represents a rich fishing ground related to coastal upwelling. Two populations of sardines (*Sardinella aurita* and *Sardinella maderensis*) are present, the adults of which migrate over long distances within the mentioned area. Exploitation is intensive and varied, but due to the inadequacy of fishing statistics it is not possible to establish production models for the entire population of each species.

Two principal nurseries receive important "sub-stocks" of young fish which remain present until their first spawning. One of the nurseries, located on the "Petite Côte" of Senegal, is intensively exploited and statistical catches and fishing effort series are available. The study of this nursery is the object of this paper.

SARDINE STOCKS AND SENEGALESE FISHERIES

The biology of the two sardine species has been studied by various authors. These references are available in Boely's synthesis (1980). *Sardinella aurita* constitute a single stock which can be subdivided in three "sub-stocks": two important nurseries are observed, one in Mauritania and the other in Senegal on the Petite Côte (Figure 1). There young fishes remain present until their first spawning and then enter in the common sub-stock of migratory adults which moves over the continental shelf between 11°N and 24°N. These migrations occur over grounds generally deeper than 25 m in relation with the thermal front (Boely et al., 1978). So, adult fishes are available in Senegal only during 5 or 6 months per year, and mainly for long range fishing boats.

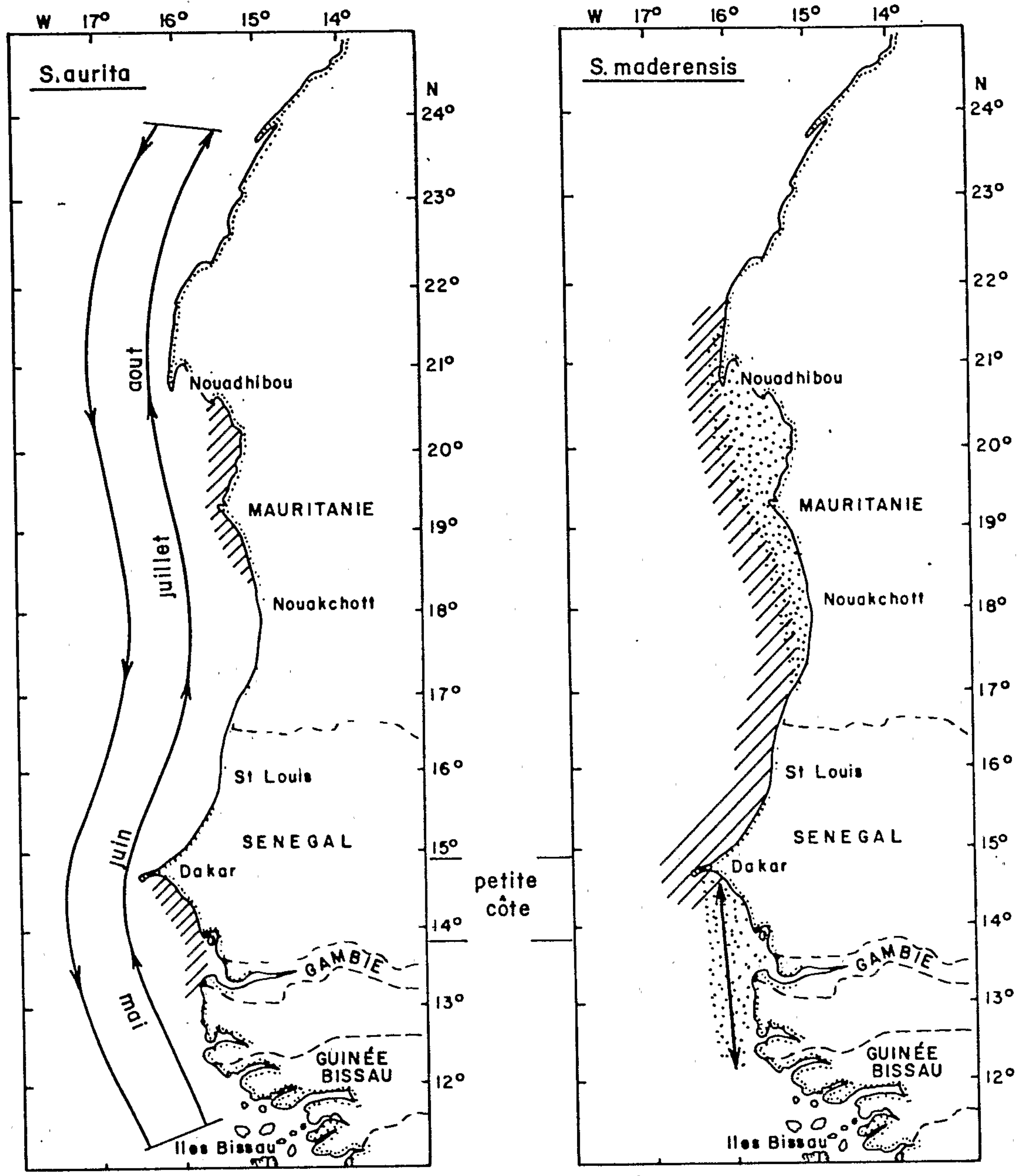
Sardinella maderensis nurseries localities are similar to *Sardinella aurita* (Figure 1) but here the young fish migrations are preponderant inside each nursery and generate local variations in availability. Opposed to the case of *Sardinella aurita*, the adult sub-stock has a low numerical importance, at least in Senegal, and it seems that exchanges between the two nurseries, if existing, are insignificant.

Senegalese fisheries are subdivided in two types: semi-industrial and artisanal. The first one is made up of a 25 m overall mean length, purse-seines fleet, already described in detail (Champagnat, 1966; Boely and Chabanne, 1975), for which the number of units has fluctuated between 10 and 20 during the last 15 years. The second one is characterized by the use of wooden canoes. This type is more diversified as it uses surrounding gill-nets, small purse-seines and beach-seines (Freon et al., 1979). The Senegalese fishery is exclusively a coastal activity. It is developed on Petite Côte where mainly young fishes are captured (Figure 2).

BASIC HYPOTHESIS

For *Sardinella aurita* the recruitment of young fishes in Senegal has two origins. First the main spawning of adults during the period of May and June on Petite Côte, and on the other hand, the secondary spawning of the young fishes themselves at the same locality during October and November before they leave their nursery (Conand, 1977). Although the relative importance of each spawning season has been calculated in terms of larval density, importance in terms of recruitment is still ignored due to the differences in larval and fry mortality between the two cohorts.

Anyway, it is clear that the exploitation of *Sardinella aurita* outside Petite Côte (adult sub-stock or Mauritanian nursery) could have consequences on its abundance only through a stock-recruitment relationship, namely the relation between adult sub-stock and the Petite Côte recruitment. The type of relationship is unknown and its precise knowledge is important from a theoretical point of view in order to forecast Petite Côte sub-stock reactions under strong abundance fluctuations of adults sub-stock.



—— Migration of adult sub-stock
///// Nurseries

∴∵ Nurseries
///// Observed distribution of adult sub-stock

Fig. 1. *Sardinella aurita* and *Sardinella maderensis* distribution (mai = May; juin = June; juillet = July; aout = August), from Boely et al. (1978).

Harris' analysis (1975) has shown that both density-dependent and stock-dependent processes are needed to establish the basically dome-shaped curve, which appears to be characteristic of the stock-recruitment relationship within the fishes. Now, in the case of adult *Sardinella aurita*, it immigrates and does not stay on the spawning grounds, which could limit the stock-dependent mechanism mainly based on cannibalism. In practice, with any figure retained, it can be considered that the adult sub-stock abundance varies around a mean level. However, the variability of recruitment in the Petite Côte sub-stock related to this former sub-stock is not important, comparatively to variability due to other factors, particularly environmental ones. Indeed, abundance fluctuations in the adult sub-stock has been estimated through one index, i.e., catches per unit of effort (CPUE), of fish larger than 25 cm (Freon et al., 1979). During the observed period, annual variations were of one order of magnitude, except for 1975 where the index was strongly under-estimated on account of the target-species change. Curves obtained from other pelagic species (Cushing, 1978) show important variations in recruitment only from three to four orders of magnitude in stock abundance variations, over a critical level of stock size.

So, we have retained as a basic hypothesis that during the period studied, fishing outside Petite Côte did not have any impact on the abundance inside the Petite Côte nursery (Freon et al., 1979).

For *Sardinella maderensis* the situation is much more simple since recruitment on Petite Côte seems to be from spawnings by young fish only. In fact the latter leave the nursery from 24 cm of fork-length (probably 1.5 years old) and adults are found in abundance only in Mauritania and north of Senegal. So recruitment on Petite Côte is probably not related to their spawning.

Under this hypothesis it can be considered that CPUE in Petite Côte nursery depends essentially on local fishing effort and eventually on environmental conditions influencing on recruitment, young fishes growth and/or mortality.

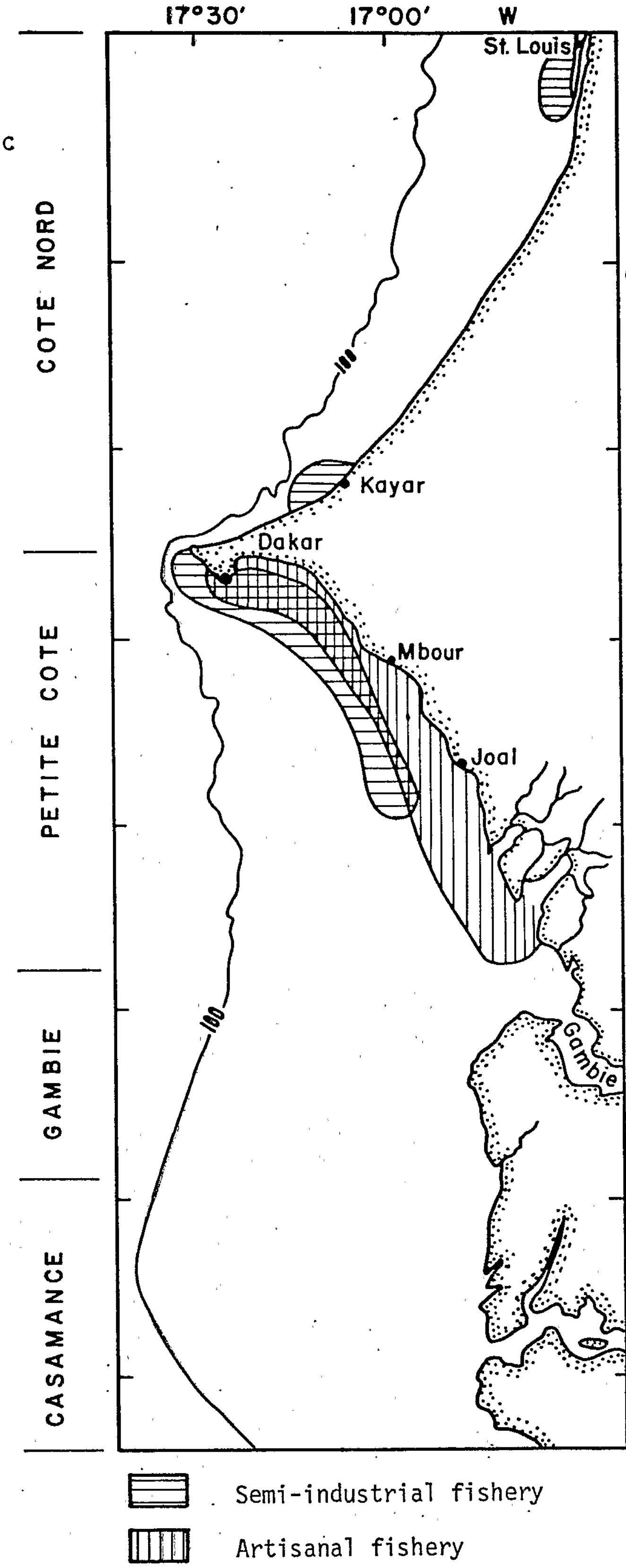


Fig. 2. Senegalese fisheries localization

Table 1: *Sardinella aurita*; catches (metric tons), fishing effort (10 hours' fishing of a standard semi-industrial purse-seiner), and catch per unit of effort (c.p.u.e.) of fisheries in the Petite Côte. Mean wind speed ($\bar{V}$) during the trade wind season of years n and n-1 (m/s).

Years	Indust. Catches	Indust. C.P.U.E.	Indust. Efforts	Artis. Catches	Artis. Efforts	Total Catches	Total Efforts	Total C.P.U.E.	Wind Speed $\left(\frac{2Vn+Vn-1}{3}\right)$
1966	4 250	13,54	314	3 970*	293*	8 220	607	13,54	4,93
1967	4 240	11,62	365	3 580*	308*	7 820	673	11,62	4,74
1968	7 060	12,70	556	4 110*	324*	11 180	880	12,70	4,53
1969	9 700	9,86	984	3 360*	341*	13 060	1 325	9,86	4,40
1970	8 390	7,56	1 110	2 710*	359*	11 100	1 469	7,56	4,32
1971	9 440	10,68	884	4 037*	378*	13 480	1 262	10,68	4,70
1972	17 250	16,32	1 057	6 500	398	23 750	1 455	16,32	5,63
1973	17 590	11,38	1 546	11 880*	1 044*	29 470	2 590	11,38	5,53
1974	17 790	9,78	1 819	16 530*	1 690*	34 320	3 509	9,78	5,76
1975	12 430	7,22	1 722	16 900*	2 337*	29 330	4 059	7,22	5,66
1976	14 800	8,06	1 836	24 050*	2 984*	38 850	4 820	8,06	5,79
1977	13 150	8,61	1 527	31 280	3 630	44 430	5 157	8,61	5,72
1978	12 660	9,15	1 384	32 280	3 356	44 940	4 740	9,48	5,21
1979	13 600	6,68	2 035	26 340	4 577	39 940	6 612	6,04	4,68
1980	14 860	7,01	2 120	28 620	3 837	43 480	5 957	7,29	4,98

* Partially estimated data

Table 2: *Sardinella spp.*; catches (metric tons), fishing effort (10 hours' fishing of a standard semi-industrial purse-seiner), and catch per unit of effort (c.p.u.e.) of fisheries in the Petite Côte.

Years	Indust. Catches	Indust. C.P.U.E.	Indust. Efforts	Artis. Catches	Artis. Efforts	Total Catches	Total Efforts	Total C.P.U.E.
1966	6 450	20,3	318	22 840*	1 125*	29 290	1 443	20,3
1967	5 410	17,7	306	20 960*	1 184*	26 370	1 490	17,7
1968	8 860	15,8	561	19 690*	1 246*	28 550	1 808	15,8
1969	14 480	14,3	1 012	18 760*	1 312*	33 240	2 324	14,3
1970	12 640	11,3	1 117	15 610*	1 381*	28 250	2 498	11,3
1971	11 480	13,2	870	19 190*	1 454*	30 670	2 324	13,2
1972	21 720	20,9	1 039	32 000	1 531	53 720	2 570	20,9
1973	26 200	16,3	1 608	33 740*	2 070*	59 940	3 678	16,3
1974	27 770	15,9	1 747	41 480*	2 609*	69 250	4 356	15,9
1975	21 930	12,5	1 754	39 360*	3 149*	61 290	4 903	12,5
1976	26 730	14,7	1 818	54 210*	3 688*	80 940	5 506	14,7
1977	22 400	14,8	1 513	55 200	4 227	77 600	5 740	13,5
1978	17 970	12,7	1 415	58 430	3 767	76 400	5 182	14,7
1979	22 310	10,7	2 085	47 160	4 415	69 470	6 500	10,7
1980	23 800	11,7	2 034	46 440	4 319	70 240	6 353	11,1

* Partially estimated data

AVAILABLE DATA

Detailed data on semi-industrial fisheries have been available since the beginning of exploitation (1961), but catches per unit of effort have been representative of abundance only since 1966. The previous period is considered as experimental (Boely and Chabanne, 1975). Fishing time (total time outside of port minus travelling time) was used as unit of effort (Freon, 1980). Considering the small size of the fishing area and the stability of the exploitation scheme, stratification by zone was not used. In return, unweighted mean of monthly CPUE was computed to get an annual index of abundance.

Artisanal fisheries data is much more incomplete for this very old activity. The first observations were done in 1972, then interrupted from 1973 to 1976 and again have been available since 1977. Estimations were obtained under the hypothesis supposing that semi-industrial CPUE fluctuations are representative of the artisanal ones. This hypothesis is based on similarity of fish length composition of the catches in both fisheries. This is confirmed by the analysis of the available data during the last years.

However, when realized for *Sardinella maderensis* the estimations lead to a global data table where the proportion of estimated catches and efforts is very high, specially before 1972 due to the predominance of gill-nets over artisanal purse-seine. Moreover, this species is not as sought after as *Sardinella aurita* by semi-industrial purse-seiners and consequently the derived abundance index can be biased by target-species changes. For this reason only two data sets were considered: one concerning *Sardinella aurita* and the other regrouping the two species of *Sardinella* and named now: *Sardinella spp.* (Tables 1 and 2). The latter presents the advantage of minimizing target-species change without differing too much from the basic hypothesis relative to production models because the two species have the same biotope.

Anyway, usual reserves must be done about the representativity of CPUE as abundance index, specially on an eventual change of the catchability coefficient related to abundance (Ulltang, 1976; Freon, 1980; Saville, 1980).

MODELLING SARDINE PRODUCTION

Apparent relations between CPUE, fishing effort, and wind intensity

The figure obtained from the 1966-1980 data for *Sardinella aurita* and *Sardinella spp.* show a negative correlation between CPUE and fishing effort, but the adjustment is very poor when applied to the whole period. In return, when data is subdivided in two periods, separated by January 1st, two decreasing lines (or curves) of regression clearly appear (Figures 3 and 4). This suggests the influence of a second factor on CPUE which strongly changed in 1972.

Both sardine species belong to the first level of the trophic web because they eat phytoplankton during their first stages of life and afterwards they will consume zooplankton. On Petite Côte, eutrophication is assumed by a coastal upwelling (Rossignol, 1973) which is probably responsible for the variations in primary production as shown by various authors, of whom Sedykh et al. (1978) in Mauritania. A time plot during the trade winds season (November to May) shows low values of mean wind intensity (expressed in speed) from 1966 to 1971 and high values thereafter, with an exception in 1979 (Figure 5).

On account of an autocorrelation observed in the seasonal wind speed with one year lag (r=8.57) it is difficult to know if the abundance in one year is related only to wind speed during the same year or also during the previous year. The latter case can be supposed because most of the fish caught are between 1 and 1.5 years old. We will see that statistical analysis is of little utility for solving this problem with the available data.

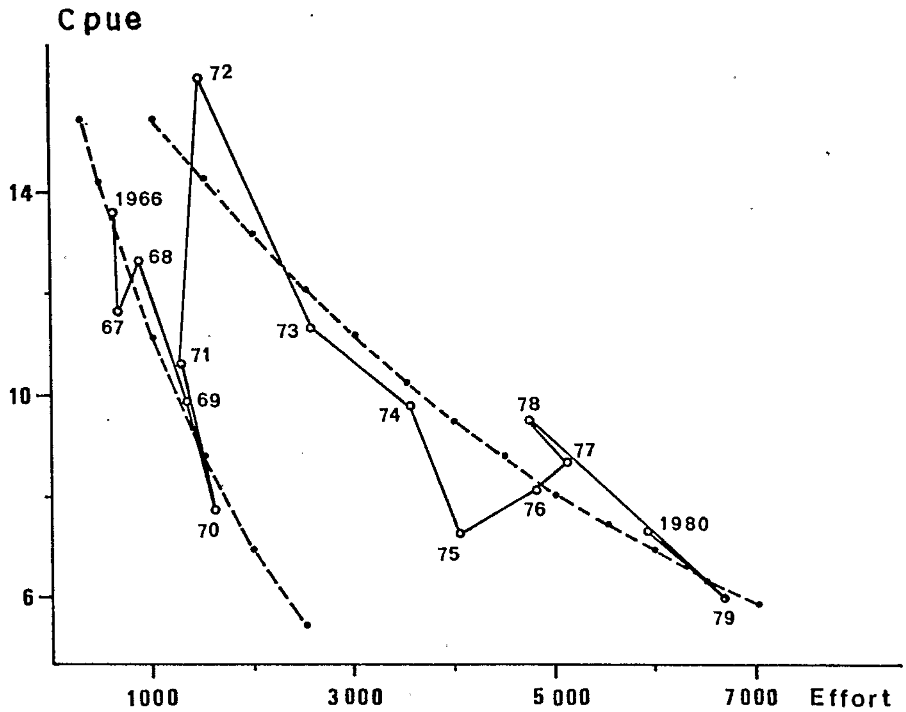


Fig. 3. *Sardinella aurita*; apparent relationship between fishing effort and catches per unit of effort (c.p.u.e.) in the Petite Côte from 1966 to 1980.

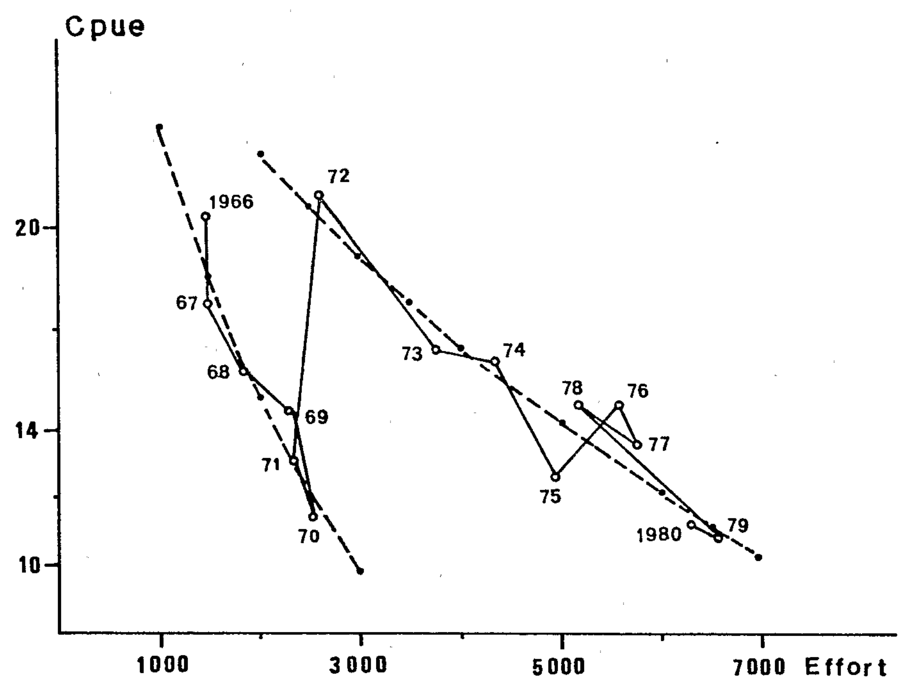


Fig. 4. *Sardinella spp.*; apparent relationship between fishing effort and catches per unit of effort (c.p.u.e.) in the Petite Côte from 1966 to 1980.

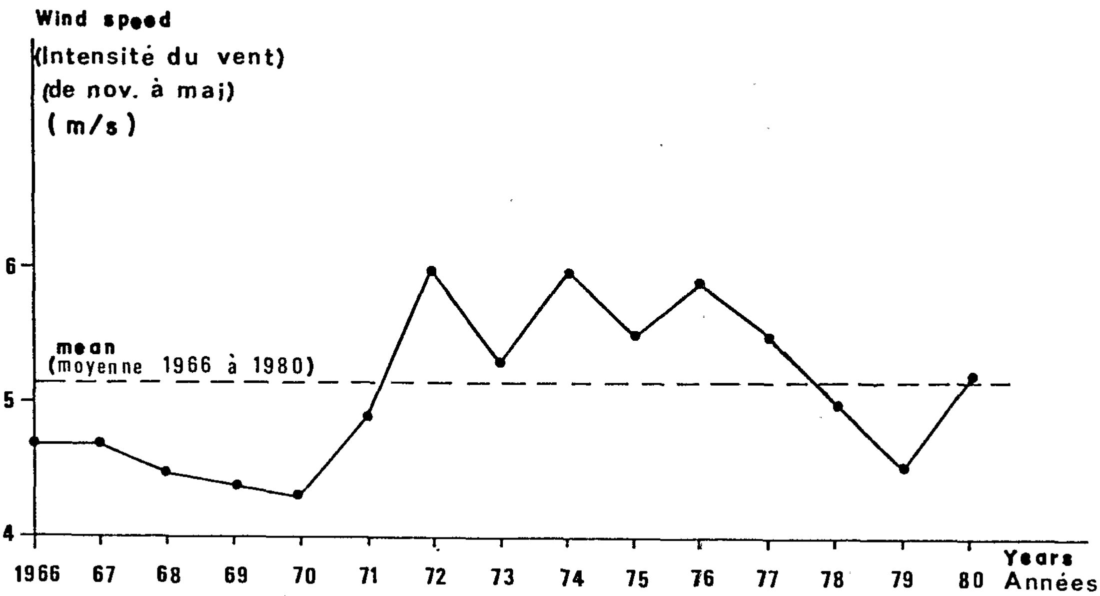


Fig. 5. Time plot of trade wind intensity (from November of year n-1 to May of year n) from 1966 to 1980.

Modelling

Let us suppose that mean CPUE observed during one year would be dependant, first, on fishing effort during the same year, second on mean wind intensity during the trade wind season of the same year and of the previous one. Various multiple - regressions between the three variables were tried, based on different hypothesis about the possible relationship between each variable.

The linear relation between CPUE and effort (Schaefer, 1957) was not used because it supposes that over a certain limit of effort, the CPUE can reach zero, which is in contradiction with our hypothesis for *Sardinella aurita* which states that part of the recruitment is independant of the exploitation on Petite Côte. So, this model seems too pessimistic and we have retained the negative exponential model (Fox, 1970), where the increase of effort assures a more progressive decline in yields. Supposing a linear relation (discussed later) between wind intensity and yield, we combined the following equations:

$$\log CPUE = -a1\ f + b1 + r1 \qquad (1)$$

$$CPUE = a2\ \bar{V} + b2 + r2 \qquad (2)$$

where CPUE is the catch per unit of effort during the year n; f is the fishing effort during the same year; $\bar{V}$ is the mean speed of trade winds (various combinations between season of year n and n-1 were used); a, b, c are parameters obtained by adjustment, and r is the residual. From (1) and (2) we obtain:

$$CPUE = a\ EXP{-a^{-}}f + b\ \bar{V} + c + r \qquad (3)$$

Fitting the observed values to the theoretical curve must be done by iterative computation. The data was processed first with a hand calculator using a multiple linear regression, with $EXP{-a^{-}}f$ considered as a variable, and searching the value of a^{-} which minimizes the multi-coefficient of correlation. Then the data was processed on a desk computer using Marquardt's algorithms (1963). In both cases the results showed that introduction of year n-1 wind speed did not improve very much the fit for *Sardinella aurita*, but was of some interest when used for *Sardinella spp*. model. The best fit was obtained with the following weighted mean:

$$\bar{V} = (2\ Vn + Vn{-}1) / 3 \qquad (4)$$

Anyway, this does not mean that equation (4) represents the real influence of wind on production. In the same way, iterative computations show that fit does not change very much according to a^{-}. However, this parameter value is strongly related to the curve shape over the observed effort values. The optimal value of a^{-} from a statistical point of view has no biological meaning. This is so when applied to relationship (derived from equation (3)) between catches (C), fishing effort and wind speed, it provides a figure where catches lead to infinite when effort increase under a constant wind speed:

$$C = (a \; EXP\text{-}a^{-} f + b \, \bar{V} + c) \; f + r^{-} \qquad (5)$$

Being one of the main problems of generalized production models, the non-independence between the two variables CPUE and effort (Sissenwine, 1978; Roff and Fairbairn, 1980), we have applied equation (5) for data fitting, using the non-linear regression analysis. This presents the advantage of allowing computation of the parameters confidence limits. None was significant, even with a 90% confidence interval, on account of, first the high number of parameters (4) in comparison with the low number or observations (15). Second, the uncertainty about the a^{-} value previously mentioned. Nevertheless, it is satisfactory to note that when a^{-} is fixed at its optimal value in equation (5), the non-linear regression provides for the three remaining parameters (a, b, and c) values which are significantly different from zero using the 95% confident intervals. This means that fishing effort and wind speed statistically have an influence on catches, although the shape of the curve is uncertain over observed effort values.

The problem with the a^{-} parameter shows that the best statistical fit is not necessarily the most suitable and that the choice of parameters values must also consider the basic hypothesis especially when the stock has not already suffered over-fishing (this problem can be compared with the choice of parameter m in Fox's generalized production model (1975)).

Table 3: Parameters values and confidence intervals got from various regressions on *Sardinella aurita* and *Sardinella spp.* data (tables 1 and 2).

Regression type and equation	Par.	Value	Lower limit	Upper limit	% confid.
S A R D I N E L L A A U R I T A					
	a	14.60	9.00 *	20.2 *	95 %
LINEAR	a^{-}	.00013 B	-	-	-
cpue = a EXP-a^{-}f + bV	b	2.49	.609	4.37	95 %
+ c + r (1)	c	-12.89	-24.85 *	-.935*	95 %
	a	11.75	5.31	18.21	95 %
NONLINEAR	a^{-}	.00013 B	-	-	-
C = (a EXP-a^{-}f + bV +	b	.911	-.534	2.36	95 %
c) f + r^{-}	c	-2.946	-10.14	4.254	95 %
	a	9.42	2.23	16.61	90 %
NONLINEAR	a^{-}	.00024 M	-.0007	.0011	90 %
C = (a EXP-a^{-}f +bV +	b	1.16	-1.11	3.44	90 %
c) f + r	c	-1.01	-8.10	6.00	90 %
S A R D I N E L L A S P P .					
	a	23.55	16.70	30.40	90 %
LINEAR	a^{-}	.00010 B	-	-	-
cpue = a EXP-a^{-}f + bV	b	4.13	2.55 *	5.72 *	90 %
+ c + r (1)	c	-22.63	-33.91 *	-11.36 *	90 %
	a	14.63	2.58	26.67	90 %
NONLINEAR	a^{-}	.00035 M	-.0004	.0001	90 %
C = (a EXP-a^{-}f + bV +	b	3.230	1.428	5.033	90 %
c) f + r	c	-6.271	-13.88	1.342	90 %
	a	19.86	10.51	29.21	95 %
NONLINEAR	a^{-}	.00010 B	-	-	-
C = (a EXP-a^{-}f + bV +	b	3.84	.849	6.83	95 %
dW + c) f + r	c	-12.44	-22.79	-2.098	95 %
	d	-1.646	-5.597	2.306	95 %

B: Optimal biological value of a^{-} (fixed before computation)
M: Optimal statistical value of a^{-} (determined by the regression)
W: Wind speed during the summer (from June to October)
*: No strictly valid limits (due to the correlation between cpue and f)

(1): Presented results on the figures

Arbitrarily, we considered as best value for a^{-} one which provided a stabilization of catches when the effort increases, inside a realistic interval, and when wind speed is high and stable (Table 3).

Equations (3) and (5) lead to tridimensional figures (Figure 6). We also present two dimensional figures, easier to use, from which four curves have been drawn corresponding to characteristic wind speeds: 4.55 and 5.55 m/s which are the two means of the respective two observed periods (1966-1971 and 1972-1980), 4.0 and 6.0 the extreme mean speed which have been observed since 1951 (Figure 7). Time-plots of observed and computed values have also been presented (Figures 8 and 9).

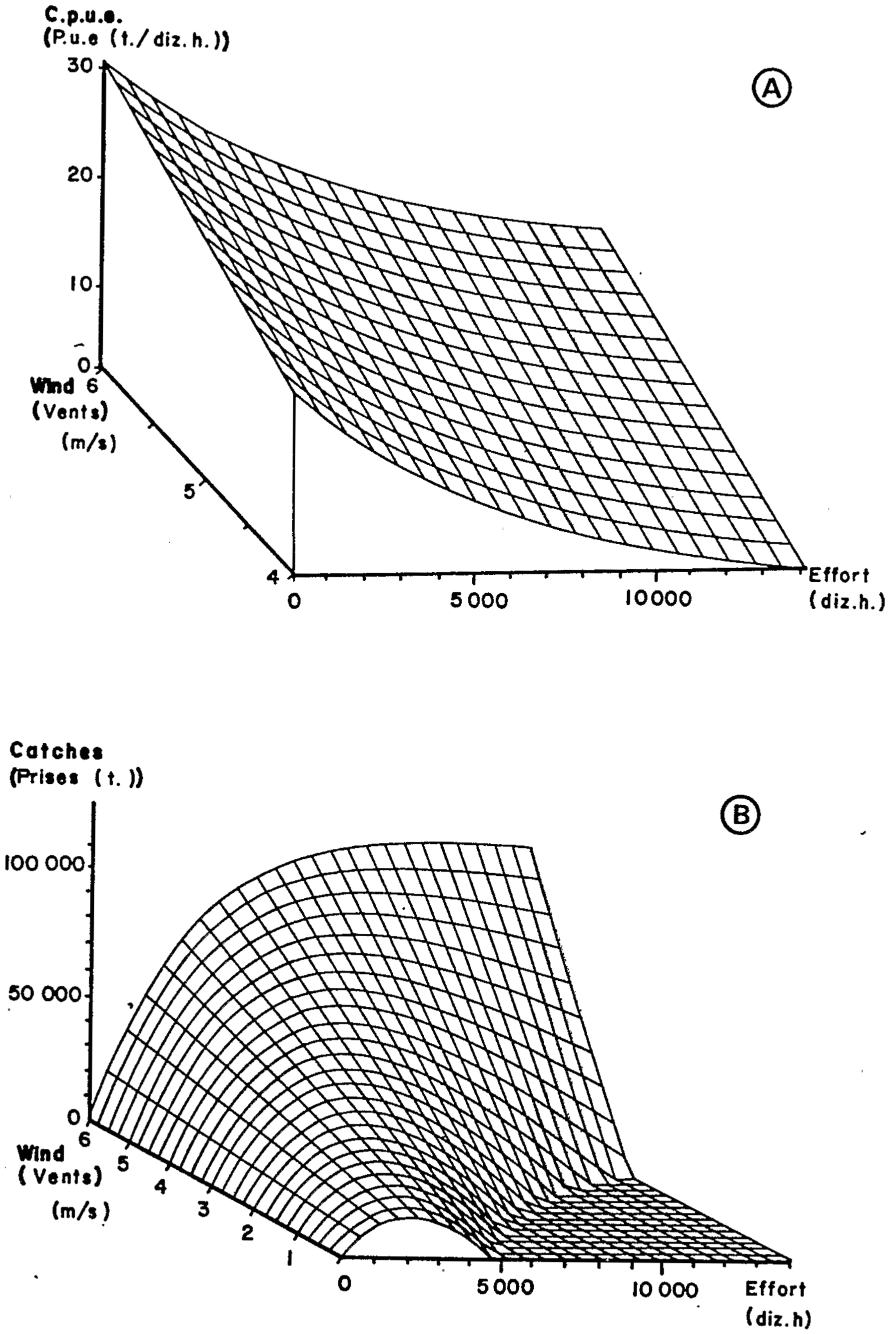


Fig. 6. Tridimensional graphics of the relationship between fishing effort, wind speed and catch per unit of effort (c.p.u.e.) in figure 6A or total catches (C)in figure 6B of *Sardinella aurita* on the Petite Côte. *Sardinella spp.* figures present the same shape and are not included in this paper.

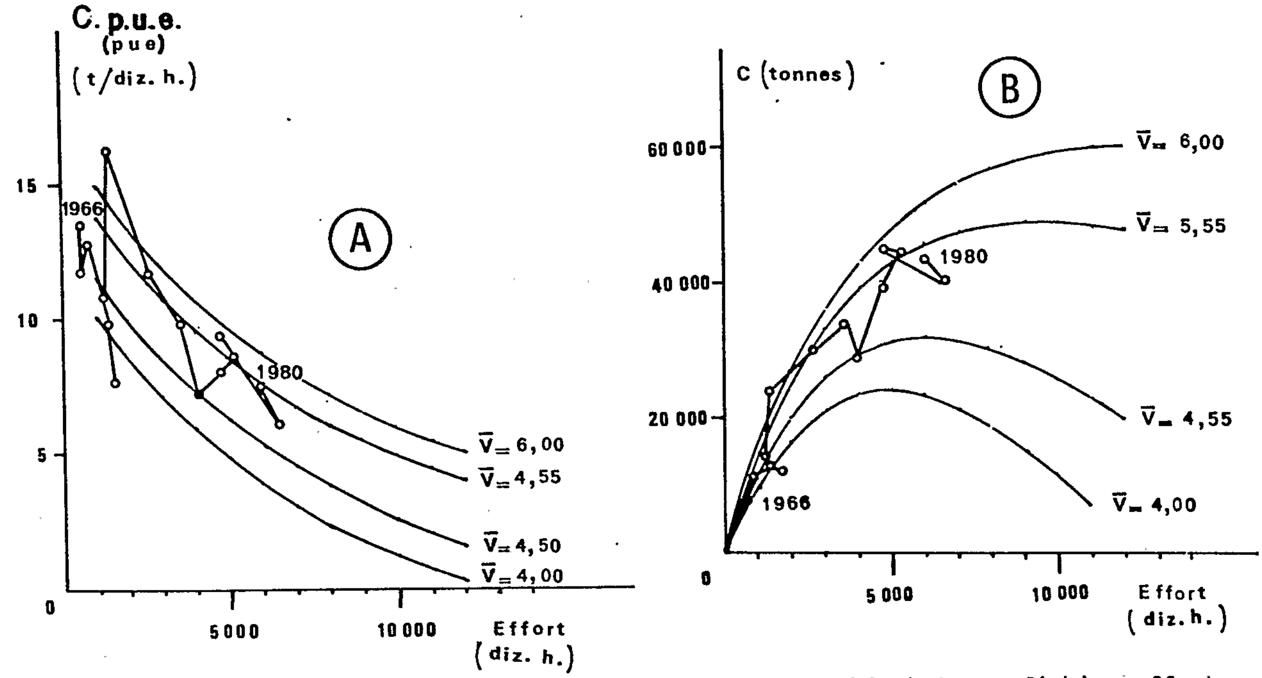


Fig. 7. Two dimentional graphics of the relationship between fishing effort, selected wind speeds and catch per unit of effort (c.p.u.e. in figure 7A) or total catches (C in figure 7B) of *Sardinella aurita* on the Petite Côte. *Sardinella spp.* figures present the same shape and are not included in this paper.

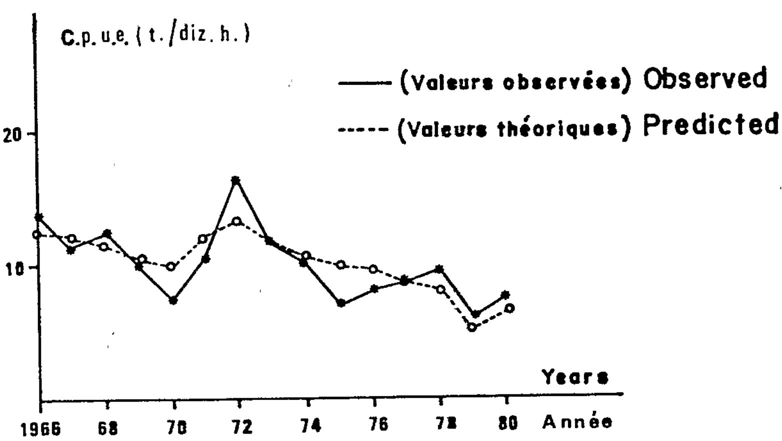


Fig. 8. *Sardinella aurita*: comparison between observed and predicted values of catch per unit of effort (c.p.u.e.) on the Petite Côte.

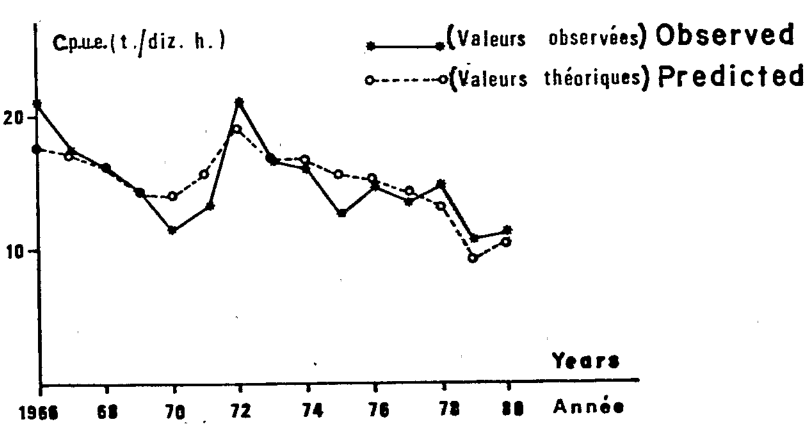


Fig. 9. *Sardinella spp.*: comparison between observed and predicted values of catch per unit of effort (c.p.u.e.) on the Petite Côte.

INTERPRETATION OF THE RESULTS

The considered parameters provide a satisfactory fit for the observed points as a whole to the theoretical curve. Anyway, for some years the residuals have not been negligible for both models (although they never exceded two standard deviations). Two main reasons could explain this fact. First, the precision of data, partially estimated is probably not very good and therefore responsible for a certain amount of the observed variability. Second, obviously fishing effort and wind speed are not the only factors influencing CPUE, and some part of the residual variance comes from numerous other variables.

Among these reasons, some could be in contradiction with our basic hypothesis (relation between adult sub-stock; immigration from other sub-stocks, etc...). These will be further analysed. Other sources of variation could take place at the level of recruitment fluctuations, independently of eutrophication and of parental stock. Thus, recent works (IOC No. 28) suggest that the superficial wind-related turbulence could cause a negative effect on larval survival. We added in the models the mean wind speed during the period following the main spawning (June to October). This improved slightly the fit for the *Sardinella spp.* model showing a negative corresponding regression coefficient (Table 3), but its value was not significantly different from zero even using a 90% confidence interval when calculated with the previously presented method. However, this result is notable because this relationship could be minimized by the positive correlation between the wind speeds during the two described periods of the year.

In the same way, it is evidence that the wind has a negative instantaneous influence on capturability related to school detection and working with purse-seines on rough seas. However, it seems that the favourable effect is dominant here, at least on CPUE expressed in catch per effective fishing time. Last of all, in order to close this non exhaustive list of additional factors, we looked at the influence of other species, considering the multi-specific aspect of the fisheries. This allows predator-prey relationships, but above all in our case, target-species changes related to the relative abundance and to market conditions are also allowed (Boely and Chabanne, 1975). In fact, a study was done (Freon, in press) which shows that during the last years the fishermen balanced their fishing activities in response to the sardine abundance fluctuations by searching for secondary species.

TESTING THE BASIC HYPOTHESIS AND MODEL REVIEW

Testing the hypothesis on the Petite Côte sub-stock independance

Comparison of the fishing effort variations on Petite Côte with the effort on the whole area of the stock distribution indicates a lack of correlation which provides an insurance against a possible confusion between the two variable effects. Moreover, it appears clearly that during the period studied the important fluctuations observed in CPUE on Petite Côte are not explained by changes of the fishing effort within the whole area. The best CPUE obtained by semi-industrial purse-seiners on Petite Côte occurred at the same time with maximum fishing effort on the whole area.

In more details, in the south of Senegal (Casamance, neighbouring Petite Côte), fishing effort was insignificant from 1973 to 1976. From 1977 to 1980 Polish pelagic trawlers got licences and caught up to 70,000 metric tons per year without any sensible effect on yields from the Petite Côte.

These observations do not mean that independance of recruitment in regard to the adult sub-stock will remain true in the future. It is evident that above a certain level of exploitation on the whole stock, the spawners biomass would be too small to assume equilibrium and a collapse could happen unexpectedly, as observed in other small pelagic stocks (Saville, 1980).

Based on the biological references concerning *Sardinella aurita*, two opposed and extreme theoretical cases could be considered. Obviously, the adult sub-stock abundance depends, on a short-termed basis, on its exploitation in the whole area, and on mean-terms on the exploitation of the two nursery sub-stocks which provide its recruitment. The same reasoning can be applied to the Petite Côte recruitment if its main contents would be provided by the adult sub-stock, particularly if the stock-recruitment relationship would be dome-shaped. Under these conditions our model would require stabile fishing effort and absence of over-fishing outside of the described Petite Côte area. This would provide a relatively stable recruitment (having a stable wind intensity) and an important resistance to local over-fishing in Petite Côte.

The second theoretical case supposes that the spawning of the young spawners in the Petite Côte nursery would assume the greatest part of the nursery recruitment. Although not being very realistic, this hypothesis would allow us to consider this stock fraction as completely independant from the other ones regarding its abundance. The situation would be similar to a single stock with a short-life species affording infinite mortality (total emigration) during the second year of life. Under these conditions the sub-stock would be very dependant on fishing effort on Petite Côte, also because an important proportion of the catches are supported by immature fishes. This case would probably justify the use of a linear regression between CPUE and fishing effort, whereas in the former case, a negative exponential regression corresponding to a low production sensitiveness to fishing effort (type m=8.5 in the Fox's generalized production model (1975)) would be suitable.

Reality is probably within these two extremes, since a quasi-constant recruitment is observed all year long on Petite Côte. This fact lets us suppose that adult and young fish spawning provide significant recruitment. Finally, *Sardinella aurita* stock, thanks to its three components distributed in different countries, probably presents a certain resistance to local over-fishing, and complex regulation mechanisms must exist. So the established model for this species seems tolerant enough in regard to the basic hypothesis concerning the stability of the exploitation rate around Petite Côte. However, the stock never supported heavy exploitation on its three sub-stocks <u>at the same time</u> due to the random distribution of fishing licences between coastal and foreign countries. If this situation should occur then our present knowledge would not allow a forecast of yield. Nevertheless, a collapse must be feared.

Sardinella maderensis sub-stock of Petite Côte (which was not studied individually) presents distinct characteristics since we are almost sure that the adult sub-stock does not spawn in this nursery. Associating both species of sardine in a single production model allows us to be more independent of the main basic hypothesis. In return the *Sardinella maderensis* sub-stock offers more sensitivity to local over-fishing.

It should be pointed out that for both species the coastal Petite Côte area is not the perfect nursery where all sardines from the Senegalese region are growing. There are obviously some exchanges of young fishes with the adjacent areas.

<u>Testing hypothesis concerning the wind intensity effect on production</u>

It is essentially the important increase of CPUE between 1970 and 1972 which lead me to include the wind speed variable in the production models. It could be supposed that this increment represents no more than the natural variability expression, independently from the upwelling, or also that the increase originated from a data bias as a change of fishing power. This last event was tested, computing separately the annual CPUE of three vessels which have been working since the early years, always with the same kind of equipment. The figures obtained from these three boats are very similar and correspond exactly to the global data figure. Moreover, it is important to notice that during the year 1972 other anomalies occurred in various eastern Atlantic areas. *Sardina pilchardus* concentrations appearance in Mauritania (Sedykh <u>et al.</u>, 1978; Freon and Stequert, 1979), a demographic bloom of *Sardinella aurita* occurred both in the Ivory Coast and in Ghana followed up by a *Balistes carolinensis* bloom (ORSTOM, 1976; FAO, 1980).

The data suggest a linear relationship between CPUE and wind speed. However, various fitting trials with other types of relationships (logarithmic, square, etc...) provide very similar results and it is not obvious that outside the observed range of variation the relation should remain linear. This forces one to use carefully forecasts for extreme wind speed (greater than 6 m/s or lower than 4.5 m/s).

Furthermore, it could be considered that the explicative variable is not the wind intensity and the corresponding upwelling but another correlated factor, i.e., surface temperature. Similar models to those presented were tried, replacing wind speed by surface temperature. They provided analogous results. The fundamental question is now to know if CPUE increase was provided only by the environmentally induced fertilization or also by a certain increase of the sardine availability. The statistical analyses, although difficult to interpret, showed the apparent predominance of the wind speed during the year n (comparatively to year n-1) on CPUE. This suggests a direct influence of wind on sardine availability. Even though, an indirect lag action remains possible because, first, the year n season of trade winds is considered between November of year n-1 and May of year n, second the fish caught is often less than one year old. Rebert (1979) studied monthly variations of sardine productivity in relation with wind anomalies and did not find small scale relations. Anyway the possibility of a combined action of the wind speed (on productivity and on availability) at the year scale is not easy to eliminate. In such a case the expression "production model" should be replaced by "CPUE model" or "catch model".

APPLICATIONS TO SUB-STOCK MANAGEMENT

The previous analysis attempted to prove that the maximum sustainable catch (which is perhaps not exactly comparable to a maximum sustainable yield, MSY) depends on wind intensity. For $\bar{V}$ variations between 4.50 and 5.55 m/s we get the following maximum catches:

Sardinella aurita: 31,000 to 49,000 metric tons
Sardinella spp: 56,000 to 90,000 metric tons

Anyway, it must be pointed out that these results are strongly related to $\bar{a}$ parameter values, which were arbitrarily defined. They are in the same range of maximum catches obtained by using a multiple-linear relationship between effort, wind speed and CPUE, i.e., a family of Schaefer's model (1957). However, they turn out to be only indicative. Nevertheless, the models allow a look at three main eventualities, from the present situation.

(i) If wind intensity remains constant, any increase of fishing effort would not change the total catches but would reduce the CPUE.

(ii) If wind intensity increases (which seems hardly likely), CPUE and catches would increase, the exploitation rate (f/fMSY) would decline and profits will rise, even if the fishing effort slightly increases.

(iii) If wind intensity lowers significantly, then CPUE, and yield would decrease, meanwhile f/fMSY would increase without any f variation, from which a strong overfishing hazard may be produced.

Finally, it seems that fishing effort on Petite Côte has reached a critical level in biological terms, according to present environmental conditions. On the other hand, economical studies pointed out that artisanal fishermen using purse-seine (which assumes most of the catches) have very low profits due to existing commercial conditions. In spite of this situation, the number of fishing canoes shows a tendency to increase because the traditional distribution of gains privileges the owners of production materials and so, favours the increase in fishing units (Weber and Freon, in press). In consequence, artisanal fishing effort does not have a self-regulation mechanism and a new intensification of fishing effort on Petite Côte should be feared if wind intensity would decrease. This would lead to the catastrophic case where overfishing is likely. Moreover, the appearance in 1981 of a new tendency toward catching very small fish is also alarming.

It appears imperative to develop management decisions in order to limit the fishing effort growth on Petite Côte which could be done through a limitation of subsidies given for buying equipment and motor-fuel. The modification of traditional habits which favour the owner-minority seems difficult to realize. A more realistic solution lays in extension of the fishing grounds which are presently limited by the boat equipment and by the localization of landing sites. The Senegalese artisanal fishery, even enclosed in its social habits, is very open to technology innovations as demonstrated a few years ago by the successful introduction of outboard engines and afterwards by small purse-seines. In fact other areas of the Senegalese shelf are also very productive all year long (Casamance), or otherwise seasonal (north coast), but the absence of landing points and of commercialisation channels limits their full exploitation. Then it would be desirable to first, increase the range of canoes (diesel engines, fish preservation); second, improve fish distribution inside the country; third, renovate the old semi-industrial fleet; and fourth, provide small ports adapted to those boats.

On account of the important variability of the maximum catches related to environmental conditions, it is desirable to maintain flexible types of exploitation in order to allow quick adjustments to production fluctuations. So, the duality of the fishery (artisanal and semi-industrial) is of main interest.

Finally, it must be kept in mind that our models are based on a hypothesis which will not remain indefinitely true. The relative independance of the Petite Côte nursery will remain effective as long as the peripheral areas will not support overfishing. Otherwise, it would be inevitable that at a certain level the relationship between the adult sub-stock abundance and the Petite Côte recruitment will have a depressive effect on the latter. This situation will make obsolete our relatively optimistic models. Senegalese fishery management must be decided in concert with that of adjacent countries.

CONCLUSION

Modelling the whole sardine stock of the described West Africa area seems difficult presently due to the complexity of the population structure and to the data inadequacy in the Senegal adjacent countries. Anyway, under a certain hypothesis, it appears possible to establish production models for the Petite Côte sub-stock which is intensively exploited.

The model parameters obtained provide a satisfactory description of the fisheries evolution during the last 15 years which was mainly related to the fishing effort and to the upwelling intensity variations. However, the validity of the available data and the relative shortness of the observed period induce us to use only with care these models for forecasting purposes.

Presently, the sub-stock yield seems to be close to the maximum catch corresponding to the present wind intensity which is relatively high. In this situation, any fishing effort increase is unproductive and the only effect is a CPUE decrease. If wind intensity will decrease, the production would lower substantially, specially for sardine species. Of course, a wind intensity increase would be beneficial and would allow an effort increase without an overfishing hazard. Although it is difficult to forecast the wind speed, the available data from 1951 seems to indicate that this eventuality is more unlikely than the former one (Figure 10).

Fishery management actions should attempt to limit the present proliferation of fishing units on Petite Côte, especially artisanal ones. This objective can be reached on short term by enlarging the fishery area in latitude and toward the open sea. And finally, Senegalese management must be conducted in collaboration with adjacent countries. Only two of the three greatest dangers of collapse appears in the model equation (Petite Côte fishing effort and wind intensity). The last one, but not the least, is unfortunately hidden in our basic hypothesis (absence of overfishing in the adjacent areas).

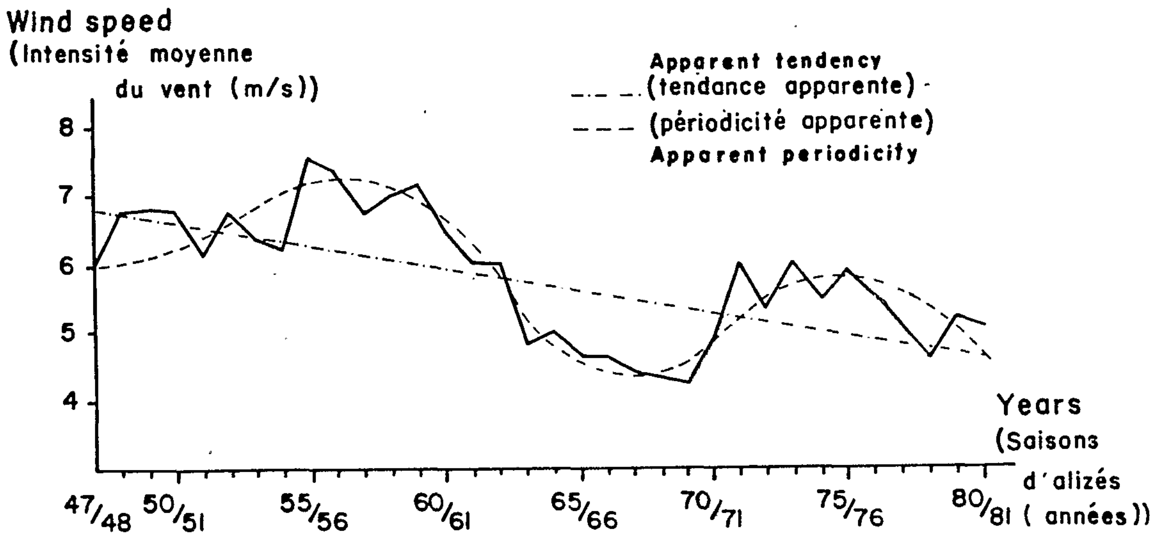


Fig. 10. Time plot of trade wind speed (meters per second) from 1947-1948 to 1980-1981 (data provided by ASECNA of Senegal and compiled by C. Teisson).

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San José, Costa Rica, 18-29 April 1983

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