COMPARATIVE ANALYSIS OF THE EXPLOITATION OF BIGEYE TUNA IN THE INDIAN AND EASTERN ATLANTIC OCEANS WITH EMPHASIS ON PURSE SEINE FISHERIES.

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ABSTRACT

The tremendous increase of bigeye catches in the Indian and Atlantic oceans since 1990 was the result of an increase catches in recent years of both juveniles by the surface fisheries and adults by longline fisheries. Although bigeye was not targeted by purse seiners, the extensive use of FADs is assumed to be one the main causes of the increase in juvenile bigeye catches. However, due to the introduction of numerous changes to purse seine fishing equipment and operations, resulting in a more efficient fishing power, it is difficult to estimate meaningful indices of abundance. In the absence of detailed information on the date of introduction of these changes we propose (1) the use of non-traditional indices and (2) a comparison between Indian Ocean and Atlantic fisheries in order to check the likelihood of the different assumptions proposed to explaining changes in bigeye catch. The analysis of the differences between the area visited and the area fished, and the catch of bigeye per log set by time of day, both suggest an increase in bigeye catchability. Changes over time of some abundance indices, such as the proportion of bigeye in log catches, the differences between the total catch and the catch of bigeye per successful log set, and the spatial distribution of log catches by species suggest that bigeye stocks were less affected by FAD fishing than skipjack (at least in the Atlantic), and that bigeye might even have benefited from this situation.

RÉSUMÉ

Les fortes augmentations des prises de patudos dans l'Océan Indien et dans l'Atlantique depuis 1990 résultent de l'augmentation des prises de juvéniles par la pêche de surface dans les années récentes, et de celles des adultes dans les pêcheries palangrières. Bien que le patudo ne soit pas une espèce cible des senneurs, l'utilisation massive des DCP est supposée être une des principales causes de la hausse des captures des patudos juvéniles. Toutefois, à cause des nombreux changements survenus dans les équipements à bord des senneurs, qui se sont traduits par un accroissement de la puissance de pêche des navires, il est difficile d'estimer des indices d'abondance pertinents. En l'absence d'informations détaillées sur la date d'introduction à bord de ces modifications, il est proposé (1) l'utilisation d'indices non traditionnels et (2) de procéder à une analyse comparative entre les pêcheries de l'Océan Indien et de l'Atlantique, afin de valider la vraisemblance des différentes hypothèses émises pour expliquer la hausse des prises de patudos. Les analyses portant sur la différence entre la surface totale prospectée et la surface totale avec prises, ainsi que sur l'évolution horaire de la capture de patudos par calée positive sous objet flottant, suggèrent toutes les deux une augmentation de la capturabilité des patudos juvéniles. Les changements au cours du temps de certains indices, tels que la proportion de patudos dans la prise totale sous objets, la différence entre la prise totale et celle de patudos par calée positive sous objet, et l'évolution spatiale des compositions spécifiques sous objet semblent indiquer que le patudo a été moins affecté par le mode de pêche sous DCP que le listao (au moins dans l'Atlantique) et qu'il pourrait même avoir bénéficié de cette situation.

INTRODUCTION

The dramatic increase of the bigeye (*Thunnus obesus*) landings in the world ocean (148,000 t in 1970 against 385,000 t en 1994) was the result of an increase of juveniles catches by surface fisheries in recent years, combined with high levels of adult catches by longline fisheries. The different habitats settled by bigeye tuna during its life cycle are similar in each ocean (Fonteneau, 1998). The young bigeye (less than 3 kg) are found in multispecies schools with juveniles of yellowfin tunas *(Thunnus albacares*) and with skipjack tunas (*Katsuwonus pelamis*). These multispecies schools are often associated to logs (including FADs) in surface waters with high sea-surface temperature (from 20°C to 27°C). With the exception of some baitboat fisheries operating in temperate waters in the Atlantic ocean (namely, the Portuguese island baitboat fisheries of Azores and Madeira), the major part of the adult catches is due to longliner activities. Large bigeye inhabit cold waters (between 10°C and 15°C) and deep layers of the oceans (between 150 m and 500 m), often with low levels of dissolved oxygen. This tolerance to low oxygenated deep waters (as low as 2 ml/l) could explain why bigeye is more abundant in the eastern than in the western Atlantic. Another constraint could be the competition between tuna species. It has been suggested by Cayré (1987) that adults of yellowfin tuna, less tolerant with respect to O_2 than bigeye, prefers

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inhabiting the well oxygenated deep layers in the western Atlantic and, in that way, could prevent the bigeye from extending to this part of the Atlantic. Accordingly, taking the spatial pattern of the environment and the habitat of yellowfin into account can help in locating the geographic distribution of bigeye catches in the world ocean (Marsac, 1994; Fonteneau, 1998).

Bigeye catches have increased sharply in the Indian and in the Atlantic oceans since 1990 (Figure 1). Maximum bigeye catches were reached in 1994 with 115,000 t in the Atlantic Ocean and in 1995 in the Indian Ocean with 120,000 t. Today, catches of bigeye from the Indian Ocean represent 30 % of the world bigeye catch. In the case of the Atlantic, the fast increase of catch, followed by a decreasing trend in the recent years, has raised serious doubts about the status of the bigeye stock and has motivated the Standing Committee on Research and Statistics (SCRS) of ICCAT to recommend an intensive research program dedicated to this species (BETYP). The rapid increase in bigeye catch in the Indian Ocean has also raised the attention of IOTC which considers that research devoted to this species should be a priority. Bearing in mind this situation, it appears that a comparative analysis of the evolution of different stocks of bigeye can be useful to understand the response of bigeye populations to different fishing patterns. Hence, the present paper analyses the historic changes of bigeye fisheries in the Atlantic and Indian oceans, emphasising the usefulness of indices based on purse-seine fisheries to understand trends in bigeye abundance.

CHANGES OVER TIME OF BIGEYE CATCHES BY GEAR

The exploitation of bigeye tuna in the Indian ocean began in the early 1950s, when the Japanese longline fishery started (Stobberup *et al*, 1998). Bigeye catches, mainly by longliners, rose progressively from 20,000 t in the sixties to 50,000 t in the eighties (Figure 2). With the beginning of purse seine operations in 1980, total catches of bigeye increased and reached 115,000 t in recent years. Other minor catches are made by the small-scale fisheries of several countries (Stequert and Marsac, 1986), by the offshore drift gillnet fishery of Taiwan (Stobberup *et al*, 1998) and by the skipjack Maldivian baitboat fishery (Anderson, 1996). In contrast, with the catch trend in the Atlantic ocean (where surface catches exceeds 40 % of the total bigeye catch), the proportion of bigeye caught by the longline fleets continued to be highly predominant in the Indian Ocean (Figure 2).

In the Atlantic, bigeye was exploited locally by small baitboat fisheries of Portuguese islands since the mid-1940s but catches began to be significant only in the mid-1960s with 25,000 t landed. The catches then increased regularly to 40,000 t in the 1970s, before levelling off around 70,000 t in the eighties (Figure 2). As a result of the increase in FAD fishing operations by the surface fishery since 1990 (mainly due to purse seiners and also, to a lesser extent, to Ghanaian baitboats), bigeye catches showed a second increase and reached a maximum of 115,000 t in 1994. As mentioned, this high level of catch was not maintained in recent years and catches dropped to 90,000 t in 1997.

THE ADULT FISHERY

The major difference in the fishing pattern between both oceans is the amount of large bigeye caught by pole-and-line fisheries in the Atlantic. Such a situation is not reported in the Indian Ocean. In the Atlantic, the Portuguese baitboat fishery has been active in Azores and in Madeira islands since the end of the second world war (Pereira, 1995). These small-scale island fisheries exploit mainly large fishes (FL between 60 to 130 cm) between the months of March and June (Pereira, 1995; Gouveia and Amorim, 1998). The baitboats operating from the Spanish islands of the Canaries also exploit adults and pre-adults with a predominant modal size class close to 80 cm (Ariz *et al*, 1998). Despite the great variability in yearly catches, related to changes in local environmental conditions, bigeye tunas appear to be a valuable resource for these three islands (the total bigeye catches has exceeded 11,000 t per year since 1990).

In contrast, the evolution of the longline fisheries in the Atlantic and the Indian oceans show similar patterns. In both cases, it can be noted that :

- longline fishing was initiated in the 1950s by the Japanese fleet, followed by the South Korean and Taiwanese fleets which entered the fishery later. In the Indian Ocean, Korean longliners were very active in the 1970s and 80s, but disappeared afterward. The Taiwanese fleet targeted albacore (*Thunnus alalunga*) during a long period (approximately from 1970 to 1985) before shifting back to bigeye in the early nineties.
- similar fishing strategies were adopted by the main longline fleets, first targeting yellowfin tuna and albacore for canning, then shifting to high-priced species such as bluefin tuna (*Thunnus thynnus*), southern bluefin tuna (*Thunnus maccoyii*) and bigeye for the sashimi market (with some shift back during short periods of time, as mentioned earlier). As a result, changes in the fishing grounds, as well as modifications in the fishing gear (from regular to deep longlines) occurred approximately at the same time in the fleets in both oceans (at least for each country). These modifications began in 1976-1977 for the Japanese fleet (Uozumi and Nakano, 1994; Okamoto and Miyabe, 1998) and after 1980 for Korea (Yang and Gong, 1987; Park *et al*., 1991).
- the major fishing grounds for bigeye tuna now stretch along two zonal areas split by a non productive sector. Nevertheless, this central area with low catch rate of bigeye is located more to the South in the Indian ocean (between 15°S and 25°S) than in the Atlantic ocean (5°N-5°S).

Other sociological, economic and industrial events, which are not specific to these two oceans, contributed to the transition from low value target species (namely, albacore) to high value target species (such as bigeye). Among the main factors, we can note:

- the progress made in term of freezing onboard industrial longliners (-50°C in the early 1970s),
- the evolution of tuna markets due to the development of the high value sashimi market in Japan in the late sixties. Frozen bigeye from distant-water fisheries appeared as a complement to bluefin in the sashimi market as early as 1975 and has become the main component since 1985 (Doumenge, 1998).
- the interest shown by some Asiatic countries (Taiwan, Korea) in obtaining a new strong and stable currency (due to money fluctuations between 1975 and 1985, these countries substituted the Japanese yen to the US dollar; Doumenge, 1998), which explained why they decided to export their catches to the Japanese tuna market.

An example of the changes in target species by the Japanese longliners in the tropical oceans is given for the Atlantic in Figure 3. It appeared that the gradual increase in bigeye catches (1979-1982, 1985-1989 and 1991-1994) can be related to gradual modification of the number of branchlines per basket, which increases the average fishing depth (Figure 4). The use of regular longlines with 4 to 7 hooks per basket (that corresponds to a maximum depth of between 150 m and 170 m) decreased regularly after 1980 and is limited today to the higher temperate latitudes of the Atlantic (35-45°N and 35-45°S), in order to capture bluefin, southern bluefin and albacore (Uozumi and Nakano, 1994). The exploitation of the deeper layers of the tropical ocean has occurred progressively, using longlines with 8-11 hooks per basket, then with 12-15 hooks per basket, and recently with more than 15 hooks per basket (reaching depths close to 500 m). Similar evolutions in the fishing gear and in the spatial distribution of the fishing effort have been reported in the Indian ocean (Okamoto and Miyabe, 1998; Stobberup *et al*., 1998).

THE JUVENILE FISHERY

In contrast to the fisheries on adults, juveniles of bigeye tuna are not targeted by the purse seine fishery but are caught as they are mixed with yellowfin and skipjack (especially in log and FAD sets). The purse seine fisheries, dominated in both oceans by the Spanish and the French fleets (but also with the participation of other countries such as Japan, Russia and Mauritius in the Indian ocean) do not, however, have the same history. The eastern Atlantic purse seine fishery began in the sixties in the coastal areas off Africa, whereas the first attempts of experimental purse seine fishing were only made twenty years later in the Indian ocean: in 1978 by Japanese vessels and in 1980 by French vessels (Stequert and Marsac, 1986). The purse seine fishery became commercially viable only after 1984 when a major part of the Spanish and French purse seine fishing effort was relocated from the eastern Atlantic to the Indian Ocean. The first fishing grounds were located in Seychelles waters but spread faster in the western Indian ocean toward the North (i.e., Somalia) and to the South (Mozambique Channel), then more recently to the East (since 1997). Since the beginning of this fishery, natural log fishing used to be very common and was followed within a few years by the deployment of artificial FADs. Depending on the strategy adopted by the skippers (log sets versus non-associated school sets) the proportion of bigeye in the total catch differs among nations. For instance 95 % of the sets made by the Japanese fleet were log sets, with 90 % on FADs (Okamoto *et al*, 1998) whereas the percent of FAD sets made by the Spanish and French fleets is close to 80 % (Pianet, 1998), thus the proportion of bigeye in the European total catches is lower (Stobberup *et al*, 1998). These authors raised the fact that the increase in log fishing operation observed in the Spanish fleet was followed by an increase in the proportion of bigeye catch. This could indicate a causal effect between the two events. The sizes of bigeye caught under FADs and in school sets are similar in both oceans. The size classes 40-55 cm are predominant with, maybe, a higher number of large fishes in the Indian ocean (Pianet, 1998; Pallares *et al*, 1998)

With the exception of some Atlantic tropical baitboat fisheries, such as in Ghana (fish length are between 40 cm and 50 cm of fork length), and partially in the Senegalese area (FL between 50 cm and 100 cm), the larger part of the juvenile catch of bigeye is due to the purse seiners activity (Pallares *et al*., 1998). The baitboat fishery operating from Tema (Ghana) is composed by Ghanaian vessels but also with some boats belonging to Japanese and Korean companies. Like the purse seiners, this fleet has used bird radars since the 1990s and targets small tunas (average weight lower than 2.5 kg) associated with FADs equipped with radio boys (Kwei and Bannerman, 1993). It can be noted that the Senegalese baitboat fishery increased its efficiency by developing a fishing mode which consisted in using the baitboat as a floating object. Once the wells of the baitboat are filled, another baitboat takes over and becomes itself the new floating object (Fonteneau and Diouf, 1994). This efficient fishing mode was later adopted by the Canaries baitboat fishery (Ariz *et al*, 1995).

The development of FAD fishing operations in the Eastern Atlantic began only in 1989-1990. Until this time, the proportion of log sets (natural or artificial, but not equipped with radio beacons) was approximately 20 % (Stretta and Slepouka, 1986). FAD fishing was adopted within a few years by the Spanish and French purse seiner skippers and now the percentage of FAD sets per year varies around 40 % to 45 % (Hallier, 1997). Bearing in mind that the majority of purse seiners belong to these two countries, the adoption of this fishing strategy produced an increase of 100 % in the total catch made under floating objects between 1990 and 1994, while the total catch made on school sets dropped by 20 % (Hallier, 1997). In order to explain the adoption of this new strategy, it must be keep in mind that, although tunas caught under logs are small and low-priced, the success rate (more than 95%) and the size of the log sets are higher than for large tunas found in non-associated schools.

One of the major impacts of the fishing on FADs was the dramatic increase in juvenile catches. In the Atlantic (although since 1980 a minimum size limit for bigeye of

3.2 kg was adopted by ICCAT to reinforce a similar regulation for yellowfin), the percentage of juvenile catches of bigeye went up from 53 % in the early 1980s to 67 % in the period 1991-1994 (Hallier, 1997). The impact of the surface catches on the demographic structure of bigeye can be assessed easily by combining the total catch per gear and the numeric catches per age class (Figure 5). It was seen that the percentage of juveniles of bigeye (age 0 and 1) increased after the adoption of the FAD fishing mode by purse seine and tropical pole and line fisheries. Nevertheless, it can be argued that (1) the proportion of juveniles in the bigeye catches was not negligible before the massive use of FADs and (2) that pre-adults and adult catches also increased (due to the longlines and the temperate water baitboat fisheries).

Another event which can effect the bigeye stocks is the temporary ban of log fishing (i.e., moratorium) developed by the E.U. purse seiner owner associations. A moratorium was adopted in the Atlantic Ocean between November 1997 and January 1998 in the major log fishing area (between latitudes 5°N to 4°S and from longitude 20°W to the African coasts to the East), then renewed the next year. An analysis made on the French fleet showed that, during the first moratorium, the tuna catches decreased by 38 % with respect to the catches made during the same spatial and temporal strata in the previous year (Goujon, 1998). Although a fraction of this fleet continued to fish on FADs outside the moratorium area, the whole proportion of log sets decreased by approximately 20-30 %. It was observed that the total purse seine catch from school sets was stable compared to previous years (Diouf *et al*., 1998). Hence, there is no evidence of a reallocation of the fishing effort from log schools to non-associated schools during this period. Based on simulation studies, these authors pointed out the positive effects of this protection plan in term of yield per recruit for the three main species of tropical Atlantic tunas. In the Indian ocean, it is not easy to assess the effect of the first moratorium established in 1998 because the strata chosen for the prohibition on log fishing did not match the core area for log fishing in the selected period.

PURSE SEINE FISHERY INDICES FOR THE SURFACE CATCHES

Bearing in mind that, in recent years, major changes have occurred in the purse seine fishery, it is not easy to take into account all these factors in developing meaningful indices of abundance. The adoption of the FAD fishing operations raise a crucial question: how to estimate fishing effort exerted on surface tuna schools adequately? The traditional definition of fishing effort in the purse seine fishery (the searching time between two consecutive sets) is not well suited as a measure of the effort exerted to detect beacon-equipped floating objects (Hallier, 1994). Other technological equipment on board also contributed to the increasing trend of catches over time: (1) the fishing power of the purse seiners and (2) the catchability of tunas in both oceans (Fonteneau *et al*, 1998). It is obvious that the increased use of fish finding equipment such as bird radar, sonar, echo-sounders, and other electronic devices, the increase in the hauling power of purse winches and power-blocks, the increased in length and depth of nets, the changes in skipper behaviour etc., should be taken into account in performing standardized abundance indices (Gaertner *et al*, 1999a). Nevertheless, due to the difficulty of knowing the date of introduction on board of new equipment, the use of non-traditional indices of abundance (seen as fishery indicators) should be encouraged. In this paper we compared, in both oceans, the changes of the following indices:

- catch per successful log set (median catch for bigeye and for the total)
- area visited versus area exploited (i.e., with catches),
- percentage of bigeye catches per fishing mode (school sets vs. log sets),
- proportion of bigeye in log catches (with respect to total log catches),
- spatial distribution of the log catches by species,
- catch per log set by time of day,
- CPUE of bigeye juveniles (catch of the commercial size class per positive log set),
- Bigeye catch by commercial size category.

This list of the complementary fishery indices is not exhaustive and other indices could be useful in stock assessment studies.

Catch per successful log set

The use of catch per successful set as an abundance index for FAD fishing operations is based on the assumption that a decrease in tuna abundance could affect the number of schools in a cluster, as well as the number of fish in a school. In the Indian Ocean, the median bigeye catch per successful log set (the median is assumed to be more robust than the arithmetic mean) reached its maximum in 1985 with 11 t (Figure 6a). This index decreased strongly to 1 t per set in 1991-1992, then showed a weak increase in the recent years (Figure 6b). At the same time, the total catch per successful set did not show any trend (the catch per set remained close to 25 t during the whole period). In the Atlantic the maximum bigeye catch per set appeared in 1994 (4-5 years after the increased use of FADs) with 6 t per set, followed by a weak decreasing trend (Figure 6c). After a short period of stability around 25 t per set, the total catch per set decreased between 1995 and 1998 (14 t per positive set). These comparative analyses show that "on average" the impact of FAD fishing on bigeye catches (mainly juveniles) occurred approximately 5 years after these were introduced. The differences observed between bigeye catch per set and total catch per set in the Indian Ocean since 1994 (the respective trends are reversed) and the Atlantic since 1995 (both series decreased but with a different slope) could suggest that bigeye is less affected by this fishing mode than skipjack or yellowfin tunas.

It should be borne in mind, however, that this index may be biased (1) by the reduction in escapement rate due to an increase in the net dimensions over the years and (2) by the density of FADs in a given local area. Net dimensions have increased since the beginning of the French purse seine fishery in the Eastern Atlantic. Observations made with a depth recorder show that today a purse seiner equipped with a net measuring 225 m depth, may purse to a depth of 108–144 m (Gaertner and Sacchi, 1999). As the thermocline is deeper in the Indian Ocean than in the Atlantic, it is likely that deeper nets are used and allow fishing at greater depth. It was shown in other purse seine fisheries in the world that tuna fishermen adapted the depth of their purse seine closely to the depth of the thermocline in the fishing area (Itano, 1998). It is interesting to note that, during a survey made in the framework of the E. U. Atlantic bigeye research programme, (Ariz and Gaertner, 1998), the French purse seiner skippers argued that the increase in bigeye catches was due to the use of FADs but also due to the increase in net depth (Gaertner *et al*, 1999b). By contrast, Spanish fishermen agreed with the first cause (increased use of FADs) but believed that a better use of sonar was the main cause of the increase in catchability of the deepest part of surface schools (assumed to be the richest in bigeye).

An index based on the minimum distance between log sets, as suggested by Okamoto *et al*. (1998), could be an interesting alternative in order to take into account the constraint represented by the local density of FADs. Another bias that must be considered is the local depletion caused by consecutive sets on the same floating object (Hallier, 1994). These consecutive sets on the same log can also produce changes in the species composition of the tuna catches. In the Atlantic, it was seen that, on the average, skipjack was the predominant species in early sets on a log. After some consecutive sets, the percentage of yellowfin increased, followed by bigeye during the last sets exerted on the same log (Ariz *et al*, 1991; Ariz *et al*, 1999). These results could confirm the assumption concerning the vertical stratification of these three species in multispecies schools under logs. Skipjack being the more superficial of the three species and bigeye the deepest.

Area visited versus area exploited

The fluctuation in the overall size of fishing grounds is a good indicator to describing the development stages of a fishery. In order to assess the efficiency of a "school-searching" fishery such as the purse seine fishery, we focussed on the yearly comparison of the number of 1°x1° squares visited (i.e., with effort) and exploited (i.e., with catches) in both oceans. We used the database for all E.U. purse seine fleets (including convenience flags), with a threshold of 5 fishing days per 1°x1° square. During the late 60s the total area visited in the Atlantic was quite stable and the coastal fishing grounds were exploited efficiently (i.e., the number of squares without catches was very low, Figure 7). The 70s was characterised by offshore expansion of the fishing grounds, followed by a period of stability from 1978 to 1984. During these two periods, numerous 1°x1° squares were visited without success (about 15 %). This ratio (total area exploited versus total area visited) remained quite stable, despite the reduction of the fishing grounds observed after the partial relocation of the fishing effort to the Indian Ocean in 1984-1985. A second weak expansion has occurred recently since the introduction of beacon-equipped logs (fishing effort reached areas as far as 30°W since 1990) but the salient result was that the number of 1°x1° squares unfished became very low (Figure 7). These results suggest that FAD fishing increased the catchability of bigeye (i.e., bigeye was caught in areas where there was no catch before the use of FADs). The situation is relatively different for the Indian Ocean as natural logs were used since the beginning of the purse seine fishery. Nevertheless, after a period of stability in the late 80s (it can be noted that the first areas were exploited efficiently), the fast expansion of the fishing grounds (especially to the eastern Indian Ocean) was also characterised by a decrease in efficiency (about 25 % of the 1° squares were unsuccessfully fished). As in the Atlantic, it appeared that the evolution of the juveniles bigeye catches was highly correlated with the evolution of the number of 1°x1° areas fished (i.e., surface exploited). This means that, in the absence of an adequate measure of fishing effort, the number of 1°x1° squares exploited should be used as an alternative.

Percentage of bigeye catches per fishing mode

As mentioned previously, it is quite clear that the percentage of bigeye in the total catch was related to the fishing strategy adopted by each fleet. It was observed that an increase in the proportion of log sets arose at the same time as the proportion of bigeye in the total catch. There was no evidence of any trend in the proportion of log catches in the total bigeye catches for the Atlantic (Figure 8) from combining the bigeye catches for all nations. The percentage of log catches remained stable at around 80 %. In the Indian Ocean this proportion showed a weak but continuous increasing trend, from 60 % in 1988 to 80 % in 1998 (a consequence of fishing to the East).

Proportion of bigeye in the catches on floating objects

The proportion of bigeye observed in the catches on floating objects has increased by approximately 10 % since 1991 in both oceans (from 10 % to 20 % in the Atlantic and from around 5-7 % to 17 % in the Indian Ocean), although this trend began since the beginning of the purse seine fishery in the Indian Ocean (Figure 9). This increase could be interpreted in different manners: (1) either the abundance or the catchability of bigeye increased, (2) or bigeye could be less affected by the fishery on logs that the two other tuna species (this assumption was also raised in the catch per set analysis). However, we may suspect that the bigeye catches were rather underestimated during the first years of the fishery (before 1987).

Spatial distribution of the log catches by species

The analysis of the spatial distribution of the catches should be one of the key elements of any stock assessment studies. These maps allow to detect the expansion (or the reduction) of the fishing grounds, as well as the changes in the species composition in a multispecies fishery. In the Atlantic, the spatial distribution of log catches showed the predominance of skipjack (Figure 10). Between 1991 and 1994, the percentage of skipjack in FAD catches showed a weak decrease, thus proportions of yellowfin and bigeye rose. Because the fishing grounds remained stable, it can be assumed that these two species partially substituted skipjack, due to change in abundance or catchability. The maps representing the catch distributions in 1997 and in 1998 give a good illustration of the impact of the log-fishing moratorium and explain why total bigeye catch decrease in the Atlantic. In the Indian Ocean, the situation observed in 1985 show that skipjack is the main species caught under logs (Figure 11). Bigeye appeared very scarce in the logs catches, but this could be due to the difficulty of distinguishing between juveniles of yellowfin and bigeye. From 1991 to 1998, the log purse seine fishery expanded to the Chagos archipelago, then recently to the eastern Indian Ocean. As in the Atlantic, skipjack catches were partially substituted by yellowfin and, at a lower level, by bigeye. In conclusion, taking into account the spatial stability of the fishery on FADs in the Atlantic and the fact that the new fishing grounds in the Indian Ocean were not specifically rich in bigeye, the increase in bigeye catch could be due to changes in abundance or in catchability of the other competing species.

Catch per log set by time of day

There were few data on the distribution of sets by time of day. We were limited to the comparison between a few observations made in the Indian Ocean in 1983-1984 (Marsac and Hallier, 1985) and with a more representative observer onboard database during the Atlantic EU bigeye programme in 1997-1998. However, it is not easy to compare observations collected at different times in different contexts. In the Indian Ocean (that is at the beginning of the purse seine fishery), it appeared that the majority of log sets were made at dawn (Figure 12). In the Atlantic, log sets made in the early morning were also the most frequent but the probability of setting on logs continued during the fishing day. Fishermen interviewed during the EU bigeye programme claimed that one of the explanations for the increase in bigeye catch in the Atlantic was the increased use of FAD sets in the early morning (Gaertner *et al*, 1999b). Bearing in mind that bigeye catch rates are higher in the early morning (Figure 13), an increase in FAD operations at dawn could be one of the causes of the increase in bigeye catch.

CPUE of bigeye juveniles

We analysed the catch rate on successful log sets of the commercial size category 1 (fish less than 10 kg) for France (1991-1998) and Spain (1991-1997). In each ocean, we selected an area known to be the major fishing ground on log fishing:

- 45°E - 60°E and 5°N - 5°S in the Indian Ocean (Figure 14),
- 25°W - 15°E and 5°N - 5°S in the Atlantic (Figure 15).

The corresponding abundance index was estimated each year by averaging the mean CPUE obtained by 1°x1° squares by fortnight. The changes in abundance indices were very similar for each fleet in each ocean (Figures 14 and 15). There is evidence that these changes reflect fairly well the changes observed in the bigeye purse seine catches, especially in the Atlantic, with a decrease in both indices after 1994 (Figure 2).

Bigeye catch by commercial size category

Changes over time of bigeye catches by commercial size categories (BET <10 kg and BET >10 kg) were analysed in both oceans by fishing mode (FAD sets versus school sets) since 1991. The proportion of large bigeye in log catches was very low (Figures 16 and 17). As expected, the drastic decrease of bigeye catches made under floating objects in the Atlantic and the corresponding increase in the Indian Ocean were due to changes of the small size category. In contrast, in school sets (non-associated sets) the proportion of large bigeye was important (but with low catch compared to log sets).

CONCLUSION

Due to the numerous changes that occurred in the surface purse seine fisheries in the last two decades (increased use of FADs, introduction of new equipment, etc.), there is a strong evidence for an increase in catchability of surface tuna schools (including juveniles of bigeye tunas). It is also suggested that bigeye was less affected by FAD fishing than skipjack (at least in the Atlantic). However, due to the multiple interactions between factors effecting the catchability of juvenile tunas in surface schools, it is not easy to test the former assumption. A brief list of possible causes involved in changes in bigeye abundance and/or in bigeye catchability is given in Table 1. The major challenge to analyse the increase in fishing power of purse seiners (i.e., in catchability) concerns (1) the difficulty in obtaining precise information on the date of introduction on vessels of the new equipment, and (2) to discriminate between the main effects (the effect of one factor can be masked by the simultaneous change of a second or by their mutual interaction). It is quite clear that, in contrast to other sciences, an experimental design can not be planned in order to analyse the changes in a fishery. To overcome these difficulties comparative analysis between oceans (i.e., a meta-analysis approach) should be encouraged. Based on the observations made on the effects of some factors in one area, similar situations observed in another area can be sufficient to reinforce strong assumptions about the impact of these factors, even if the former cannot be analysed by traditional statistical methods due to the lack of an adequate sampling design. In such a case where traditional statistical methods (namely, GLM) can be used, previous knowledge obtained from other fisheries must be included in the analysis (meta-analysis or Bayesian methods).

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Table 1. Summary of the factors that could explain the increase of bigeye catches

FACTORS	Effect on	Likelihood
Increased recruitment	Abundance	there was no evidence of an increase of the recruitment in recent years, however, an overall increase of wind-induced turbulence could lead to unfavourable conditions in the future (*)
Competition between species	Abundance	moderate, as suggested by the decrease of skipjack proportion in log catches, by the increase of bigeye in the last days of consecutive sets, etc.
Price differences between large	Catchability	there was no evidence (at least in the recent years) price changes which could explain size and small size categories a corresponding change in fishing strategy
Increased use of FADs	Catchability	very strong (confirmed by interviewed E. U. purse seiner skippers)
Increased efficiency in term of area fished	Catchability	very strong in the Atlantic since 1991 (but concern also skipjack and (decrease of the % of 1° squares unfished) yellowfin), not observed in the Indian Ocean yet.
New fishing grounds	Catchability	strong in the Indian Ocean (in the East) low in the Atlantic (except for the western areas 25°-30°W)
Increased use of electronic devices, such as sonar and echo-sounder for FAD sets.	Catchability	strong (argued by the Spanish purse seiner skippers in the Atlantic to explain catch of deeper schools, but the vertical stratification of bigeye in the multispecies schools must be confirmed)
Increased depth of the sets	Catchability	very strong until 1990 in the Atlantic, directly related to the increase in bigeye catches by French skippers, must be checked after 1990. Not analysed in the Indian Ocean yet but same probability as in Atlantic
Increased number of FADs sets in the early morning	Catchability	strong in the Atlantic, as argued by interviewed skippers (nowadays 80 % of log and FAD sets are made before 8 a. m. combined with the better availability of bigeye in the early morning. In the Indian ocean early log sets were made since the beginning of this fishery
Increased fishing power of purse seiners	Catchability	very strong (increased use of bird radar, sonar, increased of net size, increase in hauling power, FADs use, etc), but should also affect catchability of other species

(*) Marsac unpublished)

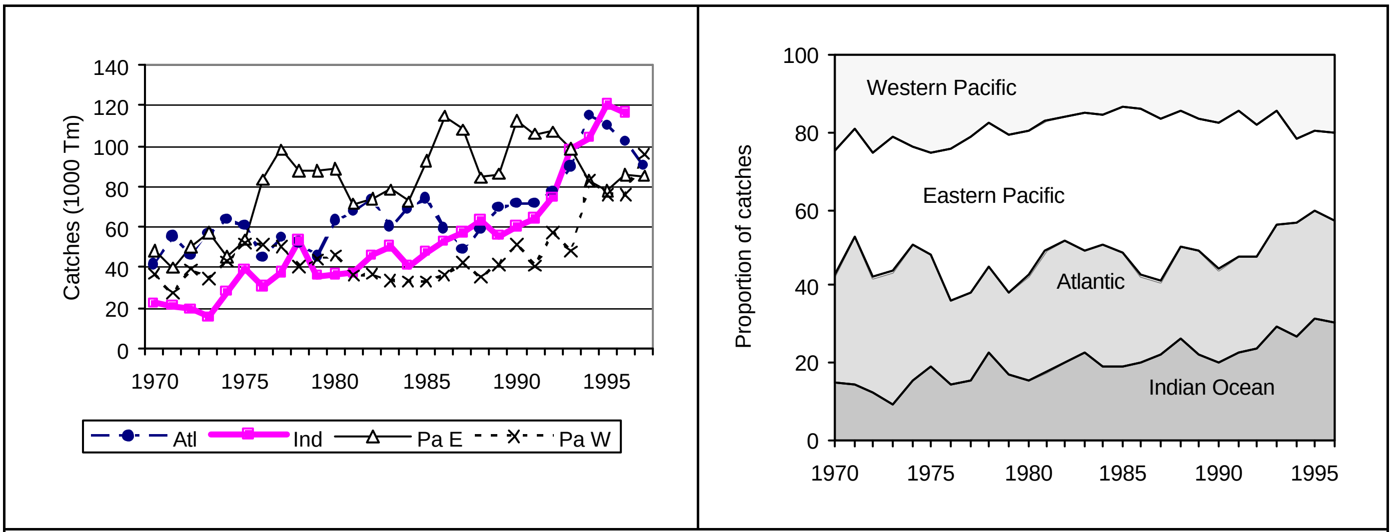


Fig. 1 Changes in bigeye catches over time in the Indian ocean, in the Atlantic, in the Eastern Pacific and in the Western Pacific in the upper panel, and changes in proportion by ocean in the lower panel.

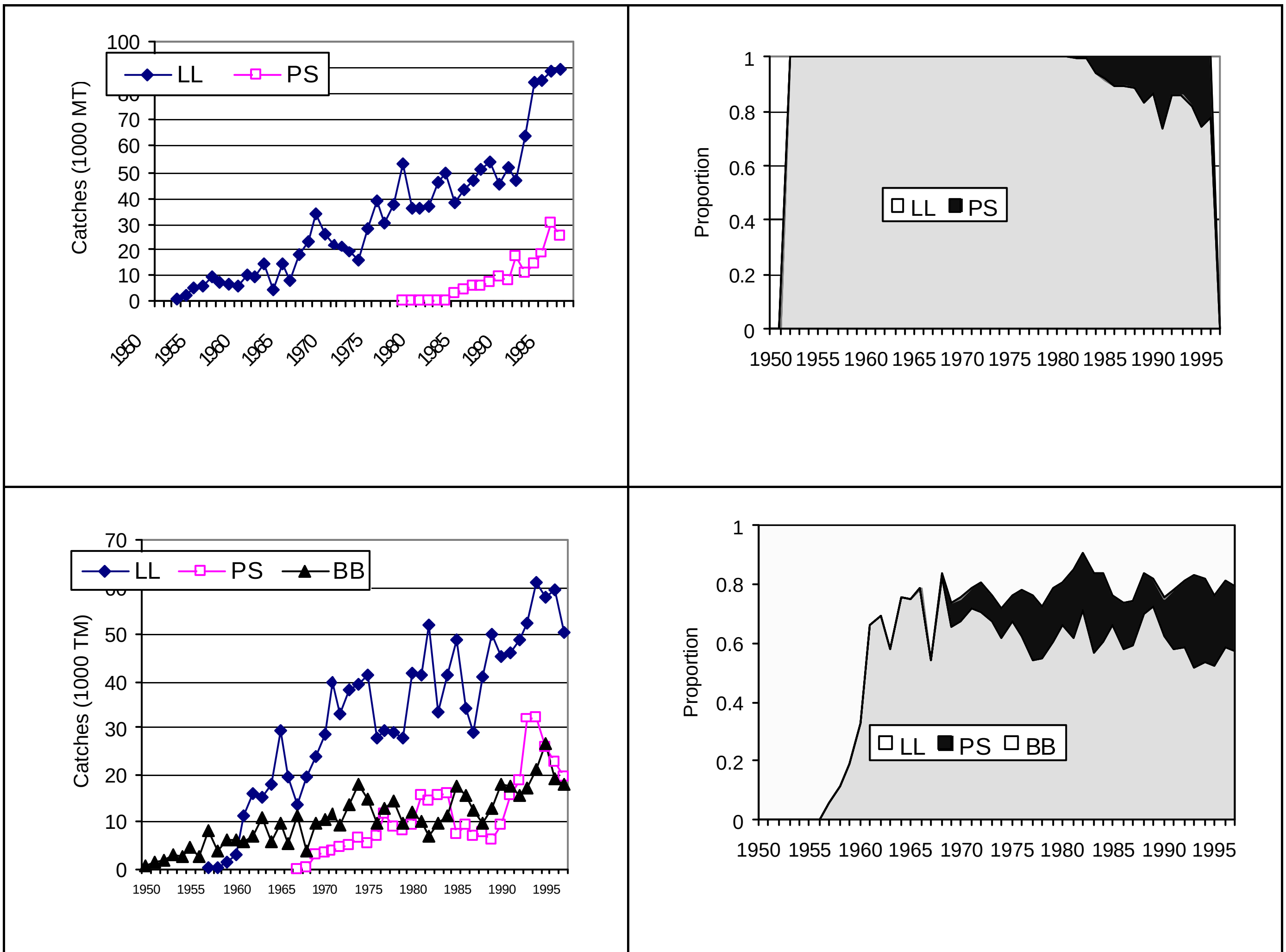


Fig. 2 Comparative changes of bigeye catches for the Indian ocean (upper panel) and for the Atlantic (lower panel) and proportions of bigeye catches taken by the main fleets (LL = longliners; PS = purse seiners and BB = bait boats).

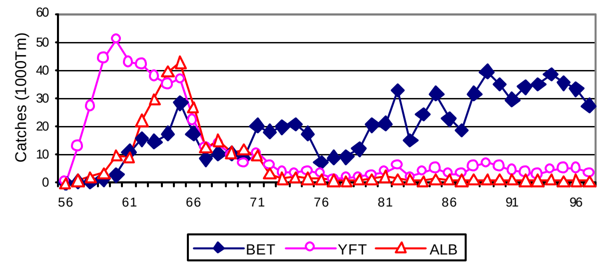


Fig. 3 Yearly catches made by the Japanese longline fishery in the Atlantic ocean.

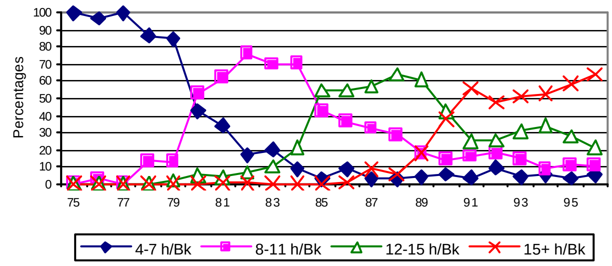


Fig. 4. Changes in proportion over time of the different types of longline expressed in term of number of hooks per basket for the Japanese longliners operating in the Atlantic Ocean (Miyabe comm. pers.)

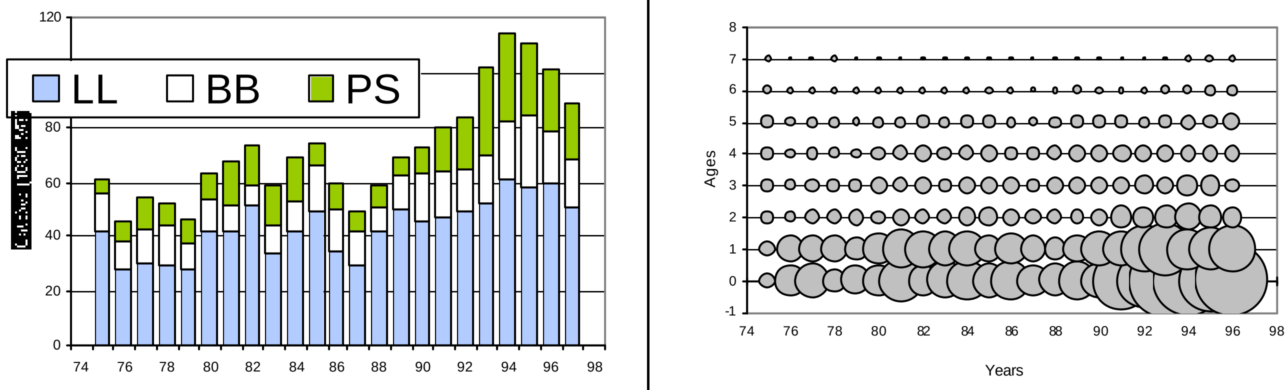


Fig. 5 Yearly catches per gear (upper panel) and proportion by age classes in number of fishes (lower panel) for bigeye tuna in the Atlantic ocean.

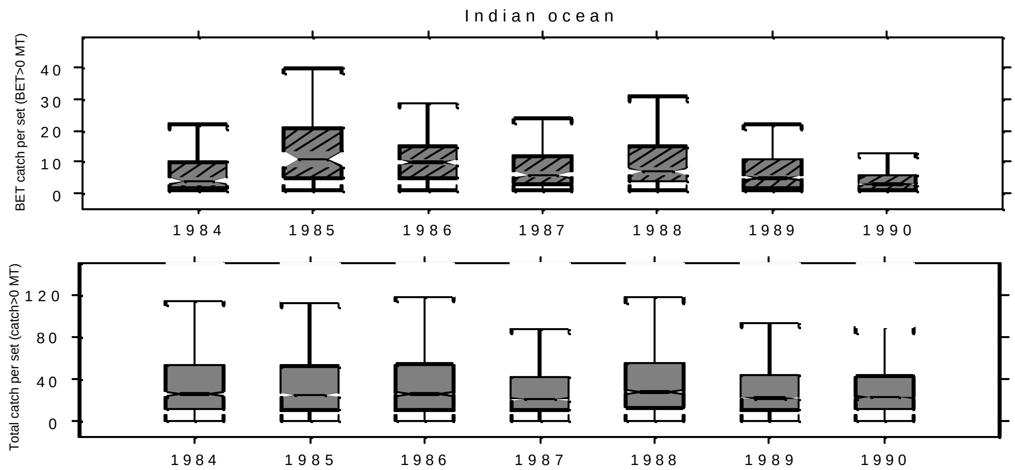


Fig. 6a. Box and whisker plot of catch per successful set for bigeye (upper panel) and for total tuna species (lower panel) in the Indian Ocean (1984-1990).

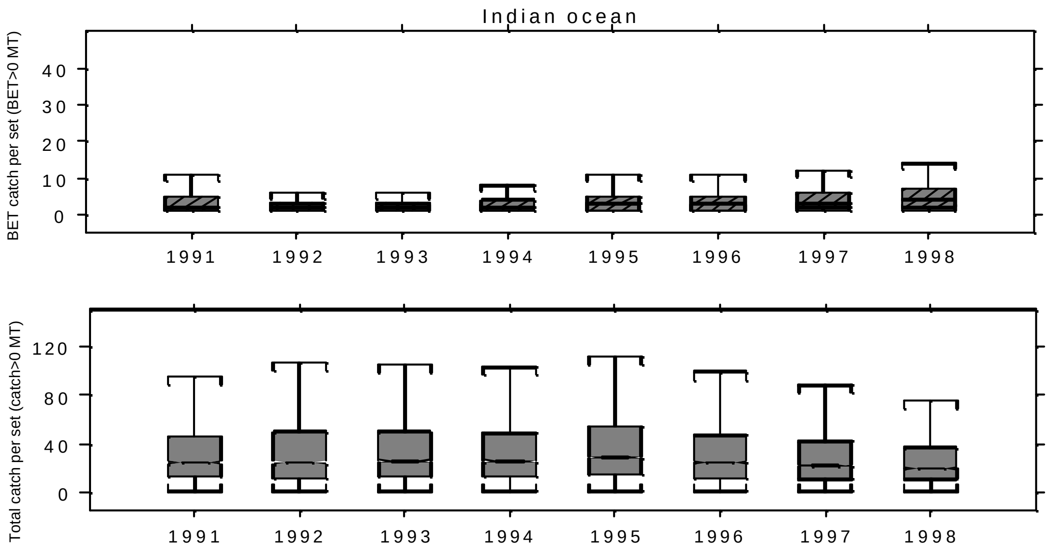


Fig. 6b. Box and whisker plot of catch per successful set for bigeye (upper panel) and for total tuna species (lower panel) in the Indian Ocean (1991-1998).

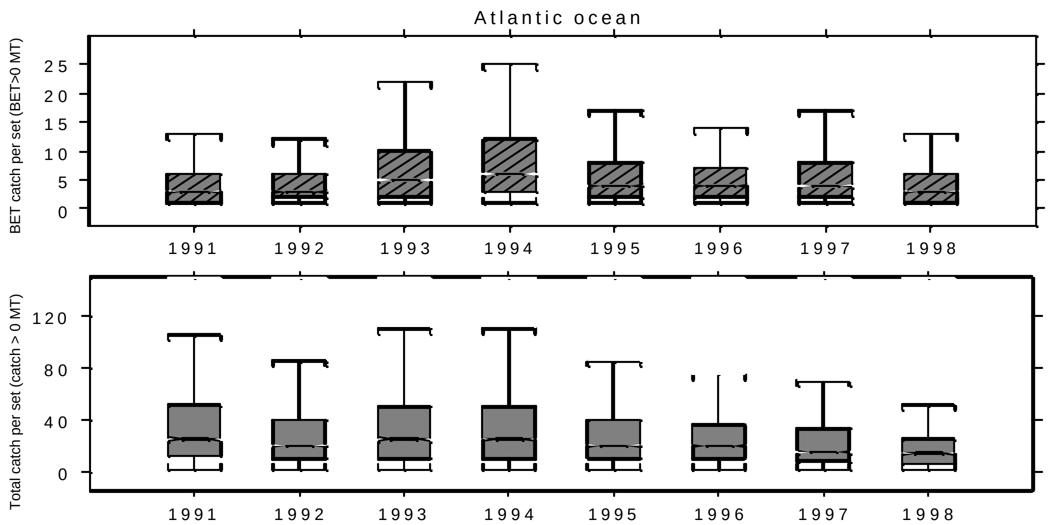


Fig. 6c. Box and whisker plot of catch per successful set for bigeye (upper panel) and for total tuna species (lower panel) in the Atlantic Ocean (1991-1998).

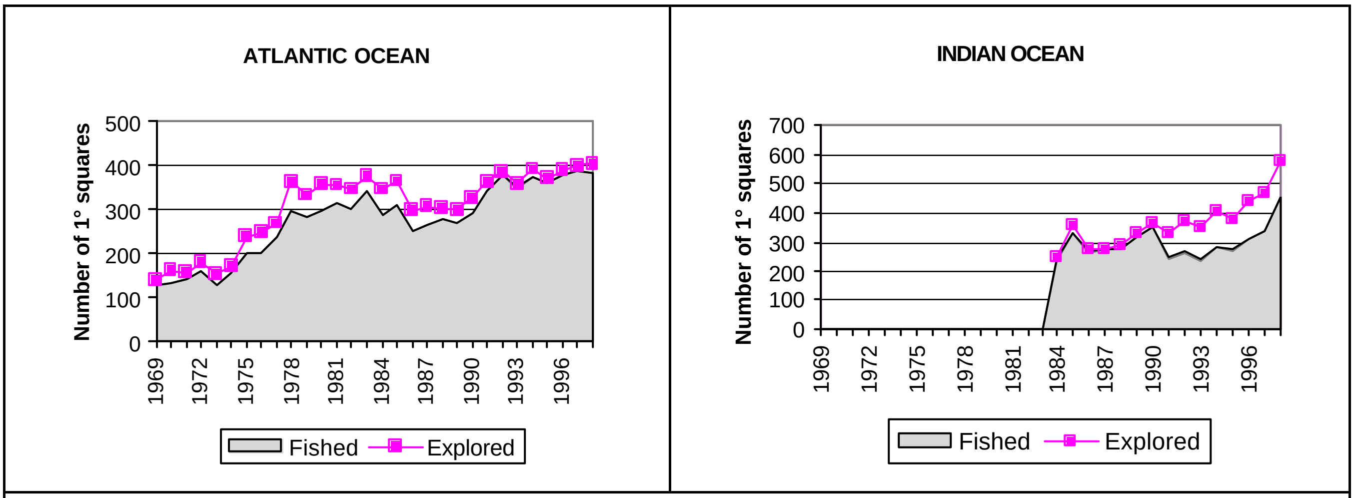


Fig. 7 Relationship between the total area explored and the total area exploited (i.e. with catch)

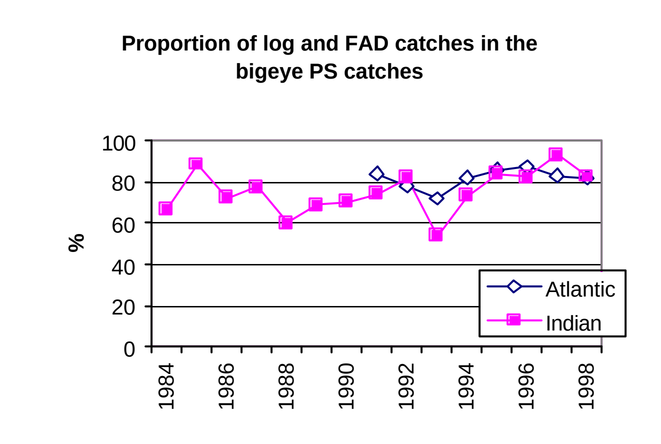


Fig. 8 Percentage of log and FAD catches in the total bigeye catches (purse seine fisheries) in the Atlantic and in the Indian Oceans.

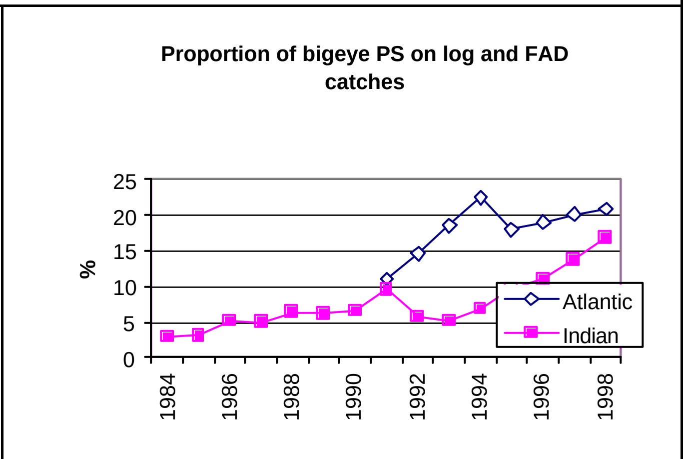
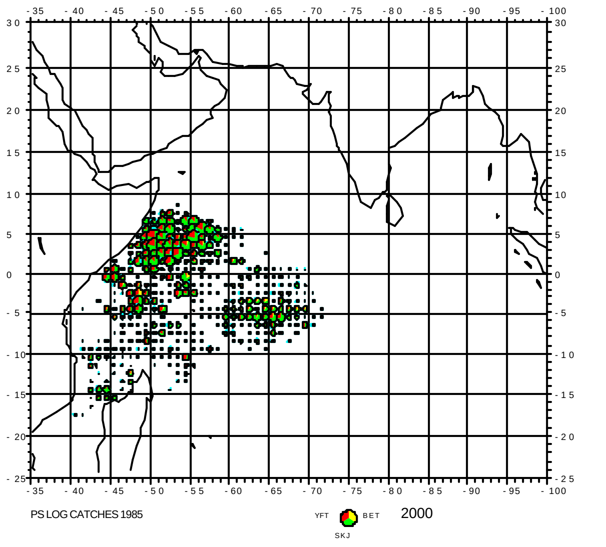
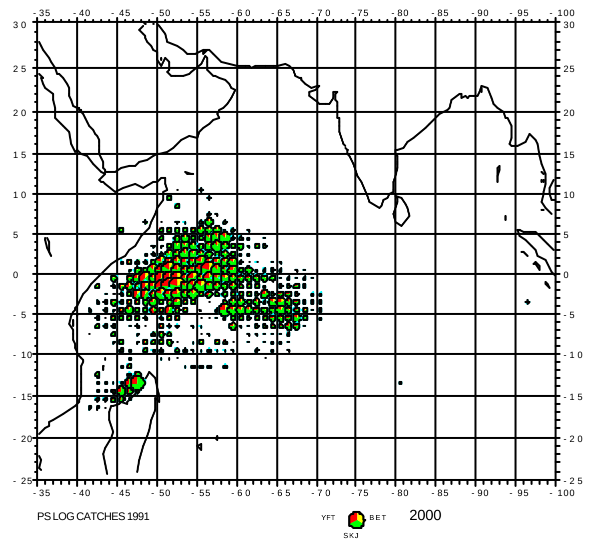


Fig. 9 Percentage of bigeye in the purse seine log and FAD catches in the Atlantic and in the Indian Oceans.



1985



1991

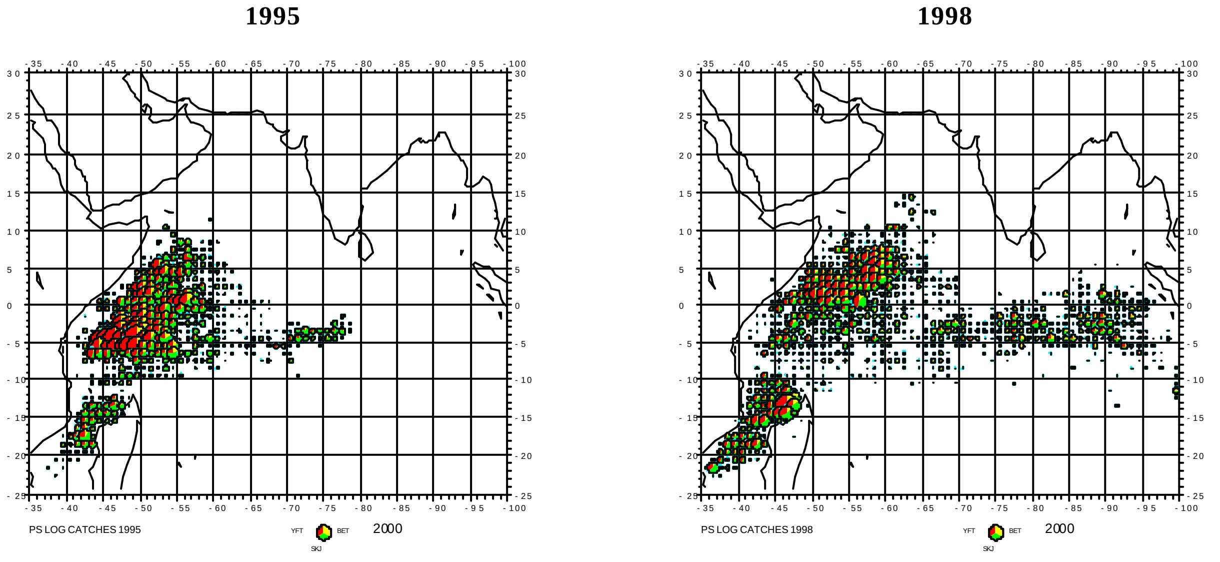


Fig. 11. Changes in the spatial distribution of log and FAD catches by species of the purse seine fishery in the Indian Ocean.

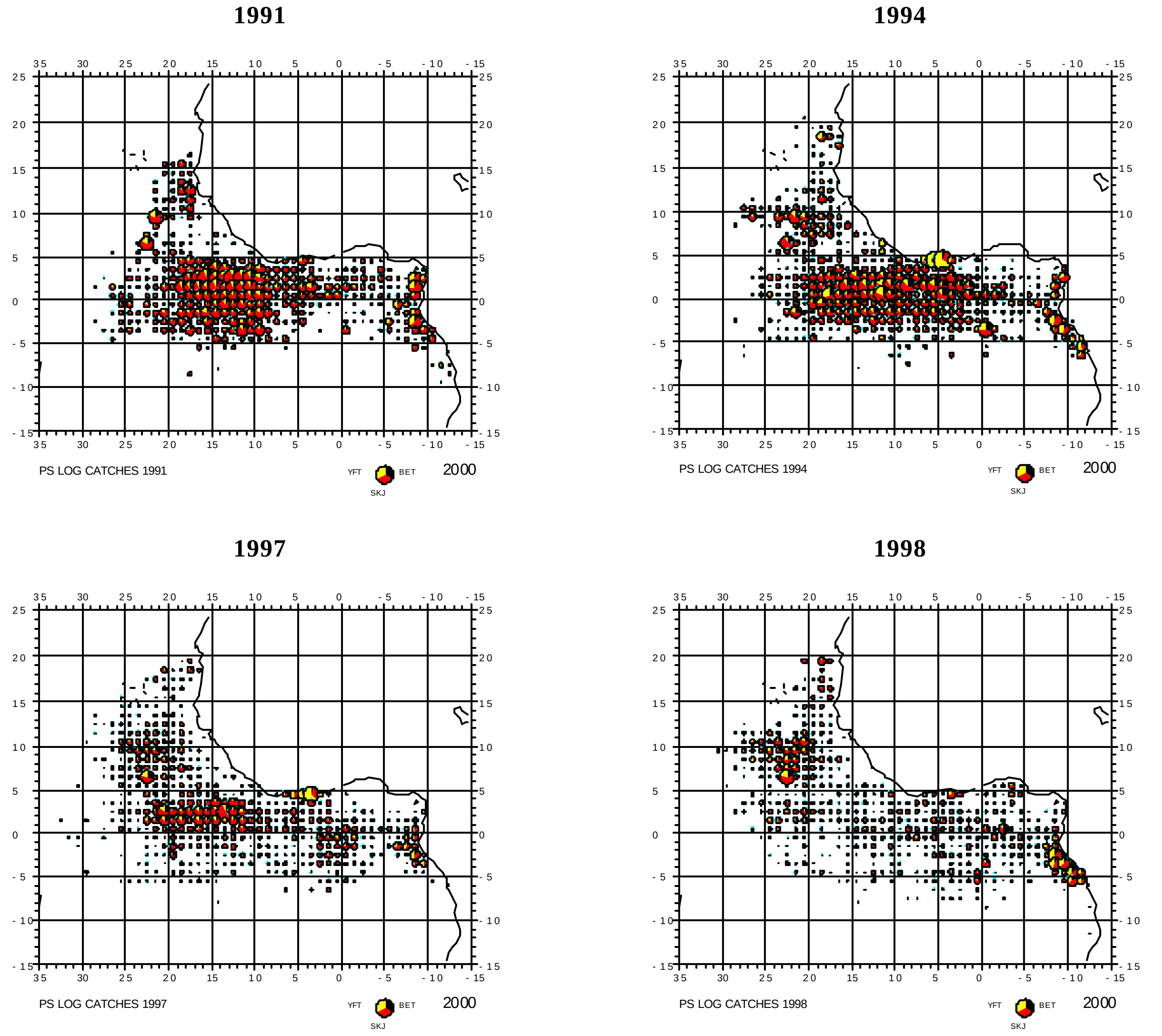


Fig. 10. Changes in the spatial distribution of log and FAD catches by species of the purse seine fishery in the Atlantic Ocean.

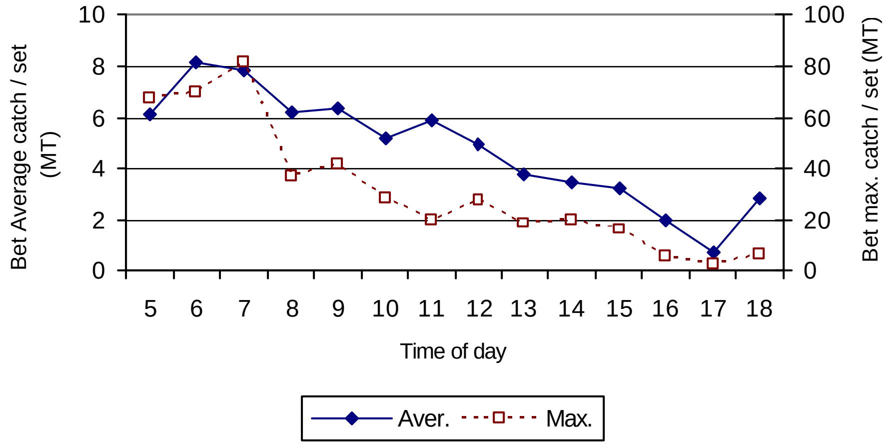


Fig. 13. Bet catch per log and FAD set (Aver. = average and Max. = maximum) by time of day from the E. U. Observer program in the Atlantic (1997-1998).

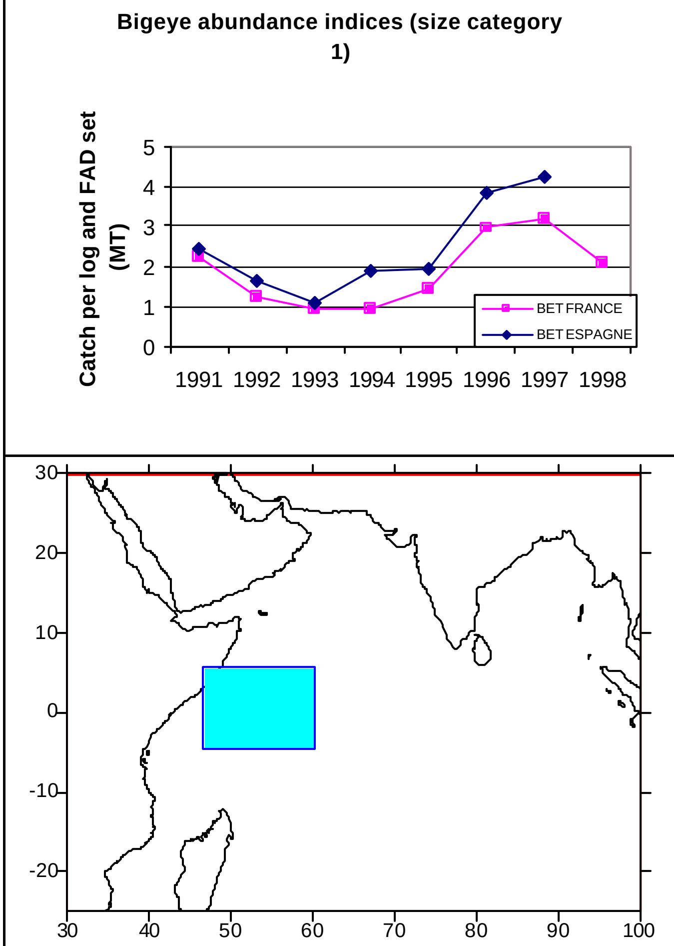


Fig. 14. Bigeye abundance index (size category 1) on logs and FADs for the Spanish and French purse seiner in the Indian Ocean (Area: 45°E-60°E / 5°N-5°S)

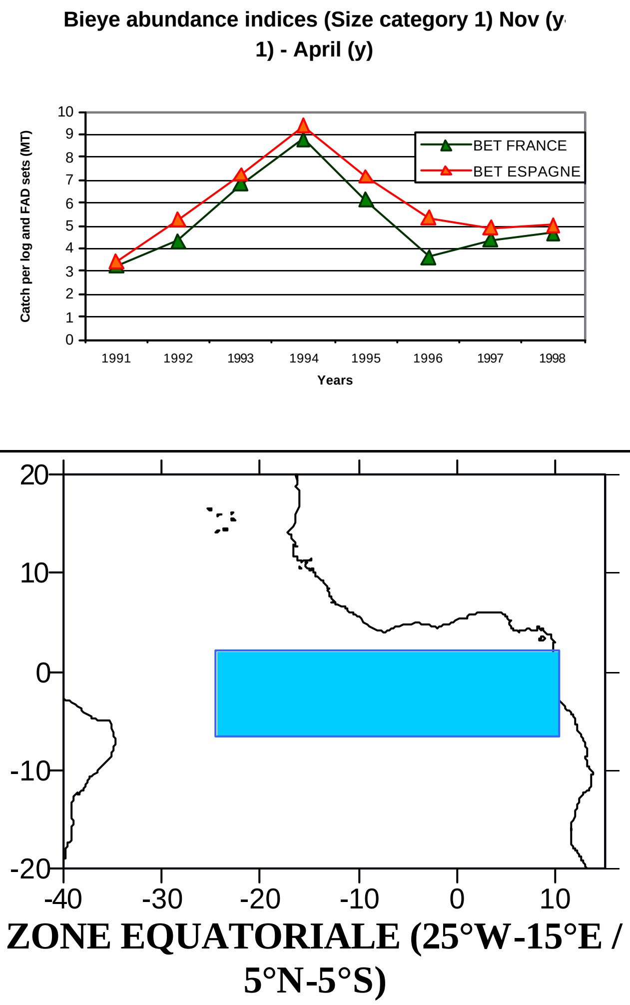


Fig. 15. Bigeye abundance index (size category 1) on logs and FADs for the Spanish and French purse seiner in the Atlantic equatorial area (25°W-15°W / 5°N-5°S)