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Mesoscale exploitation of a major tuna concentration in the Indian Ocean

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Abstract – The paper analyzes the daily catch, fishing effort and fish size data of the purse seine fleet fishing in the western Indian Ocean in February 2005, when a major concentration of tuna occurred and was heavily exploited by this surface fishery. This tuna concentration event occurred over a period of just 12 days, in an area of about 3500 square nautical miles located to the west of the Seychelles. This small stratum produced a total catch of 22 000 t, corresponding to 6.5% of the total fishing mortality of all adult yellowfin (*Thunnus albacares*) in the entire Indian Ocean in 2005. Sets were made mainly on free schools and the catch mainly composed of large yellowfin tuna. The average CPUE and the average catch per set were very large, 65 t and 85 t per fishing day, respectively. This "event" took place in a precise area where a high concentration of chlorophyll had been localized 18 days before. The subsequent concentration of tuna schools probably arose due to the high densities of their prey feeding on this large phytoplankton biomass. This phytoplankton bloom was observed at the edge of an anticyclonic eddy, but its origin and its high density cannot be fully explained by available environmental data. The adult yellowfin were probably at a reproductive stage and actively feeding on the local food chain generated by the phytoplankton bloom. Such an event is extreme, but typical of tuna purse seine fisheries where fleets often search for such tuna patches. These events play an important role in tuna fisheries due to the increase in fishing effort and fishing efficiency of purses seiners, both of which increase their impact on the resource. The fine scale study of such events and their improved integration into tuna stock assessments is recommended.

Key words: Yellowfin / Concentration / Exploitation / Phytoplankton bloom / Purse seiner / Indian Ocean

Résumé – Exploitation à méso-échelle d'une concentration de thons dans l'océan Indien. Cet article analyse les données journalières de prises, efforts et tailles des captures des thoniers-senneurs qui ont exploité en février 2005 une importante concentration de thons dans l'ouest de l'océan Indien. Cet événement s'est déroulé durant 12 jours, à l'ouest des îles Seychelles, dans une zone d'environ 3500 milles^2 nautiques de surface, Cette petite strate spatio-temporelle a ainsi permis une capture de 22 000 tonnes qui correspond à 6,5 % de la mortalité totale par pêche exercée en 2005 sur les albacores (*Thunnus albacares*) adultes de l'océan Indien. Les coups de senne ont été surtout réalisés sur des bancs libres et en majorité sur des gros albacores. Durant cet évènement, la prise par unité d'effort moyenne (PUE) de chaque senneur était très élevée (65 t par jour de pêche), de même que la prise moyenne par calée positive (85 t). Il a eu lieu précisément dans une zone où de très fortes concentrations de chlorophylle avaient été observées 18 jours avant la pêche des thons. Cet événement de pêche serait lié à l'exploitation de bancs de thons concentrés dans la zone pour des causes trophiques, et qui se nourrissaient de fortes biomasses de proies, qui elles-mêmes se nourrissaient sur cette forte biomasse de phytoplancton, qui était située à la périphérie d'un tourbillon anticyclonique. Son origine et sa forte intensité restent difficilement explicables par les données environnementales disponibles. L'hypothèse serait que ces thons adultes étaient probablement en phase de reproduction, tout en se nourrissant activement. Cet évènement halieutique est extrême, mais il est typique des pêcheries thonières à la senne dont les prospections visent fréquemment ces concentrations. Ces évènements jouent un rôle important, et sans doute croissant dans les pêcheries thonières, du fait de la pression de pêche et de l'efficacité accrues des senneurs. Ces phénomènes à très fine échelle spatio temporelle devraient donc être mieux analysés et mieux pris en compte dans les évaluations de l'état des stocks de thons.

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1 Introduction

Tuna are highly migratory species whose spatial distribution covers large areas of the world's oceans. However, due to the discontinuities in suitable habitats, a large fraction of tuna catches are often caught during short periods of time in very small areas. Such ephemeral spatial and temporal strata, called "tuna concentrations" or "tuna patches", are actively sought by tuna purse seiners. The variability of daily CPUE (catch per unit effort) in tuna purse seine fisheries is extremely high compared with that observed in other fisheries, such as tuna longliners, driftnets or bottom trawlers. Daily CPUE oscillates between zero, observed on a majority of the so called "fishing days", and very high daily catches, reaching several hundreds of tons on certain days. This particularity of tuna purse seiners is due to the fact that tuna schools are rare in the pelagic ocean (due to their relatively low biomass and very wide habitat range) and their geographical distribution is highly patchy. Furthermore, tuna schools are seldom visible from the surface, as they spend most of the day feeding in deep waters and these deep schools are difficult to identify and catch. As a consequence, most of the time that tuna purse seiners spend at sea is unprofitable: in the period 1996–2005, no tuna was caught on 53% of the fishing days spent by the Indian Ocean purse seiner fleet. During the same period only 13.5% of fishing days were highly productive, i.e. with a CPUE of over 60 t per day, but this limited fraction of the fishing time accounted for 66% of purse seiner catches. The main activity in tuna purse seiner fishing effort is searching for tuna patches, i.e. the rare time and area strata where high tuna biomass and large numbers of schools are concentrated, as the exploitation of these patches is the best or only way to obtain high CPUEs and high catches. These tuna concentrations can be described as a localized high density of tuna schools (at least several thousand tons of biomass) that gather temporarily (for few days to several weeks) within a small zone (some hundreds of square nautical miles), and are usually linked to feeding or spawning activities. Such tuna concentrations have already been analysed in the Atlantic Ocean (Fonteneau 1986; Ravier et al. 2000), and 399 exploited by purse seiners were identified during the 1980–1997 period (i.e. an average of 25 concentrations were fished each year). Tuna catches obtained on these concentrations represented an average of 70% of the total catches, highlighting their prime importance. Unfortunately, a study of tuna concentrations has never been conducted in the Indian Ocean. This lack of analyses is not due to a lack of scientific interest, but to the need for analyses to be based on exhaustive and very detailed catch, effort and size data, using daily catches covering 100% of the fleet active in the strata. This seriously limits the data that can be used and precludes analysis based on the Indian Ocean Tuna Commission (IOTC) data base, simply because the basic stratification of these data is by month and 1° square, i.e. strata that are too large to analyse the dynamics and exploitation of tuna concentrations. For the present study however, an adequately detailed dataset was available (daily catches, efforts and sizes by each set and for all the sets) collected by scientists from Spain, France and the Seychelles, on a tuna concentration that was exploited by vessels from only these countries.

Table 1. Total tuna catches (in tons) by species and by fishing modes taken during the fishing event, and numbers of tunas measured by species.

Total catches	Yellowfin	Skipjack	Bigeye	Total
Free schools	17 525	2352	1184	21 062
FAD schools	287	1290	102	1679
Total	17 812	3643	1286	22 741
Number of tunas sampled	6116	1179	270	7565

Table 2. Total number of successful and unsuccessful sets, by fishing mode, during the fishing event.

Number of sets	Free schools	FAD	Total
Successful	224	33	257
Unsuccessful	297	4	301
Total	521	37	558

The tuna concentration studied here was a major one, heavily exploited by the purse seine fleet in the area west of the Seychelles during February 2005. The goals of this paper are to analyse the corresponding daily fishing activities of the purse seine fleet, using the information from log books and size sampling made during landings, and to provide a better understanding of the process of exploitation of such a tuna concentration through a set by set daily analysis of catch and CPUE by size. Environmental data obtained by satellite in the area of this tuna concentration, hereafter referred to as the event were also analysed in order to explain the mesoscale environmental process involved in such a large concentration of tuna.

2 Material and methods

2.1 Fishery data

Analysis was primarily based on the detailed log book information and size sampling done on purse seiners from the European Union and Seychelles (offering nearly 100% log book coverage) (Tables 1 and 2). These sampled catches correspond to a great majority of the total landings (as an average 86% of the total purse seine catches were taken by this fleet during 2005), whereas none of the other purse seiner fleets fishing in the Indian Ocean were noticed in the same area during the studied event. In addition to estimated catch, logs recorded daily positions (GPS positions in degrees and minutes) for all sets and all vessels. This data set allowed us to estimate daily fishing times, expressed in fishing hours and in searching hours, calculated indirectly based on estimated time spent setting the nets (Table 3). Fishing modes, on free or on FAD-associated schools, were also known for each set. An intensive size and species sampling was also done on 100% of the fleet during landings, and these data used in the analysis, a total of 7565 tunas were sampled from this event out of the landings at Victoria, Seychelles (Table 1). Fishing vessel monitoring (VMS) of hourly positions was also available for the French fleet, allowing us to analyze the detailed search trajectories of this fleet over some days. These detailed daily

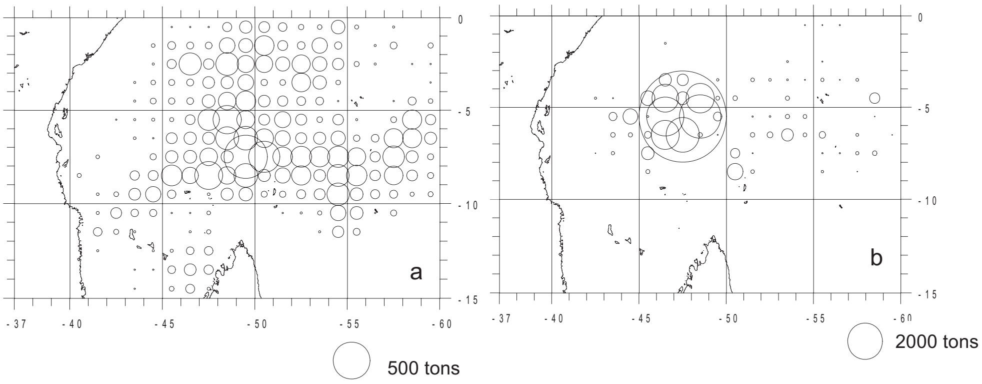

Fig. 1. Average catches of yellowfin taken per 1° square by the purse seine fisheries during the month of February: mean 1995–2004 (a); February 2005 (b). The area of each circle is proportional to its catch; note that the scales of these circles are different between these 2 maps because of the highly localized catches in February 2005.

Table 3. Fishing efforts during the fishing event: total number of fishing days, duration of sets (expressed in fishing days units assuming 13 hours of fishing time each day) and number of active purse seiners (daily average, minimum and maximum).

Number of fishing days	Duration of sets (unit of time equivalent to fishing days)	Minimum number of boats	Average number of boats	Maximum number of boats
293	106	14	24	31

data obtained on purse seiners exploiting the tuna concentration were also compared with the entire IOTC database that covers or estimates the activities of all tuna fleets (catches and catch-at-size).

Historical catch and effort data by 1° square and month are also available for the entire purse seine fishery (IOTC data). They show that the purse seine fisheries caught very large quantities of tunas between 5° and 6°S and 47° and 48°E in February 2005, whereas only moderate quantities were caught in this area and the surrounding neighbourhood in the month of February in previous years (Fig. 1). This is by far an IOTC record for a monthly catch taken in a 1° square: when compared to the historical IOTC monthly catches by 1° square, this level is twice that of any previously observed catches in an equivalent stratum.

The first step of the analysis was to identify the exact time and area strata of the main fishing events from the log book data. As a second step, the main variables characterising the purse seine activities and their corresponding catches in the stratum were analysed on a daily basis: number of fishing vessels operating in the area, fishing effort (number of fishing days and searching time), number of sets and their estimated duration, catches by species, size of the area explored and fished each day, fishing modes used (sets on FADs or free schools sets), and size distributions of the fishes taken. This analysis was conducted for total tuna catches and for yellowfin tuna, the main species caught. The yellowfin CPUE was also calculated for two fish size categories, medium and large, (above and below 120 cm), based on the heterogeneity of the sizes caught.

2.2 Environmental data

Various local environmental data (such as local weather, sea surface temperature SST, wind speed, surface current and visibility) in the fished strata were obtained from the log books. Satellite information (ocean colour and altimetry) was also obtained in this area, before and during the event, and was analyzed to evaluate if this hot spot could be linked with any visible environmental anomaly. We used global daily SeaWiFS level 3 chlorophyll *a* concentration images, at a 9 km resolution, available from the NASA ocean colour web site. Daily QuikSCAT Level 3-Derived Multialgorithm Surface Wind Stress data were downloaded from the NASA-JPL ftp site at ftp://podaac.jpl.nasa.gov/pub/ocean_wind/quikscat/L3/, provided on a global grid at a resolution of 0.25° lat/lon. Surface geostrophic U and V components of velocity and sea level anomaly were also used, produced by Ssalto/Duacs version 8.0 and distributed by Aviso, with support from CNES. These data are a composite of three sensors, TOPEX POSEIDON, JASON and ERS-2 with spatial resolution of respectively 1/3° degrees and 1/4° degrees.

3 Analysis of the fishing event

3.1 Tuna purse seiner searching patterns and tuna concentrations

The tuna concentration analysed in this paper is a representative example of tuna patches (or tuna concentrations) constantly sought by purse seiners. The fishing effort exerted by purse seiners can be stratified into the search for FADs and the search for free swimming schools, generally dominated by yellowfin tunas (this species corresponded to 69% of Indian Ocean free school catches during the 1996–2005 period). Catches on free swimming schools and fishing efforts targeting free schools tend to be dominant during the first quarter of each year, and produced a mean 68% of total catches in the first quarter during the period 1996–2005.

The exploitation of these tuna concentrations strongly affects the CPUEs of tuna purse seine fleets: for a given tuna biomass and given number and size of tuna patches, the yearly

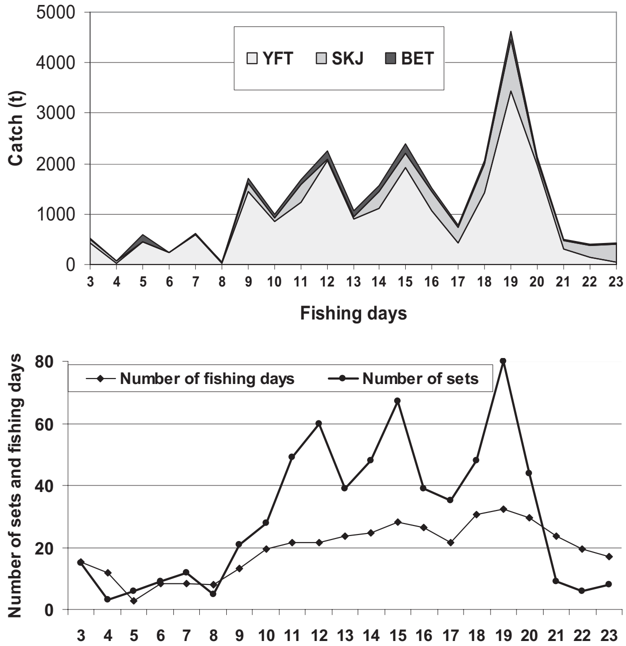

Fig. 2. February 3 to 23, 2005. Daily catches by species on free schools (a) and fishing effort expressed in fishing days and in numbers of sets (b), recorded in the area 4°–6°S and 46°–49°E during February 16–17, 2005 (Fig. 4). The period of higher catches selected as the studied fishing event is also shown on these figures (YFT: yellowfin, SKJ: skipjack, BET: bigeye).

CPUE of the fleet will be largely dictated by its efficiency, firstly in identifying these ephemeral and small hot spots, and secondly in exploiting them fully and efficiency.

3.2 Overview of the event: period and area

Figures were drawn to show the duration (Fig. 2) and geographical extent (Fig. 4) of this event. The area concerned is located in the offshore waters west of the Seychelles, in an area commonly fished by purse seiners during this season (Fig. 1a). This tuna concentration can be easily identified on the February 2005 fishing map of catches per 1° square by the purse seine fleet (Fig. 1b). The comparison of these two maps shows that the area where the 2005 event took place was not a major fishing zone for yellowfin during the period 1995–2004. Figure 1b and the analysis of catch and effort data since 1983 showed that this area is commonly fished each year by purse seiners at this season, but without high catches: an average catch of only 2800 t was taken during the period February 1984–2004 (Fig. 4 area: 3°S to 8°S, 45°E to 50°E), compared with a total catch of 34 200 t taken in this area in February 2005. Thus, this time and area stratum cannot be considered as being a typical hot spot where high catches are possible every year due to a particular environmental characteristic (such as on sea mounts).

The analysis of the fishery data (Figs. 1 and 2) shows that a record catch of 25 137 t of tunas was taken within an area of six one degree squares in the period February 3–23. Further analysis of daily catches and fishing zones shows that most of these catches (22 740 t) were taken in the central period between February 9 and 20, and in a very small area focused at 5°40' S and 4°30' E. The analysis mainly concentrated this period and location, referred to as the event. During this event, an estimated surface of about 3500 square nautical miles (i.e. smaller than a 1° square at the Equator) representing approximately 2% of the purse-seine fishing area, was exploited over a period of only 12 days. This small fraction of the fishing year and small area produced 17 810 t of yellowfin (Table 1), which amounts to 8.5% of the total purse seine catches of yellowfin in 2005. Information obtained from the other regional fishery organizations (ICCAT, WCPFC and IATTC secretariat) tends to indicate that this high level of localized catches is probably one of the greatest in the history of the purse seine fisheries operating in the Indian Ocean, Atlantic or eastern and western Pacific[1].

3.3 The fishing fleet in operation

The purse seine fleet involved in this event is owned and managed by EU companies under the flags of Spain, France and the Seychelles. In 2005, a total of 48 purse seiners were active in this fleet. The average carrying capacity of the fleet is 1880 m^3 (i.e. about 1300 t of tuna) and its average maximum speed is estimated at 16 knots. The average age of the vessels was 16 years, but all were equipped with the most modern electronic and technological equipment (such as bird radars, long range sonars, etc.)

The tuna concentration in this study was exploited by 43 purse seiners (i.e. 90% of the studied purse seine fleet), with a maximum of 32 vessels fishing simultaneously in the area in one day (February 19) and an average number of 24 vessels fishing in the area each day. Figure 2b shows the daily fishing efforts expressed in number of sets and in number of fishing days in the area (number of fishing days indicates the minimum number of vessels active in the area per day). Fishing effort increased between February 9 to 20, reaching its peak at the end of this period.

3.4 Quantities caught by species and size

Analysis of daily catches and their species composition showed that the highest catches were made on free schools during the event (Fig. 2a, Table 1); with yellowfin tuna the main species (78% of total catches), mostly taken on these free swimming schools (a total of 21 062 t, Table 1). The daily catches associated with FADs, totalled only 1680 t during the event, and showed a very different species composition dominated by skipjack (Table 1). The temporal pattern

[1] Based on the 1° square and monthly catch data, similar events may have occurred in the eastern Pacific in January 2004 at 13.5°S and 77.5°W, as well as in the western Pacific in January 2003 at 0.5° N and 157.5° E, where similar catches of 22 000 tons were also observed in each of these 1°-month strata. Unfortunately, neither the environmental causes nor the dynamics of the fisheries producing these record catches have ever been analyzed in the Pacific Ocean.

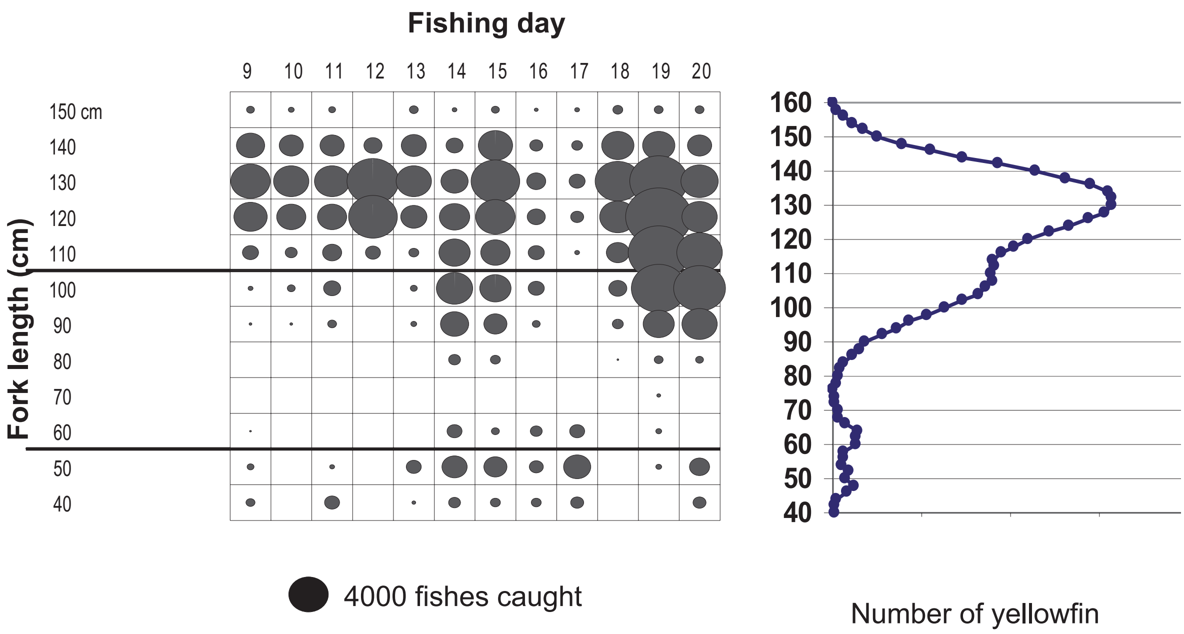

Fig. 3. Diagram of daily catches at size of yellowfin tuna taken on free schools, by 10 cm classes (a); the area of each circle is proportional to the catch-at-size in numbers. Size distribution of the yellowfin sampled from the studied fishing event (b), shown by the numbers of fish measured at each 2 cm size.

of FAD catches was also different, with a large variability in daily catch, and some days with no FAD-associated catches (most of the FAD catches were taken in the last few days of the event). The locations of these FAD-associated catches were also quite spatially scattered. Such species composition and dominant free school catches have commonly been observed in this fishing zone in previous years.

Subsequent analysis concentrated mainly on the principal group of free school catches dominated by yellowfin. These yellowfin were predominantly large fishes, as shown by their size distribution (Fig. 3a), with an estimated average weight of 38 kg (Fig. 3b). Such weights are typical of yellowfin caught in this stratum: the same average weight of 38 kg was caught by purse seiners during the first quarter in 1995–2004 on free schools in the area 0°–10°S, and west of 50°E. Most of these large yellowfin were potential spawners, as the minimal and 50% spawning sizes have been estimated to be 70 and 104 cm respectively (i.e. 7 to 21 kg) by Karpinski and Hallier 1988.

The analysis of the daily sizes of yellowfin caught and sampled (Fig. 3a) shows that very few immature yellowfin smaller than 90 cm were taken during the event (only 7.5% of the total numbers caught). The large yellowfin caught during the event can be classified into two categories:

- Adults in a range 90 - 120 cm fork length (i.e. 14 to 33 kg), that were mainly caught during the second half of the period.
- Fish larger that 120 cm, caught every day over the entire event.

Significant amounts of skipjack tuna were also taken on free schools (11.1% of free schools catches); with the majority taken at the end of the event on large free schools of pure skipjack. A small proportion of bigeye was also taken in many of these free schools (estimated at 5.6% of total catches), and these large bigeye were caught at sizes similar to the yellowfin (average weight of 37.6 kg).

3.5 Area explored and fished

Detailed fishing maps of the fleet are shown in Figure 4, with each of these maps covering individual fishing days (February 13, 14 and 15) or periods of several days when the fishing zones were either stable (February 10 to 12, 16 and 17, 18 to 20) or not well identified (February 5 to 9, 16 and 17, 21 to 23). These maps show that large catches were mainly taken over a very small area during 2 periods: February 11 to 15 and February 18 to 20. On other days, daily catches were much lower, and the fished area more scattered. These fishing maps allowed us to estimate by eye an apparent pattern of movement and trajectory of the main tuna concentration fished during the event (Fig. 5). This hypothetical trajectory corresponds to an approximate distance of 150 miles, covered between February 9 and February 20, i.e. at a rather slow average speed of about 0.52 knots.

The very small size of this fished area makes an interestingly contrast with the much larger average number of 130 one degree squares where yellowfin were caught monthly by the same purse seine fleet over the previous 10 years (1996–2005). The present case is a good illustration of the paradoxical time and space variability in daily tuna CPUEs: a wide fishing zone is fished all year round by purse seiners with many totally unsuccessful fishing days, but very high catches can be obtained in a very small area.

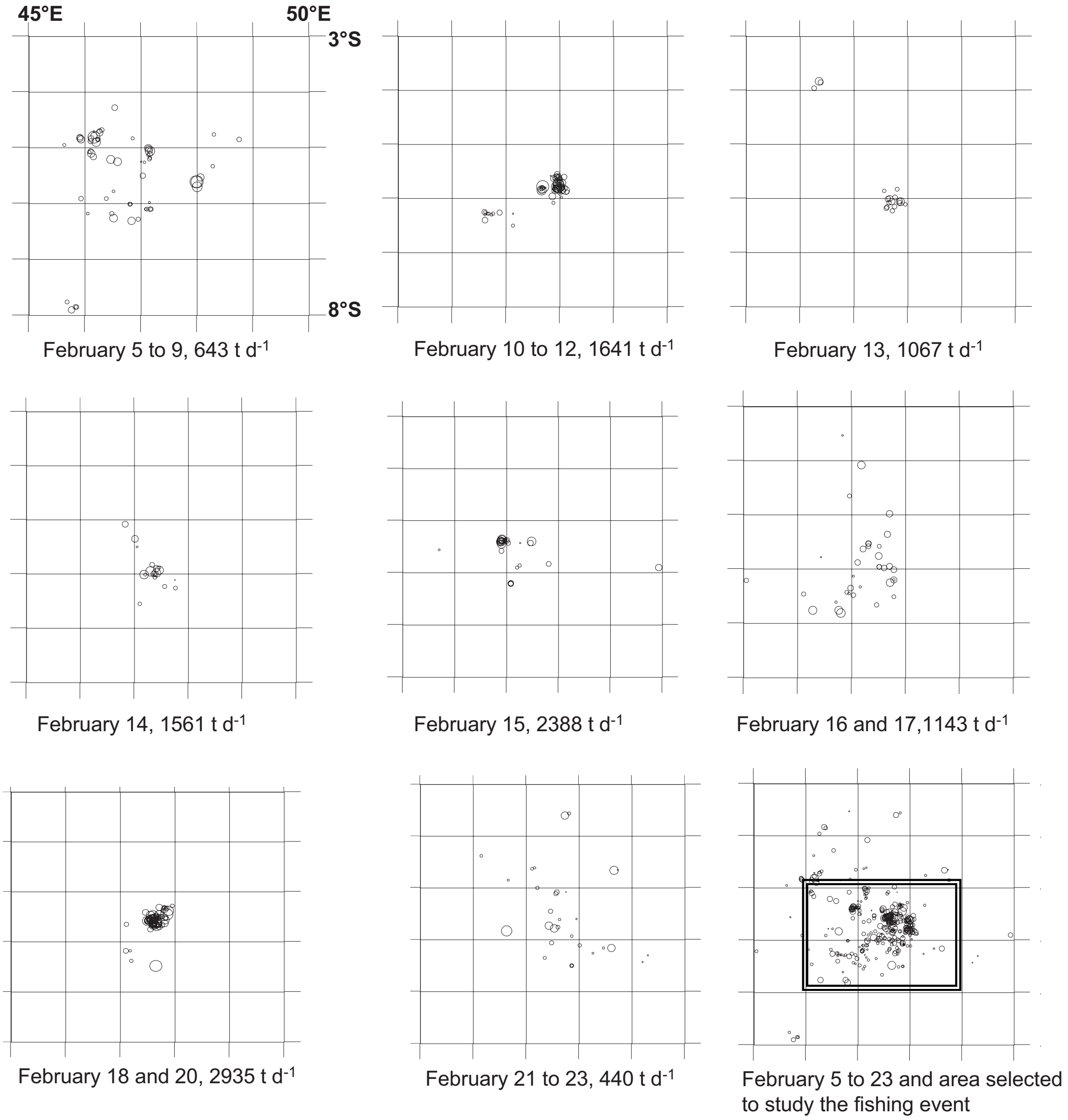

Fig. 4. Fishing maps showing the exact location (in degrees and minutes) of each individual set during the period February 5th to 23rd in the area 3°–8°S and 45°–50°E, by periods of 1 day or of several days when the fishery was stabilized in a given area or scattered and mobile.

3.6 Catch per set and number of sets

A very high average catch of 88.5 t was observed per successful set during the "event" (n = 257 positive sets), 31.3% of these sets producing very large catches over 100 t. The highest catches per set were observed during the last 2 days of the event with the maximum estimated at 400 t. The average rate of unsuccessful sets on free schools was close to 57%, which is quite a high percentage but typical of this fishing mode. It is probably an underestimate, as some unsuccessful sets may no be recorded in the log books. Based on the statistical relationship between catch per set and the duration of setting times, the total duration of these unsuccessful sets was estimated as 1383 h (positive and null sets). This period, during which the vessels were not able to search, represented 39% of the fishing time of the fleet. As setting durations have been reduced since the early eighties, it can be estimated that in 1984, the time taken for the same sets would have been about 1871 h, based on the durations of sets observed during this early period (i.e. a 26% difference in set duration). The daily number of sets was quite stable, at a relatively low level of 18.7 positive sets per fishing day, i.e. with only an average 0.91 positive sets per fishing day of each boat in the strata.

3.7 CPUE

Daily CPUE was calculated as the ratio of catches to fishing effort in the selected area. CPUE started to be fairly high in the selected area on February 5, i.e. 4 days before the date decided as the first day of the event (CPUE reached 50 tons per fishing day during the period February 5 to 9), but the total effort and catches were still quite low. During this early period, only 8 vessels were fishing in the area and these were fairly

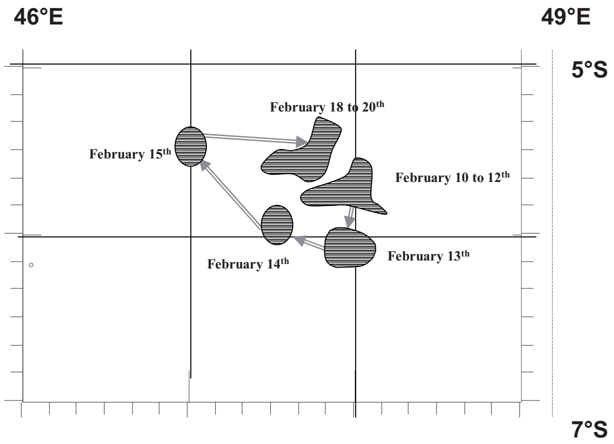

Fig. 5. Daily sizes and positions of the areas fished by purse seiners during the concentration (contour and potential trajectory estimated by eye based on the daily fishing maps).

scattered (see daily fishing maps Fig. 4), catching an average 340 t of tunas daily and fishing in 4 neighbouring one-degree squares. Figure 6a shows the daily yellowfin CPUE observed in the selected area during the event. Beginning on February 9, the CPUE fluctuated, but was later maintained at a high average level until February 20 (Fig. 6a). The main fishing operation took place first on February 10 when the entire fleet concentrated its activities in a very small fishing spot centred on 5°40S and 48°E (Fig. 4: February 10 to 12) and caught a large amount of tunas, therefore obtaining a high CPUE.

The total average CPUE of the purse seine fleet during the entire event reached 65 t per fishing day. Surprisingly significant numbers of unsuccessful fishing days were also observed for a large fraction of the purse seine fleet each day, with an average daily percentage of 37% unsuccessful fishing days during the event (Fig. 6a). This percentage is of course linked to the fairly high percentage of null sets, as each of the purse seiners made at least one daily set during this event. The average daily CPUE of 65 t was calculated from a mixture of two groups of vessels: the "unlucky" ones, about 40% of the vessels, without daily catches, and the successful "lucky" vessels obtaining extremely high CPUE at an average rate of 126 t per day. Such a high rate of unsuccessful fishing days may appear paradoxical during the exploitation of such a large tuna biomass, but it is due to the fact that free schools of yellowfin are difficult to locate and to catch.

Based on the variability of yellowfin sizes caught, another CPUE stratified into two size categories was also calculated for this species: small adults (90–120 cm FL) and large adults (>120 cm FL) (Fig. 6b). It showed that the CPUE of large fishes declined severely over the first 8 days of exploitation (with CPUE nearly reaching zero on Feb. 17). However, on February 18, a major increase of CPUEs was observed for both small and large adult groups (and in the catches of these two groups).

At the end of the event and after February 20, a significant fleet of about 27 purse seiners continued to search the same area for 3 days, but obtained a much lower mean daily CPUE of 20 t and a lower total catch of 500 t each day. Furthermore, 60% of this catch taken after the event was caught on FAD-associated schools dominated by skipjack, i.e. a completely different fishing pattern and species composition.

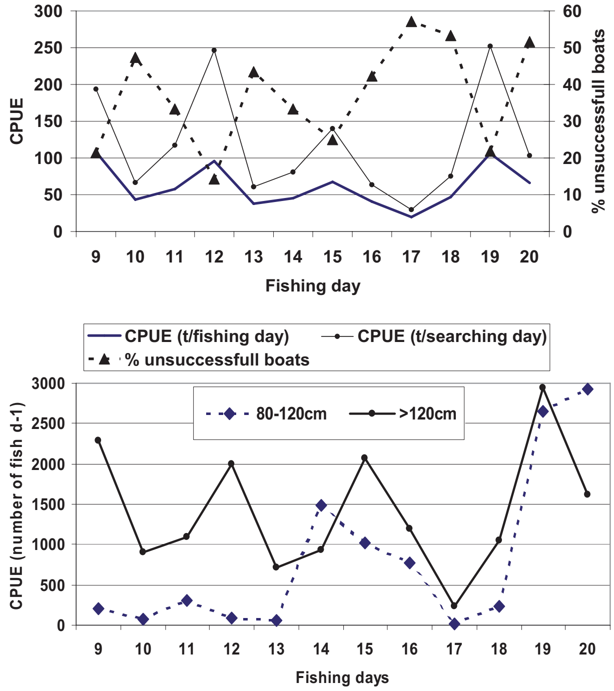

Fig. 6. Fishing activity indicators: (a) daily CPUE of purse seiners fishing large yellowfin before and during the fishing event, expressed per fishing day, and per units of 13 searching hours (the equivalent of a fishing day in the absence of sets), daily percentage of purse seiners with no catch; (b) daily yellowfin CPUE on free schools expressed by size categories for small (80 to 120 cm) and large adults (120 to 160 cm) (number of yellowfin caught per fishing day).

4 Environmental conditions

The average environmental conditions found in this area during February are typically a suprathermoclinal layer of about 100 m (Levitus and Boyer 1994).

Sea surface temperatures were recorded by the purse seiners during fishing and show that all tunas were caught in warm surface waters with a temperature range between 26 and 30 °C and a mean of 28.8 °C, typical for the area during this season. Such waters are considered to be suitable for maturation and spawning of adult yellowfin tuna (among other species) and this area around the Seychelles has been identified (Karpinski and Hallier 1988; Stéquert et al. 2001) as a typical spawning zone for adult yellowfin during the first quarter.

The local conditions encountered during the event were good weather, moderate winds in a range between 3 to 8 m s^{-1}, typical of this area (Fig. 7), and a south east surface current, estimated by skippers as being between 1 and 1.5 knots.

Phytoplankton blooms identified by satellite imagery are now increasingly used by scientists (Zainuddin et al. 2006) and by fishers wishing to identify phytoplankton blooms potentially associated with tuna hot spots. Such a chlorophyll *a* concentration was detected by SeaWiFS. It showed a major

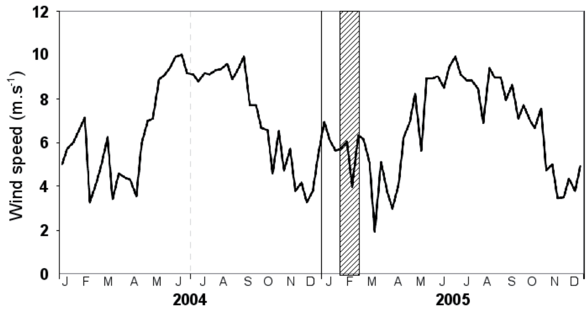

Fig. 7. Mean wind speed (m s^{-1}) between January 2004 and December 2005 in the bloom area (47°E-50°E/3.5°S-6.5°S), (QuikSCAT data). The period of the fishing event is hatched.

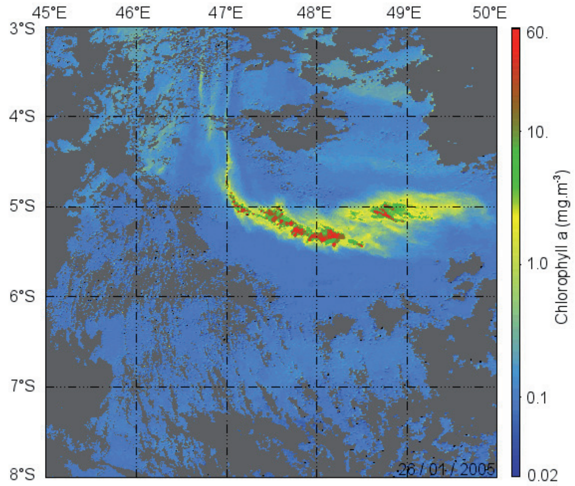

Fig. 8. Map of the surface chlorophyll concentration measured by MODIS on February 26, revealing very high concentrations.

phytoplanktonic bloom that was very dense (maximum values over 60 mg m^{-3}) and highly localized. This major environmental anomaly was first identified on the satellite image for January 23 and later fully confirmed on January 26 and 27 by the MODIS image shown in Figure 8 (i.e. 14 days before the event). The initial position of the core of this bloom was observed at 48°E and 5°20'S (Fig. 8), i.e. only 20 miles north of the event on February 9 (Fig. 4). This bloom moved southwards at an average speed of approximately 0.25 m s^{-1} and was located close to a thermal front, with surface waters <29 °C in the north, and >30 °C in the south and within the bloom itself. It remains impossible to determine the initial date of this environmental anomaly, because of a high density of clouds in the area. Nevertheless, it was observed and intermittently followed in the same area, until at least February 13, when it disappeared from the satellite view. An extended analysis of the frequency of similar events in the area delimited by the longitude 43°E and 53°E (excluding the Seychelles Islands) from September 1997 to December 2006 (Fig. 9) showed that such a concentration was rather exceptional, only having been recorded once in this area with such an intensity, in almost 10 years of observation. The only comparable events recorded with a similar intensity were visible in August 2003, far from the present fishing event, and also in February 2004, when another large concentration of yellowfin was fished.

Analysis of geostrophic current component and Sea Level Anomaly (SLA) are presented (Fig. 10). From the beginning of January to the end of February, an anticyclonic eddy was observed and monitored. During the week of January 26, the structure of this mesoscale eddy is clear (400 km in diameter) and associated with increasing positive sea level anomalies. During this period, we observed an eddy-eddy interaction with a cyclonic eddy situated immediately north and characterized by a strong dynamical gradient. The chlorophyll image for January 26 shows that the bloom was located at the edge of a cyclonic eddy associated with colder SST (image not shown). Between February 2 and February 8, the bloom lost intensity, simultaneously with the growth of a growing mesoscale structure. From February 9, the major fishing spot was located at the edge of the anticyclonic eddy that was identified during the first week of February. The close interaction between a cyclonic and an anticyclonic eddy seems to be the most influential physical factor responsible for horizontally advecting and concentrating primary production into the area. However, other factors must also have been involved because similar eddies, common in this area, have not been associated with such a strong bloom.

A detailed analysis of daily QuikSCAT wind data during the same period (Fig. 7) shows that no abnormal wind burst could be associated with the observed bloom, and that the high seasonal wind variability is a common pattern in the region, with high wind speed during the north-east monsoon (maximum 10 m s^{-1}) in austral winter and low wind speed during the south-west monsoon (minimum 2 m s^{-1}) in austral summer.

Therefore, the physical mechanism that could have produced such a bloom remains unknown, as it cannot be explained either by the large scale data sets analysed here or by atmospheric forcing.

5 Discussion

The tuna concentration under study and its particularly active exploitation by the purse seine fishery constitute an interesting event, worthy of detailed analysis. This in-depth analysis of the detailed position of set by set activities of the purse seiners would not have been possible using basic IOTC data, as this is only available as monthly data per 1° square. The main questions to be discussed concern the environmental mechanism capable of explaining such biological tuna concentration, and the fine scale processes linked with the brief intense exploitation of such a major concentration by the present purse seine fishery.

5.1 Why should such a high tuna concentration occur?

Large yellowfin tunas like those caught during the event were exceptionally abundant in the western Indian Ocean during the entire period 2003–2006 (IOTC 2007).

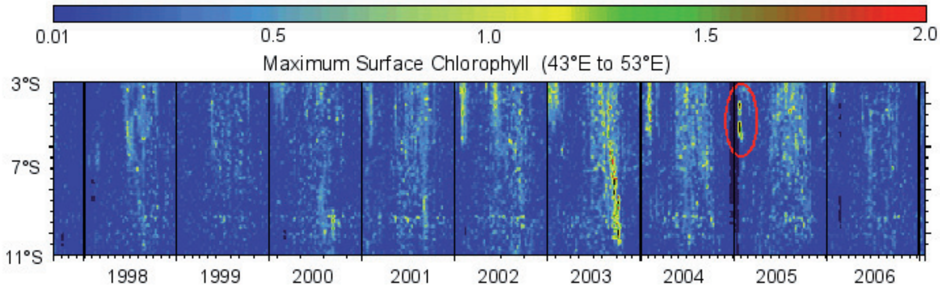

Fig. 9. Hovmoller plot of the maximum surface chlorophyll values recorded from SeaWiFS data from January 1998 to May 2006 showing the abnormal signature of the extreme event (red circle).

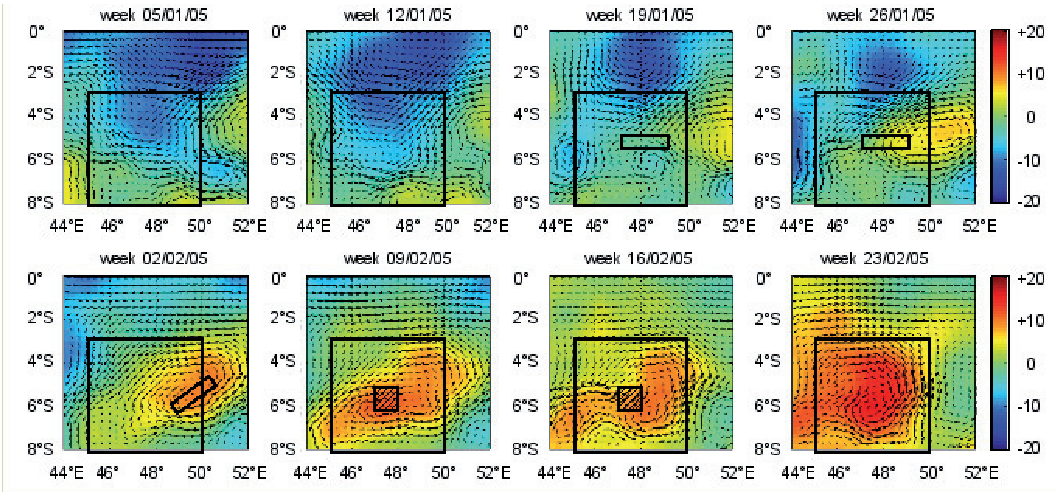

Fig. 10. Overlays of sea level anomaly (cm) maps from January 5, 2005 to February 23, 2005 and vector plots of surface velocity (cm s^{-1}). Solid rectangles correspond to the bloom areas and hatched rectangles indicate the fishing area.

One major question about such a concentration is whether its localization was linked to a feeding concentration (tunas targeting concentrated prey), or a particularly favourable environmental situation for spawning. As the event took place some weeks after and very physically close to a major phytoplankton bloom, it can be hypothesized that the tunas were feeding on prey generated by this particular environmental event.

The area covered by the bloom was approximately 4000 km^2, its longitudinal extent 300 km and maximum chlorophyll concentration 50 mg m^{-3}. Assuming an average depth of 20 m and a C/Chl*a* ratio of 50, the corresponding biomass can be estimated as at least 20 000 t of phytoplankton. Indeed, mesoscale hydrographic structures, such as eddies are considered to favour the formation of biological hotspots (Palacios et al. 2006). Because of the lack of SeaWiFS data due to clouds, we cannot determine the origin of the bloom. However, the mesoscale warm eddy can explain the temporal evolution of the phytoplankton bloom in time and space. We showed that the bloom was located at the edge of an anticyclonic eddy, known to accumulate biomass at the edge, and to enhance primary production and stimulate phytoplankton growth in the surface layers (Lima et al. 2002). There is a high probability that the persistence of this physical structure over several weeks could have allowed the maturation of the system, from primary production to top predators, thus producing a large local concentration of food available to tunas. The delay of about 2 to 3 weeks between the phytoplankton bloom and the tuna concentration appears to be a suitable time lag that would allow a tuna concentration to develop (Stretta 1991), and such a concentration of potential prey probably explains a subsequent feeding concentration of tunas in the area. The potential fauna feeding in association with such a bloom has not been identified. However, based on previous observation of such events, it can be hypothesized that after a duration of three weeks, the phytoplankton bloom observed on January 26 produced a large biomass of zooplankton at this spot, attracting in turn a large biomass of small pelagic fishes to the area (e.g. the genera *Engraulis, Cubiceps* or *Decapterus*). Such fishes are commonly a food source for tuna concentrations as they are ideal prey, even at small sizes, for large yellowfin (Potier et al. 2007). A shallow feeding concentration such as this may also be linked with the local abundance of squids or crustaceans (for instance on *Natosquilla*), but this hypothesis cannot be verified and is probably unlikely (Romanov pers. comm.). The incidence of high catches agrees well with the presence of a bloom created by a cyclonic-anticyclonic eddy-eddy interaction that optimised enrichment and concentration processes

(Bakun 2006). It seems that this association was then able to maintain favourable concentration conditions at the boundary of an active anticyclonic eddy during the whole fishing period (Fig. 10), to locally create and maintain a tuna aggregation.

However, these large yellowfin were probably also in spawning condition, as this area is typically favourable for yellowfin spawning. The literature devoted to this topic (Timochina and Romanov 1991; Karpinski and Hallier 1988; Hassani and Stéquert 1991; Stéquert et al. 2001) indicated that this fishing area around the Seychelles was a major spawning area for yellowfin during the 1st quarter, and a majority of these fishes taken in the region showed a high gonad index. It can therefore be hypothesized that this event, located in an area suitable for yellowfin spawning (with SST in a range between 26 and 30 °C), was related to the concentration of adult yellowfin for spawning. This hypothesis could be supported by the fact that large yellowfin in reproductive stages tend to be highly vulnerable to purse seine fisheries, because of their shallow schooling behaviour during spawning.

Unfortunately, no biological samples were taken on the gonads or stomachs of these yellowfin, so this question remains unanswered.

5.2 Search pattern of purse seiners exploiting the concentration and behaviour of tuna schools

Several skippers were informed of this highly visible environmental anomaly well before the period of the event, but it is difficult to associate the discovery of the concentration with the circulation of this satellite information among the skippers. One of the striking observations made concerning the exploitation of this tuna concentration is that during the 9 best days of the exploitation (days with highest catches), only a very small area was explored and fished by the fleet. On such typical days of high catches, for instance during the February 18 to 20 period, a great majority of the catches were taken from a very small geographical area (a circle with a radius of about 10 nautical miles, February 18, Figs. 4 and 11). Furthermore, the VMS data available on the French fleet indicates that most of its searching pattern was highly concentrated in this small area were most of the catches were taken, and very little outside of this main fishing zone. Each modern purse seiner prospects at a speed of about 13 knots, with an approximate sonar observation range of about 2.5 miles, a visual range of more than 3 miles using binoculars, and at least a 10 mile radius on its bird radar (birds are associated with most tuna schools fished in the Indian Ocean (from unpublished observer data collected on board EU purse seiners and from the ESTHER programme report, Gaertner and Pallares 2001; Gaertner et al. 2002). This would mean that the core of the main fishing zone was constantly repeatedly observed each day by each of the 32 vessels active in the area. In other words, during such extreme conditions of a very small spot fished by many vessels, it is likely that when a tuna school was visible at the surface (for instance a breezer), this school should have been identified simultaneously by a large number of vessels (Fig. 11). Under such conditions, the logical conclusion is that the 76 schools and 8574 t of tunas caught during these 3 days were most of the time, either scattered, swimming too fast or in subsurface waters, and

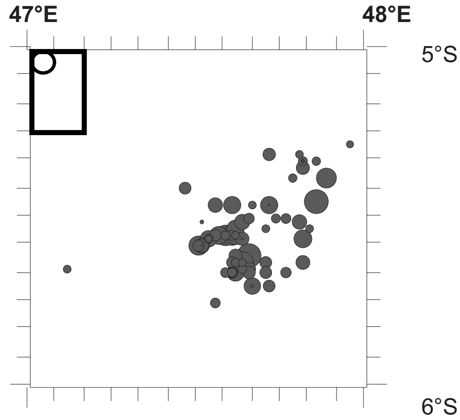

Fig. 11. Observation radius by the long range sonar (at a distance of 2.5 nautical mile, circle) and area sampled each day by the sonar of each vessel over a searching duration of 12 h (square), and the exact positions of catches taken by the 30 purse seiners active in the area over the February 18 to 20 period.

not constantly visible or available *de facto* to the fishery. In log book comments during the second half of the event, various skippers blamed their difficulties in achieving successful sets on the great abundance of medium sized yellowfin (10 to 25 kg) from February 14 onwards. Yellowfin of this size class are often classified by skippers as "*chicaneurs*" (a suitable translation could be "evasive" or "elusive" tunas), i.e. fishes that are most often highly mobile, scattered and therefore difficult to catch. It appears that in many cases, extremely large biomasses of this category of fish can lead to a low number of sets and high percentage that are unsuccessful. There was a very high day to day variability in the local CPUEs, for instance reduced catches on February 16 to 17 (Fig. 4). Unfortunately, there were no scientific observers at sea during this concentration, to observe and report upon these potential peculiarities and changes in tuna behaviour. The conclusion remains that in such exceptional fishing conditions, with very high local effort and fish density, the daily CPUEs of the fleet were probably affected not so much by the total biomass and number of schools in the area, but much more by (a) the behaviour of these schools and (b) the local competition between fishing vessels to locate and catch them.

5.3 Biomass trend during the fishing event

The local daily CPUE of the fleet is available for all the yellowfin catches (Fig. 6a) and size categories (Fig. 6b), but it remains unclear how much these CPUEs are representative of the exploited local biomass.

The total yellowfin CPUE trend observed during the period February 5 to 20 (Fig. 6a), with CPUE fluctuating at a high level but no trend, probably masks a significant variability in the exploited biomass. There was probably an increasing tuna biomass between February 5 and 8, before the event, followed by a period of declining local biomass during the main fishing period of the event (simply due to the large amount of daily catches). However, this potential decline remains widely masked in the trend of the overall CPUE. Furthermore, the day

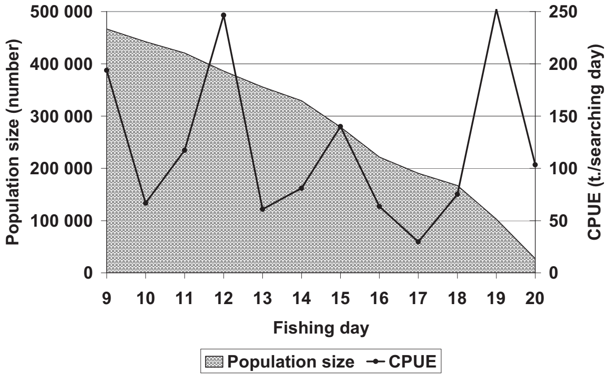

Fig. 12. Observed daily CPUE of yellowfin (expressed in tons per 13 searching hours, the equivalent of a full searching day) during the fishing event, and potential level and trend of the underlying population assuming a fully exploited local biomass.

to day changes in the size distribution of the yellowfin caught strongly indicate that after the initial period (February 9 to 13), during which only very large fishes over 100 cm were caught, there was local recruitment of a significant number of medium size fishes (Figs. 3a and 6b).

The sudden end of the event on February 21 could hypothetically be due to the extinction of the local population, possibly because of its full exploitation by the fishery. If this were the case, the initial local biomass of yellowfin would have consisted of approximately 420 000 fishes (18 000 t) that was then entirely fished out by the purse seiners over the 12 days of the event. Following this hypothesis of a fully exploited and closed population (no input or output of fish during the entire event), and assuming that there was no survivors at the end of the 12th day, the daily decline of the local biomass and daily exploitation rates of this population can easily be estimated from the known daily catches. Such a potential trend of the estimated biomass is shown in Figure 12 (the same figure also shows the observed daily CPUEs). This figure tends to show a divergence between a fairly stable CPUE during this period and a steadily declining local biomass. This lack of coherence between CPUE and biomass trend could easily be explained by the hypothesis that levels of daily CPUE may be more greatly affected by tuna school behaviour than by local biomass.

However, the alternative hypothesis, that the end of the event on February 21 was due to a rapid dispersion of the survivors, cannot be ruled out. In this case the stable CPUE trend could be more representative of local biomass.

It is also interesting to look at the relationship between these minimal estimated local biomasses and the total estimated biomass of the yellowfin spawning stock in the Indian Ocean estimated by the IOTC. Although these estimates are still provisional, based on the most recent IOTC results, the recent spawning stock of yellowfin was estimated at levels close to 500 000 t (IOTC 2005). If this result is accurate, it would mean that at least 3.4% of the entire Indian Ocean yellowfin stock would have been concentrated and heavily fished in a single 1° square during the event (while the habitat of this stock is distributed over an area more than 2000 times larger).

Furthermore, in 2005 purse seiners caught an estimated 41% of the total catches of adult yellowfin of sizes over 90 cm (IOTC catch-at-size data), and 15.8% of these catches were made during the event. As a consequence, it can be estimated that about 6.5% of the 2005 total catches of adult yellowfin in the entire Indian Ocean were caught during the event, and correspondingly that the purse seine fleet brought about 6.5% of the total fishing mortality exerted on the entire Indian Ocean adult stock in 2005 during the event.

5.4 Fishing concentration and changes in the dynamics of the exploited stocks

These spectacular and ephemeral fishing hot-spots are very interesting for scientists as well as fishers, although they have seldom been studied and analysed by scientists. Analyses of these detailed fishery data can help us to better understand the biological, behavioural and environmental processes that create such tuna concentrations. Furthermore, the interaction between tuna concentrations and the fishing effort exerted by the purse seine fishery is also of great interest. As an example, there is evidence that the early purse seine fishery active in the area at the start of the 1980s would have caught much lower quantities of yellowfin during the event. This lower expectation of historical catches would have been due to various simple additive causes such as:

- This excellent fishing area was clearly identified by satellite imagery well before the event. Such information from satellites (SST, phytoplankton and altimetry) is now routinely received by most purse seiners and allows a more efficient identification of these small time and area strata, but was not available 20 years ago.
- The lower fishing efficiency of the old purse seiners: sets over 100 t were very difficult to handle and seldom observed, while during this event, 64% of the total catches were taken on sets larger than 100 t. Furthermore, during the early 1980s, the freezing capacity of the purse seiners was not sufficient for many vessels to freeze such large catches.
- The lower average capacity of each purse seiner (average capacity was at about 1200 m^3 during the mid 1980s, but over 1800 m^3 today): each vessel can exploit the same fish concentration during a much longer period of time before reaching capacity
- The increased efficiency in handling large quantities of tunas: for all the sets observed during the present event (the duration of these sets corresponded to 39% of the fishing duration). This decrease in setting times since the early eighties (1985) can be estimated (based on observer data, EU observer database) at a level of 35%. Such a reduction in setting duration, corresponds to an equivalent increase in the potential searching time of the fleet during the event.
- The new long range sonars installed in all purse seiners in recent years now allow deep concentrations of tunas to be identified at a distance of about 4 km and for them to be followed until they can be caught, even when no fishes are visible at the surface. This type of sonar is probably very important: first to identify such concentrations of tunas that are seldom visible at the surface, and later to stay in permanent contact with this deep mobile biomass of tunas.

As a result, it appears that modern purse seine fleets fishing in the Indian Ocean have developed several technological characteristics during recent years that markedly increase their fishing power, allowing them to efficiently locate and exploit large tuna concentrations, even when these are located in very small spatiotemporal strata. The increases in fishing efficiency are probably maximal during these periods when large biomasses of tunas are concentrated in small areas and exploited by a large number of purse seiners.

5.5 How can the evaluation of tuna concentrations be improved?

Recommendations that could be made to improve the understanding of these tuna concentrations and their active exploitation by purse seiners include the need for the observers, who are routinely placed onboard purse seiners, to make a wide set of ad hoc observations on the behaviour of the fleet and the tunas, allowing a better understanding of the fine scale dynamics of the events. There is also a the need for port samplers to identify, in real time, such potential large scale tuna concentrations exploited by purse seiners; and when such events are identified, to obtain all potential information on the event from the skippers and their fishers, and to sample the gonad index and the stomach contents of these tunas. On a wider scale, it would also be very interesting to identify and to analyse the occurrence and exploitation patterns of all major tuna concentrations over the history of the Indian Ocean purse seine fishery (from 1983 until the present). The ad hoc software by Ravier et al. (2000) allows all such exploited concentrations to be automatically identified in log book data, and this software could be made available for such a purpose.

6 Conclusion

The present event appears to be among the most spectacular and important in the history of world purse seine fisheries, and it can be considered that such a tuna concentration was the ideal tuna concentration constantly sought by all tuna purse seiners. Our detailed and exhaustive fishery data used to analyse this event are also quite unique, both in their quality and volume. The detailed analysis of this data set provides the first in depth understanding of such a major event. This type of analysis is clearly very important in order to properly understand the behaviour and exploitation patterns of these tuna concentrations, which unfortunately cannot be done on the 1° monthly IOTC data. This is illustrated by the fact that in the IOTC database this event is summarised by 2 figures: the monthly total catch of 17 781 t taken in a given square during February 2005 and the 267 fishing days.

The highly detailed data available allowed us to make a quite comprehensive analysis of the event on a daily basis. Though probably linked to a major local environmental anomaly, the precise causes of the event remain undefined: the involvement of food or the potential spawning activity of the tunas fished. However, the analysis of this event widely confirms the importance of such fishing events for the purse seine fleet, for instance 15.8% of the total yearly fishing mortality of Indian Ocean adult yellowfin by purse seiners was exerted during this event. Analyzing the dynamics of this small scale event has confirmed that the large fleet of efficient purse seiners presently active in the Indian Ocean were capable of exerting a high exploitation rate on this type of tuna concentration, and significantly increased the fishing mortality exerted on tuna stocks as a whole. Such mesoscale fishery events have frequently occurred in the world's oceans in the past, but remained unnoticed by scientists, partly due to the lower catches but mainly to a lack of ad hoc scientific analysis of these events. Our detailed analysis also provides a confirmation of the paradox that daily CPUEs of purse seiners can often be null, even when they are exploiting a very large tuna biomass located in a very small area. As the role of these small scale tuna concentrations exploited by modern purse seine fleets is probably increasing in the overall exploitation of tuna stocks, it would be worthwhile to further study these events over the history of the Indian Ocean purse seine fisheries. However, such analyses have to be based on the most detailed fishery data and involve international cooperation between scientists, since they cannot be performed on the IOTC data. Forthcoming increases in the purse seine fishing efficiency, through their improved exploitation of these tuna concentrations, should also be more precisely estimated and incorporated into future assessment models.

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