The use of artificial fish aggregating devices by the French tropical tuna purse seine fleet: Historical perspective and current practice in the Indian Ocean

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Abstract. Recent resolutions of the Indian Ocean Tuna Commission (IOTC) have been implemented to improve scientific knowledge on the effects of drifting fish aggregating devices (DFADs) through increased data collection and reporting. Here, we report information on DFADs collected from three distinct data sources to describe the use of DFADs and buoys by the French PS fleet of the Indian Ocean over the last decade. First, archives of buoy purchase orders during 2002-2014 were provided by fishing companies to give insight into the historical use of DFADs. Data show an homogeneity of the numbers of buoys available to each purse seiner and a steady increase of about 10 buoys per year per vessel, from 50-60 in the early 2000s to 200 in 2013. Second, information derived from satellite transmission data was made available for the period 2010-2013 based on quarterly reports that are produced by buoy supplier companies on a vessel basis. Data show an overall relative stability of the number of French buoys having been used to monitor floating objects (FOBs) during 2010-2013. Each French purse seiner operating in the IO has been monitoring a mean number of 90 FOBs (predominated by DFADs) on a quarterly basis during 2010-2013, with some variability between vessels and seasons. The total number of FOBs monitored for the French component of the European PS fleet would be around 1,200 in the recent years. Third, an extended version of the PS logbooks has been implemented since January 2013 to include information on DFADs and associated buoys. Although incomplete for some vessels, data collection has been improving over time and several skippers now report a large amount of information on DFADs on an operation basis. This information appears complementary to the two other sources of aggregated data and allows identifying the areas of DFAD deployments for instance.

Keywords: bigeye, FAD, skipjack, yellowfin

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"A l'heure où l'on assiste à la raréfaction des bancs d'albacores en Atlantique, il serait intéressant de développer un réseau d'épaves artificielles que l'on pourrait, soit mouiller sur des hauts fonds, soit laisser à la dérive; dans ce cas les épaves devraient être équipées d'une balise ARGOS permettant un repérage aisé"

JM Stretta & M Slepoukha, ORSTOM (1986)

1. Introduction

Drifting fish aggregating devices (DFADs) constitute a major component of the effort of tropical tuna purse seine (PS) fisheries worldwide (Ariz et al. 1999, Bromhead et al. 2003, Dagorn et al. 2013). The use of DFADs has steadily increased since the mid-1990s and they substantially contribute to the overall PS fleet fishing capacity (Fonteneau et al. 2013). To date, few information is available on the total number of DFADs deployed by PS tuna fisheries despite the concerns raised by their use (Baske et al. 2012, Fonteneau et al. 2013, Davies et al. 2014). In particular, DFADs have resulted in increasing pressure on juveniles of yellowfin (*Thunnus albacares*) and bigeye (*Thunnus obesus*) over the last decades, which has resulted in the implementation of time-area closures to reduce their impact worldwide (Harley & Suter 2007, Torres-Irineo et al. 2011, Davies et al. 2012). In addition, DFAD-fishing results in the bycatch of several marine species (Amandè et al. 2010, 2012, Hall & Roman 2013, Torres-Irineo et al. 2014), including some emblematic species such as sharks (Filmalter et al. 2013) and turtles (Bourjea et al. 2014). Finally, several studies have pointed out some evidence of negative effects of DFADs on tuna condition, growth, and movements (Hallier & Gaertner 2008, Jaquemet et al. 2011, Wang et al. 2012, 2014). The effects of DFADs on the biology and ecology of tropical tunas and other marine species exhibiting associative behaviour with drifting objects remain however poorly understood and should be further investigated (Fonteneau et al. 2013, Anonymous 2014, Robert et al. 2014).

Recently, the Indian Ocean Tuna Commission (IOTC) expressed the need for improving scientific knowledge on the effects of DFADs through resolutions that mainly focus on increased data collection and reporting. In particular, the IOTC resolution 13/03 specifies that the total number of DFADs should be reported on a fishing trip basis and that activities related to DFADs should be collected at the operation scale, including event, position, and date. In addition, Annex I of the IOTC Resolution 13/08 gave guidelines for the preparation of DFAD management plans, i.e. which data should be collected on the activities related to DFADs and buoys through DFAD logbooks. Such data also include information on DFAD design in conjunction with resolution 12/04 that deals with the reduction of entanglement of turtles, sharks, and other marine species in DFADs. To address new data requirements that should be made available to the Commission from January 2015, France, Spain and Seychelles developed DFAD management plans following the IOTC guidelines. It is noteworthy that the collection of operational data on DFADs started in 2011 for the Spanish PS fleet through close collaboration with the fishing industry (Delgado de Molina et al. 2013). Also, logbooks of Spanish support vessels implemented at the end of 2004 in the Indian Ocean following the IOTC resolution 01/05 have revealed useful to describe their activities (Sarralde et al. 2007, Ramos et al. 2010).

In the present analysis, three data sources were used to describe the use of DFADs and buoys by the French PS fleet of the Indian Ocean over the last decade. First, archives of buoy purchase orders during 2002-2014 were provided by fishing companies so as to give insight into the historical use of DFADs. No information prior to 2002 could be retrieved as the systematic planning of buoys orders by French fishing companies started in the early 2000s, following the major technological improvements in the systems of buoy positioning and emitting security access through encrypted keys aimed at restricting buoy ownship. Second, information derived from satellite transmission data was made available for the period 2010-2013 based on quarterly reports that are produced by buoy supplier companies on a vessel basis. Third, activities related to DFAD and buoys have been included into PS logbooks since 2013. As the process of data collection just started, some variability in reporting between skippers is expected as well as some progressive improvement in data quality. The analysis of this dataset is then preliminary but information is available on an operational and spatialized basis and therefore complements the other data sources.

Considering that buoys and DFADs are intricate components of the PS effort, the main objectives of the present paper were to: (i) evaluate the changes in number of buoys available to each French PS during the last decade to gain insight into the rate of increase for this component of PS fishing power, (ii) analyse the relationships between the standing stock of DFADs that are actively monitored by the French PS fleet and the dynamics of buoy activation/deactivation, and finally (iii) give an overall estimation of the number of DFADs at-sea that are equipped with French buoys.

2. Materials and Methods

Hereafter, the terms DFAD and LOG are used for artificial (i.e. man-made rafts in bamboo and metal pipes) and natural (e.g. log, palm branch) objects floating at the surface of the ocean, respectively. The term FOB (standing for floating object) is used when referring to both DFADs and LOGs.

2.1. Historical buoy orders from 2002

Information on buoy orders was provided to IRD by the French fishing companies SAUPIQUET and CFTO (ex-CMB) for the periods 2004-2013 and 2002-2014, respectively. Data available on a vessel basis cover the Atlantic and Indian oceans and include information for both purse seiners and support vessels (**Table 1**). For CFTO, buoy deliveries were made by batches about 3-4 times a year. Buoys delivered in December were considered to be used in the subsequent year. Information on positioning system (i.e. HF-GPS or GPS) was available for CFTO for each buoy batch while it was indicated qualitatively for SAUPIQUET for each ocean and year.

Table 1. Description of datasets on buoy orders by French fishing companies

Company	SAUPIQUET	CFTO
Period covered	2004-2013	2002-2013
Temporal resolution	Annual	~ Quarter
Vessel coverage	IO: 100% AO: 100%	IO: 35% in 2002 IO: 100% in 2003-2014 AO: 10-14% in 2002-2004 AO: 100%
Information on positioning system	Yes (qualitative)	Yes (quantitative)
Information on buoy model	No	Yes

We used linear regession models to test for the effects of year (*Y*), fishing company (*C*) and vessel (*V*) on the number of buoys available (*B*) onboard. The assumptions of homoscedasticity and Gaussian error were checked through the residuals. Some variability in the number of buoys available could be due to some vessels that did not operate year round in a given ocean. To address this issue, a simple linear regression model was fitted to the median value of the number of buoys as a function of year.

2.2. Quarterly reports of buoy activation/deactivation from 2010

To address the IOTC Resolution 10/02 that made mandatory the provision of data on the total number and type of DFADs set by support vessels and purse seiners per quarter, French fishing companies developed the production of automatic data reports through the companies in charge of the satellite transmission of the information collected by the buoys (mainly GPS position, echo-sounder). The reports are made on a quarterly basis for each purse seiner, support vessel and groups of vessels that share a common pool of buoys. They include: (i) the number of "active" buoys at the beginning and end of the quarter, (ii) the number of buoys activated and deactivated, and (iii) the number of buoys having emitted and not emitted during the quarter. Buoys are considered as "active" when they are assigned to a specific vessel from the central transmission server, i.e. buoys can be at sea, stored on board or on land (e.g. from a fishing port). The data cover the period 2010-2013 and are available for 25 purse seiners and 2 supply vessels, these latter having been only active in the Atlantic Ocean. The information provided by the automatic quarterly reports does not allow distinguishing between DFADs and LOGs.

The number of active buoys gives a conservative (i.e. maximum) value of the number of FOBs that are monitored by each vessel at a given moment, i.e. start/end of the quarter. The number of buoys having emitted during a quarter better reflects the number of FOBs monitored, especially if the dynamics of buoy use through DFAD deployment, buoy transfer and buoy end of transmission occur within a quarter. Moreover, some of the active buoys might not emit data during the quarter beacause they have not been deployed on a FOB (still onboard) or because they have been stolen or have sunk. Fishing skippers generally consider that it takes from a few to several weeks for a DFAD to attract tunas and other marine fishes (Moreno et al. 2007) and GPS buoy data indicate that time-at-sea for many buoys can be <90 days (Maufroy et al. submitted). Hence, the number of active buoys available at the start/end of a quarter might underestimate the number of buoys used and eventually result in underestimates of the numbers of FOBs monitored. In complement, the numbers of buoys activated and deactivated by quarter give an indication of the turn-over of the buoy standing stock and associated DFADs, including new buoys that were deployed (through transfer and DFAD deployment) and the ones that were beached on the coast, sank, were stolen, etc. Simple linear regression models were used to test the effects of year and quarter on the numbers of active buoys, buoys having emitted and buoys having been activated/deactivated.

2.3. Logbooks extension from 2013

Logbooks of CFTO and SAUPIQUET purse seiners and support vessel were extended from January 2013 to include activities related to the use of DFADs and buoys. The third French tuna fishing company SAPMER implemented the extended version of the logbook in October 2013. The DFAD module includes information on the activity, i.e. deployment, transfer, visit with/without fishing, retrieval, and end/loss of transmission. DFAD type, (i.e. natural or artificial), buoy type (e.g. D+), and buoy number can also be recorded in the logbook. No information on the DFAD design is available in the current French PS logbook. Here, we first report data information on DFADs recovered from the 'raw' logbooks of 8 purse seiners in 2013 that conducted 57 fishing trips between the 4th of January 2013 and 14th of February 2014. In addition, we describe logbook information on DFAD activies for the 13 French purse seiners as collected during the first semester 2014 and managed with the extended version of the AVDTH datbase software (Le Chauve 1999, Cauquil 2014). As the duration of the fishing trips (i.e. time at-sea between departure and arrival at port for unloading) greatly varies within and among vessels, the numbers of activities related to

DFADs reported in 2014 were standardised relative to 30 days at-sea. Seasonal maps of spatial patterns in DFAD deployments were made based on the seasons defined by (Maufroy et al. 2014) for the period 2007-2013 from the GPS buoy positions.

3. Results

3.1. Historical changes in buoy availability

The number of buoys available by French purse seiner increased by an average rate of about 10 y^{-1} over the last decade in the Indian Ocean. Almost all variability in the linear model was explained by the year effect (98%). The median number of buoys significantly increased from 60 in 2002 to 200 in 2014 (adjusted Pearson's r = 0.88, slope = 10.7, p-value < 0.001) (**Fig. 1**).

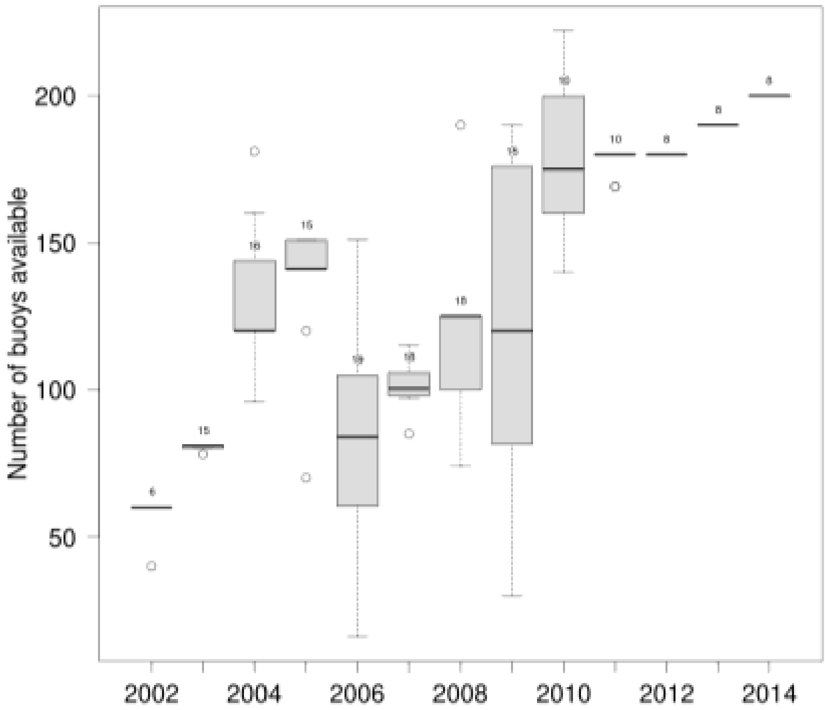


Fig. 1 Annual number of buoys available by French purse seiner during 2002-2014. Numbers indicate the number of vessels for which data were available

French fishing companies provided similar annual numbers of buoys to their purse seiners in activity in the Indian Ocean. The linear regression model showed that there was no significant difference between companies (*p*-value = 0.3). Within each fishing company, the number of buoys was evenly distributed between vessels, i.e. there was equitability between skippers despite expected differences in experience and skills and vessel's performances. The annual number of buoys supplied to each vessel has been identical for all purse seiners since 2010, with a maximum of 200 buoys available in 2014.

3.2. Technological changes

The system used for positioning buoys at-sea by the French purse seiners in the Indian Ocean changed from a combination of HF radio and GPS to a single GPS system in 2007-2008 (**Fig. 2**). The switch occurred quickly and concerned both fishing companies and all vessels simultaneously, suggesting a good efficiency of the new system that was fully in place from 2009. The decrease observed in the median number of buoys available from 120-140 during 2004-2005 to 84 in 2006 (**Fig. 1**) did not appear to be linked to the change in positioning system which occurred 1 year later and could have resulted in increased buoy unit prices.

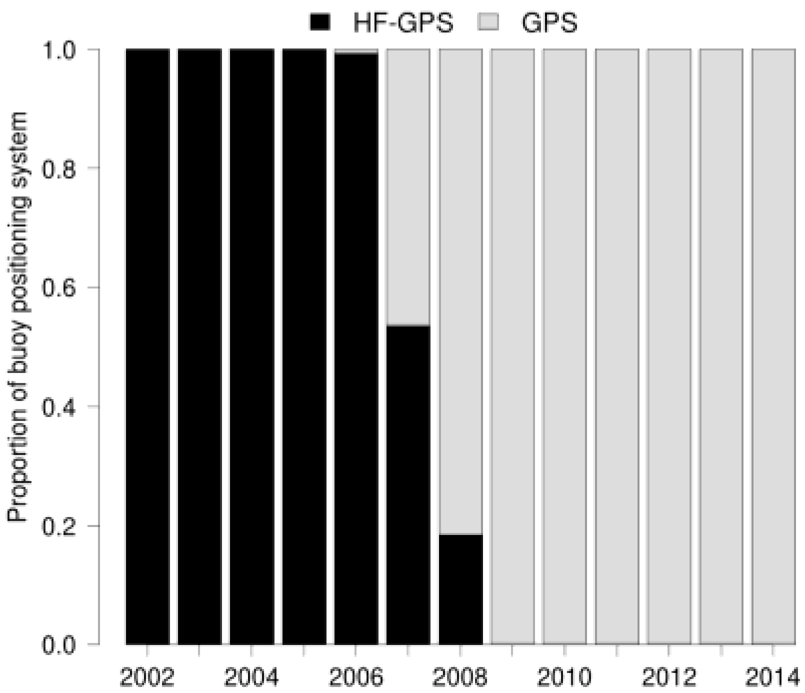


Fig. 2 Proportion of buoys by type of positioning system for the CFTO purse seiners during 2002-2014

Buoy models have evolved through constant technical innovations over the last decade. Models used by French fishing companies have been changed on average every 2 years during 2002-2014, with 1 model generally predominating each year (**Fig. 3**). Overall and despite progressive technical changes, French fishing companies have been generally relying on one main buoy supplier company and their current buoy model. Echosounder buoys have started to be used by the French fleet since 2011.

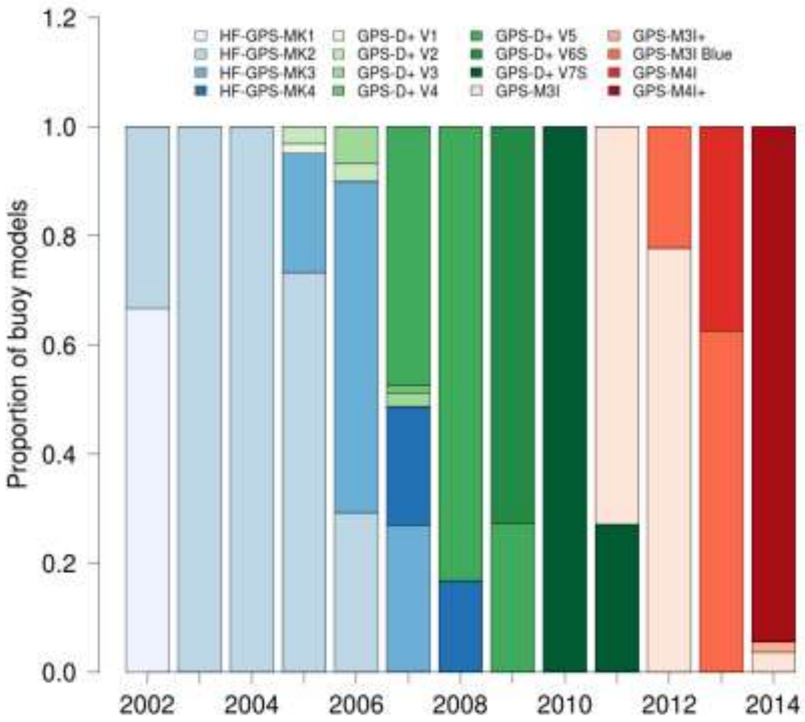


Fig. 3. Proportion of buoys by model for a French fishing company during 2002-2014

3.3. Standing stock and turn-over in buoys

The number of buoys active at the start of the quarter by French purse seiner showed some significant interannual variability during 2010-2013 without any trend (**Fig. 4**). No significant seasonal pattern was observed in the data and quarterly changes were smooth over the period considered, i.e. no abrupt change was observed with the notable exception of a strong decrease in the first quarter of 2013 that might be due to a technical problem in GPS emission for some buoys. The mean number of active buoys by vessel varied between a minimum of 62 in January 2013 to a maximum of 118 in April 2012. Small numbers of active buoys (<40) generally corresponded to the initial stock of buoys for new purse seiners arriving in the fishery.

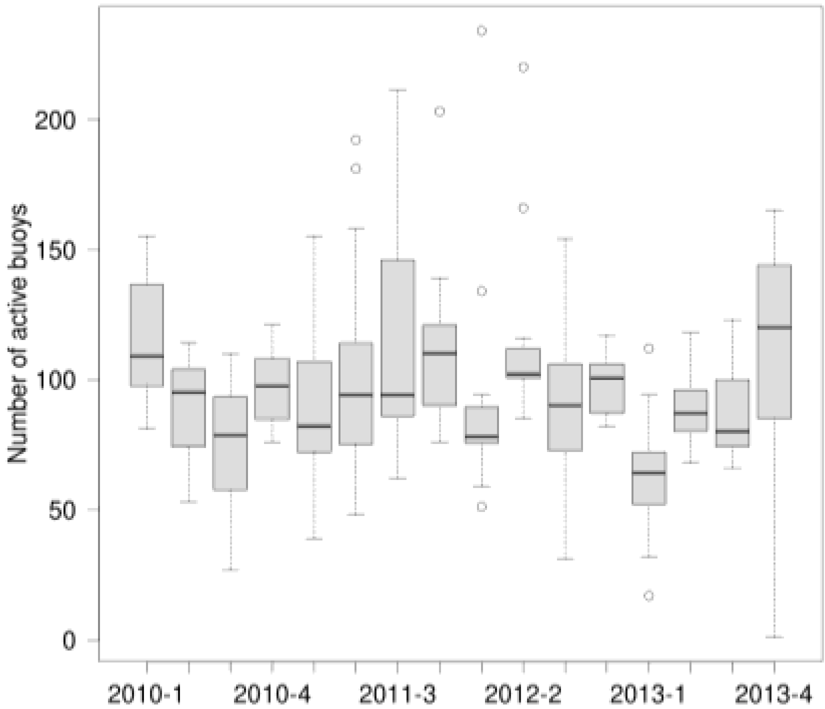


Fig. 4. Number of active buoys at the start of the quarter by French purse seiner in the Indian Ocean during 2010-2013

The total number of active buoys for the French PS fleet of the Indian Ocean at the start of quarter varied between about 800 and 1500 during 2010-2014. The maximum value of 1,530 active buoys observed in the Oct-Dec 2013 was very close to the values observed in the third and fourth quarters of 2011 (**Fig. 5a**). The number of active buoys on the 1st of January 2014 was 1,150. The magnitude of the total number of buoys having emitted during a quarter appeared similar to the number of active buoys at the start of the quarter (**Fig. 5b**). The total number of buoys having emitted by quarter significantly varied between years, with more buoys used in 2011 and 2013 than in 2010 and 2012. The total number of buoys having emitted, giving a maximum level for the number of FOBs (including DFADs) monitored at-sea, varied between a minimum of 669 in March-May 2010 to a maximum of 1,552 during Jul-Sep 2011. The use of DFADs was found to vary with the season during 2010-2013. The number of buoys having emitted by vessel was significantly higher during July-September every year (*p*-value <0.01), corresponding to the main period of DFAD-fishing off the coasts of Somalia (**Fig. 6**).

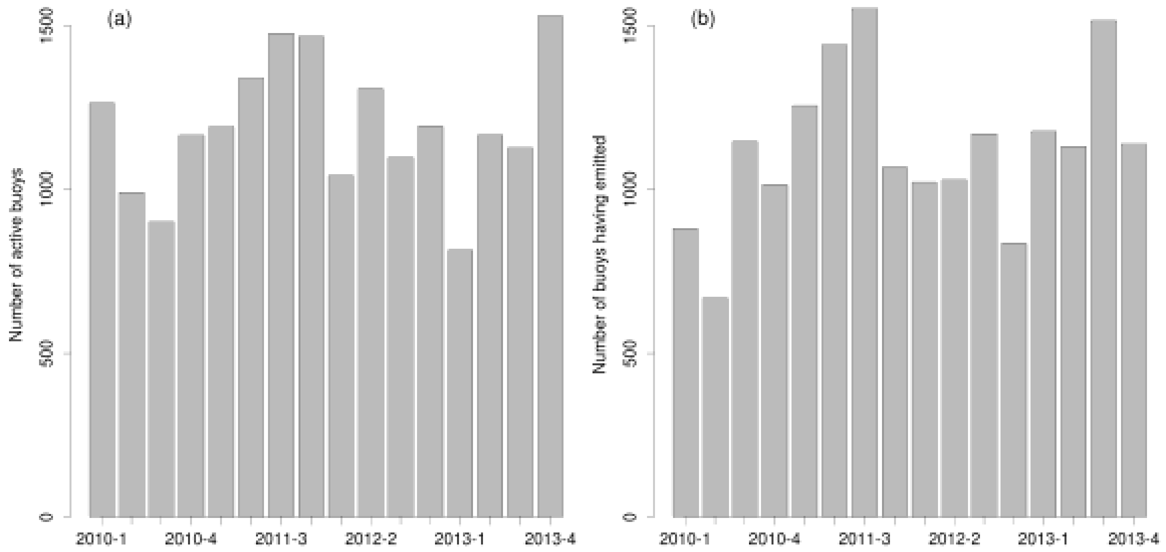


Fig. 5 (a) Total number of active buoys at the start of the quarter and (b) total number of buoys having emitted during the quarter in the French PS fleet during 2010-2013

The median number of buoys having emitted by purse seiner varied between a minimum of 53 in Apr-Jun 2010 to a maximum of 116-118 during the third quarters of the years 2011 and 2013. The overall mean number of buoys by French purse seiner used (i.e. having emitted) by quarter during 2010-2013 was 89 (SD = 30).

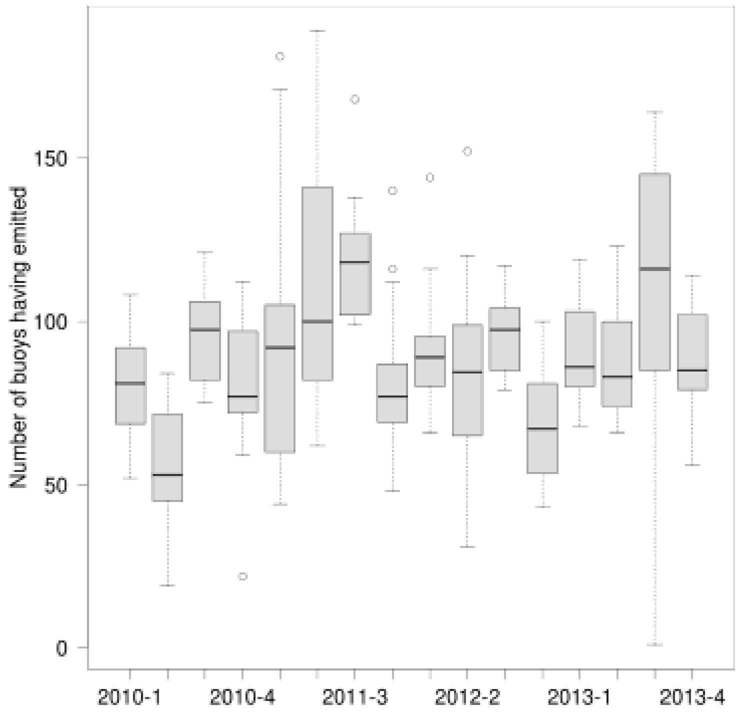


Fig. 6. Number of buoys having emitted during the quarter by French purse seiner in the Indian Ocean during 2010-2013

While the numbers of buoys active and having emitted appeared rather stable over years during 2010-2014, the total numbers of activations and deactivations of buoys showed strong increases during that period (**Fig. 7**). The median number of buoys by vessel that were activated during a quarter was found to significantly increase over time, from less than 30 in 2010 to about 80 in 2013 (Adjusted Pearson's r = 0.8, p-value <0.001, slope = +4 quarter^{-1}). Meanwhile, the median number of deactivations significantly increased in the same order of magnitude (Adjusted Pearson's r = 0.81, *p*-value <0.001, slope = +4.2 quarter^{-1}), resulting in the overall additions and removals of buoys to cancel out. Differences between the quarterly numbers of activations and deactivations at the scale of the fleet varied between -380 (Oct-Dec 2012) and +400 (Jul-Sep 2013).

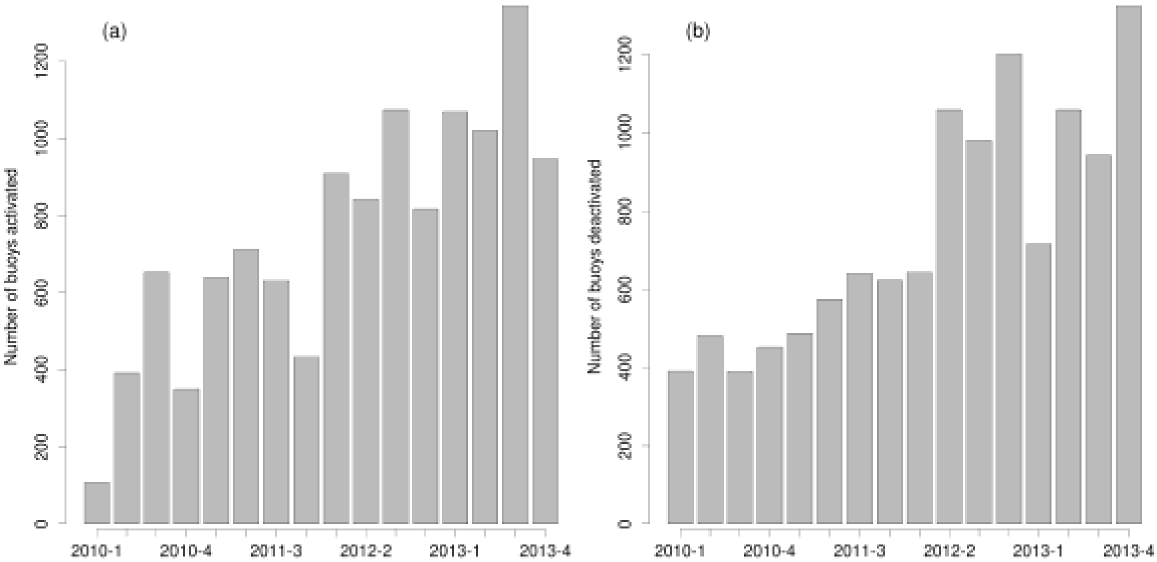


Fig. 7. Total quarterly number of buoys (a) activated and (b) deactivated in the French PS fleet during 2010-2013

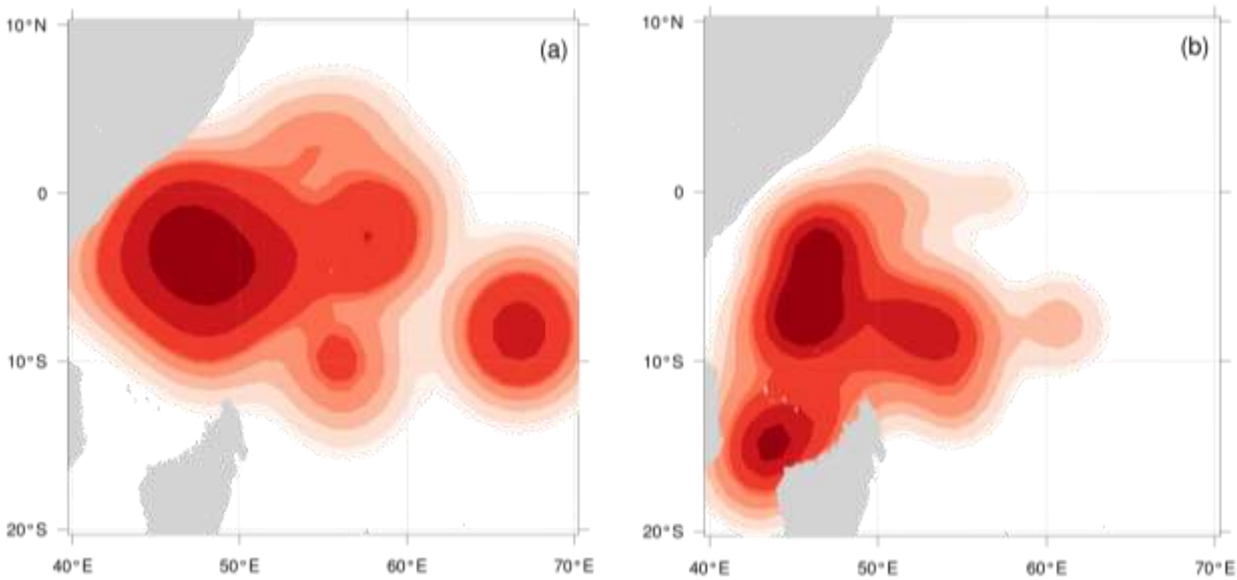
3.4. Collection of data through extended logbooks

Some French skippers provided a large amount of data on DFAD activities conducted in 2013 with detailed comments in the extended logbooks while others reported very few information. About 2,000 activities related to DFADs were reported in the logbooks as additional information relative to previous years: 621 buoy transfers, 563 DFADs deployments, 373 ends of GPS transmission, 60 retrievals of rafts from the water, 207 visits of DFADs with fishing, and 169 visits without fishing. The amount of information collected on DFAD activities varied between vessels and periods. The total number of activities varied between about 500 for 2 vessels while 1 vessel only reported 38 activities on DFADs for the whole year. Information on buoy transfers and DFAD deployments was the most reported and skippers generally provided the buoy type and identification number. Only 3 vessels reported some ends of GPS transmission. Visits of DFADs at-sea followed by a fishing set were also poorly reported because they were considered to be already included in the classical logbook. Visits of DFADs without fishing were recorded but appeared underestimated as compared to fisheries observer data. Maximum values of 55-56 visits without fishing was reported for the whole year for 2 vessels while observer data generally report more frequent visits by fishing trip (e.g. up to 56 visits in 7 weeks), with some large variability between seasons (IRD unpublished observer data). The rates of deployments and transfers relative to time-at-sea could not be computed from the 2013 dataset as only information on DFADs was recovered from the original logbooks.

More than 2,500 activities related to DFADs (including buoys) were reported in the extended version of French PS logbooks during the first semester of 2014. The number of DFADs deployed per month at sea was found to vary between a minimum of less than 1 and a maximum of 15. Similarly, the range in the numbers of buoys transferred per month at-sea was very large, with a minimum of 1 and a maximum of 21. The rates of DFADs deployments were generally lower than the rates of buoy transfers. Although skippers can have different strategies with regards to DFADs, such variations appear unconsistent with the similar numbers of buoys available to French purse seiners in the Indian Ocean (see section **3.1**) and might stem from underreporting. Also, the numbers reported appear unconsistent with the increasing trends in activations/deactivations observed over the recent years (see section **3.3**) that reflect high dynamics in buoys utilisation to ensure the renewal of each vessel DFAD standing stock. However, the sum of these 2 rates was higher than 25 mo^{-1} for 25% of the vessels, which would result in about 75 'new' DFADs monitored by quarter. Although buoy activations do not provide the exact same information (i.e. there can be a delay between buoy activation and deployment), this figure would be consistent with the median values of activations recorded for the fleet that were 70-85 in the first semester 2013. Finally, the number of DFADs visited per month was found to vary between 0.6 and 21.5. Again, such variations suggest some underreporting of information on activities related to DFAD-fishing.

3.5. Spatial patterns in dFADs

Positions of DFAD deployments reported in the logbooks for 2013 showed a strong seasonal pattern, consistent with the typical French PS fishing grounds. Deployments were scattered along a longitudinal gradient around 5-7°S during Nov-Feb, with a major deployment zone west of Seychelles (**Fig. 8a**). The western zone of deployment was still active from March to May and moved down to the Mozambique Channel (**Fig. 8b**). Deployments in June-July were 'back' to west of the Seychelles and more concentrated than during Nov-Feb (**Fig. 8c**). Finally, DFAD deployments were made off the coast of Somalia during the season Aug-Oct., with a major area at 50°E and close to the equator (**Fig. 8d**).



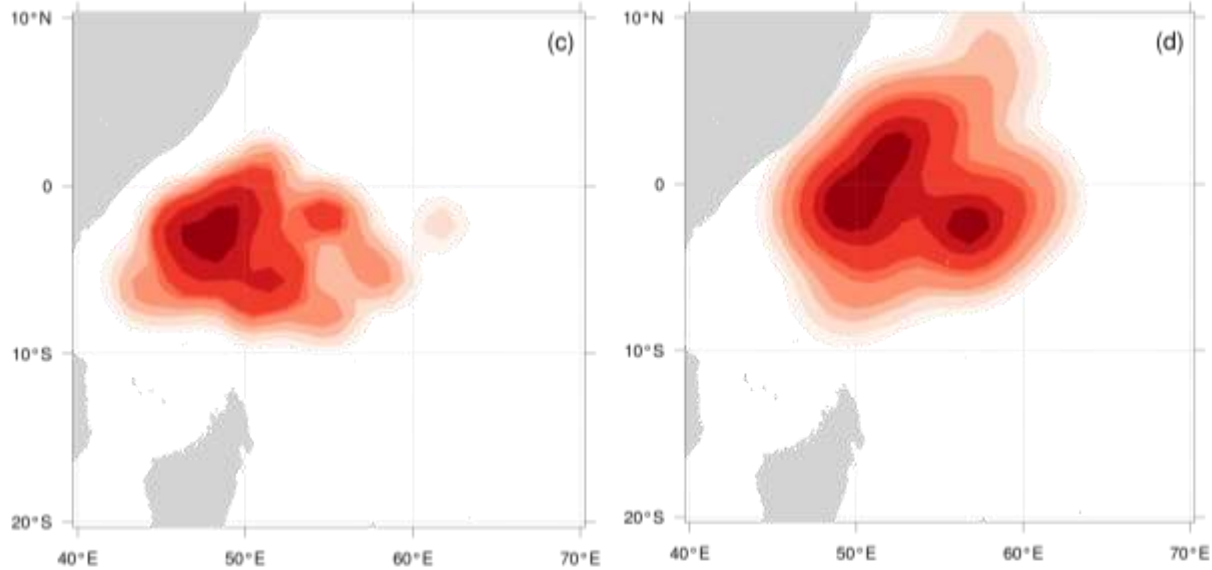


Fig. 8. Relative density maps of DFAD deployments by the French PS fishing fleet in 2013: (a) Nov-Feb, (b) Mar-May, (c) Jun-Jul and (d) Aug-Oct

Zones of DFAD deployments were found to vary between 2013 and 2014. Information on DFADs collected in 2014 showed a concentration of deployments south and west of Seychelles during Jan-Feb, without any deployment east of 60°E as compared to the observations made in 2013 for the season extending from November to February (**Fig. 9a**). Major zones of deployments in March-May 2014 significantly differed from 2013, with no operation conducted in the Mozambique Channel (**Fig. 9b**).

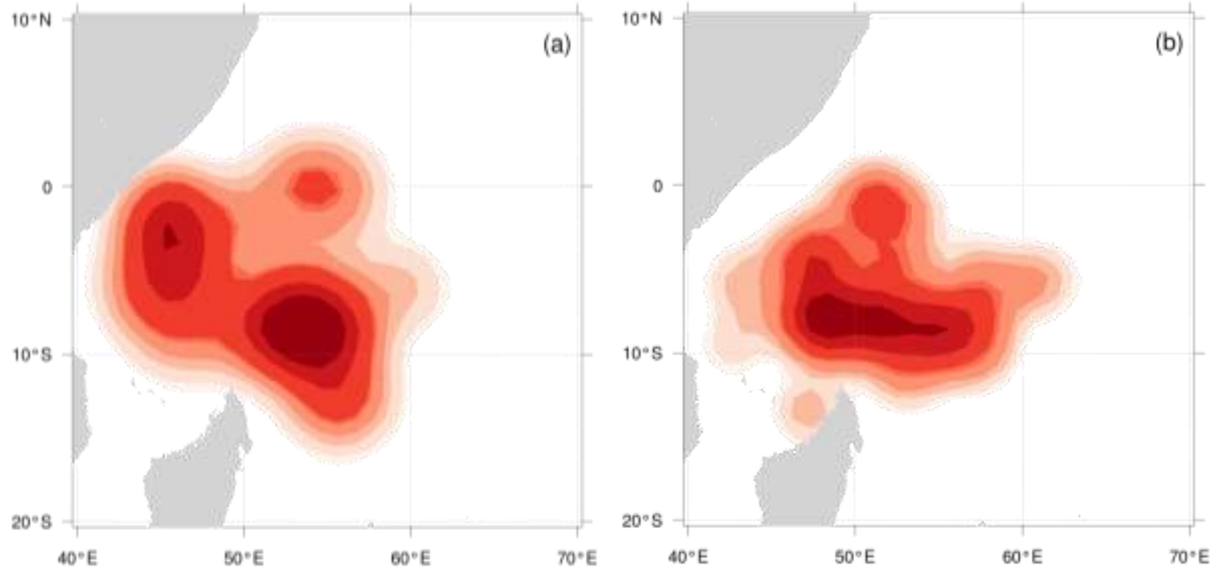


Fig. 9. Relative density maps of DFAD deployments by the French PS fishing fleet in 2014: (a) Jan-Feb, (b) Mar-May

4. Discussion

A general knowledge of the number of DFADs in the Indian Ocean is required to improve our understanding of the effects of large deployments of artificial rafts on the fishing power of PS fleets and other small-scale fleets that might also benefit from rafts drifting to the eastern part of the IO. Until recently, confidentiality aspects due to competition between companies and fleets have strongly limited the access to data on DFADs. Consequently, stock assessments of bigeye (*Thunnus obesus*) and yellowfin (*Thunnus albacares*) worldwide are principally based on abundance indices derived from Asian longline fisheries because CPUE time series for purse seine (and pole and line) are considered to be highly biased by increased fishing power that can not be properly estimated. Meanwhile assessments of skipjack generally rely on a suite of fisheries indicators (Maunder & Deriso 2007) or require large and good-quality tagging data sets (e.g. Rice et al. 2014). Here, we describe progress made in data collection through the recent implementation of FAD management plans, new resolutions of the IOTC, and good collaboration with PS French fishing companies. Our results show that there has been a substantial increase in the number of DFADs deployed and FOBs monitored in the Indian Ocean over the last decade. Data available from buoys indicate that each French purse seiner operating in the IO has been monitoring about 90 FOBs on a daily basis during 2010-2013, with some variability between seasons and among vessels. Overall, the total number of FOBs (predominated by DFADs) monitored for the French component of the European PS fleet would be around 1,200 in the recent years. As strategies with regards to DFAD fishing differ between PS companies and the number of DFADs released increase the probabilities of 'random' encounter of non-owned DFADs, it is of major importance that all purse seine fleets provide information on DFADs as described by IOTC resolutions 13/03 and 13/08 and following FAD management plans (Delgado de Molina et al. 2013). In addition, accessibility to historical data such as done by French companies for buoy purchase orders would be very useful to provide information on overall changes in fishing power. Such data sets should not raise anymore confidentiality issues and might reveal instrumental to derive abundance indices from PS CPUE time series.

4.1. Collection on DFAD activities

In the Indian Ocean, information on fishing mode (i.e. FSC or FOB) has been reported in skipper logbooks since the start of the PS fishery in 1981 as compared to the Atlantic Ocean where data separating fishing modes misses during the 1980s. Nevertheless, such data have been found to be insufficient to derive abundance indices from standardised PS catch rates as they do not provide information on the different means used to increase catchability, i.e. the components of the PS effort such as the number of DFADs at-sea (Anonymous 2012, Fonteneau et al. 2013). Recently, the collection of information on DFAD activities for the French PS fleet has greatly improved through close collaboration between scientists and fishing companies. Data on DFADs are now routinely collected from four complementary sources: (i) observations at-sea that have been covering about 5-10% of the French PS fishing trips since 2005, (ii) declarations by skippers in the extended version of the logbooks that has started in January 2013, (iii) quarterly reports of activations/deactivations of buoys by vessel that are provided by buoy supplier companies and (iv) buoy GPS positions for all the vessels of the French PS fleet (Maufroy et al. submitted). In addition, French fishing companies provided to IRD the history of buoy purchases since 2002-2004 which gives insight into the increasing trend of DFAD use over the last decade.

Collection of information on activities related to DFAD and buoys in the French logbooks started in January 2013 and appears to be variable and incomplete for some vessels. Interviews with skippers confirmed that the reporting of this information is a tedious and additional administrative task that is not a priority for them. While some skippers acknowledge that they do not report all information, there has been improvement in the reporting since the implementation of the extended logbook version and several skippers indicate that they now report most activities related to DFADs in the logbook. Communication with skippers and crews will be enhanced in 2015 to improve the data collection. It is noteworthy that the forthcoming French national version of Electronic and Reporting System (ERS) that is expected to be deployed for the French PS fleet in

2015 will include fields dedicated for recording information on DFADs and buoys.

4.2. Reconstructing long-term time series of PS CPUEs

A consistent time-series of FOBs numbers at sea is required for deriving a long-term time series of abundance indices for stock assessment models. Assuming that (i) the variability in the number of FOBs circulating in the IO has been mainly driven by changes in DFADs numbers over the last 3 decades, (ii) the interannual variations in buoys used are a good proxy of the variations in the numbers of DFADs monitored at-sea, and (iii) the increasing trend in the use of DFADs has been similar among fleets, we argue that information on the number of buoys available for the French PS fleet might provide valuable information to derive an annual index of CPUE on DFAD, e.g. number of sets per searching day per DFAD used.

In the present analysis, we only provide a time-series of buoys for the period 2002-2014. The start of deployment of DFADs at-sea in the Indian Ocean is difficult to precisely identify from the data sources available. Marsac & Hallier (1985) indicate that no artificial DFAD was used in 1981-1984 in the French PS fleet. In the Atlantic Ocean, first experimental deployments of a dozen of artificial rafts were made through a scientific cruise conducted by ORSTOM in 1983-84 (P Dewals, *pers. com*) and Bard et al. (1985) and Stretta & Slepoukha (1986) recommended in 1985 the development of an array of artificial rafts to increase the catch of the PS fishery, suggesting there was almost no artificial DFAD at that time used by the European PS fleet. Following Moron et al. (2001), the first artificial rafts would have appeared in the IO circa 1986. They were made of wood or any floating debris and accompanied with a bag of dead fish. The practice of building and deploying DFADs would have then progressively expanded over time, bamboo rafts equipped with hanging nets based on Japanese DFAD designs becoming predominant in the early 1990s (Moron et al. 2001). Observer data collected during 1986-1991 for the four PS fleets operating in the Indian Ocean at this time (Japan, USSR, France and Spain) already indicated a ratio of 1/3 DFADs among all FOBs encountered for more than 2,200 fishing sets observed (Sabadach & Hallier 1993). However, the capacity of detection of DFADs was limited before 1997-1998 as buoys were only equipped with radio-range beacons (see section 4.3 for technological aspects). Also, buoys could be easily reprogrammed when the DFAD was found at-sea which resulted in a lot of changes in buoy ‘owners’ over time. Consequently, purse seiners relied on an overall buoy 'floating stock’ that remains difficult to evaluate in absence of historical data but must have been already very important as early as the mid-1990s (Moron et al. 2001). The use of buoys strongly varied between vessels and fleets and was dependent on the skipper ability to track currents and fronts to find DFADs equipped with buoys. Within French PS companies, no real planning was made with regards to buoy technology watch before the 2000s and purchases and orders were sporadic and variable between skippers. In addition, they did not reflect the real use of buoys as some skippers were particularly efficient in finding buoys from the 'floating stock'. It appears then impossible to obtain quantitative information on the number of buoys available for the French PS fleet before 2002.

4.3. Improved buoy technology: positioning and echo-sounder

Although knowledge on the number of DFADs monitored is critical to better define the nominal effort of PS fisheries, technological changes in positioning and detection of fish associated with the DFAD through echo-sounders might have affected the relationship between the nominal and effective measures of this component of PS fishing effort. Such changes are expected to have (i) a direct effect on the ability of the vessel to find and select the DFAD having aggregated tuna and (ii) indirect effect by releasing some time for search of other schools.

The first radio beacons used on LOGs by the Spanish PS fleet in the Indian Ocean in the mid-1980s were constantly emitting and had a limited range up to 90 nm (Moron et al. 2001). The direction towards the buoys was determined through radiogoniometers (i.e. radio direction finders). Next improvements consisted in larger autonomy of the radio through sel-call system allowing for remote activation as well as increasing range up to 150 nm (Moron et al. 2001). By the mid-1990s, the French purse seine fleet relied on Ryokuseisha and Tayo buoys that were equipped with radio-range beacons of typical range of 600-900 nm. In absence of accurate position of the buoy, the final approach procedure towards the DFAD still revealed difficult within a radius of about 10 nm around the vessel. A major technological shift occurred in 1996-1997 with the emergence of buoy systems that coupled HF radio and GPS. Compared to previous systems, the new buoys developed through the company SERPE-IESM offered 3 major advantages: (i) a security key for each buoy to prevent reprogramming, (ii) an HF transmitter which involved no extra-cost of positioning, and (iii) a reception system (ARIANE) to monitor the flotsam positions and drift through a GIS software. Buoys were programmed to transmit their GPS position automatically several times a day with the possibility of remote control to increase the number of transmissions and activate flashlight for final search. This system resulted in the end of the use of radiogoniometers that fully disappeared from the fishery in the early 2000s (IRD unpublished observer data). A similar change was observed for the Spanish fleet in the Indian Ocean (Artetxe & Mosqueira 2003). It is noteworthy that the continuous and real-time cartography of DFADs drifts at-sea has provided very valuable information to the skippers on areas where to (and not to) deploy and find DFADs through improved knowledge on currents and concentration areas such as fronts and eddies. Meanwhile, DFADs drift maps also likely increased the fishing power of the purse seiners on free-swimming schools through increased detection ability since oceanographic mesoscale features have been shown to play a major role in tuna aggregations (Laurs et al. 1984, Fiedler & Bernard 1987, Young et al. 2001). The positioning system used for positioning FOBs within the French PS fleet of the IO shifted quickly from HF-GPS to a full satellite GPS system (Inmarsat D+ Neptune) in 2007-2008, mainly because the fleet of Soviet purse seiners were able to track the buoys radio signals. It is noteworthy that the ARGOS system (other localisation system by satellite, not by GPS) was adopted earlier (in 2005) by the French PS fleet of the Atlantic Ocean due to some technical problems of radio reception. Despite some minor improvements on the margin, the positioning system of FOBs through GPS has been fairly stable since the mid-2000s and is similar among fleets and oceans.

The first generation of echo-sounder buoys appeared in the early 2000s in the purse seine fleet of the Indian Ocean (Artetxe and Mosqueira 2003, Lopez et al. 2014). First, these buoys were only used in the Spanish purse seine fleet and represented in 2005-2006 a major component of the buoy stock in use by the support vessels (Ramos et al. 2010). According to interviews conducted with skippers, >50% of the Spanish buoys were equipped in 2012 with echo-sounders, with a substantial increase in the proportion of buoys between 2010 and 2012 (Lopez et al. 2014). By contrast, echo-sounder buoys appeared as late as 2011 in the French PS fishery. Most of the buoys in use by the French PS fleet are nowadays equipped with echo-sounders, despite a price >50% as compared to unequipped buoys, demonstrating the overall usefulness of echo-sounders whose technology greatly improved in the recent years (Lopez et al. 2014). Discussions held with skippers in 2014 indicate that all buoys used in the Spanish and Seychelles PS fleets are now including an echo-sounder. In absence of synoptic and comprehensive knowledge of buoy type (i.e. equipped or not with an echo-sounder) and specific experimental design, as well as due to the different brands and models that are constantly evolving, the quantitative impact of echo-sounders on PS catchability and selectivity is very difficult to assess. Information from the eastern Pacific Ocean suggests that echo-sounders have significantly increased catch rates on DFADs. Overall, the implementation of echo-sounder buoys is considered to have substantially increased the fishing power of the fleet through better selection of FOBs, increasing the catch rates and reducing the search time. Information available from observers at-sea on the "success" of visits of FOBs (i.e. with presence of tuna) could be used to assess the influence of echo-sounders presence on fishing efficiency.

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