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Data-derived fishery and stocks status indicators for skipjack tuna in the Indian Ocean

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Abstract

This paper is presenting a set of indicators that inform on trends on fisheries and potential status of the skipjack stock in the Indian Ocean. We present six categories of indicators: i) fishing power and FAD use, ii) catch-related trends, iii) catch rates, iv) size-based indicators, v) tag-recovery indicators and vi) environmental indicators. The FAD-specific fishing power has greatly increased since 2014, in terms of number of active buoys attached to FADs and number of support vessels. The FAD fishery has spatially expanded in 2016 and the proportion of catches on FADs has reached unprecedented record levels. CPUEs have declined for both purse seine (-43% for 1991-2016) and baitboats (-43% for 2005-2015). The average weight of skipjack caught by PS at FADs has been reduced by 19% (1984-2016) and by 11% for baitboats, after 2006. The proportion of immature skipjack has greatly increased in the PS FAD catches (14.5%). Among the most striking features are the anomalously low abundance of skipjack on free schools and the large dominance of small sets at FADs, suggesting a fragmentation of schools. CPUE are likely affected by ambient conditions, with low CPUEs during El Niño and Indian Ocean Positive dipole events. Most of the indicators portray a situation where the Indian Ocean skipjack stock would be fully exploited. Moreover, this analysis underlines potential concern of future overfishing since increasing catch levels, including those of immature fish, and overall trend in fishing effort and strategy as seen in the last two years, might not be sustainable.

Introduction

The development of data-based indicators is needed to provide a complementary perspective to what is provided from assessment models. This has been recommended by the WPTT at its 2016 session (WPTT18). Skipjack is a particular case as a large proportion of the catch is caught by purse seiners on drifting Fish Aggregating Devices (FADs). There is no doubt that the dramatic increase of skipjack catches worldwide (1.6 Mt in 2015) since the early 1990s was due to the expansion of FAD use, both anchored or drifting (Fonteneau et al 2013). Drifting FADs are duly recognized as a component of the purse seine fishing effort (along with supply vessels) however the technology associated to FAD fishing has tremendously evolved since 1991 (Moreno et al 2016) and makes quite complex the estimation of a standardized effort over time. Basically, as reminded by Maunder (2016), the main uncertainty is the link between catch per unit effort (CPUE) and abundance for a species that is mostly caught on FADs.

A paper on fishery indicators raising concerns on the status of skipjack stock in the Indian Ocean was presented at the 18th session of the WPTT (Fonteneau and Marsac, 2016). Here, we review fishery and stock indicators for skipjack based on different data components: FAD use, catches, catch rates, fish sizes, tagging and environment.

1- Trends in fishing power and FAD use in the purse seine fleets

a- Fishing effort: The PS fishing effort has reached an historical low level during 2009-2013, after historical high levels observed in 2006-2007 (Fig.1). The anomalously low PS effort is the consequence

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of the Somalian piracy which has been controlled since then. The trend for 2013-2016 is a linear increase of the PS effort.

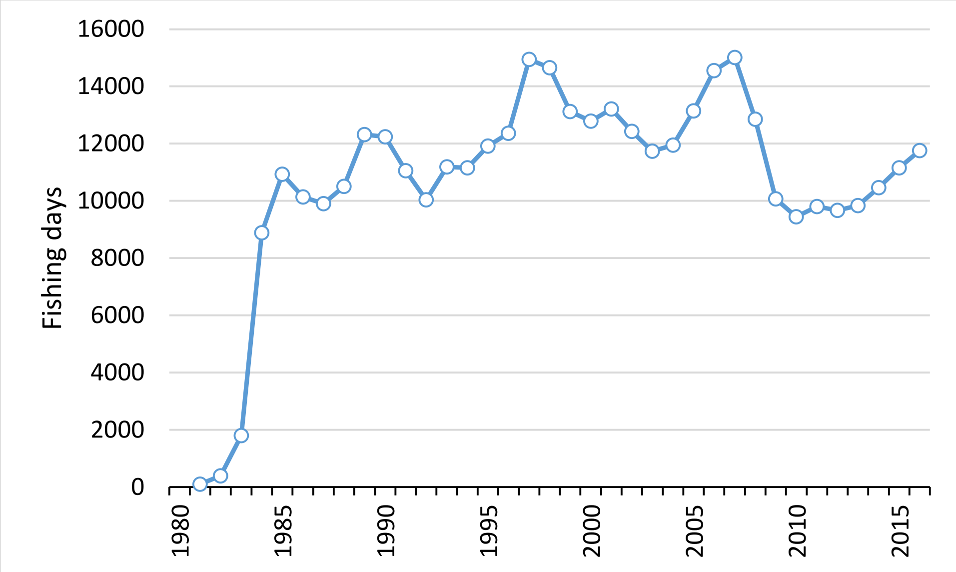

Fig.1 - Number of fishing days by year for the major PS fleets: EU (France, Spain, Italy, Mayotte), Seychelles, USSR and NEI. Source: IOTC database

b) Fleet capacity: The carrying capacity of the PS fleets is highly correlated with the effort trend, however the capacity has been growing faster than the effort since 2013 (Fig.2). In 2010-2015, the capacity of an average purse seiner was 2000 t, that is +8% compared to 2000-2009. Whereas the capacity for France and Spain has remained stable, the capacity of Seychelles PS has substantially increased since 2013.

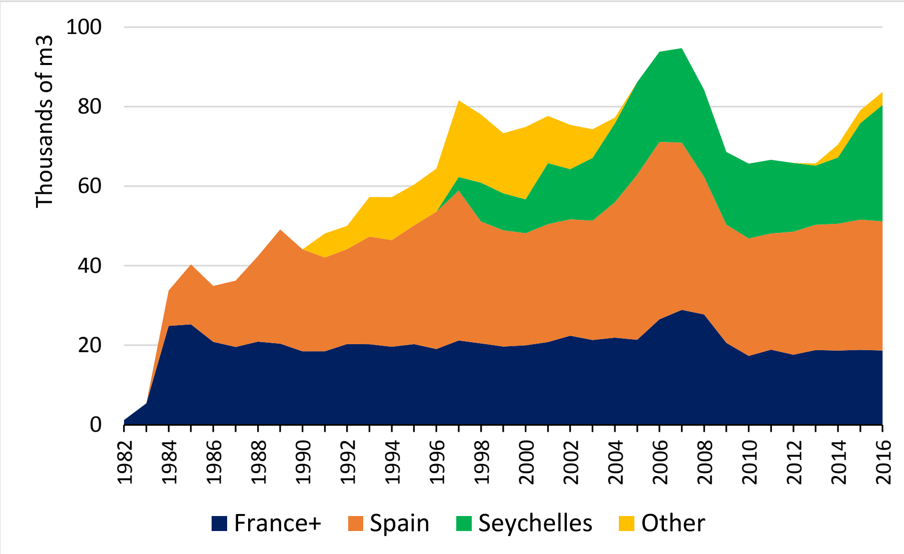

Fig.2 - Carrying capacity (in thousands of m3) for the purse seine fleets operating in the Indian Ocean, 1982-2016. The capacity is weighted by the actual number of fishing days of purse seiners per year. Source: IOTC database

c) Support vessels: These vessels assist purse seiners in their fishing operation at FADs (deployment, maintenance, retrieval, relocation) and are therefore an integral part of the FAD fishing strategy. A total of 23 support vessels were operating in 2016. Among EU vessels, it is mainly Spain that has generalized the use of support vessels in the PS fishery, compared to France (Fig.3). It must be reminded that performance of PS is largely increased when assisted by a purse seine with a 45% increase in catch and a 20% gain in terms of fishing sets per day (Maufroy, 2016).

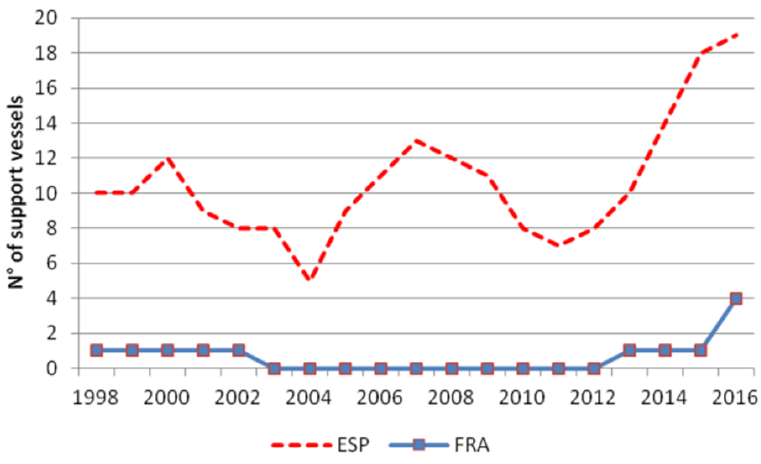

Fig. 3 - Number of support for Spain and Seychelles (labelled ESP) and France (FRA). Source: Gaertner et al, EU CPUE workshop, July 2017

d) Number of drifting FADs: The buoys attached to FADs use a satellite link to transmit their positions to a server, then to the owners of the buoys (purse seiners and their fishing company) so that a real-time monitoring of the FADs can be performed. Apart from giving indication to the skippers to deploy an appropriate fishing tactic and follow the drifting FADs over time, the status of transmission (active vs non-active buoy) is needed to comply with the FAD management plan and remain in the authorized limit in number of active buoys at any time. This limit was set at 425 in 2016 (Res. 16/01 to come into force from 1 January 2017) and then revised and reduced to 350 in 2017 (Res. 17/01). The buoy positions are archived in the FAD database maintained at the IRD Tuna Observatory (Ob7), with courtesy of Orthongel. The original dataset has been cleaned in order to remove all positions transmitted by buoys on board vessels (when there are being relocated or during transit to port), so that only buoys active at sea are counted. We built a monthly series for 2007-2016 (Fig.4). The trend has been increasing since the initial deployments of such buoys (Nov 2016), however the rate of increase has become steeper from 2014 on (Fig.4). The maximum of 4662 buoys was reached in Dec 2016, the last point of the series presented here. This amount of buoys is being used by 17 purse seiners, making an average of 274 buoys per vessel. However, these numbers which have been pooled by month, overestimate the instantaneous number of active buoys as they do not account for deactivation, reactivation or removals which can happen at finer time scales.

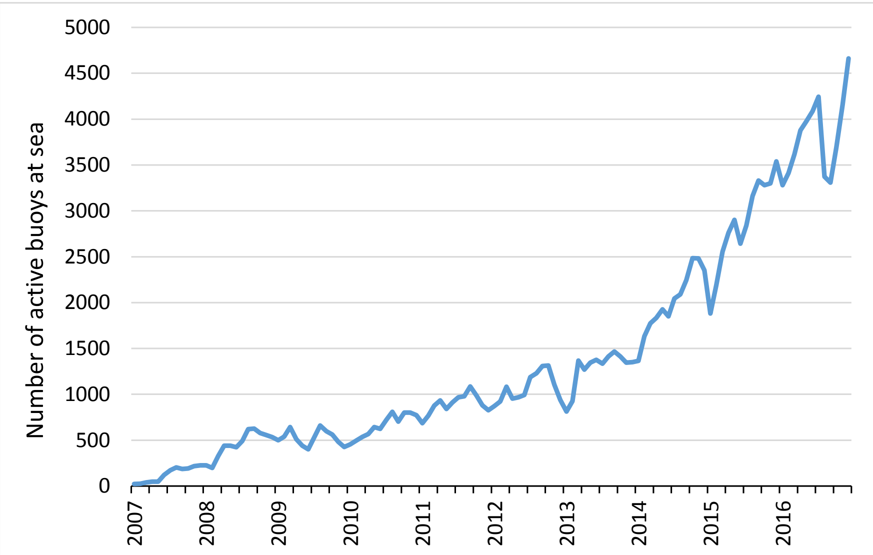

Fig.4 - Trend in total number of FAD buoys transmitting at sea, deployed by the French and associated flags (17 purse seiners in 2015 and 2016), by month, 2007-2016. Source : French FAD dataset, IRD/Orthongel

e) Persistence of the FAD fishing zone: the dispersal of FADs is driven by the surface currents which are well known in the Indian Ocean (Schott and McCreary, 2001). The core of the deployments of FADs is in the equatorial zone of the West Indian Ocean. One of the core areas is the Somali Basin, especially during the SW monsoon (June-September) when a seasonal gyre (the Great Whirl) develops and retains the drifting objects in the western region, before being pushed off to the East during the inter-monsoon by the Wyrtki Jet. This is well represented in Fig.5, where persistence of more than 20 years of FAD catches is observed from 8°N to 8°S, 45°E-65°S and also in the North Mozambique Channel. FAD catches in the East Indian Ocean by EU purse seiners is more incidental (green area in Fig.5).

f) Density of FADs: The FAD IRD/Orthongel database was used to calculate densities of active buoys by 1° square followed by French purse seiners. Yearly classed-post maps, from 2008 to 2015, show the number of buoys (each one having a distinct ID code) that have visited a given square throughout a year. The same buoy ID does appear in several squares as FADs are drifting. Such maps (Fig.6) indicate the core areas where FADs seeded by French purse seiners are concentrated before being dispersed with the currents. The grey shaded squares illustrate the drift of buoys far outside the PS fishery. Since 2008, the core areas have always been located in the Somalian basin and gradually around the Seychelles from 2010 onwards. The gradual shift to pink, red and black squares denote the increasing number of active FADs at sea, therefore more fishing opportunities at FADs over time.

g) Improved technology of drifting FADs: nowadays, the buoys have extended capabilities with new sensors and chips onboard. The most recent development is echo sounders that indicate the biomass of fish associated to the buoy, which a key information for skippers as to decide whether or not it is worth setting. Spanish purse seiners have introduced echo sounder-equipped buoys in 2004 whereas French implemented this device in 2010. Fig.7 illustrates the gradual (for Spain) or abrupt (for France) transition between conventional and echo sounder buoys, which potentially increases the fishing efficiency of purse seiners at FADs.

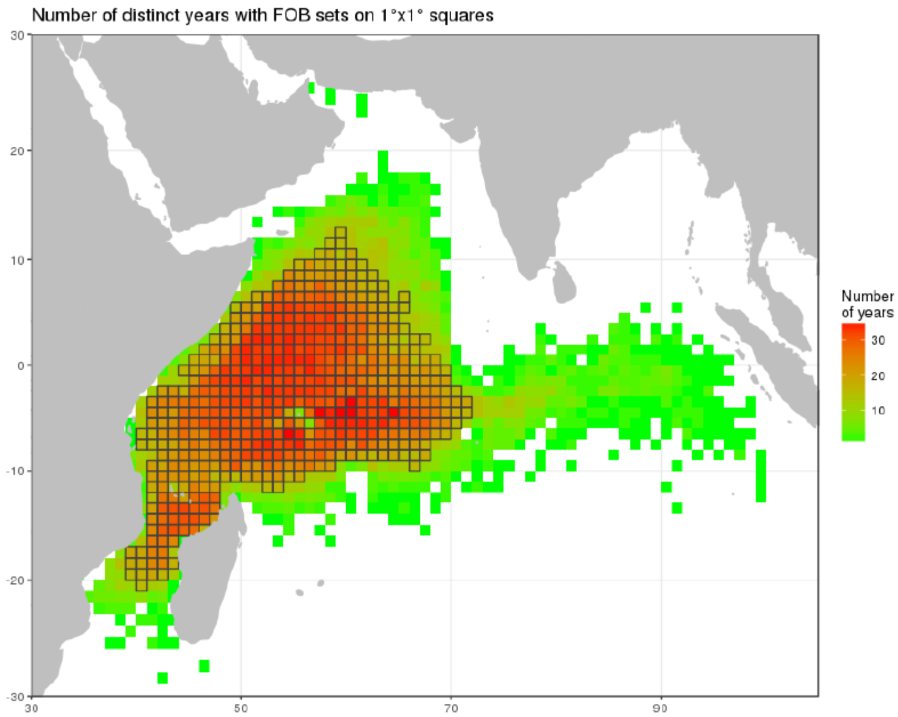

Fig.5 - Area where EU purse seine FAD fishery is operating. Shaded squares denote the number of years where FAD catches have been observed. (Red squares indicate where FAD catches have been observed for at least 20 years). The green area represents the total surface with FAD catches. Source: Gaertner et al, EU CPUE workshop, July 2017

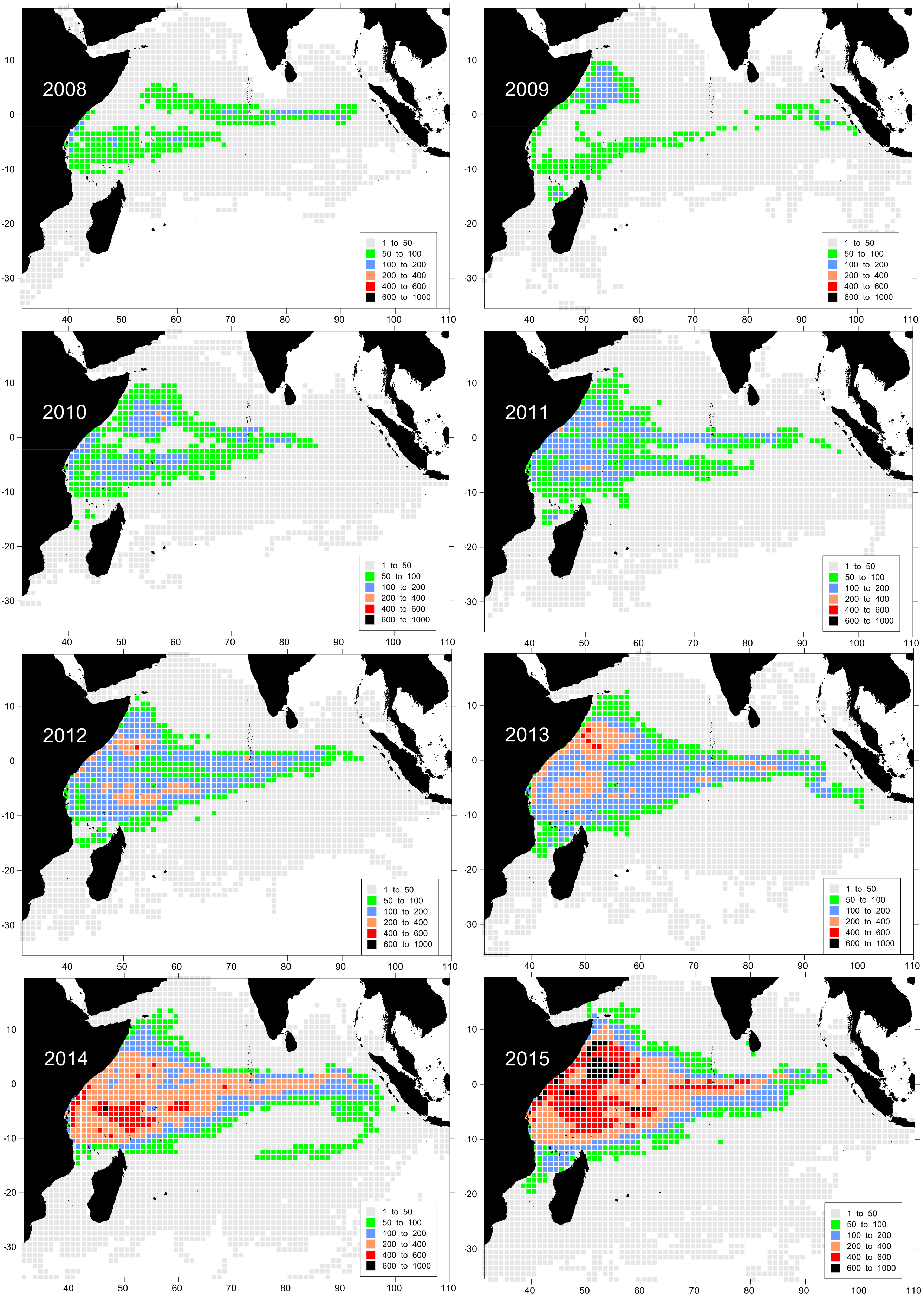

Fig. 6 - Estimated density of drifting FADs (numbers) used by the purse seine EU-French fleet, by 1 degree square for selected years. The color indicates the number of FADs by strata. Note that a given FAD can appear in different squares, as it is drifting throughout the area. Source : French FAD dataset, IRD/Orthongel

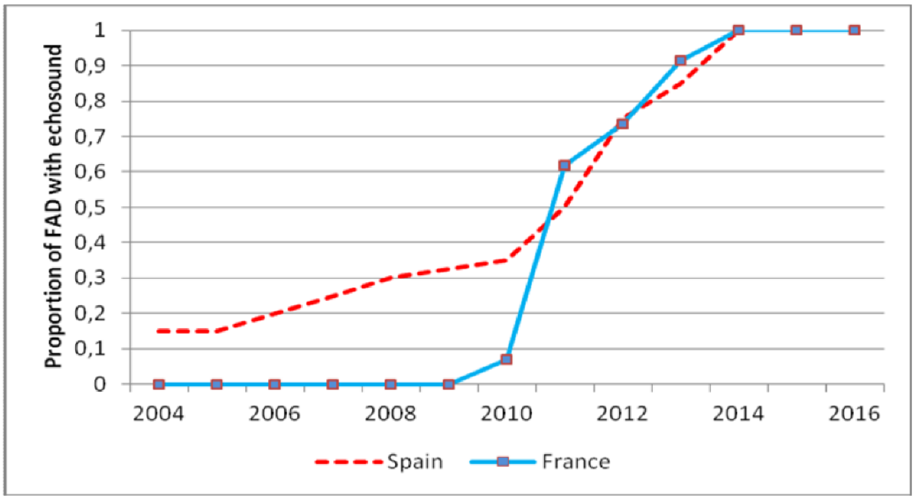

Fig. 7 - Trend in the proportion of FADs equipped with echo sounder buoy for the EU Spanish and French purse seiners operating in the Indian Ocean. Source: Gaertner et al, EU CPUE workshop, July 2017

h) Trend in FAD catches: the proportion of catches made by purse seiners on FADs was rather homogeneous among fleets during the 1980s, fluctuating in the range 50-60%. The proportion increased in 1995 and remained in the range 60-80% until 2002. The "Natosquilla outburst" (Potier et al 2004, Romanov et al 2015), a prominent forage resource for surface-dwelling tunas, aggregated tunas in large free schools in the West IO from 2003 to 2005 and this resulted in lesser fishing activity on FADs. After this event, the FAD regained much interest. The proportion is now peaking at historical levels (around 80% all fleets combined). Since 1999, it is noteworthy that French purse seiners have remained at a significant lower level (60 to 70% during the last 3 years) compared to Spain and Seychelles (Fig.8).

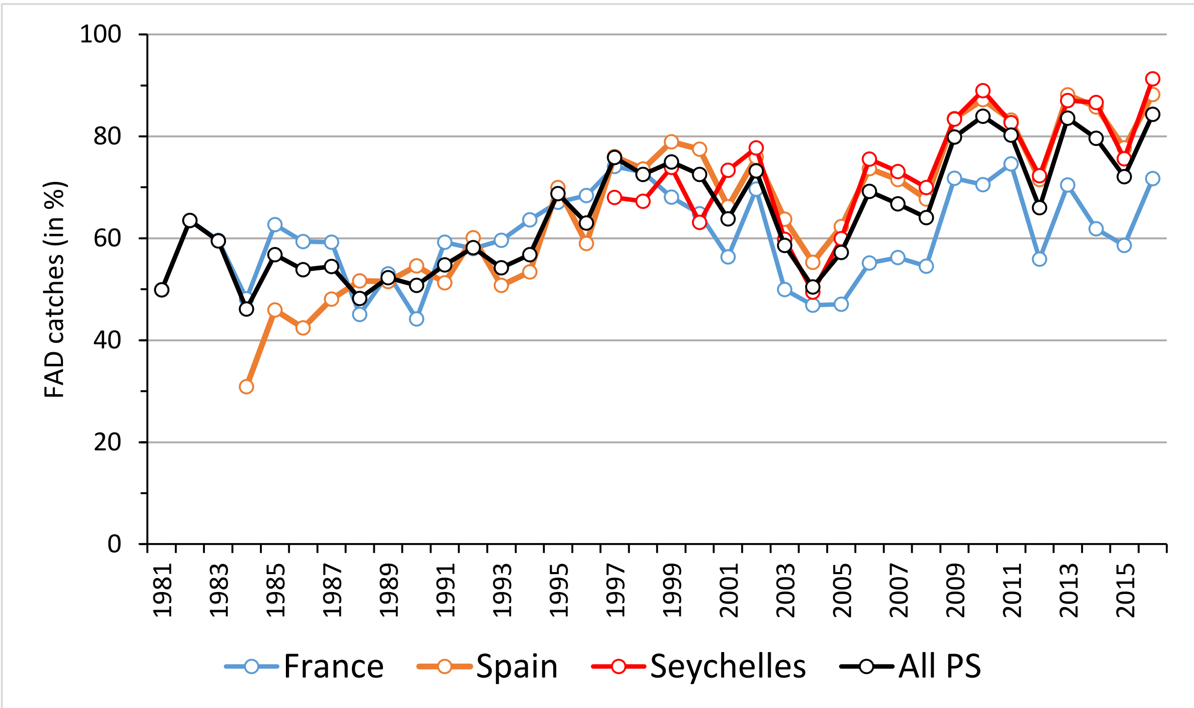

Fig.8 – Trend in purse seine catches at FADs, by year and flag, 1091-2016. Source: EU and Seychelles datasets.

2- Catch-related trends for skipjack

a) Nominal catches: The development of the EU purse seine fishery in 1984 has boosted skipjack production in the Indian Ocean which reached a maximum of 616 000 t in 2006 (Fig.9). Although operating in different areas, all gears (except the category "Other"), had historical high catch levels in 2006 and declined together to low levels in 2012. Purse seiners peaked at 271 000 t and after a minimum in 2012, increased sharply up to 231 000 t in 2016. The second most important gear since 2006 is gillnet, whereas pole and line dominated all gears other than purse seine prior to 2006. Combining gillnet, pole and line and other gears (troll, hand line), the developing coastal countries caught 217 000 t in 2016, representing 48% of the total catch. This shows the importance of catch, effort and size data from those countries to perform robust assessments, and the large uncertainties that can affect assessment when those datasets are insufficiently documented.

b) Purse seine catch by type of school: as mentioned earlier, the bulk of skipjack is caught on FADs, with a proportion that has been steadily increasing since the onset of the PS fishery until the early 2000s. Besides increasing catches on FADs, there was still a significant proportion of skipjack (average of 20% and 26 000 t for 1987-2007) caught on free schools. Since 2006-2007, it is noteworthy that skipjack on free schools has declined and became very rare in the last 5 years, at an historical low of 5% (Fig.10). A similar trend is observed in the proportion of skipjack among all free multispecies school catches (not shown). Skipjack proportion was at an average of 26.5% during 1987-2007 and has dropped to 10% for 2012-2016.

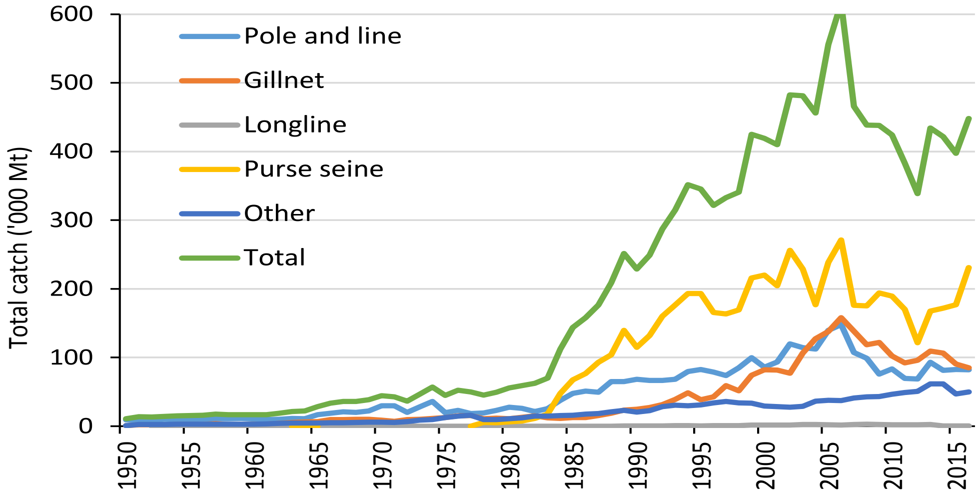

Fig.9 - Skipjack catches by gear, 1950-2016. Source: IOTC database

c) Purse seine catch by type of school: as mentioned earlier, the bulk of skipjack is caught on FADs, with a proportion that has been steadily increasing since the onset of the PS fishery until the early 2000s. Besides increasing catches on FADs, there was still a significant proportion of skipjack (average of 20% and 26 000 t for 1987-2007) caught on free schools. Since 2006-2007, it is noteworthy that skipjack catches on free schools has declined and became very rare in the last 5 years, at an historical low of 5% (Fig.10). A similar trend is observed in the proportion of skipjack among all free multispecies school catches (not shown). Skipjack proportion was at an average of 26.5% during 1987-2007 and has dropped to 10% for 2012-2016.

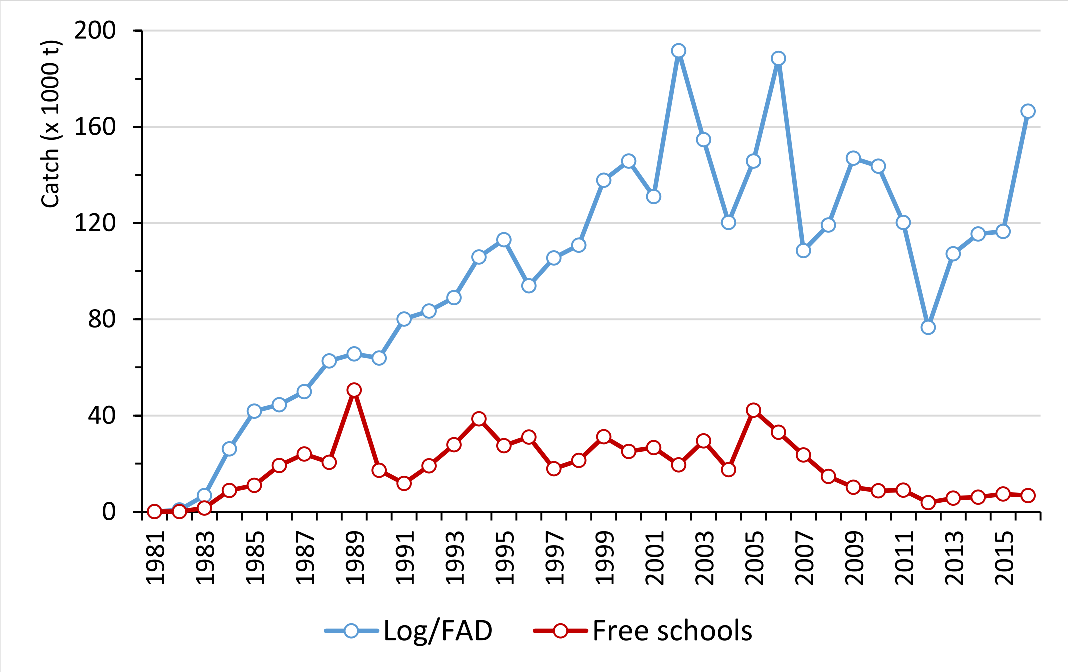

Fig.10 - Yearly skipjack catches on Log/FAD and free schools by the purse seine fleets, 1981-2016. Source: EU and Seychelles C/E datasets

d) Spatial extent of the skipjack catches: This can be illustrated by the number of 1° squares where a catch of skipjack of at least 10 tons on FAD was made (Fig.11). The area has increased steadily until 1996 then fluctuated between 400 and 550 squares until 2015. The anomalously high value for 1998 (675) is due to the wide expansion of the EU PS fleets to the East Indian Ocean during the 1997-1998 El Niño/positive dipole event (Marsac & Le Blanc 1999, Marsac 2015). The relatively large number of 1° squares fished in 2008-2009 (540-550) is probably a consequence of the Somalian piracy pushing the fleets eastwards. After minimal area fished in 2014, skipjack catches on FADs were again distributed over a large area in 2016. The expansion was mostly to the South Mozambique Channel, to the North until 14°N and to the south-east (10-15°S) in the northern limb of the tropical gyre.

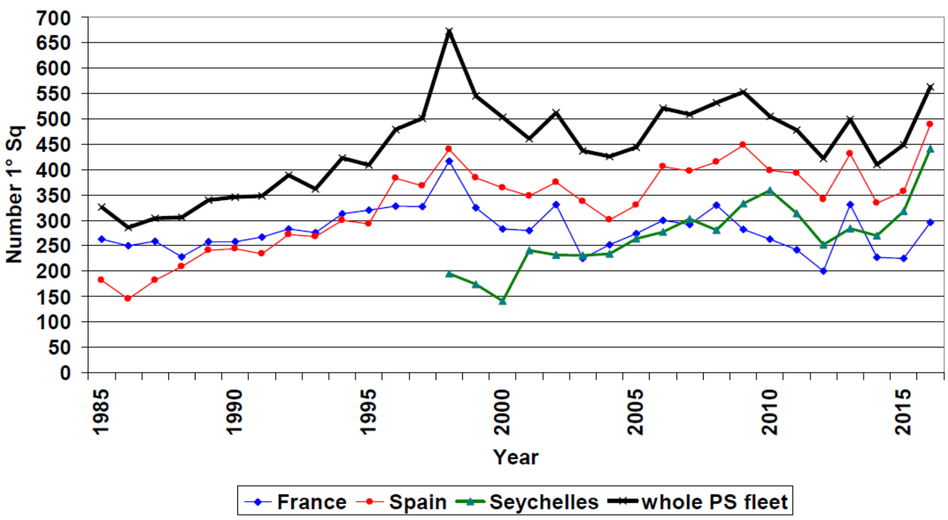

Fig.11 - Area explored by the purse seine fleets: number of 1° squares with skipjack FAD catch. Source: EU and Seychelles logbook data

The expanding geographic range of the FAD fishery is also supported by larger daily distances travelled by purse seine fleets (Fig.12). This increase is clearly related to the FAD fishing strategy; Spanish and Seychelles fleets always travelled over larger distances than the French fleet. The rate of increase has slowed down after 2007 for the French when it was keeping the same trend for Seychelles and Spain.

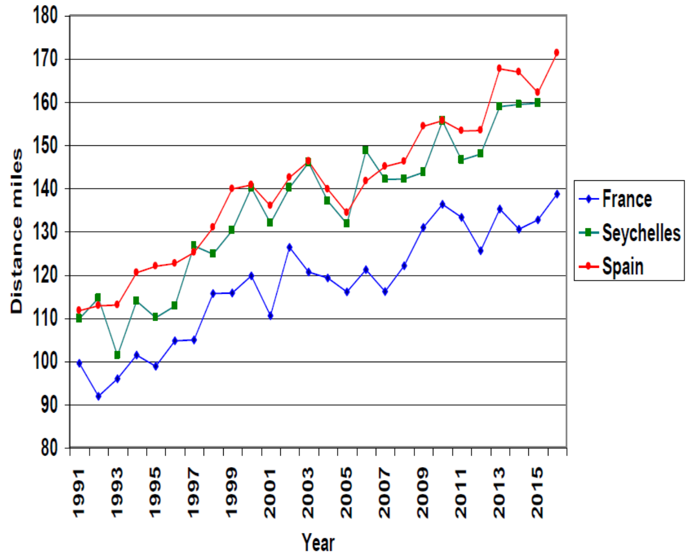

Fig.12 – Daily distances travelled by purse seiners of France, Seychelles and Spain flags. Source : logbook data

e) Trend in relative proportion of skipjack on FADs: the three species of tropical tunas are caught at FADs (Fig.13). However, the bulk of yellowfin and bigeye are juvenile fish, whereas most of skipjack are mature. Bigeye did not vary greatly over time. Yellowfin and skipjack have fluctuated in opposite direction, although skipjack has always been the prominent species at FADs (50-70%). The most striking anomaly was recorded in 2012-2013 when there was an almost equal share between the two species. Since then, the proportion of the two species went back at the level of the long-term average (61%).

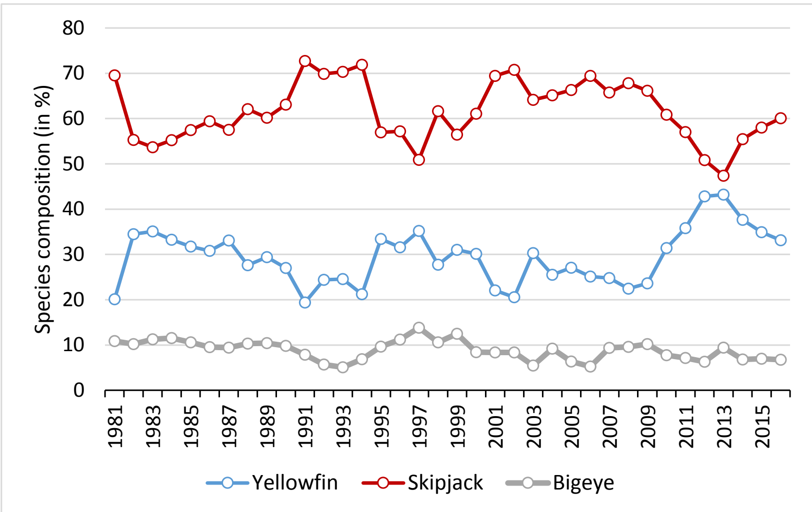

Fig.13 - Species composition of purse seine catches on FADs, 1981-2016. Source: EU and Seychelles C/E datasets

The comparison between two recent periods, 2001-2009 and 2010-2016 highlights to distinct “regimes” in species composition at FADs: a large dominance of skipjack associated to a minor proportion of large yellowfin (>30 kg) in 2001-2009, and a shift to a more balanced composition between the two species associated to a larger proportion of large yellowfin in 2010-2016 (Fig.14).

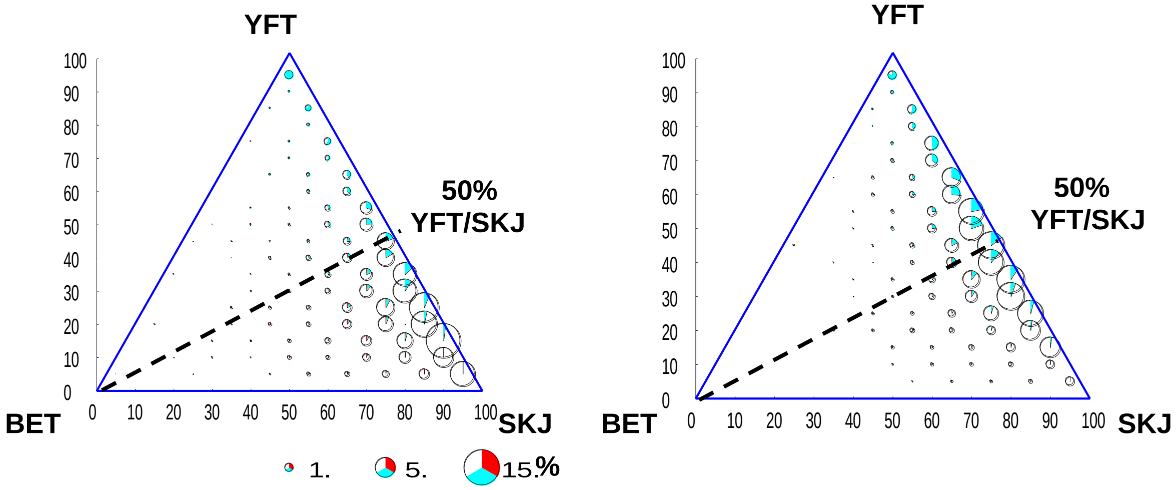

Fig.14 - DeFinetti plots of the FADs samples for two distinct periods: 2001-2009 (left) and 2010-2016 (right). Each pie indicates the percentage in weight of each combination of species composition in all FAD samples. Color as follows. White: % of small individuals (<10kg); Red: % of large bigeye; Cyan: % large yellowfin. Source: multispecies samples dataset of French landings.

f) Distribution of FAD catches by set size: we distributed the FAD sets of the EU and Seychelles PS logbooks in three size categories: small (< 30t), medium (30-60 t) and large (> 60 t) schools. It becomes clear that the overall catch trend is driven by the contribution of large sets, with two peaks in 2002 and 2006, and a historical low in 2012 (Fig.15). Since 2007, the small sets are those contributing the most to the skipjack catches on FADs, with an exceptionally high contribution in 2016, by contrast to large sets which have remained stable since 2014. The catches by medium size sets have fluctuated without trend since 1999, whereas the contribution of the small sets have showed an increased trend since 1991.

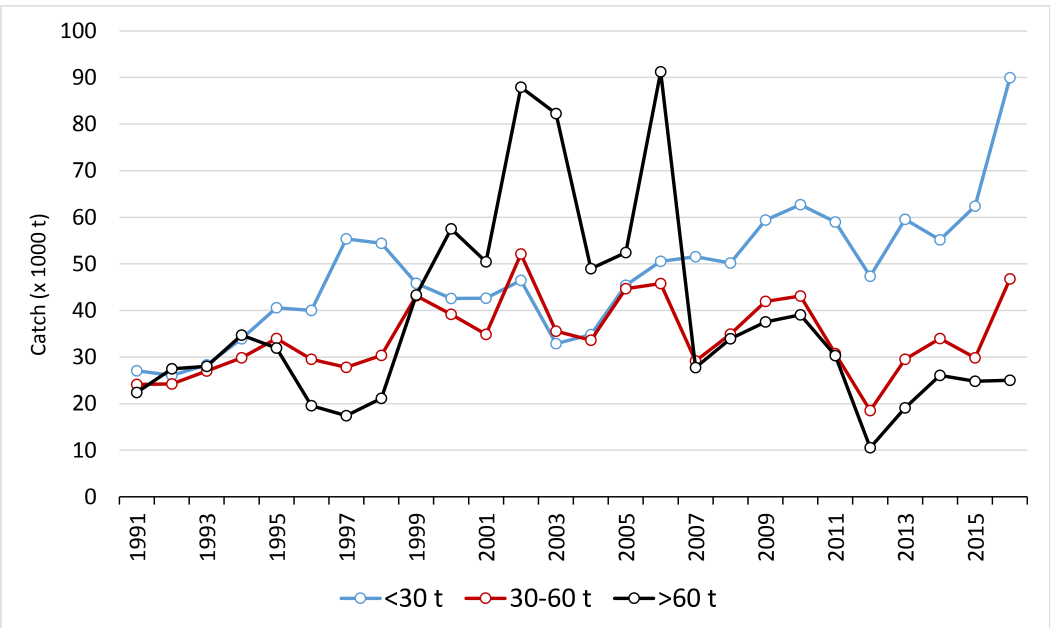

Fig.15 - Skipjack catches on FADs classed by set size. Source: EU and Seychelles PS logbooks

g) Relative rate of catch increase (RRCI): Grainger and Garcia (1996) proposed a catch-based index to obtain information on the status of a fishery. Basically, the principle is that the yearly relative rate of catch increase (RRCI) declines with time during the developing and mature phases of a fishery. Consequently, when maximum catch potential is reached (with a linear fit of the series), the index drops to 0. Gaertner et al (2001) generalized this relationship by considering that the relationship may be other than linear and by incorporating some inertia by averaging catches and the RCCI over a range of years (L) when the age classes are fully fished (equilibrium approximation). For skipjack, we took L=3. A regression (second degree polynomial fit) was performed between the smoothed RCCI (named RCCI') and the averaged previous catches (C_{av}). The approximate maximum yield is given when RCCI' equals 0. The process is quite simple and is based on the following equations:

$$RCCI_t = \left\lfloor C_t - \left(\sum_{i=1}^{L} C_{t-i}\right)/L \right\rfloor . \frac{1}{\sum_{i=1}^{L} C_{t-i}}$$

$$RCCI'_t = \left(\frac{1}{3}\right) \sum_{t-1}^{t+1} RCCI_t$$

$$Cav_t = \left(\frac{1}{L}\right) \sum_{i=0}^{L-1} C_{t-i}$$

This approach is valid only under the assumption that fishing effort has increased over time, which is consistent with the situation found in the Indian Ocean, and by considering total skipjack catches (all gears combined). The relative rate of catch increase for the whole series is given in Fig.16. There are four sets of years where RCCIs exhibits a declining trend, which correspond to gradual development of the skipjack fishery. The period 1950-1960 corresponds to data reconstitution for artisanal gears (gillnet and line) and pole and line in a developing stage. The period 1965-1979 is when pole and line catch from Maldives showed a substantial increase. The period 1984-2012 starts with the development of the PS fishery (adding to other gears still increasing their catches) and ends with the sudden and general decline of catch recorded for all gears. The period 2013-2016 is when the PS catches exhibited a sudden increase of its FAD fishing, in parallel to the introduction of more support vessels (see Fig.3). For the first two periods, fitted RCCI did not drop below 0. By contrast, for period 1984-2012, fitted RCCI crossed the 0 line in 2006 (and the last 6 years of the series had negative RCCIs).

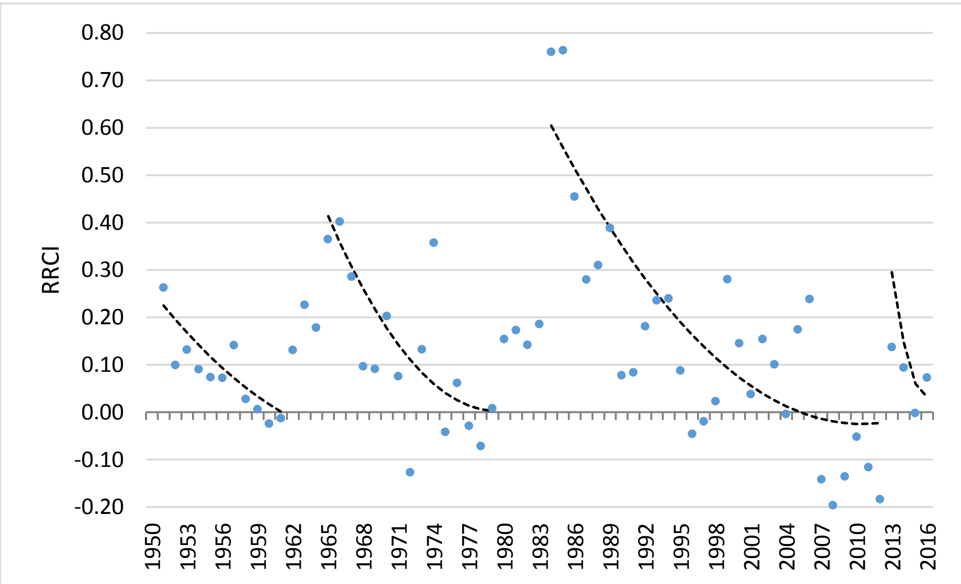

Fig.16 – Skipjack relative rate of catch increase for 1950-2016, with polynomial fit performed for 4 distinct periods: 1951-1960, 1965-1979, 1984-2012, 2013-2015. Source : IOTC nominal catch database

The plot of the smoothed catch (Cav) vs the smoothed relative rate of catch increase (RCCI') is presented Fig.17.

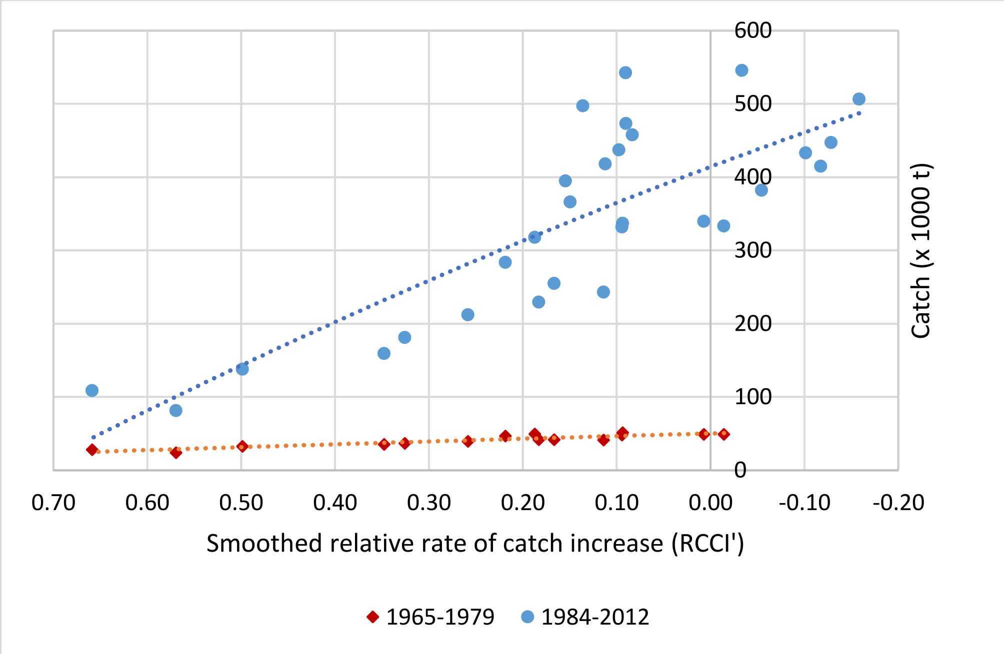

Fig.17 – Trends of smoothed catch (Cav) against RCCI' for two historical periods of the fishery, 1965-79 and 1984-2012 (second degree polynomial fits given in dashed line). The fit for 1965-79 crosses the RCCI'=0 at 50 000 t, when the fit for 1984-2012 gives a maximum yield at 415 000 t.

The estimated maximum yield differs greatly between the two periods. At the early stage of the fishery, the yield at equilibrium was estimated at 50 000 t. Three decades later, such yield is estimated at 415 000 t, reflected major changes in catchability are spatial extent of the fishery.

3- Catch rate-based indicators for skipjack

We computed 3 nominal CPUEs using the FAD set as a unit of effort and compared these CPUEs with the standardized CPUE established for the EU PS fishery (Katara et al 2017). The CPUEs are computed as monthly average by 1° square, then averaged over all squares for a given month. The series named "FAD1_WIO" was calculated over the whole WIO (West of 75°E, 30°S to 20°N). The second nominal series named "FAD1_CoreW" was calculated in the core of FAD catches (8°N-8°S / 50°E-65°E, see Fig.5). Eventually, a composite of 3 core areas in the West IO, 3 vessel size categories, 3 flags (France, Spain, Seychelles) was calculated (Avg_3areas). The CPUEs, with maximum values rescaled to 1, are given in Fig. 18. Although following the same overall trend, the different nominal series showed some important differences from 1991 to 2001. The series showed more similarity from 2001 to 2016. The standardized CPUE series follows the same pattern, smoothing peak values of the nominal series. There are 3 noticeable lows in the series: 1997, 2007 and 2012 and a secondary one in 2015. The first two lows corresponded to environmental anomalies associated to El Niño/Positive IO dipole mode in 1997-98 and 2007 which are causing depleted primary productivity conditions. The low CPUE recorded in 2012 and 2015 also corresponded to anomalously low chlorophyll productivity associated to weak positive dipoles (see environmental indicators, section 6). A linear fit performed on the standardized series indicates a 43% decline between 1991 and 2016. CPUE series based on the fishing time gave similar trend and variability as those based on sets.

It must be reminded that the fishing efficiency of purse seiners is a complex combination of technological improvements which varied with time, with great complexity to include those in CPUE standardization procedures. A summary of those factors is given in Appendix.

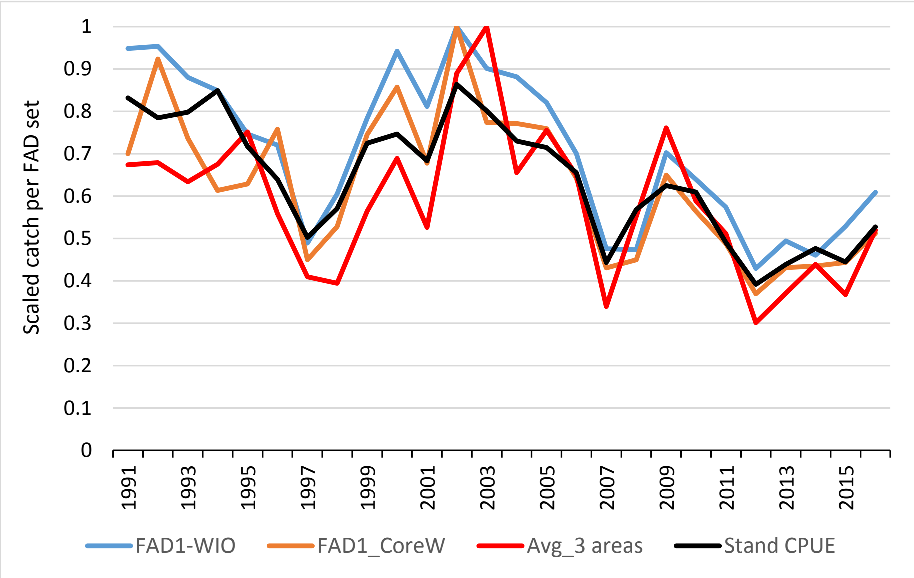

Fig.18 – Three nominal CPUE series (catch per FAD set) and standardized CPUE for skipjack (Katara et al 2017), 1991-2016. The series have been rescaled to have their maximum value set à 1.

The trends of standardized EU purse seine (Kitara et al 2017) and Maldivian baitboats (CPUEs show some difference over the period 2005-2015. The decline in PS series is not steady, with two lows in 2007 and 2012, whereas the decline of the BB series is more regular and steeper (Fig.19). The decline for 2005-2015 is 30% for PS and 43% for BB.

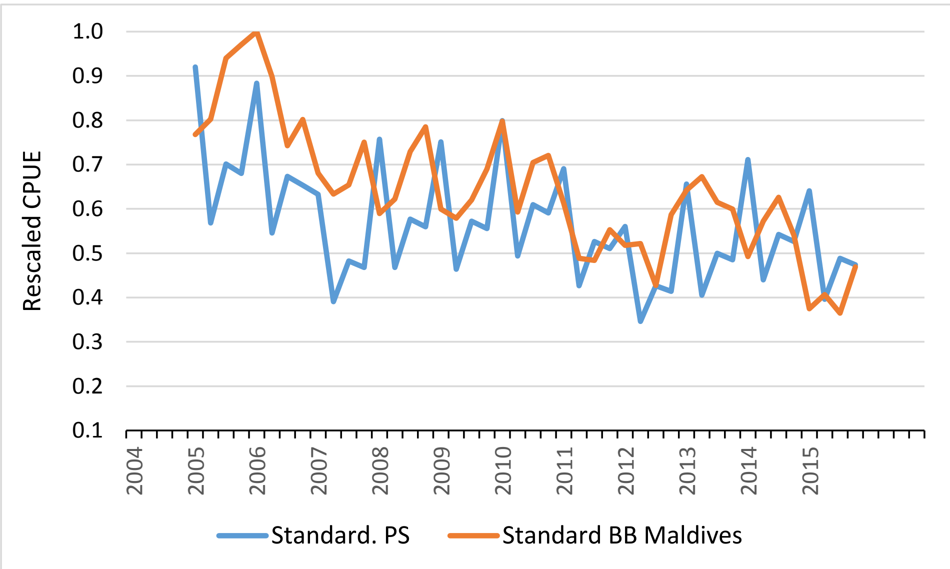

Fig.19 – Comparison of EU purse seine and Maldivian baitboat standardized CPUE over 2004-2016, on a quarterly basis. Source: Kitara et al (2017) for PS and Medley et al (2017) for BB

The catch per set for two periods, 2001-2009 and 2010-2016, were compared spatially. We computed the difference [2010 2016] – [2001 2009] for each 1° square fished during both periods (Fig.20). The period 2010-2016 was far less productive (mostly driven by year 2012) than 2001-2009, especially in the Somali Basin and around the Seychelles (red circles). The squares with larger catch per set in 2010-2016 (blue circles) were located in the North Mozambique Channel and in the easternmost part of the fishery.

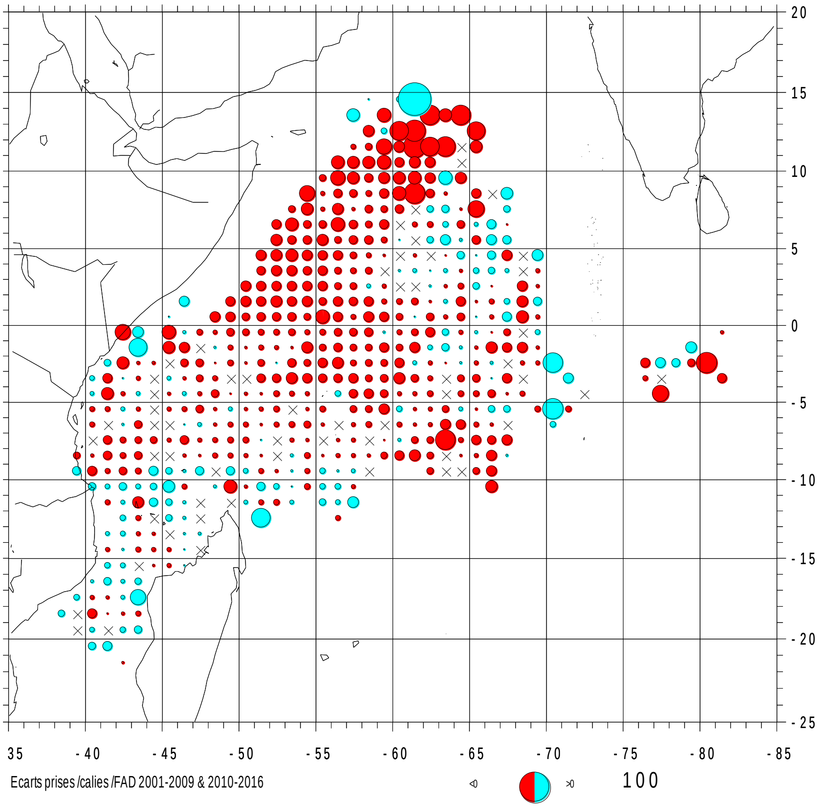

Fig.20 – Map of the difference of catch per set between 2010-2016 and 2001-2009. The red circles denote higher production during 2001-2009, the blue circles a higher production during 2010-2016. The squares noted with x denote equal catch per set between the two periods

4- Size based indicators for skipjack

a) Average weight: The average weight of skipjack, calculated from the updated IOTC Catch-At-Size, exhibits some yearly fluctuations (Fig.21). Gillnet are catching the largest sizes, with a slight declining trend since 2007 (-6%). However the areal coverage and the number of samples are very limited and these data must be considered with great caution in terms of their absolute level and trend. Skipjack caught by baitboats was fluctuating without trend with an average of 3.6 kg until 2006, then a sudden change happened in 2007 and has persisted since then (average of 3.2 kg, -11%). Skipjack caught by purse seine on FADs has declined by 19% between 1984 and 2016 (3.3 to 2.7 kg). Sizes caught on free schools have increased in 2016 but skipjack are now seldom caught on free schools.

b) Proportion of immature fish: we used the skipjack CAS prepared by the IOTC to estimate the number and proportion of immature fish caught by two main gears targeting skipjack, PS on FADs and Maldivian baitboats, for which regular size sampling is performed. A retrospective over the 2010-2016 is presented Fig.22 to cover twice the number of fully exploited age classes. The size at first maturity was established at 39.9 cm by Grande et al (2014). For PS on FADs, the number of immature skipjack fluctuated without trend until the 3rd quarter 2015, then recorded a boost with maximal value in 4th quarter 2016 (2.5 million fish, 14.5% of SKJ FAD catches). For Maldivian baitboats, catches of immature skipjack has fluctuated without trend since the 3rd quarter 2013, in the range 600 000 - 1.7 million fish by quarter.

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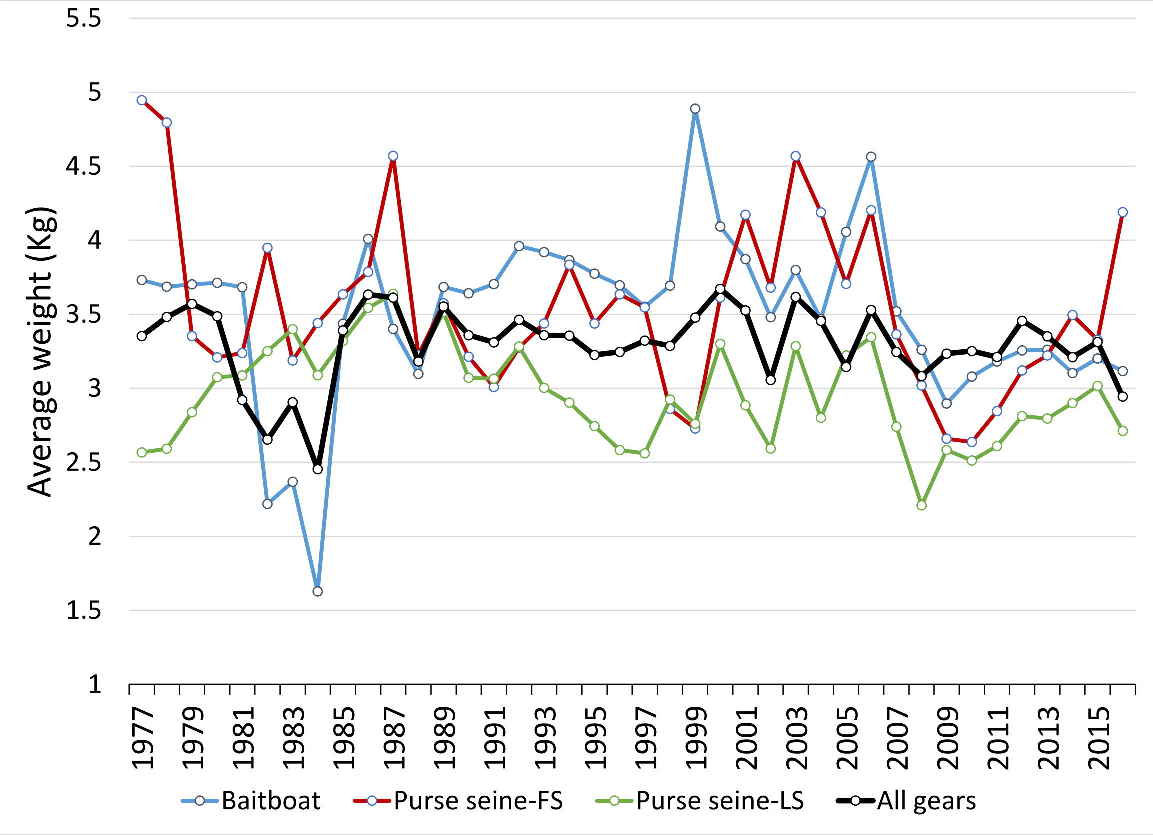
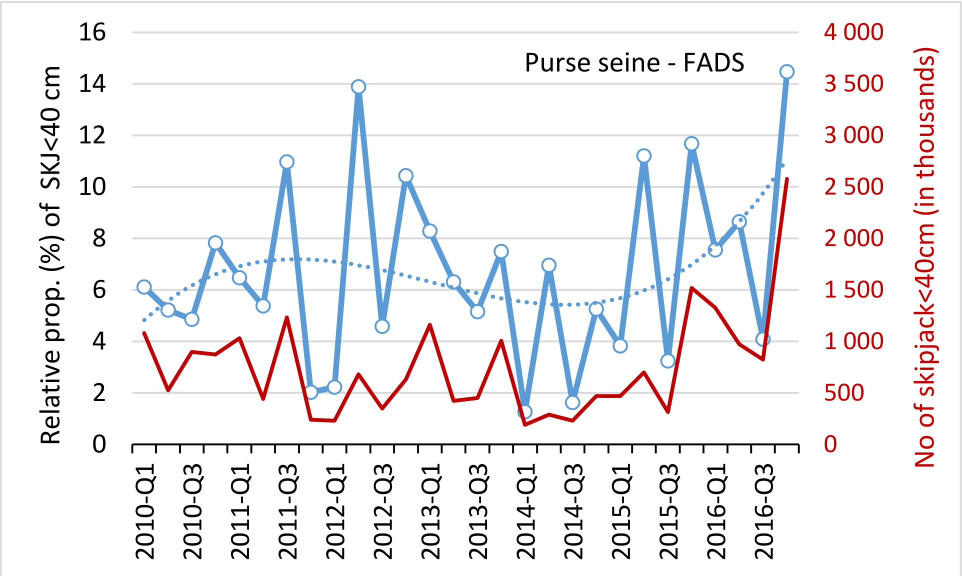


Fig.21 – Average weight of skipjack by gear. Source: IOTC CAS data.
(Gillnet data are not represented because of uncertainty on size data and lack of significant geographic coverage).



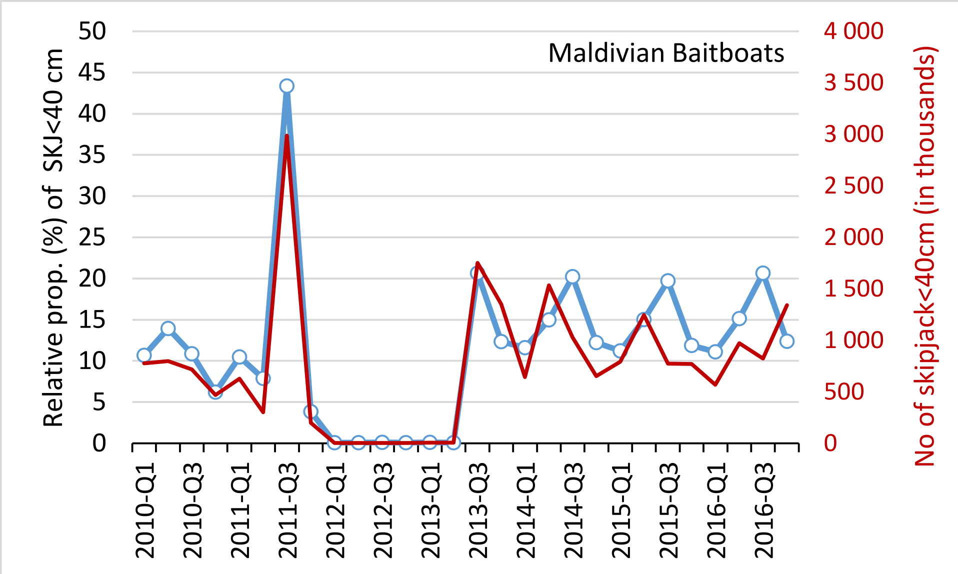


Fig. 22 - Trend in the proportion of immature skipjack (<40 cm LF) caught by PS on FADs (top) and BB (down). Source : IOTC Catch at Size.

5- Tag recovery-based indicators

The apparent monthly distances traveled between the tagging and recovery positions indicate the magnitude of movements that a species can undertake. Average monthly values do not give excessive weight to the period just after tagging during which the largest numbers of short term recoveries are most often observed (Fonteneau et al 2015). Indeed, these estimates can be affected by the reporting rate. However, skipjack reached large distances after only one month at liberty (average > 700 nautical miles) which is much greater than EEZ sizes but much smaller than ocean basins (Fig.23). The overall average travelled distance by skipjack in the Indian Ocean was estimated at 1066 nm, the second longest distance after the East Pacific Ocean (1281 nm). Average distances in the West Pacific Ocean and Atlantic Ocean were smaller, respectively 622 and 489 nm (Fonteneau et al, 2015).

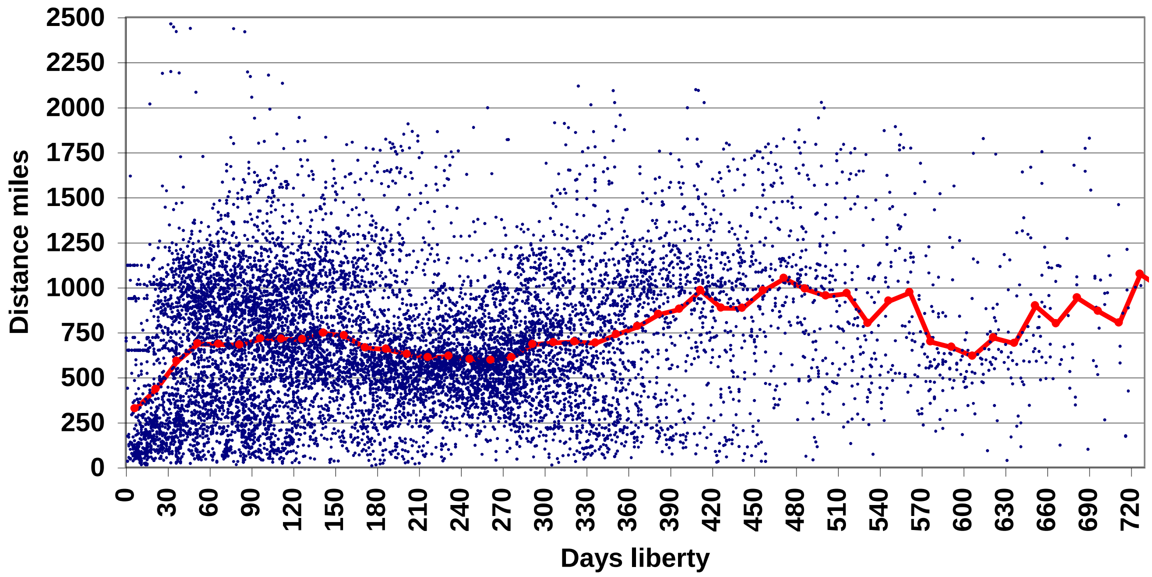


Fig.23 –Apparent monthly distances traveled by skipjack during the RTTP-IO.

6- Environmental indicators

The sea surface chlorophyll concentration is an indicator of the ocean productivity. Since 1997, when SeaWifs started to operate, 3 distinct phases can be observed (Fig. 24). Depleted surface chlorophyll conditions (40% below normal) prevailed in 1997-98, and again from 2007 to 2013 (only interrupted by a productive semester, September 2010 to March 2011). By contrast, very productive conditions were recorded from 2002 to 2006. The last 3 years of the series show highly contrasted situations with successive yearly elevated and depleted surface chlorophyll concentration.

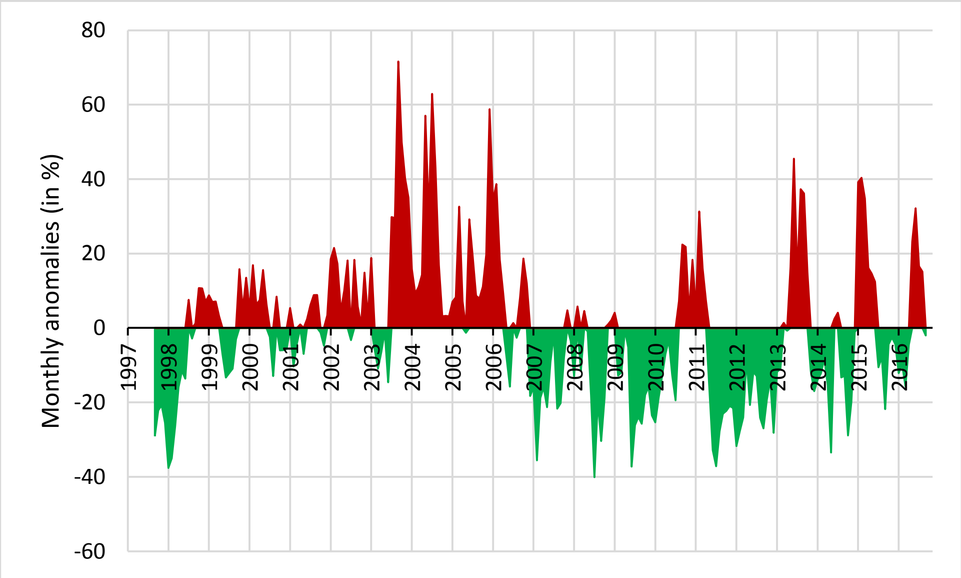


Fig.24 – Monthly chlorophyll-a anomalies in the core FAD fishing area (8°N-8°S/50°E-65°E).
Source : SeaWifs (1997-2002) and MODIS (2002-2016) sea color data

The depleted chlorophyll conditions are closely associated to positive Indian Ocean dipole (in red, Fig. 25) whereas productive conditions are mostly found during negative dipole events. (blue).

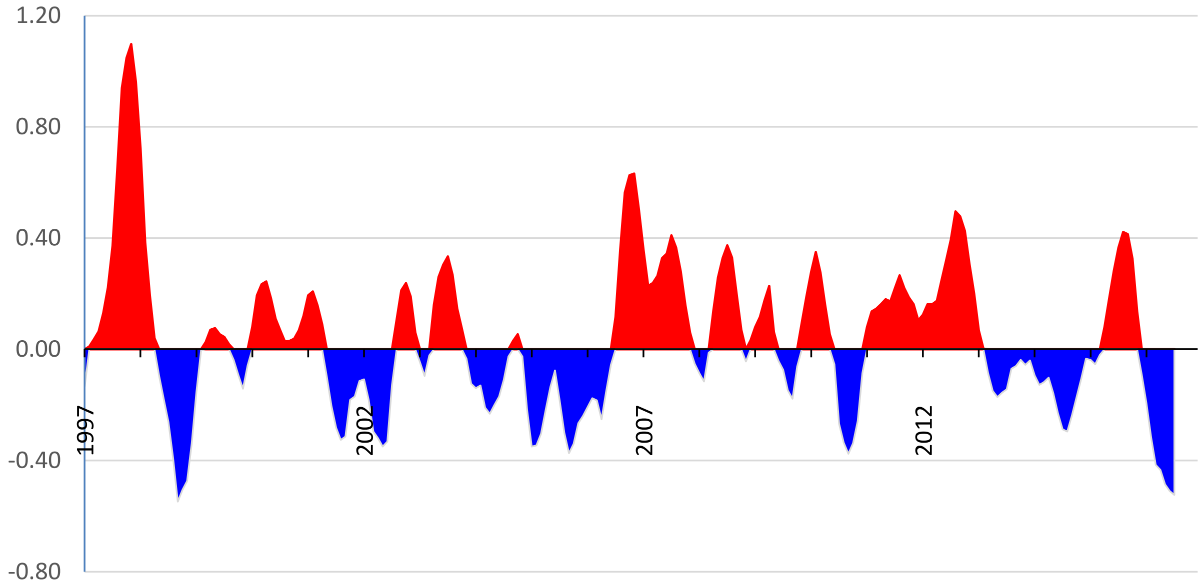


Fig.25 – Smoothed monthly variation of the Dipole Mode Index (DMI), 1997-2015

7- Discussion and conclusion

The main information emerging from the set of indicators presented in this paper can be summarized and discussed as follows:

- The fishing days (and capacity) of the purse seine fleets was reduced in 2009-2013 as a consequence the Somalian piracy but since then, the effort has increased again. More specifically for the PS FAD fishery which contributes the most to skipjack catch, the number of support vessels since 2011 has increased at a faster rate than the PS effort and capacity. Similarly, the number of FAD buoys (at least for French fleet) has shown a faster rate of deployment since 2014. It should be noted this number is largely underestimated as it does not account for Spanish and Seychelles fleet which have a more FAD-directed strategy than French vessels.
- Since the development of the PS fishery, the core of the PS FAD zone has not varied much, essentially inside a box 8°N-8°S/50°E-65°E and in the North Mozambique Channel. However, fishing pressure has increased in those areas and beyond, because of a dramatic increase of active FAD buoys in the core FAD fishing zone, which spread to the east by surface currents, increasing the area of the PS FAD fishery in 2016.
- The proportion of catches on FADs has reached unprecedented high levels (75-85%) since 2009 for Spanish and Seychelles fleets. In parallel, skipjack catches on free schools have reached historical low levels since 2009. The proportion of skipjack on FADs has decreased in recent years compared to the years 2001-2009 whilst an opposite trend was observed for yellowfin.
- Catch rates (nominal and standardized CPUE) have declined for both major gears, PS on FADs and baitboats, however at a steeper rate for baitboats compared to purse seiners. Baitboats do not have a large operating range, therefore local depletion processes are more critical on the Maldivian fleet than for purse seine fleets which cover large areas. The CPUE decline by PS shows a "bumpy" trend, where lowest values are likely to be associated to detrimental environmental conditions ($r=0.60$, $\alpha<0.05$). El Niño and Indian Ocean Positive Dipole events are conducive to lower chlorophyll productivity, which can reduce the density of forage fish for tunas. Conversely, the high CPUEs recorded for 2002-2005 by PS fleets (and 2005 for Maldivian baitboats) could be associated to anomalously high chlorophyll content observed during a regime of negative Indian Ocean Dipole.
- The PS CPUE is driven by the occurrence of large skipjack set on FADs (>60 t; $r=0.984$, $\alpha<0.01$) and such large schools have levelled off since 2013. By contrast, the smaller schools (< 30 t) have become predominant since 2007 and have increased after 2013 to reach an unprecedented high level in 2016 (90 000 t, representing 56% of skipjack catch on FADs).
- The average weight of skipjack have declined by 19% for purse seine on FADs over 1984-2016 and an 11% decline happened suddenly after 2006 for the Maldivian baitboat fishery. During recent years, the standing low occurrence of free schools with skipjack (which are composed of larger fish) is likely to explain the declining average weight of PS catches. Similarly, the proportion of immature skipjack has increased and peaked at 14.5% of SKJ FAD catch (2.5 million fish) in 2016, whereas proportion for Maldivian boats bas been fluctuating around an average of 1 million fish (15% of BB catch).
- A simple analysis based on the relative rate of catch increase versus catch levels suggests that the skipjack stock is currently exploited around its full potential (intercept at 415 000 t for a 2016 catch of 450 000 t). However, this level may be underestimated as the artisanal fleets represent a growing fraction of SKJ catches (30% in 2016) and that activities of these fleets are poorly understood, with insufficient size sampling and lack of time-area catch-and-effort series

The fast response of depleted (elevated) ocean productivity in terms of low (high) skipjack CPUE (and occurrence of large schools associated to FADs) can be interpreted as a direct impact of ambient foraging conditions on vital processes, such as growth and breeding. Skipjack would utilize an income breeding strategy (Grande et al (2016) where reproduction would be supported directly by food intake during the breeding season. Therefore, seasonal/interannual variability in primary productivity conditions would be useful to appraise stock dynamics for such a highly responsive species to ambient conditions.

The dominance of small schools sets at FADs since 2007, and its maximum reached in 2016 where ambient conditions (chlorophyll content) where favorable, could suggest school fragmentation, a concept which was introduced by Fonteneau and Marsac (2016) at the WPTT18. Under this hypothesis, the growing number of drifting FADs could have sucked out free schools (which were frequent in the 1990s) and partitioned the available biomass into smaller schools. If such situation persists, this could become detrimental to fishing fleets because of the economic cost of setting around small aggregations not being offset by a significant profit. It should be reminded that FAD-directed strategy generates substantial costs (larger purse seiners, support vessels, larger distances covered, cost of buoys…).

The apparent maximum distances travelled by skipjack of about 1000 nautical miles, a finding of tag-recovery experiments, suggest that the stock might not be homogeneous and not evenly distributed at the scale of the Indian ocean. Basically, stock assessment models could consider several sub-areas accounting for various fractions of semi-independent stocks with limited flux across the borders, as it is very unlikely that skipjack tunas move from Indonesia to Arabian Sea or West equatorial zone within one or two quarters of a year.

In conclusion, most of the indicators presented in this paper portray a situation where the Indian Ocean skipjack stock would be fully exploited. Moreover, this analysis underlines potential concern of future overfishing since increasing catch levels, including immature fish, and overall trend in fishing effort and strategy as seen in the last two years, might not be sustainable. With the growing importance of fleets from developing states fleets, significant improvement in the collection of C/E collection, size data and a better understanding of the trends in gears used and targets for those countries are necessary actions.

Acknowledgements

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References

Fonteneau, A., Chassot, E., Bodin, N. (2013). Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): Taking a historical perspective to inform current challenges. *Aquat Living Resour.*, 26: 37-48.

Fonteneau, A., Hallier, J-P. (2015). Fifty years of dart tag recoveries for tropical tuna: a global comparison of results for the western Pacific, eastern Pacific, Atlantic and Indian oceans. *Fish. Res.* 163: 7-22.

Fonteneau, A., Marsac, F. (2016). Fishery indicators suggest symptoms of overfishing for the Indian Ocean skipjack stock. IOTC-2016-WPTT18-INF02, 15p.

Gaertner D., Fonteneau A., Laloë F., 2001, Approximate estimate of the maximum sustainable yield from catch data without detailed effort information: application to tuna fisheries. *Aquat. Living Resour*. 14, 1–9.

Grainger, R.J.R., Garcia, S., 1996. Chronicles of marine fishery landings (1950–1994). Trend analysis and fisheries potential. *FAO Fish. Tech. Pap*. 359, 1–51

Grande, M., Murua, H., Zudaire, I., Arsenault-Pernet, E.J., Pernet, F., Bodin, N. (2016). Energy allocation strategy of skipjack tuna Katsuwonus pelamis during their reproductive cycle. *J. Fish. Biol*. 89: 2434-2448.

Grande, M., Murua, H., Zudaire, I., Goñi, N., Bodin, N. (2014). Reproductive timing and reproductive capacity of the skipjack tuna (Katsuwonus pelamis) in the western Indian Ocean. *Fish. Res.* 156: 14-22.

Katara, I., Gaertner, D., Billet, N., Lopez, J., Fonteneau, A., Murua, H., Daniel, P., Báez, J.C. (2017). Standardization of skipjack tuna CPUE for the EU purse seine fleet operating in the Indian Ocean. IOTC-2017-WPTT19-

Marsac, F. & Le Blanc, J-L. (1999). Oceanographic changes during the 1997-1998 El Niño in the Indian Ocean and their impact on the purse seine fishery. WPTT-99-03, IOTC Proceedings 2: 147-157.

Marsac, F. (2015). The Seychelles tuna fishery and climate change. In : Phillips BF & Perez-Ramirez M. (Eds). The Impacts of climate change on fisheries and aquaculture, pp 523-569, Wiley & Blackwell

Maufroy, A. (2016). Dispositifs de Concentration de Poissons (DCP) des océans Atlantique et Indien : modalités d'utilisation, efficacité de pêche et potentialités de gestion. Thèse de Doctorat, Université de Montpellier.

Maunder, M. (2016). Updated in indicators of stock status for skipjack tuna in the Eastern Pacific Ocean. 8th IATTC Scientific Advisory Committee, La Jolla, 8-12 May 2017, SAC-08-04c, 4p.

Medley, P.A., Ahusan, M., Adam, M.S. (2017). Maldives pole and line skipjack tuna CPUE standardization 2004-2015. IOTC-2017-WPTT19-44, 20 p.

Moreno, G., Dagorn, L., Capello, M., Lopez, J., Filmalter, J., Forget, F., Sancristobal, I., Holland, K. (2016). Fish aggregating devices (FADs) as scientific platforms. *Fish. Res.* 178: 122-129

Potier, M., Marsac, F., Lucas, V., Sabatié, R., Hallier, J-P. & Ménard, F. (2004). Feeding partitioning among tuna taken in surface and mid-water layers : the case if yellowfin (*Thunnnus albacares*) and bigeye (*Thunnus obesus*) in the Western Tropical Indian Ocean. *Western Indian Ocean J. Mar. Sci.* 3(1): 51-62.

Romanov, E.V., Potier, M., Anderson, R.C., Quod, J.P., Ménard, F., Sattar, S.A. & Hogarth, P. (2015). Stranding and mortality of pelagic crustaceans in the western Indian Ocean. *J. Mar. Biol. Assoc. UK*, 95(8): 1677-1684.

Schott, F.A. & McCreary, J.P. (2001). The monsoon circulation of the Indian Ocean. *Progr.Oceanogr.* 51: 1-123

Appendix

Major technological improvements in the purse seine fleets.

- More FADs with increased efficiency: multiple technological progress
- More supply vessels, increased performance: a large number of newly built and purposely designed vessels
- Improved nets since the early 1980's
- Use of advanced sounders and long-range sonars (since early 2000's)
- increased use of Doppler current meter
- Improved bird radars since the early 1990's
- Massive use of computers in all the fishing activities
- Perfect positioning by GPS for all purse seiners
- Multiple satellite imagery received daily allowing improved tactics & strategy
- Increased support by scientists hired by the fishing companies
- Improved & increased communication between purse seiners
- Increased height & equipment of the mast & bird nests
- Increased freezing capacity, allowing to catch larger sets
- More efficient landing process: allowing more fishing days