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# On the movements and stock structure of skipjack (*Katsuwonus pelamis*) in the Indian ocean.

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Summary

This paper discusses the skipjack movements observed in the Indian Ocean based on an analysis of fishery data of the 13.128 selected recoveries of tagged skipjack. Its goal is to evaluate the potential geographical heterogeneity of the skipjack population fished in the Indian Ocean. Significant latitudinal & longitudinal movements have been frequently observed; the geographical range of skipjack movements appears to be wide in scale, showing an average distance over 1000 miles between tagging & recovery positions. These distances are showing an increasing trend with time at liberty, and reaching average distances of 1400 miles after 2 years. Recovery data are also showing that skipjack movements are often very fast, for instance reaching average distances over 800 miles after only 1 month at liberty in the Tanzania tagging. Distances covered are the lowest for skipjack tagged in the Maldives and in Seychelles islands and much larger in the Tanzania and Seychelles tagging. these differences are discussed. Because of these fast and extensive movements of skipjack, it can be concluded that its population is highly mobile in the Indian Ocean, but that the mixing rates of individual skipjack that are fished in remote parts of the Indian Ocean are probably low or very low. Based on these results, it is proposed that skipjack indicators and future skipjack stock assessment should be stratified on at least 4 areas, and estimating the mixing rates of skipjack tunas fished in each of these areas.

## 1- Introduction:

A good knowledge of tuna movements is essential to allow a realistic stock assessment and management of every tuna stocks. The best way (and often the only way) to estimate this basic scientific knowledge is to run large scale and well conducted tagging programs, when information obtained from other sources (for instance from genetics and from fisheries) are useful, but most often of secondary interest. This good knowledge of tuna movements in addition to the knowledge of spawning zones is essential to establish the frontiers between stocks that will be used by tuna RFOs to manage these resources**.** Stocks are the management units that are chosen to efficiently manage the stocks. In an ideal case the limits between stocks correspond with self regenerating sub-populations, preferably with very minor mixing between the various stocks. Such limits between stocks should only be seen as temporary frontiers used as stock assessment and management working hypothesis. Some regions with large biomass of tunas are born in the area and later highly viscous, showing low movement

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rates in & out this region, could perfectly be considered as being “stock”: at least for assessment and management goals.

The first scientific use of knowledge on stock structure is to establish ideal homogeneous areas that are well fitted with the movement patterns of each stock. In the Indian Ocean, it has been assumed during recent years by the IOTC (Sharma et al 2012) that a 2 areas model could be used to run the SS3 stock assessment model. This hypothesis is also indirectly assuming that there is a full mixing within each of the 2 western & eastern areas.

This document will examine the biological and fishery parameters concerning the skipjack population and fisheries, and it will analyze the movement patterns of skipjack than can be estimated from the tagging results. Its final goal will be to discuss the potential areas that should be used in the assessment and management of Indian Ocean skipjack.

# 2. Material and methods

## *2-1- Overview*

This paper will examine a wide range of biological and fishery data, and it will analyze the recovery data concerning Indian Ocean skipjack and the distances and trajectories of tagged skipjack between their tagging and recoveries.

## *2-2- Fishery data*

All the fishery data (skipjack catches and catch at size by time and area and by gear) are easily available in the Indian Ocean, based on the catch and effort data released by the IOTC secretariat (IOTC WEB site). These basic data were used in the present study.

## *2-3 Tagging and recovery data*

All the skipjack tagging & recovery data in the Indian Ocean are available and circulated by the IOTC secretariat. This work is based on the tagging and recovery file circulated in September 2014 by the IOTC. The analysis of this tagging/recovery file is showing:

- that 115.718 skipjack have been tagged in the Indian Ocean during the 1990-2009 period,
- that 17.767 tagged skipjack have been recovered,

In a 1st step, all the recoveries of tunas that have been tagged and recovered as being skipjack have been selected from this file.

In a 2nd step, all the recoveries showing too much uncertainties in their fishing location or in their fishing dates have been eliminated from the recovery file. The following criterions have been used to select our skipjack recoveries:

- All recoveries tagged declared before the tagging date were eliminated
- All recoveries with a relative uncertainty in the duration at sea over 25 % was eliminated (based on the uncertainty in time at sea given in the IOTC file)
- All recoveries with a relative uncertainty in the distance travelled over 25 % was eliminated (based on the uncertainty in time at sea given in the IOTC file)

As a result, a subset of 13.128 skipjack have been recovered with a consistent species, a good date and a good fishing location; these selected recoveries are the main base for our study of skipjack movements in the Indian ocean. This number of recoveries is in fact much higher than the numbers of skipjack recoveries available to study movements in the Western or eastern Pacific and in the Atlantic oceans (Fonteneau & Hallier 2014)

# 3-Results

## 3-1- Overview of Skipjack biology

Skipjack spawning activities are widely spread in time and space, probably in most warm equatorial waters at SST >25°C. The historical Japanese surveys of skipjack larvae have identified large quantities of skipjack larvae in the Equatorial Eastern IO (Nishikawa et al 1985), but these surveys have been quite rare in the Western IO. The location of skipjack nurseries remain widely unknown, as well as the biology of skipjack early juveniles, because very small sizes of skipjack have never been exploited significantly in the IO (figure 1). It should be noted that all Indian Ocean fisheries are catching skipjack in warm waters at SST over 24 or 25°C, when various fisheries are targeting skipjack in colder waters in all other oceans) (Fonteneau 1998). Skipjack are frequently associated to floating objects in the Indian Ocean: skipjack is most often the dominant species under FADs, always present under FADs, and always associated to small bigeye and yellowfin.

## 3-2- skipjack fisheries and skipjack habitat in the Indian Ocean

### 3-2-1-Overview

Very small sizes of skipjack (for instance less than 1kg) are seldom caught by any known fishery in the IO, and then very little is know on these prerecruited sizes of skipjack, when in the Western Pacific they are actively fished by coastal fisheries of Indonesia and Philippines ; large skipjack are more commonly caught in the central Indian Ocean where they are targeted by Maldivian baitboats, but they are seldom caught by purse seiners (when in the Atlantic these large skipjack are actively fished by Brazilian baitboats).

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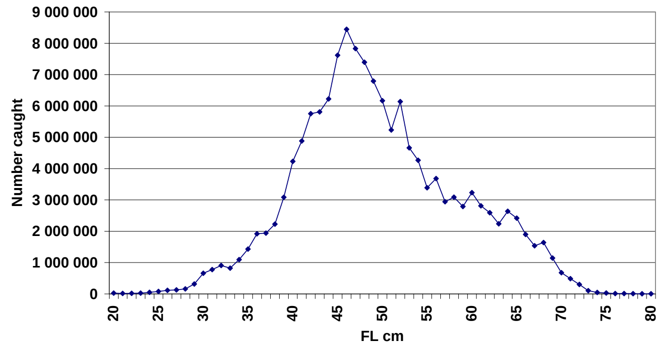


Figure 1: Average catch at size of Indian Ocean skipjack (period 2000-2011)

Skipjack habitat based on fishery data is wide in the Indian Ocean: covering all warm waters at SST >24°C between the coast of Africa and the continent of Asia, and approximately the northern frontier of the South Indian Ocean gyre. Skipjack are very seldom caught by longliners in the Indian Ocean, most often at large sizes, but these incidental catches are indicative of the wide skipjack potential habitat of large skipjack. The potential habitat of adult skipjack in the Indian Ocean is well shown by the by catches of adult skipjack that have been identified in the various LL fisheries. These catches are shown by figure 2.

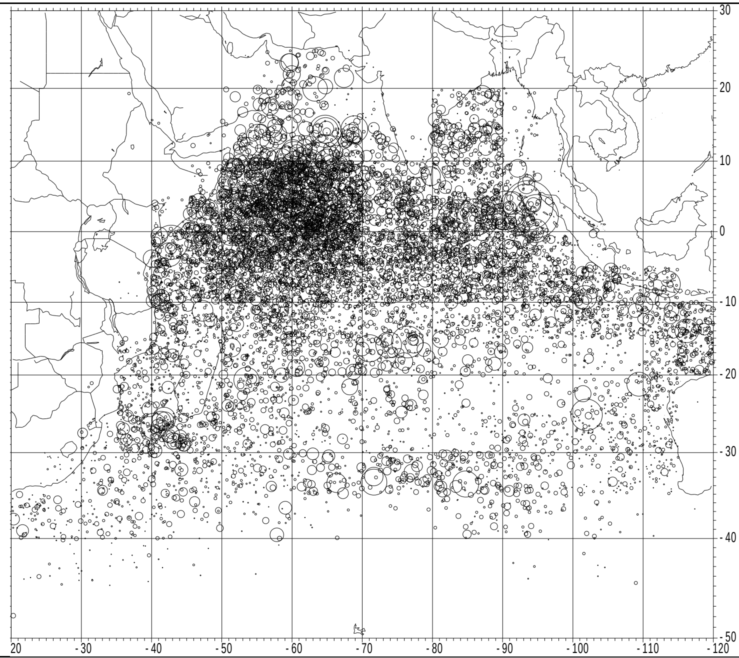


Figure 2: skipjack catches declared to IOTC by LL during the period 1950-2012 (each monthly catch being plotted on the map at a random position in each 5° square).

Even if this figure has a limited quantitative value, it would show that skipjack are caught everywhere in the Indian Ocean between northern coasts and 40°S. Skipjack by-catches caught by longliners are more important between 10°N and 10°S, and more important in the western Indian Ocean, the area that has been more actively fished by longliners during the period..

Based on fishery data, it would appear that skipjack biomass is low or very low in the southern Indian ocean south of 12°S, i e in the Indian Ocean southern gyre (Longhurst areas). This gyre is the kingdom of adult albacore, but as in the other oceans, it does do not offer a suitable habitat for skipjack. FAD fisheries developed by purse seiners since the early nineties have widely increased the catchability of the skipjack stocks, especially in the western Indian Ocean, increasing the size of the areas fished by purse seiners (solely in the equatorial waters) and also the total catches of skipjack. The percentage of skipjack caught today in the Indian Ocean associated to FADs is very high: 90 % of the skipjack catches by purse seiners were caught by purse seiners under FADs (average 2004-2013). In the ecological trap hypothesis (Marsac et al 2000), the large number of FADs that are active today in the Eastern and Western Indian Ocean may have modified the original movement pattern of skipjack (as in Hallier and Gaertner 2008, and Chang et al 2014)

Fishery data are not sufficient to evaluate skipjack movements between areas, but catches & CPUEs of the various gears by size categories in the various time and area strata, are providing some indications on the geographical distribution and on skipjack potential movements. These fishery information are of special interest when they are associated to environmental data such as sea surface temperature.

**3-2-2- Location and seasonality of skipjack surface fisheries**

The location and the seasonality of skipjack catches by surface fisheries are well known for purse seiners and for Maldivian baitboats and these fishery data may provide some useful indications concerning the skipjack seasonal movements. However it should also be noted that various major fisheries are also targeting skipjack in the Northern Indian Ocean but without providing to the IOTC any detailed statistics on their location or seasons. As the total catches of these "ghost skipjack fisheries" have been reaching about 50% of the total skipjack catches during recent years, these fisheries are introducing major uncertainties in all the skipjack studies. The location of known and of ghost skipjack fisheries is shown by figure 3.

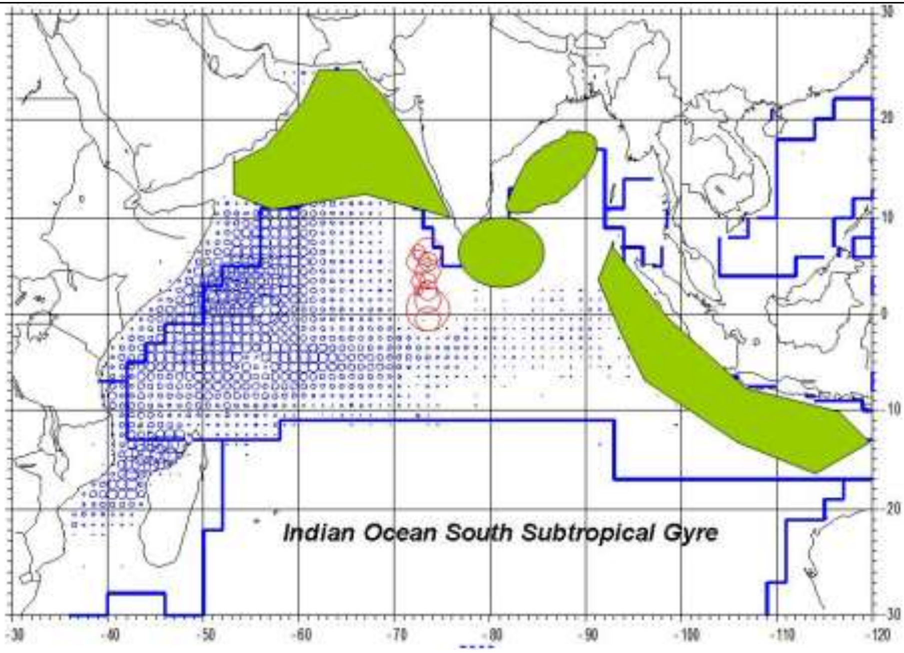


Figure 3: Average skipjack catches by purse seine fisheries (in blue) and of Maldivian pole & line skipjack catches in red (by 1° squares) and approximate location of skipjack fisheries without statistics (so called "ghost fisheries").

### 3-2-3. Seasonality of selected skipjack fisheries

The seasonality of purse seine fisheries is an interesting factor to keep in mind and figures 4 and 5 are showing the total monthly catches of skipjack by purse seiners in the Mozambique Channel and in the Somalian area (North of equator).

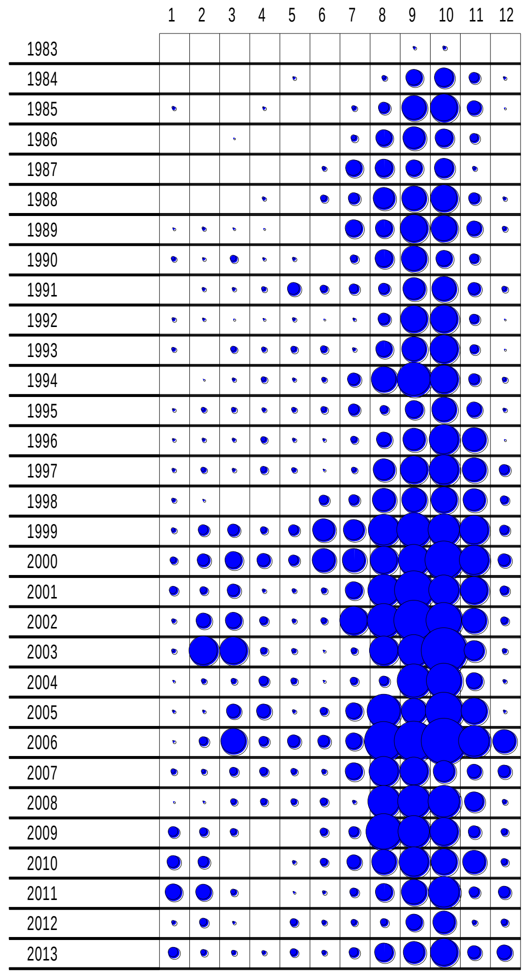


Figure 4: skipjack monthly catches by purse seiners in the Somalia area

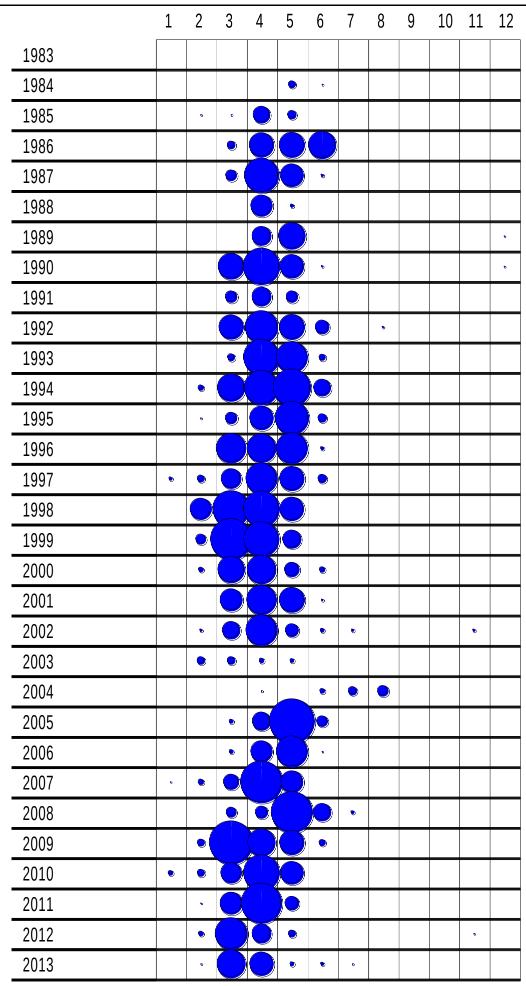


Figure 5: skipjack monthly catches by purse seiners in the Mozambique Channel area

There are strong reasons to consider that the seasonality of skipjack catches in these 2 areas are mainly due to seasonal North---North movements of skipjack. Large biomass of skipjack are temporarily moving each year between March and May in the Mozambique Channel (these seasonal movements being widely confirmed by recoveries of tagged skipjack tagged in Tanzania (figure 12a), and one year after their tagging in the Mozambique Channel (figure 12c). Similar patterns have been observed each year in the Somalia area (a very rich feeding zone because of the Somalian upwelling), an area showing large skipjack catches each year, mainly between August and October. However, if these seasonal movements appear to be realistic, the geographical origin of skipjack travelling to these areas and the distances travelled to reach them remain unknown.

## 3-2-4- Linear distances between the major skipjack fisheries

In the discussion of the potential mixing between tunas caught in various areas, it is of great importance (1) to measure the distances between each of the fisheries, and (2) to compare these distances with the potential movements that have been estimated form tagging programs. Figure 6 is showing an overview of the linear distances between the cores of some major skipjack fisheries in the Indian Ocean.

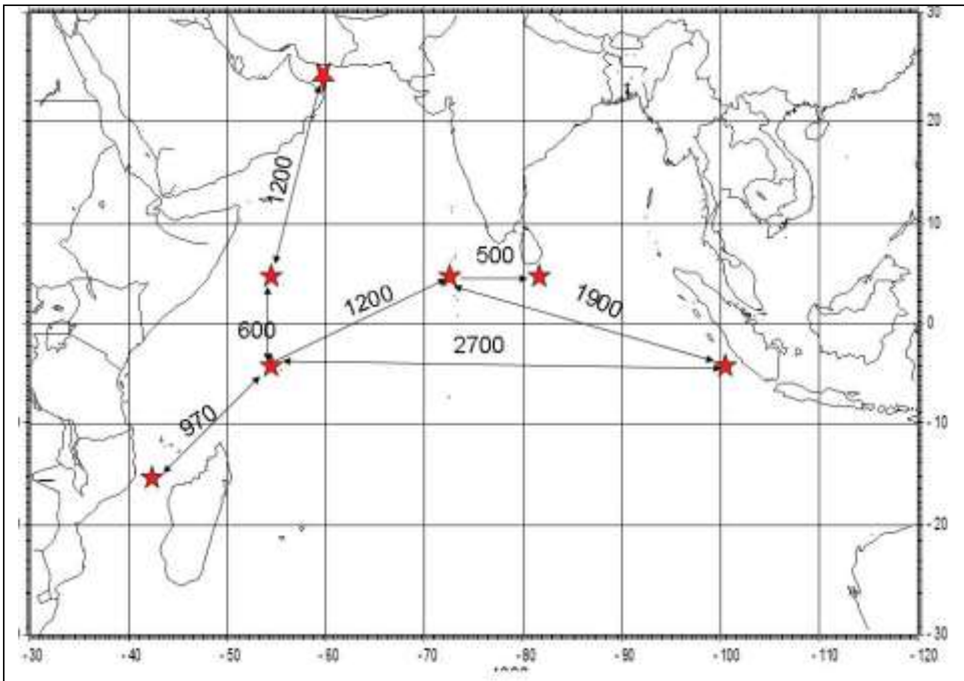


Figure 6: Linear distances between the core of the major skipjack fisheries in the Indian ocean

These distances are immediately indicative of the potential exchange of skipjack biomass between the various areas:

- Mixing rates are probably lower between remote areas such as Iran & Madagascar or between Seychelles & Indonesia (separated by distances of several 1000 miles…).
- In the absence of an environmental barrier between 2 areas, it should be assumed that the mixing rates are more significant at short distances: for instance between Seychelles & Somalia and between Maldives & Sri Lanka.

## *3-3- Analysis of skipjack movements based on recoveries*

### 3-3-1-Overview

The analysis of movements based on recovery data should ideally be fully quantitative, in order to take into account the fishing strata and CAS of the various fisheries and their reporting rates of tags (as in the studies by Sibert and Hampton 2003 or by Adam et al 2003), but unfortunately these quantitative analysis of the skipjack movement are very complex and they have never been conducted in the Indian Ocean. In the absence of this quantitative modelling of skipjack movements, it is still very interesting to analyze the distances covered by skipjack between tagging & recovery stratified by tagging areas and by durations at liberty.

All the basic fishery and tagging data needed for such study are easily available in the Indian Ocean thanks to the IOTC secretariat.

## 3-3-2- Tagging locations

The location of the present skipjack tagging done in the Indian Ocean is shown by 1° squares in figure 7.

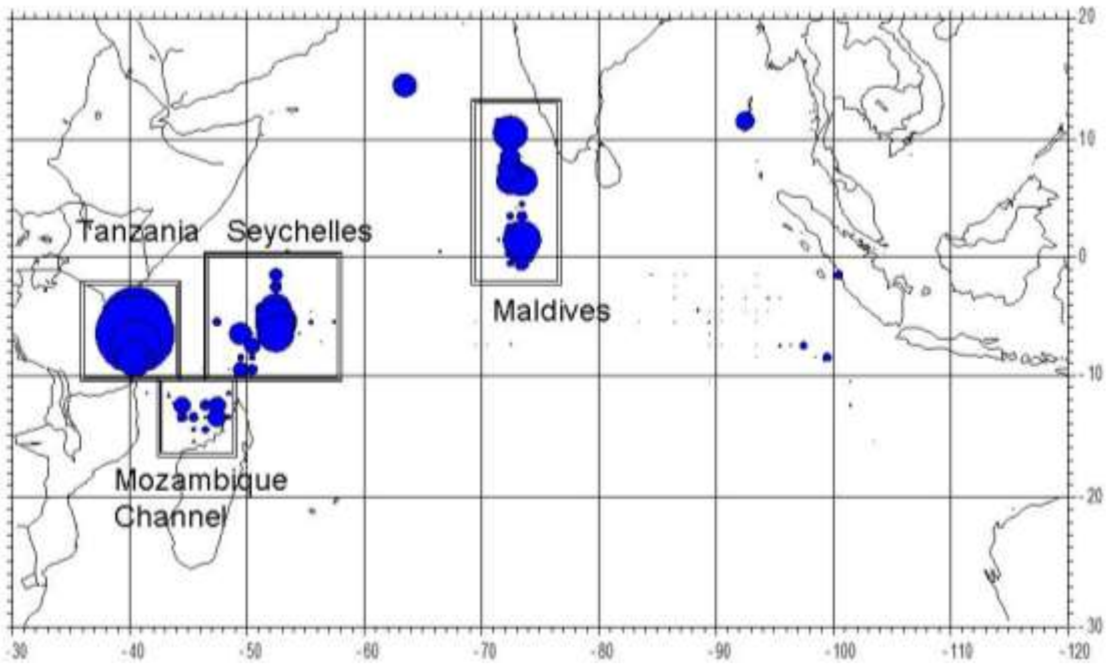


Figure 7: Location of the skipjack tagging in the Indian Ocean, by 1° square, and the 4 tagging areas selected in our study.

This map shows that very few skipjack have been tagged in the Eastern Indian Ocean and very few in the offshore equatorial areas (now the main skipjack fishing zones because of FADs). The tagging areas are quite limited, skipjack tagging mainly done in 4 areas: Maldives, Tanzania, Seychelles and Mozambique Channel and this is a serious limiting factor in the present analysis of the skipjack movements at the scale of the entire Indian Ocean.

## 3-3-3: Trajectories of skipjack Recoveries

Skipjack tagging & recovery data have been showing in the Indian Ocean (and also at a world wide scale, see Fonteneau et al 2013) that skipjack was frequently doing large scale movements, but at variable degrees in each ocean. These apparent movements are well visible on figure 8 showing the linear trajectories of skipjack between tagging and recovery locations and well summarized by table 1.

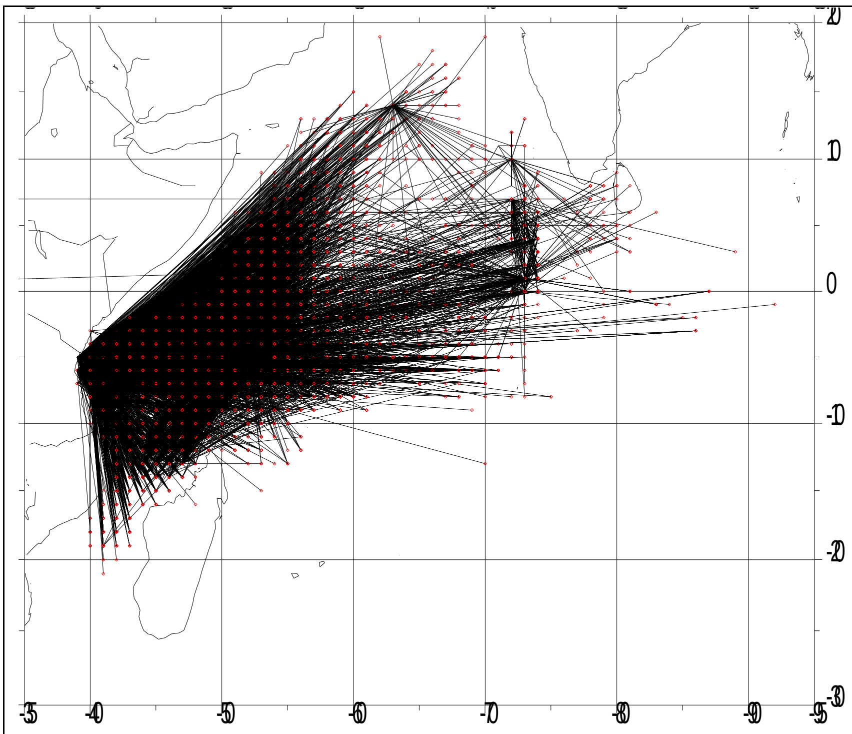

Figure 8: Linear trajectories of skipjack between tagging & recoveries observed in the Indian Ocean.

## 3-3-4- Distances travelled between tagging & recovery

Figure 9 is showing the average monthly distances between tagging & recovery positions as a function of the number of months at liberty observed in the Indian Ocean.

Table 1 is showing the average monthly distances travelled after more than 1 month at liberty in the 4 main tagging areas and for all skipjack recoveries. The same table also gives the distance travelled  by the 1% of the most mobile skipjack, in each tagging area and for all the recoveries.

Table 1: Average distances travelled by tagged skipjack in the India Ocean after more than 30 days at liberty

| | Canal | Maldives | Seychelles | Tanzanie | All recoveries |
|---|---|---|---|---|---|
| **Average distance miles** | **960** | **313** | **722** | **1165** | **1001** |
| **1% of max. distances** | **1900** | **1400** | **1300** | **2030** | **2002** |
| **Number recoveries** | **306** | **4560** | **1671** | **6509** | **13128** |

The average distances travelled between tagging & recovery can be estimated at 1000 miles (monthly average distance between 1 and 36 months at liberty). It can also be noted that the average distances between tagging and recovery locations are increasing as a function of time and that these average distances are different in the 4 main tagging areas, see figure 9. The analysis of recovery data shows that the distances covered by skipjack between tagging and recovery are also conditioned by the tagging zones:

(a) distances travelled are larger for skipjack tagged in Tanzania: an average of 1129 miles travelled by recovered skipjack between 1 & 36 months at sea. SKJ tagged in the Mozambique Channel are also showing similar large distances (an average of  894 miles travelled).

*(b)* Average distances travelled are less important but significant (for instance larger than in most SKJ tagging in the Atlantic) for skipjack tagged in the Seychelles area: only 698 miles

*(c)* distances are the lowest for skipjack tagged in Maldives Islands: an average of 358 miles travelled by recovered skipjack between 1 & 36 month at sea

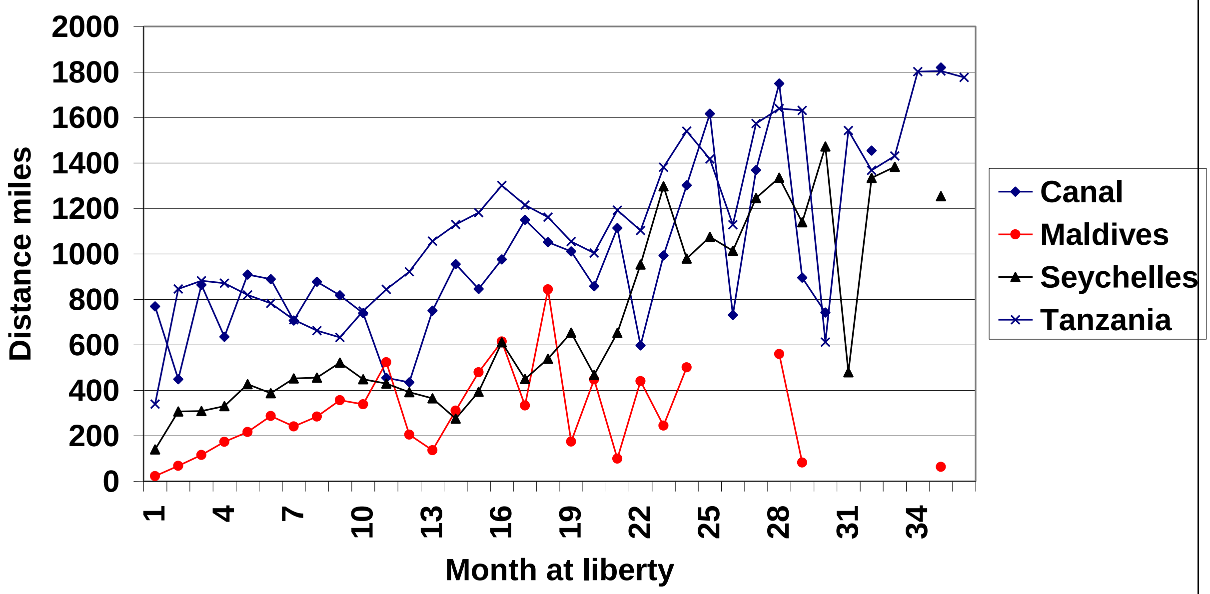


Figure 9: Average montlly linear distances between tagging and recovery covered by skipjack tagged in the 4 areas shown by figure 7.

This increase in the average linear distances between tagging & recovery position is well summarized by table 2. This marked increased of distances travelled are observed in most tagging, but not in the Maldives, an area where distances tend to be constantly low during the 3 years of the recoveries.

Table 2: Yearly average distance covered between tagging and recovery location in the 4 main tagging areas and for all recoveries

| | Canal | Maldives | Seychelles | Tanzanie | All recoveries |
|---|---|---|---|---|---|
| 1st year | 712 | 236 | 383 | 755 | 590 |
| 2nd year | 967 | 385 | 636 | 1193 | 1037 |
| 3rd year | 1297 | 235 | 1173 | 1477 | 1401 |

After 24 months at liberty the average linear distances covered by skipjack between tagging and recovery are reaching an average distance of 1400 miles.

Figures showing the apparent displacement of all the recoveries as a function of time at sea are also interesting to consider. This result is shown for all the selected skipjack recoveries figure 10) and for the recoveries obtained in each of the 4 main tagging areas (figures 12a, b,c & d).

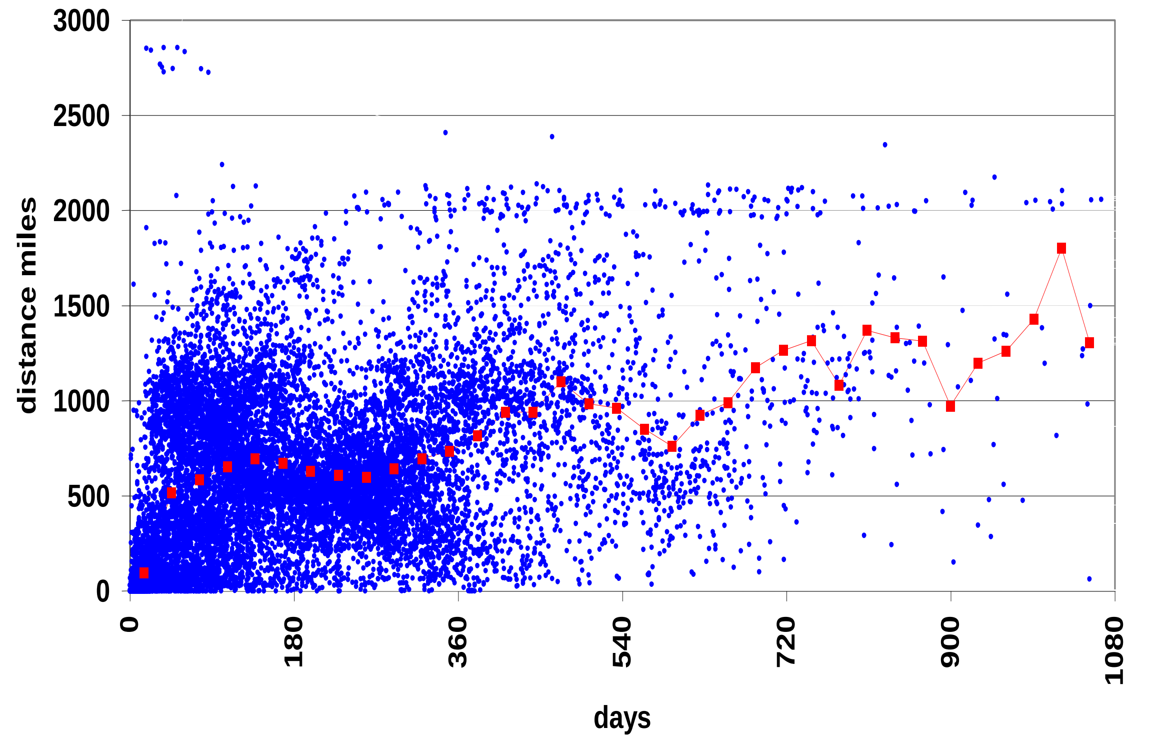


Figure 10: Indian Ocean: linear distances observed between tagging and recovery positions for all skipjack recoveries, and monthly average of these distances.(red line)

These average distances and their variability in each of the 4 tagging areas are shown by figure 11.

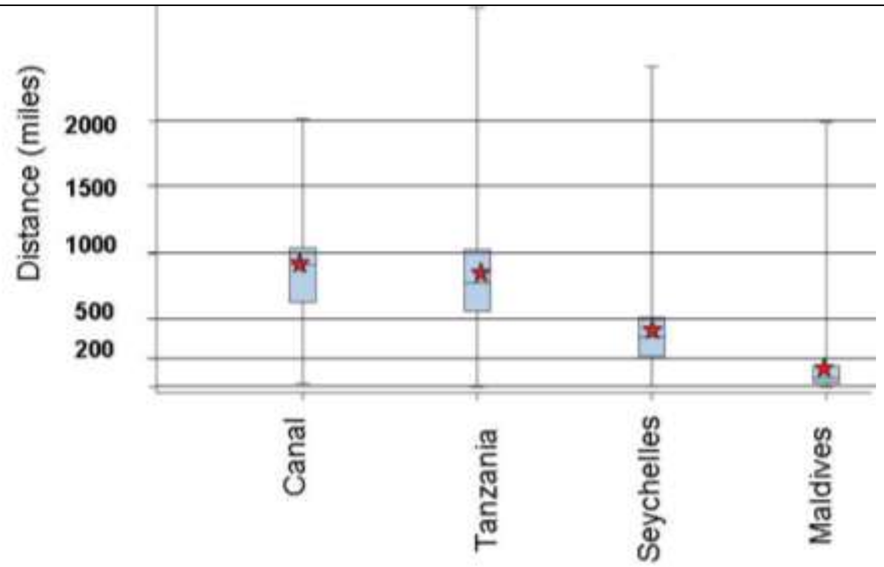


Figure 11: Distances travelled by skipjack tagged in 4 areas: average (star), minimum and maximum, and 75% of the distances travelled for all selected skipjack recoveries after more than 30 days at liberty.

The distances covered in each of these area by individual skipjack are shown on figure 12 as a function of their duration at liberty.

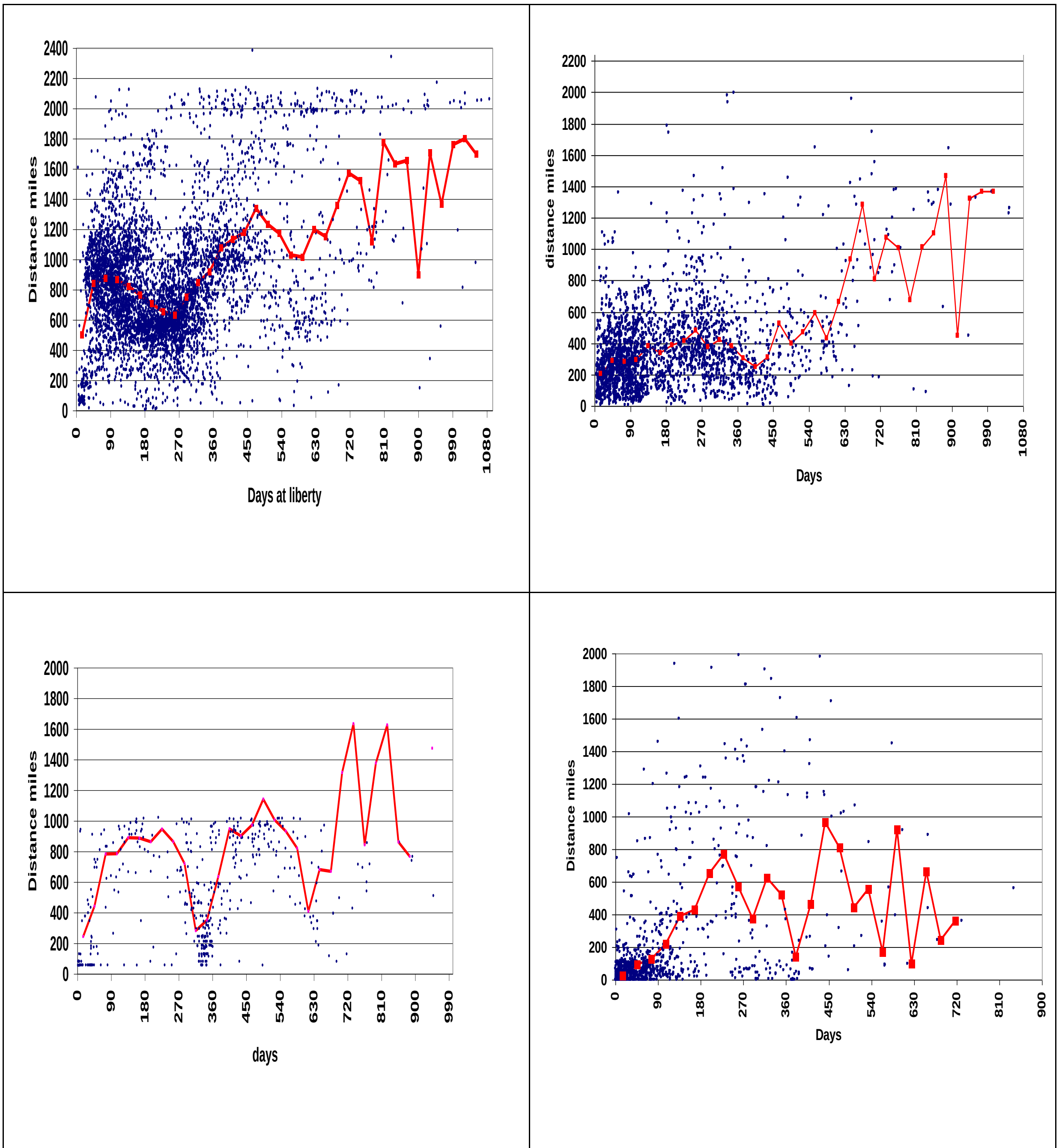


Figure 12: Distances travelled by individual skipjack and by the monthly recoveries in each main tagging area (12a upper left figure Tanzania, 12b upper right figure Seychelles tagging, 12c lower left Mozambique Channel and 12d Maldives)

The large number of SKJ recoveries also allow to show that SKJ movements out of the tagging area have been observed quickly, showing limited distances between tagging and recovery during a period of 20 days, but reaching average distances over 600 miles after only 22 days see figure 13).

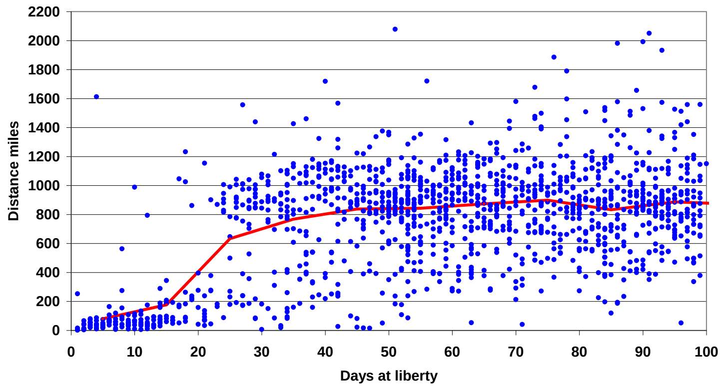


Figure 13: Distance covered by SKJ tagged in Somalia during their 100 first days at liberty

## *3-5- Discussion and conclusion on skipjack movements in the Indian Ocean*

Movements of skipjack in the Indian Ocean were totally unknown 10 years ago before the IOTTP programme. They are now quite well estimated based on large numbers of tagging and recoveries in various areas of the Indian Ocean and these results are probably very significant even in the absence of a comprehensive modelling of these movements.

The average range of linear movements during the skipjack life can be estimated at significant average distances of about 1000 miles , when maximum distances travelled by skipjack could be estimated at about 2000 miles (distances reached by 1% of the longest distances skipjack recoveries). These distances covered are very large in comparison of the scale of any EEZ and its 200 miles radius, but they are quite limited in comparison of the size of the Indian Ocean skipjack habitat and compared to the much larger distances between several major skipjack fisheries. Mixing rates between skipjack fished in Indonesia, in the Mozambique Channel and in Iran are probably quite low because of the large distances between these major fishing areas.

# 4-Discussion.

These results are clearly improving the "historical" scientific knowledge on skipjack stock structure and on the stock structure of Indian Ocean skipjack. These results should clearly be used in today and future stock assessment models and in the management of skipjack stocks. However, this study of skipjack movements based on the present results is clearly facing various structural difficulties:

(1) The areas where skipjack have been tagged are quite limited in comparison of the areas where skipjack is exploited by active fisheries: see figure 7 showing the tagging locations of skipjack in the Indian Ocean and figure 3 showing the areas of the major skipjack fisheries

(2) Various major fisheries that are catching large quantities of skipjack have been poorly reporting their recoveries of tagged skipjack (as estimated by Carruthers et al 2014), and in most cases these major fisheries have been very poorly followed by the IOTC in terms of their catches by time-area strata, and of their sizes caught.

(3) the recovery data have been tentatively corrected, selecting a sub set of recoveries, but this data set still probably contains some unidentified errors.

(4) this analysis is not based on a quantitative movement model and it does not take into account the fishery data

However, even if these results are still facing serious weaknesses, the results of the skipjack tagging programs presently done in the Indian Ocean are probably providing a quite clear global overview of the skipjack movements and stock structure in the Indian Ocean: there is no visible migration[2] pattern sensu stricto visible in the recoveries, but there is no doubt that skipjack movements in the Indian Ocean can be fast and done over large distances (in both N-S and E-W directions, at least in the warm surface waters that are typical of the Indian Ocean skipjack habitat. The average distance of about at least 1000 miles between tagging & recovery positions is probably representative of the potential scale of skipjack movement during the life of an average skipjack in the Indian Ocean. However, the distances covered by skipjack tagged in Seychelles and in Maldives Islands appears to be smaller than in other areas, but these results are probably peculiar cases that are quite easy to explain. Reduced distances estimated for Seychelles recoveries are probably due to the central position of this area: as the tagging was done more or less in the middle of the skipjack fishing zone of purse seiners, the main gear reporting the recoveries, all the observed distances between tagging & recovery locations tend to be biased (under estimated) and not representative of the real skipjack displacement. On the opposite the distances covered by skipjack recoveries from the skipjack tagging at the periphery of the fishing zones (in Tanzania and in the Mozambique Channel) are potentially more representative to show the real distances travelled by skipjack.

The reduced distances covered by skipjack tagged in Maldives Islands could also be a peculiar case due to a combination of several factors:

(1) To the effect of a network of 1200 islands in the Maldives: it has often been hypothesized that skipjack are more mobile in the open ocean than when they are positioned in a network of islands. This hypothesis would appear to be fully valid for Maldives Islands where the island effect may well create a viscous fraction of skipjack stock.

(2) To the large numbers of anchored FADs under which skipjack are exploited today by the baitboat fishery and potentially reinforcing today the historical "Island effect". As the local skipjack biomass appears to be strongly associated to the network of Maldivian anchored FADs, it can be hypothesized that these FADs are today reducing the distance travelled by skipjack, at least during several month after tagging. On the opposite, drifting FADs may increase the mobility of skipjack in the areas fished by purse seiners (Hallier and Gaertner 2008)

In this context, the stratification between 2 skipjack areas, Eastern and Western Indian Ocean, used in recent IOTC stock assessment by Sharma et al 2012 would appear to be quite a valid, but probably not an ideal one.

- On one side, these 2 areas would be valid ones, as the major fisheries and most of the fisheries that are well followed by scientists are located in the Western Indian ocean, and well fitted with the geographical scale of the observed skipjack movements: based on the skipjack recoveries, it can be concluded that each skipjack can easily be moving during its life, and very quickly, in the entire Western Indian Ocean. This conclusion is illustrated by figure 13 showing a map of the main skipjack fishing zones associated to circles with a

[2] Tuna migration **:** large scale seasonal & directional movement, most often done at sustained speeds and involving large numbers of fishes travelling in groups of schools towards given targets. These migrating tunas do not stop their trip until reaching in due time their target. These tuna migrations have 2 main distinct targets: spawning or feeding strata.

1000 miles radius that are corresponding to the average distance covered by tagged skipjack in the Indian Ocean.

- But on the other side, it would also appear that (1) the mixing rate is probably quite low between the Northern and southern western Indian Ocean (Iran and Mozambique Channel) because of the large distance of about 2500 miles between these 2 areas, and on the opposite (2) there is probably a high mixing rate and a high potential interaction between Maldives and Sri Lankan waters, 2 fishing zones that are located at very close distance. Unfortunately this mixing rate between Sri Lankan & Maldivian skipjack cannot be estimated because of the very low reporting rates of tags estimated for the Sri Lankan skipjack fisheries by Carruthers et al 2014.

Based on these observations, it could be concluded that a fully realistic stock assessment model ran in the Indian Ocean skipjack should preferably be based on a larger number of smaller areas, for instance at least using the 4 areas shown by figure 15 (these areas being in phase with the observed distances in the skipjack movements summarized by the 4 circles of figure 14, each circle positioned in a skipjack fishing zone corresponding to the average distance travelled). This number of modelled fished areas would be similar in their structure to the 5 areas presently used by WCPFC in its MFCL model applied to skipjack stock assessment (Rice & al 2014 paper).

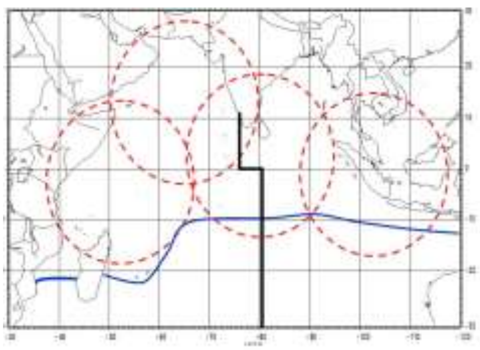

Figure 14: Location of skipjack fished zones (north of blue line) and 4 circles drawn with an approximate radius of 1000 miles and the 2 areas used by IOTC in its recent skipjack stock assessment

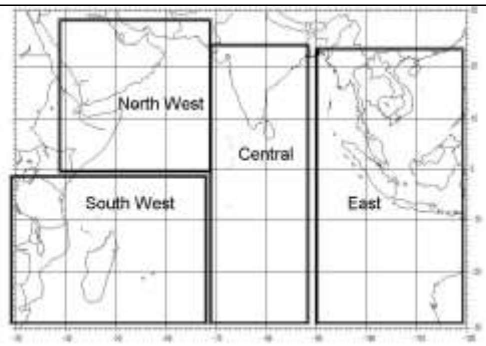


Figure 15: Potential areas used in future skipjack stock assessment models (*based on fishery and on recovery data)*

# 5- Conclusion

There is no doubt that the results of the IOTC tagging program have been recently providing to scientists a wide range of new and strong knowledge on the skipjack movements in the Indian Ocean. Even if they are not fully quantitative, these results are strongly showing that skipjack in the Indian Ocean are highly mobile and often (but not always) showing fast and long distance movements. Even if a quantitative modelling of these data should preferably be developed, the movement pattern and scale that have been observed appears to be realistic and of fundamental importance: in the stock assessment modelling of Indian Ocean and in the potential interactions between skipjack fisheries that are active in various regions of the Indian Ocean.

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