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**Analysis of environmental parameters
effects on the spatial and temporal
dynamics of tropical tuna in the EEZ of
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and catch data**

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Analysis of environmental parameters effects on the spatial and temporal dynamics of tropical tuna in the EEZ of Madagascar: coupling remote sensing and catch data

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Abstract

Potential fishing zone can be identified from the information collected regarding the relationship between the environmental factors and distribution areas of the species. In this context, the effects of environmental parameters on the spatio-temporal dynamics of yellowfin tuna, Bigeye tuna, skipjack and albacore were analysed in the EEZ of Madagascar from

2005 to 2013 using a modelling approach between remote sensed environment and monthly catch data. The result of this analysis showed that (1) there is a positive relationship between the catches data and environmental parameters, (2) the sea surface temperature (SST) and chlorophyll-a are the main parameters that influence the distributions, (3) the most productive areas are located in the northwest and east central part of the EEZ and (4) these areas are already operational and well known by tuna fishermen. Finally, for the initiative to an optimal resource management, spatial distribution predictive maps of each studied species were produced. The limit of these results and suggestions are discussed.

Keywords: Madagascar, environmental parameters, dynamic, tropical tuna, remote sensing, modelling

Resume

Titre : Analyse des effets des paramètres environnementaux sur les dynamiques spatiotemporelles des thons tropicaux dans la ZEE Malagasy : couplage télédétection et données de captures

L'identification d'une zone potentielle de pêche peut être obtenue à partir des informations sur les relations entre les facteurs de l'environnement et les aires de répartition d'une es-

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pèce. Dans ce contexte, les effets des paramètres environnementaux sur les dynamiques spatiotemporelles du thon albacore, Patudo, Listao et germon ont été analysés dans la ZEE de Madagascar entre 2005 et 2013 à l'aide d'une approche de modélisation entre les données mensuelles de captures et des images satellites. L'analyse de ces données a montré que (1) il existe une corrélation entre la distribution des captures et les paramètres environnementaux, (2) la température de surface de la mer (TSM) et la chlorophylle-a sont les principaux paramètres qui influence les distributions des thons, (3) les zones les plus productives se situent dans la partie Nord-Ouest et Centre Est de la ZEE et que (4) ces zones sont déjà opérationnelles et bien connues par les thoniers. Enfin, dans l'initiative d'une gestion optimale des ressources, des cartes prédictives de la distribution spatiale de chaque espèce étudiée ont été réalisées. Les limites de ces résultats et les mesures à prendre sont discutées.

Mots-clés : Madagascar, paramètres environnementaux, dynamique, thons tropicaux, télédétection, modélisation.

Introduction

Tuna fishes are among the most valuable of the Indian Ocean's fishery resources. This fishery has been practiced by coastal populations since millennia. Since the

1950s, tuna catches have been increasing, but the most important catches have been noticed during the past thirty years (IOTC, 2015). Report from IOTC relates that in 1980, the total catch of tuna (and related species) from the Indian Ocean was just under 350,000 tonnes. In 2006, catches peaked at over 1.7 million tonnes. That was an increase of 390%, or an average annual growth rate of 6.3%, sustained over 26 years. The same report noticed that total catches have declined since 2006, largely due to external factors including the world economic crisis and the Somali pirate situation. Between 2008-2012 the average annual catch of tuna (and related species) in the Indian Ocean was just over 1.5 million tonnes. Almost 1.1 million tonnes (71%) of this came from the western and central Indian Ocean. In 2006, for whole the western and central Indian Ocean, the recorded total catches of tuna, seerfish and billfish increased to a maximum of almost 1.37 million tonnes. The recorded catch in 2012 was 1.16 million tonnes. As for the catch weight, the main species caught are skipjack and yellowfin tuna (IOTC, 2015). Although landed in smaller quantities, bigeye, albacore and particularly southern bluefin tuna are highly prized because of their higher unit value.

Within Madagascr Exclusive Economic Zone (1 1410 000 km²), tuna fishing is one of the most important of the twelve

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main fisheries identified for sea fishing (MPRH, 2012). Tuna production is estimated at 10 000 tonnes per year (Soumy, 2004). Most of the catches are given by the foreign vessels (mainly from the EU) which participate in this activity in the framework of international agreements. Catch data analysis from various sources indicates that the worldwide landings of tuna have doubled in each decade since 1950 and exceeded 2 million mt per year in 1980s. Recent report (Wesley, 1991) noted that increases in catches of skipjack and yellowfin tuna in the Indian Ocean have been particularly great since 1982. However, the system for collecting statistics on fisheries other than foreign industrial tuna fishing is deficient or non-existent. This situation could lead to the collapse of the tuna stocks in the region. In addition to these, the accelerated growth of the human population on this planet is accompanied by an increasingly strong pressure on natural resources, including fishery resources. Many fisheries are already overexploited and only allow catches less than those they would manage (Fonteneau, 1997). As a result of this deficiency in the management of fisheries resources, many species catches could decrease further in the future; tunas that pass during their migration in Malagasy water are no exception.

Thirty government officials are involved in the management of the exploitation of tuna in Madagascar but the imbalance in the operation can be observed (Ralison and Minten, 2003) because of technical difficulties, incompetence in the field and the inability of the national tuna fishing to exploit optimally these resources. At the current stage of research, the problem is contained in the following question: Is it possible to discern a preferential areas of tunas by using easily measurable environmental parameters (Marsac, 1989)?

Several studies on tuna fishing have been carried out in the western Indian area, particularly for yellowfin tuna (eg. Marsac, 1985; 1986; 1987-a and b; 1988; 1989; 1990; 1991; 1995), but few are treating the biological aspects linked to environmental parameter variability. Marsac (1987-a, b, c; 1988; 1990); Nishida (1995) and Ianelli (1995) started using tuna catch data to analyze the relationship between tuna fishing distribution areas and environmental conditions. Up to now, no investigations have been carried out within the Madagascar EEZ and dealing the subject. Being given that the actual areas of distribution of tuna industrial fishing fleets within the Madagascar EEZ are mainly concentrated in the North West and east coast, probable new tuna potential fishing zones (PFZ) exists in the remaining zones around the island. There

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is a need to investigate these new PFZ in order to increase and sustain the income generated by tuna industrial fishing activities. This paper describes the methodology how to identify new PFZ. Catch data from tuna industrial fishing will be coupled with environmental parameters (SST, chlorophyll-a) to establish a cartographic description of the spatial and temporal distribution of four commercial tuna species (Skipjack, Yellowfin, Bigeye, Albacore) in the EEZ Madagascar in order to identify new potential fishing zones, which may contribute to the optimal management of these resources.

Material and methods

Tunas distribution is not uniform in time and space (Berges *et al.*, 1989). The abundance of food and temperature are cited among the main factors. As migrators and predators, tunas have no boundaries, following the favourable places for their survival.

Data Sources

Catch data

The catch data used in this study are from tuna fishing trips between 2005 and 2013 in the Exclusive Economic Zone of Madagascar of yellowfin tuna (*Thunnus albacares*), bigeye

tuna (*Thunnus obesus*), albacore tuna (*Thunnus alalunga*) and skipjack (*Katsuwonus pelamis*). They were provided by the Madagascar Fishing Monitoring Center that collects them from the ships logbooks or “logbooks”. In general, when seated is made, the ship’s captain systematically note in the logbook the geographical position of the vessel (longitude, latitude in degree-minute), the date of the catch, the name of the species caught (yellowfin, bigeye and skipjack), the category of catches by species and an estimate of the tonnage carried.

The satellite data

Environmental data used in this study are from MODIS Aqua Images. MODIS is an instrument of observation of the Earth on board the satellites Terra (EOS AM) and Aqua (EOS PM). MODIS images can be downloaded free of charge from NASA website - Goddard Earth Sciences Distributed Active Archive Center (DAAC) (Url 1) (1). MODIS collects Sea Surface Temperature (SST) and primary production (chlorophylls), which are available as pre-processed data: Level 1 (L1), 2 (L2) and 3 (L3) (Url 2) (2). But, Level 3 was the only database used during the study, with a spatial resolution of 4.86 km. It has sufficient resolution to describe the variability of the environment and to analyze the distribution of the catches.

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Processing of satellite images

The images (L3) have a broad global coverage. Therefore, prior to processing the data, each study area was cropped out of the image source. **Figure 1** shows the study area.

All products have been processed using ArcGIS software especially through MEGT tool (Marine Geospatial Ecology Tools). The latter is a freeware, designed by the Marine Laboratory, Duke University (Beaufort, North California). It is avail-

Figure 1: Study area, EEZ of Madagascar

able via the web (Url 3) (3). ArcGIS can read images directly from MODIS and ensure the conversion of the metadata in HDF formats into Raster formats (Geo Referenced), and pixel values in degrees centigrade for temperature (°C) (SST) or mg/m³ for Chlorophyll-a and project images in the world geographic coordinate system WGS 84.

Approach and model-analysis of the distribution of species

Maxent was used to model the distribution of the species of interest (Philips *et al.*, 2006). This program identifies the areas where tunas are most likely to occur, and the environmental conditions comparable to the tuna ecological niche. Maxent works with georeferenced data and detailed environmental factors data.

The points of presence

Presence points were extracted from catch data (see previous section). They were organized into Excel and then converted into modelling formats programs adapted to the species distribution. In this study, the data is imported as a CSV file (*.csv). They include following basic information: the taxonomic name of the species and the coordinates (longitude and latitude) from its point of presence.

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The environmental variables

There are already databases presented as an approximate value of the ecological niche known as “climate envelope” that provide detailed climate information (based on the interpolation of data collected worldwide by climate measuring stations). They are available on the Bio oracle website (Url 4) (4). Among the parameters commonly used to describe the environment and distribution of tuna: SST, Chlorophylls, bathymetry, dissolved oxygen, salinity, and sea surface current were used in this study to define where to meet tuna species (Stretta and Dufour, 1973; Stretta *et al.*, 1973; Stretta, 1977;).

Results

Seasonal variation in catches

Tuna fishing in the Malagasy EEZ are manifested throughout the year from January to December. The Skipjack (*Katsuwonus pelamis*) is the species that dominates the catches of Malagasy tuna (**Figure 2**). For Bigeye, Skipjack and yellowfin tuna species, their total catches show that the highest abundances are found from March to May with a peak in April; however for albacore species, the peak is in November. Generally a small catch is observed on July and September.

Figure 2: Seasonal variation of total catch from 2005 to 2013

Spatial distribution of catches

The most important capture is observed from March to May, and focused in the northwestern part of the EEZ (**Figure 3**). Most of which consists of Skipjack (*Katsuwonus pelamis*) sometimes mixed with yellowfin (*Thunnus albacares*). The figure also shows that the capture of albacore is localized particularly in the east-central part of the EEZ from October to December. Finally, Bigeye tuna are found, in minimum

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Figure 3: Space distribution of total catch from 2005 to 2013

amount, at almost in the whole area of the EEZ throughout the year.

Oceanographic data

Sea Surface Temperature (SST) distribution

The distribution of sea surface temperature (SST) is not homogeneous throughout Madagascar's EEZ, with a fairly pronounced seasonal variation (**Figure 4**). The west coast is warmer compared to the east coast and the north-western part is the warmest.

Chlorophylls (CH-a) distribution

The distribution of chlorophyll-a concentration also suggests a seasonal delineation. The west coast is more productive comparing to the east coast (**Figure 5**) and the important biomass is located in the south-western part.

Sea surface temperature and chlorophylls values

The value of the temperature ranges from 24 °C to 28 °C (**Figure 6**). From January to April, the temperature remains stable in the range of 28 °C. From May it falls largely to achieve its minimum in August (of approximately 24 °C). There is also a rise in the value of SST from September until December.

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Figure 4: Space distribution of Sea Surface Temperature, monthly mean from 2005 to 2013

Figure 5: Space distribution of chlorophyll-a, monthly mean from 2005 to 2013

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Figure 6: Seasonal variation of SST and Chlorophyll-a, monthly mean from 2005 à 2013 in the whole Malagasy EEZ

An increase in the concentration of Chl-a was observed from January with a maximum in April. The average concentration was estimated between 0.15 to 0.17 mg/m³ (**Figure 6**). The concentration of Chl-a remains stable in May and goes back up to reach a second peak in July. Then, it is decreasing again to a value less than 0.12 mg/m³ from September to December.

Modelling

According to all variables used (**Table 1**), the most important parameters for the model are temperature distribution and chlorophyll content for the four models.

The response curve for the temperature distribution (**Figure 7**) shows that the probability of presence of *Thunnus obesus*, *Thunnus albacares* and *Katsuwonus pelamis* are stronger for a temperature value between 28 °C and 29 °C. On the contrary, in these models, the probability of finding the three species decreased for temperature values below 27 °C.

Environment variables	Percentage of contribution in the model (%)			
	<i>Katsuwonus pelamis</i>	<i>Thunnus albacares</i>	<i>Thunnus obesus</i>	<i>Thunnus alalunga</i>
Sea surface temperature	83.7035*	56.7452*	63.5436*	7.0135
Chlorophyll-a	6.5256	24.9842*	11.5747	80.7812*
Bathymetry	4.0028	5.6035	5.9243	2.9755
Sea surface current speed	3.6093	0.5023	14.0997	0.1473
Activate photosynthetic radiation	0.5291	9.4905	3.0015	0.8287
Salinity	1.3418	1.1228	0.8944	7.4989
Ultraviolet	0.2879	1.5514	0.806	0.7549
Coral reef presence	0	0	0.1558	0

Table 1: Contribution percentages for each environment variable by Maxent.

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Figure 7: Response curve according to the SST

These results are not the same for the model applied to *Thunnus alalunga* where the probability of presence is strongest to a temperature threshold between 26 °C to 26.5 °C. However,

beyond this threshold the probability of finding the species remains relatively low (**Figure 7**).

The important environmental variable after the temperature is the chlorophyll-a. For the three species: *Katsuwonus pelamis*, *Thunnus obesus*, *Thunnus albacares* the peak is observed at a concentration of 0.15 mg/m³ (**Figure 8**). Similar results were found for the model applied to *Thunnus alalunga* but with a lower value (0.08 mg /m³).

Graphic models

Models show that the probability of finding tuna is stronger in the West Coast than in the East Coast of Madagascar's EEZ (**Figure 9**).

In one side there are some particular groupings areas evaluated by the model, as favourable for the three species: *Katsuwonus pelamis*, *Thunnus albacares*, *Thunnus obesus*, located in the northwest of the EEZ. These areas correspond exactly to the geographic coordinates from 12.5 to 16.5° S and 42.5 to 48° E. It was also noted that areas with higher temperature are considered favourable for the distribution of these species. In the other side, the model applied to *Thunnus alalunga* (**figure 9**) showed that the most likely areas to find the species are in the east-central part of the EEZ, specifically from

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Figure 8: Response curve according to the chlorophyll-a

Figure 9: Predictive map modelling (MAXENT)

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18 to 24° S and 48 to 53° E. These areas are located in the fishing zone of longliners.

Discussion

Temporal and spatial distribution of catches

The monthly evolution of tuna catch showed two different periods (March-April-May and October-November-December). Each period presents a strong spatial homogeneity of catch from the same geographical area. This result is coherent with the work of the description of the seasonal nature of this fishery by several authors (Fonteneau, 1997; Randriambola, 2012; Ramanantsoa, 2013).

The study shows that these two periods correspond to two different fishing strategies. From February to May, seiners mainly target banks Skipjack, Yellowfin and Bigeye tuna in the north-western part of the island. For longliners, even if they are operational in all seasons, the essential of their catch is located in the east-central part of the island from October to December, and the most targeted species are albacore.

Tropical tuna species are migratory pelagic species, which can travel great distances for reasons of breeding and feeding (Saulnier, 2014). Between 1994 and 1995, studies on the reproductive biology of tuna in the Mozambique Channel

carried out in Madagascar confirm that egg lying took place in Malagasy waters during the second quarter (Rajoharison, 1994.1995; Conand and Richards, 1995).

According to the IRD (2003), reproduction of albacore, mainly takes place from November to February, in an area between 17 and 28 ° S in the south of the equator.

Their spatial and temporal distribution is particularly linked to seasonal variation of weather (upwelling, thermal front), which defines primary production and therefore the amount of available prey (Tewkai *et al.*, 2009). Besides, Saulnier (2014) argues that in the Indian Ocean, the spatio-temporal distribution of tuna's catches is the result of a double phenomenon: first, the actual distribution of tuna bank that aggregate around FADs, and second, the behavior of fishermen, whose activity reflects more or less to local abundance. He also emphasized that the seiners fishing activity is marked by a strong seasonality in the Indian Ocean, which is characterized by a shift in northern Mozambique Channel from March to June (Saulnier, 2014). Indeed from March to May, the Mozambique Channel is rich in floating debris from land (tree trunks, coconut branches): a large number of catches is then conducted with natural floating matters.

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Piton and Magnier (1975) explained the reason for tuna fishermen operating in the Indian Ocean. They highlighted the potentially productive nature of the northwest coast of Madagascar, due to terrigenous nutrient inputs and anticyclonic circulation (convergence and concentration of nutrients), however, the weakness of the currents limit the productivity.

This natural variability is added by the behaviour of tunas in front of eddies. Each year three main eddies usually occur in the north and the center (diameter 50 to 300 km), which can last from one week to several months. Alternately cyclonic and anticyclonic, succeed in the Mozambique Channel (Schouten *et al.*, 2003). According Marsac and Tewkai (2010), direct catches of tuna are obtained either on the periphery or in the heart of eddies, where phytoplankton production is important. They argued that tuna use eddies to feed themselves.

Distribution of species

Katsuwonus pelamis, *Thunnus albacares*, *Thunnus obesus* are mainly captured in the northwest and *Thunnus alalunga* are caught more in the Central East part of ZEE.

This distribution is due to the variability of environmental parameters. The main parameter, which determines the distribution of the different species of tuna in the Malagasy EEZ,

is the temperature distribution. Temperature range required for each species are not the same. Albacore need colder waters than yellowfin and skipjack (Crosniere and Fourmanoire, 1961). The latter explains the dominance of yellowfin, Bigeye and skipjack tuna in the Mozambique channel while albacore clearly predominates in the East-Centre.

The temperature in the Northwest part of Malagasy EEZ has a monthly average of about 28 °C, which is warmer compared to the Central East part, with a monthly average of 26 °C.

Indeed, as various authors have described (Blackburn, 1965; Evans *et al.*, 1981; Sund *et al.*, 1981; Stretta, 1991), maximum abundance of *Thunnus albacares* is located in an area where the temperature varies between 20 and 30 °C, then between 20 and 29 °C for *Katsuwonus pelamis*. They added that for *Thunnus obesus*, their maximum abundance depends on the fishing gear used. For their part, Stretta and Slepoukha (1986) also noted that in a tropical water, *Thunnus albacares* and *Katsuwonus pelamis* are captured mainly in places where the temperature ranges from 22 °C to 29 °C. This was later confirmed by Fonteneau (1997) saying that in the Indian Ocean, catches are maximum with an average temperature of 28 °C for *Thunnus albacares*, 27 °C for *Katsuwonus pelamis* and *Thunnus obesus*, and 18 °C for albacore. These sea

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surface temperature ranges could be found in Madagascar's EEZ.

Finally, according Bonhommeau and Fromentin (2011), albacore do not approach the coast and prefer deep and open waters. The lack of oxygen and warm temperatures do not suit them (IRD, 2003). Along the linear east coast of Madagascar, there is the permanent passage of South Equatorial Current, with a maximum flow during the monsoon Northeast (STRETA et al., 2006). This current has all the necessary characteristics to influence the distribution of albacore in the east coast of Madagascar.

Madagascar has many assets on the tuna activities carried in its EEZ. This study highlighted the potentially productive zones that may contribute to the optimal management of the resources. These areas are already well known and are widely used by fishermen.

The distribution of tuna species in Madagascar's EEZ varies in time and space depending on environmental parameters. The results from modeling confirm that the temperature distribution and the distribution of chlorophyll content are the two most important parameters which determine the distribution of these resources as well as the variation of capture within the EEZ.

Fisheries Development

From this study, further development of the large-scale tuna fishery can be considered as mentioned by the Indian Ocean Fishery Commission (1985). As the tuna fishery is not primarily a one-targeted species, besides, other species can be targeted among the various sashimi-quality fish, primarily yellowfin, bigeye, and southern bluefin tunas and billfishes (Wesley, 1991). It will also be expected that, with the great mobility of the present fleets, future catches of these tuna species within the Madagascar EEZ will be depending to resource availability as well as species-specific market demand. As the results of the model used for this study show that exploitable resources can be found in new areas within the EEZ, new fleet may relocate to these areas, but future trends in catches of these species will depend on their relative abundance, the evaluation of which is not part of this study.

Fisheries Management

It is clear that the need for management of Indian Ocean tuna fisheries is increasingly discussed in area fishery management forums (Wesley, 1991). In the near future, the continued expansion of both small-scale and large-scale tuna fisheries both inside and outside the EEZ could reduce catches. Con-

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licts between traditional and industrial fishery were recently noticed in the north-west fishing area, especially for shrimp fishery. Traditional fishermen often accused industrial fleet to expand their fishing area to areas adjacent to that used by the small-scale fisheries, and ultimately lead to decreased catches in smallscale fisheries as well as the overfishing of the exploited stocks. Tuna fishery managers need the relevant results to address scientifically such issue. Though such conflicts does not occur in tuna fisheries, current research findings could be used to prevent both resource conflicts between small and large-scale of tuna fisheries and the risk of overfishing as well.

The license sales were therefore chosen not to have to suffer in terms of the economy. However, the sector remains almost unchecked: catch statistics are difficult to verify, board observer proves to be an almost impossible operation. Finally, we simply accept unilateral declarations from ship-owners. For this it will be necessary to improve the quantity and quality of data collected during fishing operations. Socio-economists as fisheries scientists must find a balance between ship owners and the Malagasy State to establish a fair sharing of rents.

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Notas

1. Url1 : <http://oceancolor.gsfc.nasa.gov/>
2. Url2 : <http://oceancolor.gsfc.nasa.gov/cgi/l3>
3. Url3 : <https://mgel.env.duke.edu/mget/download/>
4. Url4 : <http://www.oracle.ugent.be/download.html>