Investigating early stages of skipjack tuna (*Katsuwonus pelamis*) in the Indian Ocean using otolith chemistry

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Abstract

Trace elements (Ba, Sr) and stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) of otoliths from young-of-year (YOY) skipjack tuna were examined to determine whether there is sufficient distinction of chemical signatures among three main nursery areas of the equatorial Indian Ocean (West, Central and East) to retrospectively determine individual´s natal origin. Higher $\delta^{18}O$ values in the otolith material deposited during the first fourth months of life were observed in YOY skipjack tuna captured in the western Indian Ocean nursery, but, in general, the chemical signatures of the three nursery areas largely overlapped. Random forest cross-validated classification success of fish to their nursery area was low (46%). This may suggest (1) that early life history stage skipjack tunas from the three different nursery areas lived in a chemically homogenous environment or (2) that fish moved between nursery areas in the first months of life. Our results suggest the use of these

otolith signatures alone are not sufficient to understand skipjack stock structure in the Indian Ocean. Future research should explore larvae or younger skipjack tuna, ideally sampling at finer scale temporal stratification (i.e. by monsoon and year) to resolve questions regarding skipjack stock structure in the Indian Ocean.

1. Introduction

Skipjack tuna (*Katsuwonus pelamis*) is a cosmopolitan species inhabiting tropical and subtropical waters of the Indian, Pacific and Atlantic Oceans (Collette and Nauen, 1983). This species is, by far, the most commonly caught tuna worldwide, by total number and by weight (Galland et al., 2016; ISSF, 2020). Skipjack tuna are fast growing (Murua et al., 2017), early maturing species (Grande et al., 2014) and have high reproductive potential, which makes this species more resilient to fishing pressure than many other tuna species (Murua et al., 2017). The most recent stock assessment for the Indian Ocean determined that the stock is neither overfished nor subject to overfishing (IOTC, 2017b). Although stock assessments of skipjack tuna in the Indian Ocean assumes a single stock (IOTC, 2017a), there is not sufficient information to reject the presence of more than one population within the Indian Ocean. Indeed, some regional studies (Dammannagoda et al., 2011; Menezes et al., 2012) indicate a more complex stock structure than currently assumed for stock assessment and management purposes.

Understanding spatial stock dynamics of highly exploited species such as skipjack tuna is essential for developing a suitable spatial scale for management (Kerr et al., 2016) and, hence, increases the effectiveness of management (Bosley et al., 2019). There are several methods that can be used to study fish stock structure (Cadrin et al., 2014), which can provide information at different spatial and/or temporal scales. Among them, otoliths (i.e. calcified structures found in the inner ear of the fish) are widely used to explore movements and habitat use of fish based on their chemical composition (Tanner et al., 2016). This method relies on the premise that ambient water chemistry and environmental conditions (but also other intrinsic factors) affect elemental incorporation into the concentric growth of the otolith (Campana, 1999). As such, otolith elemental fingerprints can be used as natural markers to identify fish that have inhabited different

environments during certain life history stages (Kerr and Campana, 2014). It is important to note that the absence of differences does not necessarily imply that fish have inhabited the same environment, but that the signal may not be strong enough to discriminate among them (Campana, 1999). Therefore, this approach can be used as a powerful discriminator among groups as long as differences can be detected (Kerr and Campana, 2014).

Here, otoliths of young-of-the-year (YOY) skipjack tuna were collected across the equatorial strip in the Indian Ocean, where high larvae concentrations and major spawning grounds have been reported (Stéquert and Marsac, 1989; IOTC, 2017a), to determine whether skipjack tuna within the Indian Ocean can be spatially discriminated based on their early life otolith microchemistry composition. If so, the described microchemistry reference baseline could be used to assign older individuals to their potential nursery origin, which would help to improve our understanding of the stock structure, on connectivity and mixing rates of this species in the Indian Ocean

2. Material and Methods

2.1. Fish sampling

YOY skipjack tuna (n=50) were collected from three distinct nursery areas in the Indian Ocean: West (10ºS-0ºN, 40ºE-60ºE), Central, (0º-10ºN, 65ºE-75ºE) and East (ECI, 5ºS-5ºN, 85ºE-100ºE) (Fig.1).

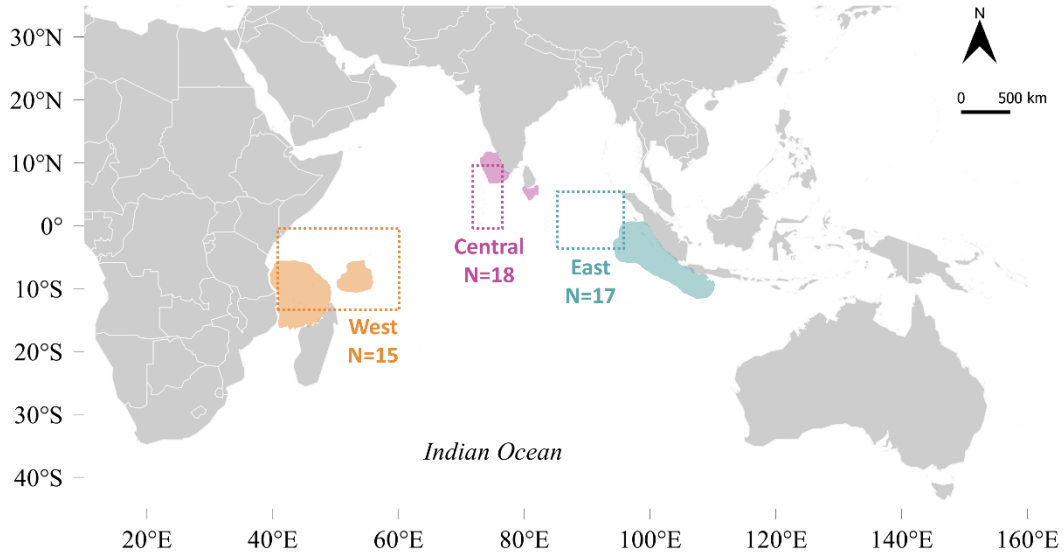

Figure 1. Skipjack tuna (*Katsuwonus pelamis*) sample distribution across the equatorial Indian Ocean. Dotted squares represent nursery areas were YOY skipjack tuna were captured from, referred to as West (orange), Central (purple) and East (green). Shaded areas represent zones of high skipjack larval concentrations according to Stéquert and Marsac (1989).

Samples were obtained directly by scientist or scientific observers on-board purse seine vessels or at port during two consecutive years (2018 and 2019), as part of a collaborative research project on Population Structure of Tuna, Billfish and Sharks of the Indian Ocean (PSTBS-IO). Fish size ranged between 24.5 and 35.0 cm fork length (FL) (Table 1), and were estimated to be about 4-6 months old following the age-length relationship described by Eveson et al., 2015. Thus, we assumed that capture locations represent nursery areas where fish reside during the early juvenile stage. Note that fish were sampled at different time periods, which implies that the otolith collection available for this study comprised fish from different cohorts, hatched at different times of the year.

Table 1. Number, sampling period and size of skipjack tuna (*Katsuwonus pelamis)* at each of the three nursery areas sampled. Size is fork length (FL) in cm.

Sampling Region	Sampling period	N	FL range	Mean FL (sd)
West	March 2018 and April 2019	15	29.0-35.0	32.0 (1.6)
Central	August 2018 and February 2019	18	28.0-33.0	30.4 (1.2)
East	April and November 2018	17	24.5-35.0	29.4 (3.1)

2.2. Otolith preparation and analyses

Sagittal otoliths were extracted, cleaned of adhering organic tissue, rinsed with ultrapure water, and stored dry in plastic vials. In the laboratory, they were embedded in two-part epoxy resin (Araldite 2020), and blocks were polished with a series of grinding papers until the core was exposed. The sections were sonicated for 10 minutes in ultrapure water (Milli-Q) and left to air for 24 h before being glued in a sample plate using Crystalbond thermoplastic glue (Crystalbond 509; Buehler). When both otoliths from the same individual were available one was used for trace elements and the other for stable isotope analyses. When only one otolith was available, all chemical analyses were conducted on a single otolith.

Otoliths were analysed for trace element chemistry using a high resolution inductively coupled plasma mass spectrometer (HR-ICP-MS), coupled to a high repetition rate femtosecond laser available at the Institut des Sciences Analytiques et de Physico-Chimie pour l'Environnement et les Matériaux of the Université de Pau et des Pays de l'Adour (Pau, France). A 30 µm spot was ablated in each otolith 200 µm apart from the primordium, which represents the chemical signature corresponding to the first 13-15 days of life of the fish according to direct age estimates. National Institute Standards and Technology (NIST) 610 and 612 glass standards with known chemical composition were used for calibration. Measurement precisions was determined based on an otolith certified reference material for trace elements (FEBS-1). Relative abundances of 6 isotopes (^{138}Ba ,^{7}Li, ^{24}Mg, ^{55}Mn, ^{88}Sr and ^{66}Zn) were estimated, as well as ^{43}Ca, which was used as the internal standard. Data reduction including background subtraction, conversion to ppm and standardization to calcium (element:Ca mmol mol^{-1}) was done using PAMAL template (Focal General version 2.27).

For stable isotope composition, microsampling of otolith powder for carbon (δ^{13}C) and oxygen (δ^{18}O) stable isotope analysis was performed using a high-resolution computerised micromill (New Wave MicroMill System, NewWave Research G. C. Co., Ltd, Cambs,UK). The area of analysis on the smallest skipjack tuna otolith (24.5 cm FL) was used to create a standard template that was then applied to the remaining otoliths, to ensure that the same portion of the otolith was analysed in every fish. Therefore, the drill path covered the area of the otolith corresponding to the first ~4 months (according to Eveson et al. 2015 age-length relationship), with a larger time period of the otolith sampled for stable isotopes than trace elements due to differences in sample material requirements. Ten drill passes were run at a depth of 50 µm per pass over a preprogrammed drill path using a 300-µm diameter carbide bit (Komet dental; Gebr. Basseler, Lemgo, Germany). Powdered material was then analysed for δ^{13}C and δ^{18}O on an automated carbonate preparation device (KIEL-III, Thermo- Fisher Scientific, Waltham, MA, USA) coupled to a gas-ratio mass spectrometer (Finnigan MAT 252, ThermoFisher Scientific) at the Environmental Isotope Laboratory of the University of Arizona. All isotope values were reported

according to standards of the International Atomic Energy Agency in Vienna. The isotope ratio measurement is calibrated based on repeated measurements of NBS-19 and NBS-18 and precision is ± 0.10 ‰ for $\delta^{18}O$ and ±0.08‰ for $\delta^{13}C$ (1 sigma). Values of $\delta^{13}C$ and $\delta^{18}O$ represent ratios of 13C/12C and 18O/16O in the sample relative to the Vienna Pee Dee Belemnite (VPDB) scale.

2.3. Statistical analysis

Only otolith variations in Sr, Ba, $\delta^{13}C$ and $\delta^{18}O$ were explored for statistical analyses as they are believed to be those that best reflect changes in the physico-chemical environment experienced by the fish (Martino et al., 2019; Hüssy et al., 2020; Macdonald et al., 2020). Univariate test for each element were performed to check for differences among nursery areas. Sr, $\delta^{13}C$ and $\delta^{18}O$ conform the parametric assumptions of normality and homoscedastic, and therefore one-way ANOVA test was used for comparisons among nurseries. Ba did not meet these assumptions, and a heteroscedastic one-way ANOVA was used instead. To test for differences in the multielemental signature between nursery areas a Permutational Multivariate Analysis of Variance (PERMANOVA) was used. The resemblance matrix was based on Euclidean distance dissimilarities. The number of unrestricted permutations was set to 999 random repeats. Statistical significance was determined based on adjusted P values after the Benjamini-Hochberg correction (Benjamini and Hochberg, 1995). Post-hoc pairwise comparisons were applied to identify the source of differences among nurseries. Random forest (RF) classification algorithm (number of trees=500, mtry=2) was implemented to discriminate between fish belonging to different nursery areas (Breiman, 2001). Data was split into a training dataset (70%) and a testing dataset (30%), and this procedure was randomly repeated 1000 times. At each time, the rate of classification success (i.e. rate of correct predicted membership to nursery areas in which the fish were collected) was calculated, and mean values were extracted. Kappa (κ) value was also calculated, which is a method that accounts for the agreement occurring just by chance (Titus et al., 1984). Prior to any multivariate analyses, the data were standardised (i.e., for each element, the data was centred by subtracting the mean and scaled by dividing by the standard deviation).

3. Results and discussion

Multielemental signatures in otoliths varied significantly among YOY skipjack tuna captured in the three different nursery areas of the Indian Ocean (PERMANOVA, p=0.002) at α=0.05 level. Posterior pairwise test show that fish captured in the western nursery were significantly differentiated from those captured in the central and eastern nurseries (Table 2).

Table 2. Results of pairwise comparisons of multielemental (Ba, Sr, $\delta^{13}C$ and $\delta^{18}O$) signatures three nursery areas in the Indian Ocean. In the significance column, a star (*) means significant differentiation at <0.05 level and two stars (**) at <0.01.

Region pair			Df	Sum of Squares	F-Stastitic	R squared	p value	Adjusted p value	Significance
West	vs	Central	1	15.43	3.94	0.11	0.010	0.015	*
West	vs	East	1	20.03	7.29	0.19	0.001	0.003	**
Central	vs	East	1	4.19	1.02	0.03	0.385	0.385	

Results were obtained using Euclidean distance to calculate the similarity matrix and the Benjamini and Hochberg (BH) method for calculating the adjusted p-value.

Overall classification success of YOY skipjack tuna back to their capture location was low, with 46% (κ=0.19) of the fish correctly re-assigned to their nursery area. Classification success varied among nurseries, and was of 53%, 35% and 52% in West, Central and East nursery areas respectively (Table 3). Misclassification of samples was lower between the two extreme nursery areas (i.e. West and East) and skipjack captured in the Central nursery were often misclassified as East nursery individuals.

Table 3. Relative proportion (%) of young-of-the.year (YOY) skipjack tuna (*Katsuwonus pelamis*) to their nursery area in the Indian Ocean based on multielemental (Ba, Sr, $\delta^{13}C$ and $\delta^{18}O$) otolith composition.

	West	Central	East
West	**53**	25	14
Central	32	**35**	35
East	14	40	**52**

Data represent the percentage (%) of individuals from the region of capture (row) assigned to their predicted region (column).

The lack of differentiation between Central and East nursery areas and low classification success of fish to their respective nursery suggests either (1) that the ocean chemistry is too similar among them to allow discrimination, or (2) that fish have moved between areas prior to capture. Depending on the monsoon period in the Indian Ocean, the regions of Maldives (Central) and eastern Indian Ocean are quite homogeneous in terms of sea surface temperature (SST), salinity (SSS), and dissolved oxygen (DO) (see section 3 in Study of population structure of IOTC species and sharks of interest in the Indian Ocean using genetics and microchemistry: 2020 Final Report to IOTC). To our knowledge, ocean scale migratory movements of YOY skipjack tuna within the first 4-6 months have not been documented, since tagging studies are generally not available for these size ranges. For larger individuals, limited large scale displacements have been reported (Fonteneau, 2003; Fonteneau and Hallier, 2015), especially in the Maldives region (Adam and Sibert, 2002).

When looking at individual elements, it appears that otolith $\delta^{18}O$ signature was the main driver of differentiation of the western nursery samples (Fig.2).

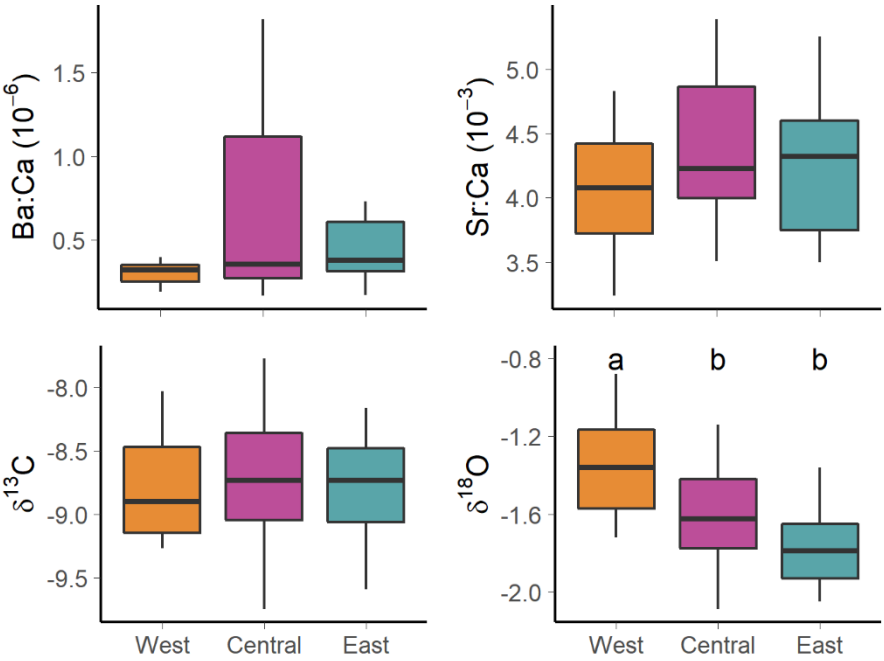

Figure 2. Boxplots comparing skipjack tuna (*Katsuwonus pelamis*) otolith element:Ca ratios and stable isotope (‰) composition between nursery areas in the Indian Ocean. Letters identify significant differences ($p<0.05$) between means.

Oxygen isotope ratios in otoliths are inversely correlated with ambient sea water temperature (Kitagawa et al., 2013). Otolith composition of YOY skipjack tuna from the Indian Ocean followed the expected trend for $\delta^{18}O$, presenting higher values in the West (expected due to lower water temperatures, under the influence of the seasonal Somali upwelling) and decreasing towards the east (expected due to higher water temperatures, as confirmed by the overall SST pattern in the Indian Ocean). Otolith Ba, Sr and $\delta^{13}C$ did not differ between YOY skipjack tuna captured at the three different nursery areas in the Indian Ocean (Fig.2). High intra-group variability was detected in the case of Ba concentration from Central samples. Indeed, Ba concentrations varied between sampling years for skipjack tuna captured both in the Central and East nurseries (t-test, $p=0.024$ and $p=0.041$). Ba content in the ocean is more abundant in areas of high productivity and upwelling zones (Wolgemuth and Broecker, 1970), and seasonal climatology strongly influences upwelling distributions throughout the northern Indian Ocean (Wiggert et al., 2006; Anderson et al., 2011). Due to sampling constrains, skipjack tuna captured in the Central and East nurseries were captured, and thus hatched, during different periods and under distinct wind regimes, and hence upwelling, which may explain the high Ba variability observed among the Central nursery samples. It is also possible that the observed high variability is due to the presence of fish from any other larval source not sampled in this study. The south coast off Sri Lanka has also been described as an area of high skipjack larvae concentration in the Indian Ocean (Stéquert and Marsac, 1989). Depending on the season, oceanographic conditions and chlorophyll concentrations may greatly vary between Maldives and Sri Lanka (Wiggert et al., 2006; Schott et al., 2009), and thus the observed variability in the Ba signatures from the Central nursery may be due to the presence of fish from these two close regions.

4. Conclusions

Otolith trace elements and stable isotopic composition of YOY skipjack tuna captured in three main nursery areas of the equatorial Indian Ocean were not sufficiently distinct to successfully

discriminate among them. This could be explained by the fact that biochemical properties of the water masses were relatively homogeneous during fish early life. Alternatively, our assumption that capture locations represent nursery areas is not true and fish moved between nurseries in the first months of life. In any case, the information derived from the chemical signature of 4-6 month old skipjack tuna in the Indian Ocean does not provide a tool to determine adult natal origin. Further research on skipjack population structure using otolith microchemistry should rely on larvae and give careful consideration to temporal stratification of sampling so that seasonal differences in oceanography can be partitioned from potential regional differences in stock structure.

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