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Morphometrics of albacore tuna (*Thunnus alalunga*) in the Western Indian Ocean

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Abstract

This paper provides information on the length-length (fork-length, FL with pectoral length, PL and first dorsal length, LD1) and length-weight relationships of albacore tuna (*Thunnus alalunga*) in five regions of the Western Indian Ocean. Data were obtained for a total of 923 female and 867 male albacore, caught by different fishing gears, and sampled from 2013 to 2015. The regression coefficients of the different relationships are presented. Possible causes of variations in length-weight, including tissue weights (gonad, liver and the rest of the viscera), sex and region are assessed using analysis of covariance (ANCOVA) and linear regressions on log-transformed equations of length and weight. There were significant differences in the relationships FL-PL ($F_{(5,1054)} = 5553$, $P<0.001$) and FL-LD1 ($F_{(5,921)} = 307.2$, $P<0.001$) between regions but no significant differences were found between sex. Significant interactions were also found between log(FL) and region ($F_{(4,1637)} = 25.3$, $P<0.001$), and log(FL) and sex ($F_{(1,1512)} = 7.62$, $P<0.01$). For the relationship of somatic gutted weight with length, significant interactions were observed between FL and region ($F_{(4,1509)} = 71.43$, $P<0.001$) but not with sex ($F_{(1,1515)} = 0.062$, $P>0.05$). The study shows that fixed values of a and b for the entire region may be misleading. To minimise fluctuations in length-weight relationships, it is suggested to use somatic-gutted weight instead of whole fish weight and to use separate relationships for the northern part of the Western Indian Ocean (where albacore may be in a fattening stage at their feeding ground) and the southern part, particularly between 10 and 30°S where spawning occurs.

1. Introduction

Albacore tuna, *Thunnus alalunga* (Bonnaterre, 1788) is a temperate species widely distributed in the tropical, sub-tropical and temperate zones worldwide (Colette and Nauen, 1983) where it supports major commercial fisheries (Chen *et al.*, 2005).

Morphometric parameters can provide insights into the delineation of a fish stock structure and are also used in studies of fish biology, physiology, ecology and in fisheries stock assessment (Ricker, 1975). In particular, the length-weight relationship of fish is important as it provides information not only on the condition and estimation of isometric / allometric growth of fish but it is also used for converting fish numbers in biomass, monitoring changes in average weight, as well as for deriving the species composition of the catch in multispecies fisheries (Oscoz *et al*., 2005, Carroceda and Colmenero 2015; Froese, 2006). In order to reduce uncertainty when evaluating a fish stock, it is important to first reduce possible causes of variability of the parameters from length-weight analyses (Carroceda and Colmenero, 2015).

Biological data of albacore available at the IOTC are insufficient and it is often necessary to use data from other regions or even species to obtain the required measurement (IOTC, 2005). For instance, length-length data are lacking for albacore whereby this biological data are available mostly for other tunas and billfish (IOTC, 2013). Such data are essential as it allows conversion of lengths of processed fish to standard lengths, which may in turn allow further analyses. Moreover, very few estimates of length-weight relationship parameters are available for albacore in the Indian Ocean. The IOTC pointed out that biological data for Indian Ocean albacore were so poor for some Asian industrial longline fisheries such as Taiwan,China, Indonesia and Japan, that it required the Secretariat to use length-weight keys for albacore from other oceans (IOTC, 2014). Currently, for the stock assessment of Indian Ocean albacore, the IOTC (2014) is making use of the length-weight relationship by Penney *et al.* (1994) rather than the previous equation by Hsu (1999) in the Indian Ocean, based on the gillnet fishery, as it includes a broader size range and because both oceans share similar geographical features (Nishida *et al.*, 2014). However, the validity of using data from other regions remains largely unknown (Fonteneau, 2015). It is likely that differences in length-weight relationships for same species may arise due to different fishing regions/seasons, the type of length-weight used, the quality of raw data, inclusion/exclusion of outliers in the fits, range of sizes available and the analytical methods used for each study (Carroceda and Colmenero, 2015). Particularly for albacore, variations could occur as they are known to develop separate groups at particular stages of their life cycle (Collete and Nauen, 1983) and also exhibit heterogeneity within the same region (e.g. Montes *et al.*, 2012) or Oceans (e.g. Chow and Ushiama,1995; Arrizabalaga *et al.*, 2007).

With the aim to improve the data available on length-length conversions for albacore tuna in the Indian Ocean, the present study focuses in providing accurate and representative estimates of the relationships of fork length (FL) with pectoral length (PL) and pre-dorsal length (LD1) and identify any potential variation between region and sex. In addition, if it is assumed that the length-weight of albacore could also fluctuate geographically in relation to its life history (such as feeding and spawning location), then the use of only one equation for the entire Western Indian Ocean region is questionable. This also forms the basis of the study, that is, to identify the differences between region and sex in the relationship between FL with whole fish weight (W) and somatic-gutted weight (SW).

2. Methodology

2.1. Sampling procedure

This study consists of the analysis of data of albacore caught in Mauritius (MRU), La Réunion (REU), South Africa (SA), Seychelles (SEY) and the Mozambique Channel (MOZ) by different fishing gears (Fig. 1). Samples of albacore from MRU were obtained from the local artisanal fishermen operating around Anchored Fish Aggregating Devices (AFADs) on the western coast of Mauritius island within a distance of 12 nautical miles from the coast, the national pelagic fishing boats and foreign longliners operating in the Exclusive Economic Zone (EEZ) of Mauritius. Albacore from REU were caught by national longliners targeting swordfish while those from SA were caught by baitboats using pole-and-line. Finally, albacore from SEY and MOZ were caught by European purse-seiners and unloaded in Victoria port (Seychelles).

As far as possible, the following were recorded for all fish sampled: (i) FL (length of the straight line from the end of the upper jaw (end of the snout) to the fork of the caudal fin in cm), (ii) PL (length between the pectoral fin and the fork of the caudal fin in cm), (iii) LD1 (length of the straight line from the end of the upper jaw (end of the snout) to the base of the first dorsal spine (the start of the first dorsal fin) in cm), (iv) W (kg), (v) whole gonad weight (g), (vi) liver weight (g), (vii) rest of viscera weight (stomach, heart, spleen, caecal mass, intestines; referred to as "viscera weight" in the present document) (g), and (viii) sex. All length measurements were collected using a caliper to the nearest 0.1 cm, fish weight was measured to the nearest 0.1 kg and tissue weights to the nearest 0.1 g.

Data for a total of 923 female (70-110 cm FL) and 867 male albacore (67-118 cm FL), caught from June 2013 to June 2015 between latitude 10°N-40°S and longitude 10°E-70°E were obtained (Fig. 1). Fish from MRU were collected monthly throughout the year with a focus on the main fishing period (austral summer) when catch rates were high, while those from REU, SA and SEY were sampled at two main periods representative of both austral summer and winter seasons; fish from MOZ were caught in intermediate season (April) only.

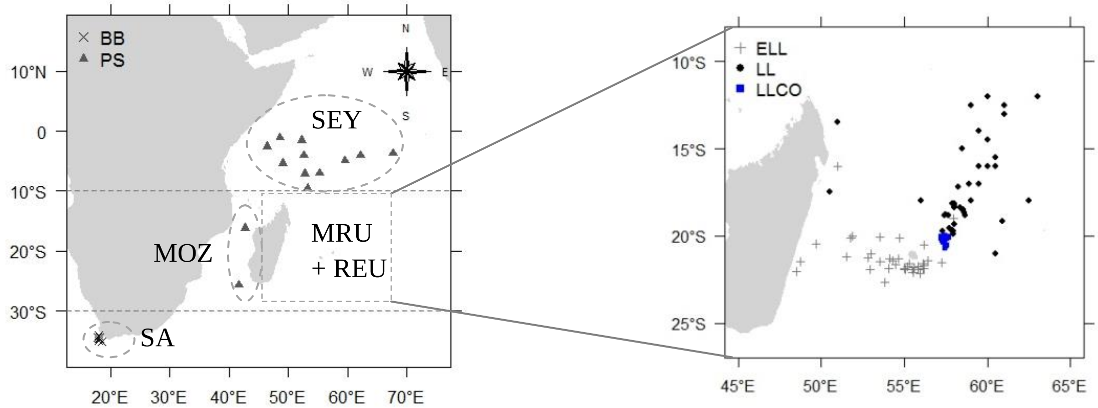

Fig. 1. Map of the Western Indian Ocean showing sampling locations of *T. alalunga* by gear and region (dotted lines) in the Western Indian Ocean: SEY: Seychelles EEZ and surrounding waters (PS), MOZ: Mozambique Channel (PS), SA: South Africa waters (BB), MRU: Mauritius EEZ and surrounding waters (LL and LLCO), REU: La Réunion EEZ and surrounding waters (ELL).

2.2. Data analysis

All the analyses were performed using R-3.2.2 (R Core Team, 2015).

2.2.1. Length-length conversions

Length-length conversions were estimated for FL-PL and FL-LD1 for males and females from each region using the linear model Y = *a**FL + *b* where Y is the PL or LD1 in cm, *a* and *b* are constants of the equation.

The linear relationships were tested for significant differences between regions using analysis of covariance (ANCOVA) with FL as covariate and region/sex as factors. FL-PL relationship was analysed only for the regions of MRU, SA and REU because only few samples were available for SEY (n=10) and no PL data were available for MOZ. FL-LD1 relationship concerned only the regions where LD1 data were available which include MRU, SEY and MOZ.

2.2.2. Variations in tissue weights

The log weights of liver, gonad and viscera weight were analysed with FL, sex and regions using ANCOVA. Analysis of viscera weight variations were performed only for fish from MRU, SEY and MOZ, due to the lack of data for fish from REU and SA.

2.2.3. Length-weight relationships

The FL-W relationship was assessed for each sex and region using the equation $W = a*FL^{b}$ where W is the total fish weight in kg, FL is the fork length in cm, *a* is the condition factor and *b* is the allometric coefficient (Ricker, 1979).

For the assumption of linearity, the non-linear model was then transformed into a linear equation by applying natural logarithms on both sides $\log W = \log(a) + b \log FL$ to identify *a* and *b* values and to examine differences between sex (separate or combined) and regions using ANCOVA. An ANCOVA was also used to test for interaction on the whole dataset between sex and region using log(FL) as continuous covariate and sex and region as factors.

SW was calculated as follows for fish from:

i. MRU, REU and MOZ
   SW = [Total fish weight (g) - (gonad weight (g) + liver weight (g) + rest of viscera weight (g))] / 1000
ii. REU and SA (visceral weight data available)
   SW = [Total fish weight (g) - (gonad weight (g) + liver weight (g))] / 1000

The FL-SW relationship between sex (separate or combined) and region was assessed using the linear model $SW = c*FL + d$, where SW is the somatic gutted weight in kg, FL is the fork length in cm, *c* and *d* are constants. An ANCOVA was used to test for interaction between sex and region using FL as covariate and sex/ region as factors.

3. Results

3.1. Length-length conversions

Table 1 gives the parameters for the relationship of FL with PL and LD1 while Fig. 2 shows the relationships between regions and sex. There were significant differences between regions in the relationships FL-PL ($F_{(5,1054)} = 5553$, $P<0.001$) and FL-LD1 ($F_{(5,921)} = 307.2$, $P<0.001$) but no significant differences between sex for both relationships. Thus, data were pooled for each sex across regions. Significant differences between regions were identified when sexes were separated or combined for the FL-PL relationship. In the case of FL-LD1 relationship, significant differences between regions were only observed when sexes were combined.

Table 1. Parameters for linear regressions between fork length and pectoral length (FL-PL) and pre-dorsal length (FL-LD1) for *T. alalunga* per sampled region (MRU: Mauritius, REU: La Reunion, SA: South Africa, SEY: Seychelles, MOZ: Mozambique Channel) and for the overall Western Indian Ocean (WIO). Significant differences between regions for males, females and both sexes combined are specified ([a] P <0.01; [b] P < 0.05). N_m = number of males, N_f = number of females, ns = non-significant.

	Region	FL range (cm)	N_m	N_f	*a*	*b*	R^2	Males	Females	Sexes combined
FL-PL	MRU	89-117	120	172	0.6571	5.5022	0.8777	SA[a], REU[a]	SA[b], REU[a]	REU[a], SA[a]
	REU	88-115	273	188	0.6958	0.9950	0.8708	MRU[a]	MRU[a]	MRU[a]
	SA	67-118	142	155	0.7025	0.4051	0.9443	MRU[a]	MRU[b]	MRU[a]
	WIO	67-118	539	521	0.7016	0.6174	0.9615	ns		-
FL-LD1	MRU	89-116	95	108	0.2316	9.3718	0.5652	ns	ns	SEY[b]
	MOZ	85-106	49	43	0.2657	5.8261	0.7322	ns	ns	ns
	SEY	83-112	275	355	0.2688	5.3085	0.6204	ns	ns	MRU[b]
	WIO	83-116	419	506	0.2678	5.4938	0.6429	ns		-

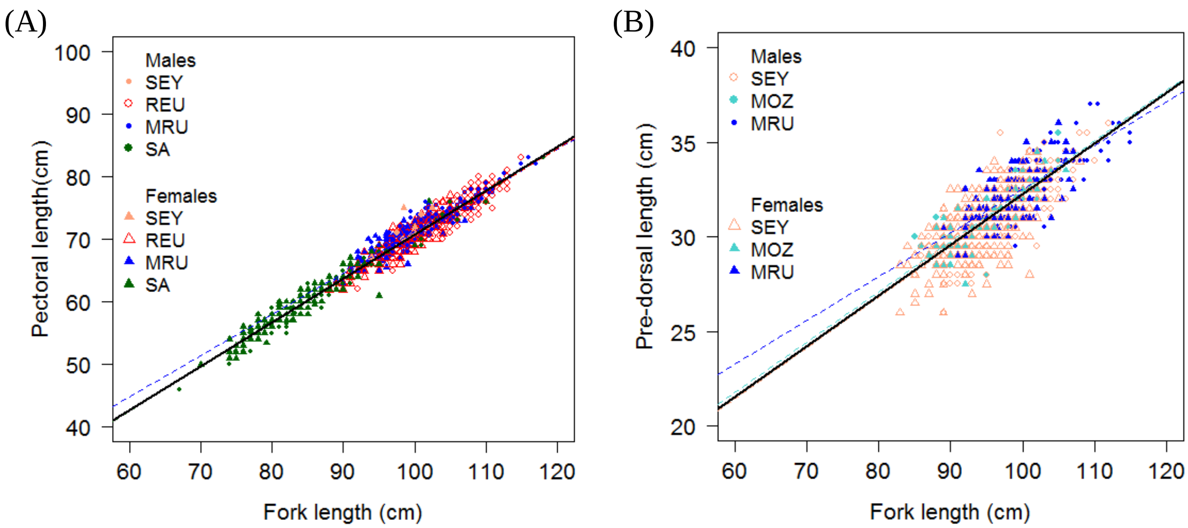

Fig 2. Relationships of fork length (FL, cm) with (A) pectoral length (PL, cm), and (B) pre-dorsal length (LD1, cm) for *T. alalunga* in the Western Indian Ocean according to sex and region. Males and females are represented with circles and triangles, respectively. Dark line indicates relationship for all the dataset (both sexes and regions combined). MRU: Mauritius, REU: La Réunion, SA: South Africa, SEY: Seychelles, MOZ: Mozambique Channel.

3.2. Variations in tissue weights

There were significant differences with FL, sex and all regions with gonad weight ($F_{(6,1684)}$ = 607.9, P<0.001) and liver weight ($F_{(6,1664)}$ = 52.04, P<0.001). Viscera weight showed significant differences with FL, sex and some regions except between MOZ and SEY ($F_{(4,1684)}$ = 51.94, P<0.001). Fig. 3 shows the variation in gonad, liver and viscera weights with FL for each sex (separated or combined) in the different regions of the Western Indian Ocean.

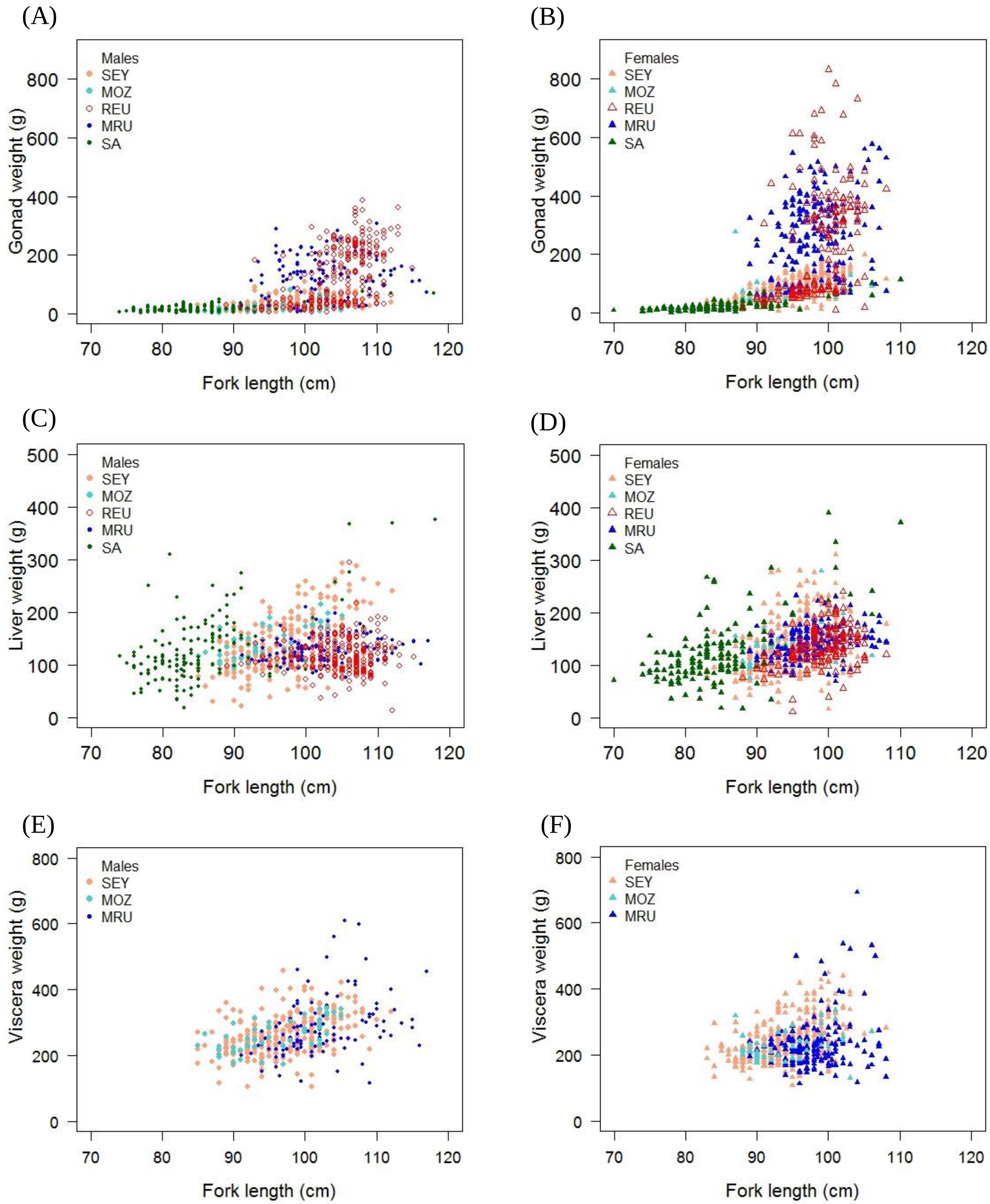

Fig. 3. Variations in gonad (A-B), liver (C-D) and viscera (E-F) weights (in g) with fish fork length (FL, in cm) for male (represented with circles) and female (represented with triangles) albacore in different regions of the Western Indian Ocean. MRU: Mauritius, REU: La Réunion, SA: South Africa, SEY: Seychelles, MOZ: Mozambique Channel. Viscera weights were not available for REU and SA.

3.3. Length-weight relationships

There were significant interactions between log(FL) and region ($F_{(4,1506)} = 25.3$, $P<0.001$) and between log(FL) and sex ($F_{(1,1512)} = 7.62$, $P<0.01$), attributed to females being slightly heavier than males depending on the region and FL (Appendix 1). Fig. 4 below shows the predicted W for male and female albacore tuna in each region sampled in the Western Indian Ocean using *a* and *b* values obtained from linear regressions of the log-transformed equation log W = log (*a*) + *b* log FL. Table 2 gives the parameters of the equation for each sex (separate or combined) for the different regions.

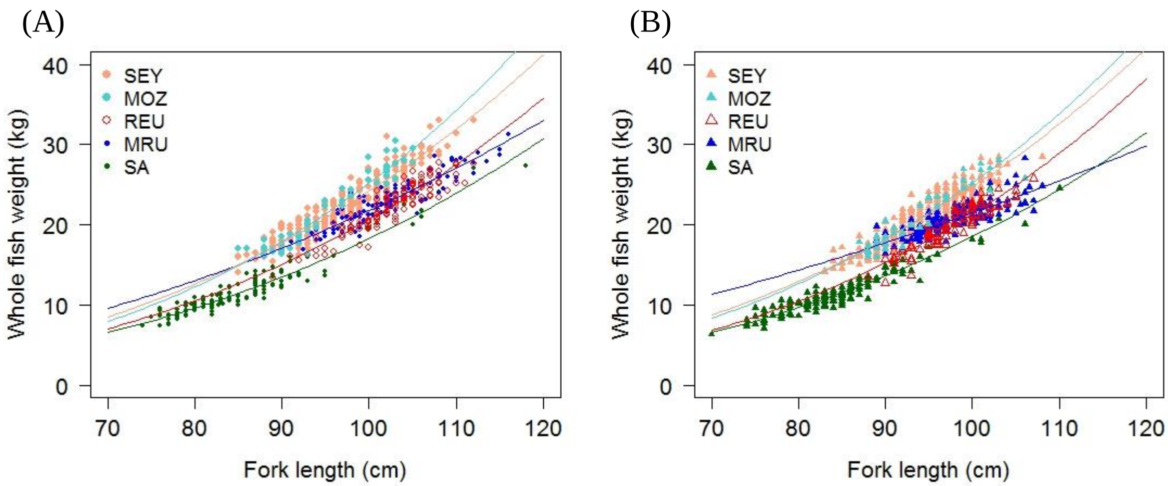

Fig 4. Relationship between fork length and whole fish weight (FL-W) for (A) male and (B) female *T. alalunga* in different regions of the Western Indian Ocean. Curves represent predicted W for each region sampled using *a* and *b* values obtained from linear regressions of the log-transformed equation log W = log (*a*) + *b* log FL. MRU: Mauritius, REU: La Réunion, SA: South Africa, SEY: Seychelles, MOZ: Mozambique Channel.

The FL-SW relationships were represented using linear regression analyses for each sex (Fig. 5). There was significant interaction between regions ($F_{(4,1509)} = 71.4$, $P<0.001$) but not with sex ($F_{(1,1515)} = 0.062$, $P>0.05$) when including SW for all regions sampled. However, excluding SW data for SA and REU led to significant difference between sex ($F_{(1,980)} = 7.12$, $P<0.01$). The comparison of FL-SW between males and females by region is shown in Appendix 2. Table 3 gives the parameters of the equation for each sex (separated or combined) for the different regions of the Western Indian Ocean. Parameters are also provided for each sex when (i) all regions were combined and (ii) only SEY, MOZ and MRU combined.

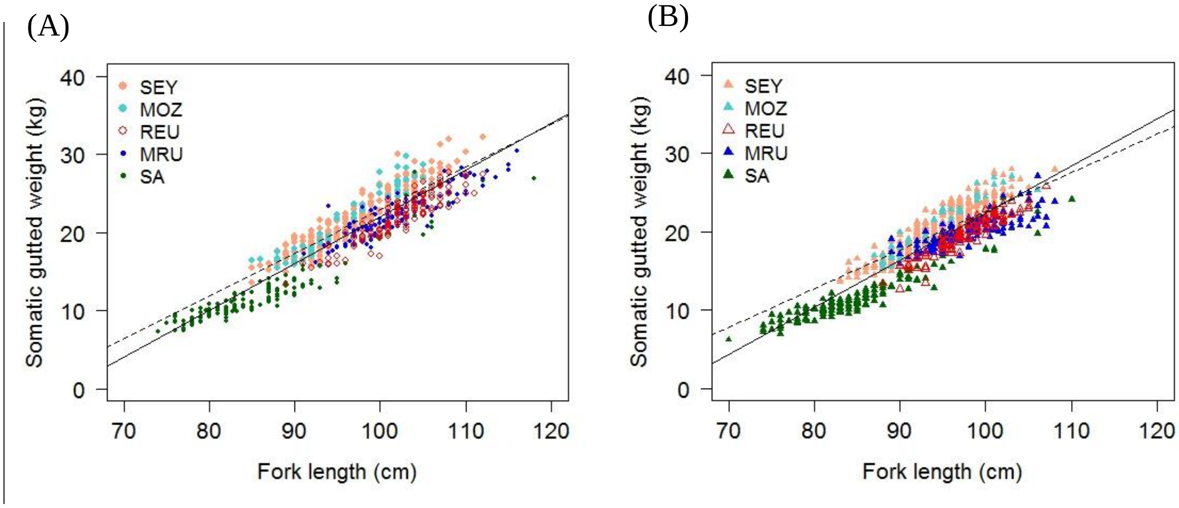

Fig 5. Relationship between fork length and somatic gutted weight (FL-SW) for (A) male and (B) female *T. alalunga* in different regions of the Western Indian Ocean. MRU: Mauritius, REU: La Réunion, SA: South Africa, SEY: Seychelles, MOZ: Mozambique Channel. SW refers to the whole fish weight minus liver, gonad and viscera weights for MRU, SEY and MOZ while it refers to whole fish weight minus liver, gonad weights only for SA and REU due to the absence of viscera weight data. Solid lines indicate the FL-SW linear regressions fitted for the entire Western Indian Ocean while broken lines indicate regressions only for SEY, MOZ and MRU combined.

Table 2. Parameters for *a* and *b* for the equation $W = a*FL^b$ derived from its linear log-transformed equation for male and female *T. alalunga* (sex separate and combined) for the different regions of the Western Indian Ocean (WIO). MRU: Mauritius, REU: La Réunion, SA: South Africa, SEY: Seychelles, MOZ: Mozambique Channel. Significant differences at $P < 0.001$ [a] and significant at $P < 0.05$ [b].

				Sexes separated					Sexes combined			
Region	Sex	FL range (cm)	n	*a*	*b*	R^2	Region effect	Sex effect	*a*	*b*	R^2	Region effect
REU	M	85-112	129	1.875×10^{-5}	3.0204	0.8483	MRU[a]	ns	3.1174×10^{-5}	2.9131	0.8519	MRU[a]
	F	83-108	107	8.5901×10^{-6}	3.1975	0.8318	MRU[a]					
MRU	M	91-116	107	5.6277×10^{-4}	2.2934	0.8344	REU[a], MOZ[a], SA[a], SEY[a]	P<0.001	1.2718×10^{-3}	2.1160	0.8012	REU[a], MOZ[a], SA[a], SEY[a]
	F	89-108	154	5.3050×10^{-3}	1.8036	0.6758	REU[a], MOZ[a], SA[a], SEY[a]					
SEY	M	89-112	275	3.3708×10^{-5}	2.9278	0.8935	MRU[a], MOZ[b]	ns	5.1120×10^{-5}	2.8397	0.8862	MRU[a], MOZ[b]
	F	88-107	355	3.7333×10^{-5}	2.9105	0.8498	MRU[a]					
MOZ	M	85-105	49	8.4834×10^{-6}	3.2364	0.9043	MRU[a], SA[b]	ns	1.3350×10^{-5}	3.1377	0.8979	MRU[a], SA[b], SEY[b]
	F	87-106	43	1.5981×10^{-5}	3.0992	0.8843	MRU[a]					
SA	M	67-118	142	3.3526×10^{-5}	2.8676	0.9136	MOZ[b], MRU[a]	ns	2.9732×10^{-5}	2.8955	0.9095	MRU[a], MOZ[b]
	F	70-110	155	2.7611×10^{-5}	2.9131	0.9057	MRU[a]					
WIO	M	67-118	702	4.3378×10^{-6}	3.3551	0.8663	-	P<0.01	3.2537×10^{-6}	3.4240	0.8484	-
	F	70-110	814	1.7551×10^{-6}	3.5625	0.8318	-					

Table 3. Relationship of SW (kg) with FL (cm) for male and female *T. alalunga* (sex separate and combined) for different regions of the Western Indian Ocean. MRU: Mauritius, REU: La Réunion, SA: South Africa, SEY: Seychelles, MOZ: Mozambique Channel. Significant differences at $P < 0.001$ [a] and significant at $P < 0.05$ [b]. WIO† includes only SEY, MOZ and MRU while WIO also includes SA and REU.

				Sexes separated					Sexes combined			
Region	Sex	FL range (cm)	n	*c*	*d*	R^2	Region effect	Sex effect	*c*	*d*	R^2	Region effect
SEY†	M	85-112	245	0.65290	-41.7155	0.8923	MRU[a], SA[a], MOZ[b]	ns	0.6375	-39.9375	0.8667	MRU[a], SA[a] REU[b], MOZ[b]
	F	83-108	315	0.62022	-38.1973	0.8410	MRU[a], SA[a]					
MRU†	M	91-116	77	0.5020	-29.0807	0.8635	SEY[a], REU[a], MOZ[a]	*P*<0.001	0.4669	-25.5996	0.7839	REU[a], MOZ[a], SEY[a]
	F	89-108	129	0.3800	-17.4236	0.6711	SEY[a], REU[a], MOZ[a], SA[b]					
REU††	M	89-112	115	0.6226	-41.7111	0.8535	MRU[a], SA[a], MOZ[b]	ns	0.5983	-38.9691	0.8644	MOZ[a], MRU[a], SA[a], SEY[b]
	F	88-107	91	0.6298	-41.8198	0.8497	MRU[a], SA[a]					
MOZ†	M	85-105	48	0.7377	-49.0731	0.906	MRU[a], SA[a], SEY[b], REU[b]	ns	0.7153	-46.8888	0.9016	REU[a], MRU[a], SA[a], SEY[b]
	F	87-106	42	0.7267	-47.8157	0.9112	MRU[a], SA[a]					
SA††	M	67-118	140	0.4380	-25.6530	0.8969	SEY[a], REU[a], MOZ[a]	ns	0.4488	-26.5006	0.8942	REU[a], MOZ[a], SEY[a]
	F	70-110	154	0.4298	-24.9014	0.8969	SEY[a], REU[a], MOZ[a], MRU[b]					
WIO†	M	85-116	419	0.5496	-32.1133	0.7819	-	*P*<0.01	0.5263	-29.8530	0.7326	-
	F	83-108	525	0.4937	-26.7491	0.6464						
WIO	M	67-118	702	0.6001	-37.9629	0.8594	-	*P*>0.05	0.5985	-37.6443	0.8441	-
	F	70-110	814	0.6035	-37.9773	0.8136						

†: SW = [Total fish weight (g) - (gonad weight (g) + liver weight (g) + rest of visceral weight (g))] / 1000
††: SW = [Total fish weight (g) - (gonad weight (g) + liver weight (g))] / 1000

4. Discussion

Morphology can be used as a way to identify different stocks as seen in past studies (eg. Bard, 1981). Albacore from SEY and MOZ share same FL-LD1 relationship while those from REU and SA have same FL-PL relationship. This is in accordance with genetic analyses conducted by Nikolic *et al*. (2015) where no significant differences were found between albacore from SEY, SA and REU. The authors also suggested that some fish could migrate through MOZ to reach SEY (Nikolic *et al*., 2015) which again agrees to the similarity in morphological traits observed between these two regions. In addition, the study found that albacore from SA were more genetically linked to those located in the north, in the vicinity of SEY, than in REU but this cannot be inferred from our study results.

The FL-PL relationships show that albacore from MRU are different from those caught in SA and REU. Since PL data were unavailable for MOZ and SEY, it is unknown if significant differences would have also been obtained with these regions. However, the additional significant difference in the FL-LD1 relationship with SEY indicate that fish from MRU could have a different origin in the Western Indian Ocean, possibly from the Eastern Indian Ocean. In contradiction to our study results, previous morphological analyses of albacore in the Indian Ocean (Yeh *et al*., 1996; Penney *et al*., 1998) concluded that albacore from the Central and Western Indian Ocean were similar while individuals from the Eastern Indian Ocean were different from the Central Indian Ocean. In the Western Indian Ocean, albacore is thought to spawn mainly on the east of Madagascar between 15° and 25°S during austral summer when sea surface temperature are high, above 24°C (Schaefer, 2001). Since fish from MRU region were collected mostly during summer, when their catch rates are highest (Dhurmeea *et al*., 2012), it is a possibility that these albacore might have migrated from the Eastern Indian Ocean for spawning, affecting the morphological traits for this region as observed in our study. The likelihood of the existence of discrete populations of albacore in the Indian Ocean should not be neglected in view of the heterogeneity observed in populations of albacore from other Oceans (for eg. Chow and Ushiama, 1995; Takagi *et al*., 2001; Arrizabalaga *et al*., 2004; 2007) despite the absence of obvious oceanographic obstructions that may limit gene flow throughout populations (Montes *et al*., 2012).

We found that albacore sampled had different gonad, liver and viscera weights, and variations occurred particularly in gonad weight fluctuated highly (from less than 10 g to more than 800 g), being higher in REU and MRU. This is likely due to the fact these fish may have been caught during the spawning season during the first and fourth quarters of the year (Schaefer, 2001; Dhurmeea *et al*., 2016). This is also reflected in the *b* values of MRU which was the lowest observed in this study, especially for females which invest a higher amount of energy into egg production compared to males. In fact, the significant difference observed in FL-W relationship between sex for the whole Western Indian Ocean is due to the significant difference in MRU with females being less heavy than males after approximately 90 cm FL (Appendices 1 and 2) which is the size around which albacore reach sexual maturity (e.g. Farley *et al*., 2013; Dhurmeea *et al*., 2016). However, high *b* values were still observed for fish in REU. This could be attributed to the fact that fish in this region were sampled both in spawning and non-spawning season suggesting both depletion and accumulation of fat reserves at different periods of the year. On the other hand, most fish from MRU were sampled during austral summer during the spawning season reflecting the use of energy store for reproduction rather than replenishing reserves. It was previously hypothesized that allometry may vary throughout the year depending on the life history such as spawning and feeding (Andrade and Campos, 2002). The authors observed significant variations of *b* with month, in the southwest South Atlantic skipjack tuna, although they lacked sufficient evidence to show that reproduction had an effect on the length-weight relationship. Interestingly, we also note that the total fish weight of females tend to be slightly higher than males in REU, SEY and SA (FL-W, Appendix 1) but when removing the effect of gonad weight (FL-SW, Appendix 2), the same trend as in MRU is observed with males being heavier than females after 90 cm FL, except in REU. However, the effect of sex is non-significant and region has a higher effect than sex.

As observed from their lower gonad weight, no spawning fish occurred in the other latitudinal areas: large mature but reproductively inactive individuals tend to remain north (SEY/MOZ) while smaller immature ones stay south of 30°S (SA) as previously described by Suda (1974) and Chen *et al*. (2005). Liver weight variations depend on the life history processes of the individuals like reproduction, migration and growth which may affect their energy store (i.e. the liver) (Campbell and Love, 1978). Viscera weight variations, which include the gut, depend mainly on the feeding behaviour of the individuals which could be particularly important if the albacore has specific feeding grounds, in the north of the Indian Ocean in SEY as suggested by Nikolic *et al*. (2015). In fact, SEY/MOZ could potentially be the primary feeding grounds of albacore in the Western Indian Ocean where they accumulate large amounts of fat reserve, as shown by their high *b* values which reflect faster weight gain with length (Andrade and Campos, 2002). It was suggested, from studies of the western Atlantic bluefin tuna (*Thunnus thynuus*), that fish at different fattening stages should not be mixed to avoid bias in the length-weight relationship (Cort and Estruch, 2016).

The literature consists of an extensive set of data on the length and weight relationships of albacore in the Atlantic and the Pacific Oceans, and regions of the Indian Ocean (Table 4).

Table 4. Length-weight relationship for *T. alalunga* from studies in different regions based on the equation W = *a* FL^b where W is the gutted/whole body weight in g, FL is the fork length in cm, and *a* and *b* are parameters.

Region/Ocean	Equation	FL range (cm)	N	Author(s)
Indian Ocean (IO)	$W = (5.69 \times 10^{-5})\ FL^{2.7514}$	46-112	2499	Hsu (1999)
Eastern Indian Ocean (EIO)	$W = (8.00 \times 10^{-5})\ FL^{2.7271}$	83-106	497	Setyadji *et al*. (2012)
Western Cape of South Africa (WSA)	$W = (1.84 \times 10^{-5})\ FL^{3.008}$	58-114	119	Stewart (2013)
Southern Atlantic (SAt)	$W = (1.37 \times 10^{-5})\ FL^{3.0973}$	52-118	1008	Penney (1994)
Northern Atlantic (NAt)	$W = (1.34 \times 10^{-5})\ FL^{3.107}$	42-117	714	Santiago (1993)
South Pacific (SP)	$W = (1.43 \times 10^{-5})\ FL^{3.1}$	46-102	1756	Williams *et al*. (2012)
Hawaii & North Pacific (NP)	$W = (2.59 \times 10^{-5})\ FL^{2.9495}$	50-128	200	Nakamura & Uchiyama (1966)

Pooling of data from all regions and sex in the current study (FL range: 67-118 cm) gives higher predicted weights of albacore as from 98 cm FL compared to the other studies, even those from previous studies in the Indian Ocean (Hsu, 1999), and is mainly the result of increased *b* values (higher fish condition) observed in albacore from SEY and MOZ areas. However, below 98 cm FL, predicted weights were lower than in the Eastern Indian Ocean (Setyadji *et al.*, 2012). This is likely due to the fact that the small fish sampled were from SA region as shown by their great similarity with predicted weights found by Stewart *et al.*(2013) off the south west coast of South Africa. Thus, the whole length-weight data in our study highly appears to be a combination of fish that tend to be resident in the region sampled and individuals that migrated from other regions. It is thus not advised using a single length-weight relationship for all the individuals of the Western Indian Ocean as it could be highly misleading.

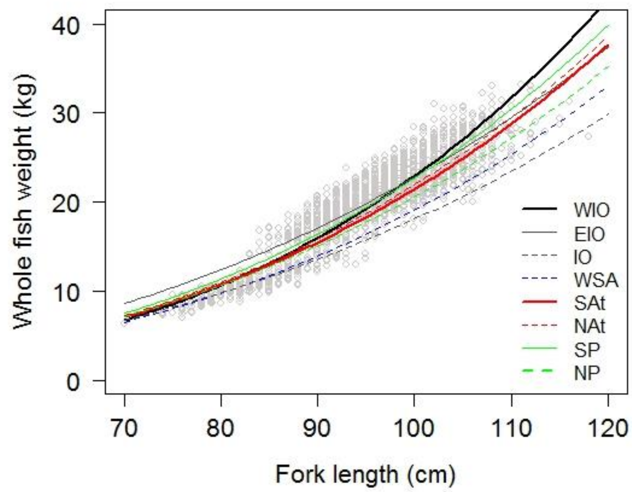

Fig 6. Comparison of predicted weights of *T. alalunga* from data of our current study (grey circles) in the Western Indian Ocean albacore (WIO) with other regions/Oceans from studies listed in Table 4.

Factors such as sampling of different stocks, sex ratio may affect the estimation of length-weight coefficients (Chen *et al*., 2012). Variation in the allometry coefficient of the same species has been observed between stocks and areas such as in the case of skipjack tuna (*Katsuwonus pelamis*): *b* is higher for individuals in the southwest Atlantic compared to their Indian and West Pacific Oceans counterparts (Marcille and Stequert, 1976; Vooren, 1976; Evans *et al*., 1978) but smaller than fish in the East Pacific and North Atlantic Oceans (Batts, 1972; Lenarz, 1974; Pianet, 1974). Apart from the possible existence of genetically different albacore populations in the Indian Ocean, the concept of metapopulation defined as a set of local populations that have different habitat patches but remain connected to one another by migration of individuals (Ricklefs and Miller, 2000), could also be a plausible hypothesis to the differences in length-length and length-weight observed in albacore and would be in agreement to individuals migrating for spawning or feeding purposes. Similar assumptions was made by Aloncle and Delaporte (1973) and Arrizabalaga *et al*. (2002) for albacore from the Northeast Atlantic Ocean whereby mixing of individuals from different populations could occur at some level. Ignoring spatial structure in fisheries assessment and management may lead to biases during estimation of population parameters, and stock status could eventually result in erroneous management target and harvest levels leading to depleting populations (Defeo and Cansado, 2015).

Finally, the present study showed that the combination of the FL-SW relationships for the entire Western Indian Ocean counteracts the effects of sex and tissue weight variability as compared to FL-W relationship where significant interaction with sex was observed. However, the FL-SW relationships will have its limits and vary by region particularly if high fluctuations occur when the fish is accumulating body fat on specific feeding grounds or is depleting its fat reserve for highly energy-demanding processes, such as in the case of MRU region where differences between sexes persisted.

5. Conclusion

We showed that fixed values of *a* and *b* for the entire region may be misleading. Estimates of *a* and *b* are dependent on each other and are linked to ecological processes and life history of the fish. Since albacore is highly migratory and develops separate life history groups at particular stages of its life cycle (Collette and Nauen, 1983), with different spawning and feeding grounds, it is highly recommended that the length-weight of this species be assessed with caution taking into consideration the combination of factors that may affect FL-W relationship. To minimise fluctuations in length-weight relationships, it is suggested to use SW instead of W and to use separate relationships for the northern part of the Western Indian Ocean (where albacore may be in a fattening stage at their feeding ground) and the southern part where spawning occurs between 10 and 30°S, reflecting accumulation and depletion of energy stores (i.e. fat). Fish in MRU should also be given particular attention as the data were obtained mostly from the catch of Taiwanese longliners which concentrate fishing effort in its waters during the austral summer (Dhurmeea *et al*., 2012) when spawning occurs (Dhurmeea *et al*., 2016).

Even if in the Indian Ocean, the existence of only one stock of albacore is assumed, the possibility that more than one stock or different populations could occur should be taken into consideration. Additional methods including genetic and /or morphometric analyses conducted with fish caught in MRU and other areas of the Indian Ocean (especially the eastern part) could provide more information on the difference observed in our study. Identifying the possible different stocks/populations in the Indian Ocean is important as it would require the use of different length-weight relationships for each of them such as in the case of the Western Atlantic bluefin tuna (ICCAT, 2014) whereby each of the two existing stocks has its own length-weight relationship.

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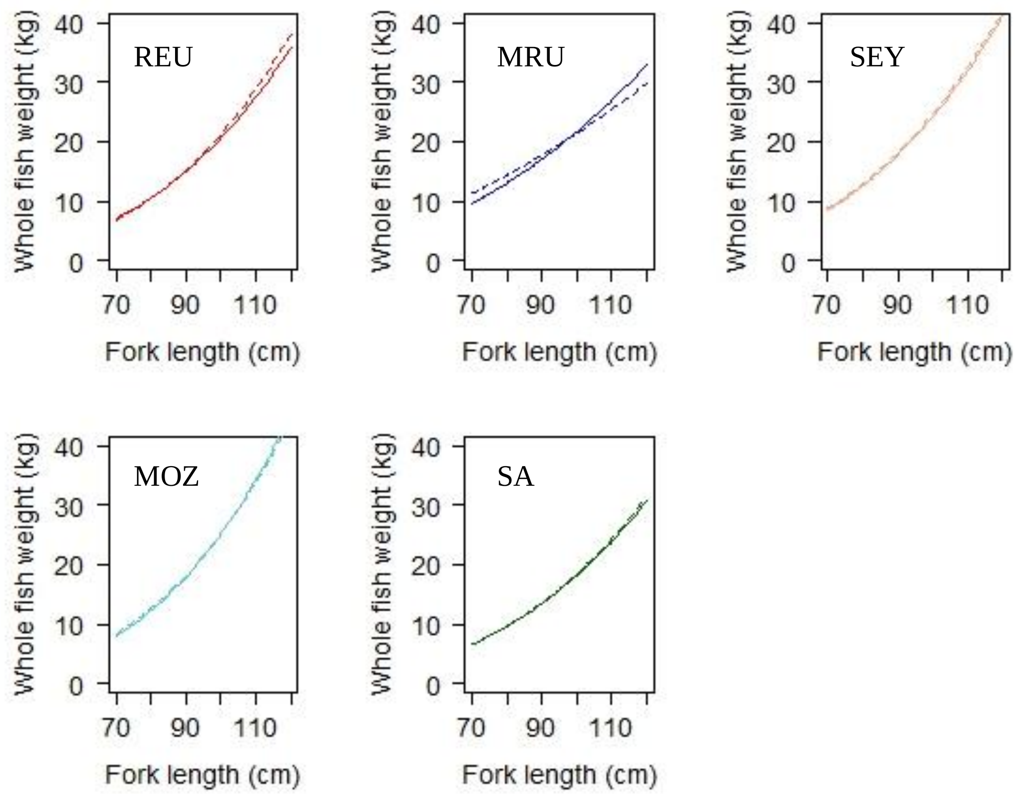
Appendix 1

Relationship of total fish weight (W, kg) with fork length (FL, cm) for male (solid line) and female (dotted line) *T. alalunga* for different regions of the Western Indian Ocean. MRU: Mauritius, REU: La Réunion, SA: South Africa, SEY: Seychelles, MOZ: Mozambique Channel.



Appendix 2

Relationship of somatic gutted weight (SW, kg) with fork length (FL, cm) for male (solid line) and female (dotted line) *T. alalunga* for different regions of the Western Indian Ocean. MRU: Mauritius, REU: La Réunion, SA: South Africa, SEY: Seychelles, MOZ: Mozambique Channel.