Indian Ocean Tuna Commission
Commission des Thons de l'Ocean Indien
iotc ctoi

IOTC–2021–WPTT23–06

Working paper for

23th Working Party on Tropical Tuna (WPTT23)

Indian Ocean Tuna Commission (IOTC)

online

21-26 October 2021

Comparative study of Indian Ocean Dipole impacts on catch rates of yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) in the Indian Ocean

Document #: IOTC–2021–WPTT23-##

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Summary

Anomalous sea temperature changes could have direct impacts on fish spatial distribution and stock dynamics. Large-scale climate fluctuations as one of the major reasons causing temperature changes has attracted extensive attention. However Indian Ocean Dipole (IOD), an ocean-atmosphere interaction causing interannual climate variability, has not been largely explored. And few of studies tested whether IOD have different effects between different tuna species and whether IOD have spatially distinct influences on one single tuna species. This study adopted public longline fishery data and spatial structure carried by IOTC comparing the differences of IOD impacts between bigeye tuna and yellowfin tuna. Results found that IOD event have significant influence on bigeye tuna only in the tropical western Indian Ocean. For yellowfin tuna, IOD showed significant effects on catch per unit effort (CPUE) both in tropical western and eastern Indian Ocean. And indicators showed that IOD have more significant influence on yellowfin tuna than bigeye tuna. In the south Indian Ocean, both for bigeye tuna and yellowfin tuna, IOD didn't show obvious relationship with CPUE.

1. Introduction

Large-scale climate fluctuations are important factors affecting fish population dynamics, altering their spatial distributions and productivity. The most important change is ocean temperature which could have direct impacts on fish distribution, growth, reproduction, etc. In response to changing temperature conditions, fish may move or shift to deeper waters to track the same water temperatures. Within US waters in the northwest Atlantic, commercial fish stocks like alewife, silver hake and red hake showed clear poleward shifts which closely associated with Atlantic Multidecadal Oscillation (AMO) positive events in the late 1990s and 2000s (Nye, Link, Hare, & Overholtz, 2009). The longitudinal gravity of fishing grounds of skipjack tuna in the western and central Pacific Ocean varied by up to 40° of longitude between strong El Niño and La Niña events (P. Lehodey, Bertignac, Hampton, Lewis, & Picaut, 1997). Demersal fish assemblage in the North Sea deepened by about 3.6 m per decade as bottom temperature get warmer (Dulvy et al., 2008).

Temperature is also an important spawning cue generating large effect on the recruitment success of populations (Houde & Hoyt, 1987; Rijnsdorp, Peck, Engelhard, Möllmann, & Pinnegar, 2009). Recruitments of tropical skipjack tuna and yellowfin tuna in the Pacific Ocean became higher during El Niño events. Whereas subtropic albacore had lower recruitment during El Niño and higher recruitment during La Niña (Patrick Lehodey, Chai, & Hampton, 2003). Reef fishes in the western central Atlantic Ocean showed lower fecundity, smaller eggs or reduced pairing with temperature increase caused by climate change (Pratchett, Wilson, & Munday, 2015).

Due to the interaction of the sea surface temperature (SST) and winds, climate aberrations also occurred in the Indian Ocean defined as Indian Ocean Dipole (IOD)(N. Saji, B. Goswami, P. Vinayachandran, & T. Yamagata, 1999; Saji & Yamagata, 2003). IOD events characterized the SST anomaly change associating with wind direction and precipitation deviations. IOD event experiences two phases: positive and negative. When the positive event, SST turns cooler in the eastern Indian Ocean (EIO) couples with a westward wind anomaly along the equator resulting in warmer SST in the western Indian Ocean (WIO). The IOD in the negative phase shows the opposite way: SST becomes anomaly cooler in the western Indian Ocean and warmer in the eastern Indian Ocean (Feng & Meyers, 2003; N. Saji et al., 1999). Yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) are the principal commercial target species accounting for 42.2% and 9.3% of the tropical tunas' total harvest in the Indian Ocean respectively (IOTC, 2020). Yellowfin tuna and bigeye tuna were both distributed in the sea pelagic layer. However, yellowfin tuna generally spread in the mixing layer or at the top of the thermocline (Brill et al., 1999). Both temperature and dissolved oxygen can affect the vertical distribution of yellowfin tuna (Cayré & Marsac, 1993; Song, Zhang, Xu, Jiang, & Wang, 2008). Different from yellowfin tuna, bigeye tuna has higher O2 affinity that can adapt to the lower temperature (Lowe, Brill, & Cousins, 2000). Therefore, the habitats of bigeye tuna are usually deeper than yellowfin tuna (Dagorn, Holland, & Itano, 2007; Holland, 1990). Based on the different habitats, we hypothesize IOD events may have different influences on bigeye tuna and yellowfin tuna.

Previous studies found that catch rates of yellowfin tuna of longline fisheries in the WIO decreased when positive IOD events along with fishing grounds were restricted to the northern and western margins of the WIO. When negative IOD events, catch rates increased and fishing grounds expanded into central regions of the WIO (Lan, Evans, & Lee, 2012). In the EIO, catch rates of longline bigeye tuna fisheries became higher in the positive IOD events (Lumban-Gaol et al., 2015). However, these studies mostly focused on effects of climate index on single tuna species, and few of them tested whether different tuna species responded differently. Furthermore, it is largely untested whether climate index could have spatially distinct effects on a single tuna species. To address these research gaps, we aim to investigate whether IOD events have different effects on bigeye tuna and yellowfin tuna, and whether the impact of IOD on the same tuna species is distinct in different areas of the Indian Ocean. Specifically, our research area covered the whole Indian Ocean and divided the Indian Ocean based on the spatial structures carried by Indian Ocean Tuna Commission (IOTC).

2. Materials and methods

2.1 Spatial structure

Spatial region of bigeye tuna was stratified into four regions by IOTC: western equatorial region which was partitioned into south equator area (R1S) and north equator area (R1N), eastern equatorial region (R2) and southern region (R3)(Fu, 2019). Considering longline fisheries of bigeye tuna mainly focused on EIO(Pillai & Satheeshkumar, 2012), we combined western area R1N and R1S as R1 in this study (Fig.1) .Yellowfin tuna stock assessment model adopted four regions structure which is different from bigeye tuna: western equatorial region (R1), eastern equatorial region (R3) , southern area divided into west-south area (R2) and east-south area (R4) showed in Fig.2 (Urtizberea et al., 2019).

2.2 Fishery data

Longline catch and effort data for yellowfin tuna and bigeye tuna were available from IOTC public datasets by month from 2000 to 2019 (https://www.iotc.org/data/datasets). The data sets contain fishery data in 5°×5° resolution (effort by number of hooks, catch by numbers) and operational data (fishing date and area coordinates). Spatial and temporal distribution of nominal CPUE of bigeye tuna and yellowfin tuna were shown in Fig.1.

2.3 Indian Ocean Dipole

IOD phenomenon is expressed as Dipole Modular Index (DMI), which is represented by anomalous Sea Surface Temperature (SST) gradient between the western equatorial Indian Ocean (50°E-70°E and 10°S-10°N) and the southeastern tropical Indian Ocean (90°E-110°E and 10°S-0°N). Positive DMI is referred as positive IOD, negative DMI represent negative IOD phenomenon. DMI was obtained from the Japan Agency for Marine-Earth Science and Technology (JAMSTC) website (http://www.jamstec.go.jp/frcgc/research/d1/iod/) from 2000 to 2019 by month. Each month has one value for the entire Indian Ocean, and the distribution of DMI shows in Fig.2.

2.4 Statistical analyses

To examine the significant of IOD effects, we used two indicators. 1) First indicator based on the Akaike information criterion (AIC). Generalized Additive Model (GAM) (Hastie, 2017) was used to analyze the effects of IOD events on catch rates of yellowfin tuna and bigeye tuna in the Indian Ocean. AIC provide the standard to select the best fitting model. Lower AIC means better model. Nominal CPUE as response variable was calculated by the number of catches captured per 1000 hooks. Independent variables included: temporal factors (year, month), spatial factors (longitude, latitude), and DMI index. We set "year + month + *s* (latitude) + *s* (longitude)" as "base model" (1) and added "*s* (DMI)" as "DMI model" (2). We ran the base model and DMI model for each subarea and the whole Indian Ocean. In each area, the AIC of DMI model lower than base model and ΔAIC > 2 as the criterion to determine DMI has a significant influence on CPUE(Burnham & Anderson, 2002). GAM model was defined as:

$$g\ (CPUE_{bet/yft} + c) \sim Year + Month + s_1\ (Latitude) + s_2\ (longitude) + \varepsilon \qquad (1)$$

$$g\ (CPUE_{bet/yft} + c) \sim Year + Month + s_1\ (Latitude) + s_2\ (longitude) + s_5\ (DMI) + \varepsilon \qquad (2)$$

Where g () is the link function, s_n is the smooth function for the explanatory variables. $CPUE_{bet/yft}$ are the nominal CPUE of yellowfin tuna and bigeye tuna. The constant c is 10% of the mean of nominal CPUE which was assumed to account for zero catch values in the data. ε is a random error.

2) Second indicator based on the p -value test for DMI model. p value of DMI index below 0.05 was considered significant. In conclusion, $p < 0.05$ and ΔAIC > 2 as the criterion to determine DMI has a significant influence on CPUE.

GAM constructed in the R software (version 3.6.1) using “mgcv” package, with the distribution family = “gaussian” and method = “REML” for smoothing parameter estimation. To avoid the multicollinearity problems which undermines the statistical significance of independent variables, we calculated the Variance Inflation Factor (VIF) for each predictor. VIF below 10 indicated the factor is effective (Menard, 2002).

3. Results

3.1 Spatial and temporal distribution of nominal CPUE of yellowfin tuna and bigeye tuna and temporal variation of DMI index

The spatial distribution of CPUE showed that higher catch rates of yellowfin tuna distributed in the western Indian Ocean, while higher catch rates of bigeye tuna mainly distributed in the middle and eastern Indian Ocean (Figure 1a,1b). CPUE of bigeye tuna for the whole Indian Ocean showed an overall steady trend. In R1 and R2, CPUE kept similar level from 2000 to 2013, after that the CPUE of R2 increased gradually and exceeded CPUE in R1. CPUE in R3 remained the lowest value with small fluctuations (Figure 1c). CPUE of yellowfin tuna in the Indian Ocean declined from 2005 to 2012, but then regained similar level as 2000. CPUE in R1 plunged significantly in 2005 and get lower than CPUE in R2 from 2006. CPUE in R3 and

R4 kept the lowest value and showed an overall slightly decease trend from 2000 to 2019 (Figure 1d).

DMI index in the positive and negative phase were almost equal from 2000 to 2006. After that, negative dipoles occurred less than positive dipoles (Figure 2).

3.2 DMI effect on the bigeye tuna and yellowfin tuna

VIFs of variables were less than 10 indicating DMI was effective in GAM models of bigeye tuna and yellowfin tuna (Table1). The histograms and QQ-plots of model residuals of bigeye tuna and yellowfin tuna are shown in appendix which followed normal distribution suggesting the model assumptions were appropriate.

In the whole Indian Ocean, DMI have significant influence both on bigeye tuna and yellowfin tuna. In the model of bigeye tuna, p value of DMI equal 0.028 which is below 0.05. The ΔAIC of DMI model and base model is 7.5 which higher than 2. The p value ($p < 0.001$) and ΔAIC (21.3) of yellowfin tuan which showed more significant influence on CPUE than bigeye tuna (Table 1). The influence plot of DMI of bigeye tuna indicated DMI have positive influence when DMI between -0.3 to 0.3 and negative influence when DMI below -0.3 or over 0.3 (Figure 3a). DMI have positive influence on yellowfin tuna when DMI under 0.1 and then turned to negative as DMI increased (Figure 3b).

Similar with the whole Indian Ocean, DMI have significant influence both on bigeye tuna and yellowfin tuna in the western equatorial Indian Ocean. Model of yellowfin tuna, which indicated a strong effect on CPUE ($p < 0.001$, ΔAIC= 57.8), also showed that had more significant influence than bigeye tuna ($p = 0.0005$, ΔAIC= 15.4) (Table 1). The influence plot of bigeye tuna indicated that DMI have positive influence when the value lower than 0.2 and turn to negative beyond 0.2 (Figure 3c). For yellowfin tuna, CPUE responded an overall decrease non-linear trend with fluctuations between -0.4 ~ 0.3. In general, similar with bigeye tuna, DMI have positive effect when DMI under 0 and negative effect when DMI beyond 0 (Figure 3d).

DMI also have significant influence on yellowfin tuna as $p < 0.001$ and ΔAIC = 14.4 in the eastern equatorial Indian Ocean (Table 1). However, for bigeye tuna, CPUE didn’t show obvious relationship with DMI as $p = 0.119$ and ΔAIC = 0.8 (Table 1). DMI exhibited positive influence on CPUE of yellowfin tuna when the value lower than zero and negative impact when higher than 0.2 (Figure 3f). As for bigeye tuna, there was no apparent trend for the influence curve of DMI (Figure 3e).

In the south Indian Ocean, DMI didn't show significant influence both on bigeye tuna and yellowfin tuna. *p*-value equals 0.085 and ΔAIC equals 1.6 of bigeye tuna (Table 1). The influence plot of bigeye tuna showed a slight increase trend: negative DMI had negative influence and positive DMI had positive influence (Figure 3g). *p* values of yellowfin tuna in R2 ($p = 0.247$) and R3 ($p = 0.568$) were both higher than 0.05. ΔAIC of yellowfin tuna in R2 (ΔAIC = 0.6) and R3 (ΔAIC = -1.1) were also lower than 2 (Table 1). Except extreme value of DMI, effect on yellowfin tuna in R2 didn't exhibit obvious trend (Figure 3h). The influence plot in R3 only showed a slight negative impact when DMI beyond 0.2 (Figure 3i).

4. **Discussion**

IOD events could lead to changes of the habitat environment. When the negative IOD event occurs in the western Indian Ocean, the thermocline becomes shallow and productivity compressed to the sea surface. The depth of habitats become more superficial than usual and the vertical movement range become limited, thus improving the fishery catchability in this environment. In the positive IOD event in the western Indian Ocean, with the extension of habitat in the horizontal and vertical directions and the level of surface productivity decreases, the distribution of tuna tends to disperse, resulting in the decline of fishery catchability (Corbineau et al., 2008; Horii et al., 2018; Lan et al., 2012). Consequently, in R1, DMI have positive effects on bigeye tuna and yellowfin tuna when negative IOD events and negative impacts when positive IOD events (Figure 3c, d). As mentioned before, bigeye tuna lives in more lower temperature environment and deeper than yellowfin tuna. Therefore, IOD had more significant influence on yellowfin tuna than bigeye tuna.

However, we found that only when IOD in the strong phases did it have obvious effects on catch rates. When the IOD was weak (DMI values around zero), there had little significant trend on the influence plots (e.g., Figure 3a,3b,3f). This can be explained by the research of Aditi *et al.*: IOD in strong years is driven by thermocline-SST coupling and is strongly interactive with the atmosphere, whereas the weak IOD events are mere response to surface winds without such dynamical coupling (Deshpande, Chowdary, & Gnanaseelan, 2014). What's more, as the IOD only had influence in the equatorial area, it's can be further proved that IOD events occurred mainly in the tropical Indian Ocean (N. H. Saji, B. N. Goswami, P. N. Vinayachandran, & T. Yamagata, 1999).

IOD events dramatically reduced the catch rates of the purse seine fleets in the western Indian Ocean (Marsac, 2008). Whereas it is likely that longline fleets are less directly affected by IOD events, because they can change the target species to offset the reduced catch rates for a given species. Moreover, the gear of longline is adjustable that the hooks can be set at various depths to exploit different tuna habitats (Marsac, 2017). Consequently, DMI only explained minor deviance in the gam models (Table 1).

Acknowledgements

This paper was supported by the National Natural Science Fund of China (32072981). We are grateful to the IOTC and Japan Agency for Marine-Earth Science and Technology (JAMSTC) for providing fishery and climate data.

REFERENCES

Burnham, K. P., & Anderson, D. R. (2002). Model Selection and Multimodel Inference: Springer-Verlag New York.

Cayré, P., & Marsac, F. (1993). Modelling the yellowfin tuna (*Thunnus albacares*) vertical distribution using sonic tagging results and local environmental parameters. Aquatic Living Resources, 6(1), 1-14. doi: https://doi.org/10.1051/alr:1993001

Deshpande, A., Chowdary, J. S., & Gnanaseelan, C. (2014). Role of thermocline–SST coupling in the evolution of IOD events and their regional impacts. Climate Dynamics, 43(1), 163-174. doi:10.1007/s00382-013-1879-5

Dulvy, N. K., Rogers, S. I., Jennings, S., Stelzenmüller, V., Dye, S. R., & Skjoldal, H. R. (2008). Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. Journal of Applied Ecology, 45(4), 1029-1039. doi: https://doi.org/10.1111/j.1365-2664.2008.01488.x

Feng, M., & Meyers, G. (2003). Interannual variability in the tropical Indian Ocean: a two-year time-scale of Indian Ocean dipole. Deep-Sea Research Part Ii-Topical Studies in Oceanography, 50(12-13), 2263-2284. doi: https://doi.org/10.1016/s0967-0645(03)00056-0

Fu, D. (2019). Preliminary Indian Ocean Bigeye Tuna Stock Assessment 1950-2018 (Stock Synthesis). Retrieved from https://www.iotc.org/documents/preliminary-indian-ocean-bigeye-tuna-stock-assessment-1950-2018-ss3

Hastie, T. J. (2017). Generalized additive models. In Statistical models in S (pp. 249-307): Routledge.

Houde, E., & Hoyt, R. (1987). Fish early life dynamics and recruitment variability. American Fisheries Society Symposium, 2, 17-29.

IOTC. (2020). Review of the Statistical Data and Fishery Trends for Tropical Tunas. IOTC–2020–WPTT22(DP)–08. Retrieved from https://www.iotc.org/documents/WPTT/2201/08

Lan, K.-W., Evans, K., & Lee, M.-A. (2012). Effects of climate variability on the distribution and fishing conditions of yellowfin tuna (*Thunnus albacares*) in the western Indian Ocean. Climatic Change, 119(1), 63-77. doi: https://doi.org/10.1007/s10584-012-0637-8

Lehodey, P., Bertignac, M., Hampton, J., Lewis, A., & Picaut, J. (1997). El Niño Southern Oscillation and tuna in the western Pacific. Nature, 389(6652), 715-718. doi:10.1038/39575

Lehodey, P., Chai, F., & Hampton, J. (2003). Modelling climate-related variability of tuna populations from a coupled ocean–biogeochemical-populations dynamics model. Fisheries Oceanography, 12(4-5), 483-494. doi: https://doi.org/10.1046/j.1365-2419.2003.00244.x

Lumban-Gaol, J., Leben, R. R., Vignudelli, S., Mahapatra, K., Okada, Y., Nababan, B., . . . Syahdan, M. (2015). Variability of satellite-derived sea surface height anomaly, and its relationship with Bigeye tuna (*Thunnus obesus*) catch in the Eastern Indian Ocean. European Journal of Remote Sensing, 48(1), 465-477. doi: https://doi.org/10.5721/EuJRS20154826

Marsac, F. (2008). Outlook of ocean climate variability in the west tropical Indian Ocean, 1997–2008. IOTC-2008-WPTT-27. Retrieved from https://www.iotc.org/documents/outlook-ocean-climate-variability-tropical-indian-ocean-1997-2008

Marsac, F. (2017). The Seychelles Tuna Fishery and Climate Change. In B. F. Phillips & M. Pérez-Ramírez (Eds.), Climate Change Impacts on Fisheries and Aquaculture (pp. 523-568): Wiley.

Menard, S. (2002). Applied logistic regression analysis. Thousand Oaks, CA: Sage Publications.

Nye, J. A., Link, J. S., Hare, J. A., & Overholtz, W. J. (2009). Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Marine Ecology Progress Series, 393, 111-129. Retrieved from https://www.int-res.com/abstracts/meps/v393/p111-129

Pillai, N. G., & Satheeshkumar, P. (2012). Biology, Fishery, Conservation and Management of Indian Ocean Tuna Fisheries. Ocean Science Journal, 47(4), 411-433. doi: https://doi.org/10.1007/s12601-012-0038-y

Pratchett, M. S., Wilson, S. K., & Munday, P. L. (2015). Effects of climate change on coral reef fishes: Cambridge University Press.

Rijnsdorp, A. D., Peck, M. A., Engelhard, G. H., Möllmann, C., & Pinnegar, J. K. (2009). Resolving the effect of climate change on fish populations. ICES Journal of Marine Science, 66(7), 1570-1583. doi: 10.1093/icesjms/fsp056

Saji, N., Goswami, B., Vinayachandran, P., & Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. Nature, 401(6751), 360-363. doi: https://doi.org/10.1038/43854

Saji, N. H., & Yamagata, T. (2003). Possible impacts of Indian Ocean Dipole mode events on global climate. Climate Research, 25(2), 151-169. doi:10.3354/cr025151

Song, L. M., Zhang, Y. U., Xu, L. X., Jiang, W. X., & Wang, J. Q. (2008). Environmental preferences of longlining for yellowfin tuna (*Thunnus albacares*) in the tropical high seas of the Indian Ocean. Fisheries Oceanography, 17(4), 239-253. doi: https://doi.org/10.1111/j.1365-2419.2008.00476.x

Urtizberea, A., Fu, D., Merino, G., Methot, R., Cardinale, M., Winker, H., . . . Murua, H. (2019). Preliminary assessment of Indian Ocean yellowfin tuna 1950-2018 (Stock Synthesis, v3. 30). Retrieved from https://www.iotc.org/documents/WPTT/21/50

FIGURE 1 Spatial and temporal distribution of nominal CPUE from 2000 to 2019 and regional stratification of bigeye tuna (a, c) and yellowfin tuna (b, d). BET: bigeye tuna; YFT: yellowfin tuna.

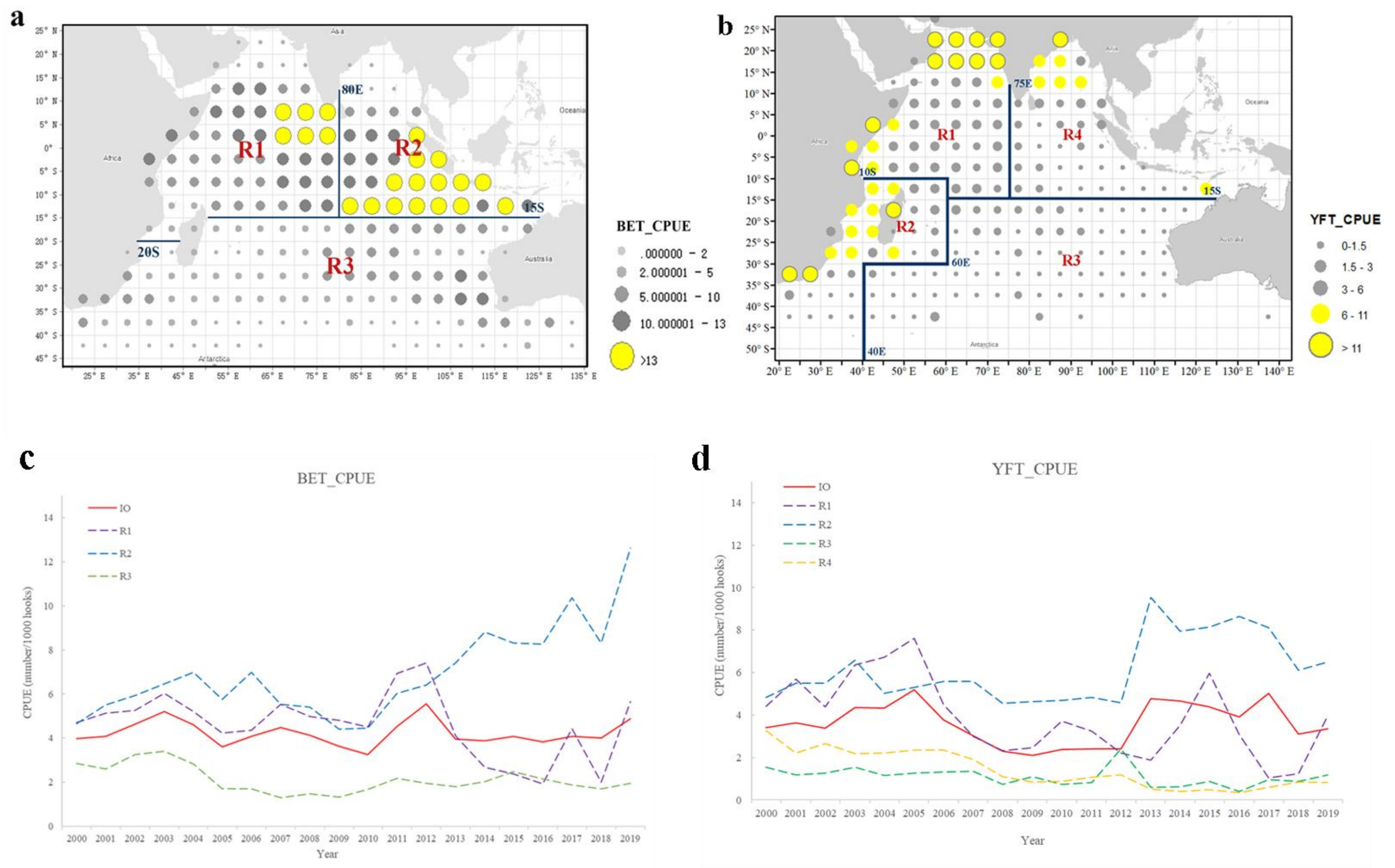


FIGURE 2 Distribution of DMI from 2000 to 2019. Positive DMI is referred as positive IOD, negative DMI represent negative IOD phenomenon.

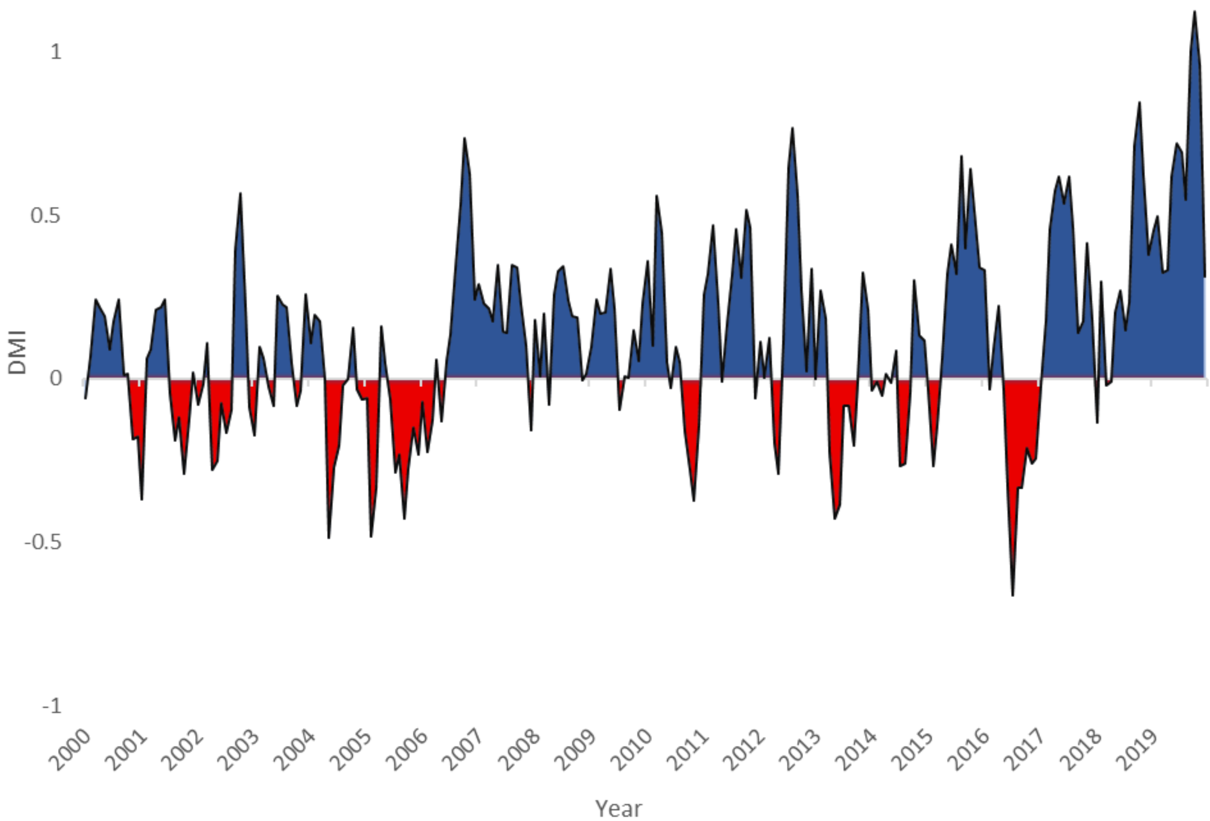
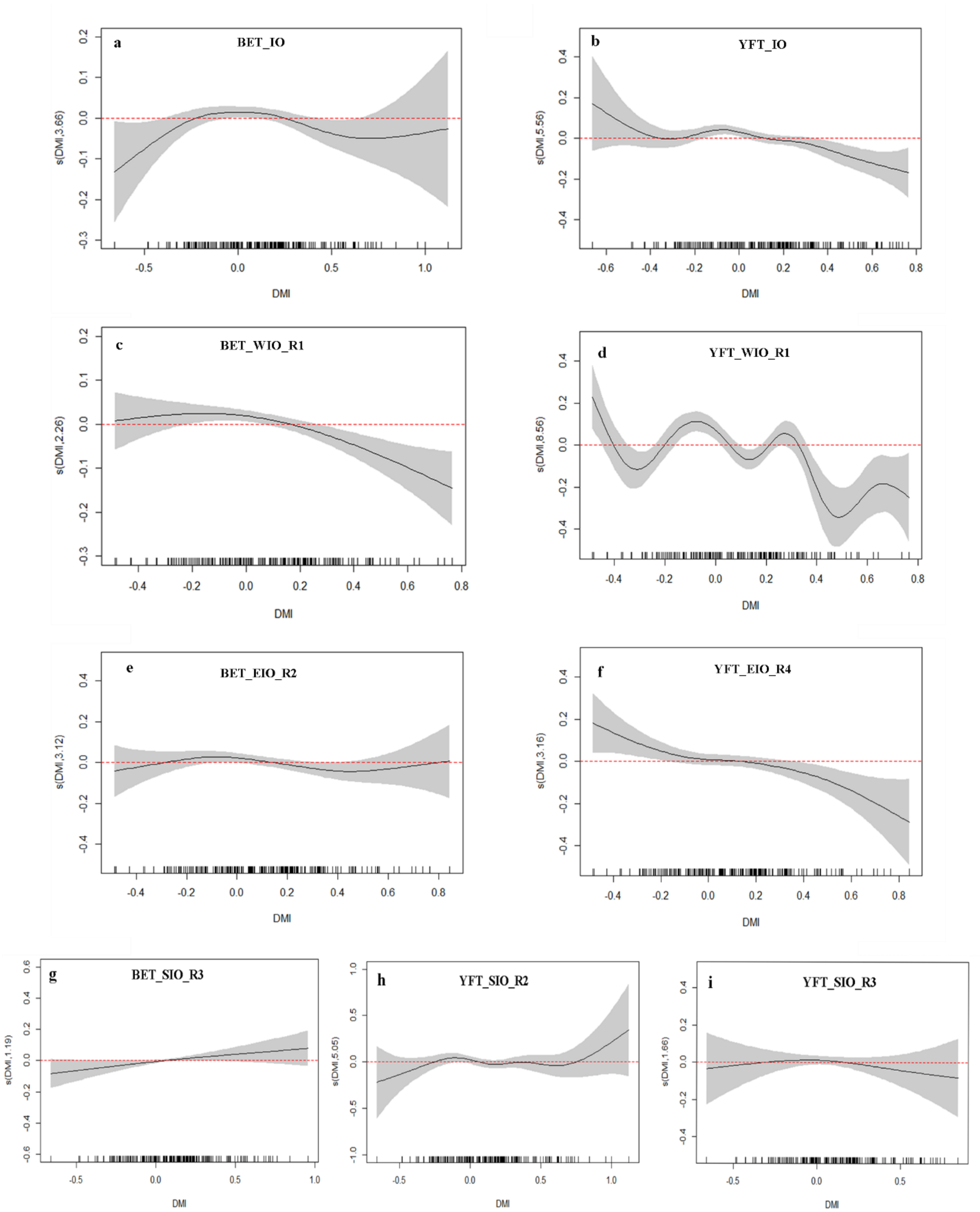


TABLE 1 Results derived from GAMs analyses of bigeye tuna and yellowfin tuna for the whole Indian Ocean, west Indian Ocean, east Indian Ocean and south Indian Ocean during 2000-2019: VIF, residual deviance, deviance explained, *p*-value of the explanatory variables and AIC values of each model. Base model designed as: Year + Month + *s* (longitude) + *s* (latitude). Significance levels of model terms: "." = 0.05 < *p* < 0.1, "*" =0.01 < *p* <0.05, "**" =0.001< *p* < 0.01, "***" = *p* < 0.001. IO: Indian Ocean; WIO: western equatorial Indian Ocean; EIO: eastern equatorial Indian Ocean; SIO: south Indian Ocean. BET: bigeye tuna; YFT: yellowfin tuna.

		Model structure	VIF	Residual Deviance	Cumulative of Deviance Explained %	*P*-value	AIC	ΔAIC
IO	**BET**	Base model		8564	31.6		36438.9	
		+ s (DMI)	1.09	8556	31.7	0.028 *	36431.4	7.5
	YFT	Base model		12714	32		43089.8	
		+ s (DMI)	1.09	12688	32.1	< 0.001***	43068.5	21.3
WIO	**BET(R1)**	Base model		2783.1	24.2		13908.6	
		+ s (DMI)	1.09	2775.7	24.4	0.0005***	13893.2	15.4
	YFT(R1)	Base model		3549.5	21.7		13415.4	
		+ s (DMI)	1.07	3502.4	22.7	< 0.001***	13357.6	57.8
EIO	**BET(R2)**	Base model		966.0	29.5		5295.2	
		+ s (DMI)	1.11	965.7	29.5	0.119	5294.4	0.8
	YFT(R4)	Base model		1970.6	35.3		8646.7	
		+ s (DMI)	1.08	1960.6	35.6	< 0.001***	8632.3	14.4
SIO	**BET(R3)**	Base model		4181.9	21.3		15065.8	
		+ s (DMI)	1.07	4169.1	21.4	0.085 ·	15064.2	1.6
	YFT(R2)	Base model		3014.8	37.1		10002.6	
		+ s (DMI)	1.09	3006.4	37.1	0.247	10002	0.6
	YFT(R3)	Base model		2823.1	22.8		8871.4	
		+ s (DMI)	1.06	2821.2	22.9	0.568	8872.5	-1.1

FIGURE 3 Effects of DMI on nominal catch per unit effort (CPUE) of bigeye tuna and yellowfin tuna during 2000-2019. Grey shade represented 95% confidence intervals. IO: Indian Ocean; WIO: west Indian Ocean; EIO: east Indian Ocean; SIO: south Indian Ocean. BET: bigeye tuna; YFT: y3ellowfin tuna.



Appendix

FIGURE A1 Histograms and QQ-plots of residuals from the GAM analyses for bigeye tuna (BET) for the whole Indian Ocean and three sub-areas.

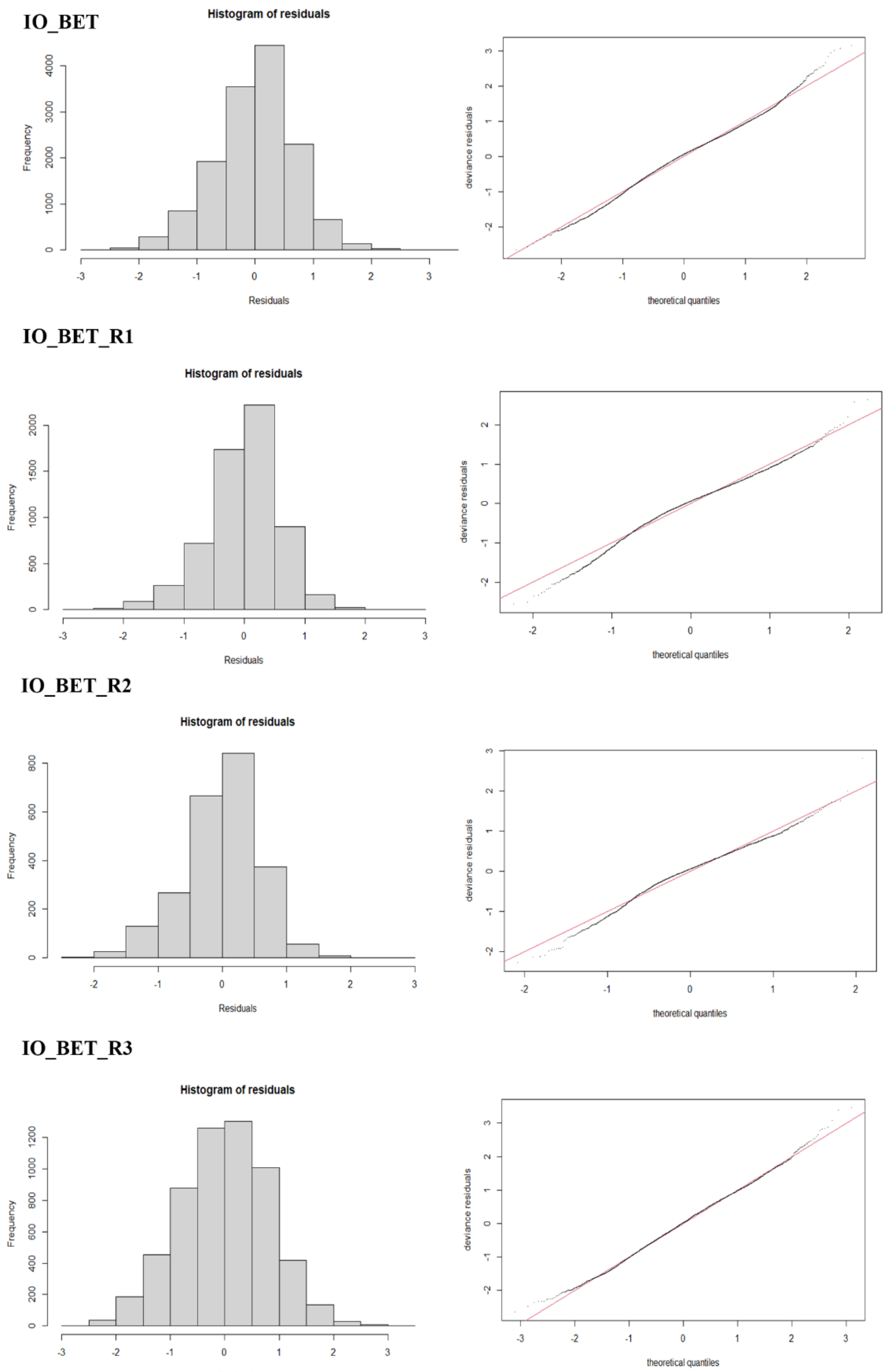
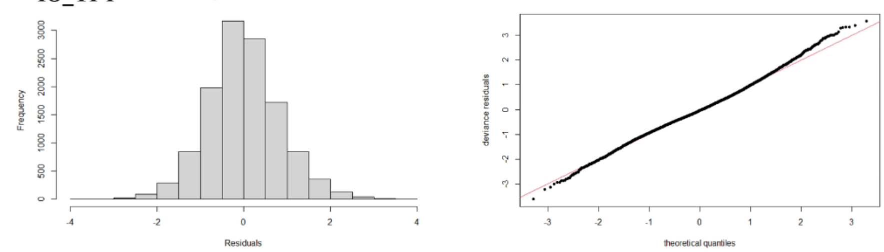
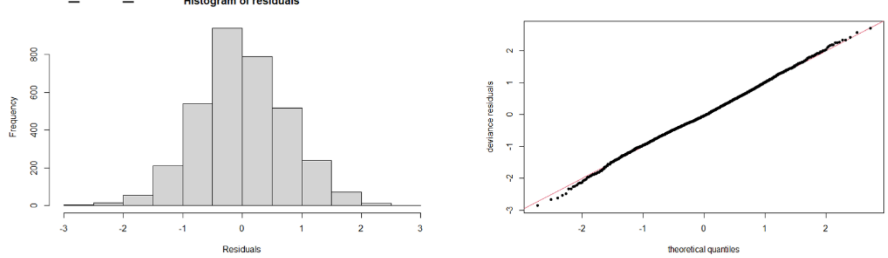


FIGURE A2 Histograms and QQ-plots of residuals from the GAM analyses for yellowfin tuna (YFT) for the whole Indian Ocean and four sub-areas.

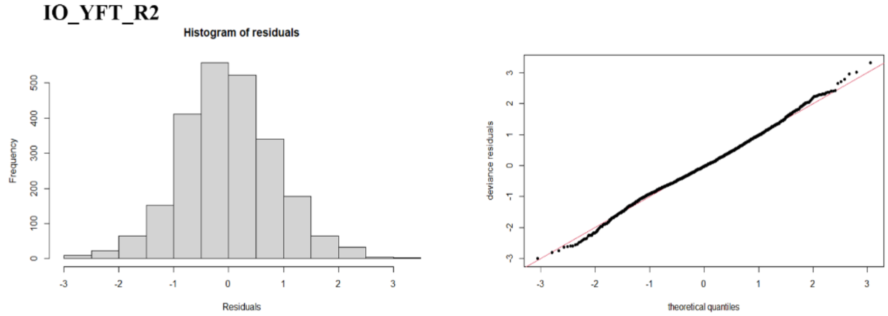
IO_YFT



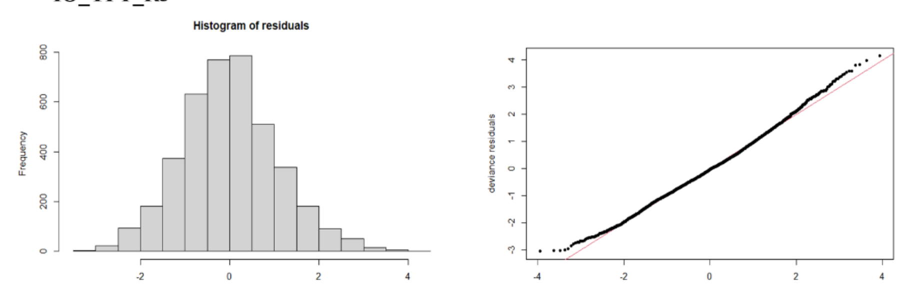
IO_YFT_R1



IO_YFT_R2



IO_YFT_R3



IO_YFT_R4