Understanding the impact of climate change on distribution shifts of the Indian Ocean bigeye tuna

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Abstract: To respond to the resolution 22/01 of IOTC, we explored the long-term changes of spatial distribution of bigeye tuna from 1975 to 2021 in this preliminary study. Climate change and fishing pressure are put forward to explain the changes. Over the past 47 years, bigeye tuna overall shifted from northern Indian Ocean (tropical area) to central Indian Ocean (temperate area) in latitude. The centre of gravity (COG) of longitude shifted to the eastward during 1978~ 1981 and 1996~2000, followed by a significant western shift in 2011~2012. Despite these periods, the COGs of longitude mainly distributed around 75°. The fishing pressure and spawning biomass are the main variables explained the distribution shifts. DMI could explain the latitudinal change and the longitude seasonal change, however the r^2 is lower than other variables. SST is a significant predictor for latitude and longitude seasonal change. ENSO didn't show any significant relationship with latitudinal and longitudinal shifts.

Key words: spatial distribution, fishing pressure, climate change

1. Introduction

From the latest conservation and management measures for the IOTC in 2023, the resolution 22/01 emphasized the importance of understanding the impact of climate change in particular on tropical tuna. Therefore, in this study, we explored the changes of spatial distribution of bigeye tuna. And two main hypotheses have been put forward to explain the changes:1) climate change and climate variabilities. Climate change is expected to result in contractions, expansions, or shifts in fish distribution. Ocean temperature has a distinct warming trend over past decades. Two main climate variabilities IOD and ENSO occurred in the Indian Ocean also led to temperature anomaly change. 2) Fishing pressure. Fishing pressure has, over the same period, been consistently higher in the western compared to eastern part of the Indian Ocean. Thus, there may have been a greater rate of fishery-induced depletion in the west, and hence, an apparent eastward shift in population distribution is to be expected.

2. Data and Method

2.1 Data and modelling of bigeye tuna distribution

The catch and effort data of bigeye tuna were obtained from the IOTC datasets from 1975 to 2021. The data sets from longline fisheries and contain the fishing effort (in number of hooks) and catch (in number) in 5°*5° resolution. Based on the resolution, the Indian Ocean area were divided into each 5°*5° rectangles. Catches and effort data by rectangle were converted into catch per unit effort (cpue, numbers*1000/effort).

Here, we do not use cpue to analyse temporal change in cod abundance, but only to look at trends in spatial distribution. To account for the confusing effect of different fishing power, the cpue values were firstly normalized in any given year by the annual mean. For each rectangle *i* in year *y*, normalized cpue (cpue′i,y) was calculated as follows (Engelhard et al, 2014):

$$\text{cpue}'_{i,y} = \frac{cpue_{i,y}}{(\sum_{i=1}^{N} \overline{cpue_{i,y}})/N} \tag{1}$$

Where $cpue_{i,y}$ represents the raw cpue values in n rectangle *i* and year *y*, and *N* is the total number of rectangles in the study area.

Next when mapping bigeye tuna spatial distribution we corrected for temporal change in overall bigeye tuna biomass. The SSB data was extracted from the 2022 stock assessment SS model conducted by the IOTC (Fu, 2022). For each rectangle i in year y, SSB-scaled cpue ($cpue''_{i,y}$) was calculated, as follows (Engelhard et al, 2014):

$$cpue''_{i,y} = cpue'_{i,y} \times \; SSB_y/\overline{SSB} \tag{2}$$

where SSB_y is the estimate of SSB in year *y* and SSB is the long-term mean SSB. By five-years step, we plotted spatial distribution of $cpue''_{i,y}$.

To quantify shifts in population distribution, the ‘centres of gravity’ of the latitudinal, longitudinal of bigeye tuna was calculated. To reveal distribution shifts over 1975-2021, cpue data were used to calculate the centre of gravity (COG) of latitudinal distribution. Considering the strong seasonal trends of fishing and environment changes, the COG was calculated both by season and by year, respectively:

$$COG = \frac{\sum_{i=1}^{N} cpue_i \cdot lat_i}{\sum_{i=1}^{N} cpue_i} \tag{3}$$

where $cpue_i$ is the cpue for each rectangle *i*, lat_i is the latitudinal centre of each rectangle *i*, and *N* is the total number of rectangles. Weighted standard deviations and standard errors of the weighted mean latitudes were calculated (Engelhard et al, 2011). Analogously, the longitudinal centres of gravity of distribution were calculated by using the longitude of the rectangle’s centre.

2.2 Modelling distribution shifts in relation to climate change and fishing pressure

We examined bigeye tuna cpue distribution in relation to: (i) climatic variables; and (ii)fishing pressure and abundance. The climatic variables include sea surface temperature, Indian Ocean Dipole (IOD) index and ENSO index. The SST data was sourced from NOAA Extended Reconstructed SST v5 (Huang et al., 2017). Index of ENSO applied the Southern Oscillation Index (SOI) (Trenberth et al, 2023). IOD index DMI was obtained from NOAA (https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/). The fishing pressure F and SSB were extracted from the 2022 bigeye tuna stock assessment models.

GAMs were used to explore which environmental, abundance, and/or fishing pressure variables might be the predictors of bigeye tuna distribution (latitudinal and longitudinal). The models starting with a full model that included all effects (F, SSB, SST, DMI, SOI. For example, the longitudinal centre of gravity of distribution the starting model was:

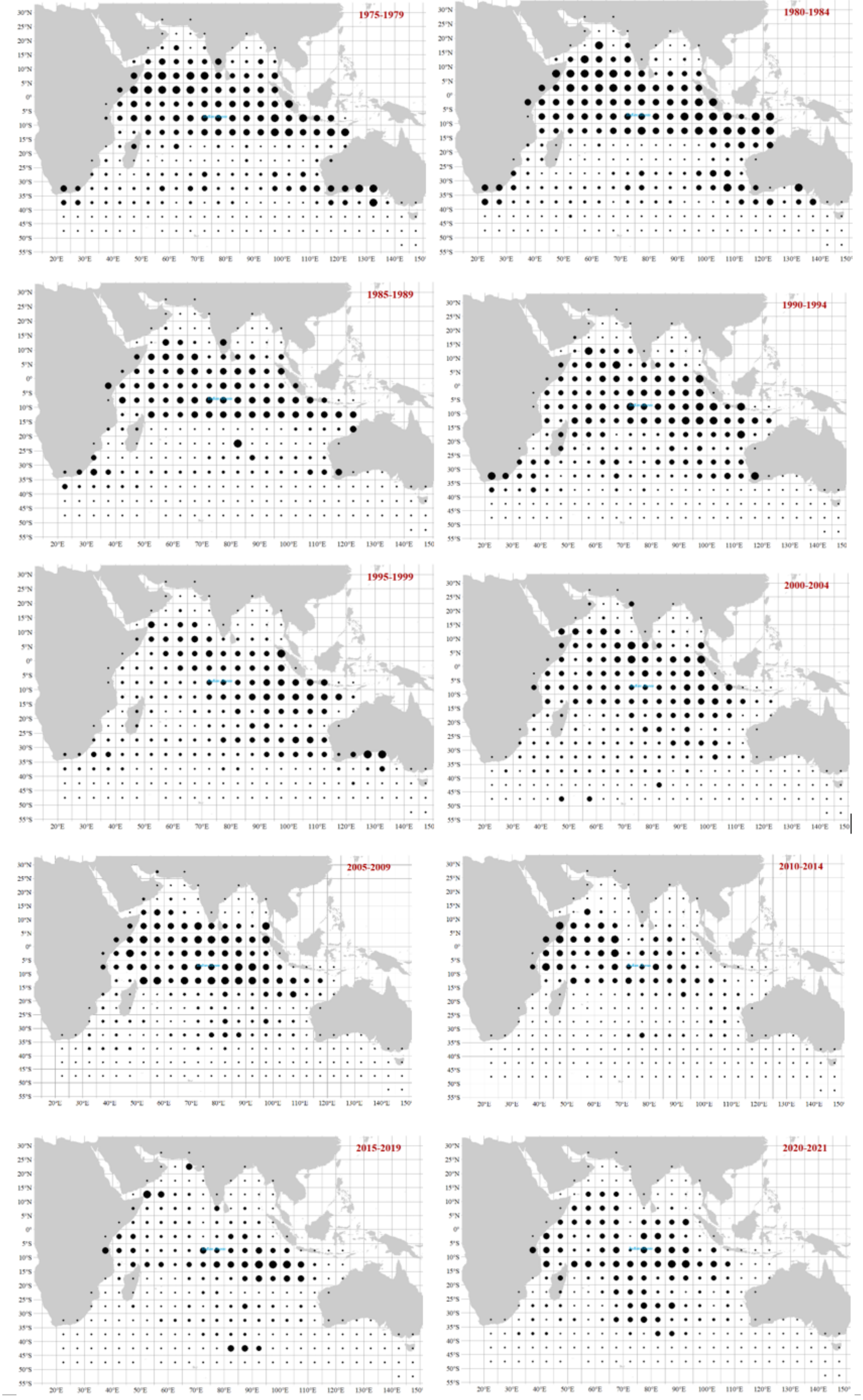
$$COG\ longitude \sim F + SSB + SST + DMI + SOI \tag{4}$$

The best-fitting models were then established by removing insignificant terms successively and based on lowest Akaike information criterion (AIC), to reach the minimum adequate model. The models were fitted and compared using deviance explain.

3.Results

3.1 Shifts in bigeye tuna distribution

Long-term cpue data of bigeye tuna spatial distributions in every 5 years were shown in Figure1. Before 1994, bigeye tuna were mainly distributed in the north Indian Ocean (tropical area), shifts within this 20-year period were comparatively minor except a slightly shift from western to eastern. During the period 1995 to 1999, bigeye tuna had a marked eastward shift, with a slightly increase in the central-southern Indian Ocean. From 2000 to 2014, the cpue distribution shifts from east to west in longitude and from south to north in latitude gradually. After 2014, the distribution of bigeye tuan changed significantly. During 2015~ 2019, the bigeye tuna mainly distributed in the eastern and central Indian Ocean, and shift to the west in 2020~2021. Dring 2015~2021, in the longitude, bigeye tuna had a notable shift from tropical area (southern Indian Ocean) to central Indian Ocean.


1975-1979
1980-1984
1985-1989
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30°N
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40°E
50°E
60°E
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
150°

Figure 1 Spatial distribution changes of bigeye tuna in the Indian Ocean from 1975-2021, based on the longline fisheries cpue. The area sizes of the black circles are proportional to bigeye tuna cpue, normalized by every 5 years (Eqn 1) and corrected for the average spawning stock biomass (SSB) in each 5 years (Eqn 2), to visualize the stock's long-term biomass dynamics.

The centre of gravity (COG) of latitudinal distribution (Figure 2a, Figure 3a) and longitudinal distribution (Figure 2b, Figure 3b) for each season and each year didn't suggest overall trend. The COGs of latitude and longitude by season showed seasonal trends. Before 1990, the COGs of latitude mainly distributed between 10°S to 12°S. The COGs of latitude suddenly shifted southward from 1990 to 1994, but again considerably northward during 1995 to 2012. After 2012, in recent years, the COGs of latitude shifted to southern Indian Ocean again. The COGs of longitude shifted to the eastward during 1978~ 1981 and 1996~2000, followed by a significant western shift in 2011~2012. Despite these periods, the COGs of longitude mainly distributed around 75°.

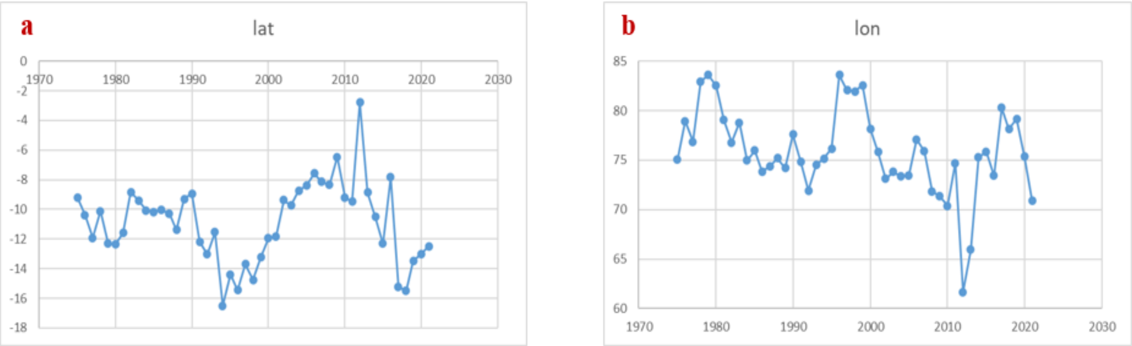

Figure 2 Long-term changes in (a) latitudinal and (b) longitudinal centre of gravity of Indian Ocean bigeye tuna distribution by year from 1975-2021.

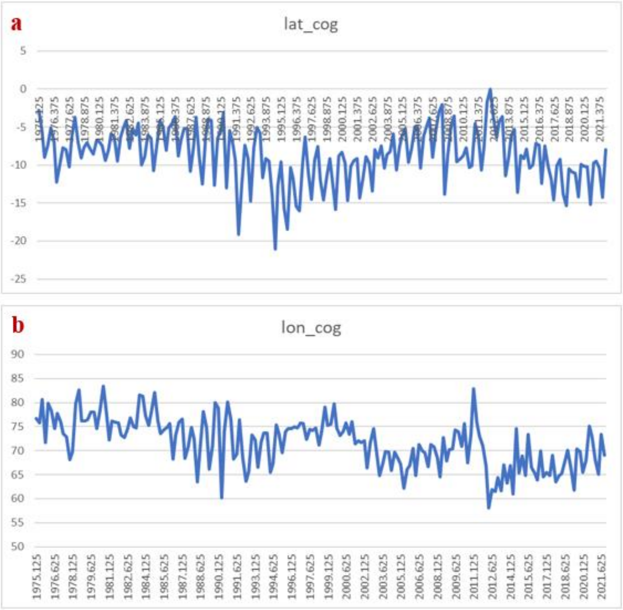

Figure 3 Long-term changes in (a) latitudinal and (b) longitudinal centre of gravity of Indian Ocean bigeye tuna distribution by season from 1975-2021.

3.2 Distribution shifts in relation to climate and fishing

The time series of SST, DMI, ENSO, F and SSB from 1975 to 2021 by season and year were shown in Figure 4 and Figure 5. Overall, the SST, DMI and F have an increase trend, SSB continuously decline over time and ENSO didn't show obvious trend.

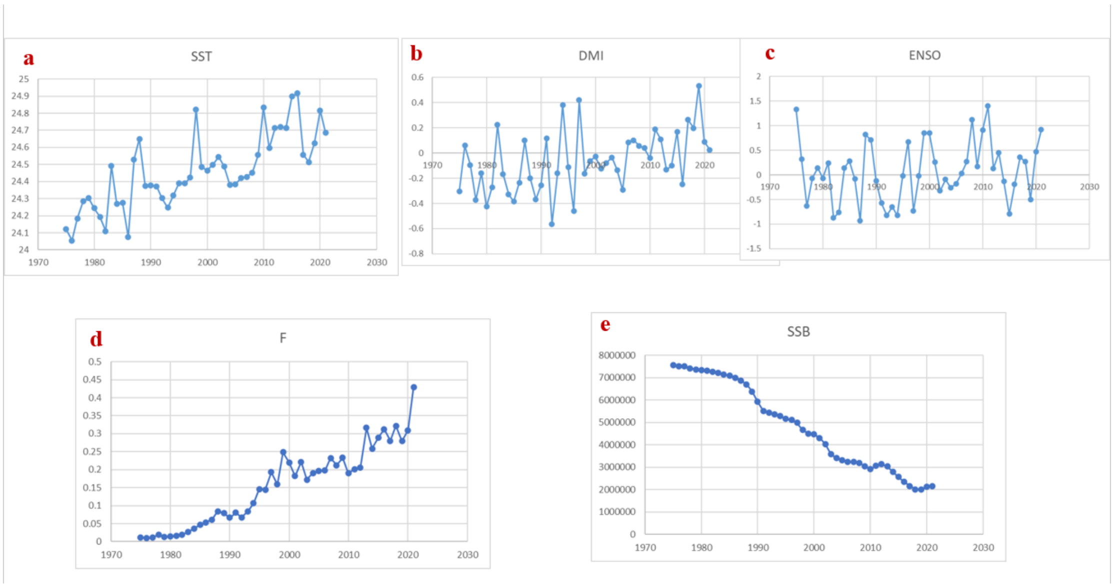

Figure 4 The time series of SST (a), DMI (b), ENSO (c), F (d), SSB(e) from 1975 to 2021 by year.

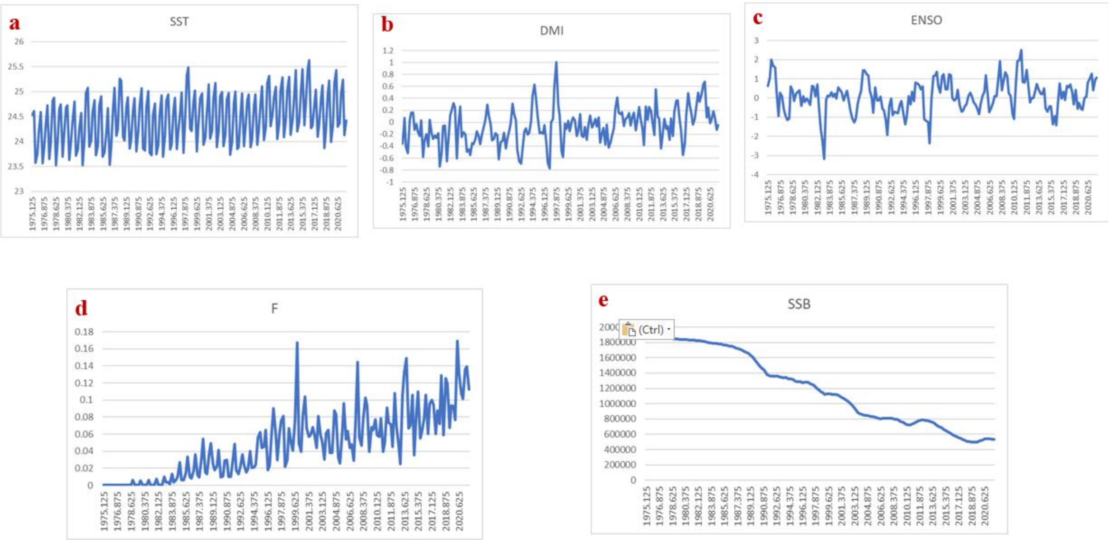

Figure 5 The time series of SST (a), DMI (b), ENSO (c), F (d), SSB(e) from 1975 to 2021 by season.

Based on the GAMs analysis (Table 1), SSB and fishing pressure are the significant predictors both for latitudinal and longitudinal shift and explained the mainly deviance. DMI could explain the latitudinal change and the longitude seasonal change, however the r^2 is lower than other variables. SST is a significant predictor for latitude and longitude seasonal change, and explained 19.6% and 23.7% deviance, respectively. ENSO didn't show any significant relationship with latitudinal and longitudinal shifts.

Table 1. GAM-derived deviance, r-square and degrees of freedom for each significant parameter.

	Year					Season				
Response variable	Predictor	edf	Deviance explained (%)	r^2	*P*	Predictor	edf	Deviance explained (%)	r^2	*P*
Latitudinal shift	DMI	232.6	15.3%	0.118	0.038	DMI	2.365	5.85%	0.045	0.027
	F	6.86	45.3%	0.3357	0.003	F	1.759	7.31%	0.064	0.002
	SSB	5.85	68%	0.634	<0.001	SST	0.176	19.6%	0.588	<0.001
						SSB	5.553	35.6%	0.337	<0.001
Longitudinal shift	SSB	4.845	41.8%	0.35	0.0018	SSB	7.115	41.8%	0.395	<0.001
	F	6.5	34.1%	0.233	0.042	F	5.132	22.5%	0.203	<0.001
						SST	6.088	23.7%	0.212	<0.001
						DMI	1	3.23%	0.027	0.013

4. Discussion

The high deviance explained of SSB and F in latitudinal and longitudinal shift support the initial hypothesis. With the continues increasing F and decreasing SSB, the bigeye tuna had an overall southward shift in latitude over the past years. IOD also influenced the latitudinal shift, when the positive occurs, the bigeye tuna may shift to the temperate area. With the high fishing pressure in the western Indian Ocean, bigeye tuna had eastward shifts now and then. In this study, we used the fishery-dependent data to analysis the spatial distribution of bigeye tuna. Survey data is necessary to better understand the mechanism of spatial shifts. Therefore, in the next steps, we will make effort to collect the fishery-independent data, and make projection for the spatial distribution in the next study.

5. References

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