Environmental signal in skipjack recruitment in the Indian Ocean: An updated analysis using the SS3-assessment outputs of 2023

Francis MARSAC[1]
IRD
UMR MARBEC, Sète, France

Abstract

A study presented at the WPTT25-Data Preparatory meeting investigated the link between interannual changes in ocean productivity and skipjack recruitment in the Indian Ocean fishery, using the then available recruitment index series produced by the 2020 skipjack stock assessment, with recruitment data up to 2018. With a new recruitment time series produced by the 2023 assessment (until 2021), we redid the analysis both in the western region of the Indian Ocean, and in a large equatorial region stretching from 40°E to 100°E. This new study using the updated recruitment index confirms the main outcome of the previous study i.e. 1) a positive response in recruitment with positive anomalies of sea surface chlorophyll (SSC) which are associated to negative Indian Ocean Dipoles; 2) a less marked response, though towards slightly reduced recruitment, in situations of negative SSC associated to positive Indian Ocean Dipoles. Such responses in recruitment can make a valuable ancillary information in the setting of a management advice for skipjack at the IOTC.

1- Introduction

A first analysis investigating whether an environmental signal could be a driver (among others) of interannual variability in skipjack recruitment, was presented at the Data Preparatory meeting of the WPTT held in 2023 (May 31st to June 2nd). Using deviations to the mean of surface chlorophyll-a in the western Indian Ocean and the recruitment deviates produced by the 2020 skipjack SS3 assessment (using data up to 2018), it concluded that 1) multi-year oscillations occur in both series; 2) these oscillations occur in synchrony; and 3) that the Indian Ocean dipole appears to be a key environmental driver (Marsac, 2023)

This paper is an update of the previous analysis, now using the 2023 SS3 skipjack tuna assessment produced for the 25th session of the WPTT (Fu, 2023). The analysis covers the period 1998-2021, using surface chlorophyll-a data and the new series of recruitment deviates.

2- Data sources

<u>2.1 Environmental descriptors</u>

- We use a climate index based on the difference in sea surface temperature between the western and eastern regions of the Indian Ocean, namely the Dipole Mode Index (DMI, Saji et al, 1999) as an indicator of the environmental variability at inter-annual scales. The DMI depicts a mode of variability that is specific to the Indian Ocean (and sometimes coupled to the ENSO), the Indian Ocean Dipole (IOD). The monthly DMI dataset used here was downloaded from the Hadley Centre, UK (HadISST1.1 product), from which we extracted the period ranging from 1998 to 2022.
- Sea surface chlorophyll-a (SSC) concentration from SeaWifs (Sept 1997 to Dec 2002) and Modis (Jul 2002 to Dec 2022) satellite-mounted sensors, used as a proxy of ocean surface productivity (enhancement or depletion). We use the Level-4 data, at a 9-km spatial resolution, by month.

[1] Email : francis.marsac@ird.fr

2.2 Recruitment series

The recruitment index is the yearly times series of recruitment deviates produced by the latest skipjack stock assessment, using data up to 2022 (Fu, 2023). SS3 produced recruitment indices for 1983-2021. Using yearly data makes sense as skipjack can spawn all year round as long as food supplies are plentiful (Ashida et al, 2007 for the Pacific; Stéquert et al, 2001, Grande et al, 2012, for the Indian Ocean). As the sea colour data start with SeaWiFS in September 1997, the analysis is run for complete years from 1998 to 2021, making a 24-years series.

Fig 1 shows the recruitment series of the SS3 assessments made in 2020 and in 2023. Differences are relatively minor. The largest differences are found in 1998, 2002 and 2005.

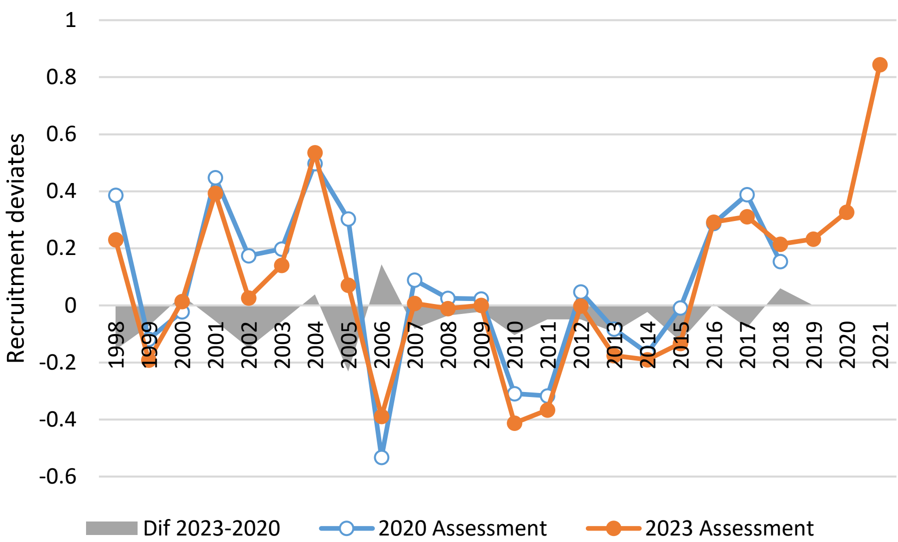


Fig. 1 – Comparison of annual recruitment series produced in the 2020 and 2023 assessments (source: Fu 2020, 2023). The difference between the two series is shown by the grey shade.

2.3 Study area

The MONW area (40°E - 77°E / 10°N – 12°S), which is the western Indian Ocean Longhurst province was used in the previous analysis. In the present analysis, we used a longitude-wider equatorial zone (40°E – 100°E / 10°N – 10°S) that covers most of the spatial distribution of the Indian Ocean skipjack fisheries. The two regions are mapped for comparison in Fig 2a, along with the distribution of skipjack catches by all gears, in Fig. 2b.

3- Results

3.1 Effect of the Indian Ocean Dipole on the SSC

The reader can refer to the paper presented at the WPTT25-Data Preparatory meeting (Marsac, 2023) which describes the ocean productivity trends over 1997-2022 in four ecoregions, based on Longhurst provinces of the tropical Indian Ocean (Longhurst, 1998). Recently, the most prominent anomaly in SSC was caused by the 2019 positive Indian Ocean dipole, with 34% rise of SSC above normal in the East IO and almost 12% decline in the West IO. In 2022, SSC declined in the East (-14%) and in the subtropical gyre - ISSG (-13%), whilst SSC exhibited an upwards trend in the West IO (+10%).

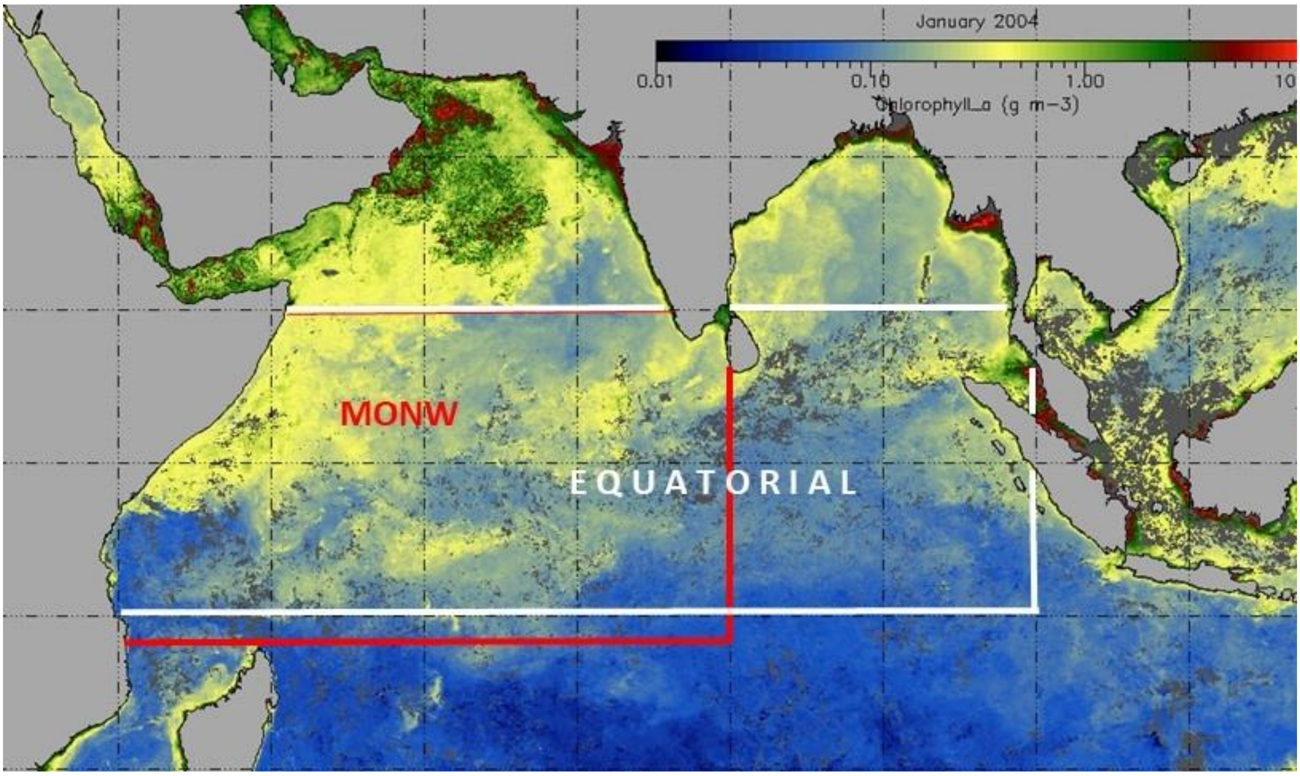


Fig. 2a – Boundaries of the areas from which chlorophyll-a data were extracted: in red, the MONW region used in the former analysis (WPTT25-DP); in white, the region used in the present analysis (the background image is the chlorophyll concentration measured by MODIS in January 2004).

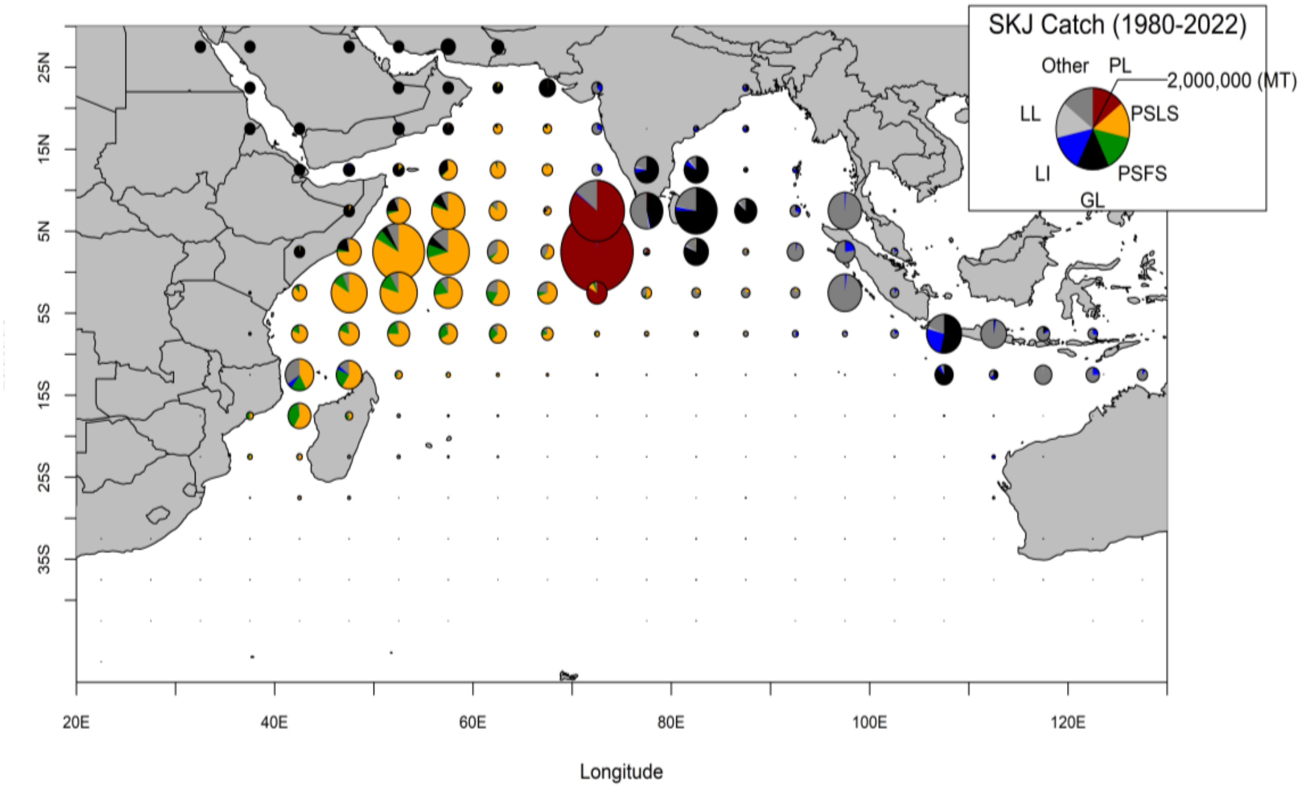
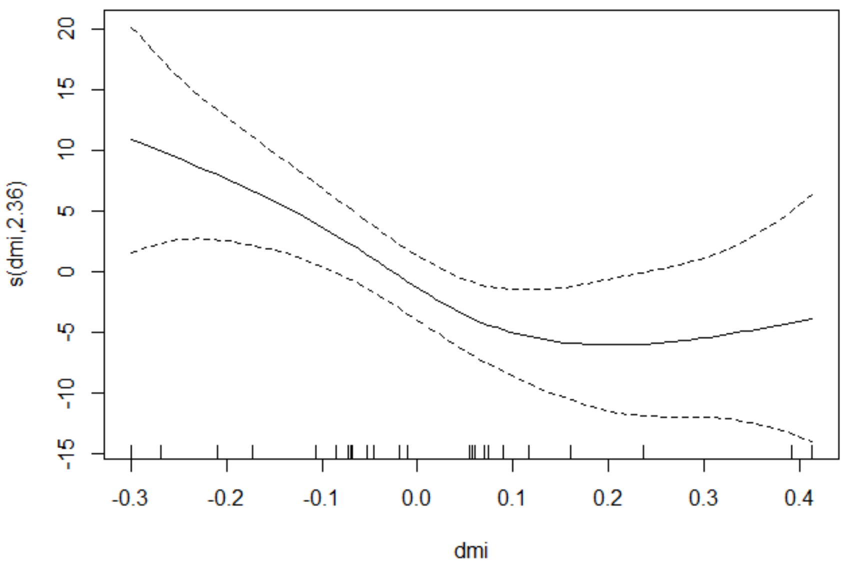


Fig. 2b – Distribution of skipjack catches by all fishing gears in the Indian Ocean (source: IOTC and Fu, 2023)

We performed a simple GAM analysis using the yearly series of DMI and SSC deviations to the inter-annual mean. As the IOD generally develops in the middle of the year and vanishes during the second quarter of the following year, we characterized an annual DMI by the mean of monthly DMI from July (year i) to June (year i+1). In a similar way, we averaged the SSC overs this "DMI-type year". The results are shown below for the equatorial region:

Family: gaussian					
Formula: chl ~ s(dmi, bs = "cs")					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	0.000	1.607	0.000	1.000	
	edf	Ref.df	F	p-value	α
s(dmi)	2.361	9	1.224	0.0121	0.05
R-sq.(adj) =	0.301	Deviance explained		37.3%	
GCV =	72.10		n =	24	



The relationship is significant at the risk level of 5%. The fit explains 37.3% of the deviance. It clearly indicates a tendency for higher SSC responses with negative DMIs (i.e. during negative IODs). By contrast, the SSC may fluctuate in various ways during positive DMIs. The plot does not show a clear SSC pattern over the study area during positive IODs.

3.2 Effect of SSC variability on skipjack recruitment

We analysed the trends of the SSC and the recruitment index in the wide equatorial zone (Fig. 3). From 1998 to 2021, the two SSC productive periods (2001-2005 and after 2016) coincided with years where the average recruitment was enhanced. It is noteworthy that low SSC concentrations in 2019 coincided with an intense positive IOD, however this did not dramatically affect the recruitment index in that particular year. Lower skipjack recruitment was associated to the reduced ocean productivity phase, from 2006 to 2014, but the magnitude of decrease in recruitment was less than in SSC.

A spline fit (Fig. 4) illustrates the synchronized oscillation between SSC and skipjack recruitment from 1998 to 2022, emphasizing more clearly the in-phase oscillation of both series. It suggests that the substantial increase in the recruitment index seen since 2019 could be sustained by an increased ocean productivity.

The shape of the relationship between the two variables was tested with a GAM (R package) over the 24 years of the series (1998-2021). We present here two models, the SSC in MONW on one hand, and SSC in the wide equatorial region on the other hand

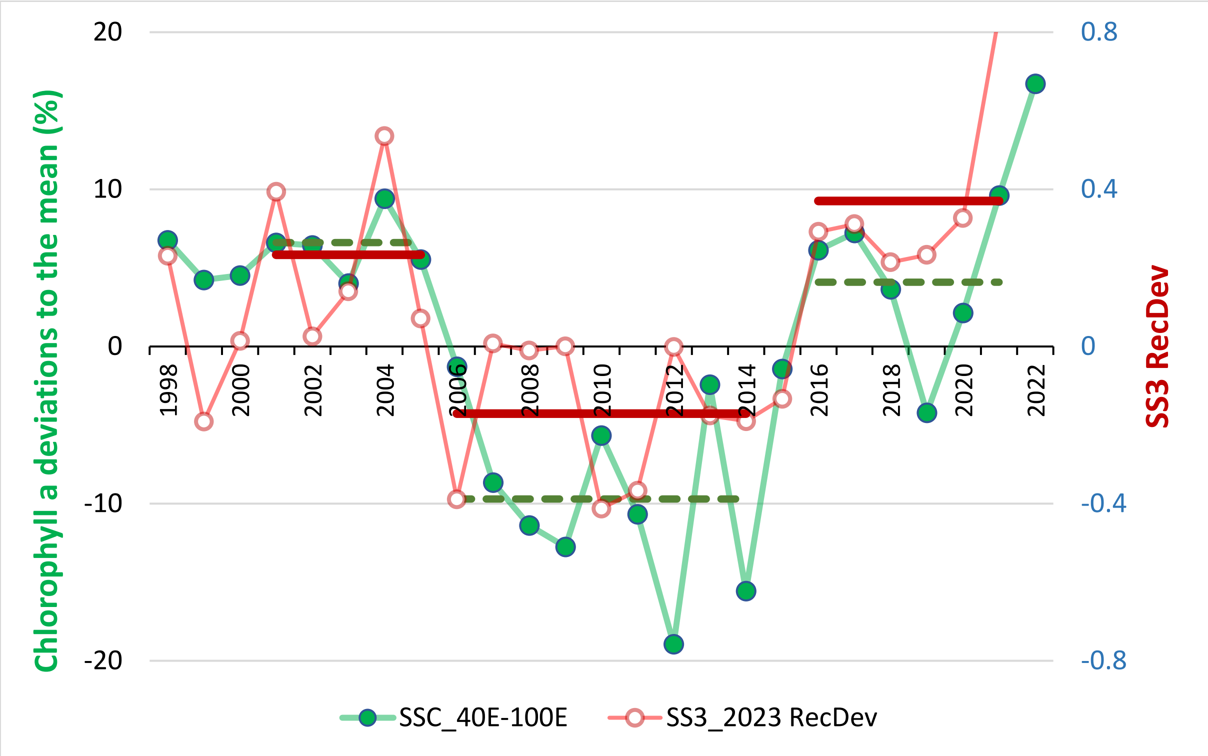


Fig. 3 – Combined plots of SSC concentration (left axis, green) and the SS3 recruitment deviates (RecDev, right axis, red) and mean levels by group of years (horizontal lines) for both variables. Grouped years: 2001-2005, 2006-2014 and 2016-2021.

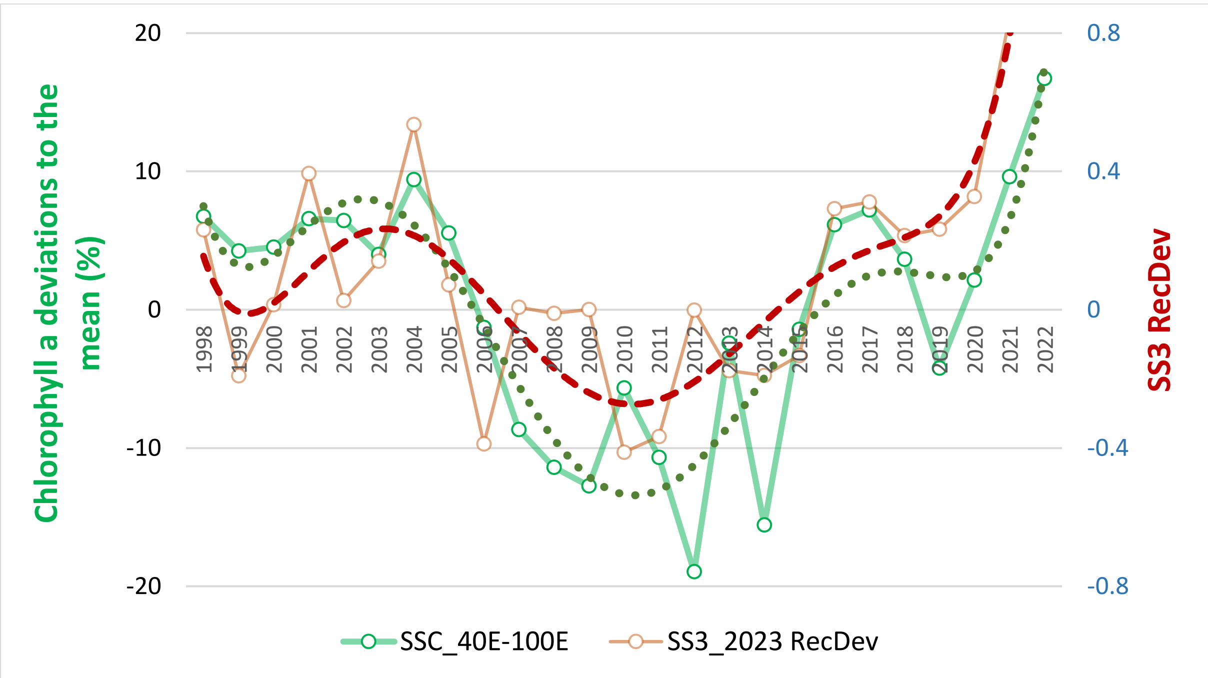
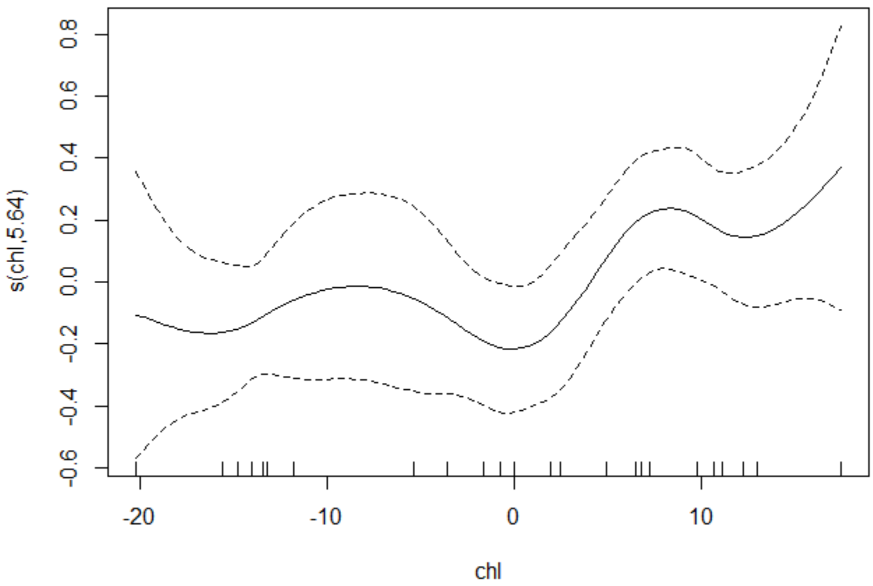


Fig. 4 – Spline fit (dashed lines) of the SSC concentration and skipjack recruitment deviates series, overlaid on original yearly values. (plain lines)

a) Recruitment index 2023 and SSC-MONW

The introduction of the new recruitment series has slightly changed the statistics of the regression obtained in the previous analysis. Whilst a highly significant regression ($\alpha < 0.01$) was obtained in 2020, with recruitment series up to 2018, the regression is less significant (p value = 0.0706, ($\alpha = 0.10$) with the updated recruitment series. The explained deviance is 47%, similar to the deviance in the previous analysis (45.5%). It indicates a tendency for a positive response in recruitment with increasing SSC concentration. Results are presented below.

Family: gaussian					
Formula:	RecDev ~ s(chl, bs = "cs")				
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	0.074	0.051	1.440	0.168	
	edf	Ref.df	F	p-value	α
s(chl)	5.637	9	1.477	0.070600	0.10
R-sq.(adj) =	0.298		Deviance explained	47.0%	
GCV =	0.08735		n =	24	

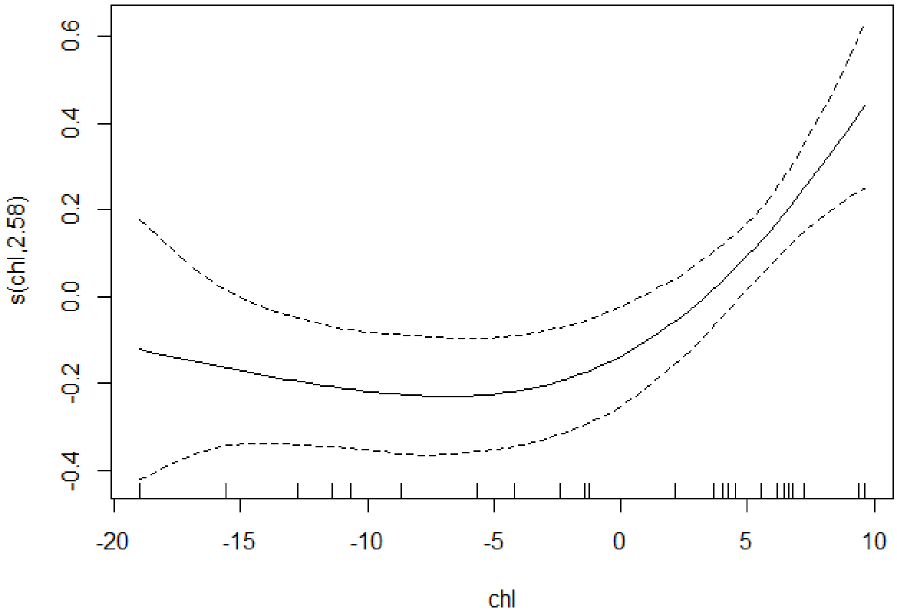


GAM regression of the response of skipjack recruitment to SSC (in mg m^{-3}) in the MONW region.

b) Recruitment index 2023 and SSC-equatorial zone

The updated recruitment series shows a more clear response to SSC in the large equatorial zone compared to MONW. The outcome is the same, i.e. an increase of recruitment with enhanced ocean productivity, but the significance of the smooth term (chl) is highly significant ($\alpha < 0.01$). The deviance explained is 59%. The shape of the relationship mimics that obtained in MONW based on recruitment index of the 2020 assessment, i.e. a constant response for negative SSC anomalies (depleted productivity) and a continuous and sharp increase of recruitment for positive SSC anomalies. The GAM results are presented below.

Family: gaussian					
Formula: RecDev ~ s(chl, bs = "cs")					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	0.074	0.042	1.775	0.090	
	edf	Ref.df	F	p-value	α
s(chl)	2.579	9	3.013	0.000195	<0.01
R-sq.(adj) =	0.538	Deviance explained		59.0%	
GCV =	0.04882		n =	24	



GAM regression of the response of skipjack recruitment to SSC (in mg m^{-3}) in the wide equatorial region (40°E-100°E)

4- Discussion

4.1 Recruitment index

The recruitment index series has slightly changed from the previous 2020 assessment. Such changes lead to a different result in the GAM regression using the SSC in the MONW area, compared to the previous recruitment series (up to 2018). However, the regression is again highly significant when a larger equatorial area is considered for SSC. Such a large equatorial zone may be more relevant to this tuna species as it encompasses the spatial range of the fishery and where skipjack can potentially spawn. The recruitment series that will be produced in the next skipjack assessment, in 2026, might also differ from the current one, potentially leading to different regression parameters, however we can consider these changes will be minor unless newly contrasted information (especially biological data such as growth) becomes available, or dramatic operational changes affecting selectivity occur in the fishery in the forthcoming years. Therefore, the outcomes of this analysis look reasonable to consider in the discussion of the current skipjack stock assessment.

4.2 Relationship between SSC and IOD

The response of SSC concentration to IOD clearly indicates that ocean productivity, depicted by the SSC, is enhanced during negative IODs. However, the opposite pattern, i.e. a well-reduced productivity during positive IODs, is not demonstrated here in the study area. The SSC is known to exhibit spatial differences, with SSC-depleted conditions in the West, and enhanced conditions in the East during a positive IOD (Murtugudde, 1999). This was observed during the 1997-98 and 2007 positive IODs (Marsac, 2017), and again in November- December 2019 at the peak of another positive IOD. Thus, the SSC-IOD relationship at the scale of the equatorial region is a mix between these two influences, which explains the large confidence interval of the regression in the right part of the plot. Overall, the IOD remains an important index of interannual variability affecting marine ecosystems and fisheries in the Indian Ocean.

4.3 Relationship between recruitment and SSC

Similarly to the previous study, this updated analysis indicates a synchronized response of skipjack recruitment with an ocean productivity index, the SSC concentration measured by satellite. We assume that the link is mediated by the tuna prey component (small pelagic fish, crustaceans, cephalopods) which is driven by the production at the base of the food web (SSC).

The GAM confirms the scenario of an increased recruitment in situations of enhanced SSC concentration, When the ocean productivity is reduced (i.e. negative SSC anomalies), the recruitment is slightly below the average, but not at the magnitude of the SSC anomalies. This could be explained by an efficient foraging opportunism and fast movements of skipjack tuna which can detect sparse areas with high density of prey that would sustain their high metabolism and trigger spawning.

Based on this relationship, the analysis presented at the WPTT25-Data preparatory meeting in May-June 2023 (Marsac, 2023) concluded that:

“The synchrony observed between the SSC concentration in the MONW and the skipjack recruitment would suggest that the enhanced ocean productivity in MONW observed in 2022, in relation to a negative IOD, would promote favorable conditions in the recruitment of skipjack for that year”.

This is actually what happened, therefore we can still consider the DMI forecast as an ancillary information in the management advice formulated for the skipjack stock trends. The IOD forecast disseminated by the Australian Bureau of Meteorology, on the basis of an ensemble of models, predicts that the positive IOD that is underway would vanish by February-March 2024, entering a neutral phase (Fig. 5). The effect of the developing positive IOD is visible in the spatial distribution of SSC. The pattern shown by the satellite ocean colour imagery since July 2023 is the development of a zonal tongue of elevated SSC stretching from Indonesia to the 65°E. By contrast, the productivity in the western region, west of 60°E, is decreasing, this denoting a positive IOD response on SSC. We show the SSC spatial pattern on 1st October 2021, 2022 and 2023 for comparison (Fig 6).

4.4 Possible impact on future recruitment (2023) from SSC

Therefore, we can expect that good foraging conditions could be promoted in the east just for a few months in the second semester of 2023. However, the annual productivity index through the equatorial zone might be qualified below normal for 2023. After the episode of elevated recruitment in 2021 (and potentially in 2022), recruitment in 2023 may return to the long-term average level, or slightly below. This interpretation could be accounted for in the discussion on the management advice to be conducted during the present 24th session of the WTTP.

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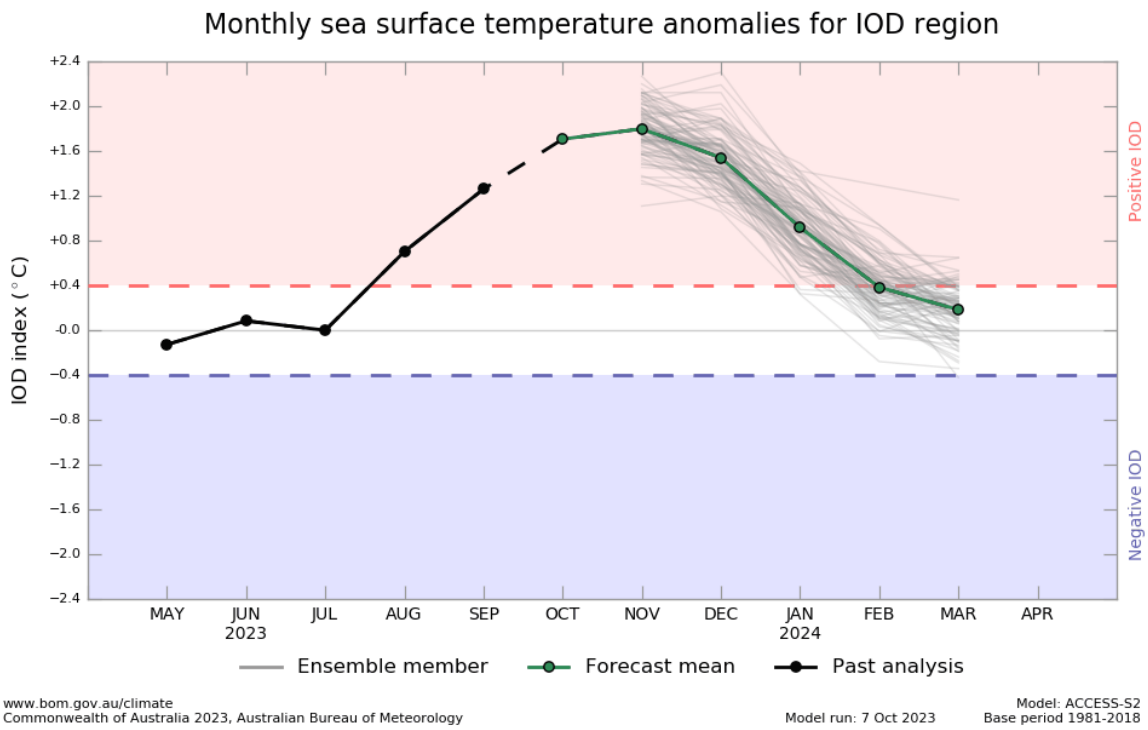

Fig.5 – Dipole mode forecast through predicted monthly sea surface anomalies for the Dipole mode region (Australian Bureau of Meteorology (http://www.bom.gov.au/climate/enso/#tabs=Indian-Ocean). Observations span until May 2023, predictions run from June to October 2023.

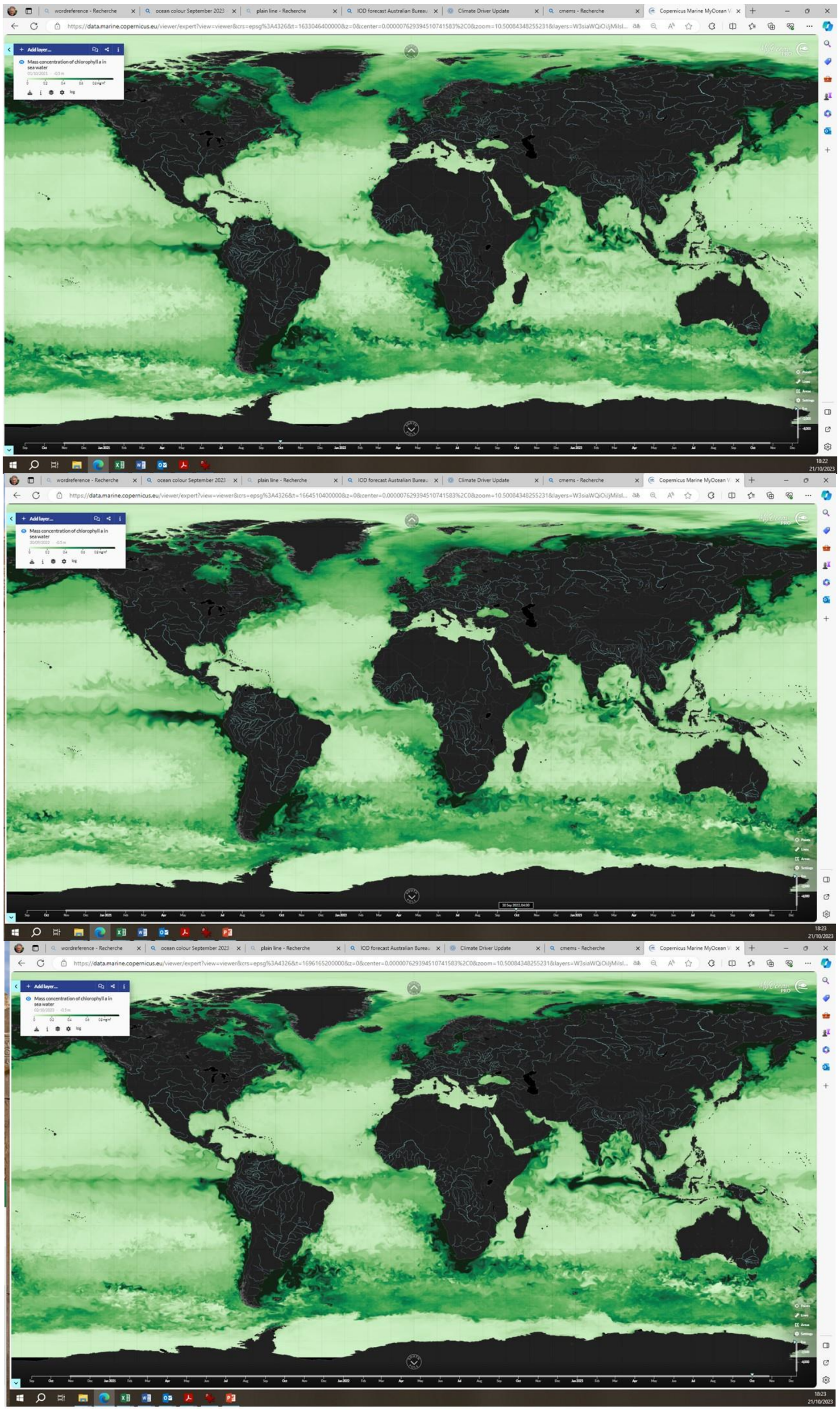

Fig. 6 - Surface chlorophyll concentration (blended product, MyOcean Pro, Copernicus system). Top: 1 Oct 2021, Middle: 1 Oct 2022; Bottom: 1 Oct 2023. The elongated zonal tongue of high SSC at the equator is clearly visible in the bottom panel, during the developing 2023 positive IOD