Environmental signal in skipjack tuna recruitment in the Indian Ocean

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Abstract

Skipjack is a tuna species that is known to respond quickly to environmental changes. The active search of prey is a requirement for this species which needs to sustain high metabolic rates. The ocean productivity is driven by physical processes that exhibit inter-annual fluctuations and cycles. Phytoplankton biomass at the sea surface is measured in routine from the space by specific sensors, whereas the secondary production which composes the diet of larvae, is only measured in situ, or is derived through biogeochemical coupled models. Here, we use the satellite-measured sea surface chlorophyll as a proxy of ocean productivity and we examine its relationship from 1998 to 2018 with annual recruitment deviates estimated by the SS3 assessment model run at the last skipjack stock assessment of the IOTC in 2020. We show 1) that multi-year oscillations occur in both series; 2) that these oscillations occur in synchrony; and 3) that the Indian Ocean dipole appears to play a leas a key environmental driver of the system.

1- Introduction

Skipjack is a fast growing tuna species inhabiting the epipelagic layer of tropical waters but also extending to temperate latitudes (~35th parallel) during summer where water temperature is above 18°C (Barkley et al., 1978, Stequert and Marsac, 1989, Marsac, 2017). Skipjack growth rate is the largest among tunas, before yellowfin then bigeye (Murua et al, 2017). Skipjack is an opportunistic feeder consuming a large range of prey sizes (small fishes, cephalopods, crustaceans), while showing predation plasticity depending on the availability of prey between times and locations. Dietary changes were observed in the West Indian Ocean for yellowfin and skipjack. Fishes dominated the tuna diet in the 1980s (Roger, 1994) whereas crustaceans became dominant in the 2000s, especially in relation to an outbreak of stomatopods (*Natosquilla investigatoris*) reported during the first half of the 2000s, and well documented by Potier et al (2004). Among the three tropical tuna species, skipjack has the greatest daily ratio of ingestion (3.5-4.2% of body weight day^{-1}) (Olson et al, 2016). Such a feeding frenzy is required to sustain the high metabolic rates of tunas, and skipjack in particular. The larval stage is a critical phase in tunas' life history. Survival and growth of larvae is enhanced when the release of larvae batches coincide with areas and periods of higher ocean productivity. Suh productivity can vary at a range of time scales. In this paper we examine the effect of sea surface chlorophyll (SSC) concentration in the seawater on skipjack recruitment at an annual timescale.

2- Data sources

2.1 Environmental descriptors

- 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 monthly DMI series used here was downloaded from the Hadley Centre, UK (HadISST1.1 product). The original data series starts in 1870, however we'll use the period of the dataset ranging from 1998 to 2022

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- Sea surface chlorophyll-a (SSC) concentration from SeaWifs (Sept 1997 to Dec 2002) and Modis (Jul 2002 to present) satellite-mounted sensors, used as a proxy of ocean surface productivity (enhancement or depletion). We use the Level-4 data, at a 9km spatial resolution, by month. SeaWifs data are used for 1997-2002 and Modis from 2003 onwards. The year 2022 is the average of the two sensors' measurements.

2.2 Recruitment series

The recruitment index is the times series of recruitment deviates provided by the base case of the SS3 stock assessment model run in 2020, for data up to 2019 (Fu, 2020). For some of the tuna species, there is an indication of a seasonal pattern in spawning, hence in recruitment. For skipjack, both in the Pacific (Ashida et al, 2007) and in the Indian Ocean (Stéquert et al, 2001; Grande et al, 2012), it has been demonstrated that spawning is continuous over the year, as long as food supplies are plentiful. In this paper, we use the annual deviates calculated by SS3 from the stock recruitment relationships, as a recruitment index. The 2020 SS3 model provided recruitment indices for 1983-2018. The quarterly indices provided by SS3 were averaged to provide an annual index. As the sea colour data start with SeaWifs in September 1997, the analysis is run for complete years over the period 1998-2018, that is 21 years.

3- Results

3.1 Primary productivity trends in four ecoregions

The same four large ecoregions that were initially presented by Marsac & Demarcq (2019) were used here. We consider two ecoregions (MONW in the West, MONE in the East, separated at the longitude 77°E) within the large MONS Longhurst province (Longhurst, 1998). Our MONW ecoregion also encompasses the Somalian part of the Longhurst's ARAB province. We also delineate an ecoregion for the Mozambique Channel (MOZ) corresponding to the northern region of the Longhurst's EAFR province but excluding the east coast of Madagascar. Finally the 4th ecoregion matches the almost entire Longhurst's ISSG province. To summarize, the four ecoregions (Fig. 1) are assigned in the following boundaries:

- MONW : 40°E - 77°E / 10°N – 12°S
- MONE : 77°E - 120°E / 10°N – 12°S (excluding regions extending east of Sumatra and north of Java)
- MOZ : 30°E – 47°E / 12°S – 30°S
- ISSG : 47°E – 120°E / 12°S – 30°S

In order to compare the overall productivity of each ecoregion, we computed the SSC annual average as displayed in Fig. 2. Based on the 1998-2022 mean, MOZ is the most productive region (0.19 mg m^{-3}), MONE ranks second (0.21 mg m^{-3}), slightly richer than MONW (0.39 mg m^{-3}). The less productive region is the ISSG.

MOZ SSC concentration (annual average) ranged from 0.35 to 0.43 mg m^{-3} with two periods of higher productivity: 1998 to 2002 (mean=0.42 mg m^{-3}), 2015-2020 (mean=0.41 mg m^{-3}) separated by 12 years or relatively lower productivity. The lowest SSC value was observed in 1997 when a strong El Niño and positive dipole was developing. The mesoscale vertical dynamics caused by eddies propagating through the Mozambique Channel and the chlorophyll-rich waters of the Mozambican and western Madagascan shelfs, transported offshore by the action of eddies, contribute to generate an average enhanced productivity in this region (Tew-Kai and Marsac, 2009).

MONW and MONE SSC concentration showed the same trend between 2015 and 2018 with enhanced conditions, the chlorophyll being slightly more elevated (+0.03 mg m^{-3}) in the East compared to the West IO. The SSC concentration varied in opposite way in 2019 under the influence of the positive dipole depleting chlorophyll in the West (0.17 mg m^{-3}) and enhancing chlorophyll in the East IO (0.28 mg m^{-3}).

Finally, SSC in ISSG fluctuated within a short range, between 0.09 and 0.13 mg m^{-3} denoting oligotrophic conditions. Slightly higher concentration was observed through 1999-2001 and 2015-2021.

The series were normalized to perform a direct comparison of inter-annual changes across ecoregions. The normalization consists in calculating the deviation (in %) of each year to the multi-annual mean, in each region. The normalized time series (Fig. 3) exhibits several features already discussed in Marsac (2021). The most recent prominent anomaly is caused by the 2019 positive Indian Ocean dipole, with 34% more chlorophyll above normal in the East IO and almost 12% less chlorophyll than normal in the West IO. The updated annual value for 2022 indicates a large drop in phytoplankton biomass in the East (-14%) and in the ISSG (-13%), whilst the SSC concentration has an upwards trend in the West IO (+10%). The SSC in the Mozambique Channel stands about the long-term average.

To illustrate short-term changes, the 3 year-average (2020-2022) indicates an increasing trend in the MONW region (-9% in 2020 to +6% in 2020) whilst the three other regions have a downward trend. The sharpest decrease is noted in MONE (+10% in 2020 to -18% in 2022) as shown in the table.

Rate of change in % : year *vs* [2020-2022] average			
	2020	2021	2022
MONW	-9 %	+3%	+6%
MONE	+10%	+8%	-18%
MOZ	+4%	-4%	0%
ISSG	+8%	+4%	-12%

3.2 Effect of SSC variability on skipjack recruitment

The trends were compared between the SSC concentrations of each ecoregion and the recruitment index (not shown). The only region where some synchronicity was detected between SSC and recruitment was in MONW. This is not surprising as the bulk of skipjack catches are from the west tropical region, and match well with the boundaries of MONW.

The result obtained with MONW SSC is shown in Fig 4. The year 1997 was excluded of the analysis because only the last four months of the year were available. From 1998 to 2018, the two productive periods in SSC (2000-2005 and 2016-2018) coincided with years where the average recruitment was enhanced. On the opposite, low skipjack recruitment was associated to the low ocean productivity phase, from 2006 to 2014.

A spline fit (Fig. 5) illustrates the synchronized oscillation between SSC and skipjack recruitment from 2000 to 2018.

The relationship between the two variables was tested with a GAM (R package) over the 21 years of the series. We also considered a one-year lag between the SSC (precursor) and the Recruitment response (following year). Results are displayed in Fig 6. Both regressions are highly significant ($\alpha < 0.01$) but the amount of deviance explained by the model is higher for the "no lag" dataset (45.5%) than for the "1-year lag" dataset ((33.9%). Both indicate a positive response in recruitment with increasing SSC concentration. The best fitted relationship (no lag) is non-linear. The recruitment response fluctuates without trend for negative SSC values, but grows rapidly for positive SSC anomalies.

4- Discussion

4.1 On the synchrony between series

This 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). At the yearly timescale, we can consider there is no lag between the environmental factor and the tuna response.

The MONW area is large and the SSC average ignores local anomalies, which are not necessarily on the same sign (positive or negative) than the mean. Thanks to its opportunistic feeding strategy and fast movements, skipjack can detect sparse areas with high density of prey that would increase its body condition and trigger spawning, although the average SSC descriptor for the MONW area is low. This would explain deviations from the general understanding of the process, e.g. slightly positive recruitment index when the SSC is low (2007-2009, 2012).

The GAM indicates that the recruitment response is more significant in a situation of enhanced SSC concentration, compared to situations of depleted SSC.

4.2 On the climatic driver at stake

The ocean productivity is often related to physical processes that can find their origin in the air-sea interactions. In the case investigated here, the Indian Ocean Dipole (IOD) plays a key role in the distribution of ocean properties, with consequences on the geographical distribution of the SSC. Negative DMIs are associated with below than normal sea surface temperature in the WIO and shallow thermocline. The comparison between the spline series and the DMI (Fig. 7) points out that the productive phase in SSC and elevated skipjack recruitment of 2000-2005 coincided with years dominated by negative DMIs, (i.e. negative dipole) whose ocean properties are prone to SSC enhancement. From 2007 on, the depleted SSC phase with low skipjack recruitment, was dominated by positive DMIs (i.e. positive dipole), with higher than normal sea surface temperature and deep thermocline not favoring high SSC concentration. Later, the two years (2013-2014) with negative DMIs may have initiated a shift in the SSC regime towards a more productive phase. The strong negative DMI in 2016 could have sustained this regime, in spite of the transient positive DMI event of 2015. Then, a DMI-positive phase was back in 2017, peaking in 2019 with a strong positive IOD that reduced significantly the ocean productivity in the MONW region. Finally, the positive IOD vanished in 2020, and the conditions shifted towards a negative IOD in 2022, boosting SSC concentrations in the MONW area.

4.3 On the perspective for skipjack recruitment after 2018

The synchrony observed between the SSC concentration in the MONW and the skipjack recruitment would suggest that the enhanced ocean productivity in MONW during 2022, in relation to a negative IOD, would promote favorable conditions in the recruitment of skipjack for that year. In its 2020 report, after setting new catch limits, the Scientific Committee (SC) noted that “it is likely that the recent catches that have exceeded the limits established for the period 2018-2020 have been sustained by favourable environmental conditions”. The SC also noted that “environmental indicators should be closely monitored to inform on the potential increase/decrease of stock productivity”, which is the subject of this study.

In December 2022, the IOD returned to a neutral phase, which continued through May 2023. The IOD forecast developed by the Australian Bureau of Meteorology indicates that a positive IOD may develop during the austral winter (June-September) with probabilities above 75% (Fig. 8). A possible return to neutral conditions could occur during the austral fall. However, the authors remind that model accuracy is low at that time of the year, therefore the outlook should be viewed with caution (BoM, 2023).

Indeed, the sole environmental drivers are insufficient to explain and predict recruitment, a process also related to fishing mortality of the adults and spawning biomass. A new assessment of the skipjack stock will be undertaken in October 2023 at the 25th WPTT (with catch data up to 2022). A significant increase of skipjack catches was pointed out between 2017 and 2018, from 525 348 to 606 133 t (revised estimates produced by the Secretariat on 11/04/2023). After a 10% decline until 2020, the skipjack catch increased again, amounting 655 115 t in 2021, which is an 8% increase from the historical record of 2018. It will be useful to consider the trend in SSC as presented in this paper to discuss the outcomes of the assessment, especially if high catches were sustained by enhanced recruitment.

5- Further work

The SSC concentration used here reflects conditions in the first tenth of meters of the water column, which is consistent with the habitat of larvae during their first life stages. We could also consider a productivity index that could cover a larger depth range by integrating the chlorophyll content over the first 100m. This index can be derived from the Global Ocean Biogeochemistry Hindcast and Forecast models starting in 1993, produced by the European Copernicus Marine Service (free access). This will be undertaken in a second phase of the study.

The relevance of average calculated over large areas has been discussed, as boundaries in the ocean can be considered as relatively arbitrary. In the next step, we will test the usefulness of SSC indices produced by Empirical Orthogonal Functions, a form of Principal Component Analysis, which are appropriate to study spatial modes of variability. The environmental series to be considered and compared with the recruitment covariates could be the one extracted in the areas of higher variability, as indicated by the spatial factor of the analysis.

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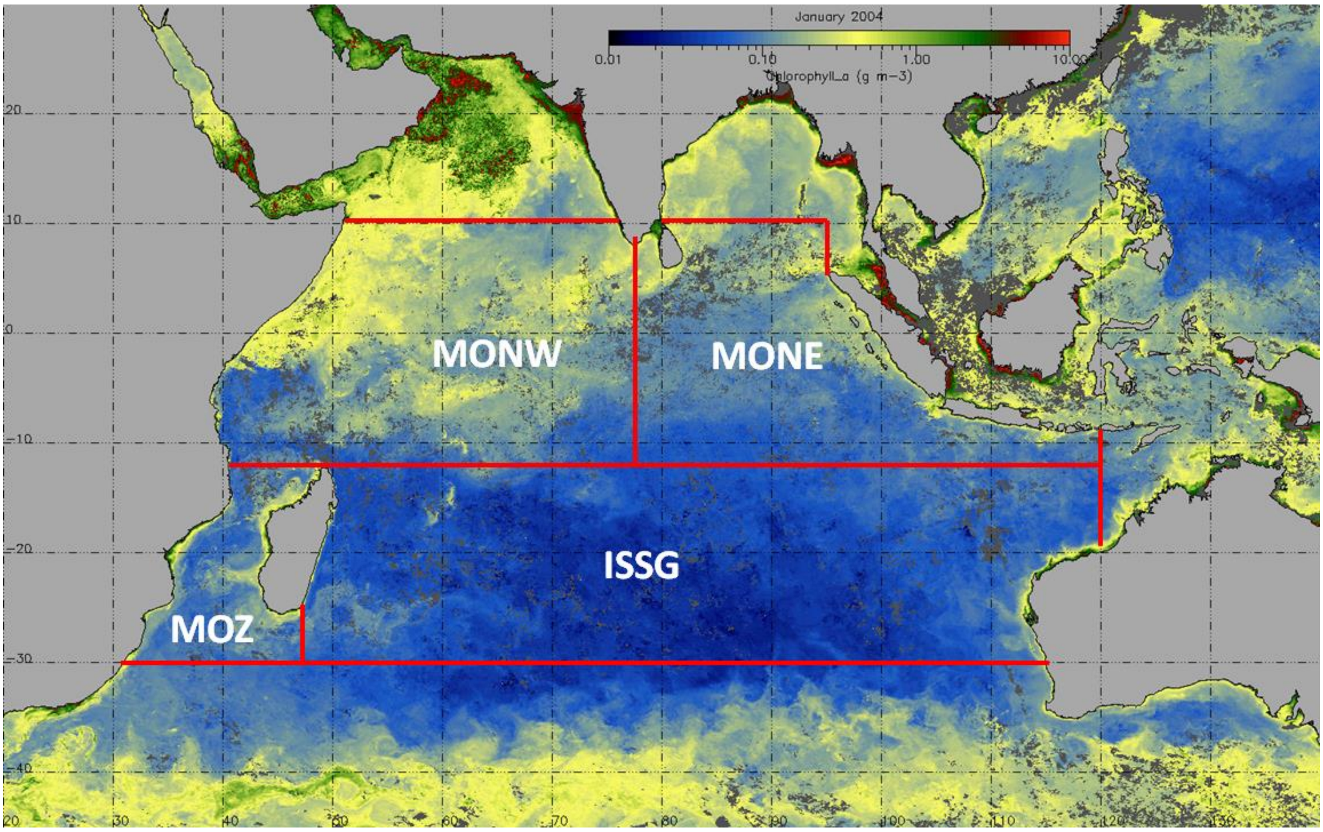


Fig. 1 – Boundaries of the four ecoregions used in this paper. The background image is the chlorophyll concentration measured by MODIS in January 2004.

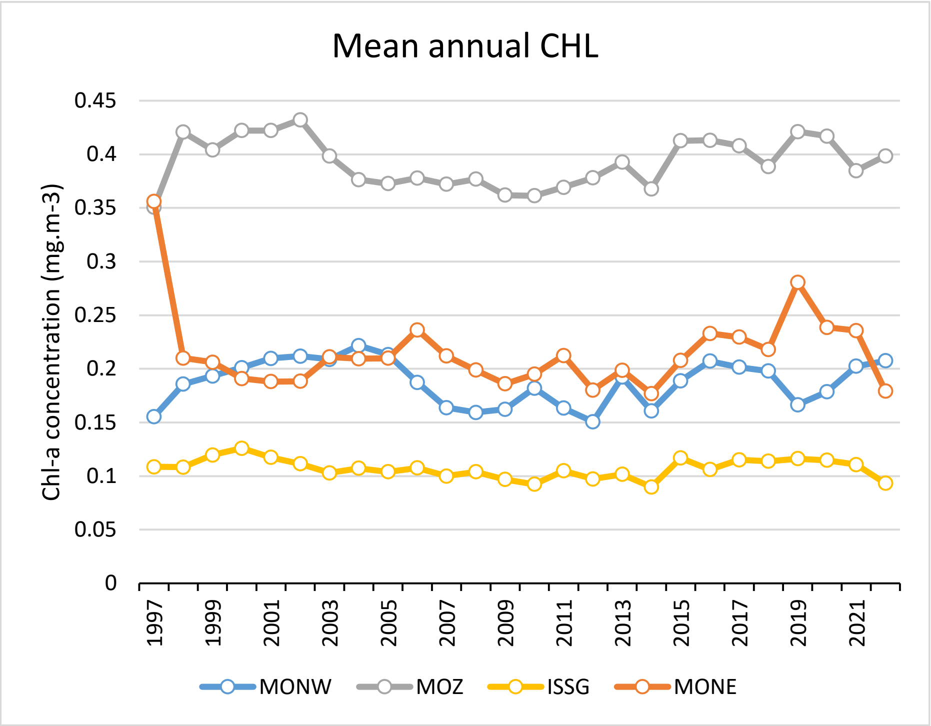


Fig. 2 - Mean annual SSC for each large ecoregion, Sep 1997 to Dec 2022

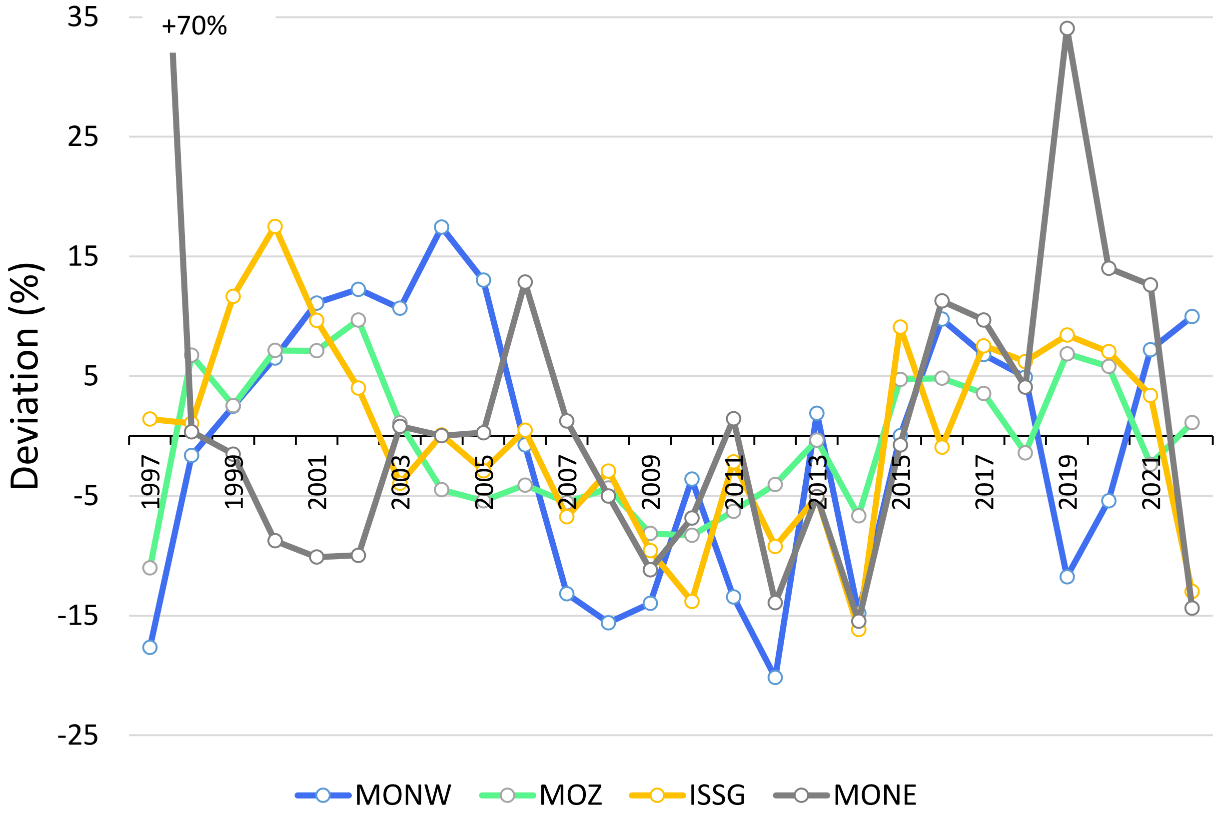


Fig. 3 – Deviation (in %) to the mean multi-annual SSC by large ecoregion,
Sept 1997 to Dec 2022

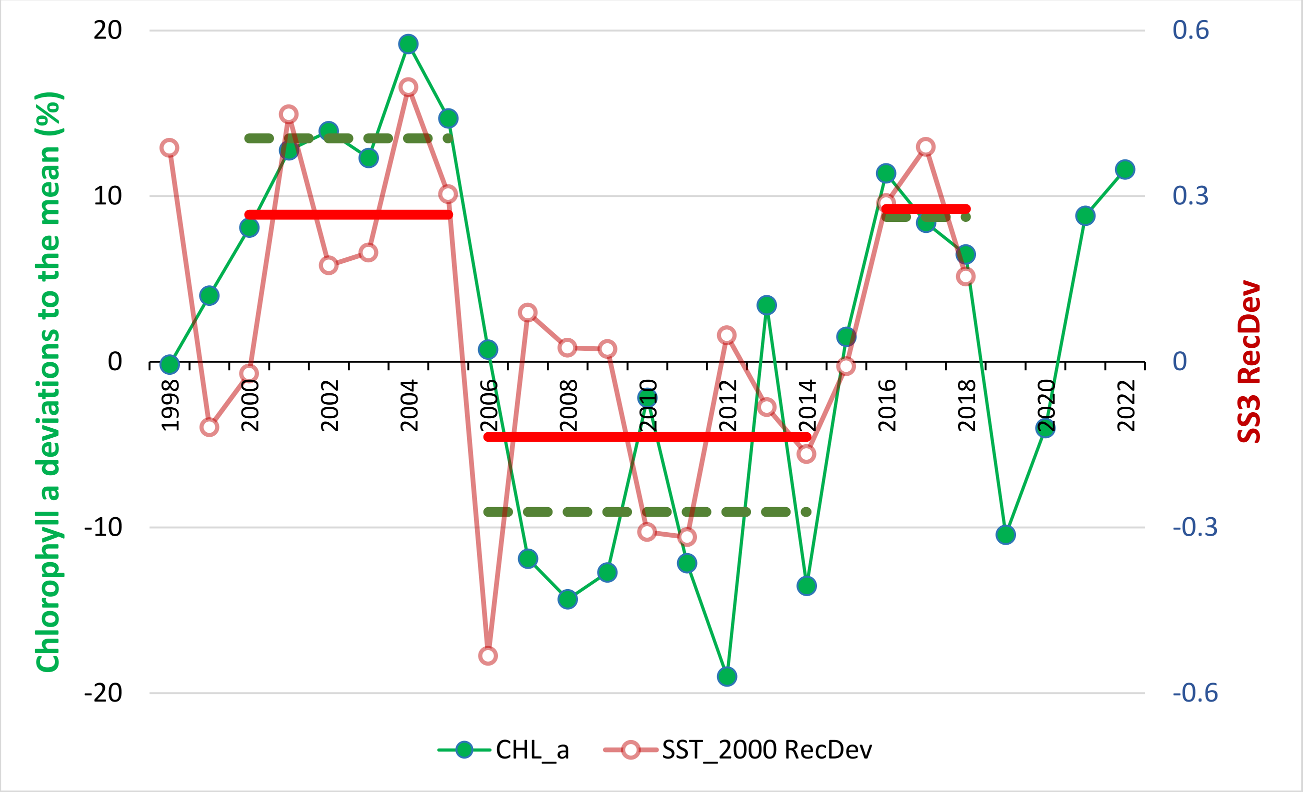


Fig. 4 – Combined plots of SSC concentration (left axis, green) and the SS3 Recruitment deviates (right axis, red) and average levels by group of years (horizontal lines) for both variables. Grouped years: 2000-2004, 2006-2014 and 2016-2018.

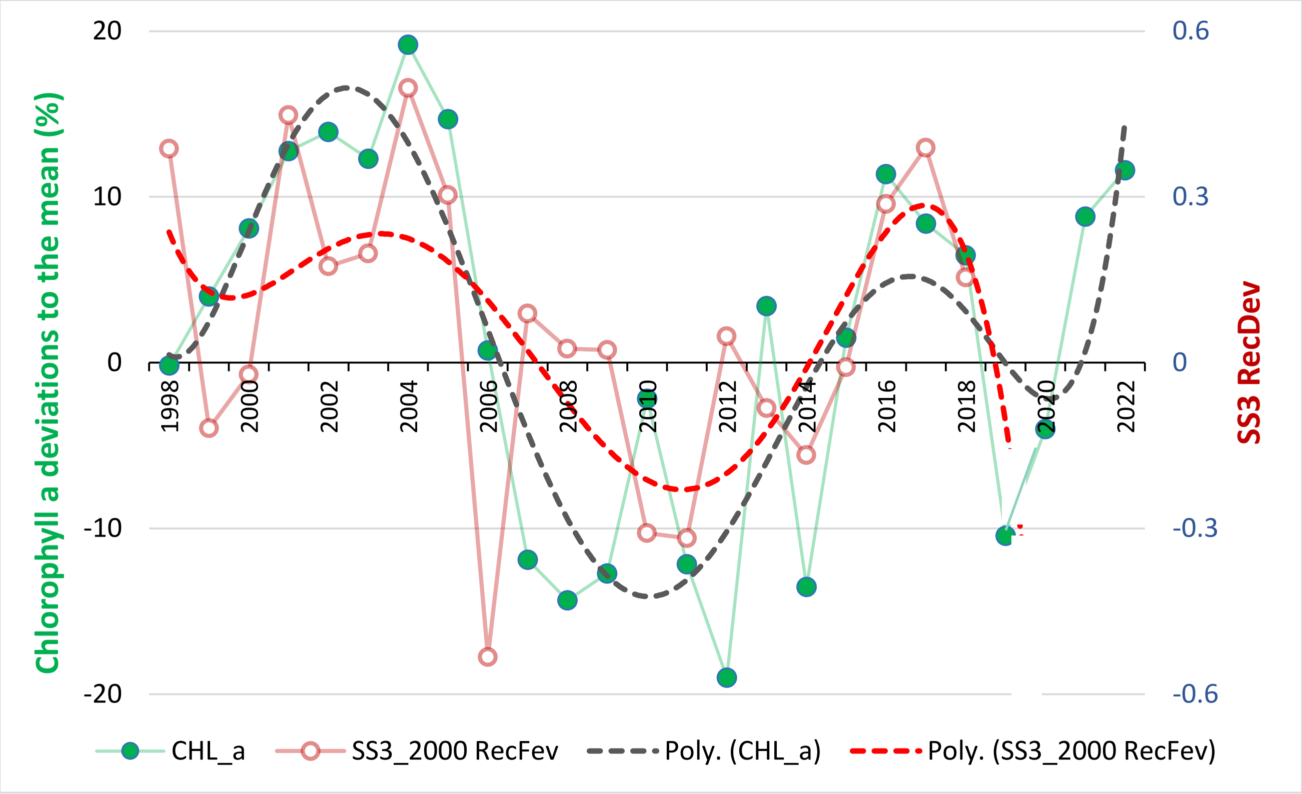
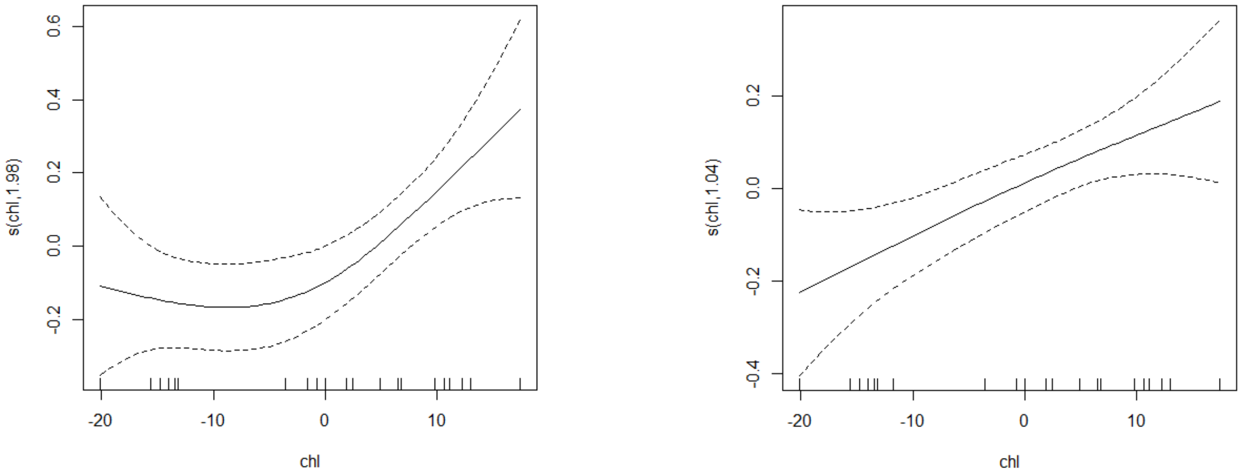


Fig. 5 – Spline fit (dashed lines) of the SSC concentration and SS3 skipjack recruitment deviates series, 1998-2022.



	Estimate	Std error	t_value	Pr(>|t|)	
`(Intercept)`	0.06984	0.04577	1.526	0.144	
	edf	Ref.df	F	p-value	α
`s(chl)`	1.979	9	1.5	0.00412	(0.01)
`R-sq.(adj)`	0.395	Deviance explained		**45.50%**	
`GCV =`	0.051265		n =	21	

	Estimate	Std error	t_value	Pr(>|t|)	
`(Intercept)`	0.06984	0.04914	1.421	0.171	
	edf	Ref.df	F	p-value	α
`s(chl)`	1.044	9	0.896	0.00603	(0.01)
`R-sq.(adj)`	0.303	Deviance explained		33.90%	
`GCV =`	0.056181		n =	21	

Fig. 6 – GAM regressions showing the response of skipjack recruitment to SSC (in mg m^{-3}). The left panel shows the result with no time lag between the two series, whereas the right panel is the result with the recruitment series lagged 1 year after the SSC.

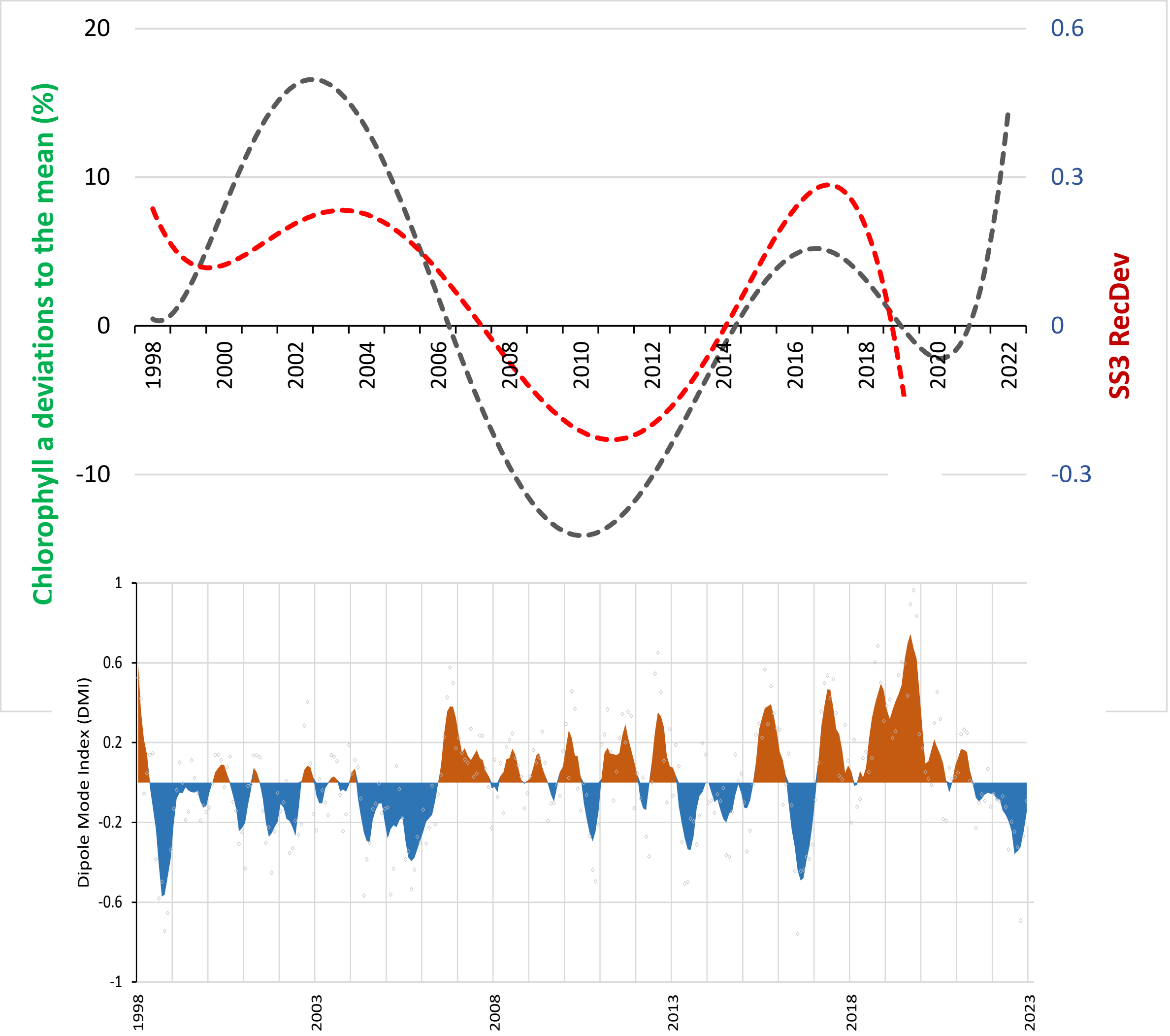
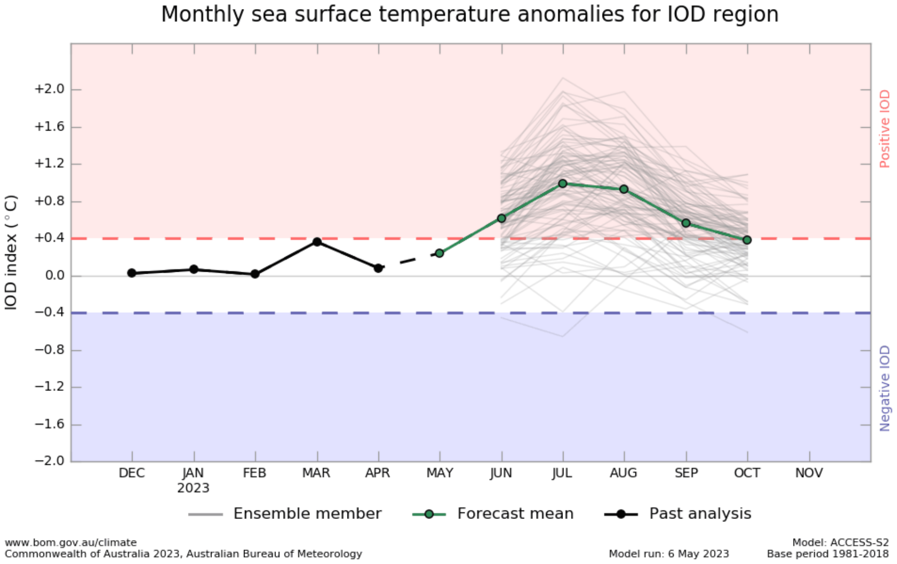


Fig. 7 – Spline series of SSC concentration (grey) and SS3 skipjack recruitment (red) -upper panel- and Dipole Mode Index series, 1998-2022 –lower panel. The blue area in the DMI series indicate negative Indian Ocean Dipole, orange areas indicate positive IOD.



www.bom.gov.au/climate
Commonwealth of Australia 2023, Australian Bureau of Meteorology

Model run: 6 May 2023

Model: ACCESS-S2
Base period 1981-2018

Fig.8 – 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.