

Contrasting effects of positive and negative Indian Ocean Dipole events on skipjack tuna abundance and purse seine CPUE

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Abstract

The Indian Ocean Dipole (IOD) is a major mode of climate variability that can affect ocean conditions and tuna fisheries in the Indian Ocean. This study examines relationships between IOD variability, skipjack tuna recruitment and purse seine catch rates. Environmental data from the Indian Ocean Digital Atlas (IODA) were analysed together with the Dipole Mode Index (DMI), skipjack recruitment deviates and standardized purse seine CPUE. Empirical Orthogonal Function analysis showed clear IOD-related patterns in temperature, thermocline depth, dissolved oxygen and primary production. Recruitment deviates were positively related to the September–November DMI of the preceding year, with the model explaining 17.2% of the deviance. This indicates that positive IOD events may be followed by increased skipjack recruitment in the subsequent year. In the western Indian Ocean, purse seine CPUE decreased with increasing temperature at 78 m and increased with integrated chlorophyll concentration in the upper 300 m. These results suggest that positive IOD events can affect the fishery through two distinct pathways: by influencing skipjack recruitment with an 8 to 10-month lag when the ocean productivity is enhanced, and by modifying the oceanographic conditions that affect purse seine catch rates. Monitoring the IOD and associated oceanographic conditions could therefore provide useful indicators for anticipating changes in skipjack recruitment and fishery performance.

1. Introduction

Skipjack is a fast-growing tuna species that inhabits the epipelagic layer of tropical waters but also extends to temperate latitudes (approximately 35°S) during summer, when water temperature exceeds 18°C (Barkley et al., 1978; Stéquert and Marsac, 1989; Marsac, 2017). Among the major tuna species, skipjack has the lowest tolerance to low dissolved oxygen concentrations and therefore spends most of its life in the warm upper mixed layer (0–200 m). When dissolved oxygen concentrations fall below 4 mg L⁻¹, skipjack increases its swimming speed to enhance oxygen uptake (Dizon, 1977). Skipjack is an opportunistic feeder that consumes a wide range of prey, including small fishes, cephalopods and crustaceans, and displays dietary plasticity in response to variations in prey availability across time and space. Dietary changes have been observed in the western Indian Ocean for both yellowfin and skipjack tuna (Potier et al., 2004).

Skipjack is the primary tuna resource harvested in the Indian Ocean in terms of volume and is currently subject to a TAC of 628,606 tonnes for 2024–2026. Skipjack is exploited by a range of fishing fleets, primarily purse seiners (53% of the catch), followed by baitboats (19%) from the Maldives and Laccadives, gillnets (17%), and other gears. Standardised CPUE trends are calculated for the European purse seine fleet and the Maldivian baitboat fleet. CPUE fluctuations may result from changes in both gear catchability and stock abundance. Recruitment estimates are also produced by the stock assessment model currently used for skipjack, the Stock Synthesis 3 (SS3) model (Methot et al., 2020). CPUE and recruitment deviates are stock indices that can be analysed in relation to environmental conditions. At present, environmental covariates are rarely incorporated into the models used to standardise CPUE. In some cases where they are included, the resulting standardised series does not differ substantially from the nominal CPUE series. A first study of this issue was conducted during the 2023 Skipjack Assessment Working Party, showing that positive recruitment responses were associated with positive deviations in sea-surface chlorophyll in relation to the Indian Ocean Dipole (Marsac, 2023).

In this paper, we examine the latest recruitment trajectory for Indian Ocean skipjack tuna, prepared for this WPTT session, together with purse seine CPUE, in relation to Indian Ocean Dipole variability, using a broader range of environmental variables than in the 2023 analysis.

2. Data and Methods

2.1 – Environmental data

The environmental data consisted of maps and time series generated by the Indian Ocean Digital Atlas (IODA) (<https://ioda-atlas.gov.sc>). IODA is a newly developed digital platform that integrates oceanographic data from data-assimilative models and satellite observations with advanced visualisation tools into a single operational system (Marsac & Noel, 2026).

Several environmental variables were extracted and analysed:

- Physical variables: temperature at 78 m and the depth of the 20°C isotherm (a proxy for thermocline depth);
- Biogeochemical variables: dissolved oxygen concentration at 110 m, net primary production at 40 m, and chlorophyll content integrated over the upper 300 m of the water column.
- Climate index: the Dipole Mode Index (DMI), which characterises the Indian Ocean Dipole (Saji et al., 1999). It is defined as the difference in temperature anomalies between the West and East Indian Ocean.

The selected depths for temperature (78m), dissolved oxygen (110m) and net primary production (40m) correspond to those at which the spatial patterns of these variables are most clearly expressed. The spatial resolution of the physical variables is 1/12° (~8 km) and that of the biogeochemical variables is 1/4° (~25 km). To reduce the size of the matrices analysed, the data were resampled to 1° in longitude and 0.25° in latitude. This resulted in a data field of 65 cells in longitude and 120 cells in latitude over 396 months (1993–2025), corresponding to a matrix of 3,088,800 elements for each variable.

The intensity of the Indian Ocean Dipole is represented by the anomalous SST gradient between the western equatorial Indian Ocean (50°E–70°E and 10°S–10°N) and the south-eastern equatorial Indian Ocean (90°E–110°E and 10°S–0°N), which defines the DMI. When the DMI is positive, the event is referred to as a positive IOD (pIOD); when the DMI is negative, it is referred to as a negative IOD (nIOD).

2.2 – Skipjack recruitment and catch rates (CPUE)

A proxy for recruitment in the skipjack tuna stock is provided by the recruitment deviates (RecDev) produced by the SS3 analysis of the Indian Ocean skipjack stock. The stock assessment model was prepared by the IOTC Secretariat (Phillips, 2026) for WPTT26, using a base-case scenario. Other values of key parameters may be proposed during the session, and the SS3 model will be re-run. Therefore, the RecDev series used in this paper is provisional. However, we assume that the main trends in the series will not change substantially with the updated model. The RecDev series is provided annually from 1983 to 2024.

We also use the standardised catch per unit effort (CPUE) presented at the WPTT26-DP meeting, held from 10 to 12 June 2026 (Correa et al., 2026). This CPUE is based on the EU purse seine fishery operating on floating objects during 1991–2025, and the series was produced on a quarterly basis.

Skipjack catches are mostly concentrated in the western Indian Ocean, where purse seining is the dominant fishing method. Catches are also highly concentrated around the Maldives, where pole-and-line vessels operate (Fig. 1).

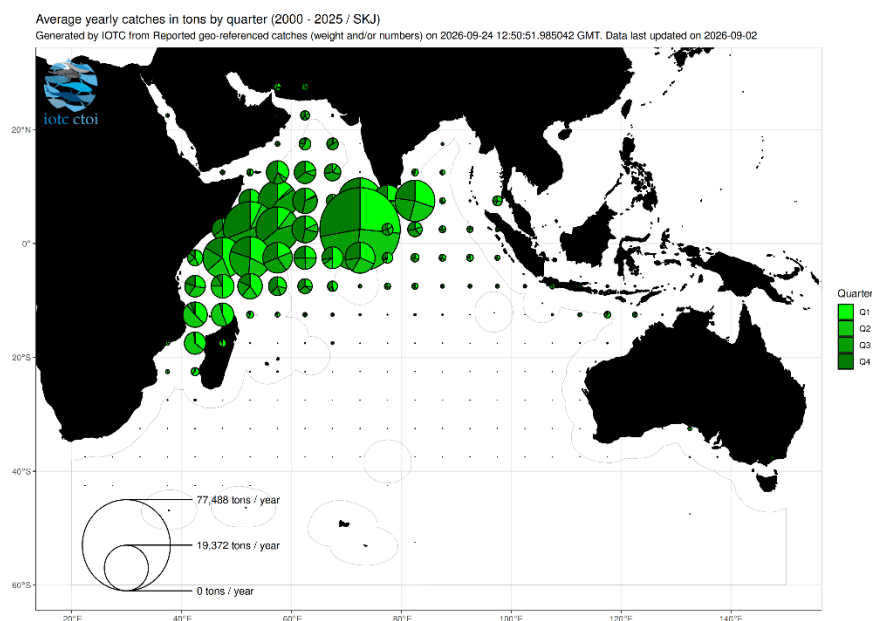


Figure 1. Average annual catches of skipjack tuna (2000–2025) (IOTC data browser)

2.3 – Spatial and temporal pattern analysis

We used Empirical Orthogonal Functions (EOFs) (Lorenz, 1956) to identify structures in the physical and biogeochemical datasets selected for this study. EOF analysis, also known in statistics as principal component analysis, is a common statistical tool in atmospheric and ocean sciences for identifying spatial modes (patterns) of variability and examining how they change over time. A field is partitioned into mathematically orthogonal (i.e. independent) modes. The EOFs are obtained by computing the eigenvalues and eigenvectors of the covariance matrix of a spatially weighted anomaly field (NCAR, 2013; Baldwin et al., 2009).

In detail, the method represents the data as a sum of products of functions: $f(x,y,t) = \sum [F_i(x,y) \times G_i(t)]$ where x , y and t denote longitude, latitude and time, respectively; F_i describes the spatial distribution, and G_i represents the contribution of the corresponding spatial pattern at a given time. An infinite sum of functions would reproduce the observations, but in practice the expansion is truncated after the first few terms. The contributions are arranged so that the first term (first mode) accounts for more of the variance in the observations than any other term, the second term accounts for most of the remaining variance, and so on. The eigenvalues are dimensionless and are proportional to the variance associated with each mode. They provide a measure of the percentage of variance explained by each mode. The product of the spatial coefficient at grid point (x,y) and the temporal coefficient at time t determines the sign of the anomaly at that location and time.

Atmospheric and oceanographic processes are typically characterised as 'red', meaning that most of their variance (power) is concentrated in the first few modes. In this analysis, we selected the first two modes of variability. Each mode is represented by a map showing its spatial pattern and a time series covering the period under study. The magnitude of the anomaly represented on the map is given by the product of the spatial and temporal coefficients.

The EOF input data consisted of anomalies. We used the monthly anomalies generated by IODA for each variable. The anomalies are defined as the difference between the monthly value and the climatological value at each grid point. The climatology was calculated over the period 1993–2016.

3. Results

3.1 Indian Ocean Dipole variability and temporal patterns

The IOD is a prominent mode of climate variability in the Indian Ocean. Figure 2 shows the oscillation of the IOD between negative (blue shading) and positive (orange shading) events. Since 1983, typical pIOD events have occurred in 1994, 1997, 2006, 2015, 2019 and 2023. Typical nIOD events occurred in 1984, 1992, 1996, 1998, 2010, 2016 and 2022. Overall, dipole intensity is greater during positive events than during negative events, particularly since 2006.

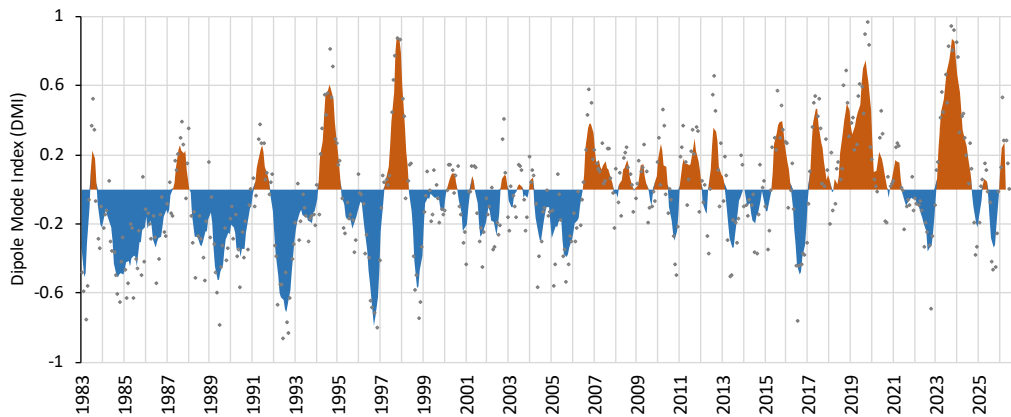


Figure 2. Dipole Mode Index (DMI) from January 1983 to May 2026. Grey dots represent monthly values, and the shaded areas show the 5-month moving average of the DMI (source: https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/dmi.had.long.data).

The monthly evolution of the DMI during typical pIOD and nIOD years is shown in Figure 3, which presents the median and quartiles of the DMI for each type of event.

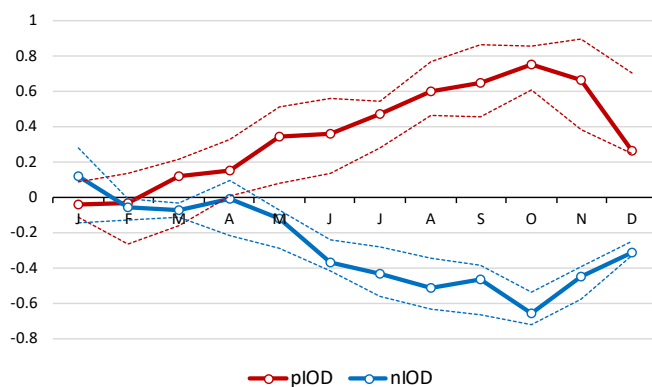


Figure 3. Monthly evolution of DMI values during typical IOD years (pIOD and nIOD). The main lines represent the median, and the dotted lines represent the first and third quartiles.

The temporal patterns of the two modes are approximately symmetrical, with a peak in October. We used the average DMI over September–November to characterise the intensity of the dipole in a given year (Y).

3.2 EOF analysis

The EOF domain extended from 15°N to 15°S and from 40°E to 105°E. The EOF analysis was performed using a Fortran script processing matrices of 3,088,800 elements. Only the first two EOFs are presented in this paper. We show the EOFs for temperature at 78 m, thermocline depth, dissolved oxygen at 110 m, and net primary production at 40 m. The integrated chlorophyll content in the upper 300 m is not shown because of its high correlation with net primary production.

Temperature at 78 m

The first EOF (EOF1) captures 55% of the variance and depicts the interannual oscillation associated with the IOD. The spatial pattern (Fig. 4a) clearly exhibits the ocean response to the IOD, with an eastern pole characterised by negative coefficients from 10°N to 5°S east of 80°E, and a western pole with positive coefficients extending west of 70°E. The peaks in the EOF1 time series (Fig. 4b) highlight the positive and negative IOD events identified in Section 3.1. In 2023, the product of the spatial and temporal coefficients of EOF1 indicates that, during the positive dipole event, temperature at 78 m decreased by approximately 4.5–6°C in the eastern pole (east of 85°E) and increased by approximately 9°C in a corridor between 0° and 10°S and 55°E–75°E. These changes are expressed relative to the climatological mean.

The second EOF (EOF2) captures 11% of the variance, and its temporal component (Fig. 4d) reflects the long-term trajectory associated with climate change. The areas with the largest variability (Fig. 4c) are located between 5°S and 15°S, with a significant temperature increase from 70°E to 80°E (~+6°C) and a smaller temperature decrease from 55°E to 65°E (~-1.8°C) between 1997 and 2025.

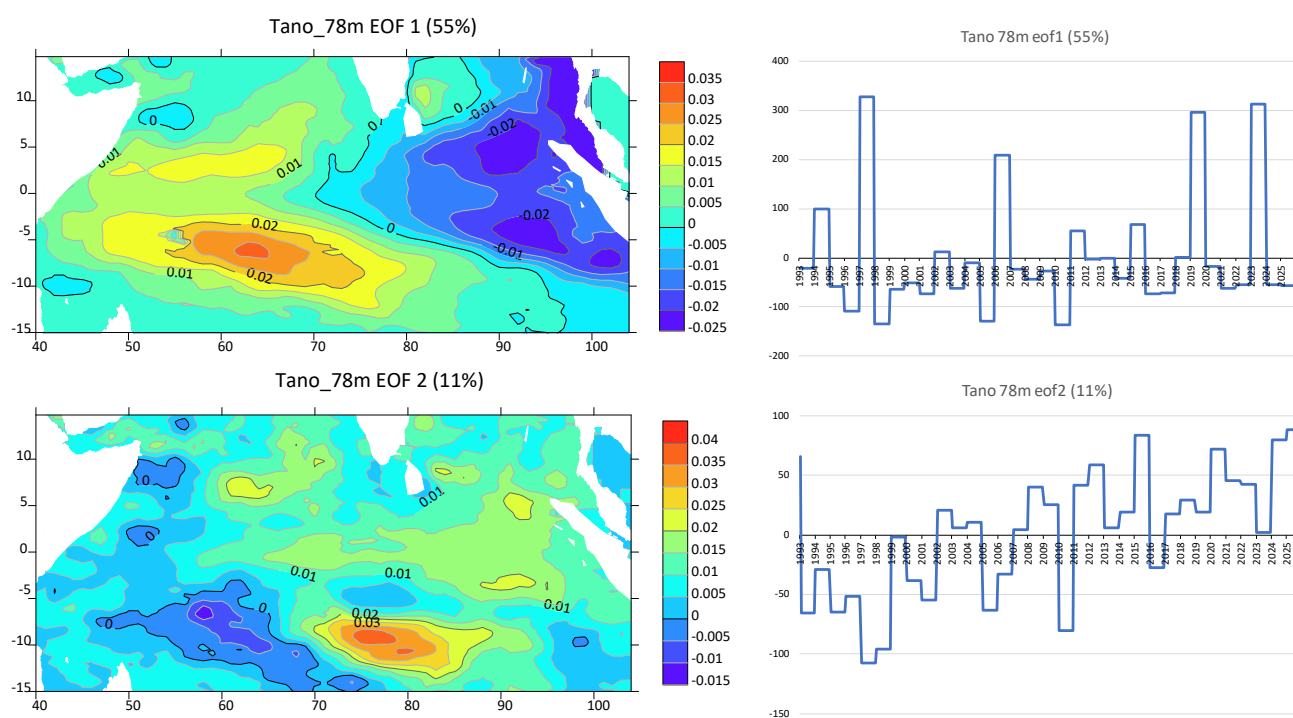


Figure 4. EOF spatial (left) and temporal (right) patterns for temperature at 78 m. EOF1: a) top left; b) top right; EOF2: c) bottom left; d) bottom right

Thermocline depth (20°C isotherm depth)

EOF1 (Fig. 5a) reproduces the dipole pattern already shown by temperature at 78 m, as the two variables are highly correlated. It explains 14% of the variance. In November 2023, this mode indicates that the thermocline shoaled by up to 35–50 m in the eastern pole and deepened by 65–70 m in the western pole (5°S–10°S, 55°E–75°E). By contrast, during the 2010–2011 negative dipole, the thermocline deepened by 22–25 m in the eastern pole and shoaled by 40–45 m in the western pole. The EOF1 temporal component also clearly identifies pIOD events through large positive coefficients and nIOD events through strong negative coefficients (Fig. 5b).

The second EOF of thermocline depth (Fig. 5c,d) explains 12% of the variance. It expresses a continuous trend towards a deeper thermocline throughout the study domain, except along a ridge with positive coefficients extending from

5°S–60°E to 15°S–95°E. The strongest deepening trend is located in the eastern pole, where the thermocline has deepened by approximately 26 m since 1993.

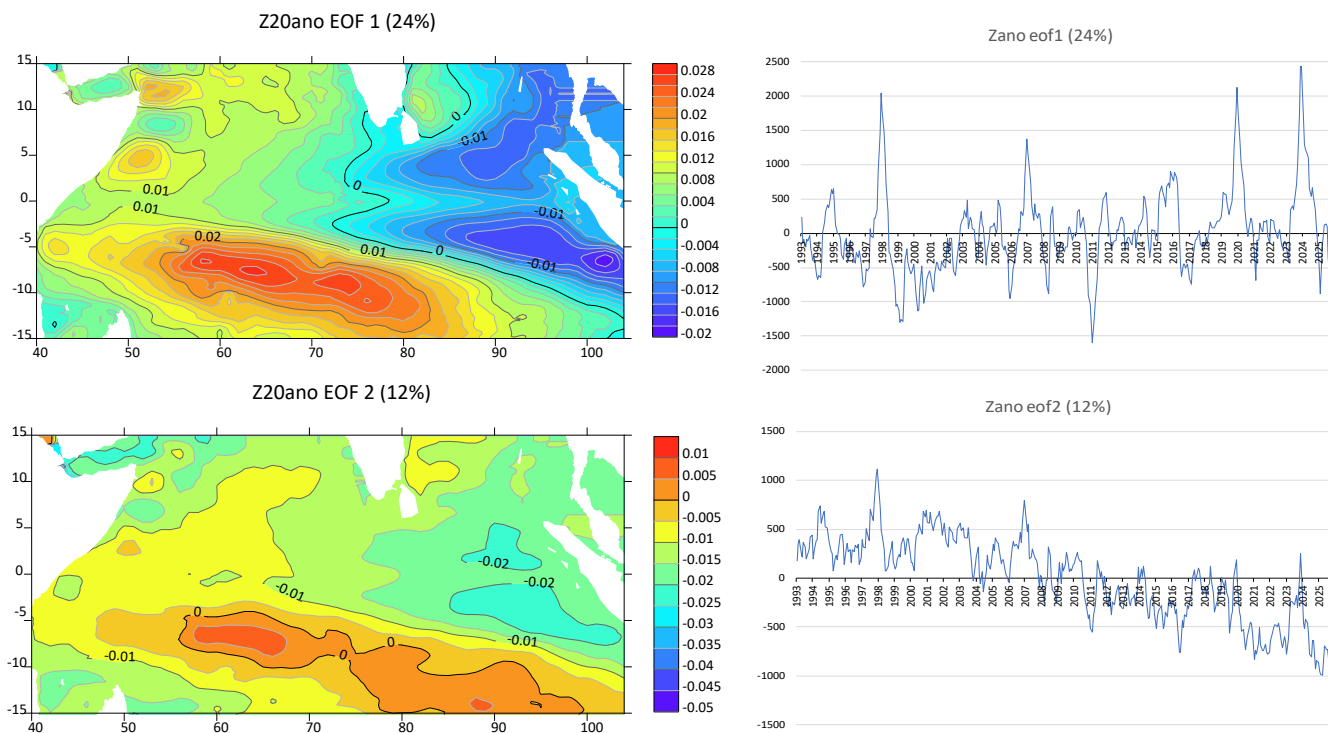


Figure 5. EOF spatial (left) and temporal (right) patterns for the thermocline depth. EOF1: a) top left; b) top right; EOF2: c) bottom left; d) bottom right

Dissolved oxygen (DO) at 110 m

As for temperature and thermocline depth, EOF1 for dissolved oxygen (DO) at 110 m (22% of explained variance) describes the east–west dipole pattern, as well as two north–south dipoles, with cores at 5°N–10°N and 5°S–15°S (Fig. 6a). The temporal component of EOF1 (Fig. 6b) shows large positive and negative coefficients reflecting pIOD and nIOD events, respectively. During a pIOD, DO can decrease by up to 1.0–1.5 ml L⁻¹ in the eastern pole and increase by up to 0.3 ml L⁻¹ in the equatorial zone of the western Indian Ocean, corresponding to changes of –50% and +10%, respectively, relative to the November climatological means (2.8 ml L⁻¹ and 3.0 ml L⁻¹). In the two cores already mentioned, south of the Arabian Sea and in the south-eastern part of the domain, the increase in DO can reach 0.8 ml L⁻¹ during pIODs, which is 40% above the November climatological mean (2.0 ml L⁻¹). These two cores therefore become more oxygenated than the western pole during a pIOD. Conversely, during the 2010–2011 nIOD, DO increased by 1.0–1.5 ml L⁻¹ in the eastern pole and decreased by 0.7 ml L⁻¹ in the western pole and by 0.8 ml L⁻¹ in the two latitudinal cores.

EOF2 (9% of explained variance) displays elongated belts of positive and negative coefficients (Fig. 6c). Its temporal component (Fig. 6d) exhibits multi-year oscillations, with higher coefficients after 2020 than in the 1990s. From 1993 to 2025, the trend indicates a significant DO decrease (–0.6 ml L⁻¹) in the southern part of the domain, along 10°S, and a decrease of similar magnitude in the eastern pole off Sumatra, while little change occurs along the equator in the western Indian Ocean. North of 5°N, except in the area influenced by the Somali upwelling, DO has increased by approximately 0.3–0.4 ml L⁻¹ in the southern regions of the Arabian Sea and the Bay of Bengal.

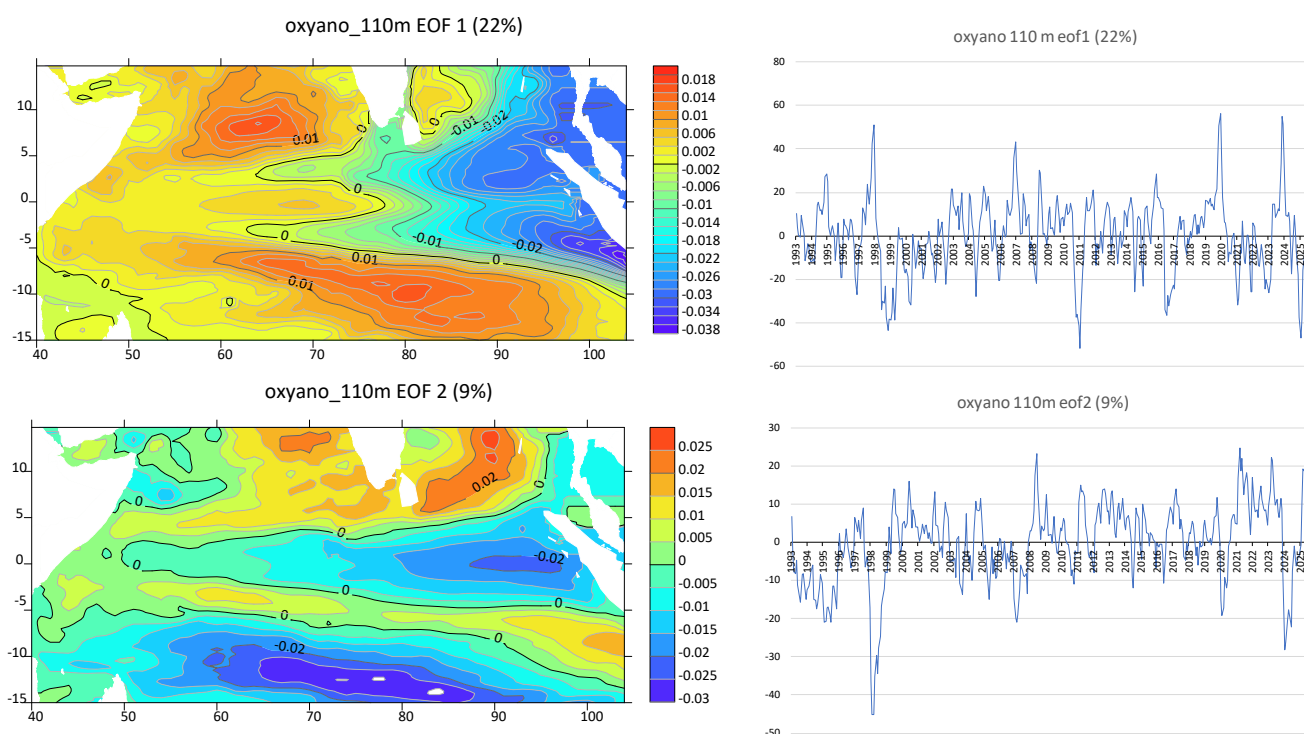


Figure 6. EOF spatial (left) and temporal (right) patterns for dissolved oxygen at 110 m. EOF1: a) top left; b) top right; EOF2: c) bottom left; d) bottom right

Net primary production (NPP) at 40 m

The dipole pattern is expressed in the EOF1 spatial pattern (Fig. 7a), which explains 14% of the variance. However, as for DO, two additional cores are identified south of India and between 20°S and 8°S, between 70°E and 80°E. pIODs are clearly marked by negative coefficients in the EOF1 time series (Fig. 7b). During pIOD events, this indicates an increase in NPP of approximately $9\text{--}11\text{ mg m}^{-3}\text{ day}^{-1}$ in the eastern pole (50% above normal) and a decrease in NPP of $2\text{--}6\text{ mg m}^{-3}\text{ day}^{-1}$ in the western pole (15–35% below normal). The NPP reduction is larger in the two cores, reaching $8\text{--}11\text{ mg m}^{-3}\text{ day}^{-1}$ (50–70% below normal).

The EOF2 spatial pattern (Fig. 7c) is characterised by an area of high variability in the central Indian Ocean (5°N–5°S, 65°E–90°E). The temporal component (Fig. 7d) shows a V-shaped trend, with minimum coefficients between 2008 and 2013 and higher coefficients during 1996–1998 and 2022–2024. In the central area, the change over the time series ranges from $+8$ to $-8\text{ mg m}^{-3}\text{ day}^{-1}$. In the western basin, variability is much weaker, ranging from $+2$ to $-2\text{ mg m}^{-3}\text{ day}^{-1}$.

3.3 Response of skipjack recruitment deviates to IOD variability

The relationship was studied over the period 1983–2024 using generalised additive models (GAMs) (Hastie and Tibshirani, 1986). We examined the response of skipjack RecDev in year Y to the average DMI for September–November of the previous year (Y–1). The rationale for using September–November is explained in Section 3.1. The response is almost linear (Fig. 8), indicating that recruitment in a given year responds positively to a pIOD occurring during the previous year. This model, using a single covariate, explains 17% of the deviance.

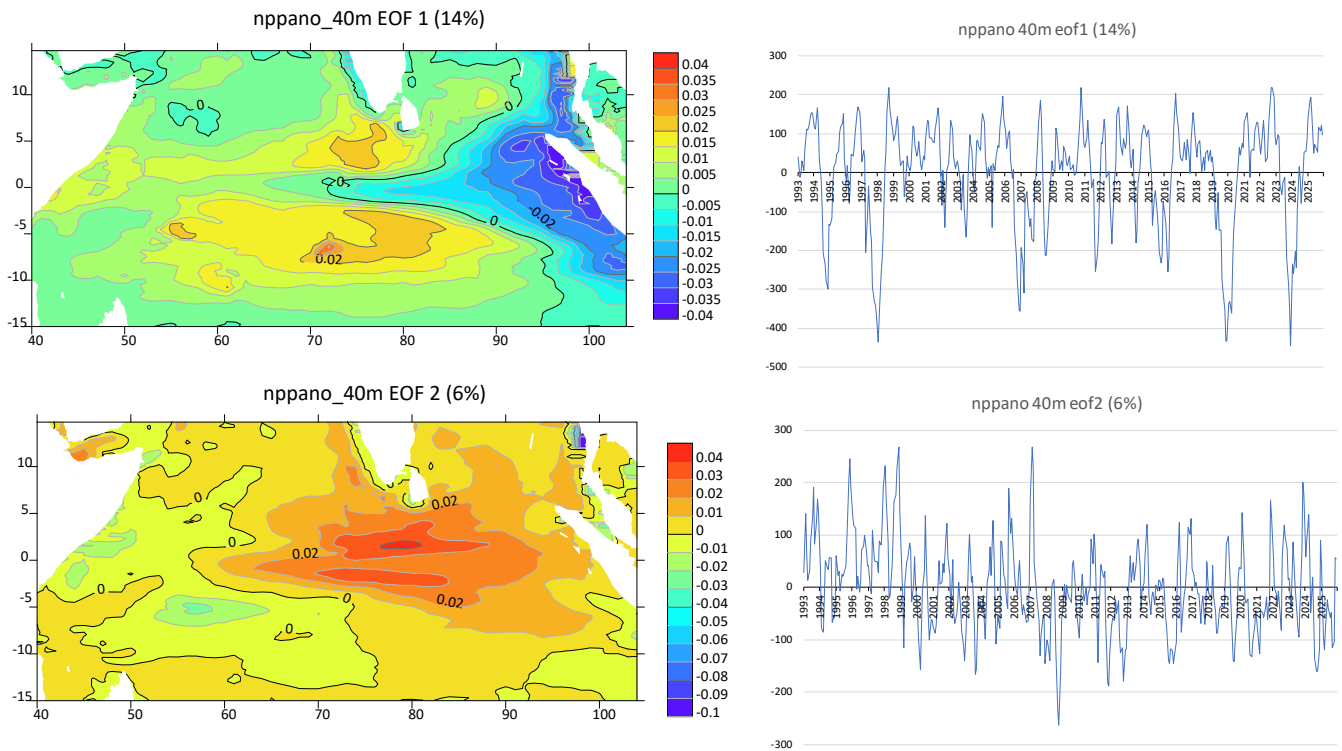


Figure 7. EOF spatial (left) and temporal (right) patterns for net primary production at 40 m. EOF1: a) top left; b) top right; EOF2: c) bottom left; d) bottom right

Family : gaussian					
Formula : SKJ_Rec ~ s(dmi_SN, bs = "cs")					
	Estimate	Std. Error	t value	Pr(> t)	
(Intercept)	-3.03E-08	4.22E-02	0.000	1.000	
	edf	Ref.df	F	p-value	α
s(dmi_SN)	0.9972	9	0.792	0.00662	0.01
R-sq.(adj)	0.152	Deviance explained		17.2%	
GCV	0.078352	n		42	

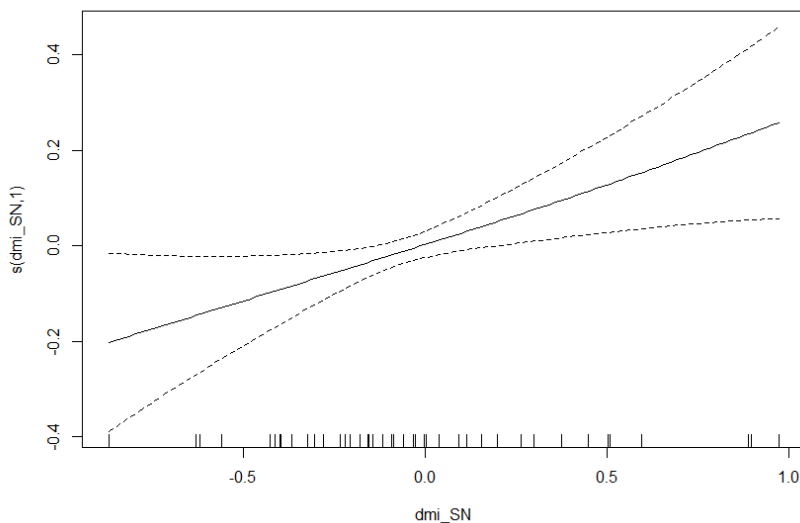


Figure 8. GAM showing the response of skipjack recruitment deviates in a given year to the DMI recorded from September to November (dmi_SN) in the previous year.

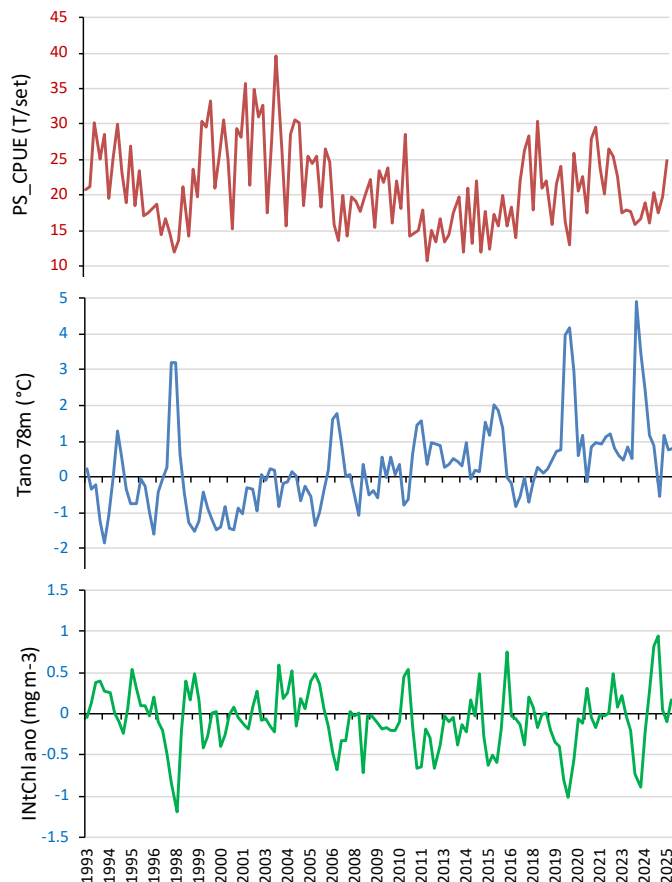
3.4 Response of skipjack purse seine CPUE to ocean conditions

We used the spatial patterns identified by the EOFs to define a region with similar variability where ocean conditions could be averaged in a meaningful way. Because the skipjack purse seine fishery is concentrated in the western Indian Ocean, we delineated a region in the western part of the dipole, extending from 5°N to 10°S and from 50°E to 70°E.

IODA was used to extract the environmental variables for this selected area for 1993–2025. The initial monthly values were averaged by quarter to match the quarterly CPUE series. A Spearman correlation matrix was then calculated between the environmental variables and the purse seine CPUE index (Table 1).

Table 1. Spearman correlation matrix between the environmental variables in the western Indian Ocean (5°N–10°S, 50°E–70°E) and the purse seine CPUE index, on a quarterly basis (132 observations)

	tano78	z20ano	oxyano110	nppano40	intchlano	dmi	PSCPUE
tano78	1	0.935	0.148	-0.697	-0.650	0.501	-0.367
z20ano		1	0.118	-0.575	-0.541	0.487	-0.344
oxyano110			1	-0.612	-0.512	0.232	-0.114
nppano40				1	0.914	-0.581	0.331
intchlano					1	-0.549	0.354
dmi						1	-0.156
PSCPUE							1



The purse seine CPUE series and the *tano78* and *intchlano* time series are plotted in Fig. 9. The low CPUE values recorded in the first quarter of 1998, second quarter of 2007, second quarter of 2020, and first quarter of 2024 correspond to the peak development of pIODs in the western Indian Ocean. The low CPUE values observed from 2012 to 2015 (mean = 15.5 t/set) cannot be attributed to pIODs; however, this period was characterised by low primary productivity, as indicated by *intchlano*.

Figure 9. Time series of purse seine CPUE, temperature anomalies at 78 m, and integrated chlorophyll content in the water column in the western Indian Ocean.

Finally, we examined the response of purse seine CPUE to *tano78* and *intchlano* using GAMs. Temporal lags of one and two quarters were investigated but did not produce conclusive results (not shown). The results presented here use synchronous observations, with no time lag. The results are shown in Figs. 10 and 11.

Family : gaussian					
Formula : s(tano78, bs = "cs")					
	Estimate	Std. Error	t value	Pr(> t)	α
(Intercept)	21.107	0.475	44.480	<2e-16	0.001
	edf	Ref.df	F	p-value	α
s(tano78)	2.323	9	2.514	1.75E-05	0.001
R-sq.(adj)	0.141	Deviance explained		15.6%	
GCV	30.492	n		132	

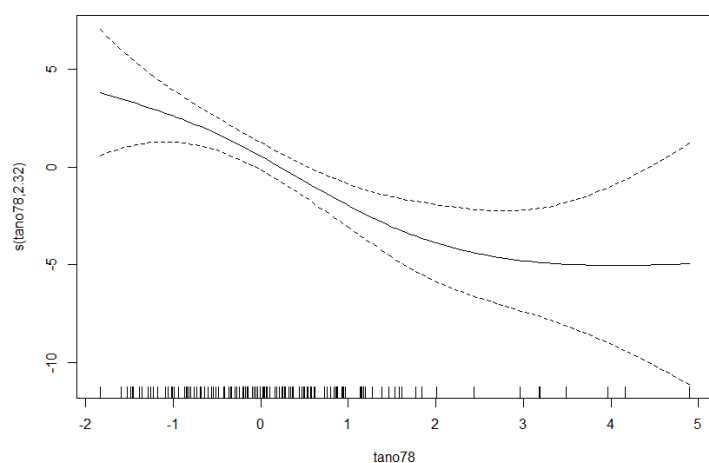


Figure 10. GAM showing the response of purse seine CPUE to temperature anomalies at 78 m in the western Indian Ocean.

Family : gaussian					
Formula : s(intchlano, bs = "cs")					
	Estimate	Std. Error	t value	Pr(> t)	α
(Intercept)	21.107	0.481	43.930	<2e-16	0.001
	edf	Ref.df	F	p-value	α
s(intchlano)	1.088	9	1.906	3.22E-05	0.001
R-sq.(adj)	0.119	Deviance explained		12.6%	
GCV	30.962	n		132	

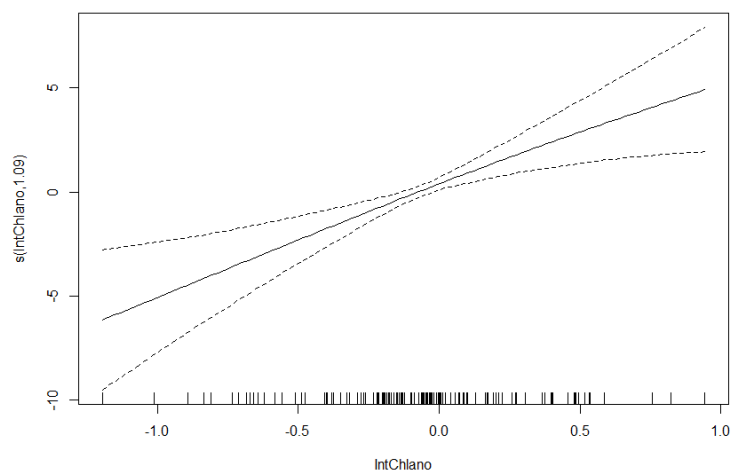


Figure 11. GAM showing the response of purse seine CPUE to anomalies in integrated chlorophyll content in the upper 300 m in the western Indian Ocean.

Purse seine CPUE responds negatively to increasing temperature at depth, which also reflects a deepening thermocline. The sharpest decline in CPUE occurs when temperature anomalies at depth increase from 0 to +1.5°C. In contrast, the response to chlorophyll anomalies is clearly positive and almost linear over the range of chlorophyll concentrations observed in the area. Thus, warmer conditions at depth are associated with reduced purse seine catch performance, whereas increased ocean productivity is associated with higher purse seine CPUE. In the discussion, we examine how these responses may be related to IOD variability.

4. Discussion

4.1 IOD and skipjack recruitment

This analysis considered lagged effects because the IOD is a dynamic process. A pIOD begins in the middle of the year with the development of unusually strong easterly winds along the equator, accompanied by stronger southerly winds along the coasts of Java and Sumatra that drive intense coastal upwelling and cooling. The atmospheric forcing triggers subsurface and surface anomalies, forming the dipole (a reversed SST gradient), while eastward-propagating Rossby waves and westward-propagating Kelvin waves cross the basin (Webster et al., 1999). The Rossby wave induces downwelling as it propagates westward (Fig. 12). The warm anomaly in the western Indian Ocean maintained by the Rossby waves can persist into the first quarter of the following year. The warm event ends with the onset of the south-west monsoon, around June. The stronger the event, the stronger the monsoon, which enhances mixing and Ekman transport and thereby reinforces coastal upwelling. The system then returns to a normal configuration, with equatorial winds reverting to westerlies, relaxation of the positive sea-surface-height anomaly in the west, and propagation of downwelling Kelvin waves that deepen the eastern Indian Ocean (Webster et al., 1999; Saji et al., 1999).

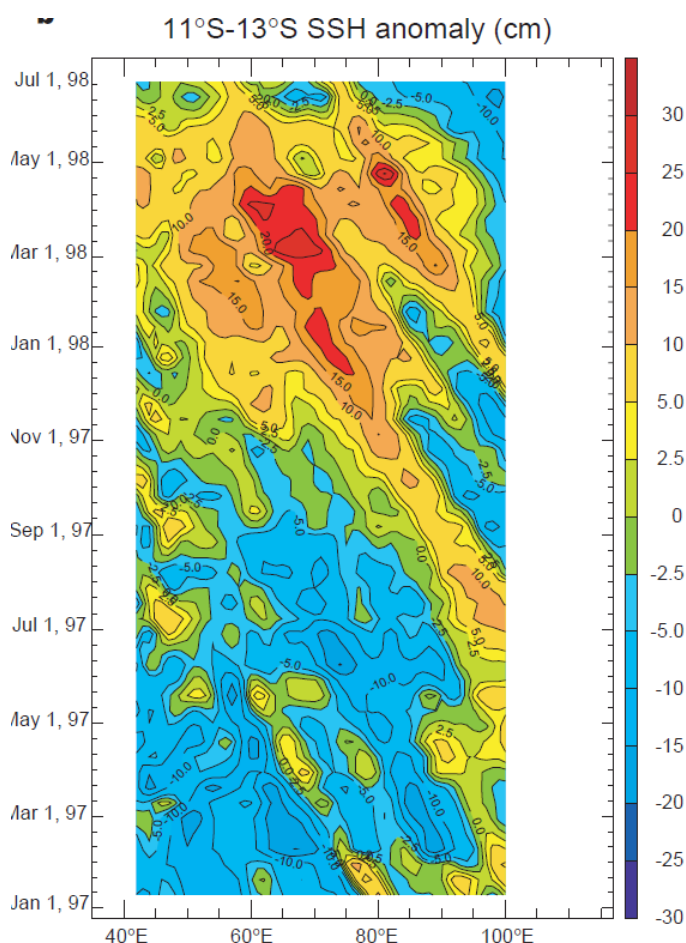


Figure 12. Evolution of the sea-surface-height (SSH) field associated with a Rossby wave during the development of the 1997 positive Indian Ocean Dipole (from Webster et al., 1999). Higher SSH anomalies denote downwelling and warm cores, which propagate from 100°E in July 1997 to 60°E in January 1998 and remain in the western basin during the first quarter of 1998.

The GAM analysis indicates that skipjack tuna recruitment is enhanced in the year following a positive dipole event. Two processes may be hypothesised to explain this relationship:

- In the short term, i.e. during the first quarter of the year following a pIOD, a positive dipole supplies the western Indian Ocean with warmer and more oxygenated water masses. Skipjack has the lowest tolerance to low dissolved oxygen concentrations among the tuna species (Dizon, 1977); therefore, more oxygenated waters may improve its habitat, while warmer temperatures may help satisfy its metabolic requirements.
- In the longer term, i.e. during the second semester of the year following a pIOD, primary productivity exhibits positive anomalies, which may indicate a more productive food web that benefits the growth and survival of juvenile

skipjack tuna. This productivity enhancement is shown in Fig. 13. The red line indicates the monthly trajectory of integrated chlorophyll content in the upper 300 m during the year following a pIOD. Concentrations are clearly below average at the beginning of the year and become above average during the second semester, 8 to 10 months after the Sept–Nov DMI peak. Conversely, during the year following an nIOD (blue line), chlorophyll concentrations are close to average during the first and second quarters and become below average during the second semester. The symmetrical pattern observed between pIOD and nIOD years (Fig. 3) is also reflected in the productivity patterns during the year following these events.

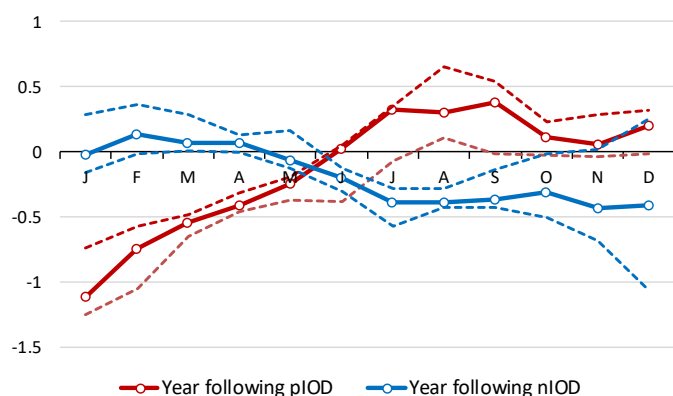


Figure 13. Monthly evolution of anomalies in integrated chlorophyll content in the upper 300 m during the year following typical IOD events (pIOD and nIOD). The main lines represent the median, and the dotted lines represent the first and third quartiles.

Therefore, the September–November averaged DMI in a given year could be used as a proxy to anticipate the recruitment trend in the following year.

4.2 IOD and purse seine CPUE

Purse seine fleets are sensitive to anomalous environmental conditions. Warming events such as pIODs, with Rossby waves causing downwelling, positive temperature anomalies at depth, and a deeper thermocline, can reduce the accessibility of tuna to purse seine gear by facilitating the escape of fish below the net as their habitat becomes deeper than normal. This is consistent with the significant inverse relationship identified by the GAM analysis (Fig. 10). Conversely, higher chlorophyll concentrations are associated with higher CPUEs, possibly as a result of a more dynamic food web for tunas and other apex predators, which may enhance the formation of larger schools.

Positive dipole events have a stronger effect than negative dipole events in the western Indian Ocean. This asymmetry may explain the strong downward signals in CPUE during pIODs (higher temperature and reduced primary productivity), whereas the opposite response is not so clearly observed during nIODs which are less intense. Monitoring the development of positive dipole events is therefore important for anticipating the performance of purse seine fleets in the western Indian Ocean.

4.3 Limitations of the study

As with any study, the limitations that may affect the interpretation of these results should be considered. First, we used data from ocean models. The models used are accessible through the Copernicus Marine Service. They are data-assimilative models, meaning that observations of different types (e.g. from vessels, moored buoys and satellites) are incorporated into the models to produce fields that are as close as possible to observed conditions. However, model data can never reproduce observations with complete accuracy, and some fine-scale dynamics may be overlooked. Second, the recruitment-deviate time series remains provisional because the Stock Synthesis 3 model will be re-run using different configurations, which may lead to slightly different recruitment levels. However, the series used in this paper is very close to that used in the previous assessment (2023) for the years in common, and we assume that the final recruitment trajectory will not differ substantially from the one used here.

5. Conclusion

This study investigated the relationships and possible processes linking the response of the skipjack tuna fishery in the Indian Ocean to ocean environmental variability. The Indian Ocean Dipole is a prominent mode of climate variability that influences both recruitment in the skipjack stock and the catchability of the purse seine fleet harvesting this species around floating objects. One interesting result is that the Dipole Mode Index, which characterises IOD intensity, could be used as a predictor to anticipate both recruitment trends and the catchability of the fleet responsible for the largest skipjack catches. However other factors are involved in this process as the GAM explains only 17.2% of recruitment deviance. IOD is a well-studied and well-monitored climate mode, for which real-time observations and forecasts are available. The Australian Bureau of Meteorology publishes bulletins reporting several climate indices in real time, including the IOD, together with outlooks. The last available bulletin in October 2026 stated that “the IOD was neutral, although recent index values had been above the positive-IOD threshold. Models suggested that a positive IOD was likely to develop during the Southern Hemisphere spring, although uncertainty remained regarding the strength and duration of the event”.

Further analyses are needed to investigate the subject addressed in this paper. A major gap in interpreting the tuna response is that primary production is used to infer changes in the food web, whereas intermediate trophic levels (e.g. micronekton), which constitute important prey for tunas, are highly complex and can change in structure depending on environmental conditions. Simulations using ecosystem models such as APECOSM (Maury et al., 2007a,b) could greatly improve our understanding of the processes involved.

References

- Baldwin, M.P., Stephenson, D.B. & Jolliffe, I.T. (2009). Spatial weighting and iterative projection methods for EOFs. *Journal of Climate*, 22, 234–243. <https://doi.org/10.1175/2008JCLI2147.1>
- Barkley, R.A., Neill, W.H. & Gooding, R.M. (1978). Skipjack tuna, *Katsuwonus pelamis*, habitat based on temperature and oxygen requirements. *Fishery Bulletin*, 76, 653–662.
- Correa, M.G., Kaplan, D.M., Grande, M., Uranga, J., Merino, G., Imzilen, T., Duparc, A., Floc’h, L., Baez-Barrionuevo, J., de la Rosa, J. & Ramos Alonso, M.L. (2026). Standardized catch per unit effort of skipjack tuna in the Indian Ocean for the European purse seine fleet operating on floating objects. IOTC-2026-WPTT28(DP)-10, 61 p.
- Dizon, A.E. (1977). Effect of dissolved oxygen concentrations and salinity on swimming speed of two species of tunas. *Fishery Bulletin*, 75, 649–653.
- Lorenz, E.N. (1956). Empirical orthogonal functions and statistical weather prediction. Scientific Report No. 1, Statistical Forecasting Project, MIT, USA, 52 p.
- Marsac, F. & Noel, E. (2026). Explore ocean patterns and trends at your fingertips with the newly released Indian Ocean Digital Atlas (IODA). IOTC-2026-WPEB22(AS)-29, 16 p.
- Marsac, F. (2017). The Seychelles tuna fishery and climate change. In: Phillips, B. & Perez-Ramirez, M. (Eds), *Climate change impacts on fisheries and aquaculture*, Vol. II, pp. 523–568. Wiley Blackwell. <https://doi.org/10.1002/9781119154051.ch16>
- Marsac, F. (2023). Environmental signal in skipjack recruitment in the Indian Ocean: an updated analysis using the SS3 assessment outputs of 2023. IOTC-2023-WPTT25-22, 10 p.

- Maury, O., Faugeras, B., Shin, Y., Poggiale, J., Bari, T. & Marsac, F. (2007a). Modeling environmental effects on the size-structured energy flow through marine ecosystems. Part 1: the model. *Progress in Oceanography*, 74, 479–499.
- Maury, O., Shin, Y., Faugeras, B., Bari, T. & Marsac, F. (2007b). Modeling environmental effects on the size-structured energy flow through marine ecosystems. Part 2: simulations. *Progress in Oceanography*, 74, 500–514.
- Methot Jr, R.D., Taylor, I.G. & Doering, K. (2020). Stock Synthesis User Manual Version 3.30.15. U.S. Department of Commerce, NOAA Processed Report NMFS-NWFSC-PR-2020-05.
- NCAR (2013). The Climate Data Guide: Empirical Orthogonal Function (EOF) Analysis and Rotated EOF Analysis. Retrieved from <https://climatedataguide.ucar.edu/climate-data-tools-and-analysis/empirical-orthogonal-function-eof-analysis-and-rotated-eof-analysis>.
- Phillips, G. (2026). Preliminary stock assessment of Indian Ocean skipjack tuna (*Katsuwonus pelamis*) using Stock Synthesis. IOTC-2026-WPTT28(AS)-18, 103 p.
- Potier, M., Marsac, F., Lucas, V., Sabatié, R., Hallier, J.-P. & Ménard, F. (2004). Feeding partitioning among tuna taken in surface and mid-water layers: the case of yellowfin (*Thunnus albacares*) and bigeye (*T. obesus*) in the western tropical Indian Ocean. *Western Indian Ocean Journal of Marine Science*, 3, 51–62.
- R Core Team (2025). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.
- Saji, N.H., Goswami, B.N., Vinayachandran, P.N. & Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. *Nature*, 401, 360–363.
- Stéquert, B. & Marsac, F. (1989). Tropical tuna surface fisheries in the Indian Ocean. FAO Fisheries Technical Paper 282. FAO, Rome.
- Webster, P.J., Moore, A.M., Loschnigg, J.P. & Leben, R.R. (1999). Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997–98. *Nature*, 401, 356–360.
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