An investigation of the recruitment dynamics of Indian Ocean yellowfin tuna

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Executive Summary

A review of the IO yellowfin tuna stock assessment was conducted in February 2023. The review highlighted the divergent trends in regional recruitment, particularly since the mid 2000s. This study investigated the influence of key data sets in the estimation of regional recruitment to improve the understanding of the model dynamics in advance of the next stock assessment scheduled for 2024.

The model estimates of regional recruitment are strongly driven by the regional longline CPUE indices, in conjunction with removals (catches) and key biological parameters (growth and natural mortality). Trends in the longline CPUE indices from the two western regions (R1 and R2) deviated from the mid 2000s and the higher CPUE indices from R2 contribute to the higher level of recruitment estimated for the western regions relative to the eastern regions (R3 and R4). Length composition data from the main western longline and purse-seine fisheries vary considerably due to a high degree of sampling error and/or temporal variability in size-based availability to the individual fisheries. Regradless, the trends in the length composition data are broadly consistent with the model estimates of recruitment for the period prior to 2006. There is increased conflict between the LL1 CPUE indices and the LL and PSFS length composition data in the subsequent period (from 2006) and the overall fit to the LL1 CPUE indices deteriorates during that period.

There are strong similarities between the individual regional longline length compositions amongst the four regions in some periods and no persistent differences in the length compositions from adjacent regions. These observations are suggestive of ocean scale mixing of adult yellowfin tuna.

Trends in regional longline CPUE indices and recruitment were compared to established oceanographic indices for the Indian Ocean. There is no indication that trends in the equatorial longline CPUE indices (LL1 and LL4) are strong influenced by the prevailing oceanographic condistions, whereas short-term (1-2 y) trends in the subtropical longline CPUE indices (LL2 and LL3) appear to be influenced by sea surface temperatures in the respective regions. Nonetheless, the divergence in regional longline CPUE indices from the mid 2000s does not appear related to a persistent trend in regional oceanographic conditions.

For the two equatorial regions (R1 and R4), periods of stronger recruitment generally corresponded with warmer sea surface temperatures in the western Indian Ocean (positive Dipole Mode Index). The similarities in estimated regional recruitments are indicative of an equatorial scale recruitment process and/or the dispersal of fish through the equatorial regions from a core spawning area.

The study provides a number of additional recommendations to those included in the IO yellowfin tuna stock assessment review (February 2023).

1. Introduction

Stock assessments for Indian Ocean (IO) yellowfin tuna are conducted using an age structured population model implemented in Stock Synthesis (SS). The most recent assessment was conducted in 2021 (Fu et al 2021). The assessment model was spatially structured with four model regions: western and eastern tropical regions (Region 1 and Region 4, respectively) and southwestern and southeastern subtropical regions (Region 2 and Region 3, respectively). A substantial proportion of the total catch (approx. 70-80%) is taken in western equatorial region, dominated by the industrial purse-seine (PS) fishery (comprised of free school FS and floating object LS fisheries).

Distant-water tuna longline (LL) fisheries have operated in each region since the 1950s. Catch and effort data from those fisheries have been used to derive quarterly region-specific LL CPUE indices. Those indices repesent the primary sets of abundance indices included in the stock assessment model. The most recent assessment included quarterly CPUE indices for 1975-2020.

Length composition data are available from the main fisheries in each region, although the quality of the data varies between fisheries and the constituent fleets and over time (Hoyle et al 2021).

The IO Regional Tuna Tagging Programme (RTTP) tagged a large number of yellowfin tuna, predominantly juvenile fish, during the 2005-2007 release phase and continued to recover tags until about 2010. Almost most all tag releases were within the western equatorial region and most (>90%) recoveries occurred within the release area, typically after a relatively short period at liberty (Fu et al 2021). The tag release/recovery data are integrated in the stock assessment model and provide information regarding fishery selectivity, recruitment strength and exploitation rates for a limited time period (2006-2010).

The model estimates separate sets of recruitments for the two equatorial regions, at a quarterly interval (Fu et al 2021). The trends in the regional recruitments diverge from the mid 2000s, with the model estimating low recruitments in the eastern equatorial region (R4) in the subsequent period. Yellowfin recruitment to the sub-tropical regions via emigration from the adjacent equatorial regions. The model assumes movements rates are constant over time.

Estimates of recruitment are strongly informed by the magnitude of fishery catches (known without error) and the assumption that the LL CPUE indices provide a reliable, long-term index of relative abundance (within and between regions). The assessment models have considerable flexibility to accommodate trends in increasing catch and changes in productivity assumptions via the estimation of differential trends in recruitments (Gorka et al. 2022). This may indicate that the models are over-parameterised, given the information available to discriminate individual recruitment deviates. Length composition data may be relatively uninformative regarding cohort strength for a number of reasons: miss-specification of growth, including temporal or spatial variability in growth, sampling variability (sampling error) for individual fisheries, temporal variability in fishery selectivity (related to changes in fishery operation and/or fleet configuration), miss-specification of other key model assumptions (e.g. natural mortality and movement assumptions). The individual fisheries typically catch yellowfin tuna within a discrete life stage (juvenile, sub-adult or adult) and, hence, do not track individual cohorts over a sustained period. Accordingly, length composition data from all fisheries are routinely assigned a relatively low weighting in the model estimation procedure.

A review of the IO yellowfin tuna stock assessment was conducted in February 2023 (Maunder et al 2023). The review provided a range of recommendations for refinements to the 2021 stock assessment. An important recommendation was to evaluate the utility of the length composition data, particularly from key fisheries that have routine and comprehensive sampling programmes, most notably the equatorial purse-seine fisheries. Those data may provide additional information to support the evaluatation of trends in recruitment estimated by the assessment model, increasing the understanding of the divergence in the regional recruitment trends. Further, a detailed exploratory analysis of the key model inputs may support the development of alternative stock hypotheses for evaluation in the assessment process, via alternative parameterisation (e.g. regional) of the model spatial structure, recruitment processes, and movement dynamics. Following the formal review, IOTC funded additional work to progress these key recommendations in advance of the next IO yellowfin stock assessment scheduled for 2024.

2. 2021 assessment model

Model estimates of recruitment are informed by the trends in abundance indices, catch (by individual age class) and length/age compositional data. The assessment model integrates the main sources of data, weighted by the relative information content, within the model likelihood function. Ideally, the model input data will provide coherent trends in recruitment from the various data sets, assuming the structural assumptions of the model are correct (with an allowance for sampling error). The tag release/recovery data inform the model about the magnitude of individual year classes for a limited period only, rather than longer term trends in recruitment.

The 2021 IO yellowfin tuna stock assessment model estimated quarterly recruitments from 1972 to 2019 with temporal variation in recruitment to the two equatorial regions (R1 and R4) from 1977 to 2019 (Fu et al 2021). Recruitments to R2 and R3 were proportional to recruitment in R1 and R4, respectively, and mediated by constant age-specific movement between the adjacent equatorial regions. The model estimated that movement between R1 and R4 was negligible.

The main input data sets were examined relative to the respective trends in recruitment estimated from the assessment model.

2.1 LL CPUE indices

There is a relatively strong correlation between the LL CPUE indices from R1 and R4 and a moderate correlation between R4 and R3, while correlations are weaker between the other combinations of CPUE indices (Table 1).

Table 1: Correlations between the sets of longline CPUE indices included in the 2021 IO yellowfin tuna stock assessment.

Region A	Region B	Correlation coefficient	N. Obs	P value
1	2	0.38	177	4.08e-08
1	3	0.49	179	4.128e-12
1	4	0.71	179	< 2.2e-16
2	3	0.28	178	9.265e-05
2	4	0.29	178	6.425e-05
3	4	0.64	182	< 2.2e-16

Most of the correlation between the R1 and R4 LL CPUE indices was attributable to the long term (declining) trends in the two sets of indices. The indices are not correlated at the decadal scale (except for 2005-2015) indicating a lack of a strong reciprocal short-term trends in the two sets of indices (negative correlations) or persistent short-term trends among the two regions (positive correlations).

The positive correlation between the R4 and R3 LL CPUE indices persisted at the decadal scale, indicating the short-term conditions influencing the CPUE indices were comparable between the two regions.

The synchrony of short term (1-2 yr) trends in regional LL CPUE indices were evaluated by comparing the moving average (4 quarters) of the change in the quarterly CPUE indices ($CPUE_{r,t}/CPUE_{r,(t-1)}$) (Figure 1). Prior to the late 2000s, there was broad correspondence in the trends in the CPUE indices from R1 and R2. The trends deviated in the subsequent period corresponding to higher variability in the LL1 CPUE indices.

Prior to 2005, there was a general correspondence in the fluctuations in the LL CPUE periods of increasing and decreasing trends in CPUE between R2 and R3, with the fluctuations in the latter region being more pronounced (Figure 1).

Persistent patterns in the regional CPUE indices may indicate comparable recruitment signals between regions or, alternatively, broad scale fluctuations in longline catchability. Changes in catchability might be expected to be limited to an individual region or adjacent regions rather than at the oceanic scale. Further, regional changes in catchability might be expected to contrast the trends in catchability in other regions. There is no indication of a contradictory trends in the CPUE indices between regions, although there were several periods when large increases in CPUE in R4 coincided with a marked decline in LL1 CPUE indices (Figure 1).

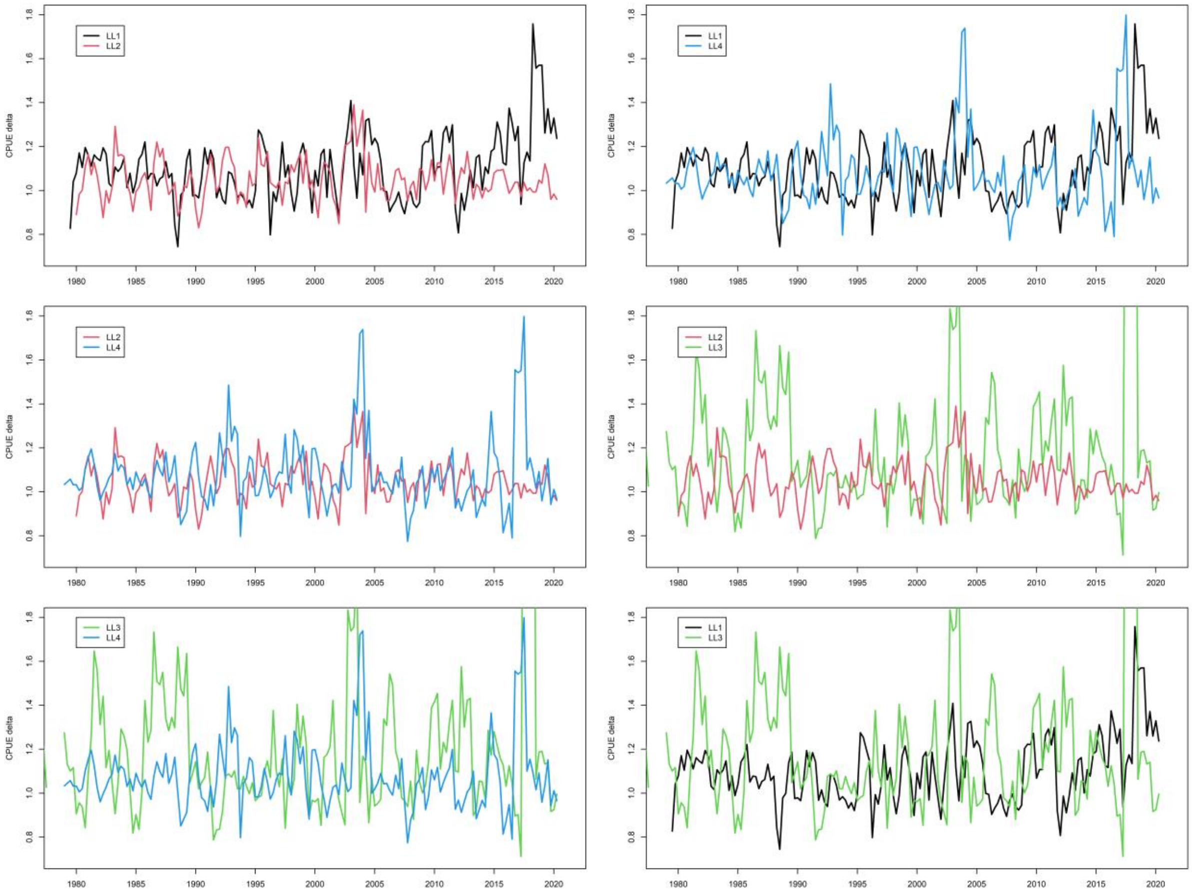

Figure 1: A comparison of the trends in the change in IO yellowfin tuna LL CPUE indices ($CPUE_{r,t}/CPUE_{r,(t-1)}$) from combinations of regions. The lines represent an annual lowess smoother.

Trends in the regional recruitment (number of age 1 fish) were compared to the corresponding regional LL CPUE indices, with the recruitment estimates lagged by 15 quarters to approximate age of 50% selectivity estimated for the longline fisheries.

The trends in recruitment are equivalent for R3 and R4 due, in part, to the structural assumptions of the model. There is a general decline in recruitments with markedly lower recruitment since the early 2000s. Catches from R3 were relatively minor and the trend in recruitment estimates closely followed the R3 LL CPUE indices (Figure 2 and Figure 3). For R4, the decline in the LL CPUE indices from the late 2000s was more pronounced than for R3. Both sets of CPUE indices (LL3 and LL4) have equal influence in the estimation of recruitment in the eastern IO regions (R3 and R4). The estimates of recruitment are also influenced by the magnitude of catch from the two regions. From the mid 1990s, there was a large increase in catch from the fresh longline (LF4) fishery in R4. During this period, recruitment was estimated to have been maintained at about average levels to sustain the higher catches, while LL3 and LL4 CPUE indices declined (Figure 2 and Figure 3).

Prior to 2005, the general shared trends in estimated recruitments for R1 and R2 are broadly consistent with the trends in the LL1 and LL2 CPUE indices (Figure 2 and Figure 3). The large decline in LL1 CPUE indices in the late 1980s coincided with the development of the purse-seine fishery and a large increase in total catches from R1. Catches were relatively minor from R2 and the LL2 CPUE indices remained relatively stable over time (Figure 2 and Figure 3). The significant increase of catches and CPUE amongst key fisheries 2003–2005 was believed to be associated with favourable oceanic conditions. Since 2005, there was a marked decline in R1 LL CPUE indices. This may be partly attributable to the large increase in the catch from the handline (HD) fishery since 2010, while catches from the PSFS fishery also increased. From 2005, the model estimated R1 and R2 recruitments at about the long-term average level (Figure 2 and Figure 3). The trend contrasted the decline in LL1 CPUE and is attributable to the higher recent catches in R1 and mediated by the relatively high LL CPUE in R2. The effect of removing the regional linkage between R1 and R2 was explored in the single region model (Section 4).

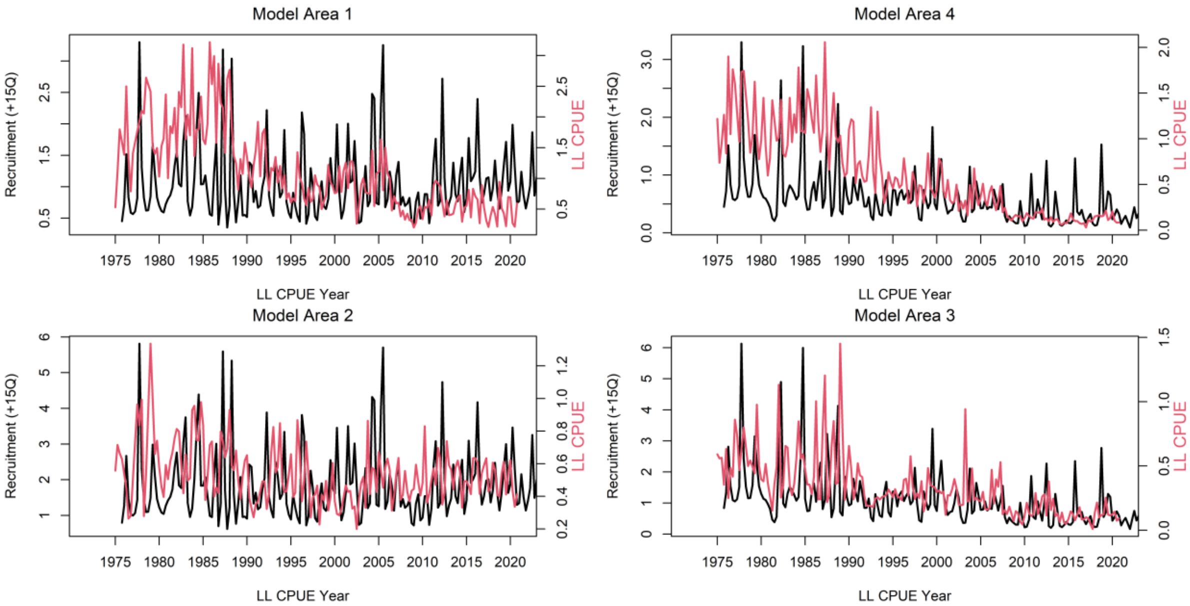

Figure 2: A comparison of regional LL CPUE indices and estimated recruitment (age 1 quarter fish). The estimates of recruitment are shifted 15 quarters to aligned with the approximate age of 50% selection of the longline fisheries.

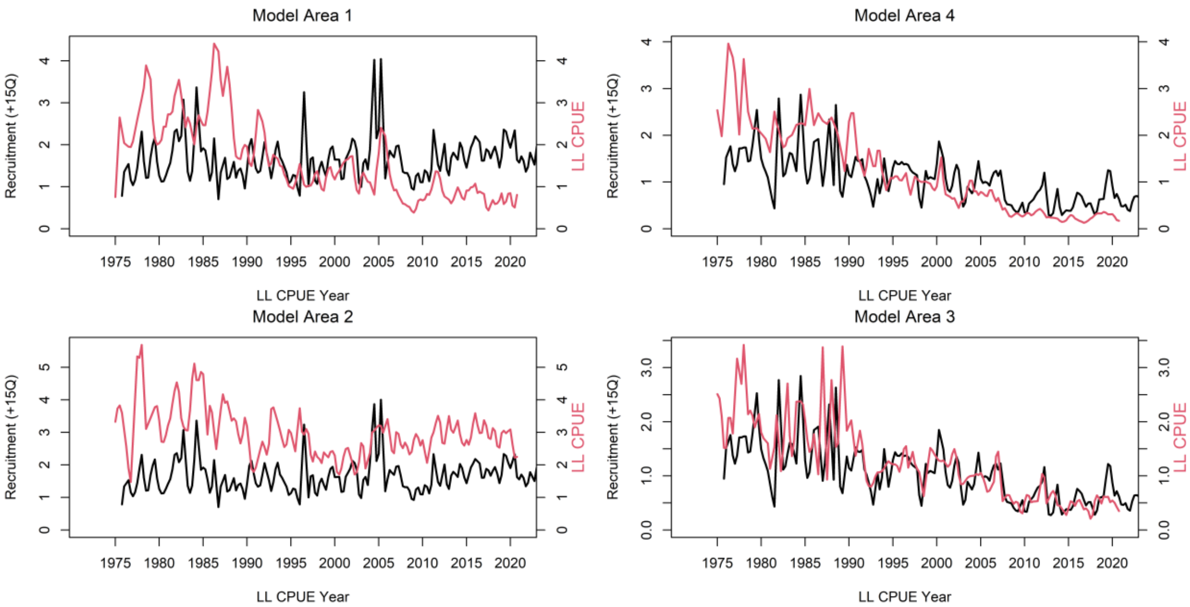

Figure 3: A comparison of the smoothed trends in regional LL CPUE indices and estimated recruitment (age 1 quarter fish). The estimates of recruitment are shifted 15 quarters to aligned with the approximate age of 50% selection of the longline fisheries. The smoothing was conducted using a lowess function (approximately annual).

The initial decline in R4 recruitment in the late 1980s and further decline from the early 2000s generally corresponded to significant increases in the catch from the R1 purse seine fishery (FS or LS) (Figure 4). In contrast, recruitment in R1 was higher in the early 2000s immediately prior to the period of larger catches from the PSFS fishery and increased from the late 2000s preceding the recent increase in the catch from the PSLS fishery.

The current assessment interprets these trends as spatially discrete populations in the western and eastern IO with diverging trends in recruitment to account for differential trends in LL CPUE between R1 and R4. An alternative explanation for these trends is assume a total recruitment is dominated by recruitment within R1 and subsequent dispersal of yellowfin from the western “hub” to the adjacent regions. The higher catches within R1, particularly of younger yellowfin tuna by the PSLS fishery, may directly effect the magnitude of “recruitment” to the adjacent regions, especially R4

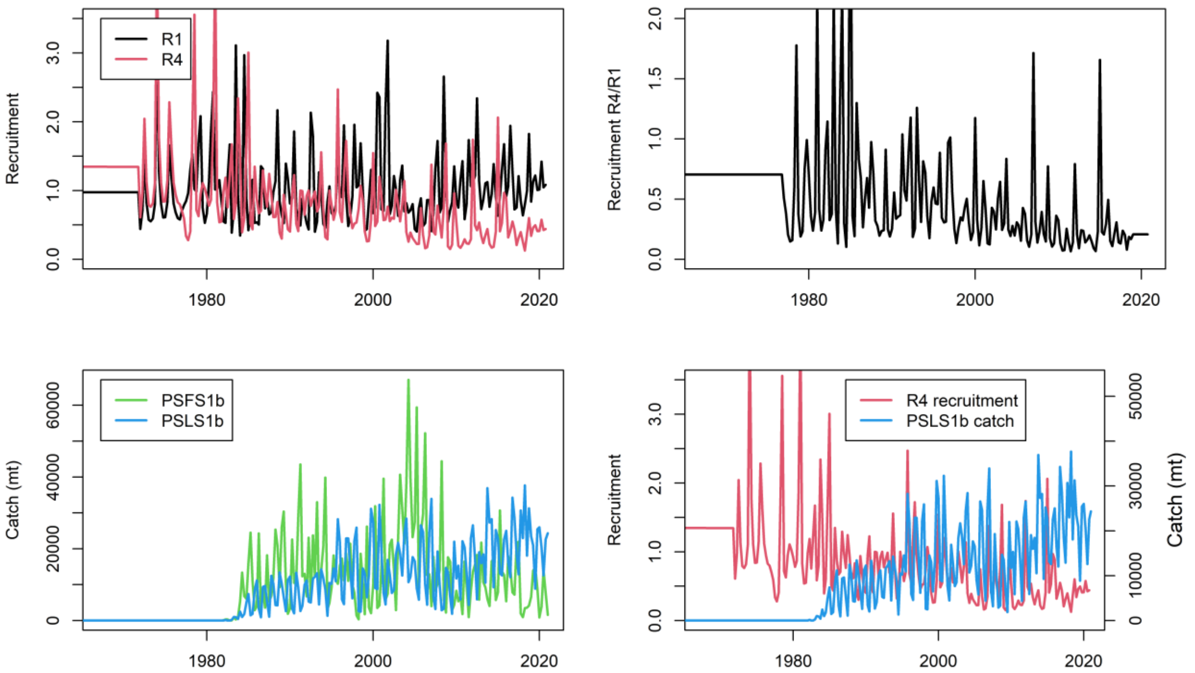

Figure 4: A comparison between estimated trends in recruitment for region 1 and region 4 from the 2021 base assessment model and a comparison with quarterly catches from the region 1 PSFS and PSLS fisheries.

3. Length composition data

A qualitative analysis of the length composition data from the main R1 fishery data sets was conducted. A large number (152) of quarterly length compositions were available from the PSFS fishery. However, only a limited number of periods were identified that revealed modal progression in the successive length compositions from the fishery. A strong length mode was present at 82-90 cm LF in model year 228 (2003 Q3) (Figure 5). The cohort was absent in the following interval (229) but was evident at about 105 cm in 230 and merged with the adult mode in 231.

Those trends were compared with the length composition data from the other fisheries within Region 1 (Figure 5). The strong mode in the PSFS fishery was preceded by a strong mode in the PSLS fishery in 225 (2003 Q1). However, the progression of the cohort into the PSFS fishery is not consistent with the growth parameters used in the 2021 stock assessment. Alternatively, the cohort may have been present in the broader length range of larger fish sampled from the baitboat fishery in periods 225 and 226 (Figure 5). Limited length composition data were available from the equatorial LL (LL1b) fishery for the corresponding years.

The strongest modal structure is evident in the length composition data from the Arabian Sea GN fishery. For example, the small (~55 cm) length mode in the 226 sample was observed in successive samples, with the mode of the cohort progressing at a rate consistent with the 2021 assessment growth parameters (Figure 5). However, this cohort was not observed in the PSFS (or LL1b) fishery over the period or over subsequent model years.

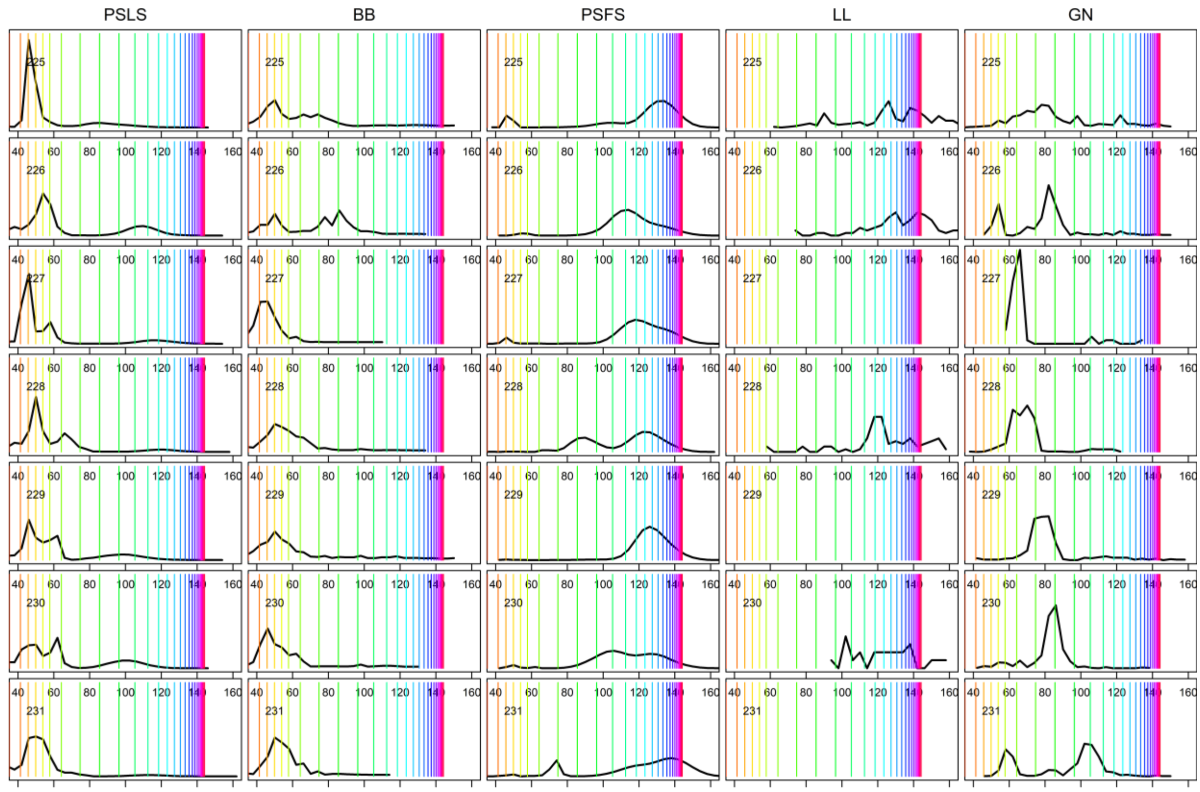

Figure 5: A comparison of quarterly length compositions from R1 fisheries for a period selected to illustrate modal progression in the length composition data sets. The vertical lines represent the average length-at-age from the growth parameters included in the 2021 base stock assessment.

Overall, the individual fisheries tend to catch yellowfin within a relatively restricted length range. There are few fisheries that catch an individual cohort over a sustained period (6-8 quarters) to enable the estimation of the strength of a cohort relative to adjacent cohorts. Further, there appears to be considerable variability in the length structure between successive sampling periods, due to either sampling error and/or variability in the selectivity of the fishery (seasonally, temporally). This is particularly evident in the PSFS fishery, despite the relatively comprehensive sampling regime for the purse-seine fleet.

The GN fishery appears to be exploiting intermediate length/age classes, although the relative strengths of the sampled cohorts do not appear to be consistent with the modal structure of the PSFS length composition.

3.1 Purse seine fishery length composition

The length composition data from the PSFS fishery were analysed to investigate potential sources of variation in length of the adult mode (fish greater than 90 cm). The data were sourced from the IOTC website (data set IOTC-DATASETS-2022-12-19-SF-YFT-1952-2021.xlsx), aggregated by fleet, PS set type, year-month and 5 degree latitude/longitude cell. For each stratum, the average length of yellowfin tuna was determined. A simple GLM explained 39 % of the variation in the average fish length with the categoric explanatory variables *Year, Month, Fleet* and the spatial *grid* (Lat, Long cell) (Table 2).

Table 2: ANOVA in the average length of yellowfin tuna (>90 cm) sampled from the R1 PSFS fishery.

	Df	Deviance	Resid. Df	Resid. Dev
Null			7237	534708
Year	39	121212	7198	413496
Month	11	47390	7187	366106
Fleet	6	497	7181	365609
Grid	41	39130	7140	326479

The model estimates a strong overall spatial effect with smaller yellowfin caught in the southwestern and northwestern areas of Region 1, while largest fish were caught in the eastern portion of the region (Figure 6). There is a relatively small seasonal effect with smaller yellowfin caught during Q2 and Q3. Since 2012, there was a general increase in the size of the yellowfin caught from PSFS sets (Figure 6). There was no appreciable shift in the spatial distribution of the sampled catch during that period.

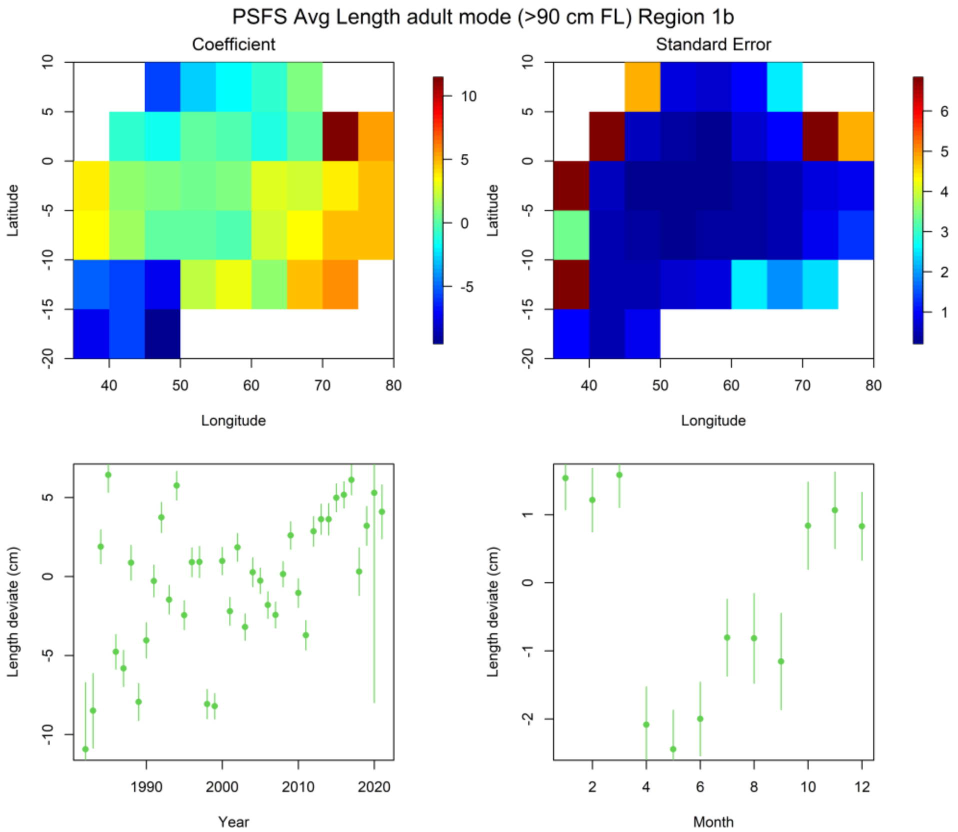

Figure 6: Predicted deviation in average length of yellowfin tuna from the PSFS fishery relative to the main explanatory variables.

A similar analysis was conducted for the PSLS fishery using the average length of fish in the juvenile mode (< 70 cm) as the predictor variable (Table 3). There is a significant seasonal variation in the length of fish caught with largest fish caught during April-June and a decline in fish size during July-October (Figure 7). There is a strong spatial effect with fish size increasing southward; smallest fish were caught north of the equator off the Somali coast and largest fish were caught in the Mozambique Channel. The seasonal trend in fish size may be linked to the spatial distribution of the sampling data with a higher proportion of samples collected from the southern area of the fishery during April-June (Figure 8).

Since 1990, there has been a general decline in the average length of fish caught by the PSLS fishery (Figure 7). The decline in fish size has corresponded to the general increase in the catch from the annual catches from the PSLS fishery over the same period. However, it is unclear as to whether the decline in fish size is attributable to an increased level of fishing mortality or other processes, such as a shift in the selectivity of the fishery due to changes in the operation of the fishery (increased use of FADs, changes in the spatial distribution of the fishery, etc). There was a reduction in the proportion of the catch taken from the Mozambique Channel since the late 1990s.

Table 3: ANOVA in the average length of yellowfin tuna (<70 cm) sampled from the R1 PSLS fishery.

	Df	Deviance	Resid. Df	Resid. Dev
Null			14672	160883
Year	39	34644	14633	126239
Month	11	11820	14622	114419
Fleet	7	56	14615	114363
Grid	41	9544	14574	104819

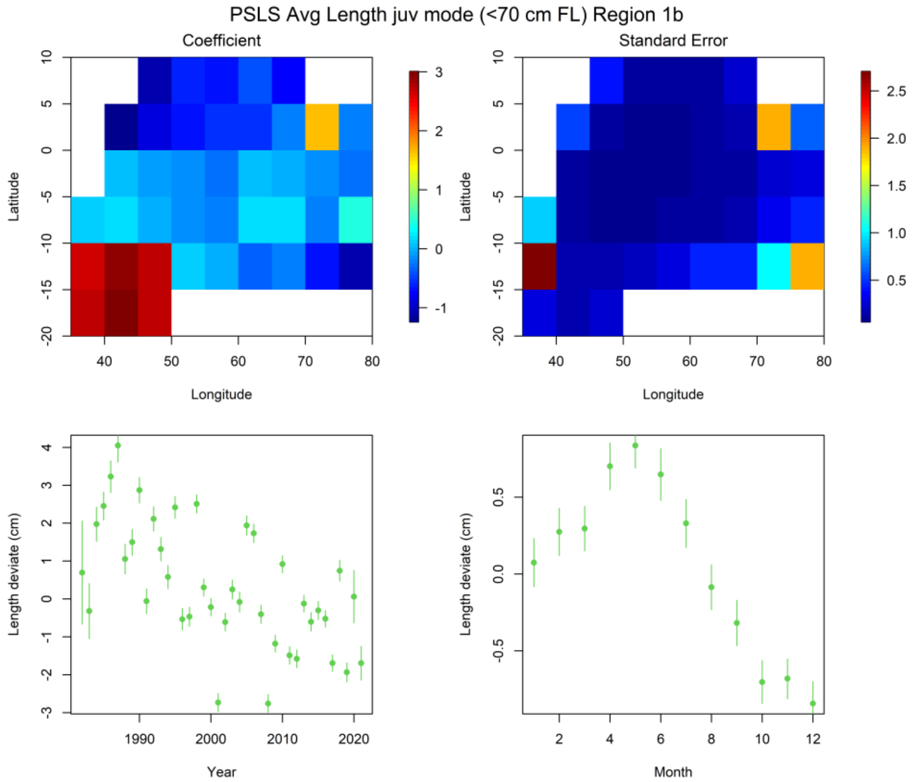

Figure 7: Predicted deviation in average length of yellowfin tuna from the PSLS fishery relative to the main explanatory variables.

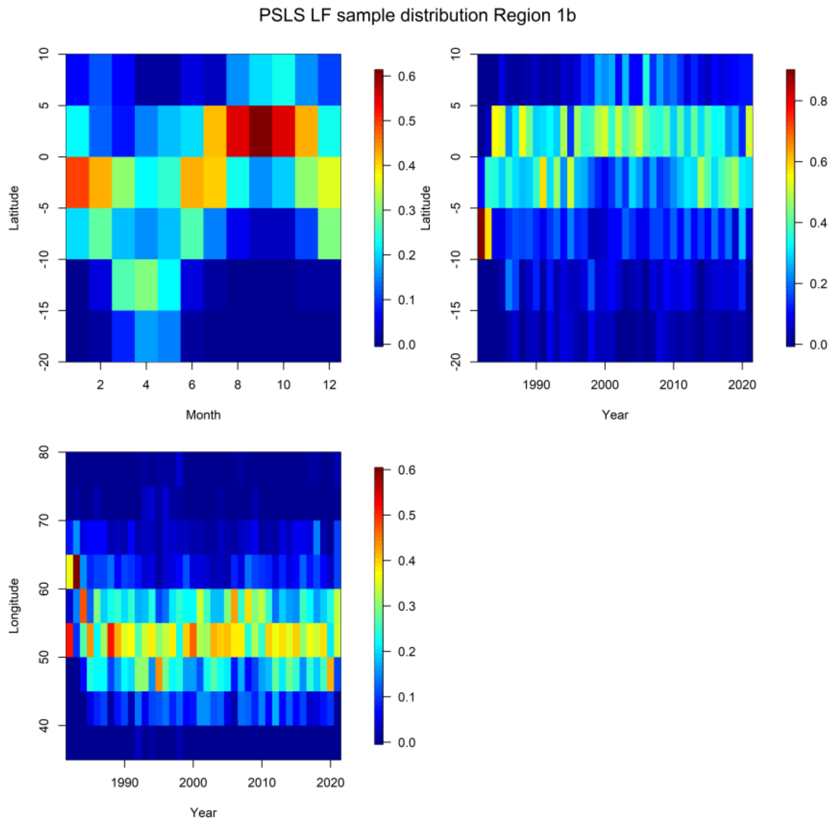

Figure 8: **Proportional distribution of yellowfin tuna sampled from the R1 PSLS fishery. Vertical cells (month or year) sum to 1.0.**

Overall, the yellowfin catch from the purse seine free school fishery in the Mozambique Channel was dominated by small fish, similar to the size of fish taken by the PS floating object fishery (PSLS) (Figure 9). Correspondingly, large yellowfin represented a relatively small proportion of the PSFS catch from the Mozambique Channel compared to the remainder of the western equatorial area. Nonetheless, the Mozambique Channel accounts for a small proportion (~ 1-3%) of the total equatorial PSFS catch.

The PSLS fishery in the Mozambique Channel has tended to catch slightly larger yellowfin compared to the remainder of the western equatorial region (Figure 9).

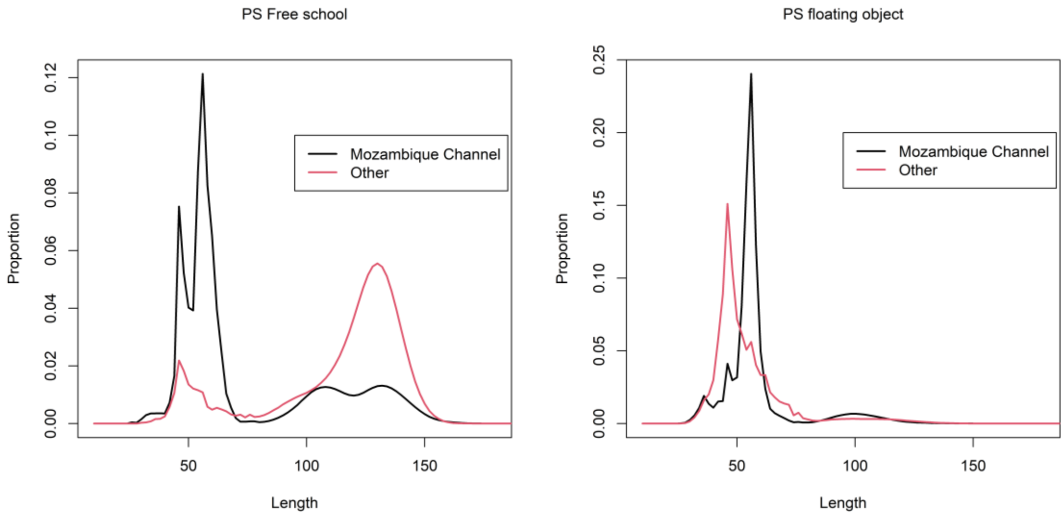

Figure 9: A comparison of the length composition of yellowfin tuna caught by the purse seine free school (left) and floating object (right) fisheries from the Mozambique Channel and the remainder of the western equatorial fishery (Other). The length composition data are aggregated from all samples collected from 2000 onwards.

The time series of aggregated quarterly length compositions from the PSLS fishery (from the 2021 base assessment model) (Figure 10) were compared to the time series of R1 recruitment estimates from the 2021 base assessment. Initially, the proportions at length (4 cm intervals) were assigned to individual cohorts based on the average length at age (assuming 2021 growth) and the sample period (year/quarter).

For the cohorts at ages 3-10 q, there was a weak positive correlation between the proportion at length and the model estimates of recruitment with the highest correlation (0.524) for the proportion at length corresponding to fish aged 7 q (Figure 11). Recruitments were typically higher from spawning during Q3 and Q4, with low recruitment from spawning in Q1.

The proportions at length are not considered to provide reliable estimates of recruitment strength, primarily because the proportion in the relevant length class will be influenced by the strength of the adjacent cohorts. There is also potential that the overall selectivity of the fishery has shifted over time (to slightly smaller fish) influencing the proportion in each length interval. However, there is considerable variation in the proportion of fish corresponding to the 7 q age class (58 cm length bin) both seasonally and over time. This length interval is within the upper range of the main length mode sampled from the PSLS fishery (Figure 11). This length interval appears to provide the model with some information regarding the relative strength of recruitments and/or is consistent with other recruitment signals from the other model data sets. This suggests that stronger cohorts may remain vulnerable in the PSLS for a longer period than weaker cohorts.

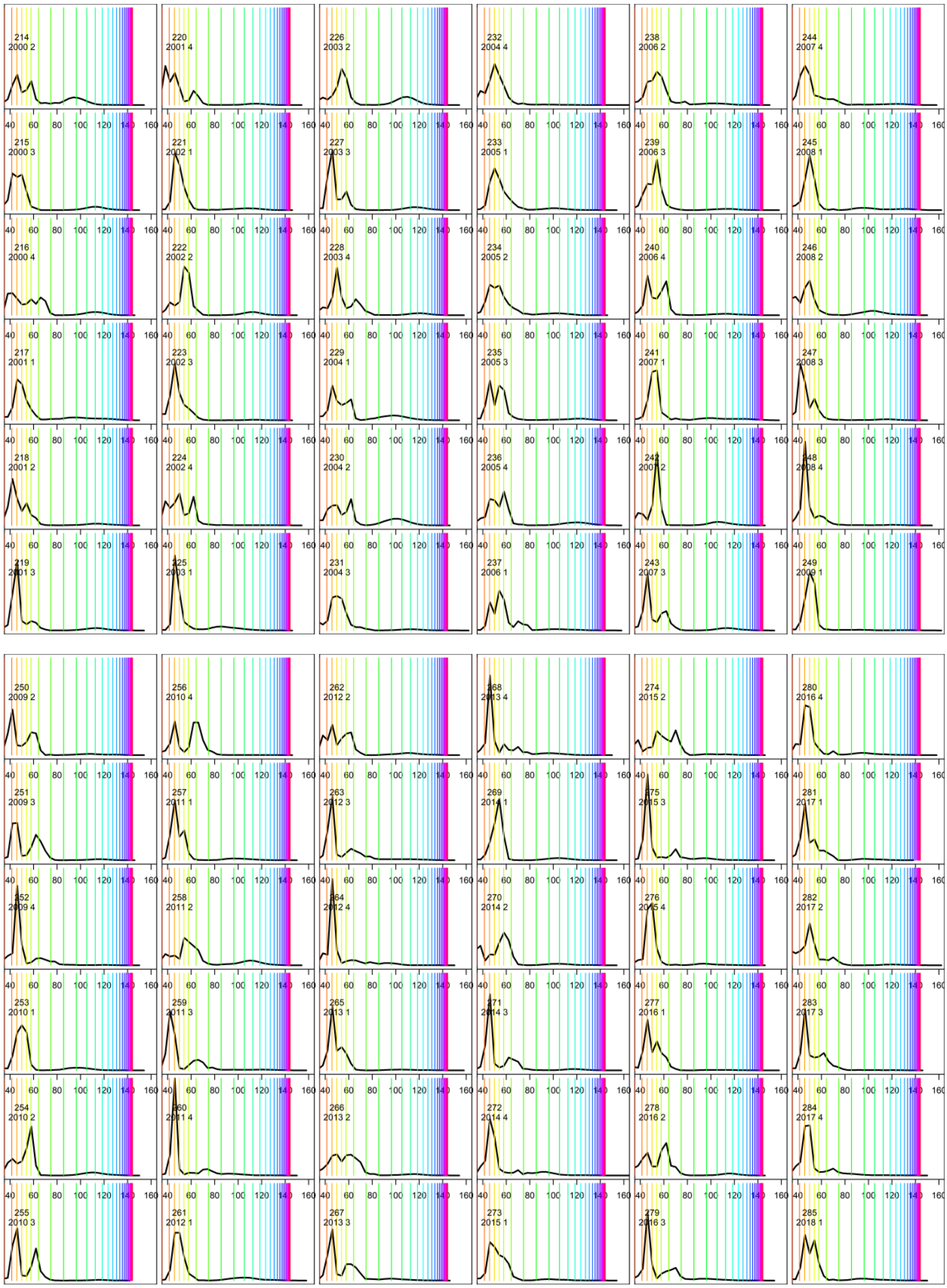

Figure 10: A subset of the sequence of length compositions from the R1 PSLS fishery. The vertical lines represent the average length-at-age from the growth parameters included in the 2021 base stock assessment.

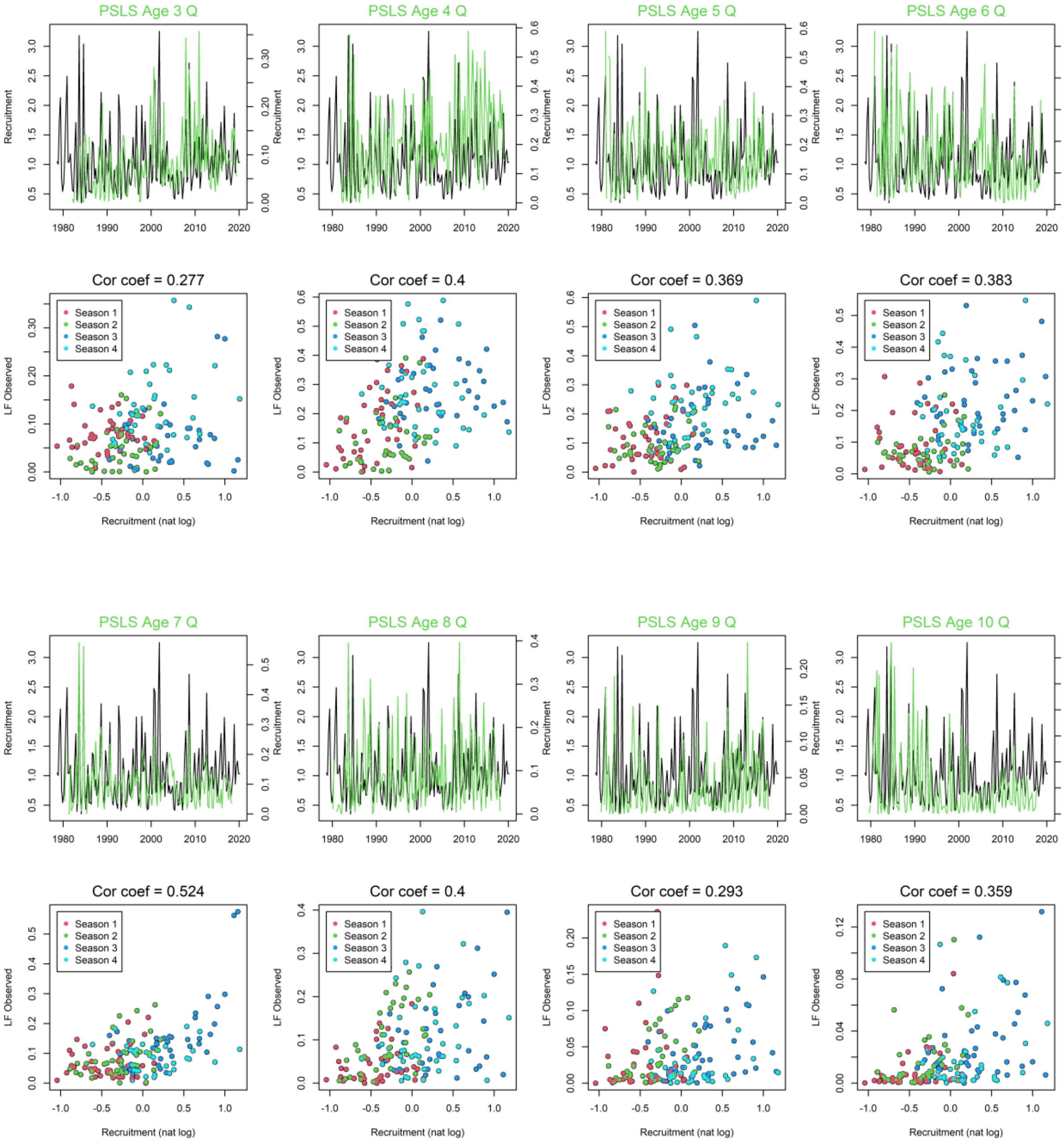

Figure 11: **A comparison between the proportions at length corresponding to individual cohorts, by age class, from the PSLS length compositions and R1 recruitment estimates from the 2021 base assessment model (both series are normalised to have a mean of 1).**

3.2 Longline length composition

Comparison of the length compositions between the four longline fisheries and with the PSFS fishery. These comparisons are probably not very informative, particularly between the longline fisheries, due to changes the collection of length composition data over time (between fleets and sampling programmes) and concerns regarding the reliability of the sampling data (Hoyle et al 2021).

There are no persistent patterns evident between the LL length compositions from the four regions (Figure 12). In some years, there are strong similarities in the length composition between individual areas while in other years there are marked differences between the same sets of regions and marked differences between successive years from the same region.

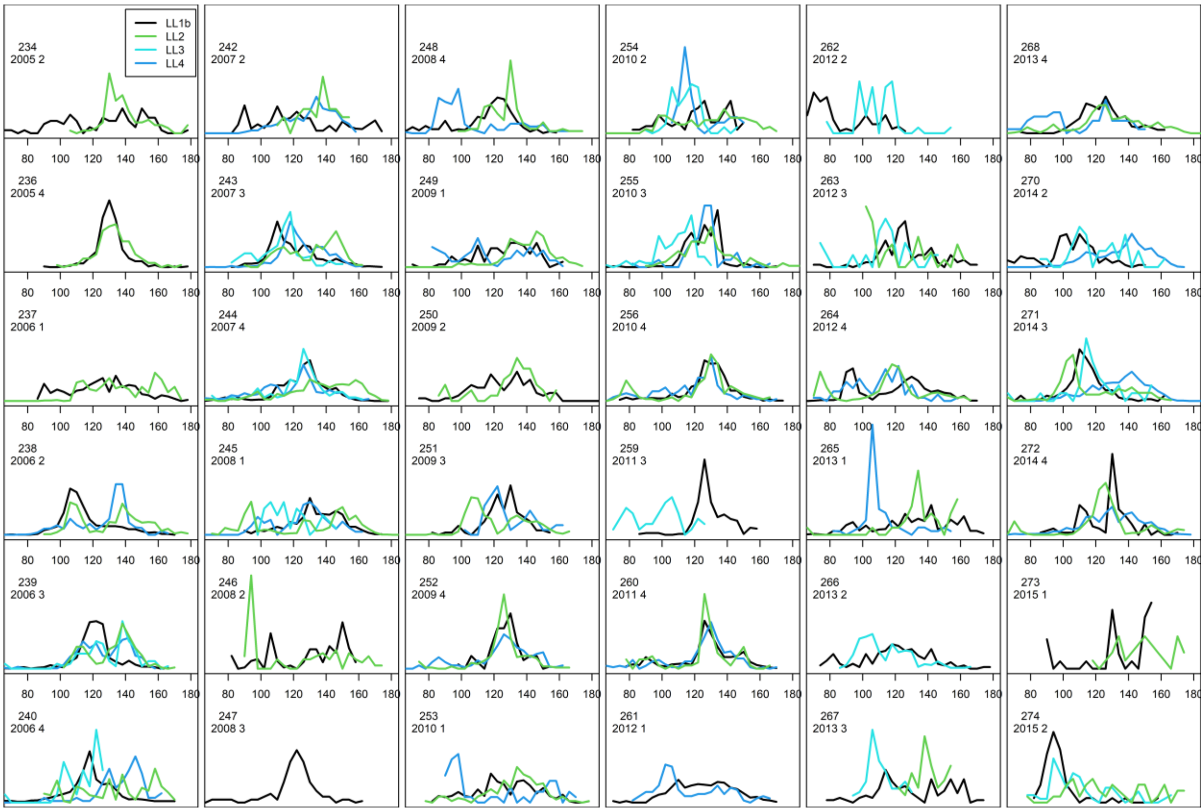

Figure 12: A comparison of a series of quarterly length compositions from the four regional longline fisheries included in the 2021 base stock assessment.

The overall length composition of the yellowfin catch from the PSFS fishery in regions 1 and 2 is comparable in most years (Figure 13). The length compositions are also similar in structure the length compositions from the LL1 and/or LL2 fisheries in many of the years.

These observations suggest a high degree of sampling error between year/quarter samples from a particular fishery. However, the results also indicate some comparability of samples between regions and fisheries with similar modal structure in the length composition suggesting similar recruitment patterns between regions. This may indicate a single, dominant recruitment process in the Indian Ocean.

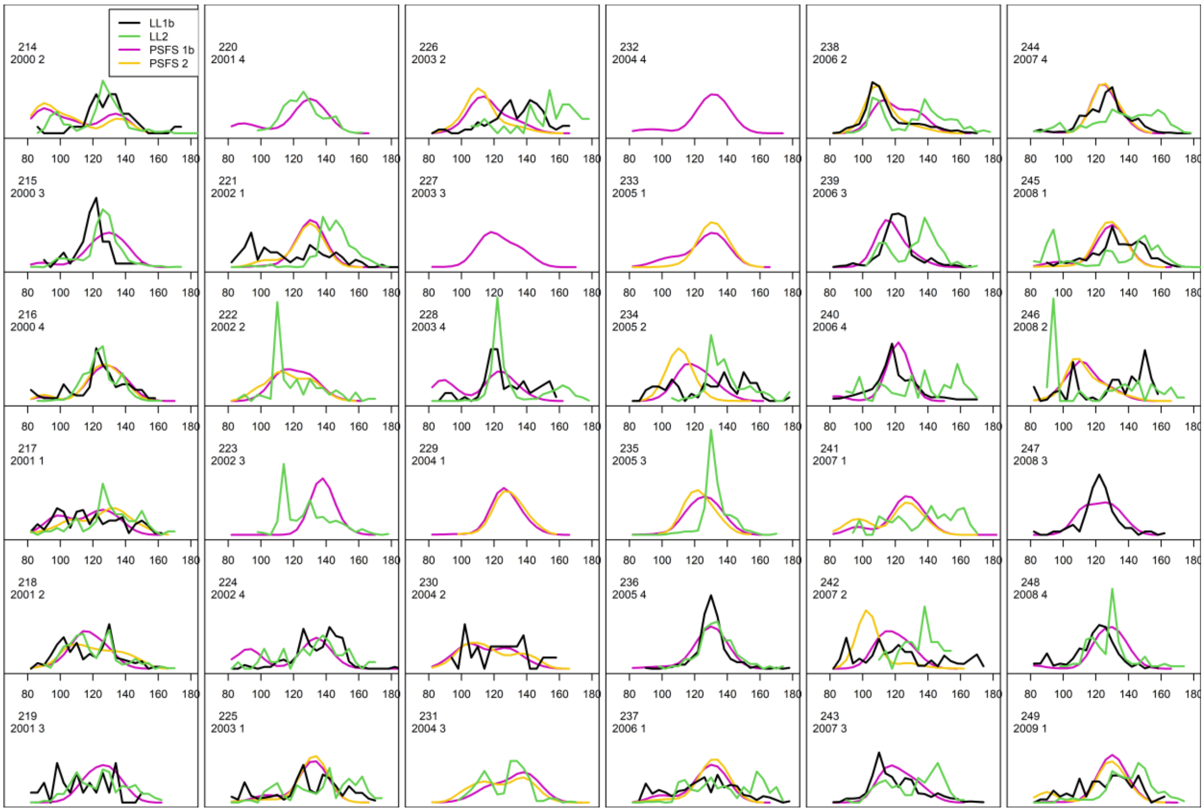

Figure 13: **A comparison of a series of quarterly length compositions from the LL1b and LL2 longline fisheries and corresponding PSFS fisheries, included in the 2021 base stock assessment.**

4. Length mode analysis

The main length composition data sets from three key fisheries within Region 1 (GN, LL and PSFS) were examined to identify individual length modes from the time series of data. The purpose of the analysis was to identify persistent strong length modes across multiple fisheries catching different size groups of yellowfin tuna.

For each length composition, individual length modes were identified and attributed to an individual cohort based on the year/quarter of the sample, the median length of the mode and assuming the growth model used in the 2021 stock assessment. Strong, persistent length modes were most evident in the length compositions from the GN fishery (Figure 14).

Individual cohorts were followed over time amongst the four main fisheries. Under the presumption that a strong cohort progresses through multiple fisheries, it would be expected that the cohort could be tracked over successive time periods (quarters), increasing in length following established growth parameters (Figure 15). There are some cohorts that were sampled from the same fishery over successive years, particularly from the PSFS fishery. However, there are very few occurrences of strong modes of smaller, younger fish (< 70 cm, age 4-8 quarters) persisting through intermediate length intervals (70-100 cm, age 9-11 quarters) and be observed at larger sizes (> 100 cm) (Figure 15).

There is some suggestion that individual cohorts (year classes) that were observed more frequently in the length composition data were associated with estimates of stronger year classes from the 2021 base assessment model, while cohorts with fewer observations were more likely to be associated with weak year classes (Figure 16). However, the overall correspondence between the model estimates of recruitment and the length modal frequency is poor and deviates over a number of time periods.

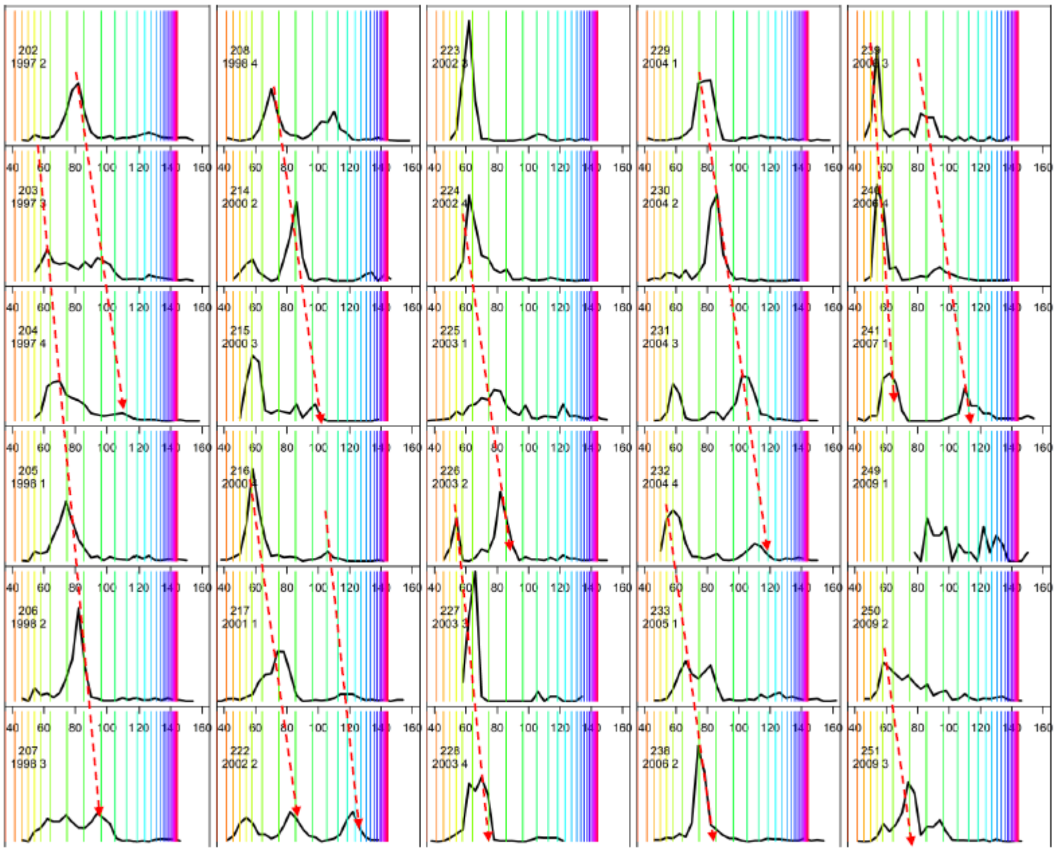

Figure 14: **An example of the time-series of quarterly length compositions from the gillnet fishery. The vertical lines represent the average length-at-age from the growth parameters included in the 2021 base stock assessment. The red arrows represent the tracking of an individual cohort over successive quarters.**

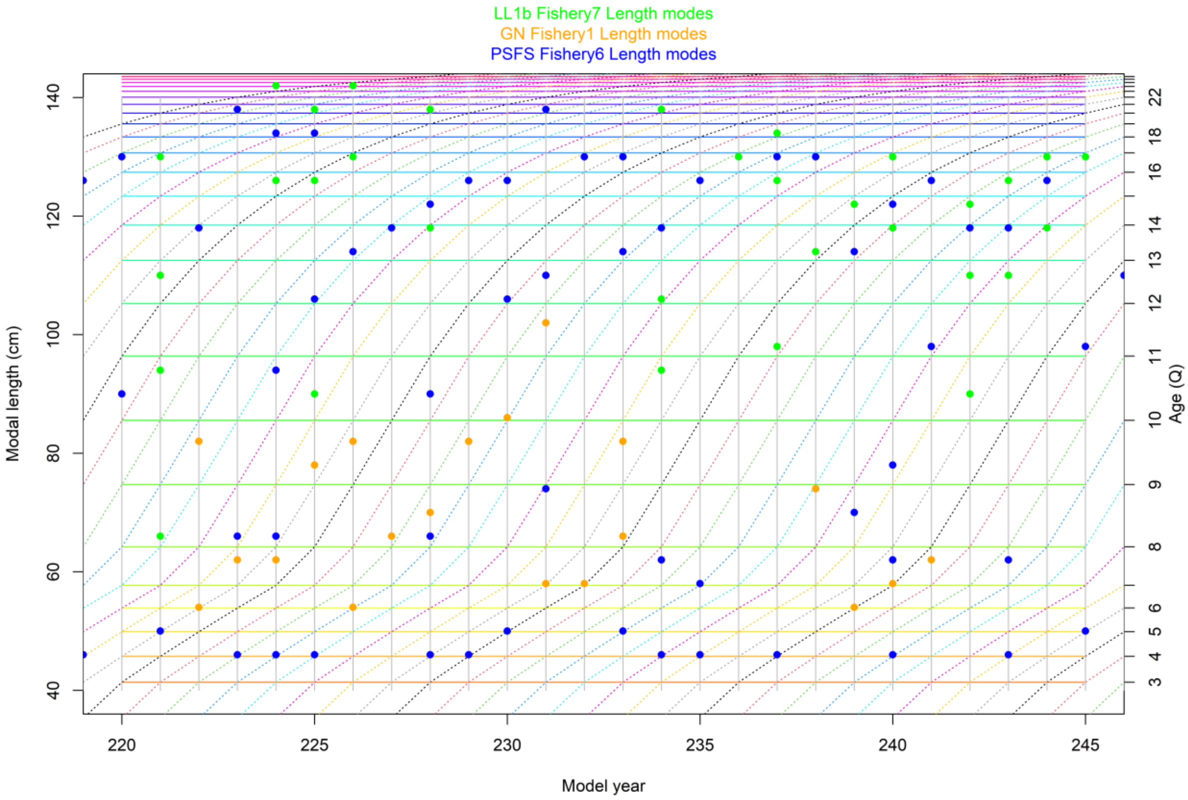

Figure 15: The modal lengths of individual strong cohorts (points) sampled from three Region 1 fisheries (colours) by quarter (model year) for a limited time period. The dashed coloured lines represent the expected growth of an individual cohort (based on 2021 model growth parameters). The horizontal lines represent the average length at age.

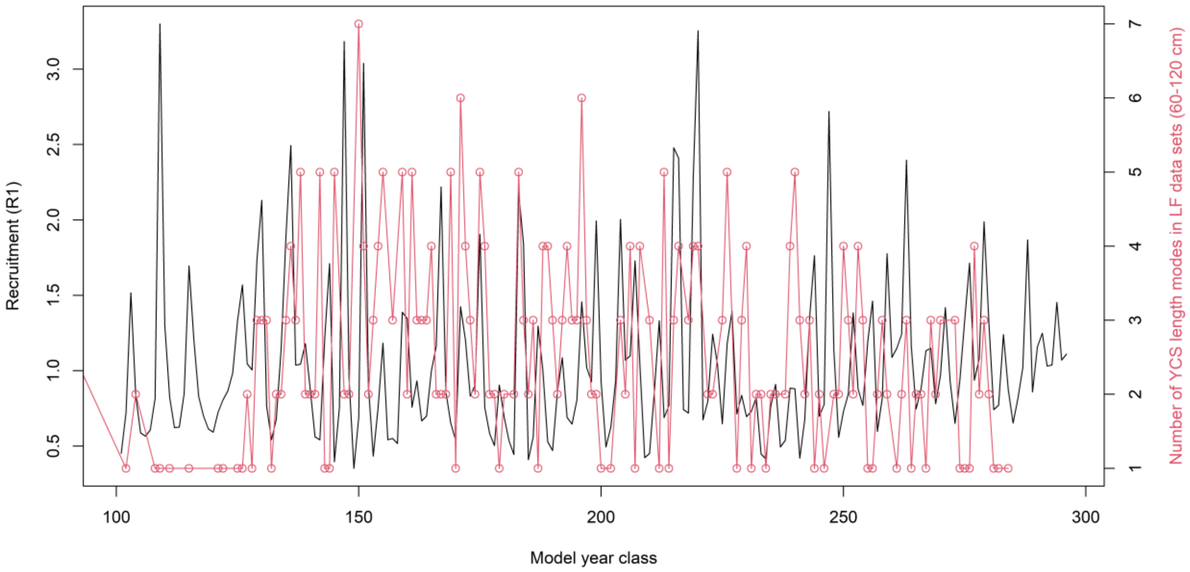

Figure 16: A comparison of the frequency of observations of an individual cohort (year class) from Region 1 GN, LL and PSFS fishery length compositions and estimates of quarterly recruitments from the 2021 base assessment model.

5. Single region model

A large proportion of the total yellowfin catch from the IO is taken within the western region (R1). This region also includes the fisheries with the most comprehensive sets of length frequency data. To evaluate the influence of those data in the estimation of recruitment, a single region model was configured based on data from R1 only. The model was configured for exploratory purposes only. It is not intended to provide an estimate of stock status for the region.

The tag release/recovery data were excluded from the single region model. This was primarily to remove the influence of the tagging data on the estimation of the fishery selectivities and exploitation rates during the limited recovery period.

The single region model used the R1 fishery length composition data from the base assessment model. However, there were a number of refinements to the individual fishery length data sets, specifically 1) the variable mode of small fish (less than 75 cm) sampled from the PSFS fishery was excluded from the fishery length compositions and 2) length composition data from the gill net fishery (GI) post 2010 from were excluded as there was a significant change in the length structure of the sampled catch at that time.

The single region model retained the biological parameters used in the 2021 stock assessment (including growth). Recruitment deviates were estimated for each quarter from 1972 to 2019.

The main length frequency data sets (GN, LL1b, PSFS, PSLS) were assigned an Effective Sample Size (ESS) of 20 for all observations. The remainder of the length frequency observations were assigned an ESS of 5.

A comparison of recruitment from the single region model and the R1 recruitment from the 2021 four region assessment model reveals that the recruitment from the single region model is lower from the late 1990s (year/qtr 200) (Figure 17). This is attributable to the influence of the LL2 CPUE indices in the four region model which do not reflect the decline in LL1 CPUE from about 2005.

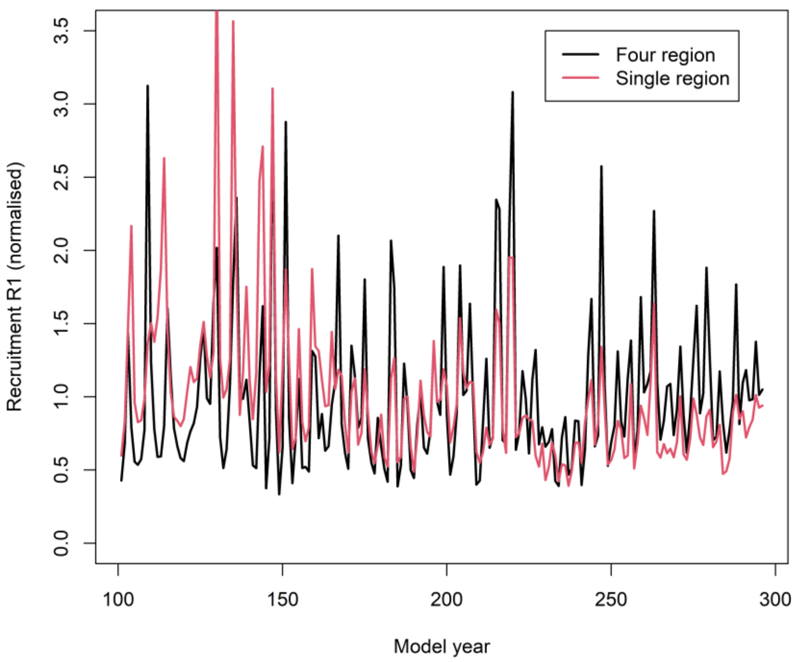

Figure 17: A comparison of quarterly recruitments estimated for Region 1 from the 2021 base stock assessment (four region) and from the single region model.

5.1 Growth

Recruitment estimates will be influenced by the assumed growth parameters. Four growth options were considered for the single region model: a) the growth parameters included in the 2021 assessment (incorporating deviations in the *k* parameter for age classes 2-12), b) re-estimation of the *k* parameters based on the 2021 growth, c) the parameters from the recent growth study (Farley et al 2021) and d) re-estimation of the *k* parameters based on the parameters (L1 and Linfinity fixed) from the recent growth study. For all four model options, natural mortality was assumed equivalent to the 2021 stock assessment.

The main differences in growth were for the juvenile age classes (Figure 18). The model estimates of growth were sensitive to the initial starting values (L1 and Linfinity fixed). Using the starting values from Farley et al (2021) resulted in faster growth at younger ages while still estimating the similar deviation from Von Bertalanffy growth (via estimating deviations in the *k* parameter) evident in the 2021 assessment growth model (Figure 18). Effectively, the growth curve was shifted by approximately 2-3 quarters. Farley et al (2021) provided a number of potential explanations for the retardation of growth rates informed by length composition data; the slower growth rates may be attributable to the length specific selectivity of the PSLS fishery introducing a bias in the estimation of growth rates of younger yellowfin.

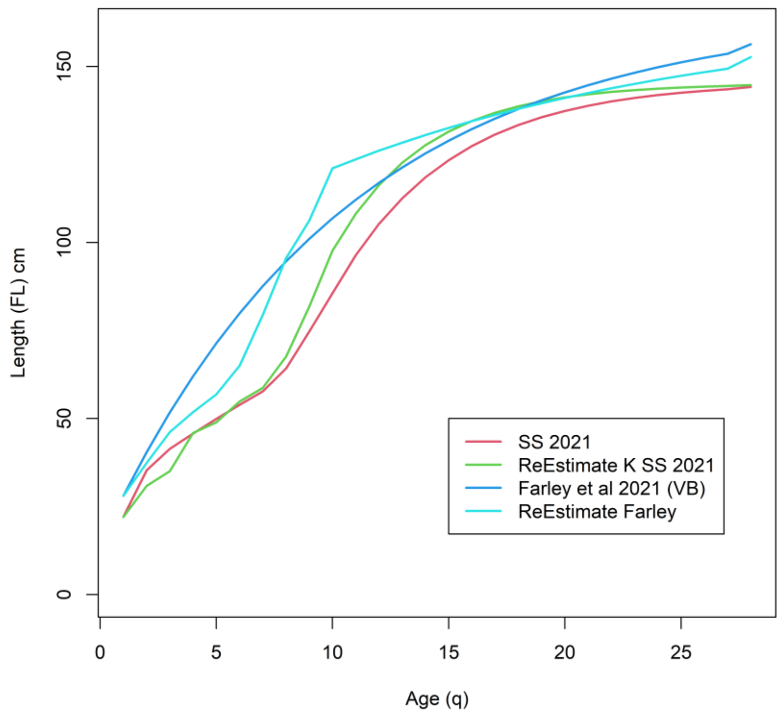

Figure 18: A comparison of alternative growth models for IO yellowfin tuna.

The new growth parameters (Farley et al 2021) resulted in a substantial deterioration in the fit to the length compositions from the baitboat (BB) and purse-seine free school (PSFS) and floating object (PSLS) fisheries (Figure 19). There was also an appreciable deterioration in the fit to the LL1 CPUE indices with the new growth parameters (likelihood value -6.7 compared to -21.5).

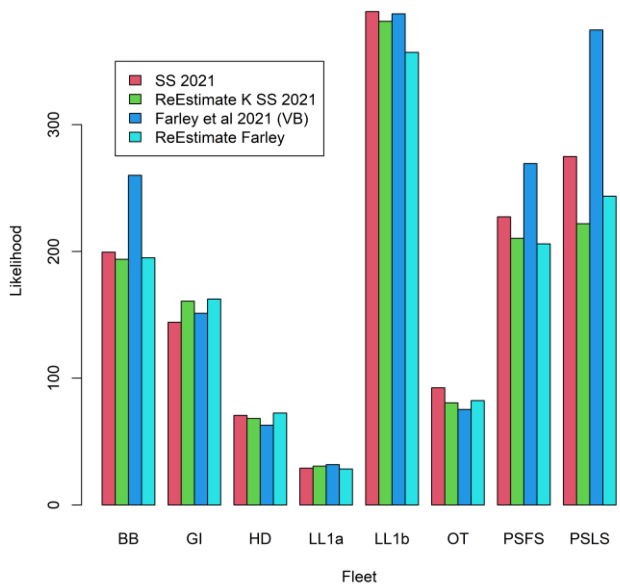

Figure 19: A comparison of the fishery specific length composition likelihoods with four different growth assumptions for the single region model.

The deterioration in the fit to the BB and PSLS length composition data was primarily attributed to the deterioration in the fit to the dominant 46 cm length class (46-50 cm length interval), while the deterioration in fit to the PSFS length composition was associated with the 126, 130, 134 length classes (Figure 20). For length classes larger than about 150 cm there was an improvement in fit associated with the new growth parameters.

However, the re-estimation of the growth informed by the *L1* and *Linfinity* parameters from Farley et al (2021) resulted in an overall improvement in the model fit relative to the base model (SS 2021). The improvement in fit was attributable to the LL, PSFS and PSLS length composition data and an improvement in the fit to the LL1 CPUE indices (likelihood value -25.9 compared to -35.2). The two model options yielded very similar trends in quarterly recruitments, although the recruitments were offset by 2 or 3 quarters, reflecting the difference in the initial growth rates for the two models (Figure 21).

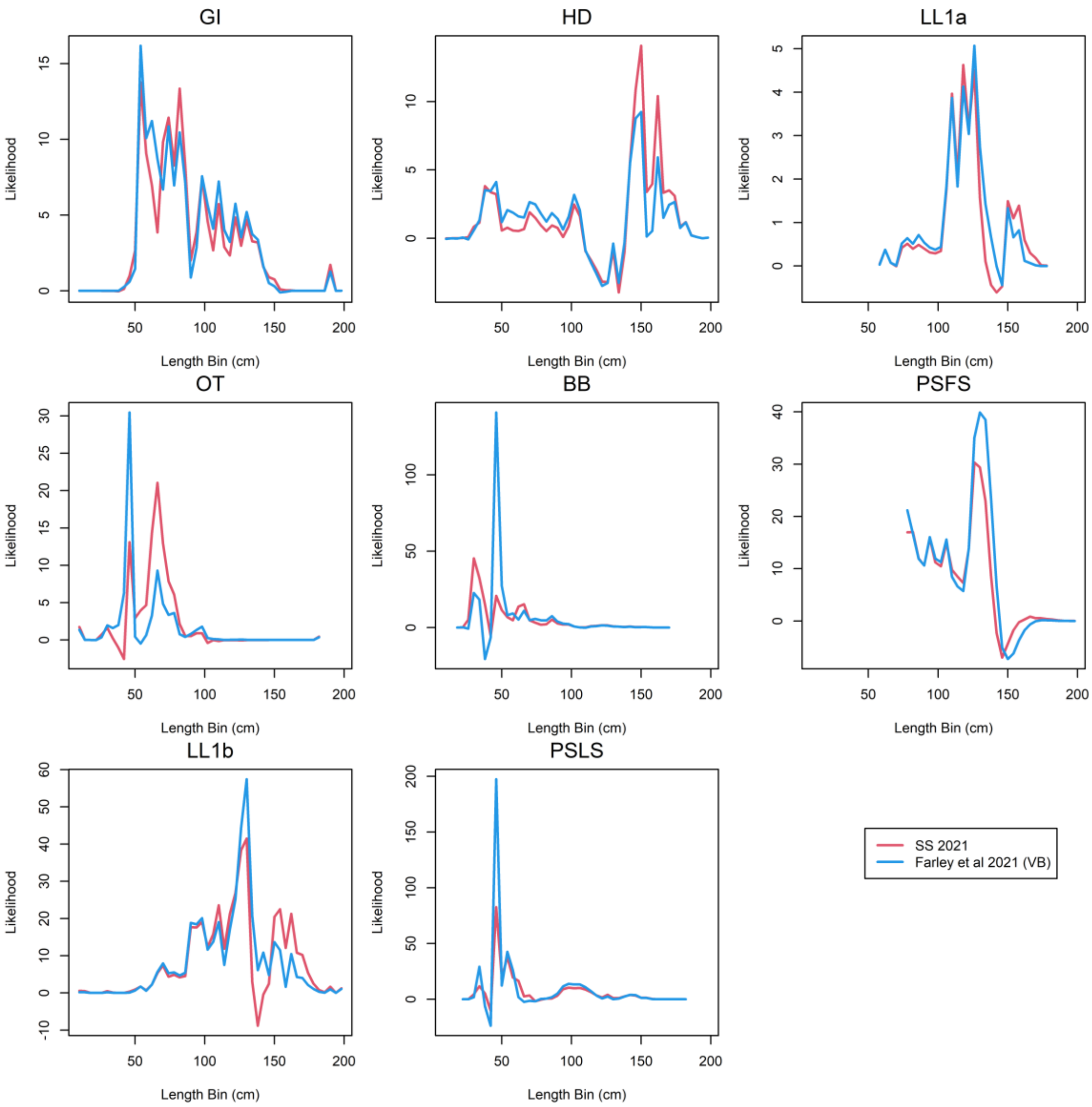

Figure 20: A comparison of the fishery length composition likelihoods by length class (4 cm interval) with alternative growth assumptions for the single region model.

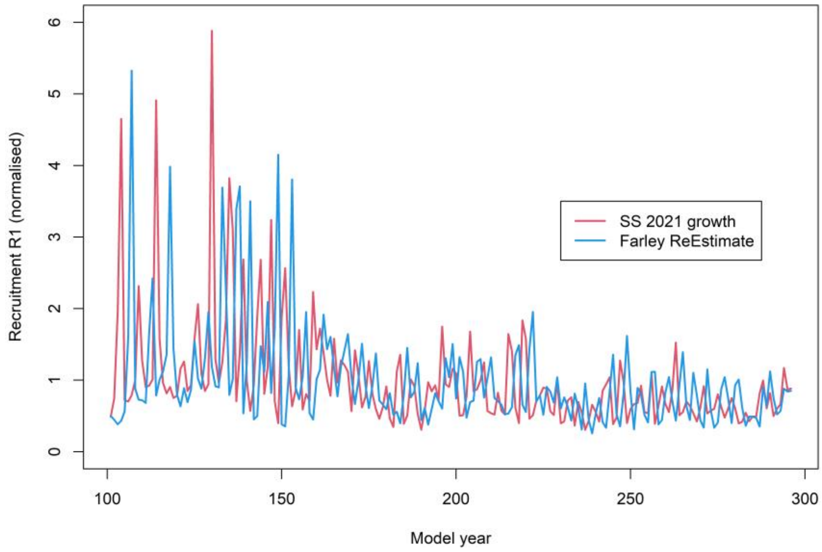

Figure 21: A comparison of recruitments for the single region model with alternative growth assumptions.

5.2 Recruitment estimation

The single region model (with 2021 SS growth) was applied to compare estimates of recruitment informed by differentially weighting individual data sets, particularly the length composition data from individual fisheries (Table 4).

Table 4: Effective Sample Sizes (ESS) for each set of fishery length compositions for the range of single region model options.

Model option	Fishery				
	GN	LL1b	PSFS	PSLS	Others
Base	20	20	20	20	5
GN_length	200	5	5	5	5
LL_length	5	200	5	5	5
PSFS_length	5	5	200	5	5
PSLS_length	5	5	5	200	5
DWT_length	5	5	5	5	5

For all model options, the fits to the LL CPUE indices deteriorated from the mid 2000s (Figure 22). However, the model fit to the CPUE indices deteriorates considerably when the length composition data from the PSFS fishery were upweighted. There is also a minor deterioration in the fit when the longline length composition data were upweighted.

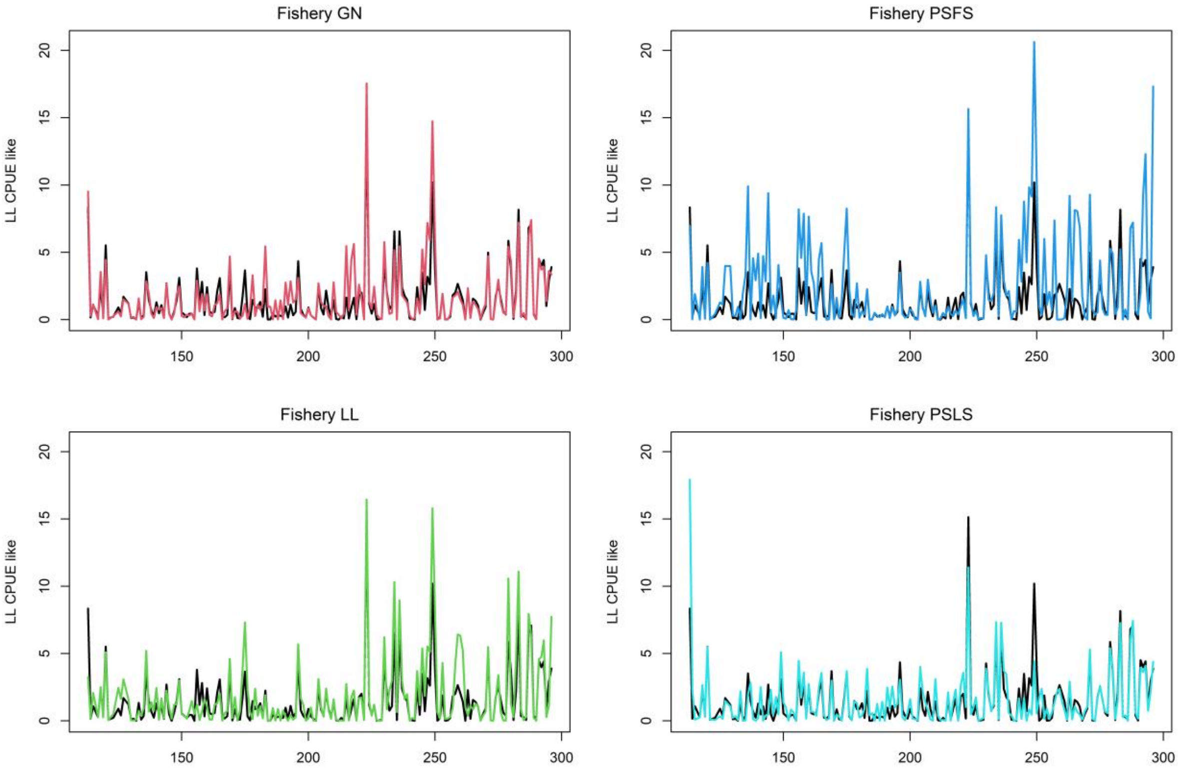

Figure 22: A comparison of the LL CPUE likelihood for each quarterly observation from the base single region model (black line) with options increasing the relative weighting of the length composition data from individual fisheries (coloured lines).

A comparison of the model likelihoods indicated that the largest conflict is between the GN and PSFS length composition data, between LL & PSFS and PSLS length composition data, and between the PSFS length composition data and the LL 1b CPUE indices (Table 5).

Table 5: A comparison of the fishery length and LL CPUE indices model likelihoods from individual model options with different weighting of the length composition data sets.

Model	LL CPUE	Length composition			
		LL1b	PSFS	PSLS	GN
Base	-21.5	389	227	275	144
GN_length	12.8	417	265	341	107
LL_length	52.4	353	230	376	194
PSFS_length	166.2	405	174	382	236
PSLS_length	-8.4	480	262	236	192
DWT_length	-53.9	401	234	221	154
Relative to Base					
GN_length	34.3	28	38	66	-37
LL_length	73.9	-36	3	101	50
PSFS_length	187.7	16	-53	107	92
PSLS_length	13.1	91	35	-39	48
DWT_length	-32.4	12	7	-54	10

Increasing the weighting of the PSFS, PSLS and GN length composition increased the magnitude of the variation in the recruitment estimates, indicating a strong seasonal pattern in the length compositions (Figure 23). Typically, recruitments informed by the GN length composition data were high during Q1 and/or Q4, while recruitments informed by PSFS length data were higher in Q2 and/or Q3 and PSLS length data estimated higher recruitment in Q3. These results suggest different seasonal patterns in recruitment from the Arabian Sea (GN fishery) compared to the equatorial region (Figure 23).

The increased emphasis on the PSLS length composition data resulted in a general increasing trend in recruitment deviates (Figure 23), reflecting the overall decline in the average length of fish sampled from the fishery.

The GN fishery length composition data is more consistent with a period of lower recruitment during 1996-2004 (Figure 23 and Figure 24); there was a lower proportion of large (> 100 cm) fish sampled from the fishery during that period (model years 200-230).

The increased emphasis on the LL length composition data did not appreciably change the trend in recruitment deviates for the period prior to 2006. However, lower recruitment deviates were estimated for the subsequent years (Figure 23 and Figure 24).

Similarly, trends in the PSFS length composition data were broadly consistent with the recruitment deviates for the period prior to 2006. In the subsequent years, the PSFS length composition data a higher degree of variability in the recruitment deviates relative to the base model (Figure 23 and Figure 24).

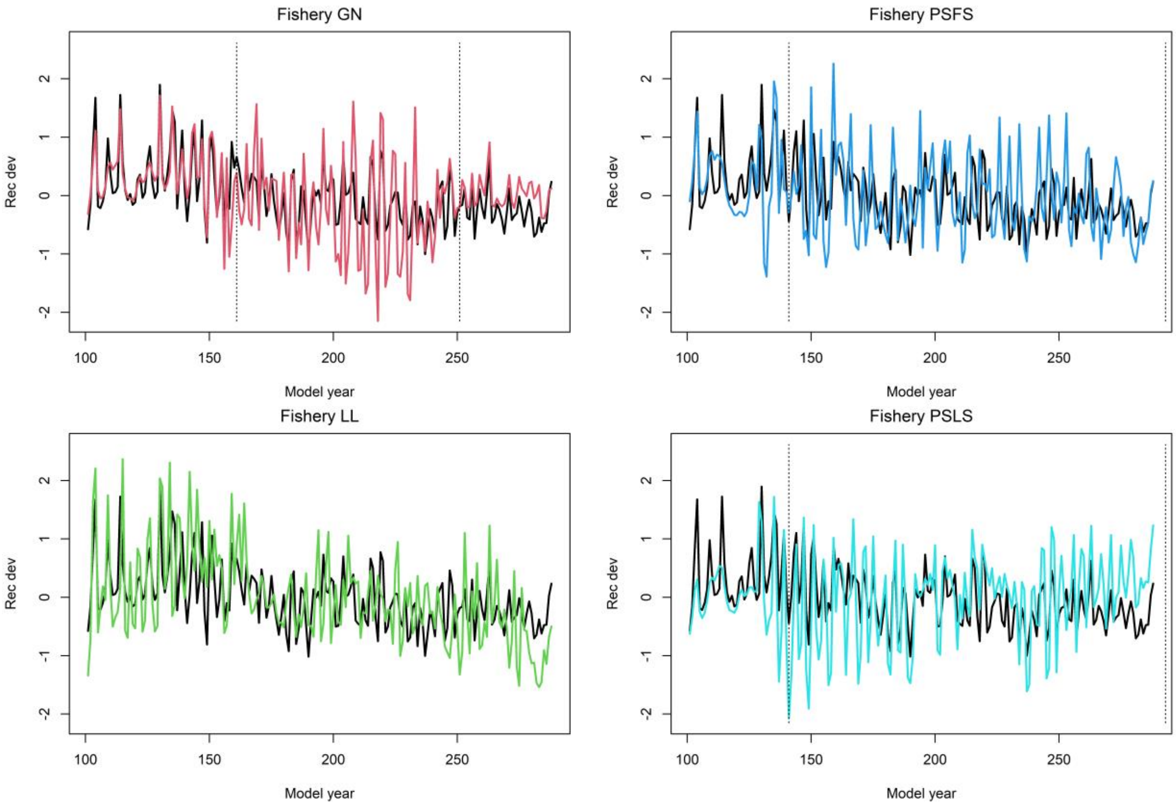

Figure 23: A comparison of recruitment deviates estimated for the single region base model (black line) and the model options with differential weightings of the individual fishery length data sets (coloured lines). The dashed vertical lines indicate the period over which length data were available for the individual fishery.

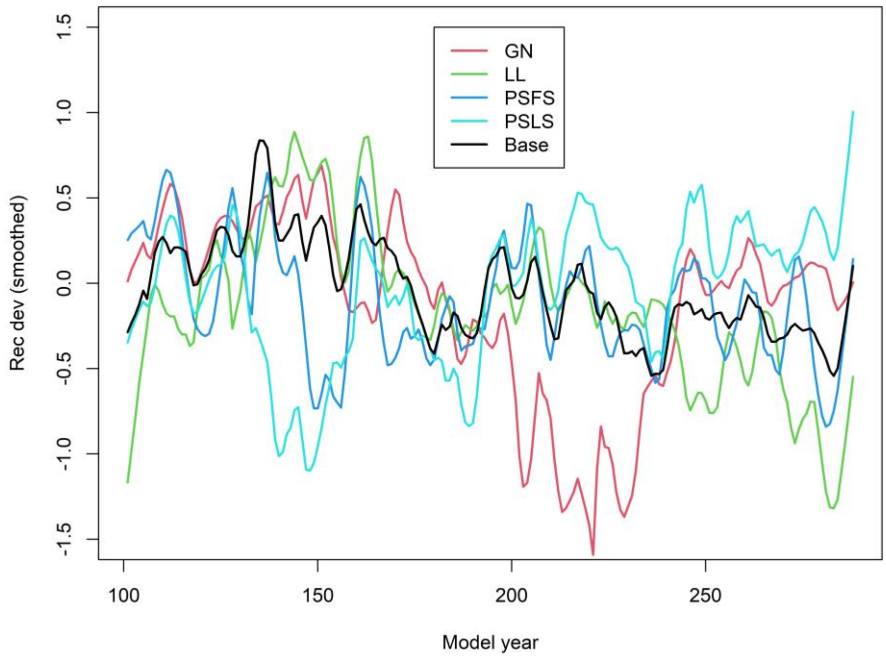

Figure 24: A comparison of the lowess smoothed trends recruitment deviates estimated for the single region base model (black line) and the model options with differential weightings of the individual fishery length data sets (coloured lines).

6. Oceanographic indices

Oceanographic indices have been derived for the Indian Ocean following Saji et al (1999). The Western Tropical Indian Ocean (WTIO) SST anomaly index is an indicator of the surface temperatures in a cross-equatorial region spanning the western tropical Indian Ocean (Figure 25). It is calculated with SSTs in the box 50°E to 70°E, 10°S to 10°N. The Southeastern Tropical Indian Ocean (SETIO) SST anomaly index is an indicator of the surface temperatures in the southeastern tropical Indian Ocean, west of the Indonesian island of Sumatra. It is one half of the Dipole Mode Index, an indicator of the east-west gradient in sea surface temperatures in the Indian Ocean. It is calculated with SSTs in the box 90°E to 110°E, 10°S to 0°. The Dipole Mode Index (DMI) index is an indicator of the east-west temperature gradient across the tropical Indian Ocean, linked to the Indian Ocean Dipole or Zonal Mode. It is calculated as the difference of the WTIO and SETIO indices (https://stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php) (Figure 25).

The Southwestern Tropical Indian Ocean (SWIO) SST anomaly index is an indicator of the surface temperatures in a region east of South Africa and south of Madagascar. It is calculated with SSTs in the box 31°E to 45°E, 32°S to 25°S (Figure 25).

The weekly indices sourced from for the period 1982-2022. The sets of indices were calculated using the Reynolds OIv2 SST analysis, made available by NOAA/ESRL.

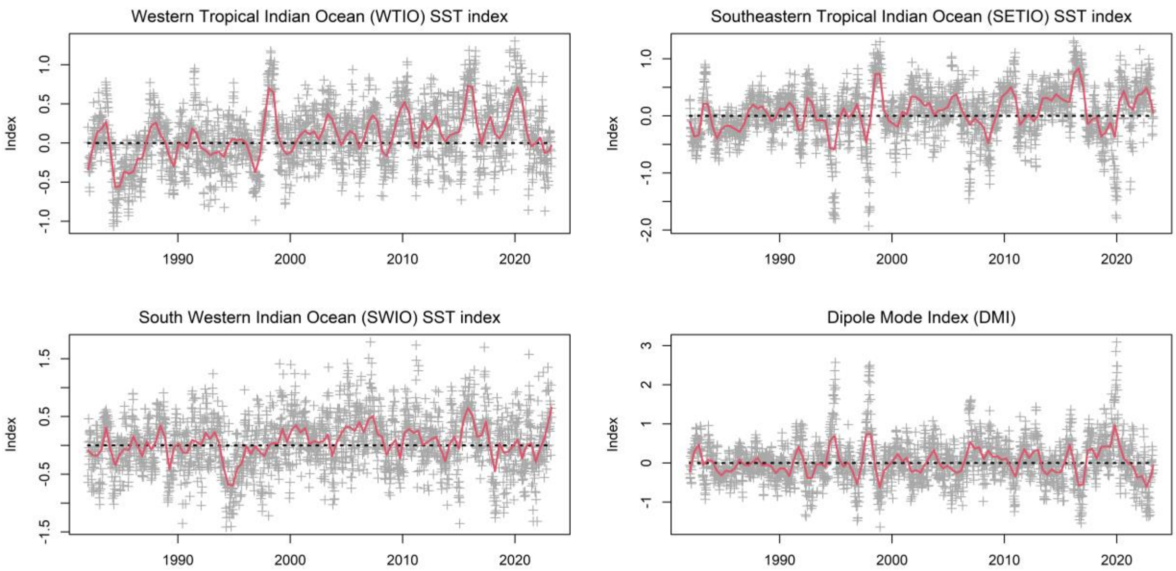

Figure 25: Weekly oceanographic indices for the Indian Ocean (points) and a lowess smoothed (annual) trend in the indices (red line).

Under positive DMI conditions, the thermocline is shallower in the eastern equatorial region, while lowering the thermocline in the western equatorial region (R1) (Saji et al 1999). The negative DMI corresponds to a deeper thermocline in the eastern equatorial region and a shallower thermocline in the western equatorial region (R1).

The depth of the thermocline has the potential to influence the catchability of yellowfin to the longline fishery; typically increasing catchability with a shallower thermocline. Therefore, under positive DMI conditions, the shallower thermocline in the eastern region has the potential to increase the LL4 CPUE indices, while the deeper thermocline in the western region has the potential to depress the LL1b CPUE indices.

There is no apparent correspondence between the short-term (annual) trends in the four environmental variables and the LL CPUE indices from each of the main regions (Figure 26 to Figure 29).

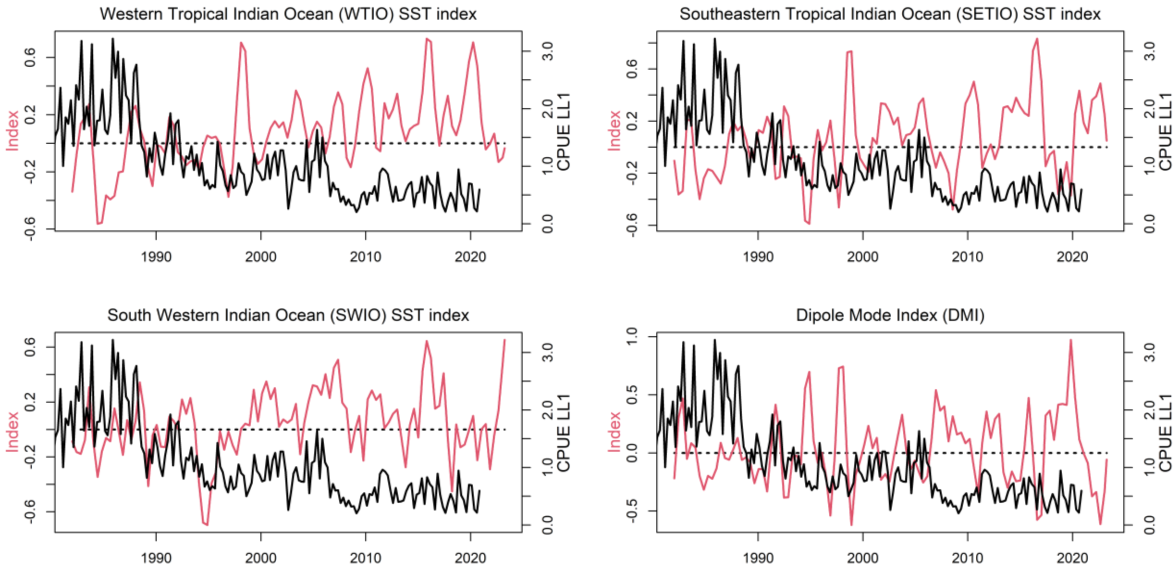

Figure 26: A comparison between the LL1b CPUE indices and the four sets of IO oceanographic variables (lowess smoothed).

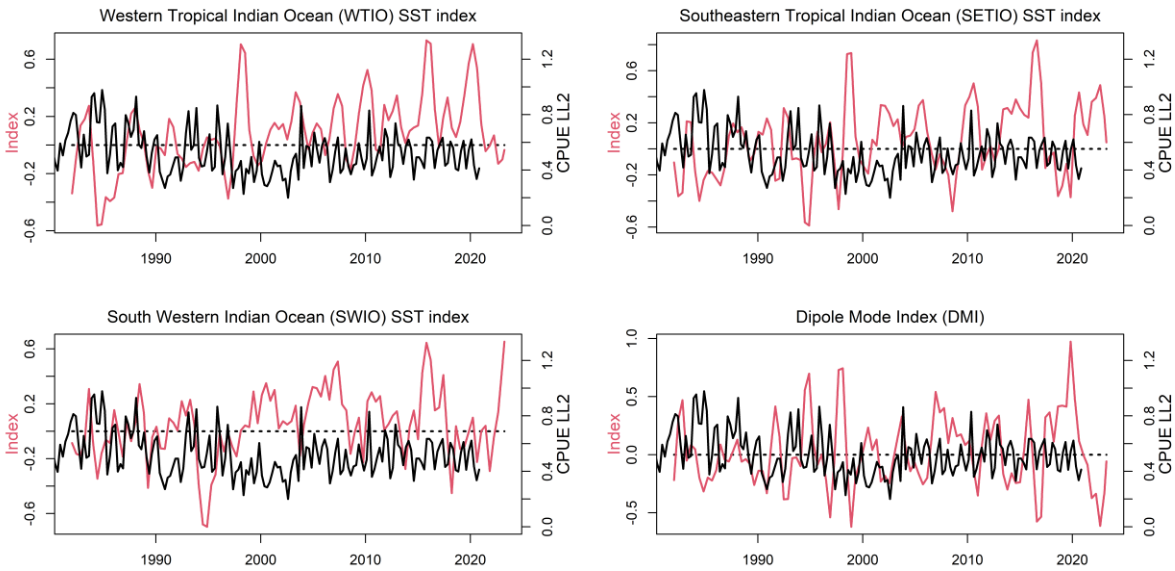

Figure 27: A comparison between the LL2 CPUE indices and the four sets of IO oceanographic variables (lowess smoothed).

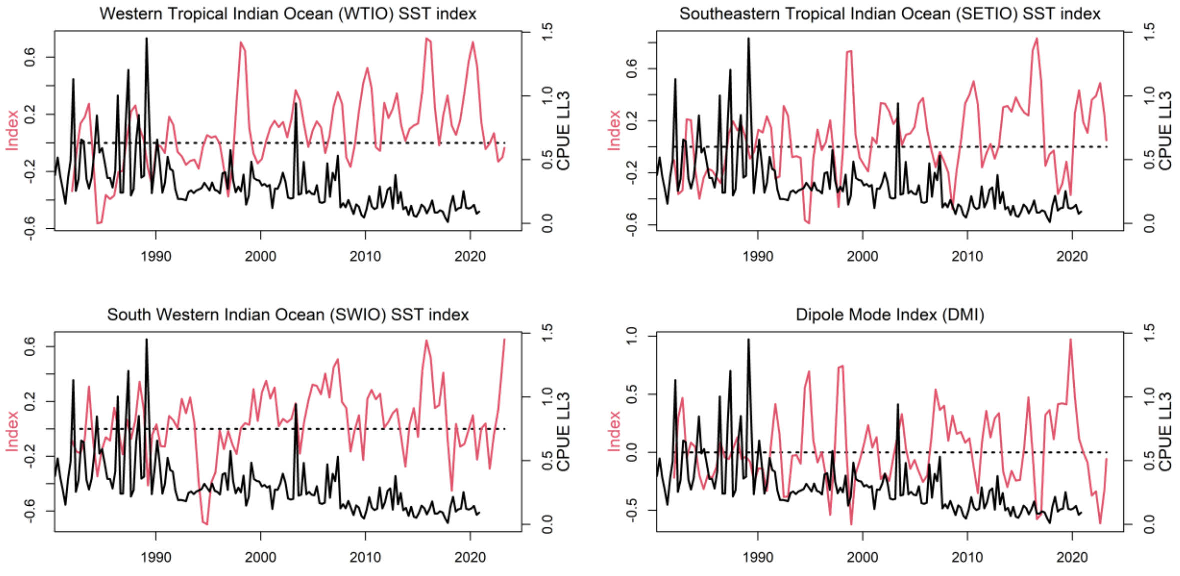

Figure 28: A comparison between the LL3 CPUE indices and the four sets of IO oceanographic variables (lowess smoothed).

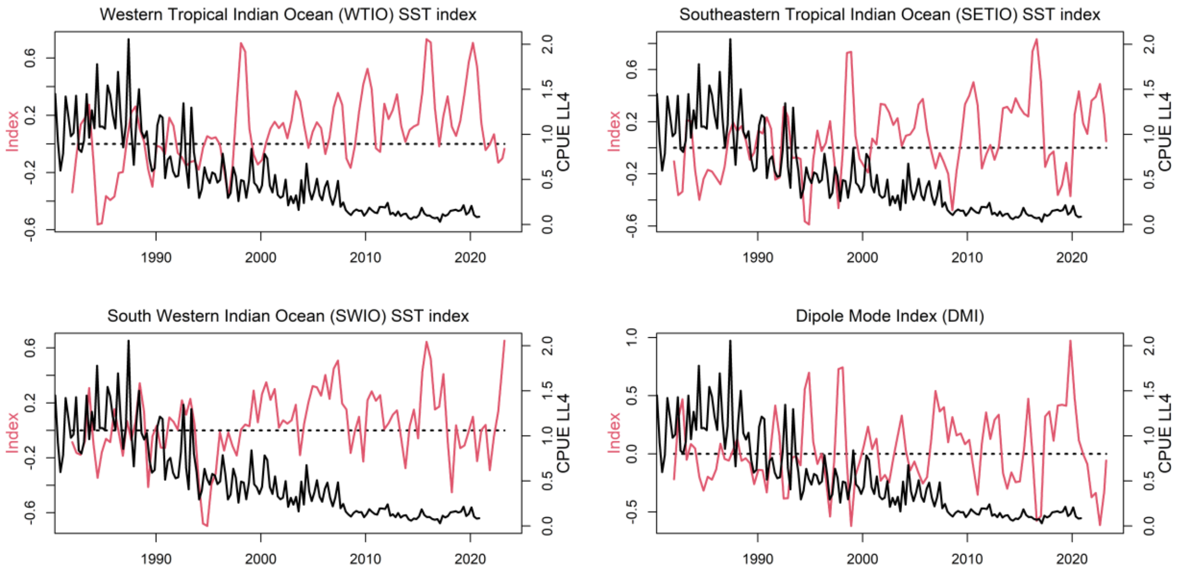

Figure 29: A comparison between the LL4 CPUE indices and the four sets of IO oceanographic variables (lowess smoothed).

The CPUE indices incorporate both long term trends in abundance and shorter term (1-2 yr) fluctuations in abundance. Changes in catchability are more likely to occur over the shorter time scales. The trends in the quarterly change in regional CPUE (Section 2.1) were also compared with the available oceanographic indices (Figure 30 to Figure 33). There was some indication that the short term fluctuations in the LL2 CPUE indices broadly corresponded to the variation in the DMI and WTIO indices for the period prior to 2005 (Figure 31), with catch rates increasing during periods characterised by positive DMI and WTIO conditions and decreasing or remaining stable during negative periods. There is some suggestion that large increases in the LL3 CPUE indices corresponded to positive trends in the SETIO index (Figure 32). The changes in the CPUE indices in both regions are too rapid to be responding to local (regional) scale recruitment processes.

There was no indication that fluctuations in the two sets of equatorial LL CPUE indices (LL1 and LL4) strongly corresponded to the four sets of oceanographic indices, although some suggestion that under higher DMI and WTIO conditions there was less variability in the LL1 CPUE indices (Figure 30).

Overall, there is no strong indication that the catchability of the equatorial longline fisheries (LL1 and LL4) is strongly influenced by the prevailing environmental conditions, as characterised by the available IO oceanographic indices. There is some indication that oceanographic conditions may influence short-term (1-2 yr) variation in longline catchability in the sub tropical regions (LL2 and LL3) than in the equatorial regions.

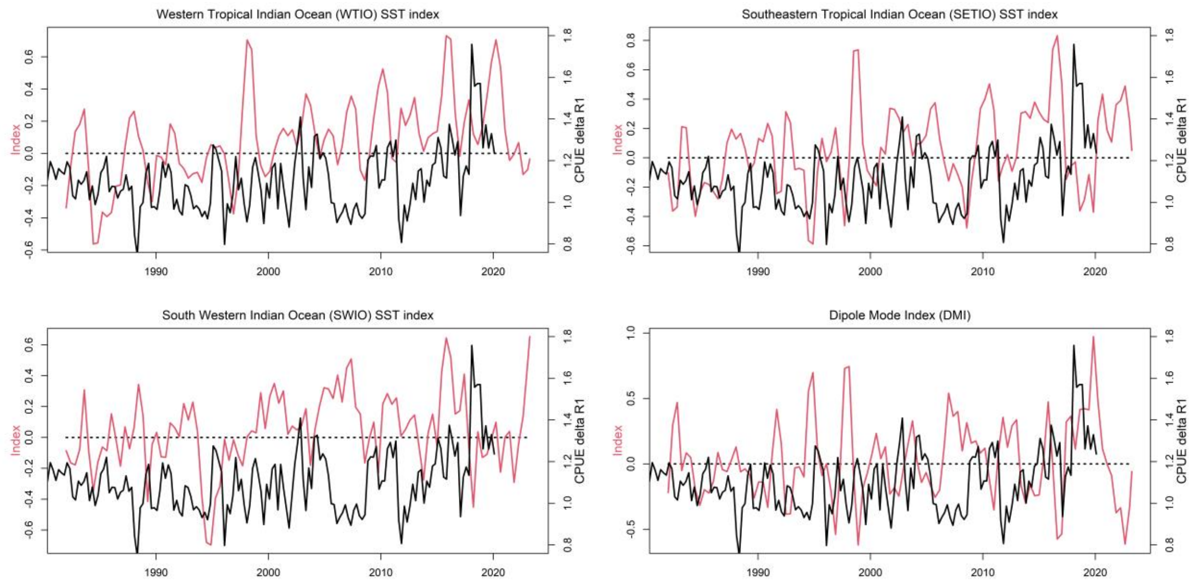

Figure 30: A comparison between the smoothed change in LL1b CPUE indices (*$CPUE_{r,t}/CPUE_{r,(t-1)}$*) and the four sets of IO oceanographic variables (lowess smoothed).

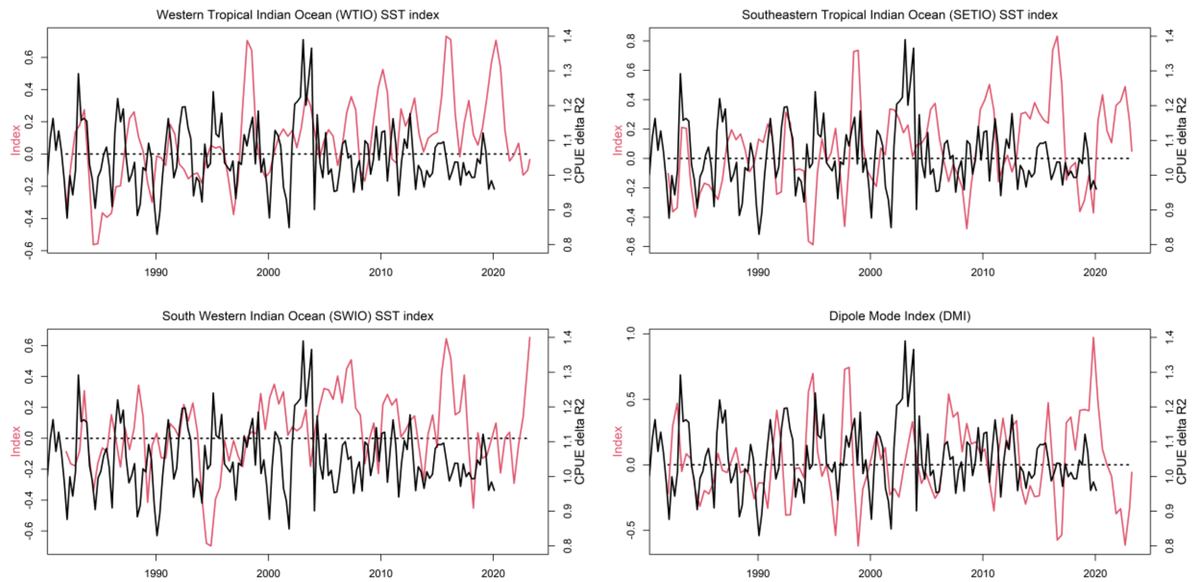

Figure 31: A comparison between the smoothed change in LL2 CPUE indices (*$CPUE_{r,t}/CPUE_{r,(t-1)}$*) and the four sets of IO oceanographic variables (lowess smoothed).

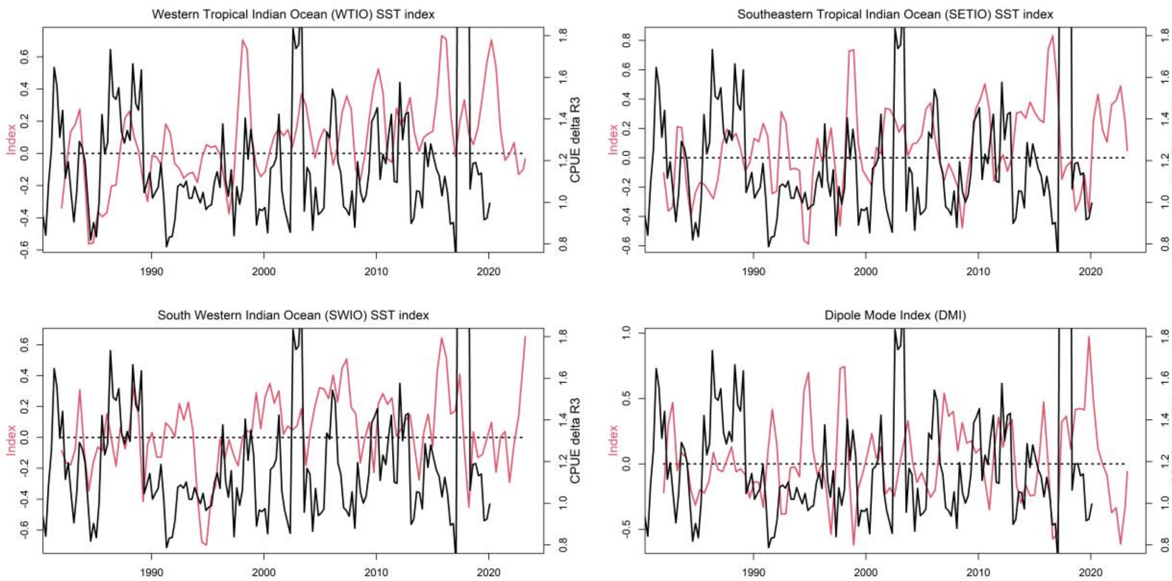

Figure 32: A comparison between the smoothed change in LL3 CPUE indices (*$CPUE_{r,t}/CPUE_{r,(t-1)}$*) and the four sets of IO oceanographic variables (lowess smoothed).

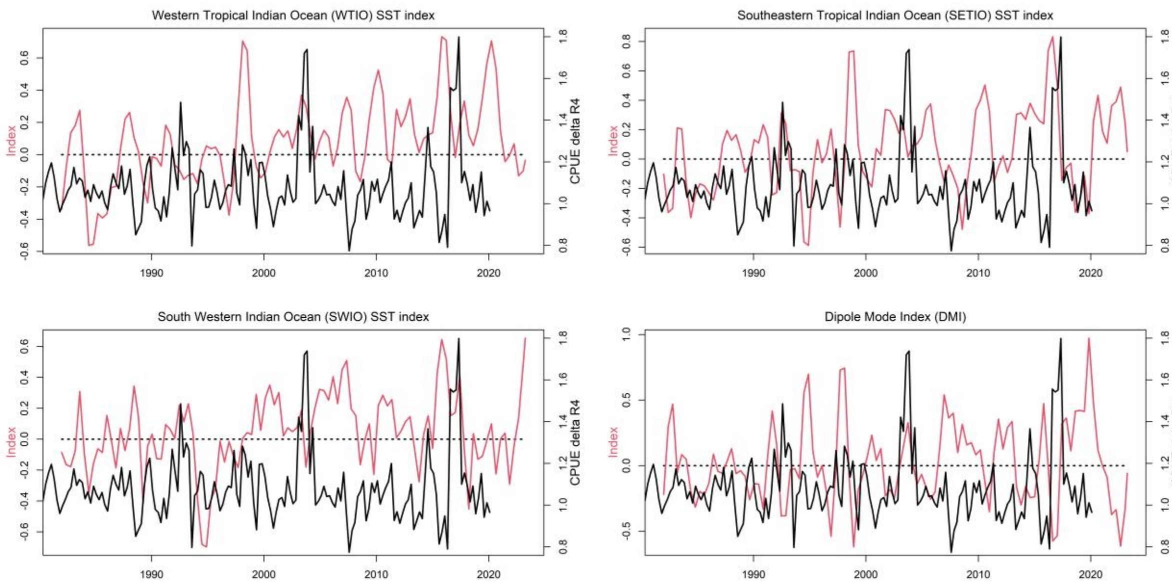

Figure 33: A comparison between the smoothed change in LL4 CPUE indices (*$CPUE_{r,t}/CPUE_{r,(t-1)}$*) and the four sets of IO oceanographic variables (lowess smoothed).

The four sets of oceanographic indices were compared to the estimates of regional (R1 and R4) and total (R1 and R4 combined) recruitment from the 2021 base assessment model. The recruitment estimates were aggregated by calendar year to remove the seasonal variation in the quarterly recruitments derived from the model. Annual fluctuations in recruitments are similar for the two regions, although the extent of the variation in recruitment is higher in Region 4 (Figure 34).

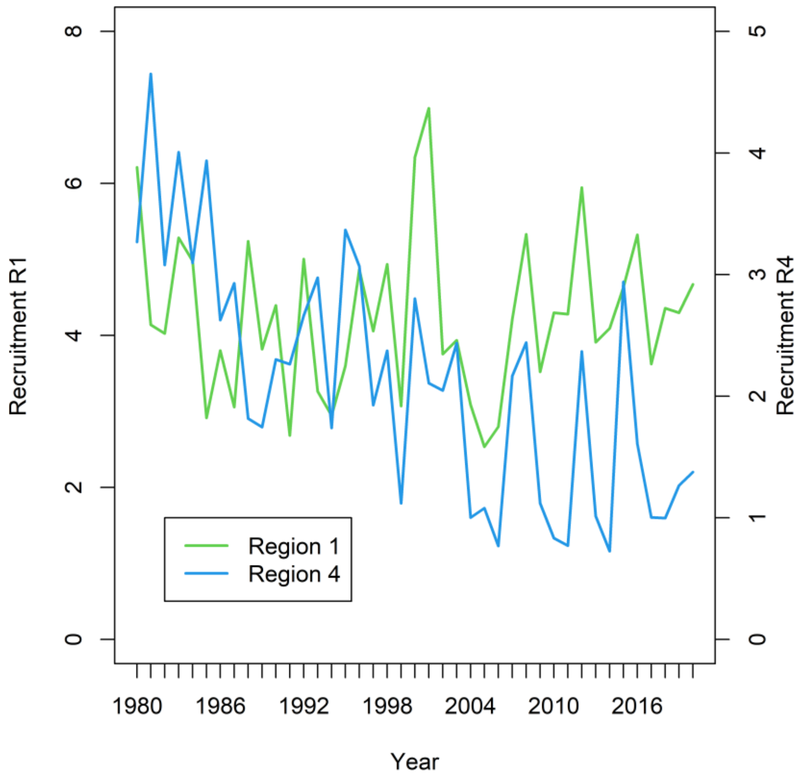

Figure 34: Annualised estimates of yellowfin tuna recruitment for Region 1 and Region 4 from the 2021 base assessment model.

Annual recruitments in R1 tend to fluctuate at 5-7 year intervals (Figure 35). The variation in annual recruitments generally corresponded to the trends in both the SWIO SST index; i.e. stronger recruitment occurring in years of positive SST anomalies in the SW region (Figure 35). The notable exception was during the mid 2000s when recruitment was estimated to be low, despite positive SWIO conditions. Recruitment estimates for the mid 2000s are potentially biased low during this period due to the influence of the RTTP tag release/recovery data and the negative impact of the effect of piracy on the LL1 CPUE indices during 2008-2011 (influencing estimates of recruitment in the preceding period).

The higher SWIO indices correspond to warmer sea surface temperatures in the southwestern region of the IO (32°S to 25°S). Warmer sea temperatures in that region may be indicative of an expansion of the main yellowfin tuna spawning habitat in those years. The periods of higher annual recruitment also tended to correspond to positive DMI conditions (Figure 35) that generally indicate warmer seas surface temperatures in the western Indian Ocean.

The periods of higher recruitment within Region 4 also tend to correspond to positive DMI conditions (Figure 36) resulting in the combined R1&R4 recruitment also corresponding to trends in the DMI (Figure 37). This suggests that the prevailing equatorial oceanographic conditions (indexed by DMI) are influencing the recruitment process in both regions and/or there is a single recruitment process (presumably in the western region) and recruitment is subsequently distributed between the two equatorial regions via movement.

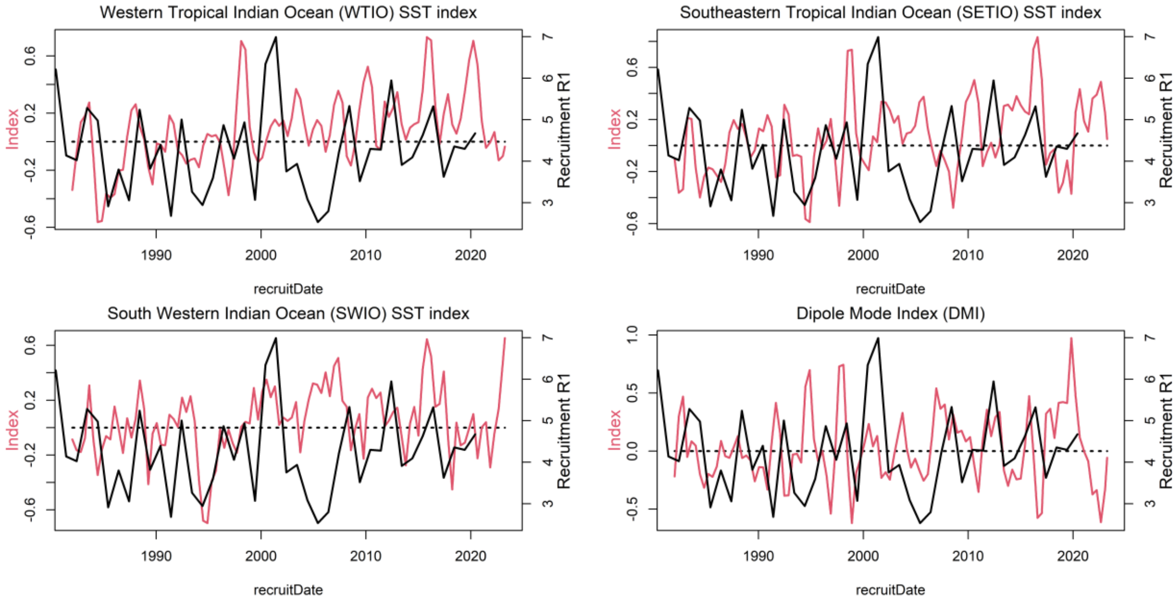

Figure 35: A comparison between the annual recruitment for Region 1 (from the 2021 base assessment model) and the four sets of IO oceanographic variables (lowess smoothed).

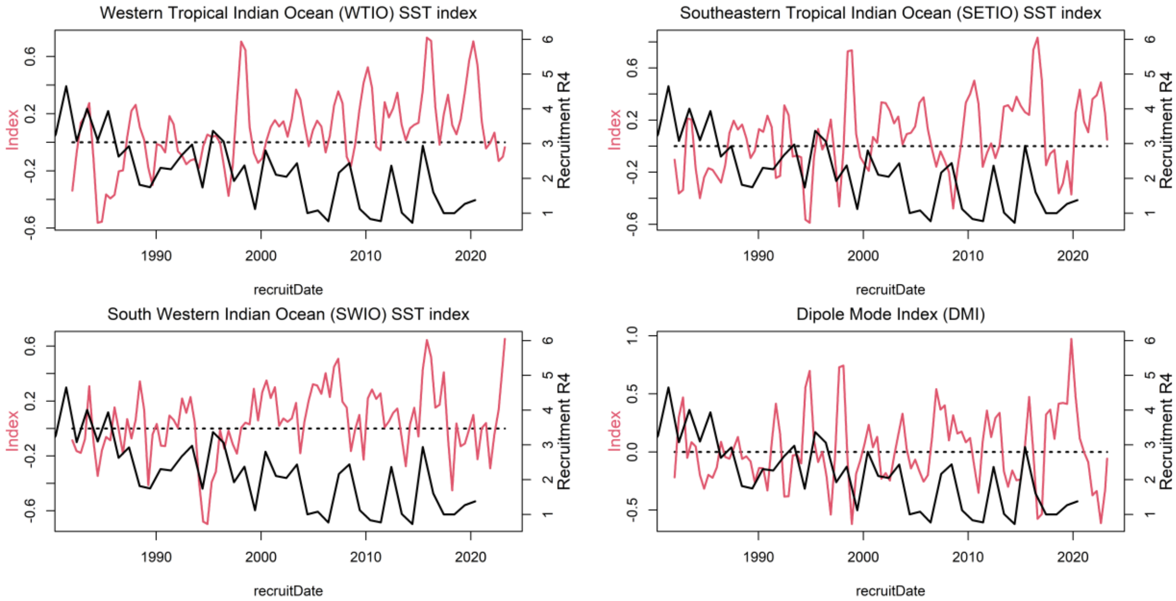

Figure 36: A comparison between the annual recruitment for Region 4 (from the 2021 base assessment model) and the four sets of IO oceanographic variables (lowess smoothed).

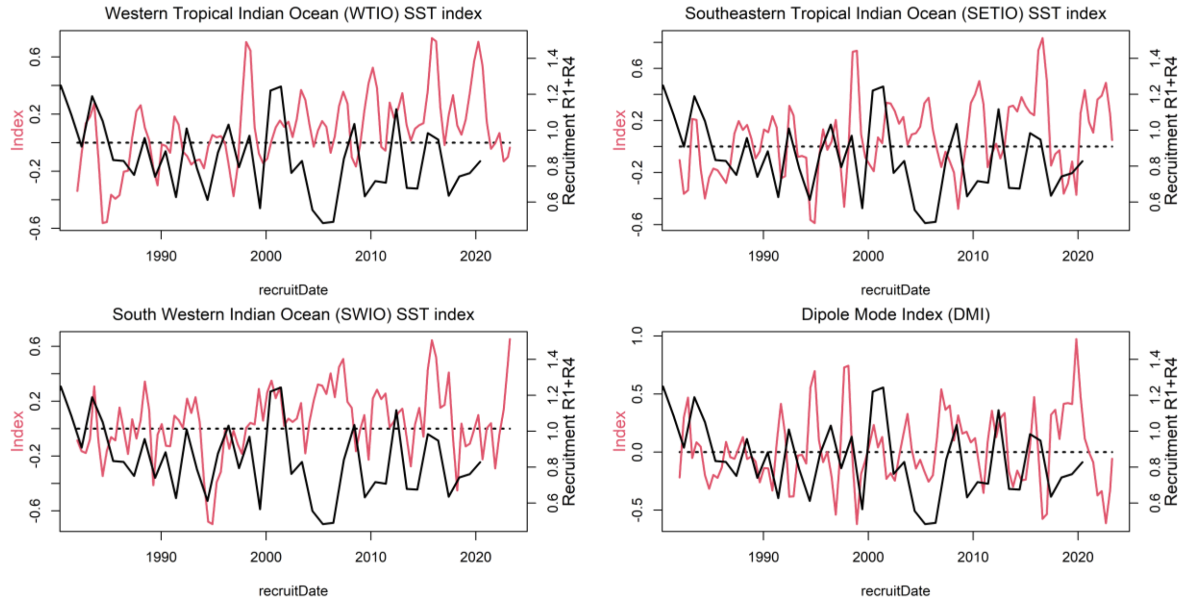

Figure 37: A comparison between the annual recruitment for Region 1 and Region 4 combined (from the 2021 base assessment model) and the four sets of IO oceanographic variables (lowess smoothed).

7. Four region movement based model

For exploratory purposes, an alternative four region model was configured based on the hypothesis that recruitment primarily occurs within Region 1 and the recruitment into other regions (particularly Region 2 and Region 4) occurs via a dispersal process that may vary over time, potentially driven by the prevailing environmental conditions. This stock hypothesis was based on the magnitude of the catch from the small fish fisheries within R1, similarities in recruitment between R1 and R4, the correspondence in the trends in the CPUE indices between R1 and R4 and the broad similarities in the length compositions of the longline fisheries among regions (suggesting a high degree of mixing). The hypothesis also incorporates the potential for fishery impacts reducing the biomass available to move from R1 to the adjacent areas (R2 and R4) as a consequence of the increased catches within R1, particularly of younger yellowfin.

The model was based on the 2021 four region assessment model. The new configuration of the model limited recruitment to R1 (instead of R1 and R4). The movement parameterisation was equivalent for the two models, with the exception that quarterly variation in movement was estimated for R1 to R4 and for R1 to R4 (fish age 8 and older) (for 1977 to 2019).

Overall, the total likelihood of the model improved relative to the base model (from 9756 to 9693), while the number of estimated parameters increased from 405 to 655 (by 250) and hence the improvement in the model likelihood is not significant based on AIC. Most of the improvement in the likelihood was attributable to the substantial improvement in the fit to the LL CPUE indices, especially for the seasonal variation in the LL2 and LL3 CPUE indices. There was some deterioration in the fits to the length composition data, principally for to PSLS fishery. Overall, the model estimated a similar stock status to the 2021 base assessment model.

The movement model provides some opportunity to investigate potential processes that may influence the spatial distribution of yellowfin tuna within the Indian Ocean. The strongest persistent seasonal movement was estimated from R1 to R4 with higher movements occurring in Q1 and Q2 and lower movements in Q3 and Q4. The higher rates of movement coincided with the strong eastward flow of the South Equatorial Countercurrent during January-February.

By contrast, seasonal movements southward from R1 to R2 were estimated to be higher in Q3 and Q4 and lower in Q1 and Q2. This probably relates to the increased availability of yellowfin in R2 during the austral summer as indicated by higher LL CPUE indices in summer.

The model estimated relatively high return movements from R4 to R1 (temporally invariant). The model varied the abundance of yellowfin in R4 via the temporal variation in the movement rate from R1 to R4 and the overall exploitation rate in each area. The movement model attributed the decline in the abundance of yellowfin in R4 since 2006 to the increased exploitation rates in R1 and the lower overall level of movement to R4 from the mid 2000s (Figure 39), while also increasing the movement of yellowfin from R1 to R2 over the same period (Figure 38).

Medium term trends in the estimated movement parameters were compared to the available oceanographic variables. There is no strong indication that the movement parameters from R1 to R2 are correlated with any of the four environmental variables. Variability in the R1-R4 movement temporal deviates is broadly consistent with the fluctuations in the Dipole Mode Index with higher movement estimated under positive IOD conditions. However, any mechanism for such a relationship is unclear. Positive IOD conditions correspond to easterly wind anomalies across the Indian Ocean and warmer sea surface temperatures in the western Indian Ocean and cooler sea surface temperatures in the eastern Indian Ocean (Ocean Sci., 17, 1677–1751, 2021). Those conditions would not be expected to correspond to higher abundance of yellowfin tuna in the eastern Indian Ocean.

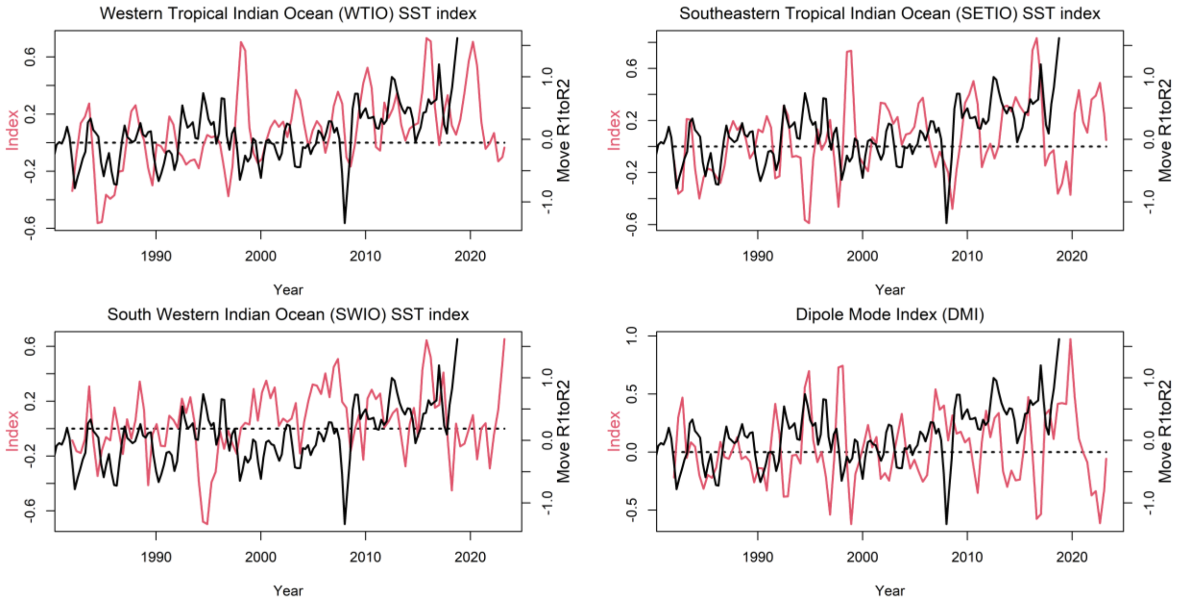

Figure 38: A comparison between the R1 to R2 movement deviates (smoothed) from the four region movement model (current study) and the four sets of IO oceanographic variables (lowess smoothed).

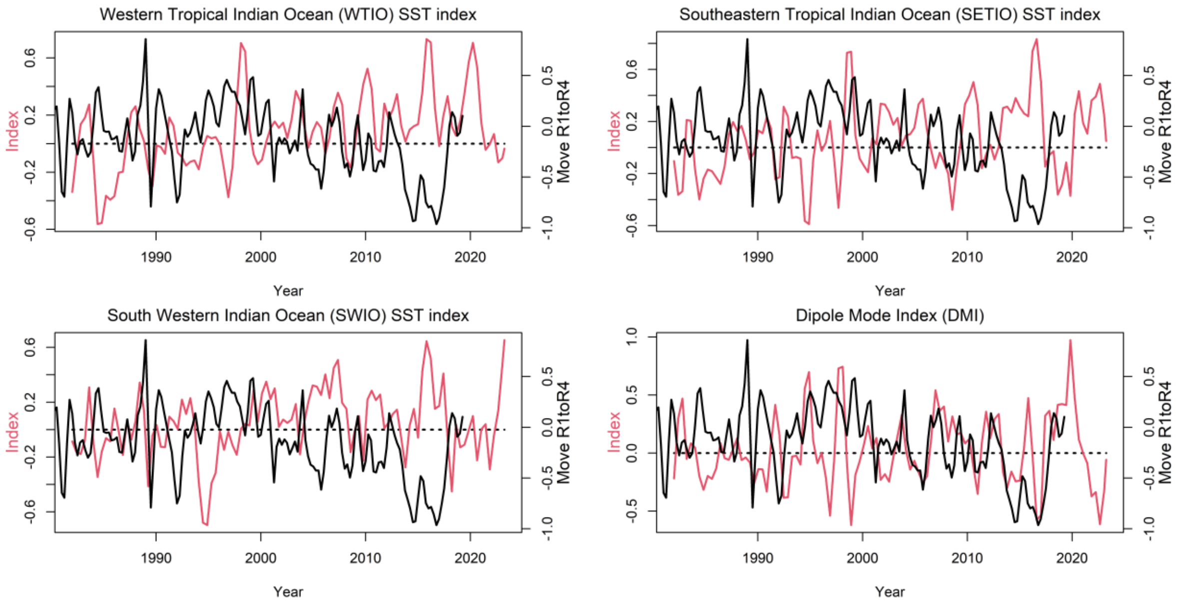

Figure 39: A comparison between the R1 to R4 movement deviates (smoothed) from the four region movement model (current study) and the four sets of IO oceanographic variables (lowess smoothed).

A simpler model option was implemented that excluded the temporal variation in movement, while still limiting recruitment to R1 only. The model was implemented to investigate if the differential trends in regional LL CPUE indices could be accounted for solely through differential exploitation patterns.

The likelihood deteriorated from the 2021 base model (NLL of 10131 with 319 parameters), largely due to a deterioration to the CPUE likelihood component. The model provided a reasonable fit to the CPUE indices from LL1, LL3 and LL4 although the fit to LL2 CPUE indices was poor.

A further model was evaluated that estimated a separate recruitment series for R2 only (NLL of 9902 with 405 parameters). The overall likelihood was worse than the 2021 base model primarily due to a deterioration in the fit to the LL3 and LL4 CPUE indices. The overall stock status was similar for the two model options.

The various model options all estimated a similar stock status while the 2021 base model was the most parsimonious of the four model options based on AIC. This simply indicates that the differences observed in the CPUE trends between R1 and R4 are easier for the model to explain through recruitment variation, particularly given the relative freedom the model has to estimate separate recruitments between the two regions. Alternative stock hypotheses should continue to be considered in the overall assessment framework, particularly given the strong similarities in the model dynamics evident between R1 and R4.

8. Conclusions

1. Model estimates of recruitment are most strongly influenced by the regional LL CPUE indices (and corresponding levels of regional catch).
2. The long-term trends in LL CPUE indices are similar for regions R1, R3 and R4. Prior to 2005, LL CPUE indices from R2 were comparable to R1 both in long-term trend and short-term (1-2 yr) fluctuations. More recent trends in the LL CPUE indices deviated considerably between the two regions with LL2 CPUE indices remaining relatively stable while LL1 CPUE indices declined markedly in the late 2000s and then stabilised at a lower level. LL CPUE indices from R3 and R4 were also at a (very) low level from the late 2000s.
3. For the main region of the assessment (R1), length composition data from the LL and PSFS fisheries are variable between model time intervals, seemingly due to variability in the operation of the fishery and sampling error. Consequently, there is a relatively poor fit to the length composition data and the data are not very informative in the estimation of recruitments. Nonetheless, the length compositions appear to be broadly consistent with the model estimates of recruitment for the period prior to 2006 (informed by the LL1 CPUE indices). There is increased conflict between the LL1 CPUE indices and the LL and PSFS length composition data in the subsequent period (from 2006) and the overall fit to the LL1 CPUE indices deteriorates during that period.
4. The length composition data from the R1 PSLS fishery is also broadly consistent with the model estimates of recruitment, although the length data do not appear to be very influential. The PSLS length composition data contradict the trends in the length composition data from the LL1 and PSFS fisheries, seemingly due to the declining trend in the length composition from the PSLS fishery. This declining trend may relate to a change in the operation of the PSLS fishery over the last two decades.
5. The Arabian Sea GN fishery (pre 2010) provided the most informative length composition data with very consistent progression of length modes. However, the recruitment signal from those data deviated from the estimates of recruitment informed by the LL (1b) CPUE indices from the wider western equatorial region (R1). The seasonal timing of the recruitment of the cohorts observed in the Arabian Sea GN fishery also differed from the cohorts sampled from the equatorial purse-seine fisheries (PSFS and PSLS).
6. Estimates of recruitment informed by length composition data will be sensitive to the model growth assumptions. The recent growth study (Farley et al 2021) suggests the growth parameters included in the current (2021) assessment may under-estimate initial growth. This study was primarily based on recruitments estimated from the 2021 assessment. Regardless, comparison between modal structure and recruitment are unlikely to be compromised by a miss-specification of the growth function as the estimates of recruitments (informed by the length data, especially the selectivity of the LL fishery) will shift in accordance with the differential in growth. Nonetheless, the comparisons between model estimates of recruitment and exogenous variables (e.g. the oceanographic variables) will be more sensitive to the growth assumptions (effecting the timing of recruitment).
7. There are strong similarities between the individual regional longline length compositions amongst the four regions in some periods and marked differences in other periods and/or between successive intervals. There are no periods when there were persistent differences in

the length compositions from adjacent regions. There is probably a high degree of sampling error in the longline length sampling data. Regardless, the broad similarities between the regional length compositions in some years are suggestive of ocean scale mixing of the adult population, at least in some periods. Similarly, the length compositions from the R1 and R2 PSFS fisheries are also very similar, with the exception of the PSFS fishery in the Mozambique Channel that is dominated by catches of juvenile fish.

8. There are short-term (1-2 y) trends in the subtropical longline CPUE indices (LL2 and LL3) that appear to be influenced by the prevailing oceanographic conditions. Changes in LL catchability in those regions may introduce short-term bias in the regional LL CPUE indices. The linkage between the equatorial and subtropical regions (via movement parameters) may potentially extend any bias in the CPUE indices to the adjacent (equatorial) regions. There was no indication that longline CPUE in the equatorial regions (LL1 and LL4) were influenced by prevailing oceanographic conditions as characterised by the available range of indices.
9. The divergent trend in the LL CPUE indices from LL2 from mid 2000s, relative to the other longline fisheries (LL1, LL3, LL4) does not appear to be correlated with recent oceanographic conditions, although there was a general increase in the WTIO SST anomalies over that recent period. This period also corresponded to the shift in the operation of the longline fishery in response to the peak in piracy in the western equatorial region during the late 2000s. Those changes may have the influenced the relative catchability of the longline fleet in each region.
10. There are strong similarities in the temporal trends in the recruitment estimated for the two equatorial regions from the 2021 stock assessment model. Periods of strong recruitment in both regions appear to correspond with oceanographic conditions indexed by DMI. The similarities in recruitment patterns suggest a common recruitment process occurring at an equatorial scale with broad scale mixing of fish, rather than the current (2021) model structural assumption of spatially partitioned recruitment in the western and eastern equatorial regions. The alternative stock hypothesis is also commensurate with the similarities in trends in LL CPUE indices and LL length compositions between the two regions. However, there are limited observations from the tag release/recovery data to support the assumption of large scale mixing and no other data to inform regarding movement. Nonetheless, alternative stock hypotheses should be routinely considered as key model sensitivities in the stock assessment process.

9. Recommendations

This study highlighted some specific issues that should be considered in the next (2024) stock assessment for yellowfin tuna, extending the wider range of recommendations from the 2023 review of the yellowfin tuna stock assessment (Maunder et al 2023). Recommendations specific to this study are, as follow.

1. Refine growth estimates for IO yellowfin tuna (in conjunction of other key biological parameters, particularly natural mortality).
2. Further investigate impact of piracy on the derivation of the regional LL CPUE indices, particularly the LL CPUE indices for Region 1, including an evaluation of the area and fleet distribution of the distant-water longline catch and effort data. Alternatively, partition the composite R1 LL CPUE indices into two time blocks (pre- and post piracy period) and estimate a separate catchability coefficient for the more recent period.
3. Further evaluation of the influence of prevailing oceanographic conditions on the regional LL CPUE indices, especially in the subtropical regions (R2 and R3). Minimise the influence of recent short-term changes in those CPUE indices (R2 and R3) on the estimation of recent stock status.
4. Investigate factors than may have influenced the length-based selectivity of the PSFS and PSLS fisheries over time, particularly the change in the spatial distribution of the sampled component of the catch.

5. Investigate alternative model weighting of the length compositions data from key fisheries, including the relative weighting of individual length observations and/or the criteria for the inclusion/exclusion of individual length observations. Further investigate patterns in the length composition data (seasonal, spatial, fleet) to account for the variation in the length observations.
6. Evaluate a range of stock hypotheses within the set of key model sensitivities included the stock assessment process, including the spatial configuration of recruitment and movement dynamics.

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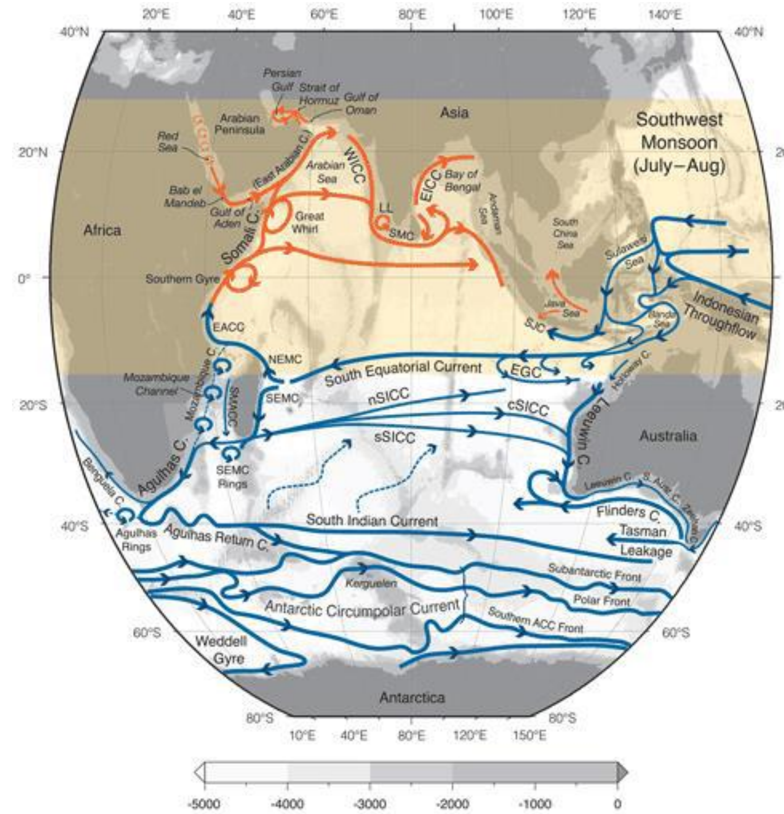

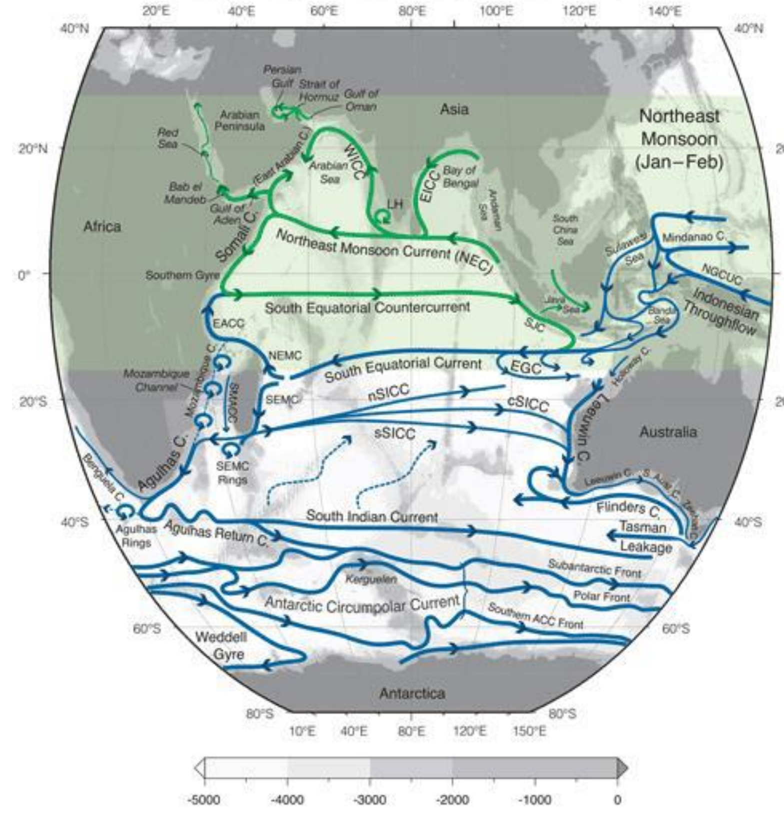

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