Received: 7 November 2014

SKIPJACK TUNA CPUE TRENDS USING ALTERNATIVE INDICES FROM THE FRENCH PURSE SEINE LOGBOOKS

Francis Marsac[1] and Laurent Floch[2]

Abstract

We used the French purse seine data to examine the trend of skipjack CPUEs for the period 1984-2013. Only sets made on drifting objects (logs and fish aggregating devices –FADs) are used in this analysis. Sensitivity tests were performed to evaluate the effect of the size of the core area in the north equatorial area (0-13N/45'70E) as well as effort minimal thresholds, on CPUE estimates (filtered nominal indices based on the catch per set). No significant effect was noted suggesting that the north equatorial area, as a whole, is a pertinent skipjack core area. A standardization procedure was applied to datasets based on CPUEs aggregated by 1°longitude/0.33° latitude and by month, to which corresponding environmental data such as the depth of the mixed layer, the sea surface anomaly, the speed of the current and the chlorophyll concentration were added. Generalized additive models (GAMs) were used to explore the shape of relationships with fishery-derived and environmental covariates, and undertake transformation in the dataset used by generalized linear models (GLMs). Seven models with various assumptions were tested. They denote a clear skipjack CPUE decline since 2002, with a steeper rate of decline since 2009. We suggest that the massive deployment of FADs during the 1990s and the development of efficient FAD fishing tactics have likely contributed to such decline, as more than 60% of skipjack is caught on FADs. However, environmental fluctuations are also at stake in such decline and notably the chlorophyll concentration which reflects the productivity level at the base of the food chain. The surface chlorophyll concentration has been anomalously low in the Somali Basin since 2006 and this could lead to detrimental foraging conditions for the upper trophic levels, or trigger spatial shift of the population in search of more productive areas. The biological and ecological processes associated to this decline would deserve more research. However, the fact that a sustained CPUE decline for skipjack has been occurring since 2002 could become a concern for the conservation of this stock.

Keywords : skipjack, purse seine fisheries, CPUE standardization

1. Introduction

Skipjack (SKJ) is one of the target species of the purse seine fleets and the amount taken by the purse seine (PS) gear overrides that of any other gear. From 1987 to 2003, SKJ PS catches represented more than 50% of the total SKJ catches. Since then, this proportion slightly decreased and is now fluctuating

[1] IRD/ICEMASA, Dept of Oceanography, University of Cape Town, Private Bag X3, 7701 Rondebosch, South Africa (francis.marsac@ird.fr)
[2] IRD, PO Box 570, Victoria, Mahe, Seychelles

about 40%. In the meantime, the proportion taken by gillnets, which was around 12% in the mid-90s has increased to an average of 26% for 2003-2013.

The SKJ PS catch have always been dominant over other species on sets made on drifting floating objects, whatever natural (logs) or FADs (man-made) (Fig.1). SKJ has represented 63.5% the object associated catches made by the European purse seiners during 1991-2012. SKJ taken on free schools amounted a yearly average of 22 000 t, which represents 15% of total PS SKJ catches, compared to the 122 500 t caught on object-associated sets. However this proportion has changed in the recent years, as it was around 30-35% in the mid-80s. Fonteneau (2014) has shown that SKJ free schools have almost disappeared, with CPUE declining dramatically from 17 t/day in 2005, to 0.3-0.7 t/day in 2012-2013. The interesting point is that a similar and synchronized decline took place in the East Atlantic PS fishery. Fonteneau (op cit) hypothesizes that a major cause of such declines is the steady increase in the numbers of FADs released by purse seiners during the past 10 years in these 2 oceans, leading to non-linear relationships between free school CPUEs and actual stock biomass. Consequently, the declining trend of the skipjack free schools CPUEs would not be indicative of declines in the SKJ stock biomass

Log and FAD fishing also display a very typical spatial pattern. The vast majority of object-associated catches take place to the north of the equator, from the Somalian coast in the West, to 70°E in the East. During the eighties, the northern range of the log associated sets barely exceeded 8°N. In the nineties and 2000s, the range of FAD sets extended gradually to the north, to 15° of northern latitude.

The long (30 years, 1984-2013), interrupted and well-documented catch and effort PS datasets places this fishery component in a key position to analyze CPUE trends for skipjack. The information presented above advocates the use of object-associated sets to estimate CPUEs. Previous analyses of CPUE standardization for yellowfin and skipjack, based on European PS datasets, were presented by Soto et al (2008, 2013). In this paper, drifting objects associated sets were selected to calculate SKJ CPUEs, with units of efforts being searching time and number of positive (successful) sets.

In this paper, we update the analysis that was presented by Soto el al (2013), ending in 2011, by examining a 30-years series (1984-2013) from the French PS datasets and by incorporating environmental covariates. We use two approaches :i) an area-averaged approach with various filters applied on nominal CPUE indices, and ii) a coupled GAM/GLM approach with environmental covariates.

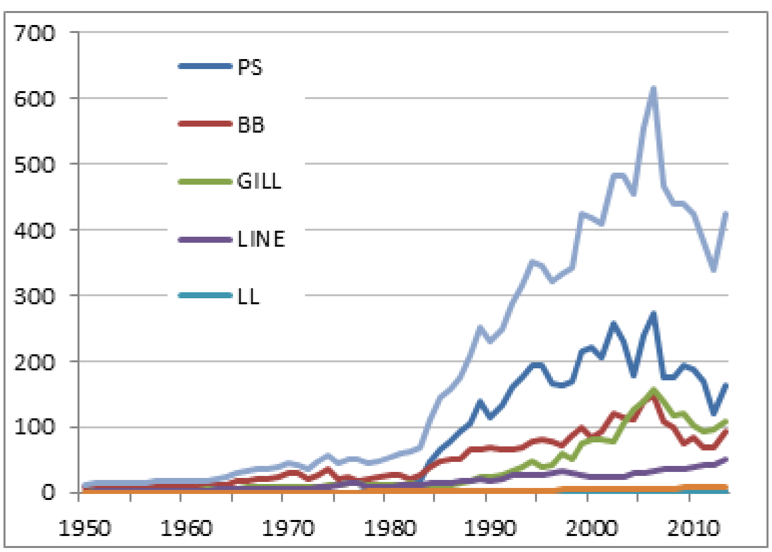


Fig.1 – Skipjack catches by gear in the Indian Ocean (source IOTC)

2. Materials and methods

2.1 Fishery data

The French PS catch and effort data have been collected since the early stage of the fishery (1981) under the supervision of the IRD (Institut de Recherche pour le Développement), through its Tuna Observatory. The logbook data are checked and consolidated, then aggregated by 1°-month, prior to their submissions to the IOTC Secretariat by the French Maritime Authorities (DPMA) and the European Union DG-MARE.

The spatial distribution of SKJ CPUEs, by decade and for the last 3 years (2011-2013) shows the huge concentration of sets in the north equatorial area (Fig.2). The highest CPUEs and largest distribution (up to 15°N) was obtained during the decade 2001-2010.

The French logbook data[3] holds 183 319 observations for 1981-2013 but the series examined starts in 1984 after the exploratory campaigns of 1981-1983. Different processing were applied on the original logbook data to produce the datasets used this paper

- Not all sets are documented as objects-associated or free schools in the logbooks. Therefore, for the catch of unknown sets only, we applied a statistical proportion assigning the catch in associated and free schools. This proportion was calculated from the ratio between the two types of sets when specified and is disaggregated by year, month and 1°square for 1984-2013. Eventually, we could reconstitute a dataset containing all PS SKJ catch by associated set.
- Three different effort units were used to compute CPUEs: the fishing day (fd), the set on drifting object and the positive set on drifting object. Therefore, CPUEs were expressed in tons/fd, tons/set and tons/positive set.
- Catch and effort units were also aggregated in rectangular boxes of 1° longitude x 0.33° latitude, by fortnight. Different filters were applied to select the boxes to be used. We generated monthly data tables with boxes where at least 1 positive/fortnight, or 3 positive sets/fortnight were performed. These different thresholds were selected to test the sensitivity of CPUEs to minimum level of effort by strata

2.2 Environmental data

We used the GODAS (Global Ocean Data Assimilation System) monthly outputs produced by the NOAA-NCEP (National Center for Environmental Prediction) to derive environmental parameters. Anomalies for the mixed layer depth (MLDa) and the sea surface temperature (SSTa) – the temperature at the 5m depth level - were calculated by difference with a climatology established by the lead author over the period 1980-2005. We also calculated the velocity of the surface current from the GODAS u and v components. The spatial resolution of the monthly GODAS products is 1° in longitude and 0.33° in latitude, this is why fishery data were aggregated on a similar grid.

These environmental variables were included as covariates in the GLMs (see below) following preliminary analyses using generalized additive models to investigate the relationships between these predictors.

Sea surface chlorophyll-a concentration (mg/m^3) was computed from monthly composites of SeaWiFS (Sept 1997-Dec 2002) and MODIS (Jan 2003-Dec 2013) sea color sensors. The initial resolution of those data being 9 km, data was aggregated and averages along a 1° longitude and 0.33° latitude grid. Chlorophyll concentration was log-transformed because of the highly skewed distribution of original data.

[3] The so-called "French data set" encompasses the French-flagged vessels and other purse seiners registered in Mayotte, Mauritius and Italy

2.3 Filtered nominal CPUE

Filtered nominal CPUEs were computed in the area situated north of the equator (NEQ, 45E-70E / 0-13N) during July-November, using the purse seine set (successful or not) and the positive set (successful only), as units of effort. We used two different thresholds for the positive set: minimum of 1 and 3 sets by 1°/fortnight box. This allowed an assessment of the effect of such effort thresholds on CPUE estimates.

We also tested the effect of the size of the area on CPUEs. To do so, in addition to NEQ, we considered two nested sub-areas (shown in red and green in Fig. 1) within the NEQ.

Monthly series of CPUEs for each of the areas considered were obtained by averaging the mean 1°-month CPUEs that complied with the effort threshold.

2.4 CPUE standardization

The shape of the relationships between covariates was investigated using generalized additive models (GAM) (Hastie and Tibshirani, 1990) after testing that covariates entered in the models were not correlated. GAMs allow to define thresholds (e.g. in case of asymptotical relationships) leading to data transformation into the GLM. The CPUEs analyzed were log-transformed : *lcpue = log(CPUE+0.1)*.

We used the GLM in R statistical software package to standardize CPUEs. The GLM method (McCullagh and Nelder 1989) was applied to datasets based on aggregated data (1° longitude/0.33° latitude) and by month. Depending on the observed CPUE data distribution, the GLM approach assumed a lognormal or delta-lognormal error distribution. When the proportion of zeros was higher than 5%, the delta-lognormal model was applied. The abundance indices were obtained from GLM analyses. On one side, a positive CPUE was estimated from yearly average fitted values of the lognormal model. On the other side, estimated proportions of catches were estimated from yearly average fitted values of the binomial model. The CPUE index for each species was finally calculated as the product of year average fitted values of lognormal model and binomial models.

Seven datasets (leading to 7 models, Mod.1 to Mod.6 + Mod.5b) were prepared for the GLM analyses, in order to explore the CPUE trends in various situations (Table 1). All datasets are based on SKJ catches on object-associated sets only, aggregated by 1°lon/0.33°lat / month. The first level of partitioning was the area. We considered the whole West Indian Ocean (35E-80E / 20S-13N) where the PS fleets operate, for the entire year, on one hand, and the NEQ (previously defined) in July-November on the other hand. Then we considered various effort units and thresholds.

Table 1 – Summary on datasets used for the GAM and GLM analyses

Model	Area	Year range	Season	Effort	Minimum effort threshold	CPUE
1	WIO	1984-2013	All year	fishing days	2	t / fish day
2				all sets	0	t/set
3				positive sets	3	t/positive set
4	NEQ	1984-2013	July-November	fishing days	2	t / fish day
5				all sets	0	t / set
6				positive sets	3	t/positive set
5b		1997-2013		all sets	0	t / set

The covariates entered in the models were : year, month, lon, lat, average number of sets/day (ctotday), cpue, SST anomaly (SSTa), Mixed layer depth anomaly (MLDa), velocity of the surface current (SurfCurrent), and whether cpue is null (0) or positive (1). The latter was defined to be used in the binomial models (pue_bin). The variable *ctotday* was selected as a proxy of the abundance of drifting objects exploited in the fishery, under the assumption that a single log or FAD is not fished more than once a day and that only object-associated catches are considered in the study. The selection of the most parsimonious model was conducted by the *stepAIC* procedure of the R package, ending up with the lowest value for the Akaike criterion.

3. Results

3.1 Temporal patterns of the fishery

Purse seine French catch trends on drifting objects (logs and FADs) and free schools for the two species targeted by PS, yellowfin and skipjack, are shown in Fig. 3 for the whole Indian Ocean. Yellowfin catches on drifting objects have remained more or less stable. Skipjack catches have declined dramatically in the period 2002-2012, and have slightly increased in 2013 compared to 2012 (Fig 3a).

Free schools catches are dominated by yellowfin (Fig. 3b). Until 2007, SKJ was also caught on free schools (average of 7200 t/year) but these catches have collapsed to an average of 800 t in 2012-2013, a phenomenon also noted by Fonteneau (2014).

Because of Somalian piracy, the number of 1° squares fished has decreased since 2008. This affected primarily the free school sets (67% decrease from 2008 to 2013), but also the FAD sets with a lesser magnitude (25% from 2008 to 2012). The number of squares fished for FADs increased abruptly in 2013 (Fig. 3c).

In the North Equatorial area, the object-associated catches are very seasonal. The annual cycle of various indicators are represented in Fig.4. The fishing season kicks off in June and ends in December but the bulk of catches (> 1000 t, on average) is distributed from July to November. Number of sets, number of fishing days, number of 1° squares visited and number of vessels display the same pattern. The success rate (number of positive sets/total numbers of sets) gets its highest values (>90%) from July to November as well. By contrast, the number of sets/day increases from 1 to 1.2 throughout the fishing season

3.2 Filtered nominal CPUE indices (Table 2 and Fig. 5)

The series produced using the two effort thresholds (1 and 3 sets minimum) did not lead to significant differences in CPUE estimates (R^2 ranging from 0.86 to 0.93, $p<0.001$). Likewise, the size of the area (NEQ, sub-areas 1 & 2) did not affect the level of CPUE estimates (R^2 of 0.89 to 0.99, $p<0.001$).

Overall, the filtered-nominal CPUE indices showed an overall declining trend, with a steeper rate of decline over the past 4-5 years (Fig. 5)

A linear fit applied to the less-filtered series (NEQ, all sets) leads to an overall decline of 49% between 1984 and 2013. We could also consider that the large fluctuations seen for 1984-1998 do not reflect a trend. However, a downward trend cannot be refuted for the period starting in 1999, and the corresponding decline estimated by a linear fit would be 54% between 1999 and 2013.

3.3 Standardized CPUE indices

a) Exploratory GAM analyses

The use of GAMs was intended to highlight any existing non-linear relationships that would require a transformation of variables in the subsequent GLMs. We cannot present all the graphs produced during this phase, but the main outcome can be summarized as follows:

- The model tested to examine the shape of *ctotday* and *MLDa* was :
  lcpue ~ Year + Month + Lon + Lat + s(ctotday) + s(MLDa), family=gaussian
- For CPUEs based on the fishing day, the number of set/day (*ctotday*) displayed an asymptote illustrating a threshold beyond which the response in CPUE is flat (Fig. 6a). Another significant factor, the mixed layer depth anomaly (*MLDa*) was close to a similar trend, with higher (lower) CPUEs for shallow (deep) thermocline (Fig. 6b). Therefore, we only transformed *ctotday* in the GLM whereby we considered a linear trend from 0 to 1.5 number of sets/day, and we assigned a value of 1.5 to all *ctotday* values beyond this threshold.
- For CPUEs based on number of sets, *ctotday* and *MLDa* displayed a rather linear declining trend, hence no transformation was required for those two factors in the GLM (Fig 7a,b)
- The velocity of the surface current never appeared as a significant factor.

We also introduced the satellite-derived chlorophyll-a concentration (CHL) for the period when such information was available (since Sept 1997). Among all environmental covariates during 1997-2013, only CHL was significant. The variable *ctotday* was not either significant in this model:

*lcpue ~ Year * Month + Lon + Lat + s(CHL, bs = "cs"), family=gaussian*

This simple model explained 16.9% of the deviance. The CPUE increases with increasing CHL until a threshold of -0.5 (equivalent to 0.60 mg/m^3) (Fig 8). Likewise *ctotday* for the fishing day-based CPUE, CHL will be transformed in the corresponding GLM to account for the non-linear relationship.

b) CPUE standardization using GLMs

The detailed result tables, QQplots, distribution of residuals and nominal/standardized CPUE indices for the 7 selected models are presented in the Appendix. CPUE time series are plotted in Fig.9b,c. The series were scaled to the average value for 1984-2013.

The salient points emerging from this analysis are:

- In Mod 1 and 4, where CPUE indices are based on the fishing day, the most influential factors are the year and the number of sets/dat. The cumulated deviance explained by the two factors is 70% and 60% for Mod 1 and 4 respectively. The next two factors are the *year:month* interaction and the *latitude*, whereas *MLDa* takes a minor part of the deviance.
- With CPUE indices based on the fishing day, the binomial model explains more deviance than the lognormal model (considering only non-null CPUEs): 46% versus 17% in the Western IO case, 51% vs 23% in the NEQ case.
- In Mod. 2, 3, 5 and 6, where CPUE indices are based on the sets or positive sets, the year, month and their interaction held most of the deviance of the models: 59, 64, 74 and 79% for Mod 2, 3, 5 and 6 respectively. The number of sets/day and the MLDa, although highly significant, took a minor part of the deviance.
- By contrast to Mod 1 and 4, the binomial models applied in Mod.2 and 5 explained a negligible deviance; the deviance explained by the lognormal models was 16 and 33% for Mod. 2 and 5 respectively.

- The models concerning the NEQ area explained approximately twice more deviance than those concerning the WIO.
- The GLMs showing the residuals distribution that are the closest to a Gaussian are Models 2 and 5, which are based on all object-associated sets. Model 6 displays a very good fit (well aligned QQ plot points, Gaussian distribution of residuals) but the distribution is not aligned with the line y=x.
- An additional model performed on the same dataset as Mod.5, but where chlorophyll has been incorporated, gave a slightly better fit than Mod.5, in terms of QQ plot and distribution of residuals. Surface chlorophyll concentration was the second most explanatory factor after year to explain the variability of non-null CPUEs, whereas it had a very minor effect in the binomial model.

4. Discussion

The sensitivity tests performed on nominal filtered CPUEs advocates for keeping the whole NEQ as the core area for estimating PS CPUEs on drifting objects. The difference exiting between the analyses based on “all sets” and those based on “3 positive sets” is a long term decline since the beginning of the fishery with the latter whereas the former suggest fluctuations without trend for 1984-2002. However, all series converge towards a substantial decline of CPUE indices for 2002-2013, with a steeper rate over the past 4-5 years.

The filtered nominal indices show an overall declining trend with CPUE in 2013 being half that of 1984 (Fig 9a). All series, nominal and standardized, are characterized by a deep trough in 1997-98 which might be related to the combination of two unfavorable factors: a deeper than- normal thermocline on one hand, and anomalously low chlorophyll concentration on the other hand (Fig 10). Deep thermocline tends to reduce the density of fish in the upper layer, hence becoming less vulnerable under floating objects, and low chlorophyll concentration indicates less productivity from the base of the food chain. The extreme low chlorophyll concentration in Jul-Nov 1997 was caused by the strongest El Niño event in the 20th century. The effect of such event on PS fisheries has been well documented by Marsac and le Blanc (1999, 2000), Ménard et al (2007) and Vialard et al (2009). The fleets when the fleet moved to the east IO because surface dwelling tuna were no longer available for purse seine fleets in the usual fishing grounds.

As we worked on aggregated data, which makes that one observation in the data matrix is a spatial box and a month, we could not incorporate vessels characteristics. Anyhow, Soto et al (2013) noted that in general, the standardization procedure showed that vessel characteristics (country, harvest capacity and age of vessel) have a relative minor explanatory effect on the catch rate of juveniles of tropical tuna in the purse seine fishery.

The CPUE response with *ctotday* (a proxy of abundance of drifting objects exploited in the fishery) examined with the GAMs (Fig. 6 and 7) displays a different kind of relationship across the two types of efforts used for the CPUEs. In the case of fishing days, CPUE increases rapidly with the number of sets/day then levels off after the value 1.5. This can reflect a sort of saturation effect (maximum possible number of sets for each vessel) as the number of drifting objects increases. In the case of sets used as effort unit (all sets or positive sets), CPUE decrease almost linearly with *ctotday*. In other terms, the abundance around drifting objects would be reduced when the number of objects increases, possibly because the resource may become more scattered in such situation.

The best fits obtained with models using the catch per sets compared to the catch per fishing day confirms the fact that CPUEs expressed in t/ set (or t/positive sets) should be preferred for skipjack assessments.

The standardized CPUEs calculated on the WIO show an oscillating pattern (Fig. 9b) whereas the indices established for the NEQ (July to November) show a sustained downward trend since 2002 (Fig. 9c). Considering the NEQ only, the high CPUE indices from 1984 to 1992 are in phase with shallower thermocline. The upward trend of CPUEs following the El Niño might be triggered by increasing chlorophyll concentration and a return to shallower thermocline. The subsequent CPUE decline appears well in-phase with the decreasing chlorophyll concentration, whereas no clear relationships is noted with MLDa with denotes a shallow thermocline situation at least until 2010. The GAM analysis performed on the fraction of the time series where surface chlorophyll data were available shows a prominent effect of the chlorophyll on CPUE indices, with an almost linear increase until a concentration of 0.60 mg/m^3, then a levelling off at higher concentration. This is confirmed in the GLM analysis (Mod.5b) where the chlorophyll has a stronger explanatory power than MLDa does over the series 1997-2013.

Finally, by reducing the size of the area fished and shifting the fleet activities to the eastern part of the Somali basin, the effect of Somalian piracy could be seen as a contributing factor of the steep CPUE decline over the past 4-5 years. However, longitude explains a minor part of the deviance of the NEQ models. Furthermore, the RTTP-IO showed that skipjack moves actively all over the area, therefore it is unlikely that the Somalian piracy has contributed to the CPUE decline.

5. Conclusion

The overall 50% decline of skipjack CPUE from 1984 to 2013, as shown by the French PS dataset, can be considered as a realistic estimate. What can be discussed is whether such a decline started right at the beginning of the fishery or occurred later, e.g. in 2002. For the period 2002-2013, all CPUE indices exhibit a sharp decline. As object associated catches are dominated by skipjack, we cannot exclude that the tremendous deployment of FADs since 1991-1992 triggered the biomass decline in a substantial way. Indeed, the decline is not visible in the 90s when FADs started to be deployed, but the well-recognized improvements of the FAD technology and the development of a dedicated FAD fishing tactics in the subsequent years may have resulted in detrimental lagged effects.

However, environmental fluctuations are also at stake in such decline and particularly the chlorophyll concentration which is a proxy of the productivity at the base of the food chain. The underlying processes linking productivity to SKJ CPUEs are still unclear: i) unfavorable foraging conditions leading to increased natural mortality of skipjack, ii) dispersal and spatial shift of the population towards more productive areas, iii) or a combination of these two factors. Further research should be undertaken using indices from other fleets, notably from coastal countries in the East of the ocean, to account for more contrasted environmental conditions.

References

Fonteneau, A (2014). On the recent steady decline of skipjack caught by purse seiners in free schools sets in the eastern Atlantic and western Indian oceans. 16th Session of the Working Party on Tropical Tunas, 15-19 Oct 2014. SCRS/2014/134 and IOTC-2014-WPTT16-INF02, 11 p.

Hastie, T.J., Tibshirani, R.J. (1990). Generalized Additive Models. Edited by Chapman and Hall, New York.

Marsac, F, Le Blanc J.L (1998). Dynamics of ENSO events in the Indian Ocean : to what extent would recruitment and catchability be affected ? In Ardill (Ed) Proceedings of the Expert Consultation on Indian Ocean Tunas, 7th session, IOTC, Victoria, Seychelles, 9-14/11/98. IOTC Proceedings 1 : 89-101.

Marsac, F, Le Blanc J.L (1999). Oceanographic changes during the 1997-1998 El Niño in the Indian ocean and their impact on the purse seine fishery. 1st session of the IOTC working party on tropical tunas, Mahe, Seychelles, 4-8/09/99. WPTT/99/03. IOTC Proceedings 2 : 147-157.

Marsac, F. (1988). Purse seine tuna fishing and environmental conditions in the Somali Basin (0°-12°N/43°E-60°E) at the cessation of the southwest monsoon. 3rd Expert Consultation on Indian Ocean Tunas, Ile Maurice, 22-27/06/88. *IPTP Coll. Vol. Work. Doc*., 3: 154 - 163.

McCullagh P, Nelder JA (1989) Generalized Linear Models. Chapman and Hall, London, 509 pp

Ménard, F., Marsac F., Bellier, E., Cazelles B. (2007). Climatic oscillations and tuna catch rates in the Indian Ocean: a wavelet approach to time series analysis. *Fisheries Oceanography* 16 (1): 95-104.

Soto, M., Chassot; E., Marsac F. (2008). Standardized catch rates for yellowfin (*Thunnus albacares*) and skipjack (*Katsuwonus pelamis*) for the European purse seine fleet of the Indian Ocean, 1984-2007. 10th Session of the Working Party on Tropical Tunas, 23-31 Oct 2008.. IOTC 2008-WPPT-26, 21 p.

Soto, M., Delgado de Molina A., Chassot E (2013). Standardized CPUE for juveniles yellowfin, skipjack and bigeye tuna from the european purse Seine fleet in the Indian ocean from 1981 to 2011. IOTC-2013-WPTT15-23, 15 p.

Vialard, J., J.P Duvel, M. McPhaden, P. Bouruet-Aubertot, B. Ward, E. Key, D. Bourras, R. Weller, P. Minnett, A. Weill, C. Cassou, L. Eymard, T. Fristedt, C. Basdevant, Y. Dandonneau, O. Duteil, T. Izumo, C. de Boyer Mentegut, S. Masson, F. Marsac, C. Menkes, S. Kennan (2009). Air-sea interactions in the Seychelles-Chagos thermocline ridge region. *Bulletin of the American Meteorological Society*, 90(1): 45-61

Table 2 – Filtered nominal French PS skipjack CPUEs for the NEQ area and 2 sub-areas (see red and green lines in Fig.1), July-November. Two minimal thresholds are used for the three areas, whereas no threshold is assigned for the total sets.

Year	Positive sets only						All sets
	Sub-area 1		Sub-area 2		NEQ		NEQ
	1 set mini	3 sets mini	1 set mini	3 sets mini	1 set mini	3 sets mini	no thresh.
1984	27.1	24.8	27.3	25.0	27.7	24.8	26.2
1985	23.4	36.6	23.4	36.6	29.4	33.0	27.2
1986	24.9	36.0	24.9	36.0	28.5	33.3	25.3
1987	25.8	28.3	25.8	28.3	27.2	29.7	23.8
1988	32.2	37.6	32.2	37.6	31.1	38.4	28.3
1989	21.3	23.5	21.3	23.5	22.1	24.0	21.4
1990	25.7	19.5	25.7	19.5	26.9	20.7	25.6
1991	25.5	23.7	25.5	23.7	25.8	23.4	23.4
1992	36.5	35.6	36.5	35.6	36.4	37.3	33.9
1993	26.5	33.1	26.5	33.1	26.0	29.4	25.4
1994	22.1	25.6	22.3	25.9	23.3	26.2	21.3
1995	21.6	24.2	21.6	24.2	21.8	23.4	19.7
1996	20.6	23.2	20.6	23.2	20.7	22.4	19.9
1997	17.0	16.5	17.0	16.5	16.0	15.8	14.8
1998	17.0	17.0	17.0	17.1	17.0	17.2	15.6
1999	24.8	24.7	24.7	24.9	25.3	24.4	23.7
2000	23.3	26.6	23.1	24.8	25.2	25.4	23.0
2001	23.5	23.2	23.5	23.2	23.3	22.5	21.3
2002	27.6	29.2	27.6	29.2	28.4	27.8	26.5
2003	26.3	29.9	26.3	29.9	26.3	28.6	23.8
2004	17.1	15.7	17.5	15.7	16.3	15.6	14.1
2005	26.6	28.3	26.6	28.3	26.6	29.1	24.2
2006	23.8	24.8	23.9	24.8	23.7	25.0	21.3
2007	16.4	19.4	16.4	19.4	16.1	19.5	13.4
2008	15.2	18.4	15.1	18.4	15.1	18.2	13.8
2009	23.0	23.1	23.0	23.1	23.0	22.9	21.9
2010	17.2	17.6	17.4	17.6	17.1	17.6	16.0
2011	13.9	13.2	13.9	13.2	13.7	13.2	12.9
2012	10.5	10.2	10.5	10.2	10.7	10.2	9.3
2013	9.5	11.6	9.5	11.6	9.8	11.5	8.8

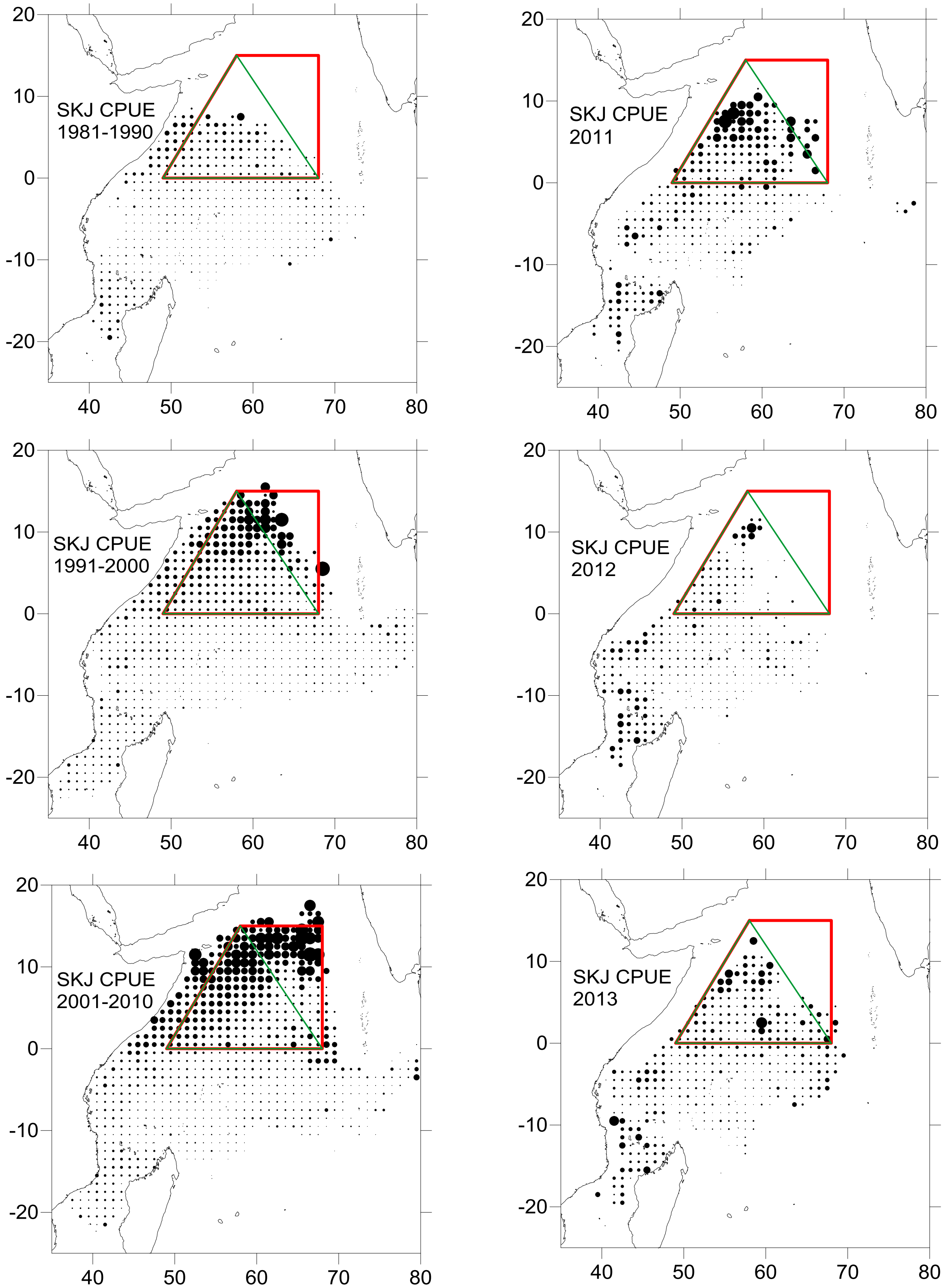


Fig.2- Annual average of skipjack CPUEs, from sets made on associated sets (logs and FADs), by decade (1981 to 2010) and for the last three years available in the French PS dataset. The red and green lines delineate two sub-areas used to assess the sensitivity of CPUE estimates to the size of core areas.

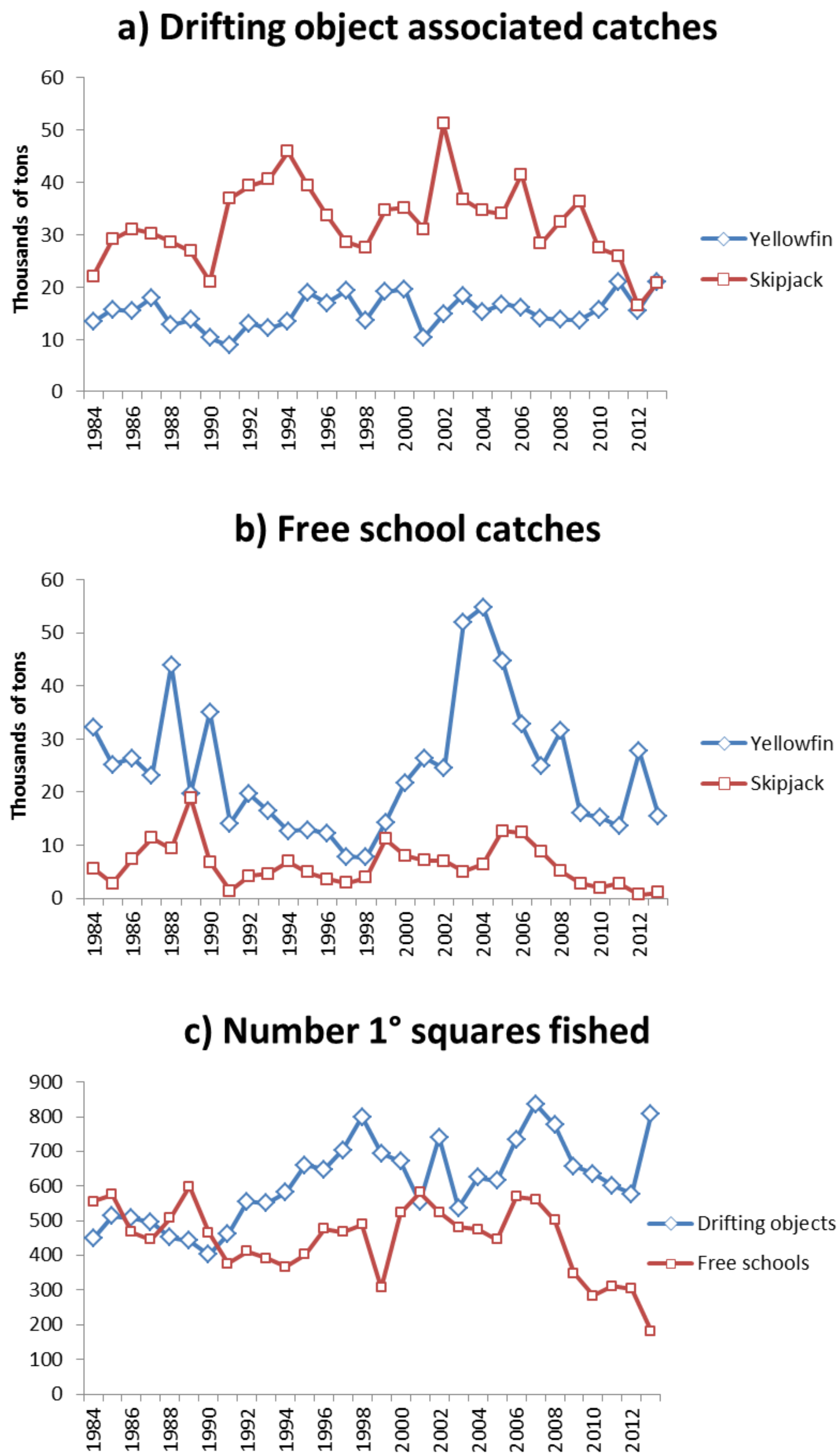


Fig.3 – Catches by school type and proxy of the area fished (number of 1 squares) for the French PS fishery, whole Indian Ocean, 1984-2013.

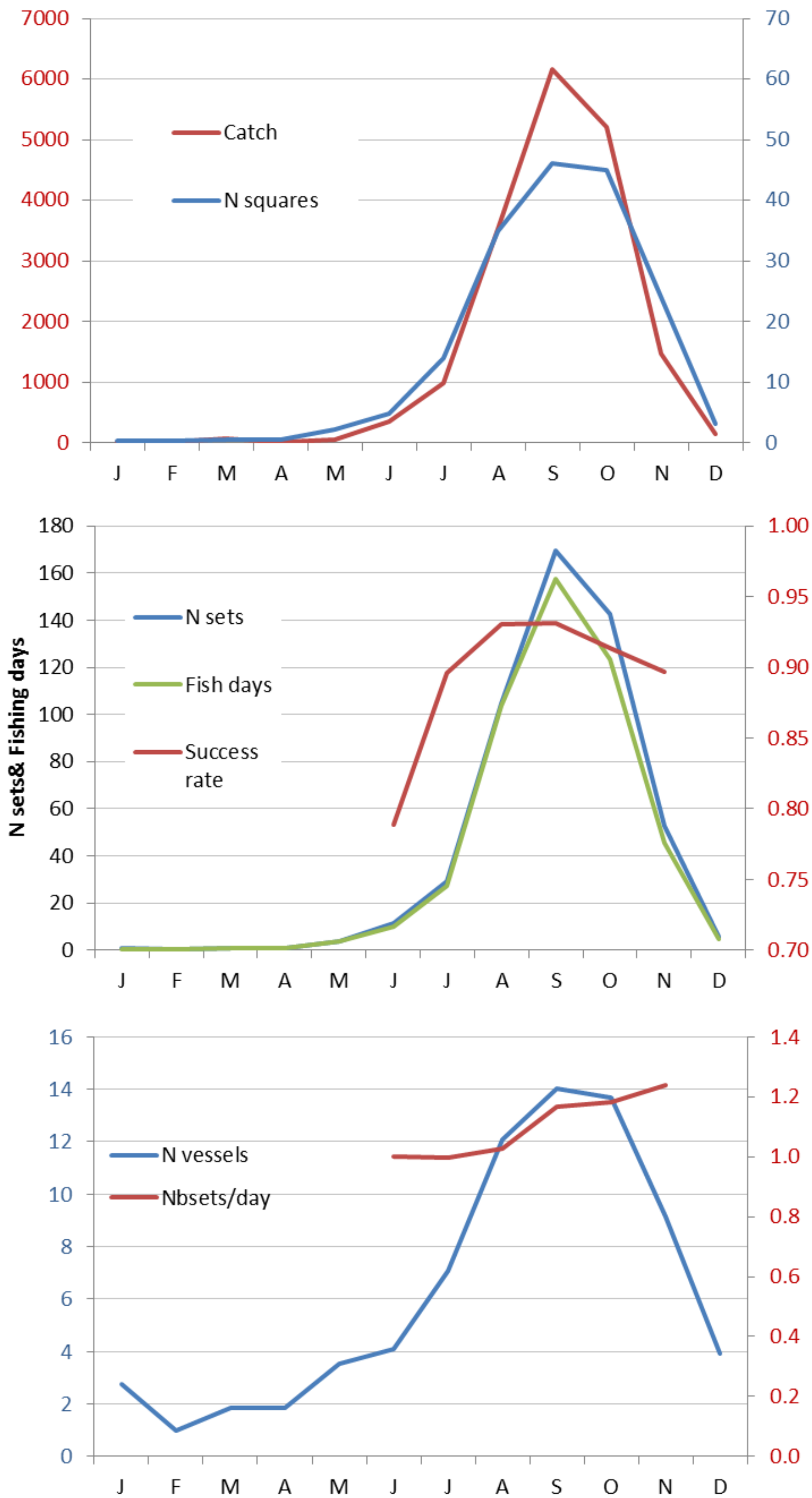


Fig.4 – Annual cycle of several variables illustrating the French purse seine SKJ fishery in the North Equatorial area, average 1984-2013.

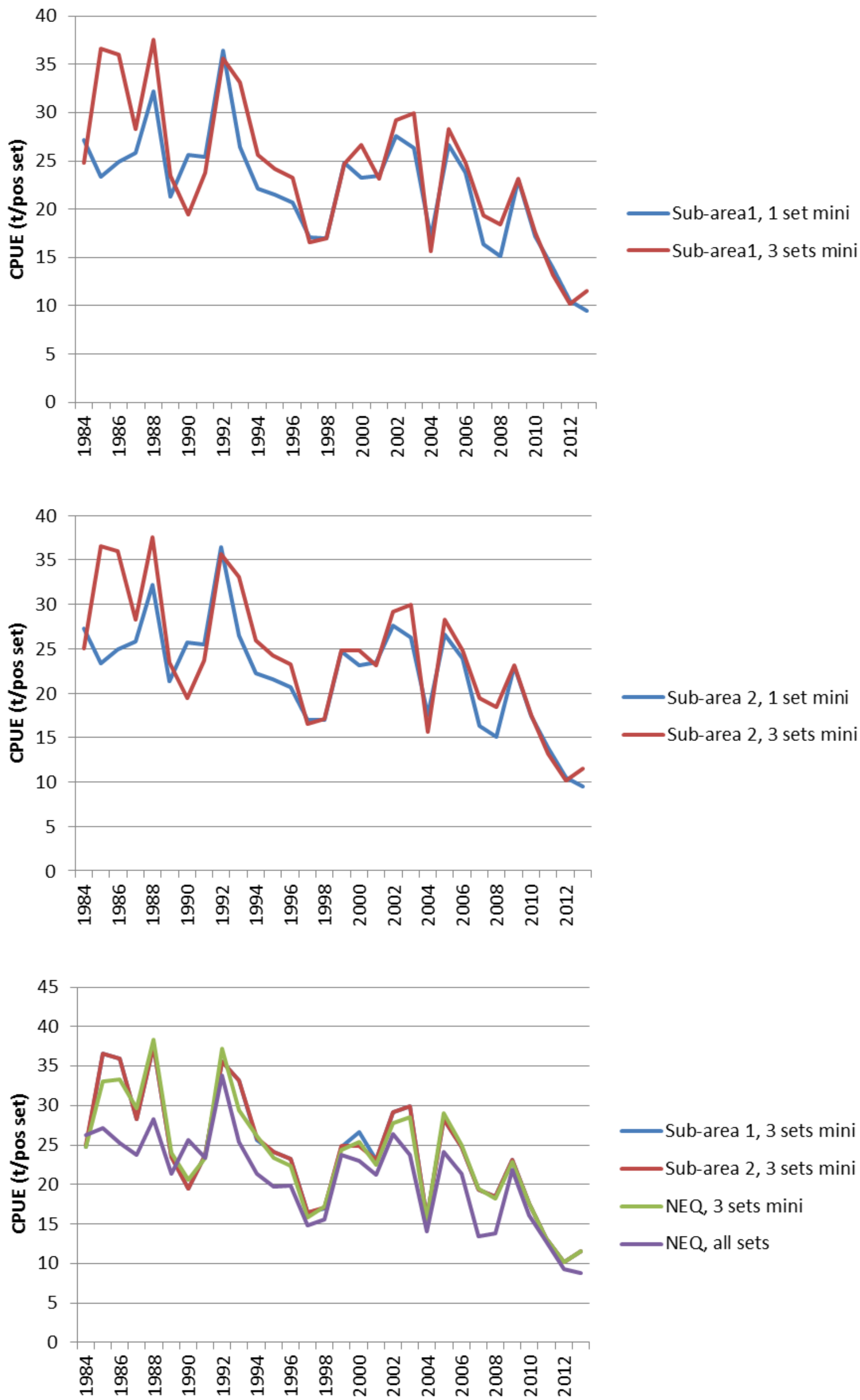
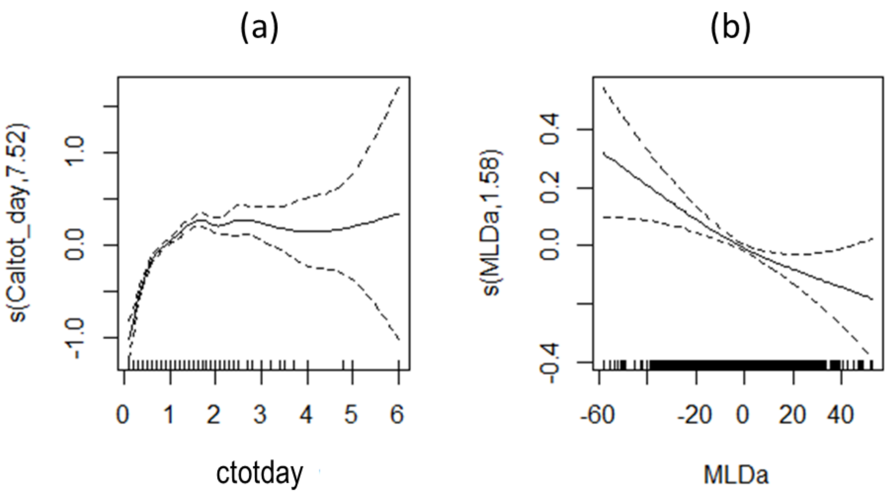


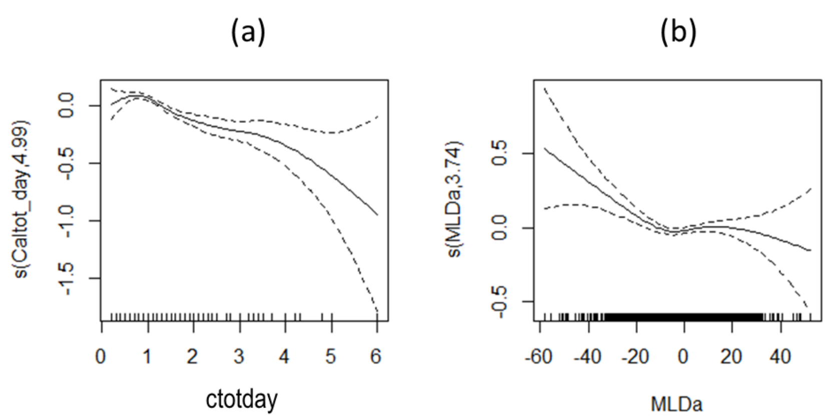
Fig. 5 – Filtered nominal CPUE indices (in tons/set) according to different areas and effort thresholds (data presented are from Table 2)



	Edf	*F*	*p-value*
s(ctotday)	7.521	37.068	< 0.001
s(MLDa)	1.576	8.589	< 0.001

Explained deviance = 16.7%

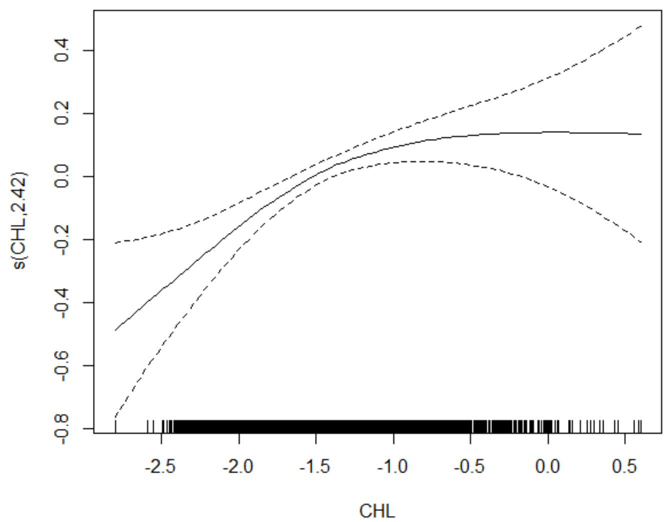
Fig. 6 – GAM output for Model 1 (WOI, CPUE based on the fishing days)



	Edf	*F*	*p-value*
s(ctotday)	3.902	18.52	< 0.001
s(MLDa)	4.559	5.153	< 0.001

Explained deviance = 17%

Fig. 7 – GAM output for Model 3 (WOI, CPUE based on the number of positive sets)



	Edf	*F*	*p-value*
s(CHL)	2.419	6.243	< 0.001
Explained deviance = 16.9 %			

*Fig. 8 – GAM output for a model based on Model 5 dataset (WOI, CPUE based on the number of sets) having only CHL as environmental covariate : lcpue ~ Year * Month + Lon + Lat + s(CHL, bs = "cs"). Only the spline is shown in the table. CHL is expressed in log scale. The period considered is 1997-2013*

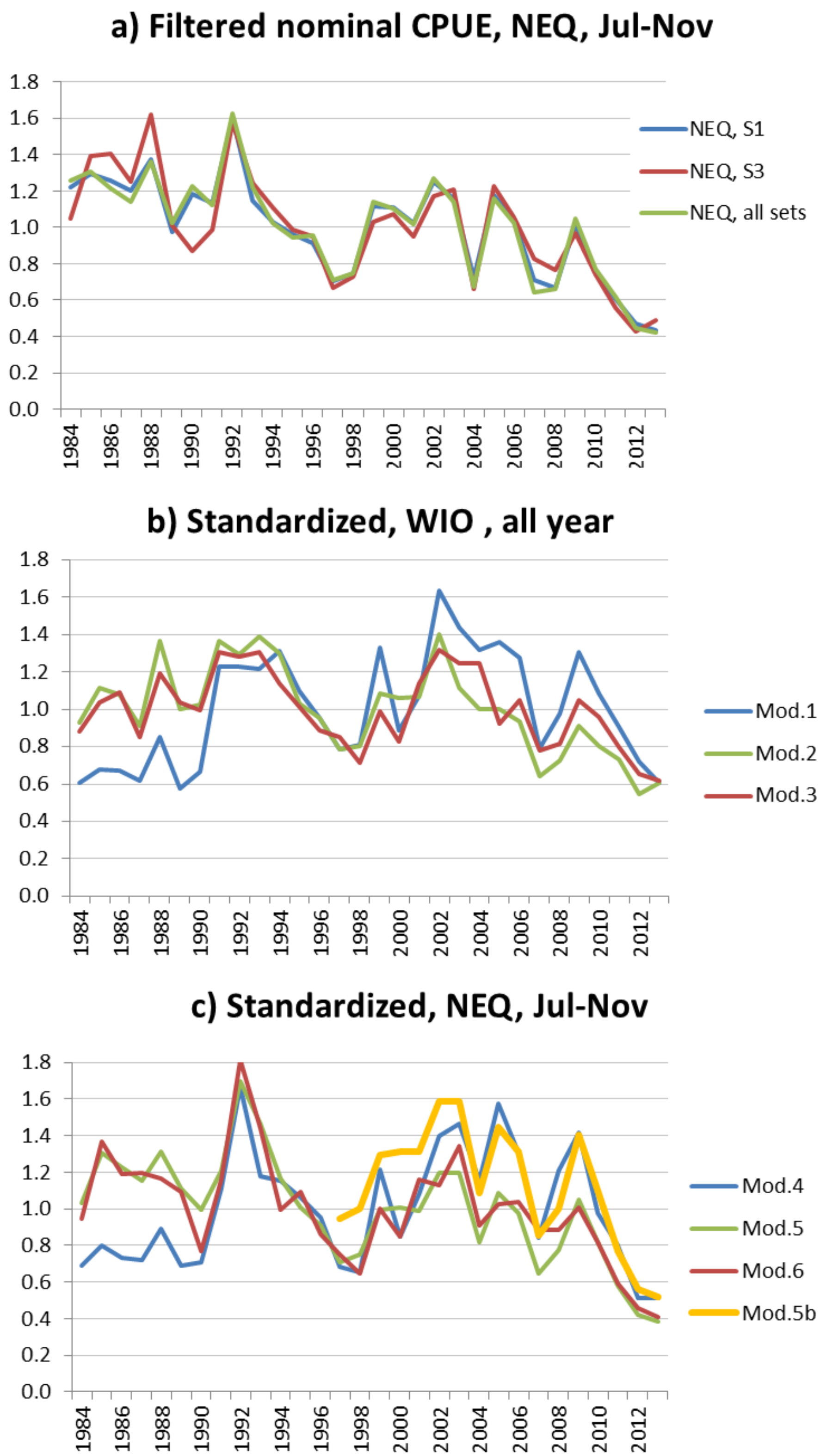


Fig. 9 – Series of filtered nominal and standardized CPUE indices (7 models). Values are scaled to the 1894-2013 mean.

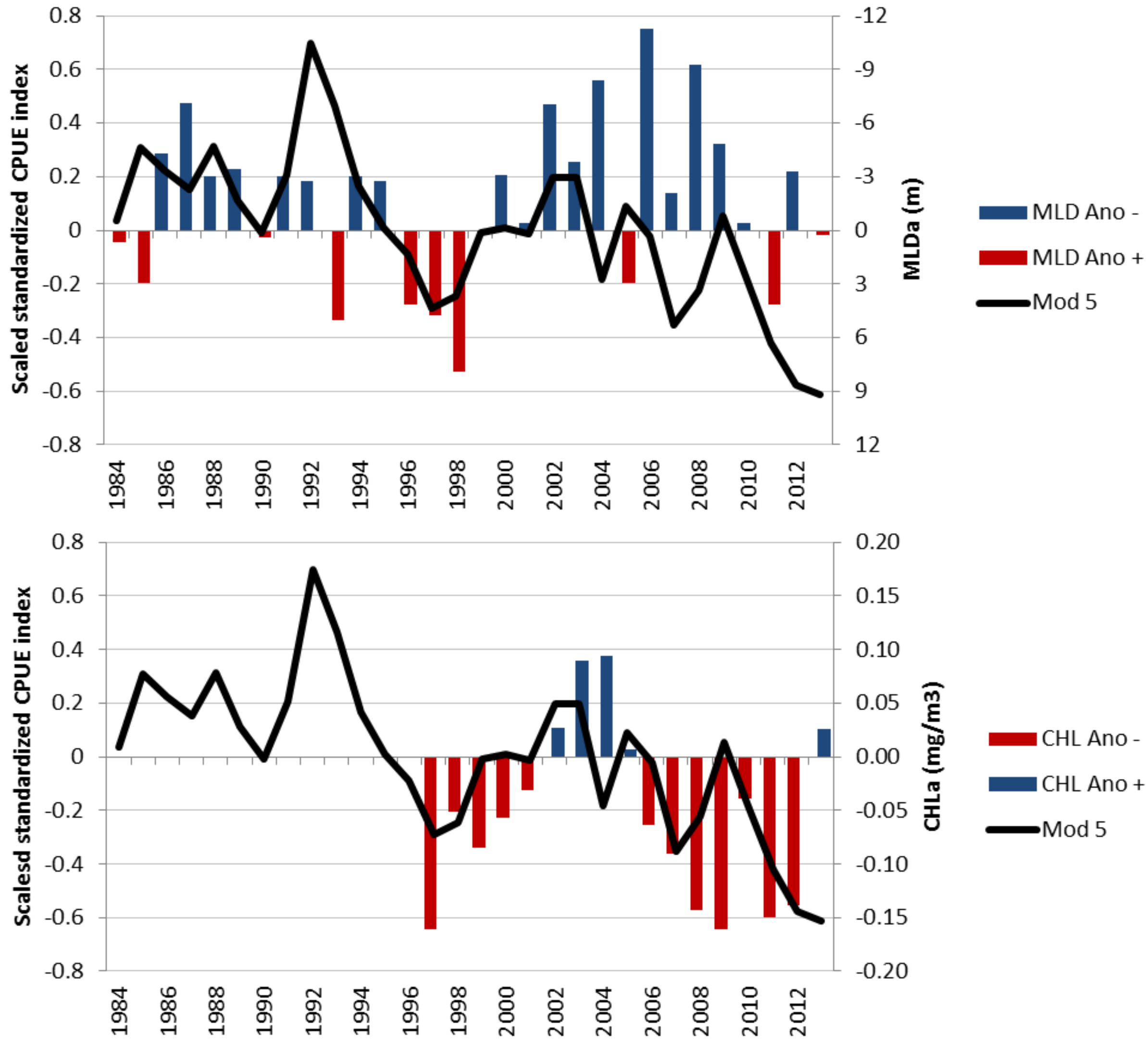
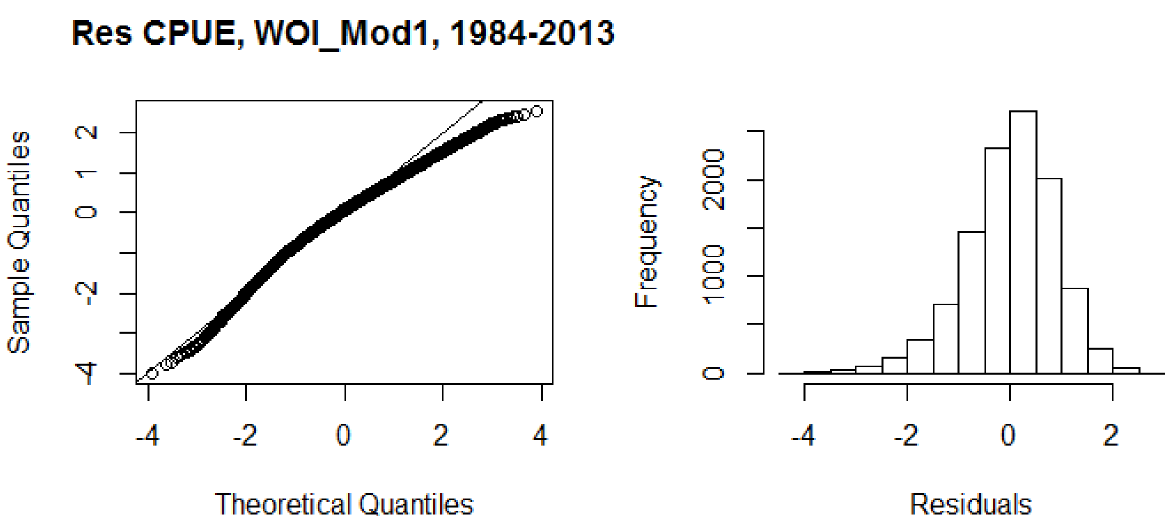


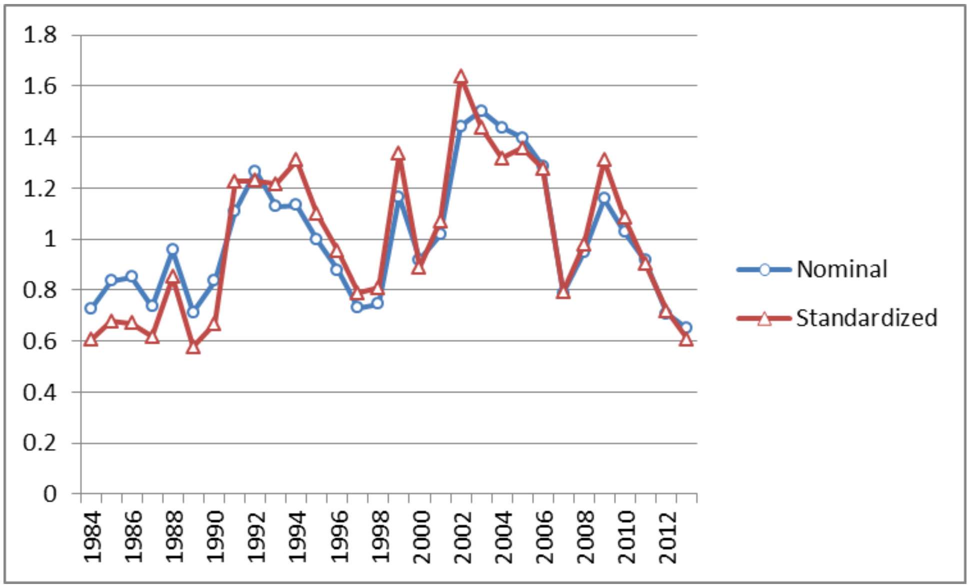
Fig. 10 – Combined series of Model 5 (NEQ, July-November) standardized CPUE? mixed layer depth anomalies (top) and chlorophyll anomalies (bottom) in the Somali basin. A negative MLDa reflects a shoaling of the thermocline, a positive MLDa indicates a deepening of the thermocline

APPENDIX : GLM outputs of the 6 skipjack PS CPUE models

MODEL 1 : Western Indian Ocean, CPUEs based on the fishing day

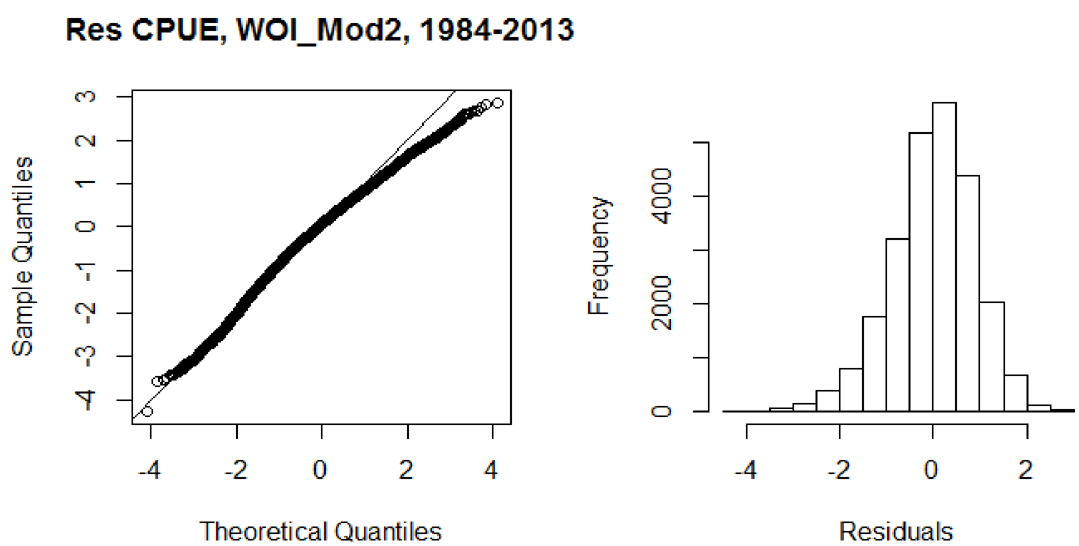
Model formulation	Df	Change in deviance	Residual deviance	p-value	% of total deviance	Pseudo R^2
Positive CPUE						
1	1		9923.2			0.17
Factor						
Year	29	667.91	9255.3	< 0.001	39.18	
Month	1	65.49	9189.8	< 0.001	3.84	
ctotday	1	545.37	8644.5	< 0.001	31.99	
MLDa	1	28.47	8616	< 0.001	1.67	
Lon	1	42.66	8573.3	< 0.001	2.50	
Lat	1	192.39	8380.9	< 0.001	11.29	
Interaction						
Lon:Lat	1	0.03	8380.9		0.00	
Year:Month	29	162.32	8218.6	< 0.001	9.52	
Proportion of positive CPUE						0.46
1	1		7391.9			
Factor						
Year	29	842.37	6549.6	< 0.001	24.42	
ctotday	1	2548.68	4000.9	< 0.001	73.90	
Lat	1	9.12	3991.8	< 0.01	0.26	
Month	1	0.27	3991.5	0.60	0.01	
Interaction						
Year:Month	29	48.52	3943	5.00E-02	1.41	

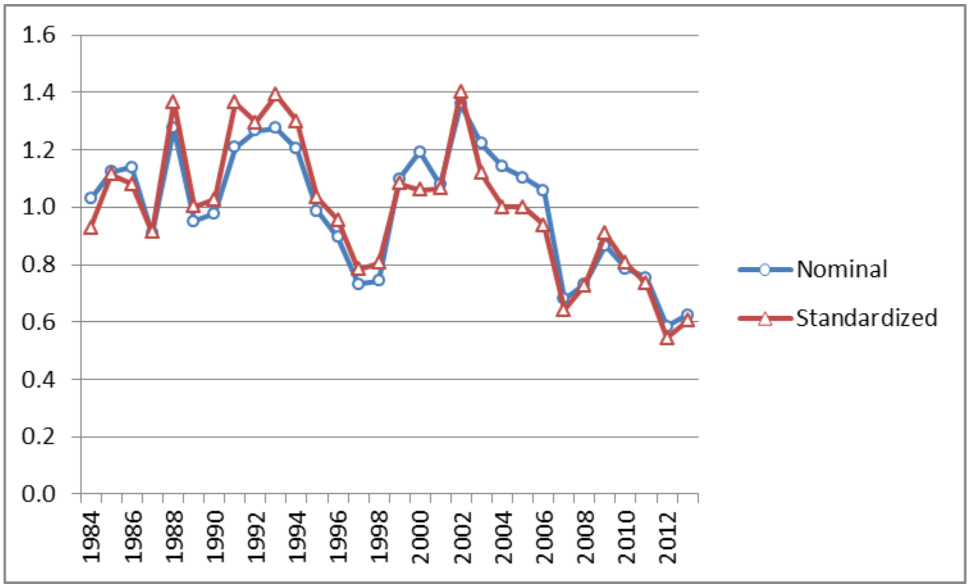



1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Nominal
Standardized

MODEL 2 : Western Indian Ocean, CPUE based on total number of sets

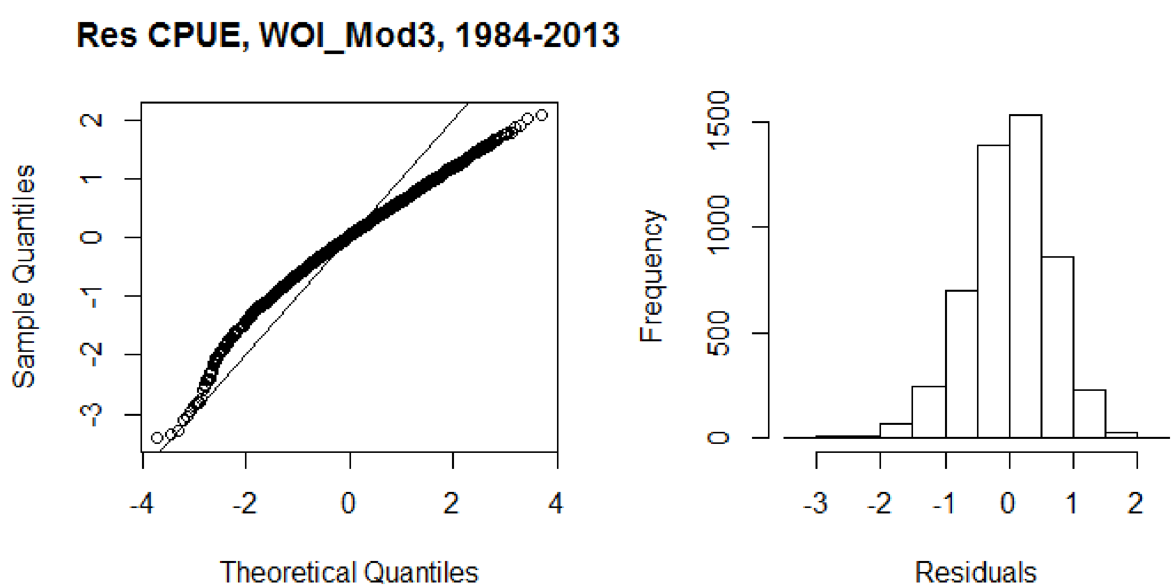
Model formulation	Df	Change in deviance	Residual deviance	p-value	% of total deviance	Pseudo R^2
Positive CPUE						
1	1		22718			0.16
Factor						
ctotday	1	15.91	22702	< 0.001	0.44	
MLDa	1	106.05	22596	< 0.001	2.91	
SSTa	1	79.03	22517	< 0.001	2.17	
SurfCurrent	1	32.29	22484	< 0.001	0.88	
Year	29	1166.65	21318	< 0.001	31.97	
Month	11	959.68	20358	< 0.001	26.30	
Lon	1	47.1	20311	< 0.001	1.29	
Lat	1	73.71	20237	< 0.001	2.02	
Interaction						
Lon:Lat	311	1165.51	19072	< 0.001	31.94	
Year:Month	1	3.03	19069	0.05	0.08	
Proportion of positive CPUE						
1	1		13703			0.04
Factor						
ctotday	1	164.06	13539	< 0.001	14.96	
Year	29	199.63	13339	< 0.001	18.20	
Month	11	157.27	13182	< 0.001	14.34	
Lon	1	9.22	13173	< 0.01	0.84	
Lat	1	24.24	13148	< 0.001	2.21	
Interaction						
Year:Month	311	535.93	12612	< 0.001	48.86	
Lon:Lat	1	6.45	12606	< 0.05	0.59	

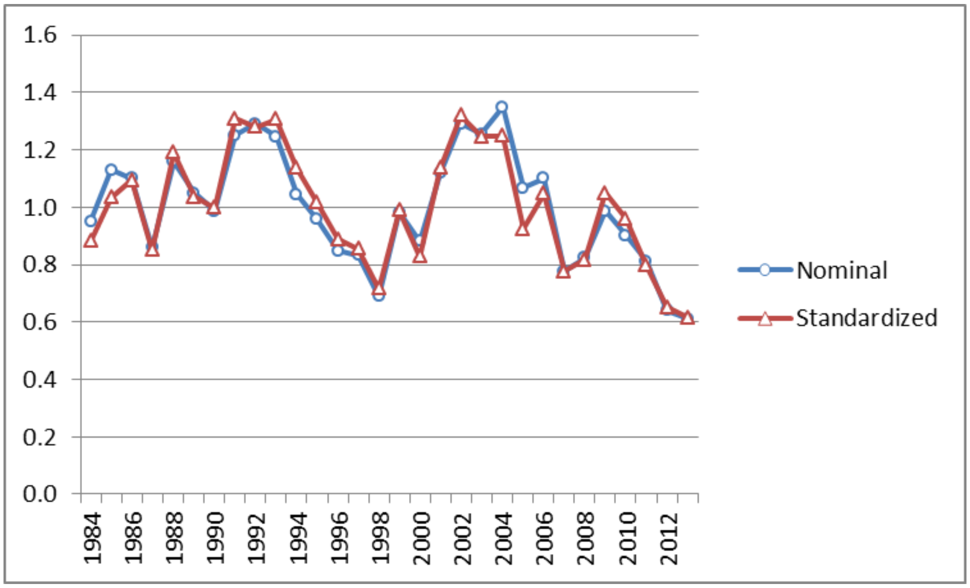



1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Nominal
Standardized

MODEL 3 : Western Indian Ocean, CPUE based on number of positive sets, minimum of 3 sets/stratum

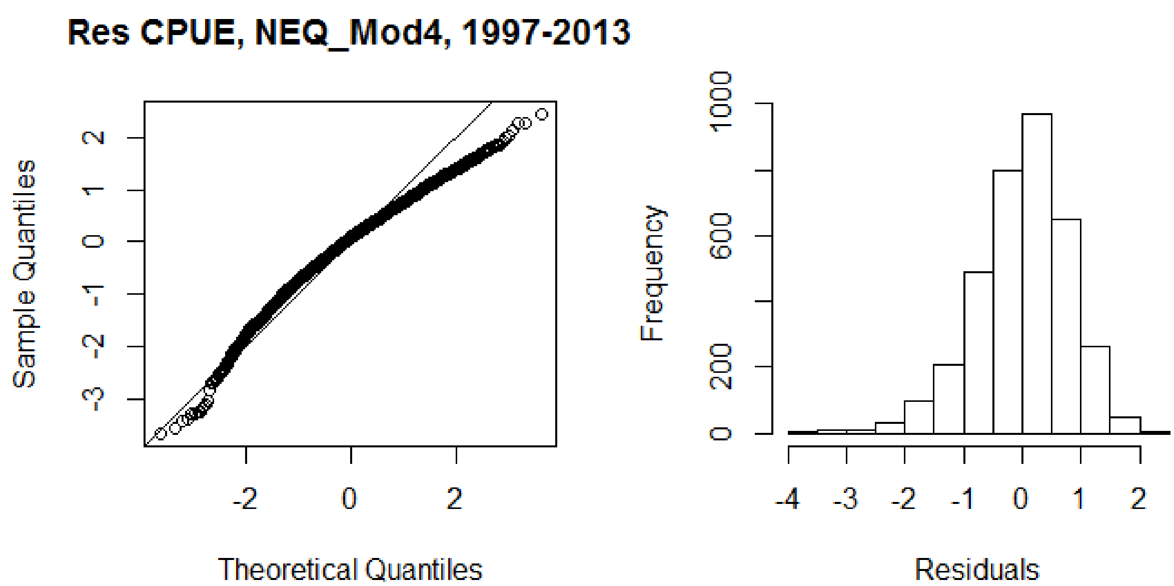
Model formulation	Df	Change in deviance	Residual deviance	p-value	% of total deviance	Pseudo R^2
Positive CPUE						
1	1		2636.2			0.17
Factor						
Lat	1	111.438	2524.8	< 0.001	24.52	
ctotday	1	42.629	2482.2	< 0.001	9.38	
MLDa	1	11.498	2470.7	< 0.001	2.53	
Year	29	188.771	2281.9	< 0.001	41.53	
Month	1	0.665	2281.2	0.21	0.15	
Interaction						
Year:Month	29	99.52	2181.7	< 0.001	21.90	

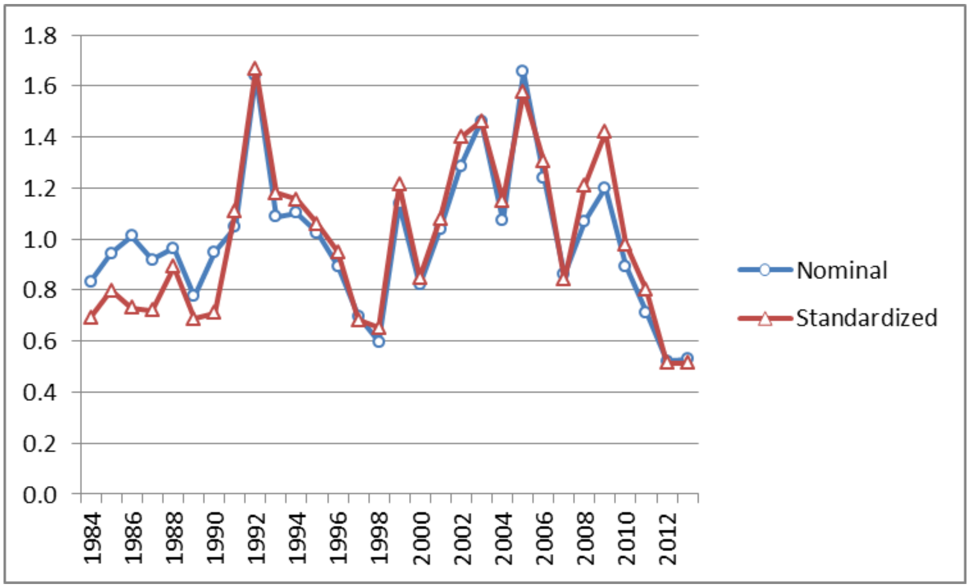



1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Nominal
Standardized

MODEL 4 : North Equatorial area, CPUEs based on the fishing day

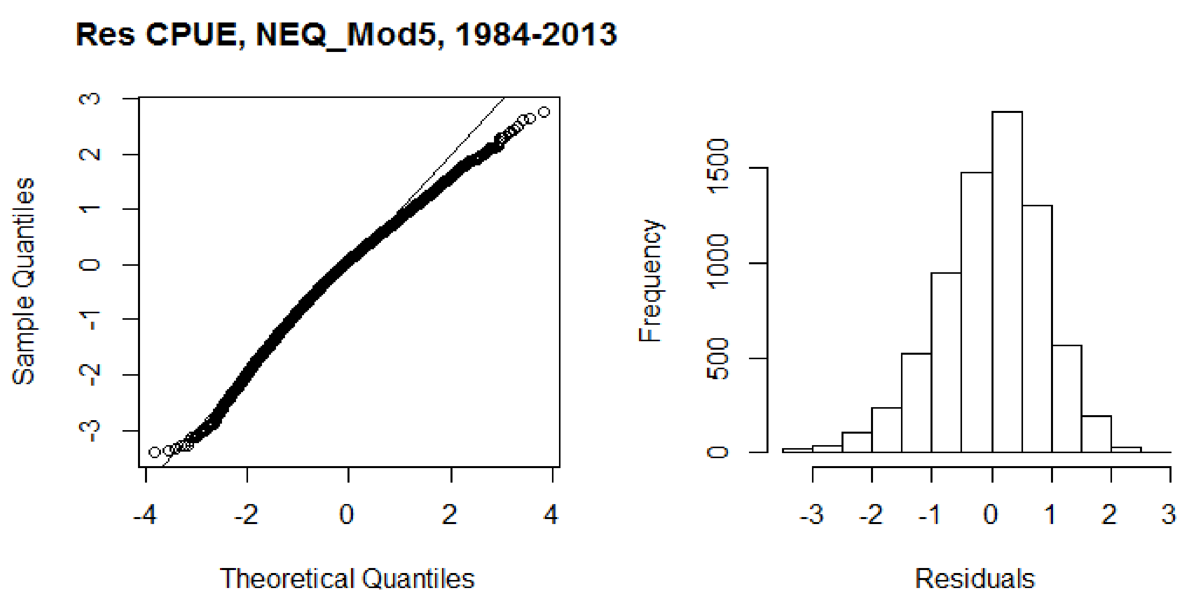
Model formulation	Df	Change in deviance	Residual deviance	p-value	% of total deviance	Pseudo R^2
Positive CPUE						
1	1		2913			0.23
Factor						
ctotday	1	178.22	2734.8	< 0.001	26.76	
MLDa	1	22.528	2712.3	< 0.001	3.38	
SSTa	1	9.159	2703.1	< 0.001	1.38	
Year	29	218.263	2484.8	< 0.001	32.77	
Month	4	39.943	2444.9	< 0.001	6.00	
Lon	1	49.027	2395.9	< 0.001	7.36	
Interaction						
Year:Month	102	148.923	8218.6	< 0.001	22.36	
Proportion of positive CPUE						0.51
1	1		2054.91			
Factor						
Year	29	300.91	1754	< 0.001	27.30	
Month	4	30.77	1723.23	< 0.001	2.79	
ctotday	1	765	958.24	< 0.01	69.41	
Lon	1	5.44	952.8	0.05	0.49	

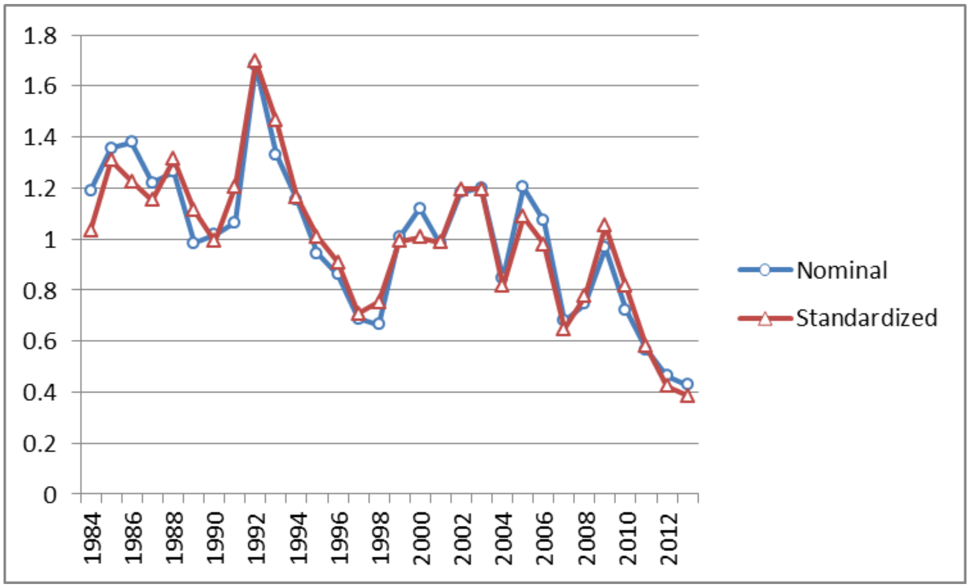



1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Nominal
Standardized

MODEL 5 : North Equatorial area, CPUE based on total number of sets

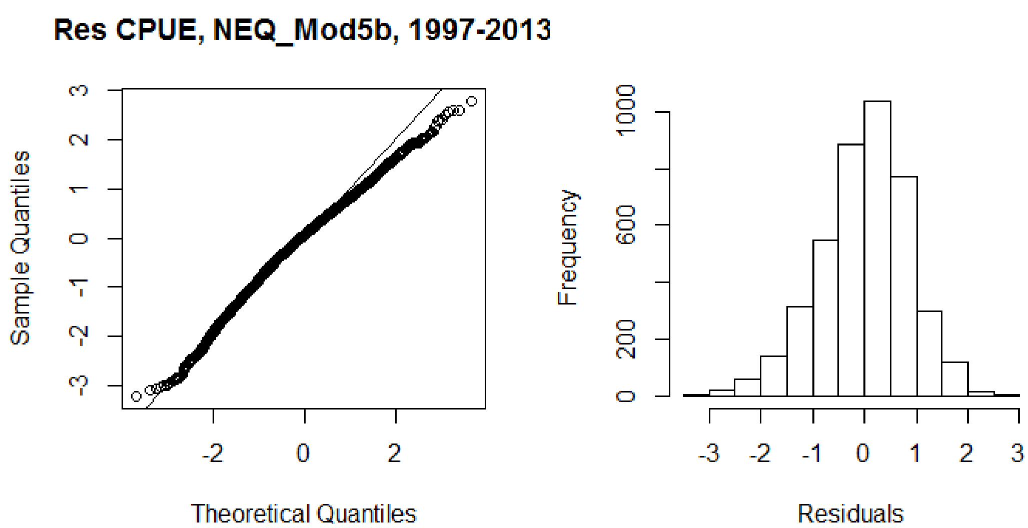
Model formulation	Df	Change in deviance	Residual deviance	p-value	% of total deviance	Pseudo R^2
Positive CPUE						
1	1		6661.3			0.33
Factor						
ctotday	1	46.47	6614.8	< 0.001	4.07	
MLDa	1	45.39	6569.5	< 0.001	3.98	
SSTa	1	53.05	6516.4	< 0.001	4.65	
SurfCurrent	1	15.56	6500.8	< 0.001	1.36	
Year	29	549.23	5951.6	< 0.001	48.13	
Month	4	87.92	5863.7	< 0.001	7.70	
Lon	1	127.18	5736.5	< 0.001	11.14	
Lat	1	11.13	5725.4	< 0.001	0.98	
Interaction						
Year:Month	111	205.29	5520.1	< 0.001	17.99	
Proportion of positive CPUE						0.08
1	1		3146.5			
Factor						
ctotday	1	46.321	3100.2	< 0.001	12.34	
Year	29	89.608	3010.6	< 0.001	23.87	
Month	4	37.238	2973.3	< 0.001	9.92	
Lon	1	27.429	2945.9	< 0.001	7.31	
Lat	1	31.245	2914.6	< 0.001	8.32	
Interaction						
Year:Month	111	137.427	2777.2	< 0.05	36.60	
Lon:Lat	1	6.167	2771.1	< 0.05	1.64	

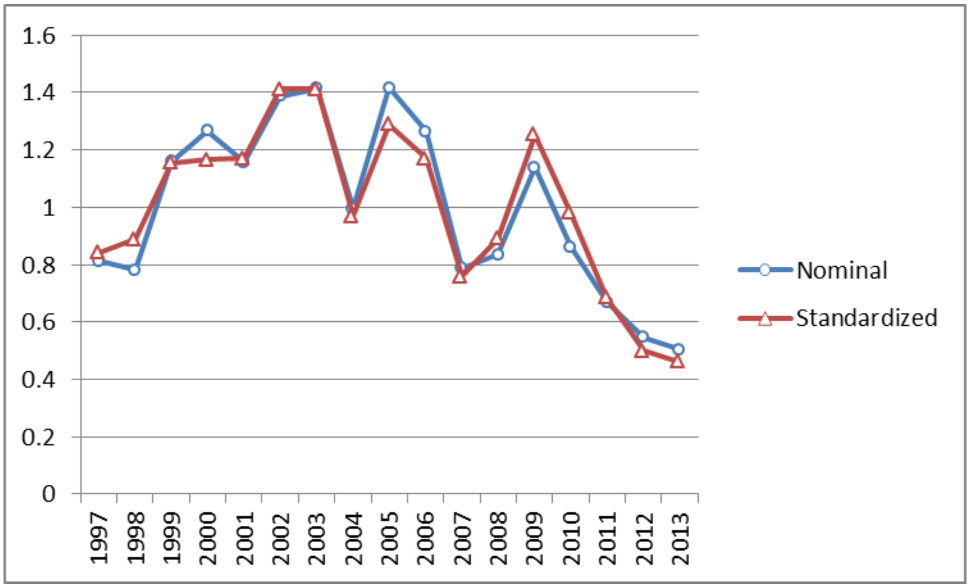



1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Nominal
Standardized

MODEL 5b : North Equatorial area, CPUE based on total number of sets, with Chlorophyll (1997-2013)

Model formulation	Df	Change in deviance	Residual deviance	p-value	% of total deviance	Pseudo R^2
Positive CPUE						
1	1		3795.4			0.17
Factor						
SSTa	1	10.089	3785.4	< 0.001	1.60	
MLDa	1	24.294	3761.1	< 0.001	3.86	
CHL	1	101.074	3660.0	< 0.001	16.04	
Year	16	310.168	3349.8	< 0.001	49.22	
Month	4	17.538	3332.3	< 0.001	2.78	
Lon	1	34.239	3298.0	< 0.001	5.43	
Interaction						
Year:Month	59	132.718	5520.1	< 0.001	21.06	
Proportion of positive CPUE						0.09
1	1		1934.5			
Factor						
ctotday	1	38.674	1895.8	< 0.001	22.60	
CHL	1	6.432	1889.4	< 0.05	3.76	
Year	16	47.29	1842.1	< 0.001	27.64	
Month	4	18.301	1823.8	< 0.01	10.70	
Lon	1	20.206	1803.6	< 0.001	11.81	
Lat	1	23.261	1780.3	< 0.001	13.60	
Interaction						
Lon:Lat	1	16.933	1763.4	< 0.001	9.90	

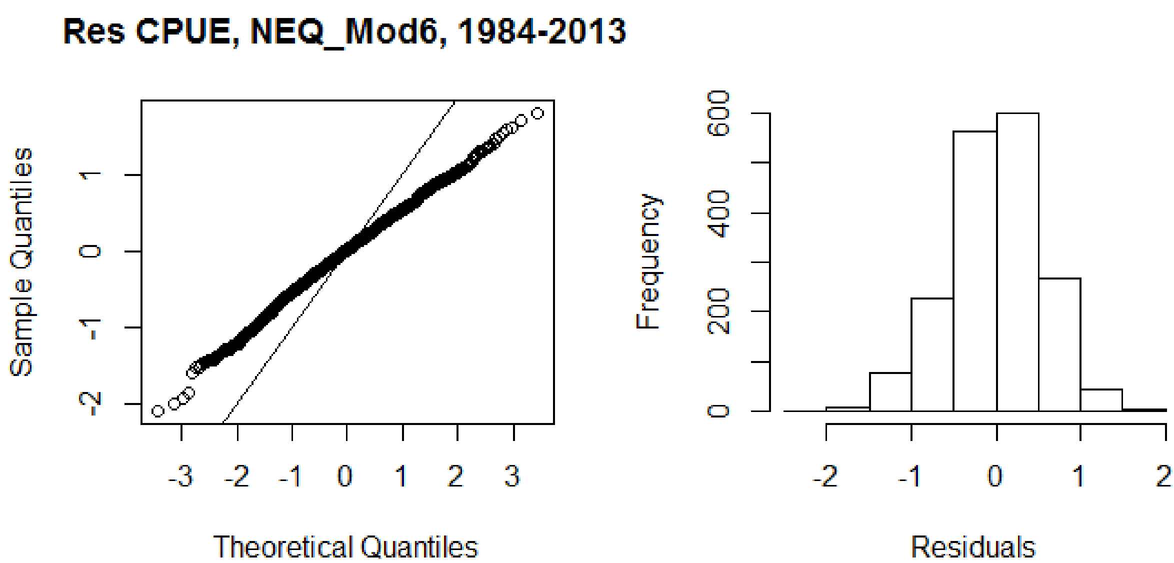


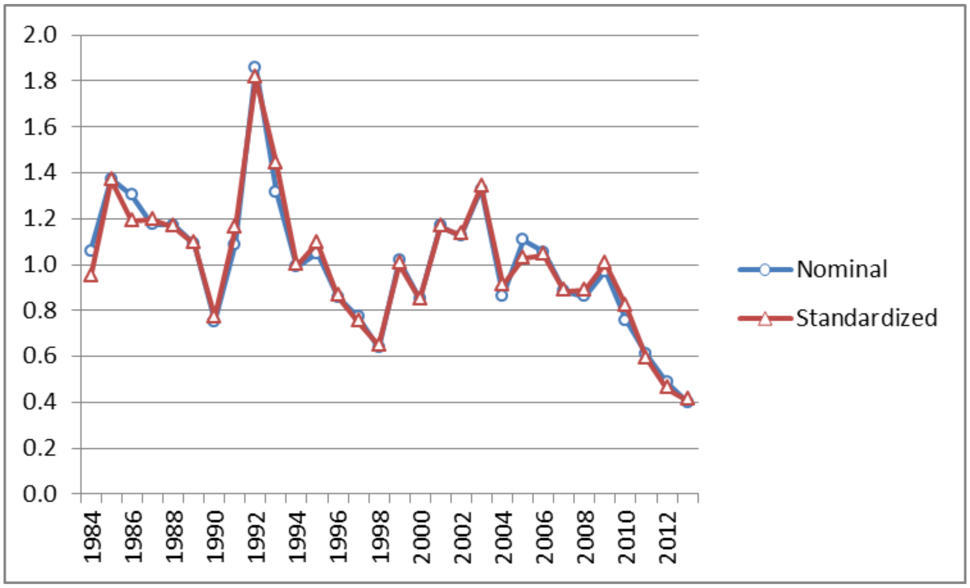


1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
Nominal
Standardized

MODEL 6 : North Equatorial area, CPUE based on number of positive sets, minimum of 3 sets/stratum

Model formulation	Df	Change in deviance	Residual deviance	p-value	% of total deviance	Pseudo R^2
Positive CPUE						
1	1		820.12			0.34
Factor						
ctotday	1	18.089	802.03	< 0.001	6.67	
MLDa	1	17.623	784.41	< 0.001	6.50	
SSTa	1	3.639	780.77	< 0.001	1.34	
Year	29	131.021	649.75	< 0.001	48.30	
Month	4	23.556	626.19	< 0.001	8.68	
Lon	1	17.429	608.76	< 0.001	6.43	
Interaction						
Year:Month	92	59.9	548.86	< 0.001	22.08	




2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Nominal
Standardized