Received: 13 July 2014

Stock assessment of Indian Ocean albacore (*Thunnus alalunga*) using age structured assessment program (ASAP)

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Abstract

This study conducted a stock assessment for Indian Ocean Albacore (ALB; *Thunnus alalunga*) using Age Structured Assessment Program (ASAP), based on fishery-specific catch and catch-at-age data (1980-2012). The assessment considered that the ALB stock were subject to 7 fisheries, i.e., Longline fishery of Japan in northern Indian Ocean (LLJPNnorth), Longline fishery of Japan in southern Indian Ocean (LLJPNsouth), Longline fishery of Tawan,China in northern Indian Ocean (LLTWNnorth), Longline fishery of Tawan,China in southern Indian Ocean (LLTWNsouth), Driftnet fishery (DF), Purse seine fishery (PS), and Other fishery (Other). Standardized catch-per-unit-effort (CPUE) series from longline fisheries of Taiwan, China were used as abundance indices for fitting the model. In addition to base case model, sensitivity analysis was conducted as to two key parameters (i.e., steepness of Beverton-Holt stock-recruitment relationship and natural mortality). The assessment results, including MSY and related biological reference points, were sensitive to the steepness and natural mortality assumptions. However, both the base case and sensitivity analyses suggested that the Indian Ocean albacore be not overfished, but overfishing was probably occurring in 2012.

Content

1 Introduction

Albacore tuna (ALB; *Thunnus alalunga*) are widely distributed in all three oceans between approximately 50° N and 40° S, although their abundance is relatively low in equatorial waters (Collette and Nauen, 1983). The Indian Ocean albacore resource was initially harvested by longlines since the 1950s and now is one of the main tuna recourses in the Indian Ocean. Currently they are mainly caught by longlines (deep-freezing and fresh-tuna longliners), and by driftnet, purse seine, and other small-scale fleets as well (IOTC, 2001).

A range of quantitative modelling methods (ASPIC, ASPM and SS3) were applied to the ALB assessment in the last Working Party on Temperate Tunas (WPTmT) in 2012 (IOTC–SC16, 2013). However, there is a large amount of uncertainties associated with the Indian Ocean ALB stock status due to the lack of complete fishery data and population biology knowledge (IOTC–WPTmT03, 2011). Therefore, assessments using different methods are necessary to better understand the stock status by synthesizing results from various modeling frameworks.

This working paper presented a stock assessment of Indian Ocean ALB using Age Structured Assessment Program (ASAP, Version 3; Legault and Restrepo, 1998; NOAA Fisheries Toolbox, 2013). ASAP has been used as an assessment tool for assessing many commercially exploited stocks, e.g., red grouper, yellowtail flounder, Pacific sardine, Greenland halibut, Gulf of Maine cod, and Florida lobster (see NOAA Fisheries Toolbox, http://nft.nefsc.noaa.gov).

The assessment included a base case model and sensitivity analyses designed for the consideration of alternative key assumptions regarding population dynamics (i.e., natural mortality and the stock-recruitment relationship). Stock status was evaluated based on fishing mortality and spawning stock biomass based reference points. Kobe plots were presented to show historical trends in stock status, as recommended by the Scientific Committee.

2 Biological parameters and assumptions

2.1 Stock structure

Various studies have been conducted by tagging (e.g., Arrizabalaga *et al*., 2004) and genetic techniques (e.g., Takagi *et al*., 2001) for investigating population structure of ALB among different oceanic areas. Current evidences indicate that there are at least six genetically distinct stocks of albacore, distributed in the North and South Pacific Ocean, North and South Atlantic Ocean, Indian Ocean, and Mediterranean Sea (Wu *et al*., 2009; Davies *et al*., 2011; Takagi *et al*., 2001; Arrizabalaga *et al*., 2004; Viñas *et al*., 2004). Arrizabalaga *et al*. (2004) showed that the Indian Ocean and the South Atlantic populations are proximate in their genetic distance.

Although different studies on larvae concentration zones (Stequert and Marsac, 1989), morphometric (Penney *et al*., 1998), and genetic characteristics (Yeh *et al*., 1996) suggested that there might be two ALB populations in the Indian Ocean separated by 90°E longitude. The albacore was considered as a single stock in recent assessments (Nishida and Matsumoto, 2011). The single stock assumption was also assumed for the present assessment as suggested by Nishida et al (2014).

2.2 Movement

The Indian Ocean ALB was considered to be a unit stock and its size composition varies with latitude (Hsu, 1994). Based on size segregation from length frequency data, Hsu (1994) classified the Indian Ocean ALB by latitude, with the mature group northward of 10° S, the spawning group between 10° S and 30° S, and the immature group southward of 30° S.

Similarly, Chen *et al*. (2005) found that immature albacore were mainly distributed in areas south of 30° S although some displayed a north–south seasonal migration. Mature albacore, which were mainly concentrated between 10° S and 25° S, also showed a north–south migration. Within 10° S and 30° S, the separation of albacore of mature, spawning, and immature life history stages roughly coincided with the boundaries of the three oceanic current systems in the Indian Ocean (Chen *et al*., 2005). It is likely that the adult Indian Ocean albacore tunas do yearly circular counter-clockwise migrations following the surface currents of the south tropical gyre between their tropical spawning and southern feeding zones (IOTC, 2009). Movements can be modeled in complex assessment platform such as stock synthesis. However, it has not been done so far for Indian Ocean ALB, most probably due to lack of necessary data. For the present assessment, movement was also not considered since the ASAP does not allow movement to be modeled.

2.3 Growth model

The length-weight relationship of Indian Ocean ALB was very different from those from the northern and southern Atlantic albacore, probably due to the different sample sizes and estimation methods (Hsu, 1999). The growth of Indian Ocean ALB was investigated by various authors using samples from different fisheries (See Nishida *et al*., 2014). A von Bertalanffy growth equation derived using vertebra-ring reading method was estimated by Lee and Liu (1992), who also found that there was no significant differences in the length-weight relationship and the von Bertalanffy growth equation between females and males. Nishida *et al*. (2014) conducted a review of growth model of Indian Ocean ALB and suggested that the model developed by Well *et al*. (2013) might be the most appropriate. Therefore, we used the model of Well *et al*. (2013), and assumed no sexual differences in growth for the present assessment.

2.4 Reproduction

Little is known about the reproductive biology of ALB in the Indian Ocean. Like other tunas, adult ALB prefer to spawn in warm waters (SST>25°C; IOTC, 2009). It appears that the main spawning grounds of Indian Ocean ALB are located east of Madagascar between 15° and 25°S during the 4th and 1st quarters of each year (IOTC, 2009). Therefore, for the present assessment, the fraction of year elapses before spawning occurs (before spawning stock biomass calculation) was assumed to be 0.5, implying ALB spawns during the 3rd and 4th seasons. The maturity ogive suggested by Nishida et al. (2014) was used in present ALB assessment (**Figure 1**).

2.5 Natural mortality

Natural mortality rate (M) was assumed to be constant and equal to 0.3 per year for all age classes for the South Atlantic albacore and also the Mediterranean albacore stock assessments (ICCAT, 2011). The M of South Pacific ALB is believed to be between 0.2 and 0.5 per year and the longest period at liberty for a recaptured tagged albacore in the South Pacific is 11 years (Hoyle, 2011). The M of Indian Ocean ALB was estimated to be 0.221 per year by Lee and Liu (1992) and 0.22-0.25 per year by Chang et al. (1993). Natural mortality of Indian Ocean ALB was also reviewed in Nishida et al. (2014). Therefore, we follow the suggestion of Nishida et al. (2014) for the M values in base case (M=0.4, 0.3641, 0.3283, 0.2924, 0.2566 per year for ages 0 through 4, and M=0.2207 per year for ages 5 and older; see **Figure 2**) and sensitivity analysis (M=0.3 per year for all age classes).

3 Data

3.1 Definition of fisheries

The Indian Ocean albacore are caught mostly by longlines (98%) between 20°S and 40°S, with remaining catches recorded as bycatch from purse seines and other gears (IOTC–WPTmT03, 2011). The catches of albacore were relatively stable until the mid-1980s, except for high catches recorded in 1973 and 1974. The catches increased markedly during the mid-1980s due to the use of large-scale drifting gillnet by Taiwan,China, with total catches in excess of 30,000 t. Following the removal of large-scale drifting gillnet, catches dropped to less than 20,000 t by 1993. However, catches more than doubled over the period from 1993 (less than 20,000 t) to 2001 (44,000 t). Record catches of albacore were reported in 2007, at around 45,000 t, and again in 2008, at 48,000 t. Catches for the current year (2012) was estimated to be **33,864** t. The mean catch over last 5 years (2008-2012) was **37,090** t. Historical catch trend for each fishery type was shown in **Figure 3**.

While most of the catches of albacore have traditionally come from the western Indian Ocean, in recent years a larger proportion of the catch has come from the eastern Indian Ocean. The relative increase in catches in the eastern Indian Ocean since the early 2000s is mostly due to increased activity of fresh-tuna longliners from Taiwan, China and Indonesia. In the western Indian Ocean, the catches of albacore mostly result from the activities of deep-freezing longliners and purse seiners.

Ideally, the fisheries for stock assessment should to be defined to have selectivity and catchability characteristics that do not vary greatly over time. For the present assessment, Indian Ocean ALB are assumed to be subject to 7 fisheries, i.e., Longline fishery of Japan in northern Indian Ocean (LLJPNnorth), Longline fishery of Japan in southern Indian Ocean (LLJPNsouth), Longline fishery of Tawan,China in northern Indian Ocean (LLTWNnorth), Longline fishery of Tawan,China in southern Indian Ocean (LLTWNsouth), Driftnet fishery (DF), Purse seine fishery (PS), and Other fishery (Other), according to the available fishery statistics provided by the IOTC Secretariat.

3.2 Basic fisheries data

Catch data (total catch and catch-at-age) are basic fishery data for assessment using ASAP. The time span of catch data maintained by IOTC Secretariat varied greatly: Longline fishery of Japan (1952-2012), Longline fishery of Tawan,China (1954-2012), Driftnet fishery (1982-1992), Purse seine fishery (1981-2012), and Other fishery (1950-2012). It was noted that catch of Purse seine fishery in some years (1981-83, 1989) was very low compared with the remaining years. No catch was recorded for the Driftnet fishery in 1984. Catch of Other fishery for 1950-1966 was estimated roughly. It was believed that the fishery statistics quality for the earlier period of fishery was poorer than those for the later period.

Fishery-specific total catch and catch-at-age for 1980-2012 were used as basic data for conducting the current stock assessment of ALB in the Indian Ocean, i.e., we modeled the stock dynamic from 1980 to 2012 using ASAP. We did not include the data for the years pre-1980 since the trial runs indicated that doing so (i.e. increasing too many parameters need to be estimated) always caused non-convergences, probably due to incomplete catch statistics for those years.

3.3 Indices of abundance

Catch and effort data from major longline fleets (i.e., Japan, Korea, and Taiwan, China) are routinely used in developing abundance indices for Indian Ocean ALB. However, recent analysis indicated that the standardized catch-per-unit-effort (CPUE; number of fish caught per 1000 hooks) trends of Taiwan,China tend to be quite different from that of Japan and Korea. It was noted that CPUE should not be simply averaged across series with different trends as this is likely to result in spurious trends (IOTC–SC16, 2013).

For the present ALB assessment, the standardized CPUE series from longline of Taiwan,China (Lee *et al*. 2014) were used as abundance indices in fitting the assessment model. There were three CPUE series developed by Lee *et al*. (2014), i.e., CPUEs for the northern Indian Ocean, CPUEs for the southern Indian Ocean, and CPUEs for the whole Indian Ocean. However, CPUEs for the whole Indian Ocean was not actually used in model fitting since we used area-specific fishery definition (i.e., the longline fisheries have been separated by north and south). The two Taiwanese CPUE series in fitting the present ALB assessment model was shown in **Figure 4**.

We did not use indices based on other fisheries (i.e., longlines of Japan and Korea) because there was more confidence in the abundance indices in recent years due to the additional CPUE analyses from Japan and Taiwan,China, and the exploration of the Rep. of Korea catch and effort data (IOTC–SC16, 2013). That is, it was noted that the Taiwan,China CPUE series is more likely to closely represent albacore abundance, because a substantial part of the Taiwanese fleet has always targeted albacore (IOTC–SC16, 2013). Conversely, the Japanese CPUE series seems to demonstrate very strong targeting shifts away from albacore (1960s) and back towards albacore in recent years (as a consequence of piracy in the western Indian Ocean). Similar trends are seen in the Rep. of Korea CPUE series (IOTC–SC16, 2013).

4 Stock assessment

4.1 Model configurations

The ASAP uses forward computations assuming separability of fishing mortality into year and age components to estimate population sizes given observed catches, catch-at-age, and indices of abundance. Technical details of the ASAP model can be found in Legault and Restrepo (1998) and NOAA Fisheries Toolbox (2013). The population dynamics model of ASAP is briefly described in the **Appendix A** of this report.

The objective function in ASAP is the sum of a number of model fits and two penalties. There are two types of error distributions in the calculation of the objective function: multinomial and lognormal. Multinomial distribution is assumed for catch-at-age data, with effective sample size iteratively adjusted based on tentative model runs. The lognormal error distribution is assumed for total catch (in weight), abundance indices, and stock-recruitment relationship (recruitment deviation).

The CV for total catch in model fit was assumed to be 0.1 for each of seven fisheries and constant for the whole time period. We have tried much lower CVs for the total catch (e.g., 0.01) during initial runs, which caused model not to converge.

Since there was no strong evidence supporting which index is more reliable than the other, the two Taiwanese CPUE indices were equally weighted, i.e. equal lambdas and CVs (CVs=0.1).

Beverton-Holt stock recruitment (S-R) model was adopted as in previous assessments. Steepness was regarded as most important parameter influencing stock assessment results. The steepness for ALB model was assumed at 0.7 for the base case.

4.2 Parameter estimation

The following parameters are assumed to be known for the present ALB stock assessment in the Indian Ocean (see previous sections for their vales):

(1) Length-at-age and weight-at-age;
(2) Age-specific maturity;
(3) Age-specific natural mortality rates;
(4) The deviation for indices of abundance;
(5) The steepness of the B-H stock-recruitment relationship.

The following parameters are to be estimated in the present ALB stock assessment in the Indian Ocean:

(1) Recruitment in each year from 1980 through 2012;
(2) Catchability coefficients (*q*, constant over time) for the abundance indices (LLTWNnorth, LLTWNsouth);
(3) Selectivity curves for the 7 fisheries. The selectivity curves for longline fishery were assumed to be Single Logistic (two parameters). The selectivity curves for Driftnet and Purse seine were assumed to be Double Logistic (four parameters). Age-specific parameters were defined for Other fishery, but selectivity for age 0 was fixed at 1.0 as this fishery seems to catch high proportion of juveniles. This fix is somewhat arbitrary, but fixing at least one parameter at 1.0 is required by the ASAP model configuration.
(4) Effective sample size (ESS) for catch-at-age for each fishery (iterative adjustment);
(5) Initial population size and age structure;
(6) Fully recruited fishing mortality (*F*mult) for each fleet for the first year, and deviations for *F*mult for the remaining years.

4.3 Management quantities

The program computes a number of biological reference points (BRPs) based on the estimated selectivity pattern, weights at age, natural mortality rate, and relative fishing intensity among fleets in the terminal year of the assessment (i.e., 2012). The reference points computed are F_{MSY}, $F_{current}/F_{MSY}$, SSB_{MSY}, $SSB_{current}/SSB_{MSY}$, MSY, $C_{current}$/MSY. The term “current” denoted last year in the model (i.e., 2012).

4.4 Base case and sensitivity analysis

The base case model is chosen so as to most probably represent the real state of nature of the Indian Ocean ALB stock based on current knowledge available. The steepness of B-H stock-recruitment relationship and natural mortality were known as key uncertainty sources for many fisheries stock assessments. Therefore, these two parameters were subject to sensitivity analysis using their alternative assumptions (i.e., M=0.3 per year for all age classes, and steepness=0.8). Thus, combining steepness assumptions and natural mortality assumptions produced 4 models which were used to conduct the present ALB assessment.

4.5 Retrospective analyses

Retrospective analyses were performed by successively removing the last year of the data (index and catch) and re-running the model to estimate parameters. The key population parameters derived from each analysis were compared. Retrospective analysis was only conducted for the base case model.

4.6 Stock assessment results

The assessment results presented in the following sections are likely to change in future assessments because (1) future data may provide evidence contrary to these results, and (2) the assumptions and constraints used in the assessment model may change. Future changes are most likely to affect the estimates of biomass, recruitment, and fishing mortality.

4.6.1 Model fit diagnostics

There were totally 323 parameters estimated for the present model configurations (base case). Model fit diagnostics was done by looking at likelihood components, the fits of total catch, effective sample size for composition data, and abundance index. They are shown in **Figures 5-8**. The model fit the time series of total catch closely except for a few years. The model produced the worst estimate of effective sample size for the Driftnet fishery. Overall, the model fit the CPUE series closely except for the period of pre-1990 in which the model underestimate the abundance indices.

4.6.2 Recruitment estimates

The recruitment time series for Indian Ocean ALB were shown in **Figure 9**. It seemed there might be two recruitment regimes shifted at around 1989. The first was a higher level of recruitment period between 1980 and 1989, with high recruitment variation. The second was a lower level of recruitment period between 1990 and 2012, with low recruitment variation. The B-H stock-recruitment relationship curve was shown in **Figure 10**.

4.6.3 SSB, fishing mortality, catchability, and selectivity estimates

The trends in spawning stock biomass and fishing mortality estimates were shown in **Figure 11.** The SSB of albacore showed a decreasing trend since 1980, coincided with the increasing trend of fishery mortality. Catchability of abundance indices was given in **Figure 12**. The fishery-specific selectivity-at-age curve was shown in **Figure 13**.

4.6.4 Retrospective pattern

Retrospective analyses were conducted by removing one year (2012) and two years (2012 and 2011) of data. The retrospective analyses showed the same trend in the fishing mortality and spawning stock biomass as the base case model (**Figures 14**). The magnitude and direction of the bias in the fishing mortality and SSB estimates were different (**Figures 14**). As Aires-da-Silva and Maunder (2009) pointed out that the retrospective bias does not necessarily indicate the magnitude and direction of the bias in the current assessment, only that the model may be mis-specified. Retrospective analysis is useful for determining how consistent a stock assessment method is from one year to the next. Inconsistencies can often highlight inadequacies in the stock assessment method (Aires-da-Silva and Maunder 2009).

4.6.5 Biological reference point estimates

Biological references points for ALB calculated based on parameter estimates from stock assessment models were given in **Table 1**. It was noted that MSY-related management reference points were very sensitive to the steepness parameters which were fixed for the assessment models. If the steepness was fixed at 0.7 and time-varying natural mortality was assumed (Model-1, base case), the current level of fishing mortality was 1.28 times of the level corresponding to MSY. However, if the steepness was fixed at 0.8, with the same natural mortality (Model-2), the current level of fishing mortality was 0.91 times of the level corresponding to MSY. When natural mortality was assumed to be 0.3 per year for all age classes, the model either did not converge (Model-3) or produced too optimistic results which might be unrealistic (Model-4).

5 Status of the stock

Four assessment models were configured for the ALB; however, only two models produced reasonable results. Model-3 failed to converge, whereas Model-4 seemed to produce unreasonable stock status (**Table 1**). Therefore, stock status was evaluated based on Model-1 (base case) and Model-2 (sensitivity analysis). Base on Model-1, the Indian Ocean ALB was experiencing overfishing, but not overfished at the time of 2012. Based on Model-2, the Indian Ocean ALB was neither experiencing overfishing, nor overfished at the time of 2012. Kobe plots showing the stock trajectories were given in **Figure 15**.

Figures

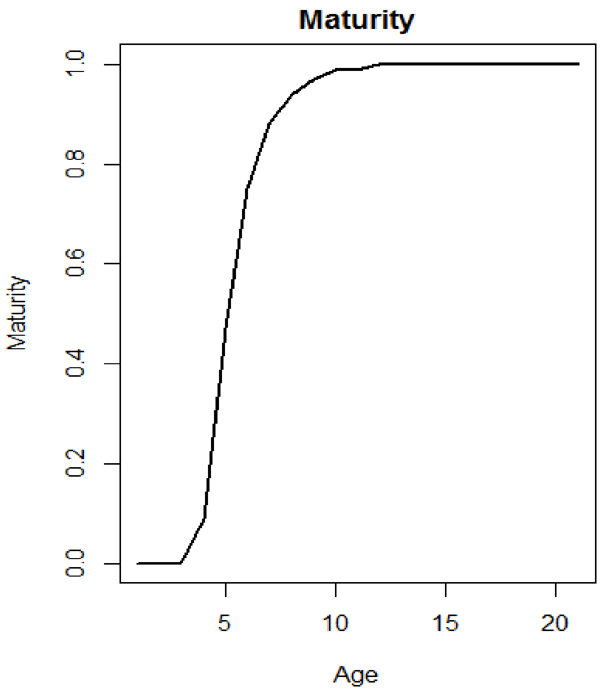

Figure 1 Maturity ogive for Indian Ocean albacore

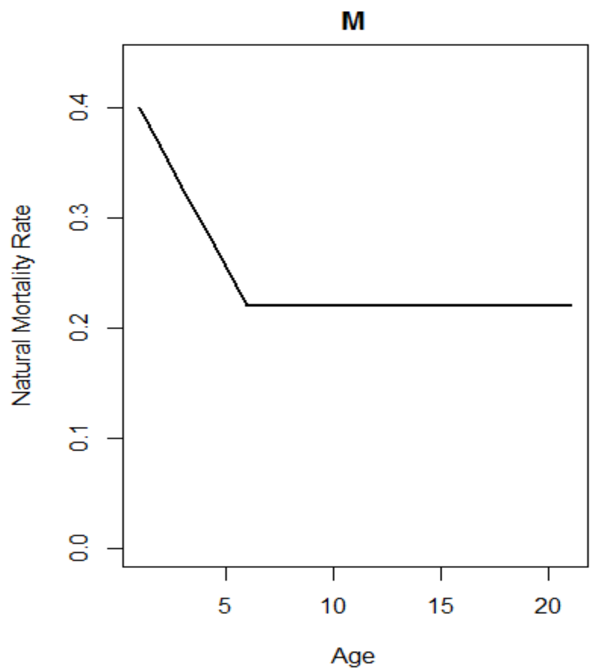

Figure 2 Natural mortality rates for Indian Ocean albacore for the base case model

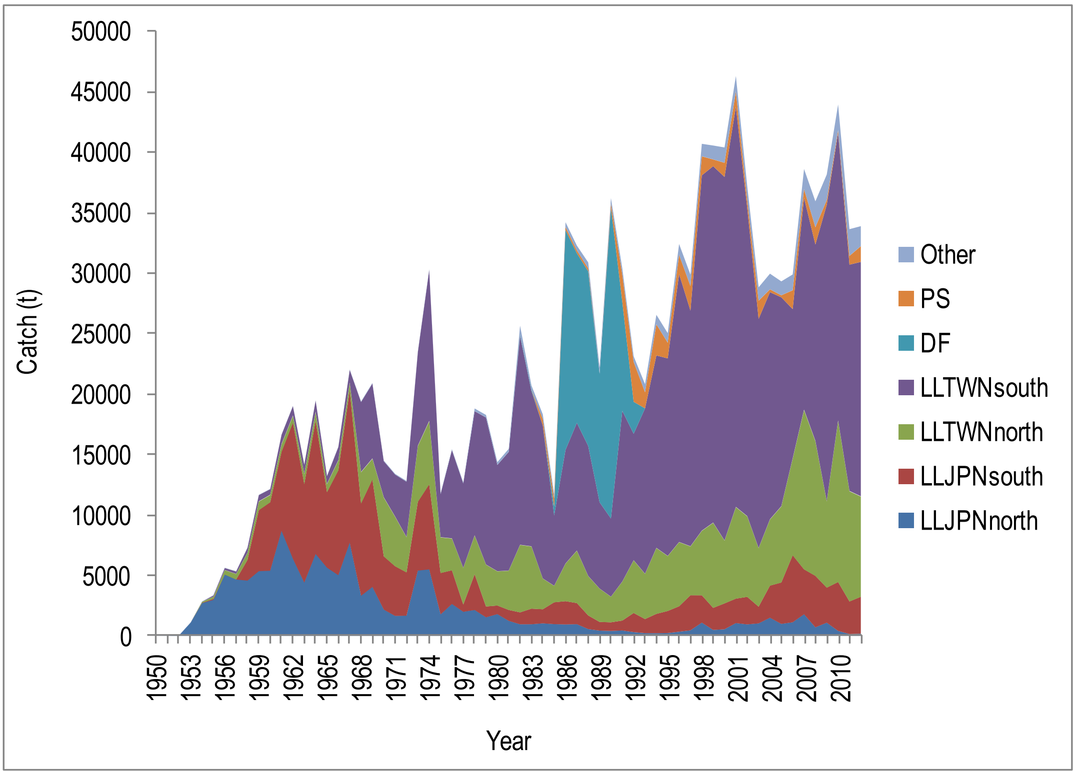

Figure 3 Historical catch by major fishery for albacore in the Indian Ocean

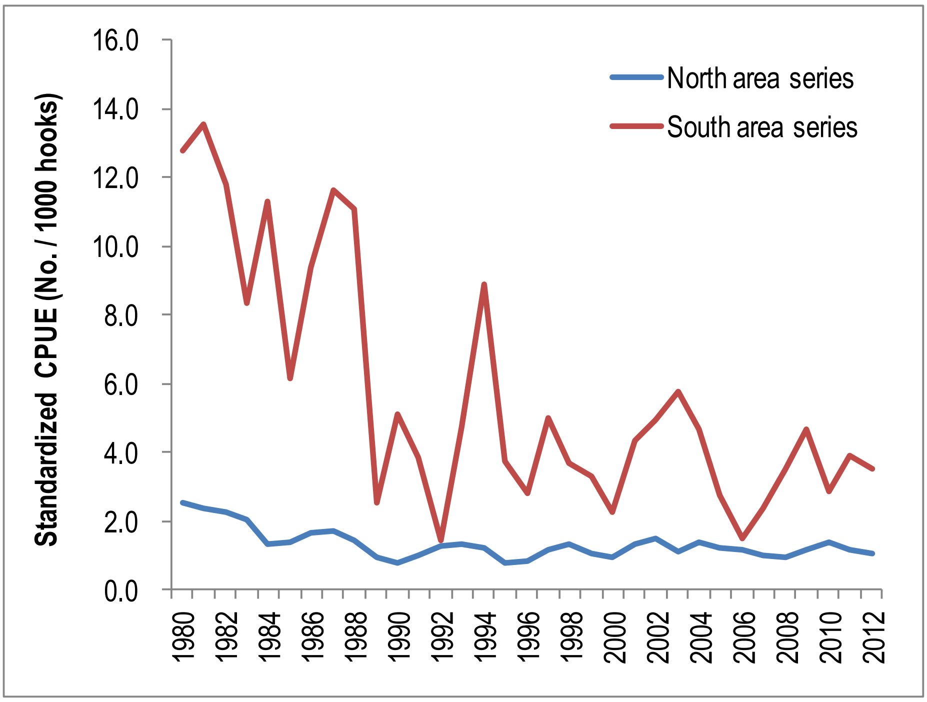

Figure 4 Two Taiwanese CPUE series used in fitting the ALB assessment model

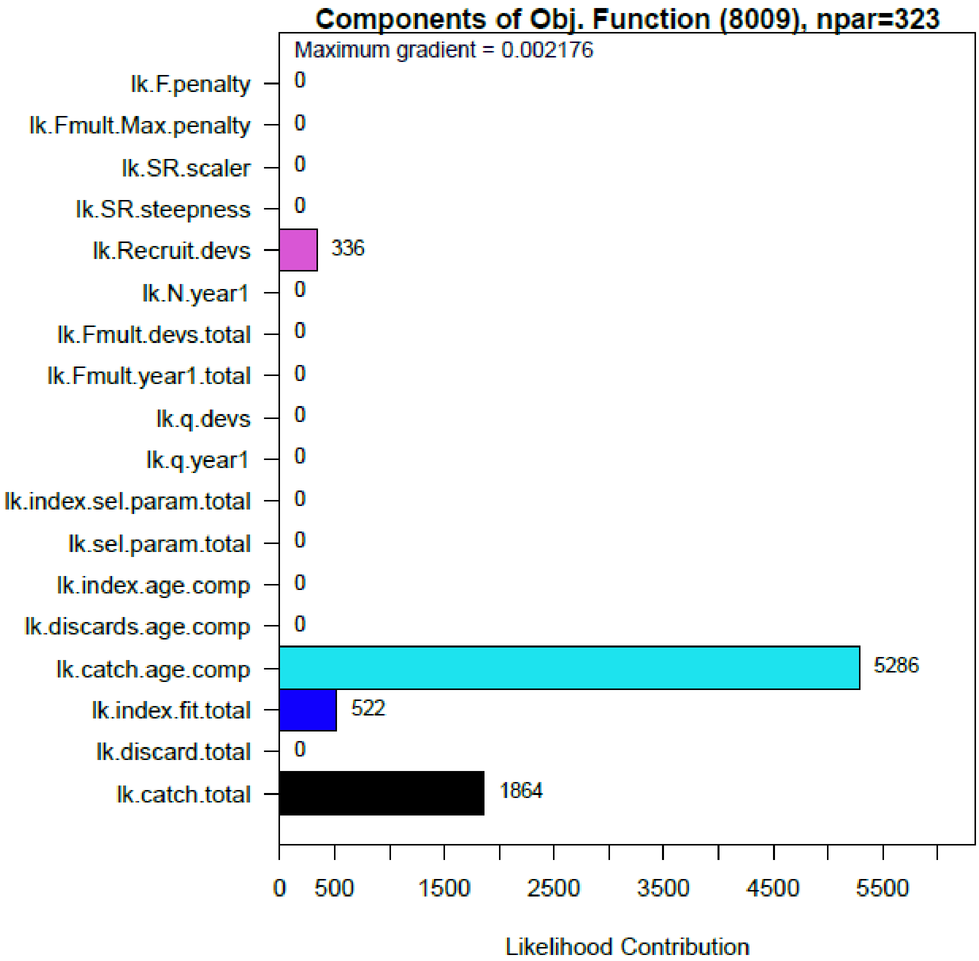

Figure 5 Likelihood contributions of different components in the objective function for the base case model

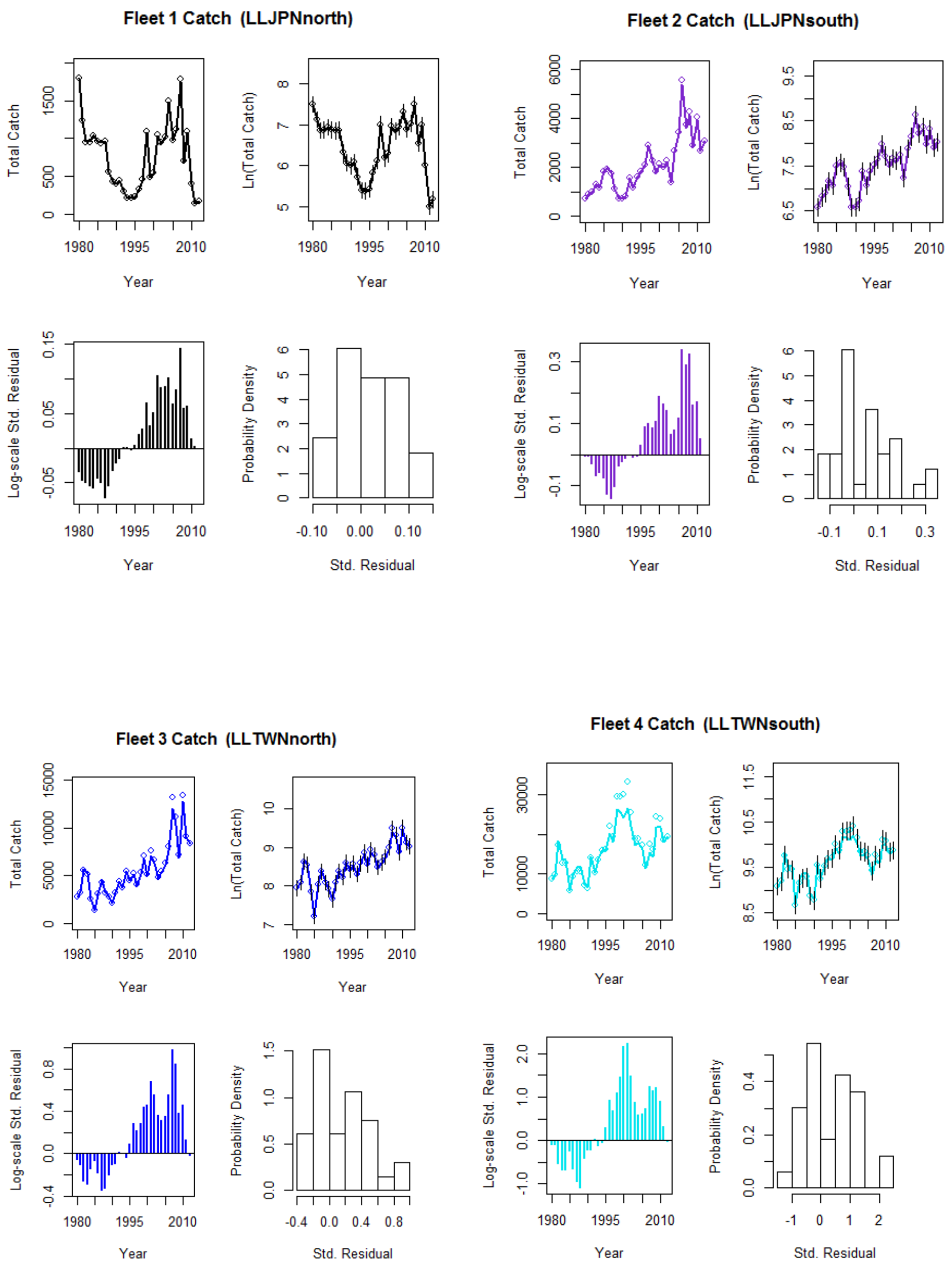

Figure 6 Model fits of total catch data for the base case model

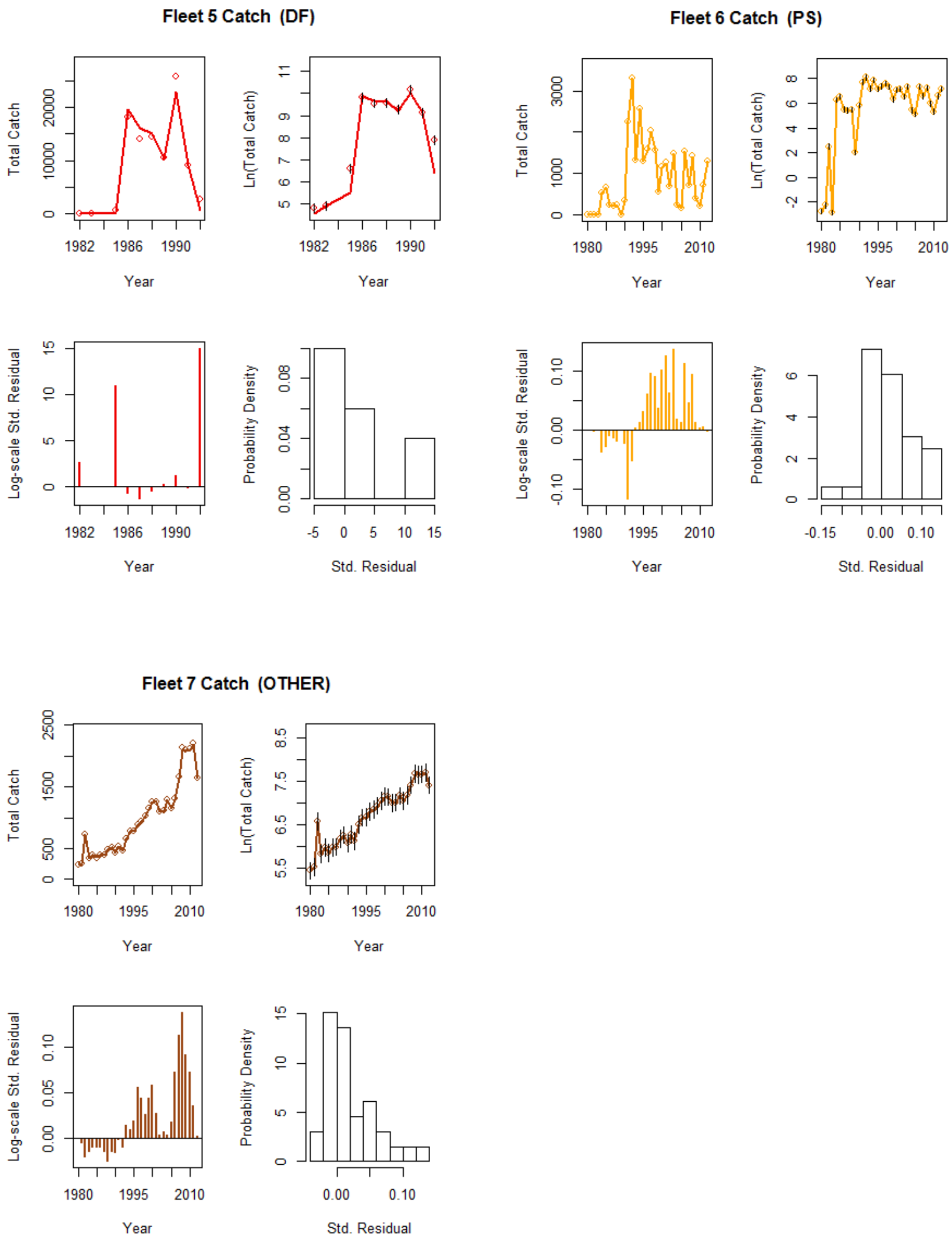

Figure 6 Model fits of total catch data for the base case model (continued)

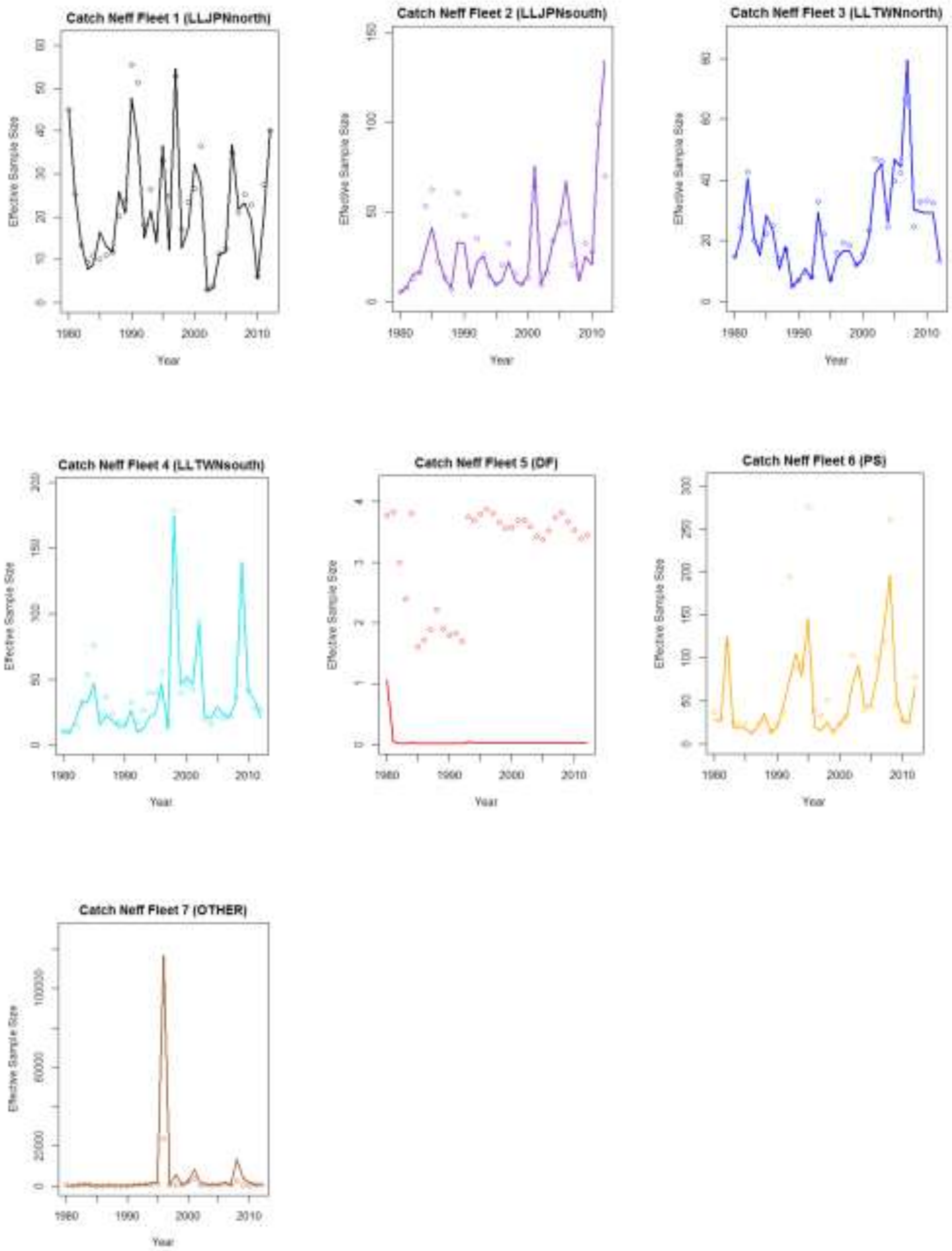

Figure 7 Model fits of effective sample size for the base case model

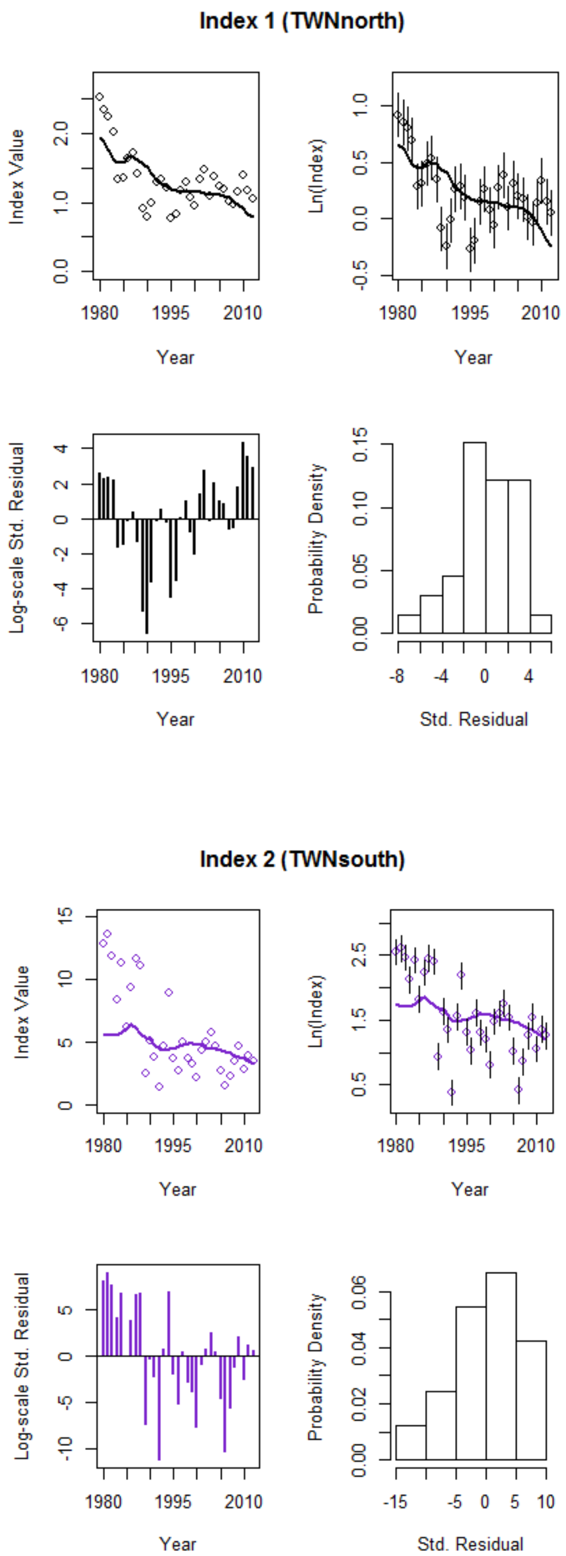

Figure 8 Model fits of abundance indices for the base case model

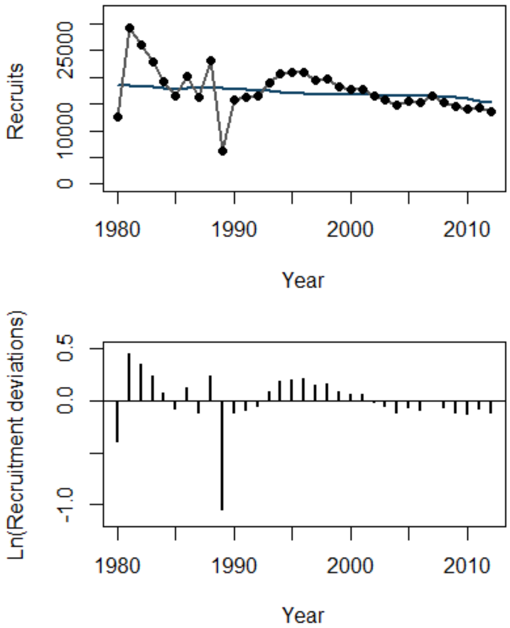

Figure 9 Estimated recruitments for the base case model

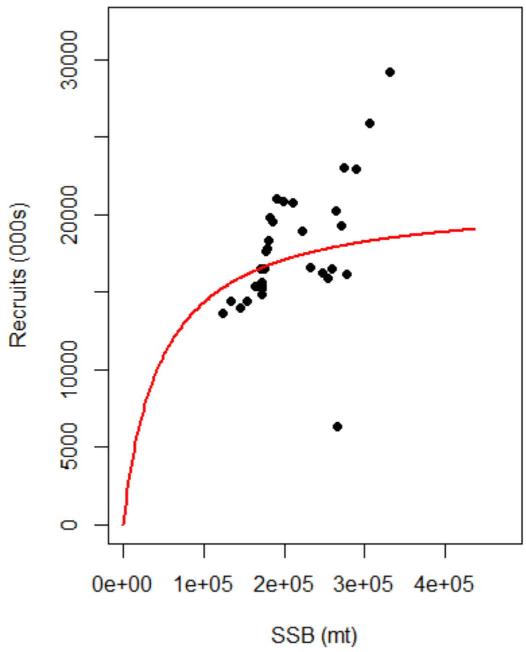

Figure 10 Observed and estimated (red line) spawning stock biomass and recruitment trend for the base case model

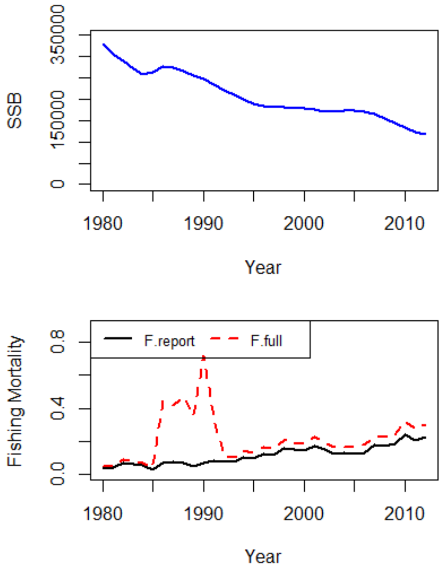

Figure 11 Spawning stock biomass (*SSB*) and fishing mortality estimates for the base case model

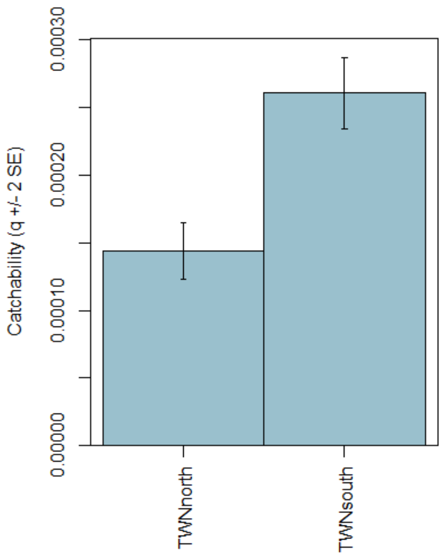

Figure 12 Catchability estimates of two abundance indices for the base case model

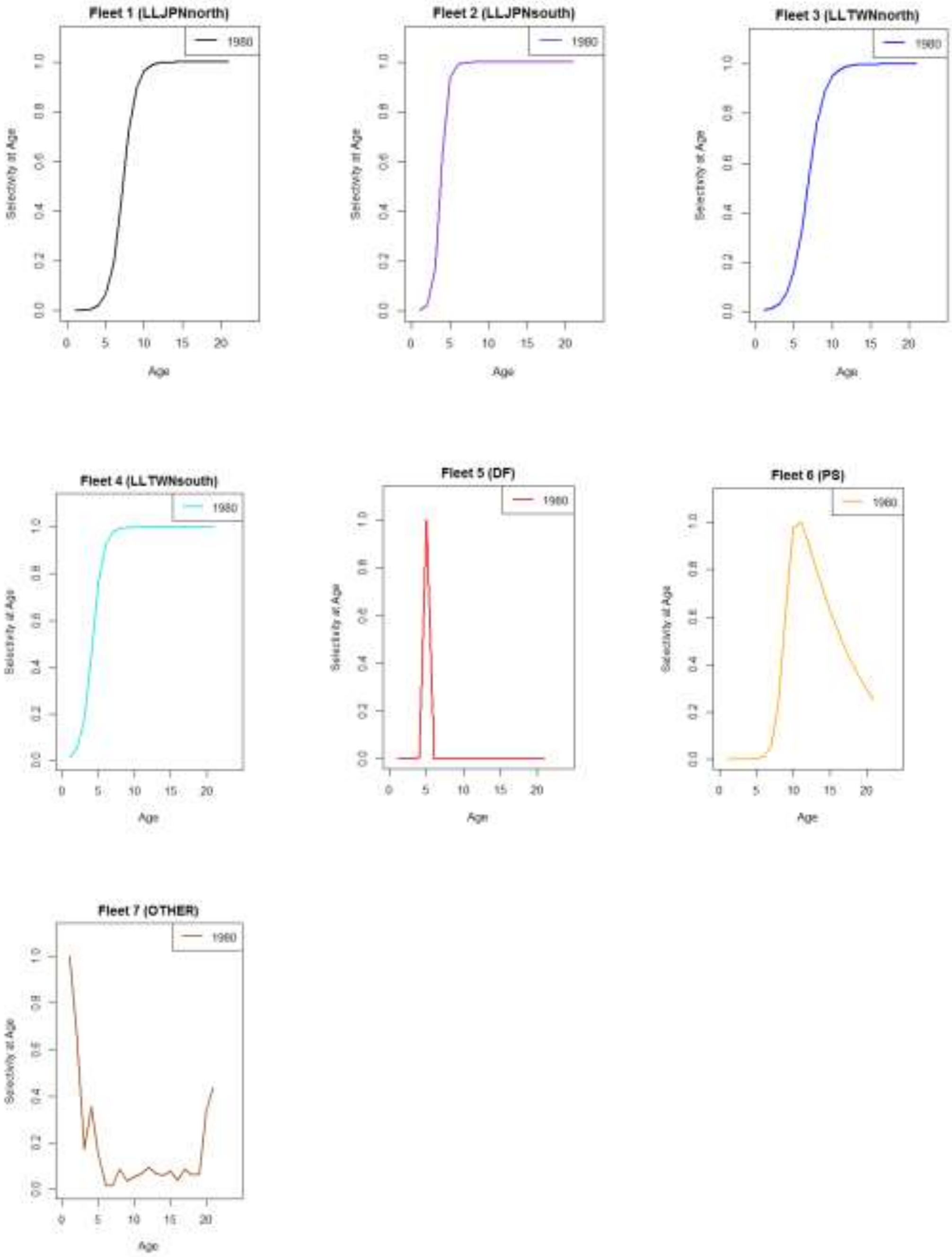

Figure 13 Selectivity-at-age estimates of each fishery for the base case model

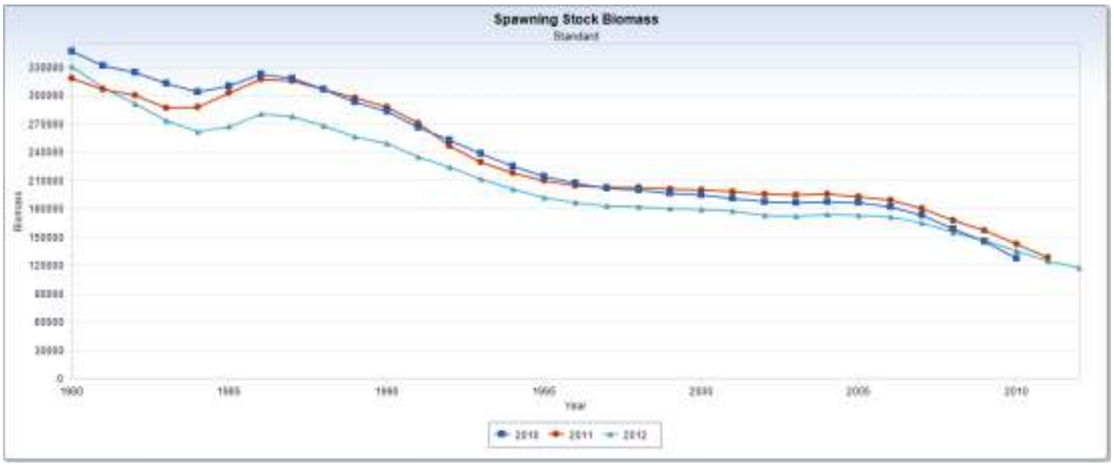

Figure 14a Retrospective comparisons of estimates of the spawning stock biomass (t). The estimates from the base case model are compared with the estimates obtained when the most recent year (2012), two years (2012 and 2011), were excluded.

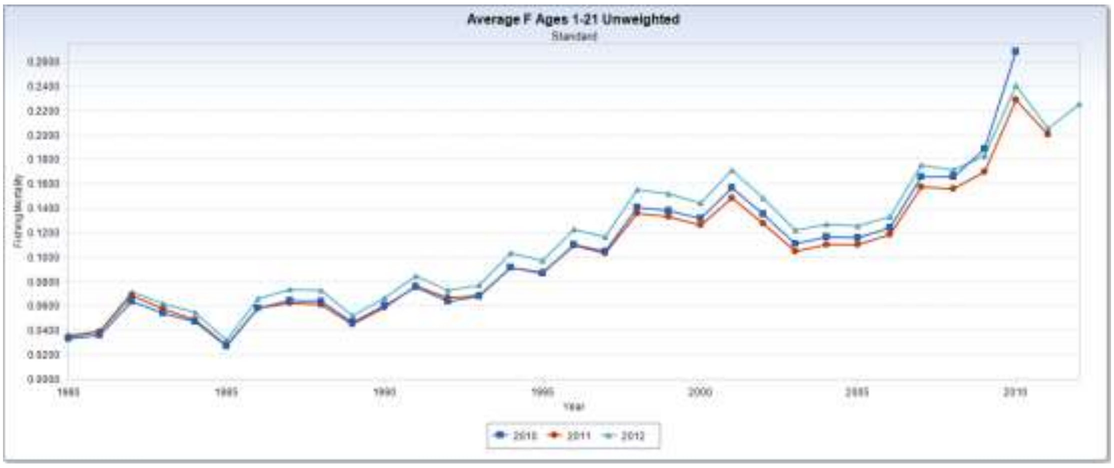

Figure 14b Retrospective comparisons of estimates of the average fishing mortality. The estimates from the base case model are compared with the estimates obtained when the most recent year (2012), two years (2012 and 2011), were excluded.

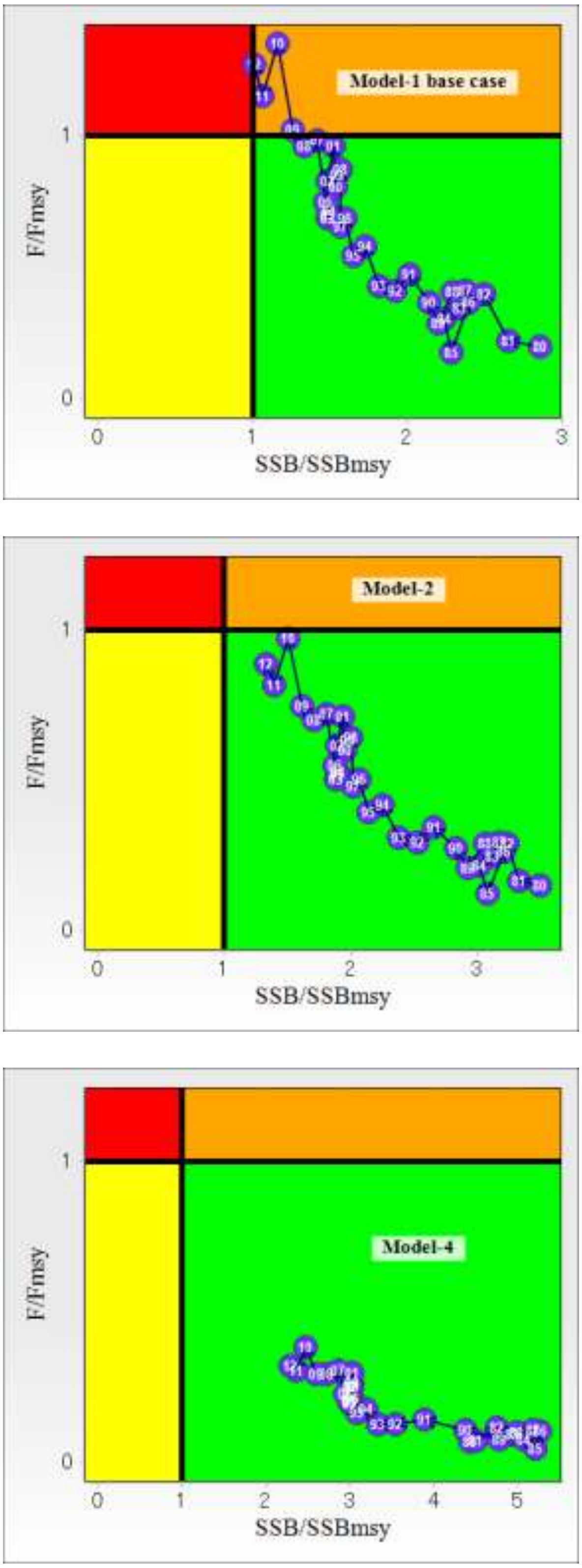

Figure 15 Kobe plot of three converged model runs of ALB in the Indian Ocean

Tables

Table 1 Biological reference points for base case assessment model and sensitivity analyses for Indian Ocean albacore

	Model-1 (h=0.7, M time varied)	Model-2 (h=0.8, M time varied)	Model-3 (h=0.7, M=0.3)	Model-4 (h=0.8, M=0.3)
F_{curr}	0.23	0.20	not converged	0.10
F_{MSY}	0.18	0.22		0.32
F_{curr}/F_{MSY}	1.28	0.91		0.31
SSB_{curr}	116,782	133,617		277,758
SSB_{MSY}	115,679	100,569		121,071
SSB_{curr}/SSB_{MSY}	1.01	1.33		1.35
C_{curr}	33,864	33,864		33,864
MSY	26,583	30,083		50,125
C_{curr}/MSY	1.27	1.13		0.68
	base case			

Unit for catch and biomass: metric ton

Acknowledgements

The study was supported by National Distant-water Fisheries Engineering Research Center at Shanghai Ocean University (SHOU), Collaborative Innovation Center for Distant-water Fisheries based in SHOU, and International Center for Marine Studies at SHOU.

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Appendix A

Population dynamics model of ASAP

The spawning stock biomass is calculated based on the population abundance at age ($N_{t,a}$), the fecundity ($\Phi_{t,a}$), and the proportion of the total mortality ($Z_{t,a}$) during the year prior to spawning (p_{SSB}) as

$$SSB_t = \sum_a N_{t,a}\Phi_{t,a}\mathrm{e}^{-p_{SSB}Z_{t,a}} \quad (1)$$

The Beverton and Holt stock recruitment relationship is used to calculate the expected recruitment in year t+1 from the spawning stock biomass in year t as

$$\hat{R}_{t+1} = \frac{\alpha SSB_t}{\beta + \mathrm{SSB}_t} \quad (2)$$

The equation is reparameterized to use parameters unexploited spawning stock biomass (SSB_0) and steepness (h) and a constant of unexploited spawning stock biomass per recruit (SPR_0) so that

$$\alpha = \frac{4h(SSB_0/SPR_0)}{5h-1} \text{ and } \beta = \frac{SSB_0(1-h)}{5h-1} \quad (3)$$

SSB_0 is a parameter to be estimated. The recruitments, assumed to occur at age 1, are calculated as

$$N_{t,1} = R_t e^{\log(Dev(R_t))} \quad (4)$$

Selectivity at age for each fishery was modeled as separate blocks. Within each block, there are three selection model options:

(a)Estimate parameters for each age (one parameter for each age, and at least one age should be fixed at 1.0);

(b) Logistic function (2 parameters: α_1, β_1):

$$Sel_a = \frac{1}{1+e^{-(a-\alpha_1)/\beta_1}} \quad (5)$$

(c)Double logistic function (4 parameters: α_1, β_1, α_2, β_2):

$$Sel_a = \left(\frac{1}{1+e^{-(a-\alpha_1)/\beta_1}}\right)\left(\frac{1}{1+e^{-(a-\alpha_1)/\beta_1}}\right) \quad (6)$$

Fishing mortality (F) at age is the product of a fully-recruited fishing mortality ($Fmult$) and selectivity at age. In ASAP, the $Fmult$ for a fleet (i) is determined by two sets of parameters, $F\mathrm{mult}_{i\mathrm{fleet},\,1}$, the parameter for first year for that fleet, and $Dev(F\mathrm{mult}_{i\mathrm{fleet},\,t})$, where t=2 to the number of years, the deviation of the parameter from the value in the first year for that fleet. Both sets of parameters are estimated in log space and then exponentiated as

$$Fmult_{i\mathrm{fleet},1} = \mathrm{e}^{\log(Fmult_{i\mathrm{fleet},1})},\ t=1 \quad (7)$$

$$Fmult_{i\mathrm{fleet},t} = Fmult_{i\mathrm{fleet},1}\mathrm{e}^{\log(Dev(Fmult_{i\mathrm{fleet},t}))},\ t\geq 2$$

The population abundance in the first year for ages 2 through the maximum age are derived from the initial guesses $Nini_{1,a}$ and the parameters $Dev(N_{1,a})$ as:

$$N_{1,a} = Nini_{1,a}\mathrm{e}^{\log(Dev(N_{1,a}))} \quad (8)$$

Then, a partial spawning stock biomass for ages 2 through the maximum age is calculated and used in the stock recruitment relationship (Eq. 2) to estimate an expected recruitment in the first year. The recruitment deviation for the first year is applied to create the population abundance at age 1 in the first year (Eq. 4). The full spawning stock biomass is then computed for the first year using all ages (Eq. 1).

The population abundance for years 2 through the end year are filled by first computing the expected recruitment using stock-recruitment relationship (Eq. 2) and then applying the recruitment deviation to create the abundance at age 1 (Eq. 4). Ages 2 through the maximum age are filled using the following set of equations:

$$N_{t,a} = N_{t-1,a-1}e^{-Z_{t-1,a-1}}, \quad 2 \le a < A \tag{9}$$
$$N_{t,A} = N_{t-1,A-1}e^{-Z_{t-1,A-1}} + N_{t-1,A}e^{-Z_{t-1,A}}, \quad a = A$$

Each year the spawning stock biomass is computed (Eq. 1) and the cycle continued until the end year is reached.

The model predicted catch in units of numbers of fish for each fleet, year, and age are derived from the Baranov catch equation:

$$C_{i\text{fleet},t,a} = N_{i\text{fleet},t,a}F_{i\text{fleet},t,a}(1 - e^{-Z_{t,a}})/Z_{t,a} \tag{10}$$

The predicted total catch in weight is calculated by multiplying the catch in number by weight at age. The predicted catch proportions at age for each fleet and year are computed.

Catchability for each abundance index (*ind*) over time is computed similarly to the *Fmult*, with one parameter for the catchability in the first year ($q_{ind,1}$) and a number of deviation parameters for each additional year of index observations (Dev($q_{ind,t}$)). These parameters are combined and exponentiated to form the catchability value for the fleet and year as

$$q_{ind,t} = e^{\log(q_{ind,1})+\log(Dev(q_{ind,t}))} \tag{11}$$

Where the parameter for the deviation in the first year *Dev*($q_{int,1}$) is defined as one.

The estimated population numbers at age are modified to match the average population numbers, which are used for calculating the abundance index, according to

$$\bar{N}_{ind,t,a} = N_{t,a}\frac{1-e^{-Z_{t,a}}}{Z_{t,a}} \tag{12}$$

The predicted abundance index (I_{pred}) is formed by summing the product of $\bar{N}$ and selectivity associated with each index over the appropriate ages and multiplying by the catchability for the index

$$Ipred_{ind,t} = q_{ind,t}\sum_{a=ind\_start}^{ind\_end}\bar{N}_{ind,t,a}Sel_{ind,t,a} \tag{13}$$

After any index selectivity parameters are estimated, the proportions at age are computed in the same manner as the catch at age.

Appendix B

ASAP Input data sets for the base case of ALB assessment.