# Addendum to IOTC-WPTT-2005-09
# (Final ASPM runs)

## Table 8 Summary of final ASPM runs

P: Something may not be OK with this run  NC:  No convergence  catch (2003)=0.45 million tons

| Run No. | Period | Area | AI (CPUE) | Growth Curve & M | selectivity | Results | MSY (million tons) | -ln (likely hood) | R2 | Steep-ness | B Ratio (SSB) | F ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | J | Stequert | Fwd VPA | Ok | 0.30 | -75 | 0.82 | 0.99 | 1.2 | 1.2 |
| 2 | | | (68-2) | | Sep VPA | ok | 0.30 | -69 | 0.77 | 0.99 | 1.6 | 1.1 |
| 3 | 1968 | | T | Viera | Fwd VPA | ok | 0.32 | -71 | 0.77 | 0.99 | 1.3 | 1.0 |
| 4 | - | Whole | (68-1) | | Sep VPA | ok | 0.33 | -66 | 0.76 | 0.99 | 4.1 | 0.73 |
| 5 | 2003 | | J | Stequert | Fwd VPA | ok | 0.30 | -71 | 0.82 | 0.99 | 1.0 | 1.4 |
| 6 | | | (68-2) | | Sep VPA | ok | 0.29 | -63 | 0.76 | 0.99 | 1.4 | 1.2 |
| 7 | | | T | Viera | Fwd VPA | P | | | | | | |
| 8 | | | (68-2) | | Sep VPA | ok | .0.32 | -62 | 0.75 | 0.99 | 2.9 | 0.86 |

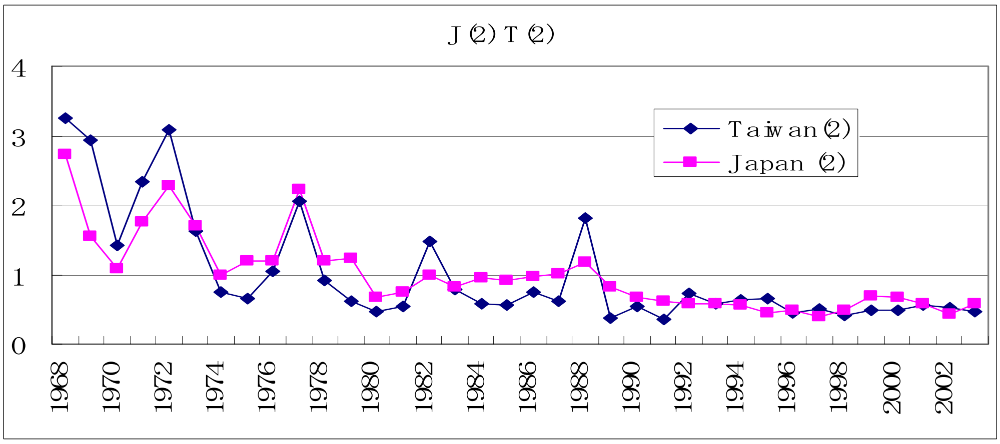
### BIOLOGICAL INPUT (RUN5)

| Age | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Weight (kg) | 0.74 | 2.84 | 7.39 | 14.6 | 23.8 | 33.9 | 43.9 | 53.1 | 61.0 | 73.0 | 77.2 | 80.5 |

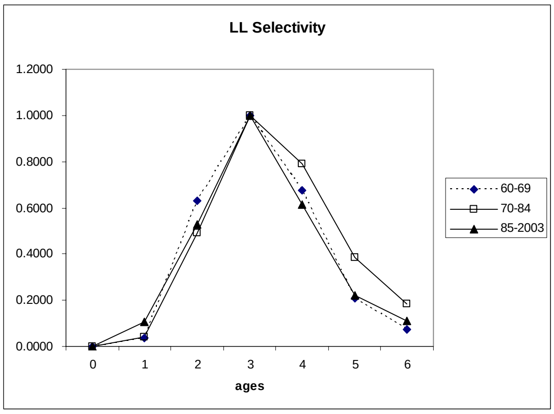
| age | 0 | 1 | 2 | 3 | 4 | 5 | 6+ |
|---|---|---|---|---|---|---|---|
| M vector | 0.8 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Fecundity ( if FL <100cm 1 if 100cm < FL) | 0 | 0 | 23.8 | 43.9 | 61.0 | 73.0 | 80.5 |

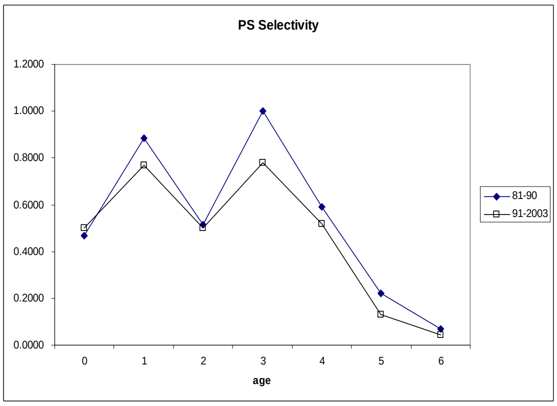
## INPUT (Abundance index & selectivity) for RUN 5

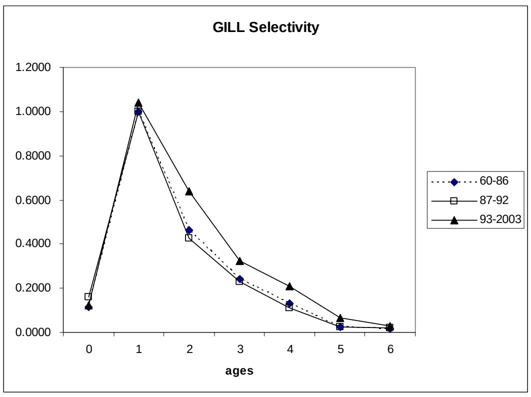
### Abundance index

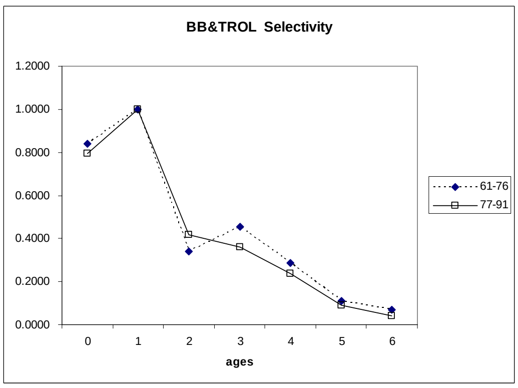



### Selectivity

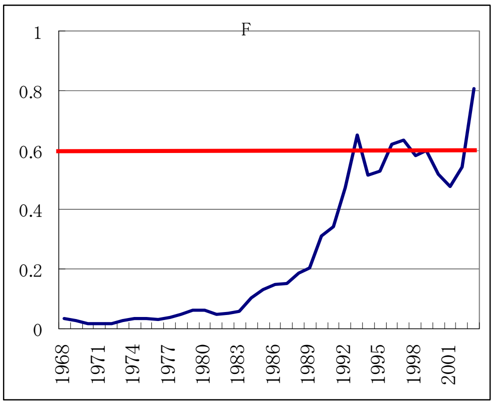


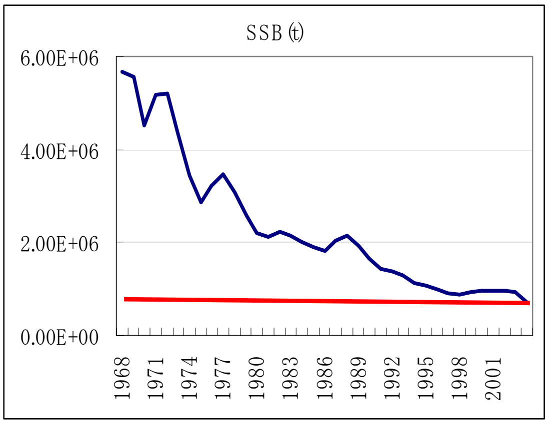



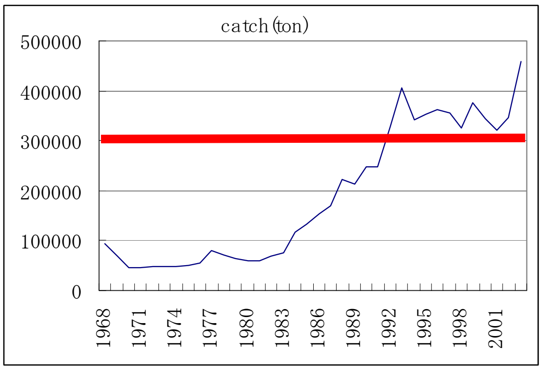



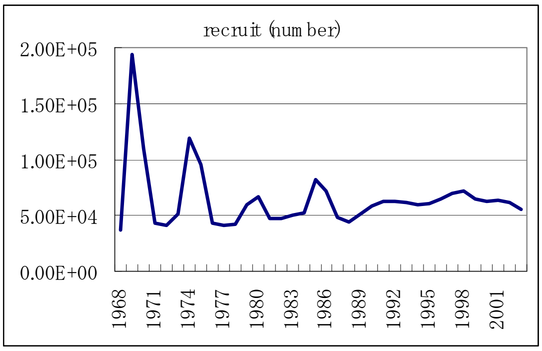



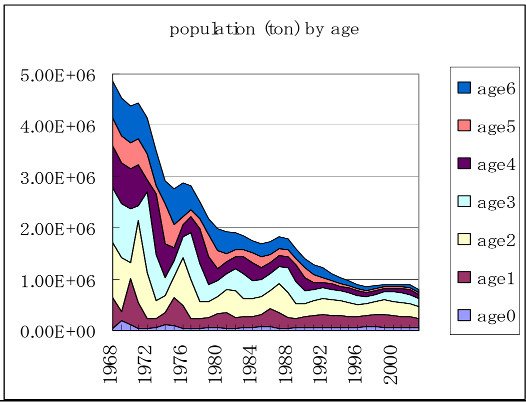
**Summary of the results for Run 5** **(Red) thick horizontal line : levels at the MSY**

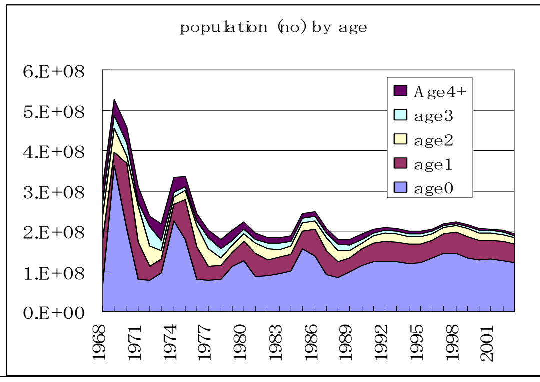


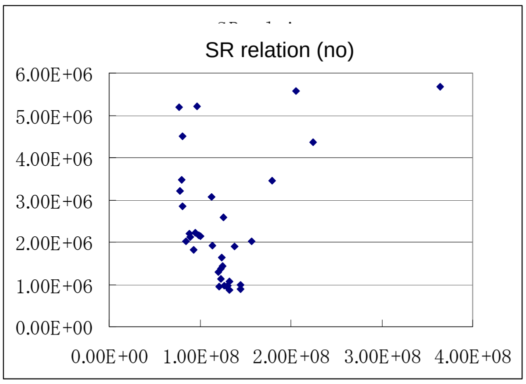



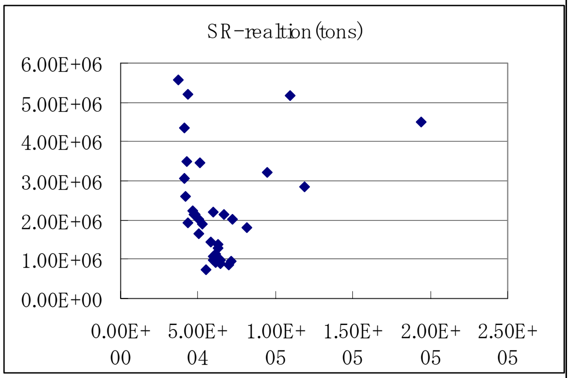



**(IOTC-WPTT-2005-　　)**

# Stock assessment of yellowfin tuna (*Thunnus albacares*) resource in the Indian Ocean by the age structured production model(ASPM) analyses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July, 2005


**Abstract**

We attempted to assess yellowfin tuna (*Thunnus albacares*) (YFT) resource using the data for 44 years from 1960-2003 by the age-structure production model (ASPM). The ASPM was recommended to conduct the tropical tuna stock assessments in the Indian Ocean during the IOTC ad hoc Working Party on Methods (WPM) meeting at the IRD, Sète, France 23-27, April, 2001. We assumme that YFT in the Indian Ocaen is a single stock.


Contents



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*Submitted to the IOTC 7th WPTT meeting, July 18-22, 2005, Phuket, Thailand*

## 1. Introduction

In this paper, we attempted to assess yellowfin tuna (*Thunnus albacares*) (YFT) resources using the age-structure production model (ASPM) as this approach was recommended for the tropical tuna stock assessments in the Indian Ocaen in the recent IOTC ad hoc working party meeting on methods held in IRD, Sète, France 23-27, April, 2001 (Anonymous, 2001). We assumme that YFT in the Indian Ocaen is a single stock.

## 2. Data

We use YFT catch and size data by country (area), gear, year and season for 44 years from 1960-2003, which were from the IOTC's updated database.

## 3. ASPM

ASPM have been used in assessments carried out by the International Commission for the Conservation of Atlantic Tunas (ICCAT) in the past, particularly for albacore tuna (*Thunnus alalunga)* in the south Atlantic and bluefin tuna (*Thunnus thynnus*) in the western Atlantic. Conceptually, ASPMs fall somewhere between simple biomass-based production models (e.g., Schaefer 1957; Prager 1994) and the more data-demanding sequential age-structured population analyses (Megrey, 1989). Typically, simple production models estimate parameters related to carrying capacity, rate of productivity, biomass at the start of the time series, and coefficients that scale indices of abundance to the absolute magnitude of biomass. ASPMs estimate similar parameters but make use of age-structured computations internally, rather than lumped-biomass ones, and directly estimate parameters of a stock-recruitment relationship. Their main advantage over simpler production models is that they can make use of age-specific indices of relative abundance.

In this paper, we used the ASPM software developed by Victor Restrepo (1997) called as ASPMS (stochastic version of ASPM). The detail formation of the ASPM is provided in Appendix A.

## 4. INPUT for the ASPM

There are three types of the age specific input data required for the ASPM, i.e., Biological parameters, Catch with selectivity and Index (CPUE). In our YFT ASPM analyses, we use six age classes from age 0-5+.

## 4.1 Biological parameters

For Biological parameters, three types of age-specific inputs are needed, i.e., natural mortality (M), weights (beginning and mid of the age) and fecundity. These inputs are decided (or assumed) as follows:

(1) Natural mortality vector (M)

We use two types of M vectors as shown in Table 1. M vector 2 is suggested by Fonteneau.

Table 1 Two M vectors as ASPM input

| Age | 0 | 1 | 2 | 3 | 4 | 5+ |
|---|---|---|---|---|---|---|
| M vector 1 (IATTC) | 2.40 | 1.28 | 0.90 | 1.10 | 1.08 | 0.80 |
| M vector 2 (SPC) | 1.48 | 0.80 | 1.20 | 1.80 | 1.35 | 1.02* |

* M at age 6.

(2) Weights at the beginning and the middle of the age

To estimate these parameters, we use the following growth curve and the L-W relationship:

Growth equation (Stequert *et al*, 1995)

$$L_{t(cm)} = 272.7\left(1 - e^{-0.176[t-(-0.266)]}\right)$$

***Based on the results of the otolith increment data collected in the (western ) Indian Ocean.***

L-W relationship (IPTP, 1990)

*For fork length < 64 cm :* $W = (5.313 \text{ x } 10^{-8})l^{2.754}$
*For 64cm <=fork length:* $W = (1.585 \text{ x } 10^{-8})l^{3.045}$

As results, we obtained Age-L-W key as shown in Table 2.

Table 2 YFT age-length-weight keys in the Indina Ocaen

| Age (at end) | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Length (cm) | 34.4 | 54.5 | 72.9 | 89.7 | 105.1 | 119.2 | 132.2 | 144.0 | 154.8 | 164.8 | 173.9 |
| Weight (kg) | 0.91 | 3.36 | 7.45 | 14.0 | 22.7 | 33.3 | 45.6 | 59.2 | 73.8 | 89.3 | 105.1 |

(3) Fecundity

We assume that fecundity is proportional the body weights at the middle of each age and also assume 0 fecundity (maturity) for age 0-1, 50% for age 2 and 100% for age 3-5+. Table 3 summarizes this information.

Table 3 Maturity and fecundity of YFT in the Indian Ocean

| Age | 0 | 1 | 2 | 3 | 4 | 5+ |
|---|---|---|---|---|---|---|
| Maturity | 0 | 0 | 0.5 | 1 | 1 | 1 |
| Fecundity (kg) | 0 | 0 | 11.4 | 45.6 | 73.8 | 105.1 |

### 4.2 Catch

Appendix B lists the annual catch by gear based on the IOTC database (June, 2005 version). According to Appendix B, there are eight types of gears including others, which exploit the YFT in the Indian Ocean. In the ASPM analyses, we need to estimate selectivity for each gear. As we don't have enough size data to estimate accurate selectivities for these eight gears, we classify them into four types considering similarities of the age compositions and depths of the gears, which are shown in Table 4 and Fig. 1.

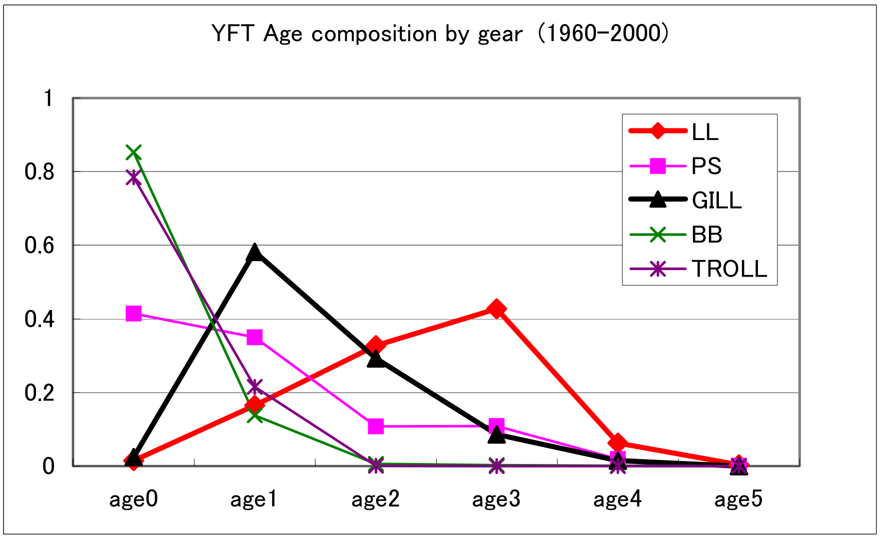



Fig. 1 YFT age compositions by gear based on the IOTC size database (1960-2000).

Table 4 Four gear types, their codes, relevant gears, major age class & size to exploit YFT.

| Type (code) | Gear Code | member gears | Depth of the gear | Major age classes for catch |
|---|---|---|---|---|
| (1) Surface (SUF) | BB_TL | BB, TROLL, LINE, and OTHER (*) | Surface | 0 |
| (2) Sub-surface (SUB) | GILL | GILL and OTHER (*) | 30m (?) | 1 |
| (3) Surface to Sub-surface (SUF_SUB) | PS | PS | Surface to 30 m (?) | 0-1 |
| (4) Mid water (MID) | LL | LL, HAND, LINE(*), and OTHER(*) | 50-250 m | 2-5+ |

*Note (*) for classification of OTHERS : see Table 5..*

There are OTHER gears listed in Table 5, which are mainly the combined gears. They are also classified into four categories by considering compositions of combined gear types, which are based on the information provided by Miguel Herrera (IOTC). Using these four gear categories, trends of the YFT catch are re-summarized in Fig. 2 from 1960-2000 as we will use this period for the ASPM analyses. For a reference, Fig. 3 shows the gear compositions of the cumulative YFT catch for 41 years from 1960-2000.

Table 5 List of OTHER type of gear and LINE by country, cumulative YFT catch and assigned gear type code defined in Table 4.

| IOTC gear category | IOTC country code | Cumulative YFT catch (t) (1950-2000) | Assigned gear type code and their compositions(*) |
|---|---|---|---|
| OTHER | AUS | 80 | SUF(100%) |
| OTHER | COM | 2,158 | SUF(50%) MID(50%) |
| OTHER | IDN | 32,577 | SUF(80%),SUB(10%), SUF_SUB(10%) |
| OTHER | IND | 12,298 | SUF(33%),SUB(33%), MID(33%) |
| OTHER | JPN | 2 | SUF(100%) |
| OTHER | LKA | 142,193 | SUB(80%), MID(20%) |
| OTHER | MDV | 27 | SUF(100%) |
| OTHER | MOZ | 218 | SUF(100%) |
| OTHER | SYC | 2,946 | SUF(20%), MID(80%) |
| OTHER | TZA | 1,050 | SUB(100%) |
| OTHER | YEM | 15,026 | SUB(100%) |
| OTHER | ZAF | 161 | SUF(100%) |
| LINE | | | SUF(50%), MID(50%) |

*Note (*): Gear compositions are roughly estimated based on Nishida (1999) and personal communication with Miguel Herrera (IOTC).*

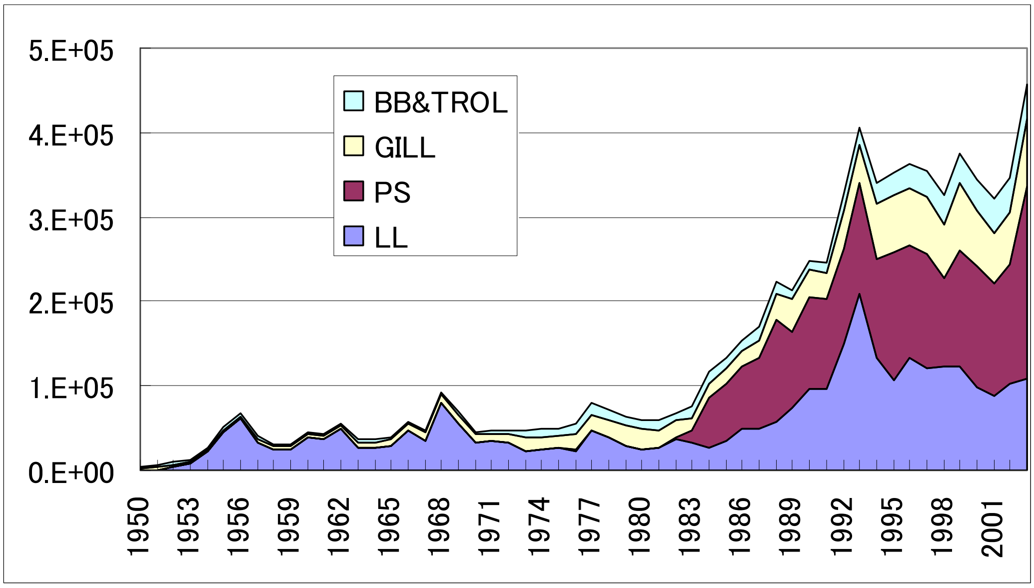



Fig. 2 YFT annual catch trends by FOUR gear category (1960-2003)(tons)

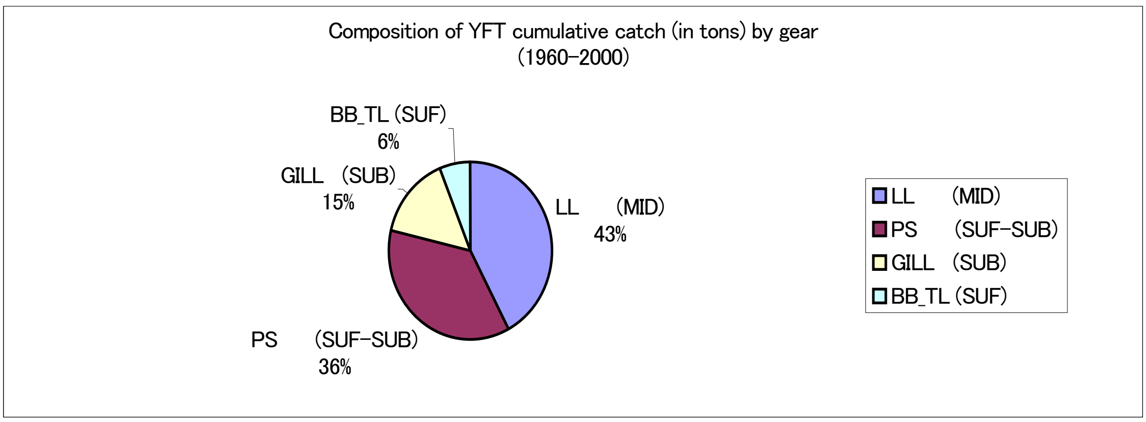
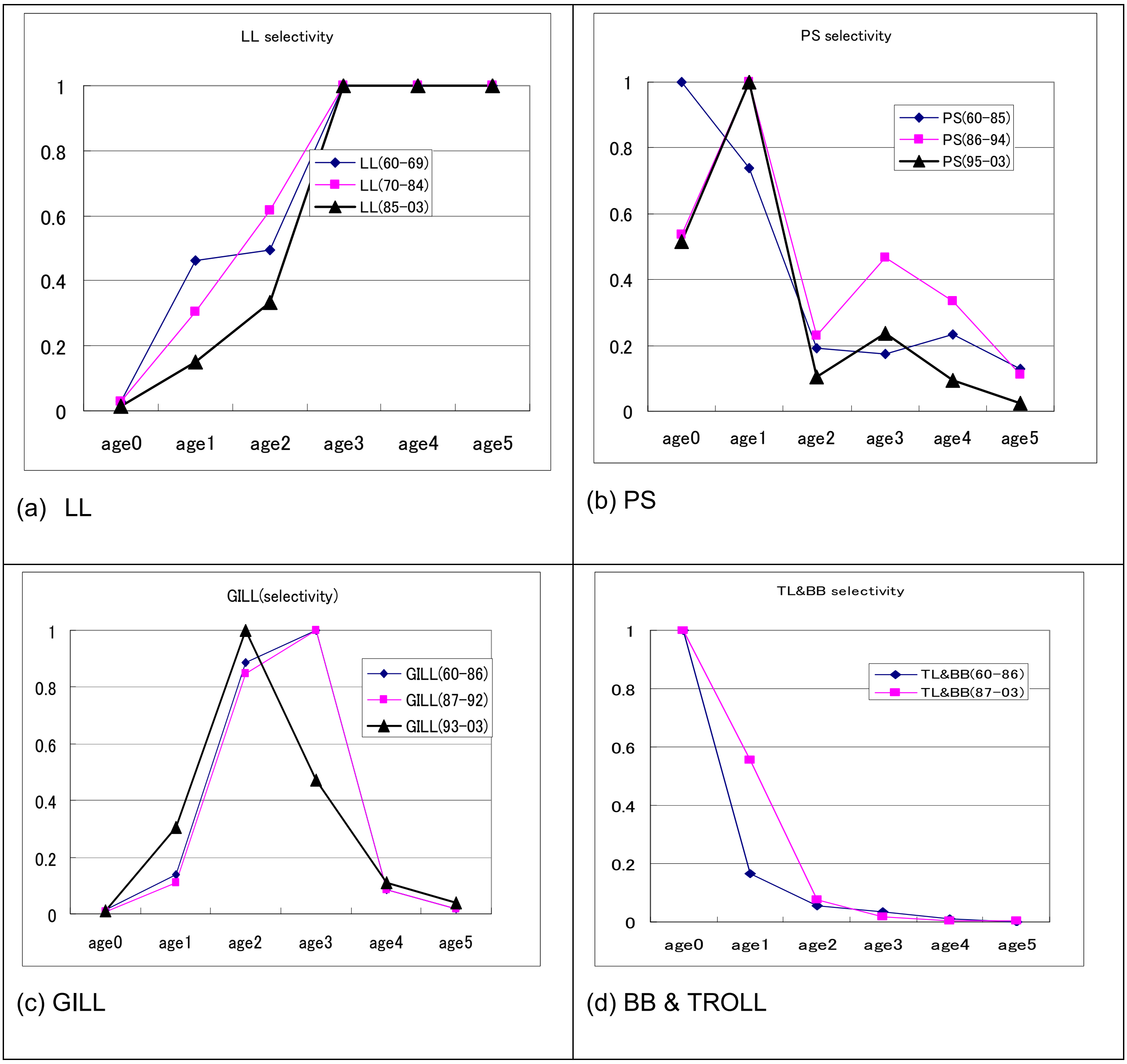



Fig. 3 Gear compositions in the cumulative YFT catch for 41 years from 1960-2000.

### 4.3 Selectivity

In estimating the selectivity, we need the catch-at-age (CAA) matrix. To estimate the CAA, we need the age compositions. However, as we don't have enough size data for FOUR types of gears, we will estimate the age compositions by some period (3-5 years). CAA was estimated during the WPTT meeting in Shanghai in 2002 based on these age compositions. Then, by looking at the similarity of the patterns of age compositions and catch trends among these periods, we will further pool them into a few longer periods during 1960-2000. For each longer period, we estimate one vector of selectivity (see Fig. 4). We assumed that selectivity from 2001-2003 are homogeneous to those in the most recent years before 2000. Appendix C shows the data process to determine such longer periods for the selectivity and also the resultant CAA. Based on this information we estimate the selectivity using the separable VPA by gear. The results are shown in Fig. 4. For the LL, we assume that the selectivity for age 3-5+ to be 1.




(a) LL

(b) PS

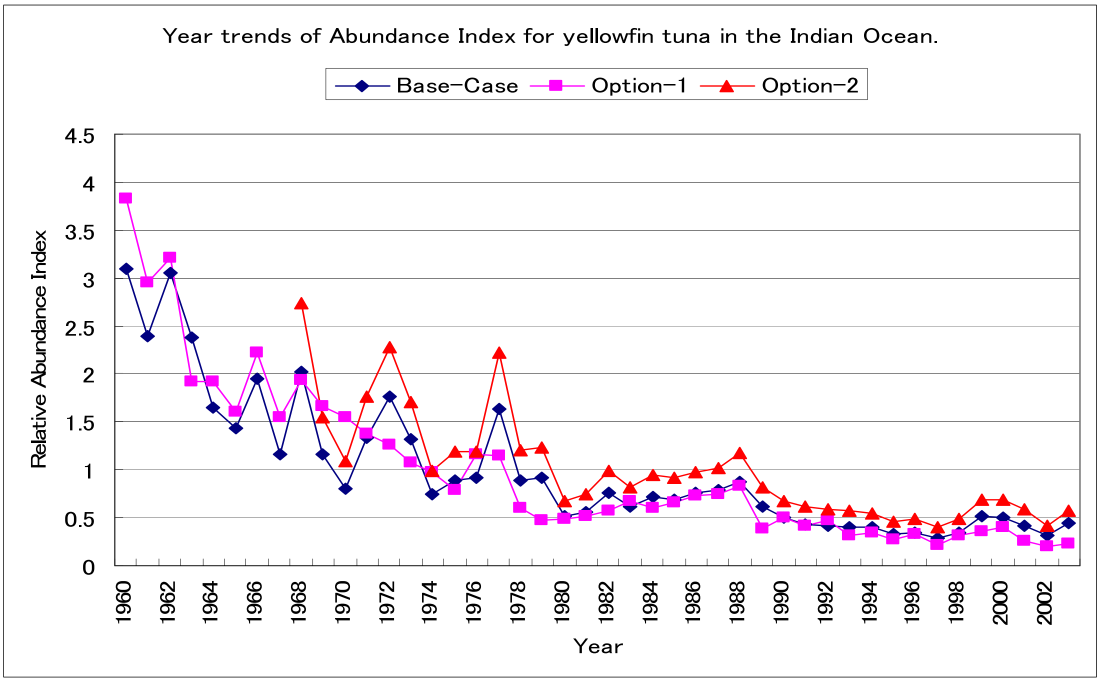
(c) GILL

(d) BB & TROLL

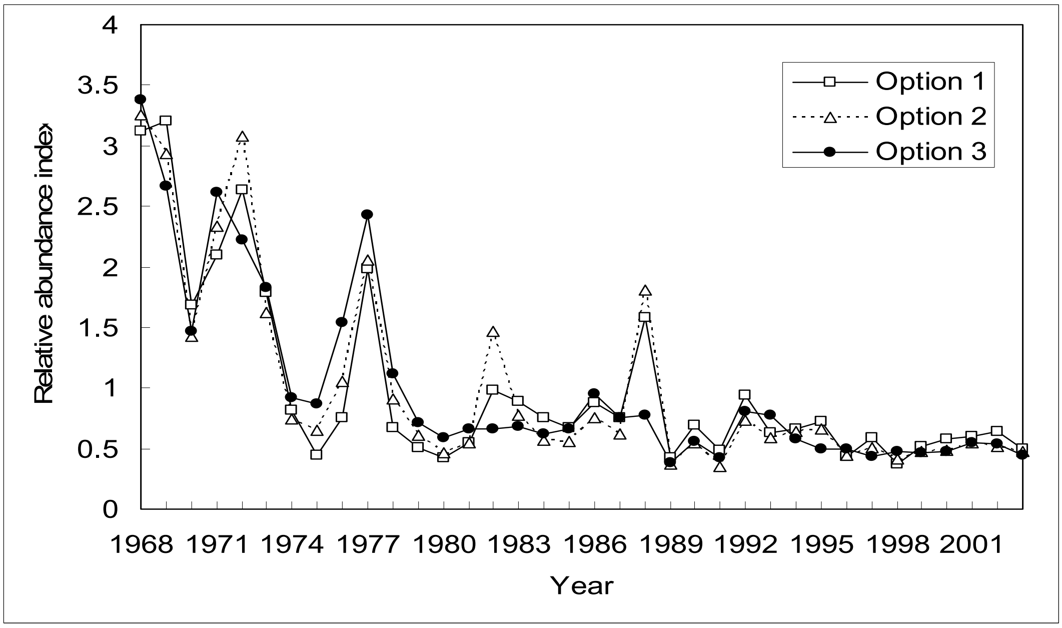
Fig. 4 Estimated Selectivity by gear

### 4.4 Abundance Index (AI)

We use the AI based on the Japanese and the Taiwanese standardized CPUE by the GLM as the index inputs, which are described in IOTC-WPTT-2004-_____(Shono *et al*, 2005) and IOTC-WPTT-2005-_____ (Wang *et al*, 2005) respectively. Fig. 5(a) and (b) shows trends of the AI in Japan and Taiwan respectively. There are three options for each AI.




(a) Japan




(b) Taiwan

Fig. 5 Trends of annual abundance indices based on the standardize CPUE of (a) Japanese and (b) Taiwanese LL (1960-2003)

## 5. ASPM runs (Results)

Initially we attempted 20 ASPM runs explanatorily as listed in Table 6. Appendix B shows details of all the 20 Runs. Based of the situation of convergence, -in (likelihood), R2, B ratio and, F ratio we consider Run 13 is the best result. Then we set Run 13 as our base case we explore further Runs as listed in Table 7. As a conclusion we consider that Run 13a, 13b and 13c are likely realistic although MSY seems to be low. We need to discuss options for the final Runs during the WPTT.

Table 6 **Summary of initial exploratory 20 ASPM runs**

***P: Something may not be OK with this run NC: No convergence catch (2003)=0.45 million tons***

| Run No. | Period | Area | CPUE | M | S-R | Results | MSY (million tons) | -ln (likely hood) | R2 | Steep ness | B Ratio (SSB) | F ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1968-2003 | Whole | J(2), T(1) | SPC | BH | Ok | 0.45 | -79 | 0.85 | 0.99 | 3.6* | 0.46 |
| 2 | | | | | R | NC | | | | | | |
| 3 | | | | IATTC | BH | Ok | 0.46 | -73 | 0.82 | 0.99 | 9.2* | 0.36 |
| 4 | | | | | R | NC | | | | | | |
| 5 | 1960 -2003 | Whole | J(BC), T(1) | SPC | BH | P | | | | | | |
| 6 | | | | | R | NC | | | | | | |
| 7 | | | | IATTC | BH | P | | | | | | |
| 8 | | | | | R | NC | | | | | | |
| 9 | 1960 -2003 | Tropical | J(1), T(3) | SPC | BH | P | | | | | | |
| 10 | | | | | R | NC | | | | | | |
| 11 | | | | IATTC | BH | P | | | | | | |
| 12 | | | | | R | NC | | | | | | |
| 13 | 1960 -2003 | Whole | J(BC), T(2) | SPC | BH | OK | 0.232 | -90 | 0.90 | 0.40 | 0.89 | 1.98 |
| 14 | | | | | R | NC | | | | | | |
| 15 | | | | IATTC | BH | P | | | | | | |
| 16 | | | | | R | NC | | | | | | |
| 17 | 1968 -2003 | Whole | J(2), T(2) | SPC | BH | OK | 0.41 | -77 | 0.85 | 0.99 | 3.1* | 0.55 |
| 18 | | | | | R | NC | | | | | | |
| 19 | | | | IATTC | BH | OK | 0.43 | -70 | 0.82 | 0.99 | 7.6* | 0,43 |
| 20 | | | | | R | NC | | | | | | |

* unrealistic (too large)

**Table 7 Results of secondary ASPM runs (Run 13 as a base case)**

**P: Something may not be OK with this run  NC: No convergence**
**catch (2003)=0.45 million tons**

| Run No. | Period | Area | CPUE | M | S-R | Results | MSY (million tons) | -ln (likely hood) | R2 | Steep ness | B Ratio (SSB) $=B_{2003}/B_{MSY}$ | F Ratio $=F_{2003}/F_{MSY}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13** **Base case** | 1960 -2003 | Whole | J(BC), T(2) | SPC | BH | OK | 0.23 | -90 | 0.90 | 0.40 | 0.89 | 1.98 |
| 13a** | | | J(BC) | | | OK | 0.34 | -100 | 0.99 | 0.99 | 0.45 | 0.73 |
| 13b** | 1968 -2003 | | T(2) | | | OK | 0.28 | -44 | 0.83 | 0.54 | 1.09 | 1.42 |
| 13c | 1968 -2003 | | J(2) | | | OK | 0.45 | -76 | 0.96 | 0.99 | 3.4* | 0.46 |
| 13d | 1960 -2003 | tropical | J(1) | | | P | | | | | | |
| 13e | 1968 -2003 | Whole | T(1) | | | OK | 0.32 | -49 | 0.88 | 0.56 | 6.8* | 1.00 |
| 13f | 1968 -2003 | tropical | T(3) | | | OK | 0.34 | -67 | 0.96 | 0.99 | 2.5* | 0.73 |

*** unrealistic (too large)**

**** likely realistic although MSY seems to be the low level**

## 6. Discussion

Using the available input parameters, we attempted various ASPM Runs. As results, we could not get the satisfactory solutions. This is probably because catch (Fig. 2) and CPUE-AI (Fig. 5) trends are not properly reflected, i.e., during 1960's -1970's CPUE dramatically deceased although catch was constant, while during 1980's – 2000's, CPUE were constant although catch dramatically increased.

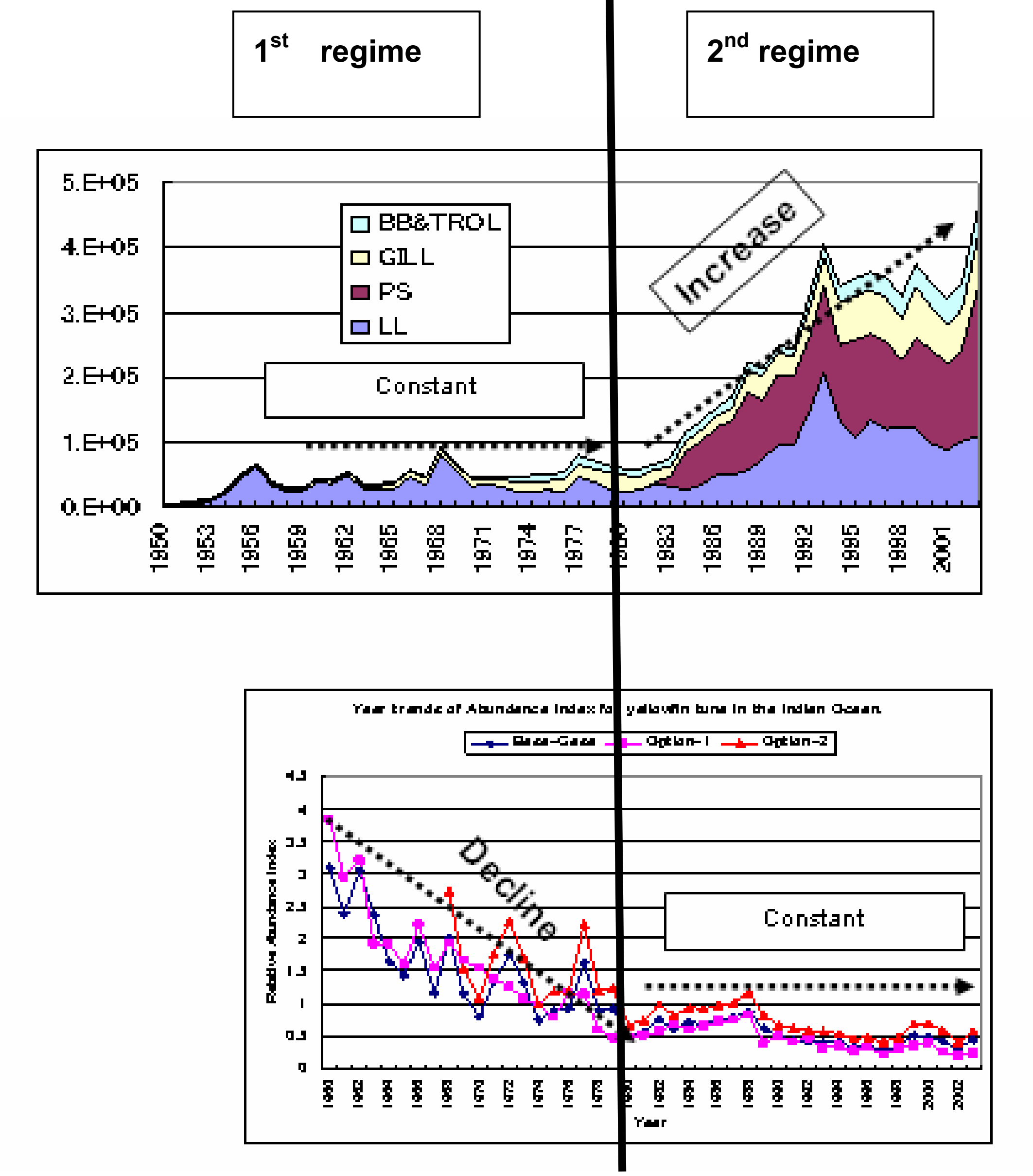


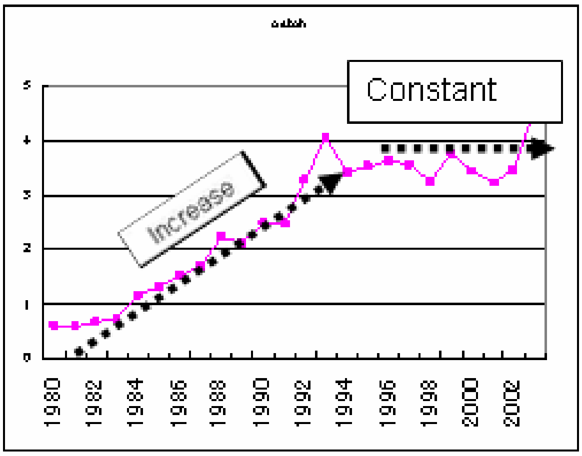

Fig. 2 Catch trend (above; Fig 2, page 5) and CPUE(AI) trend (below; Fig. 5, page 7) in 1950-2003

We consider that there are two Regimes before & after 1980 in YFT dynamics, i.e., the first regime, 1950's – 1970' and the second regime, 1980's-2000's. We then consider that reflection of CPUE against catch are completely different in between these two regimes. In the first regime, CPUE highly reflected even by small catch and for the second regime, the reflection was dull against even very high catch. It is very difficult to interpret these large gaps.

But we consider that the YFT dynamics in the second regime is more realistic because (a) large catch will provide us more real & concrete population dynamics than the situation when there are only small catch and (b) YFT fishing grounds expanded fully to the whole area in the 2nd regime while those in the first regime was mainly in the tropical waters and it is meaningless to analyze HETEROGENEOUS spatial data (see FOLLY & FANTASY in the analyses of spatial catch by Carl Walter, 2003).

In fact if we focus the catch and CPUE in the second regime we can see reasonable reflections between catch and CPUE (AI) (Fig. 6). This is because dynamic of CPUE (AI) in second regime have been masked by the large CPUE scales in the first regime in the past because the CPUE in 1950's -1970's (first regime) are too large to show the real ups & downs of CPUE(AI) in the second regime.

<u>Hence we suggest that ASPM analyses need to be re-attempted using the data in the second regime after 1980 so that we may be able to obtain more realistic results because YFT fishery-resources dynamics are likely more realistic than those in the first regime before 1980, in addition YFT tuna fishing grounds are fully expanded in the 2nd regime which reduce the problem of the heterogeneous spatial data.</u>



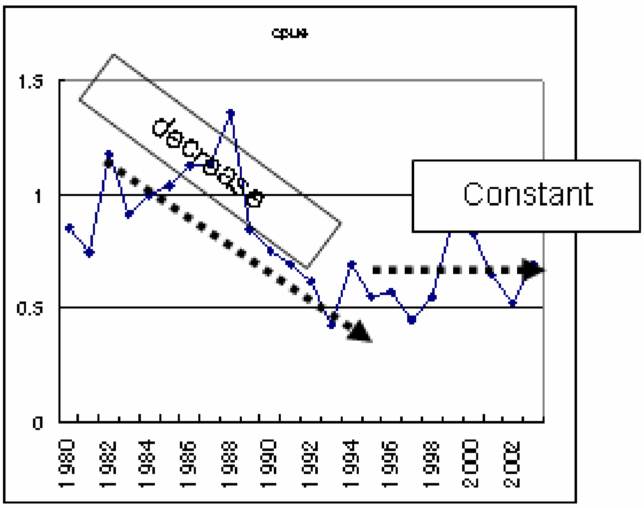




Fig. 6 Dynamics and reflection between catch (above) vs CPUE(AI) in the 2nd regime after 1980.

## Acknowledgements

We very much appreciate Miguel Herrera and Alejandro Anganuzzi (IOTC) for providing the data and suggestions on the fishing gears and fisheries. We further thank Ziro Suzuki and Hiroaki Okamoto (NRIFSF) who provided the constructive suggestions to improve this paper.

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## Appendix A Formulation of the ASPM

The deterministic formulation, for ease of presentation, precedes the formulation for the stochastic model. A Beverton and Holt (1957) type of stock recruitment relationship (SRR) is assumed here. Note, however, that other forms could be implemented following the same basic procedure outlined here.

Deterministic formulation

The deterministic model is essentially like that of (Punt 1994), which was based on ideas presented by Hilborn (1990). It consists of a forward population projection,

$$N_{1,t+1} = f(S_t) \qquad \text{for age 1} \qquad (1a)$$

$$N_{a+1,t+1} = N_{a,t} e^{-z_{a,t}} \qquad \text{for other ages except the "plus" group, and} \qquad (1b)$$

$$N_{p,t+1} = N_{p-1,t} e^{-z_{p-1,t}} + N_{p,t} e^{-z_{p,t}} \qquad \text{for the plus group, } p, \qquad (1c)$$

where $f(S)$ *is* a stock-recruitment function ( explained below ), *a* and *t* index age and year, and age 1 is, for simplicity, assumed here as the age of recruitment. *Z* denotes the total age and year-specific mortality rate, which is the sum of natural mortality ($M_a$, an assumed input value) and fishing mortality, *F*. In the (Restrepo *in press*) implementation, *F* is calculated based on total yields, weights at age $(\overline{W}_{a,t})$, and age –specific selectivities that are input and assumed exact, for up to five fisheries. This is accomplished by solving for the fishery-specific multipliers $(F_{g,t})$ of the input selectivities ($s_{g,a,t}$) that result in the observed yields (*Y*), given the estimates of stock sizes:

$$Y_{g,t} = \sum_{a=1}^{p} F_{g,t} s_{g,a,t} \overline{w}_{a,t} N_{a,t} U_{a,t} \qquad \text{with}$$

$$U_{a,t} = \frac{\left[1 - e^{-\sum_g F_{g,t} s_{g,a,t} - M_a}\right]}{\sum_g F_{g,t} s_{g,a,t} + M_a} \qquad (2)$$

Thus, the population projection is conditioned on known yields. The Beverton and Holt SRR can be described by the equation

$$R_{t+1} = f(S_t) = \frac{\alpha S_t}{\beta + S_t}, \qquad (3)$$

where *R* is the number of recruits $(N_{l,t+1}$ in eq.1a) and *S* is the reproductive output, namely the product of numbers times maturity times fecundity, summed over all ages. For simplicity, we hereafter refer to *S* as “spawning biomass”, which is often used as a proxy for reproductive output.

Formulation (3) is not very desirable for estimation because starting values of the parameters α and β are not easy to guess. For this reason, the ASPM uses a different parameterization, following (Francis 1992). It consists of defining a “steepness” parameter, τ, which is the fraction of the virgin recruitment $(R_0)$ that is expected when *S* has been reduced to 20% of its maximum (i.e., $R = \tau R_0$ when $S = \gamma / 5$, where $\gamma$ is the virgin biomass). The SRR can thus be defined in terms of steepness and virgin biomass, two parameters that are somewhat easier to guess initial values. For a Beverton-Holt relationship, virgin biomass should generally be of similar magnitude to the largest observed yields, while steepness should fall somewhere between0.2and1.0, with higher values indicating higher capacity for the population to compensate for losses in spawning biomass with increases in the survival of recruit. Nothing that equilibrium recruitment at virgin biomass can be computed as the ratio of virgin spawning biomass to spawning biomass per recruit in the absence of fishing $(S/R)_{F=0}$,

$$R_0 = \frac{\gamma}{(S/R)_{F=0}} \tag{4}$$

α and β are given by

$$\alpha = \frac{4\tau\ R_0}{5\tau - 1} \tag{5}$$

and

$$\beta = \frac{\gamma(1-\tau)}{5\tau - 1} \tag{6}$$

The spawning potential ratio*, SPR,* is measured by the spawning biomass per recruit obtained under a given *F,* divided by that under *F*=0 (Goodyear 1993). A useful benchmark for management is the *SPR* corresponding to the slope of the *SRR* at the origin, i.e., at the point when the stock is expected to "crash". From equations (4) to (6) it follows that this $SPR_{crash}$ is given by

$$SPR_{crash} = \frac{(S/R)_{crash}}{(S/R)_{F=0}} = \frac{\beta/\alpha}{\gamma/R_0} = \frac{1-\tau}{4\tau} \tag{7}$$

Hence, in a deterministic sense, any fishing mortality that results in an *SPR* lower than $SPR_{crash}$ is not sustainable.

Fitting the model requires finding the values of the **SRR** parameters that best explain the trends in indices of abundance, given the observed yields and other inputs. For a set of initial conditions ($N_{a,t}$ for all ages in *t*=1), equations (1) and (3) are used to project the population forward, with the fishing mortalities being calculated conditional on observed yields, by equation (2). Values of the parameters γ and τ are chosen to minimize the negative log-likelihood,

$$-\ln(L_1) = \sum_i \left[ \frac{n_i}{2} \sum \ln\left(\sigma^2_{i,t}\right) + \sum_t \frac{1}{2\sigma^2_{i,t}} \left(I_{i,t-} \hat{I}_{i,t}\right)^2 \right] \tag{8}$$

where í denotes each available index. The last term is for the squared differences between observed and predicted indices (these could be in logarithmic units if a lognormal error is assumed), and $\sigma^2_{i,t}$ are variances whose computation is explained below. The predicted indices are obtained as the summation of stock sizes, times an input index selectivity, *u*, over all ages:

$$\hat{I}_{i,t} = q_i \sum_a N_{a,t} u_{a,i} \omega_i \tag{9}$$

where ω indicates some input control as to whether the index is in numbers or biomass (in which case the product being summed include weight at age), and whether computations are for the start or middle of the year. The parameters $q_i$ scale each index to absolute population numbers (or biomass) and their maximum likelihood values can be obtained analytically by setting the derivative of equation (8) with respect to $q_i$ equal to zero, and solving for the $q_i$.

There are several options for handling the variances, $\sigma^2_{i,t}$. If all the values for all indices are given equal weight, they can be set to

$$\sigma^2_{i,t} = \sum_i \left[ \frac{1}{n_i} \sum_t \left( I_{i,t} - \hat{I}_{i,t} \right)^2 \right] \tag{10}$$

or, if all values within an index are to have equal weights but each index is weighted depending on how it is fitted by the model (maximum likelihood weighting)then:

$$\sigma^2_{i,t} = \frac{l}{n_i} \sum_t (I_{i,t} - \hat{I}_{i,t})^2 \tag{11}$$

Alternatively, the variances could be input for each value, based on external information.

So far, the presentation of the method has indicated that parameters γ and τ (or, equivalently, α and β ) are estimated directly in the search, and the parameters $q_i$ and $\sigma^2_{i,t}$ are obtained indirectly or externally The remaining requirement to complete the estimation procedure has to do with the initial conditions. This can be handled in various ways and perhaps the easiest is to assume that the initial age composition corresponds to anequilibrium one in virgin state. For this to be approximately valid, the time series of yield data should be extended as far back in time as possible, preferably to the onset of fishing. In this case,

$$N_{1,1} = R_0 \tag{12a}$$

$$N_{a,1} = N_{a-1,1} e^{-M_{a-1}} \qquad \text{for ages } a = 2 \text{ to } p-1, \text{and} \tag{12b}$$

$$N_{p,1} = \frac{N_{p-1,1} e^{-M_{p-1}}}{(1 - e^{-M_p})} \qquad \text{for the plus group.} \tag{12c}$$

An alternative consists of estimating the equilibrium recruitment in year *t* =1 as an additional parameter and solving for the initial age composition that produces a spawning biomass that results in that recruitment given τ and γ. Several other options exist, but it appears that none will generally be superior unless there is adequate relative abundance information for the start of the time series. A useful option may be to “fix” the initial age composition at same scaled fraction of the virgin one, and to conduct sensitivity trials for that choice.

The computation of statistics such as maximum sustainable yield (*MSY*) and related benchmarks (e.g. $S_{MSY}$, $F_{MSY}$ ) is straightforward once the parameters for the *SRR* have been obtained. Shepherd (1982) describes the procedure used to compute equilibrium yield curves from a *SRR*, together with yield-per-recruit and spawning biomass-per-recruit calculations. Conditional on a given *F* (including an overall selectivity pattern), equilibrium spawning biomass, recruitment and yield are computed as (for the Beverton and Holt SRR)

$$S_F = \alpha (S/R)_F - \beta \quad , \tag{13a}$$

$$R_F = \frac{S_F}{(S/R)_F} \quad , \text{ and} \tag{13b}$$

$$Y_F = R_F (Y/R)_F \tag{13c}$$

where $(S/R)_F$ and $(Y/R)_F$ are the spawning biomass and yield per recruit values resulting from exploitation at *F* . To search for *MSY* –related statistics, this procedure is built into an algorithm to obtain the desired target, e.g. to find the maximum $Y_F$ as the estimates of *MSY.* Note that, if the selectivity pattern changes over time, then the computed MSY-related values will also change as a result of changes in the per-recruit computations.

Stochastic formulation

A stochastic ASPM requires that a recruitment value be estimated for every year. If this were attempted without constrains on the possible recruitment values, while simultaneously estimating the SRR, the application would be over-parameterized in most real situations. In this work, we have chosen to estimate the recruitments as lognormal deviations from the equilibrium SRR, assuming that these deviations follow a first-order autoregressive process.

The population projection equations are as in equation (1), except that recruitment is estimated as

$$N_{1,t} = R_0 e^{v} \qquad (14)$$

That is, recruitment is estimated as deviations from a virgin level. Instead of estimating γ and τ directly as parameters, the model estimates γ and all the $v_{t.}$. $R_0$ is computed from equation (4). These are essentially all parameters that would be needed to project the population forward and compute the log-likelihood in equation (8). The AR [1] process is incorporated by assuming that the recruitment estimates thus obtained vary around the expected stock recruitment relationship as

$$R_{t+1} = \frac{\alpha S_t}{\beta + S_t} e^{\varepsilon_{t+1}} \qquad (15)$$

with $\varepsilon_{t+1} = \rho\varepsilon_t + \eta_{t+1}$, $|\rho| < 1$, the η have zero expectation and variance equal to $\sigma_\eta^2$. In equations (14) and (15) we distinguish between recruitment values estimated as parameters ( $N_{1,t}$ ) and those predicted from the estimated stock-recruitment relationship ( $R_t$ ). The negative log-likelihood for these residuals would be (Seber and Wild 1989):

$$-\ln(L_2) = \frac{n_t}{2}\ln(\sigma_\eta^2) - \frac{1}{2}\ln(1 - \rho^2) + \frac{1}{2\sigma_\eta^2}\left[(1-\rho^2)\varepsilon_1^2 + \sum_{t=2}^{n_t}(\varepsilon_t - \rho\varepsilon_{t-1})^2\right] \qquad (16)$$

Where the residuals would be computed as

$$\varepsilon_{t+1} = \ln(N_{1,t+1}) - \ln(R_{t+1}) = \ln(N_{1,t+1}) - \ln\left(\frac{\alpha S_t}{\beta + S_t}\right) \qquad (17)$$

Computation of the first residual would depend on the initial conditions. For example, in a virgin state, it would be

$$\varepsilon_1 = \ln(N_{1,1}) - \ln(R_0).$$

Note that α and β in equations (15) and (17) could be computed from knowledge of virgin biomass and steepness (see equations (5) and (6)). However, only the former is being estimated directly as a parameter. To include steepness as an additional parameter to be directly estimated by the search would confound the information contained in $R_0$ and γ (refer to equations. (4), (5), and (6)). Our approach is to replace α and β in the *SRR* of equation (17) by a function of those parameters being estimated in the search, and steepness. From equations (5) and (6) it follows that

$$R_{t+1} = \left( \frac{4R_0 S_t \tau}{\tau(5S_t - \gamma) - S_t + \gamma} \right), \text{ such that} \qquad (18)$$

$$\varepsilon_{t+1} = \ln(N_{1,t+1}) - \ln\left(\frac{4R_0 S_t \tau}{\tau(5S_t - \gamma) - S_t + \gamma}\right) \qquad (19)$$

We take advantage of this relationship in order to solve for τ, nothing that, for a given ρ and $\sigma_\eta^2$, equation (16) will be at a minimum when

$$\sum_{t=2}^{n_t-1}\left[\ln(N_{1,t+1})-\ln\left(\frac{4R_0S_t\tau}{\tau(5S_t-\gamma)-S_t+\gamma}\right)-\rho\ln(N_{1,t})+\rho\ln\left(\frac{4R_0S_{t-1}\tau}{\tau(5S_{t-1}-\gamma)-S_{t-1}+\gamma}\right)\right]^2 \qquad (20)$$

is also at a minimum. Thus, in every iteration in the search, a subprocedure is invoked to minimize (20) with respect to τ. Having thus calculated the steepness (and, consequently, α and β), the log-likelihood of equation (16) is added to the overall objective function.

It remains to be mentioned what to do about the parameters ρ and $\sigma_\eta^2$. In theory, there is a potential for these to also be estimated. In practice, however, it is unlikely that data will contain so much information as to determine the relative contribution from recruitment variability with respect to the variability in the index values (see equations (8) and (16)). In our limited experience with this model, it appears that these values should be controlled by the analyst in much the same way as contributions to the likelihood from different data sources are weighted externally in other assessment methods (e.g., Deriso et al.1985). Lower $\sigma_\eta^2$ values will result in lower stochasticity in recruitment, while higher $\sigma_\eta^2$ values will allow recruitment to fluctuate more widely in order to better fit the index data. A value of ρ=0 would assume no autocorrelation between successive recruitment deviations. Empirical studies such as those of Beddington and Cooke (1983) and Myers et al. (1990) may yield information about likely ranges of values for ρ and $\sigma_\eta^2$ for species groups. Reported values for these parameters (Myers et al.1990) are quite variable across species.

Estimating the initial conditions for the stochastic model can be problematic, as with the deterministic model. Estimating the age structure in year 1 would not generally be an option as the model would easily become highly over-parameterized unless there were age-specific relative abundance data for the start of the series. Thus, using a long time series of data extending to the onset of fishing, and assuming an initial equilibrium state at γ, remains a useful option. Other alternatives are also possible. In this paper we examine one in which we calculate a stable age structure (with only natural mortality) resulting from a pre-series recruitment that is fixed. That is, we fix $v_{t=0}$ and set the starting population sizes as

$$N_{2,1}=R_0e^{v_0}e^{-M_1} \qquad (21\text{a})$$

$$N_{a,1}=N_{a-1,1}e^{-M_{a-1}} \quad \text{for ages } a = 3 \text{ to } P\text{-}1\text{, and} \qquad (21\text{b})$$

the plus group is calculated as in equation (12c). This alternative allows the initial age structure to be either higher or lower than that corresponding to an equilibrium virgin state. The parameter $v_{t=0}$ could potentially be estimated in the search procedure as well. If it is, it may be desirable to place a penalty on how much it can alter the initial biomass, say, away from γ. This could be accomplished with the term

$$-\ln(L_3)=\frac{\ln(\sigma_v^2)}{2}+\frac{(\ln(S_1)-\ln(\gamma))^2}{2\sigma_v^2} \qquad (22)$$

where $\sigma_v^2$ is a variance value to be fixed by the analyst.

Estimation of the stochastic model parameters for any given data set then requires several choices associated with how much recruitment can fluctuate around its deterministic predictions and about the initial conditions. In addition to choices about variances ($\sigma_\eta^2, \sigma_v^2$ and possibly $\sigma_{i,l}^2$), the log-likelihood components could be given different emphases ($\lambda$) to obtain model estimates by minimizing:

$$-\ln(L_T)=-\ln(L_1)-\lambda_2\ln(L_2)-\lambda_3\ln(L_3) \qquad (23)$$

Appendix B(a) Summary of the first 20 ASPM runs : INPUT and RESULTS * unit : million tons

| INPUT & Assumptions | | | | |
|---|---|---|---|---|
| Years analyzed | 1968-2003 | | | |
| Stock (area) | Single stock (whole Indian Ocean) | | | |
| Gear types for catch (depth of the gear) | LL (mid water)<br>PS (surface to sub-surface)<br>GILL (sub-surface)<br>BB_TROLL (surface ) | | | |
| Growth | Stequert *et al* (1995) | | | |
| L-W relation | IPTP (1990) | | | |
| M vector | SPC | | IATTC | |
| Run number | Run 1 | Run 2 | Run 3 | Run 4 |
| SR | B-H | Ricker | B-H | Ricker |
| Selectivity (separable VPA) | Three different selectivities for three different periods are estimated for each gear | | | |
| penalty (weighting values) to fit to the objective function (residual sum of squares) | ρ(serial correlation coefficient in the error terms of the S-R model) = 0.00<br>$\sigma^2$ (weighting for the stock-recruitment relationship) = 0.20<br>$\sigma^2$ (weighting for the initial population size) = 0.40 | | | |
| Abundance Index (all ages combined) | Japan (Shono et al, 2005) option 2 1968-2003<br>Taiwan (Wang et al, 2005-) option 1 1968-2003 | | | |
| Results | | | | |
| Steepness | 0.99 | No convergence | 0.99 | No convergence |
| -ln (likelihood) | -79.0 | | -73.1 | |
| R-squared | 0.845 | | 0.816 | |
| MSY*(current catch* in 2003=0.459) | 0.447 | | 0.464 | |
| TB(2000)* | | | | |
| TB(MSY)* | | | | |
| B ratio(TB)= TB(2000)/TB(MSY) | | | | |
| SSB(2000)* | | | | |
| SSB(MSY)* | | | | |
| B ratio(SSB)= SSB(2000)/SSB(MSY) | | | | |
| B1 ratio = TB2000/B1 | | | | |
| F(2000) | | | | |
| F(MSY) | | | | |
| F(ratio) = F2000/F(MSY) | | | | |

Note : TB: Total Biomass, SSB: Spawning Stock Biomass B1: Biomass at the start year

| Age | 0 | 1 | 2 | 3 | 4 | 5+ |
|---|---|---|---|---|---|---|
| M vector 1 (IATTC) | 2.40 | 1.28 | 0.90 | 1.10 | 1.08 | 0.80 |
| M vector 2 (SPC) | 1.48 | 0.80 | 1.20 | 1.80 | 1.35 | 1.02* |

Appendix B(b) Summary of the first 20 ASPM runs : INPUT and RESULTS * unit : million tons

| INPUT & Assumptions | | | | |
|---|---|---|---|---|
| Years analyzed | 1960-2003 | | | |
| Stock (area) | Single stock (whole Indian Ocean) | | | |
| Gear types for catch (depth of the gear) | LL (mid water)<br>PS (surface to sub-surface)<br>GILL (sub-surface)<br>BB_TROLL (surface ) | | | |
| Growth | Stequert *et al* (1995) | | | |
| L-W relation | IPTP (1990) | | | |
| M vector | SPC | | IATTC | |
| Run number | Run 5 | Run 6 | Run 7 | Run 8 |
| SR | B-H | Ricker | B-H | Ricker |
| Selectivity (separable VPA) | Three different selectivities for three different periods are estimated for each gear | | | |
| penalty (weighting values) to fit to the objective function (residual sum of squares) | ρ(serial correlation coefficient in the error terms of the S-R model) = 0.00<br>$\sigma^2$ (weighting for the stock-recruitment relationship) = 0.20<br>$\sigma^2$ (weighting for the initial population size) = 0.40 | | | |
| Abundance Index (all ages combined) | Japan (Shono et al, 2005) base case 1960-2003<br>Taiwan (Wang et al, 2005-) option 1 1968-2003 | | | |
| Results | | | | |
| Steepness | 0.39 | No convergence | Something may not be OK with this run | No convergence |
| -ln (likelihood) | -94.9 | | | |
| R-squared | 0.901 | | | |
| MSY*(current catch* in 2003=0.459) | 0.234 (too low?) | | | |
| TB(2000)* | | | | |
| TB(MSY)* | | | | |
| B ratio(TB)= TB(2000)/TB(MSY) | | | | |
| SSB(2000)* | | | | |
| SSB(MSY)* | | | | |
| B ratio(SSB)= SSB(2000)/SSB(MSY) | | | | |
| B1 ratio = TB2000/B1 | | | | |
| F(2000) | | | | |
| F(MSY) | | | | |
| F(ratio) = F2000/F(MSY) | | | | |

Note : TB: Total Biomass, SSB: Spawning Stock Biomass B1: Biomass at the start year

| Age | 0 | 1 | 2 | 3 | 4 | 5+ |
|---|---|---|---|---|---|---|
| M vector 1 (IATTC) | 2.40 | 1.28 | 0.90 | 1.10 | 1.08 | 0.80 |
| M vector 2 (SPC) | 1.48 | 0.80 | 1.20 | 1.80 | 1.35 | 1.02* |

Appendix B(c) Summary of the first 20 ASPM runs: INPUT & RESULTS * unit : million tons

| INPUT & Assumptions | | | | |
|---|---|---|---|---|
| Years analyzed | 1960-2003 | | | |
| Stock (area) | Single stock (TROPICAL) | | | |
| Gear types for catch (depth of the gear) | LL (mid water)<br>PS (surface to sub-surface)<br>GILL (sub-surface)<br>BB_TROLL (surface ) | | | |
| Growth | Stequert *et al* (1995) | | | |
| L-W relation | IPTP (1990) | | | |
| M vector | SPC | | IATTC | |
| Run number | Run 9 | Run 10 | Run 11 | Run 12 |
| SR | B-H | Ricker | B-H | Ricker |
| Selectivity (separable VPA) | Three different selectivities for three different periods are estimated for each gear | | | |
| penalty (weighting values) to fit to the objective function (residual sum of squares) | ρ(serial correlation coefficient in the error terms of the S-R model) = 0.00<br>$\sigma^2$ (weighting for the stock-recruitment relationship) = 0.20<br>$\sigma^2$ (weighting for the initial population size) = 0.40 | | | |
| Abundance Index (all ages combined) | Japan (Shono et al, 2005) option 2 1960-2003<br>Taiwan (Wang et al, 2005-) option 3 1968-2003 | | | |
| Results | | | | |
| Steepness | Something may not be OK with this run | No convergence | Something may not be OK with this run | No convergence |
| -ln (likelihood) | | | | |
| R-squared | | | | |
| MSY*(current catch* in 2003=0.459) | | | | |
| TB(2000)* | | | | |
| TB(MSY)* | | | | |
| B ratio(TB)= TB(2000)/TB(MSY) | | | | |
| SSB(2000)* | | | | |
| SSB(MSY)* | | | | |
| B ratio(SSB)= SSB(2000)/SSB(MSY) | | | | |
| B1 ratio = TB2000/B1 | | | | |
| F(2000) | | | | |
| F(MSY) | | | | |
| F(ratio) = F2000/F(MSY) | | | | |

Note : TB: Total Biomass, SSB: Spawning Stock Biomass B1: Biomass at the start year

| Age | 0 | 1 | 2 | 3 | 4 | 5+ |
|---|---|---|---|---|---|---|
| M vector 1 (IATTC) | 2.40 | 1.28 | 0.90 | 1.10 | 1.08 | 0.80 |
| M vector 2 (SPC) | 1.48 | 0.80 | 1.20 | 1.80 | 1.35 | 1.02* |

Appendix B (d) Summary of the first 20 ASPM runs: INPUT & RESULTS * unit : million tons

| INPUT & Assumptions | | | | |
|---|---|---|---|---|
| Years analyzed | 1960-2003 | | | |
| Stock (area) | Single stock (whole Indian Ocean) | | | |
| Gear types for catch (depth of the gear) | LL (mid water)<br>PS (surface to sub-surface)<br>GILL (sub-surface)<br>BB_TROLL (surface ) | | | |
| Growth | Stequert *et al* (1995) | | | |
| L-W relation | IPTP (1990) | | | |
| M vector | SPC | | IATTC | |
| Run number | Run 13 | Run 14 | Run 15 | Run 16 |
| SR | B-H | Ricker | B-H | Ricker |
| Selectivity (separable VPA) | Three different selectivities for three different periods are estimated for each gear | | | |
| penalty (weighting values) to fit to the objective function (residual sum of squares) | ρ(serial correlation coefficient in the error terms of the S-R model) = 0.00<br>$\sigma^2$ (weighting for the stock-recruitment relationship) = 0.20<br>$\sigma^2$ (weighting for the initial population size) = 0.40 | | | |
| Abundance Index (all ages combined) | Japan (Shono et al, 2005) base case 1968-2003<br>Taiwan (Wang et al, 2005-) option 2 1968-2003 | | | |
| Results | | | | |
| Steepness | 0.40 | No convergence | Something may not be OK with this run | No convergence |
| -ln (likelihood) | -90.1 | | | |
| R-squared | 0.896 | | | |
| MSY*(current catch* in 2003=0.459) | 0.232 (too low) | | | |
| TB(2000)* | | | | |
| TB(MSY)* | | | | |
| B ratio(TB)= TB(2000)/TB(MSY) | | | | |
| SSB(2000)* | | | | |
| SSB(MSY)* | | | | |
| B ratio(SSB)= SSB(2000)/SSB(MSY) | | | | |
| B1 ratio = TB2000/B1 | | | | |
| F(2000) | | | | |
| F(MSY) | | | | |
| F(ratio) = F2000/F(MSY) | | | | |

Note : TB: Total Biomass, SSB: Spawning Stock Biomass B1: Biomass at the start year

| Age | 0 | 1 | 2 | 3 | 4 | 5+ |
|---|---|---|---|---|---|---|
| M vector 1 (IATTC) | 2.40 | 1.28 | 0.90 | 1.10 | 1.08 | 0.80 |
| M vector 2 (SPC) | 1.48 | 0.80 | 1.20 | 1.80 | 1.35 | 1.02* |

Appendix B(e) Summary of the first 20 ASPM runs: INPUT & RESULTS * unit : million tons

| INPUT & Assumptions | | | | |
|---|---|---|---|---|
| Years analyzed | 1968-2003 | | | |
| Stock (area) | Single stock (whole Indian Ocean) | | | |
| Gear types for catch (depth of the gear) | LL (mid water)<br>PS (surface to sub-surface)<br>GILL (sub-surface)<br>BB_TROLL (surface ) | | | |
| Growth | Stequert *et al* (1995) | | | |
| L-W relation | IPTP (1990) | | | |
| M vector | SPC | | IATTC | |
| Run number | Run 17 | Run 18 | Run 19 | Run 20 |
| SR | B-H | Ricker | B-H | Ricker |
| Selectivity (separable VPA) | Three different selectivities for three different periods are estimated for each gear | | | |
| penalty (weighting values) to fit to the objective function (residual sum of squares) | $\rho$(serial correlation coefficient in the error terms of the S-R model) = 0.00<br>$\sigma^2$ (weighting for the stock-recruitment relationship) = 0.20<br>$\sigma^2$ (weighting for the initial population size) = 0.40 | | | |
| Abundance Index (all ages combined) | Japan (Shono et al, 2005) option 2 1968-2003<br>Taiwan (Wang et al, 2005-) option 2 1968-2003 | | | |
| Results | | | | |
| Steepness | 0.99 | | 0.99 | |
| -ln (likelihood) | -76.6 | | -70.2 | |
| R-squared | 0.851 | | 0.821 | |
| MSY*(current catch* in 2003=0.459) | 0.405 | | 0.425 | |
| TB(2000)* | | | | |
| TB(MSY)* | | | | |
| B ratio(TB)= TB(2000)/TB(MSY) | | No convergence | | No convergence |
| SSB(2000)* | | | | |
| SSB(MSY)* | | | | |
| B ratio(SSB)= SSB(2000)/SSB(MSY) | | | | |
| B1 ratio = TB2000/B1 | | | | |
| F(2000) | | | | |
| F(MSY) | | | | |
| F(ratio) = F2000/F(MSY) | | | | |

Note : TB: Total Biomass, SSB: Spawning Stock Biomass B1: Biomass at the start year

| Age | 0 | 1 | 2 | 3 | 4 | 5+ |
|---|---|---|---|---|---|---|
| M vector 1 (IATTC) | 2.40 | 1.28 | 0.90 | 1.10 | 1.08 | 0.80 |
| M vector 2 (SPC) | 1.48 | 0.80 | 1.20 | 1.80 | 1.35 | 1.02* |