APPLICATION OF THE PROCEAN MODEL TO THE INDIAN OCEAN YELLOWFIN TUNA (THUNNUS ALBACARES) FISHERY

Olivier Maury

IRD (Institut de Recherche pour le Développement) UR THETIS

SFA B.P. 570 Victoria Mahé Seychelles Islands

E-mail: maury@ird.fr

ABSTRACT

In this paper is applied the PROCEAN (PRoduction Catch / Effort ANalysis) modeling framework (Maury, 2001) to the yellowfin tuna fishery of the Indian Ocean. Total yield for the fishery are used as well as yields and efforts for Japanese longliners and french and Spanish purse seiners. Results for three different values of the shape parameter m are compared and discussed.

INTRODUCTION

In this paper we apply the PROCEAN (PRoduction Catch / Effort ANalysis) modeling framework (Maury, 2001) to the yellowfin tuna fishery of the Indian Ocean. PROCEAN is a multi-fleet non equilibrium generalized production model which includes process error for both catchability time series and carrying capacity of the stock. Parameters estimation is conducted in a bayesian context.

Our objective is not to propose a very realistic representation of the fishery. We propose a tool to extract the maximum amount of information from the data set by structuring it given a simple and well established theoretical model. Then, modeling is used here as a mean to explore data sets according to various hypotheses.

MATERIAL AND METHOD

The data set

Yield and effort data are extracted from the IOTC database for three fleets:

- Japanese longliners from 1952 to 2000; data are agregated on the whole area excluding the zones where the bft fishery is dominating the fishery.
- spanish purse seiners from 1984 to 2000;
- french purse seiners from 1981 to 2000;

Fishing efforts are nominal. Yields in weight are derived from catches in numbers by using mean weights by spatial strata and quarters.

Catches from the other components of the fishery are agregated in a category « diverse ».

THE PROCEAN MODEL

The PROCEAN model is based on the classic Pella and Tomlinson (1969) generalized production model which links the stock biomass B to the fishing mortality F by the mean of an ordinary differential equation continuous in time:

$$\frac{dB_t}{dt} = rB_t\left(1-\left(\frac{B_t}{K_t}\right)^{m-1}\right) - F_tB_t \qquad with \quad m>1 \quad (1)$$

With B_t, the biomass at time t; F_t, the instantaneous fishing mortality rate; K, the carrying capacity of the stock; r, the per capita intrinsic growth rate of the population and m, the shape parameter (the model becomes a simple Schaefer model when m=2).

To introduce catches and effort for multiple fleets into the model, the fishing mortality F_t is expressed as the sum of each fleet's instantaneous fishing mortality:

$$\begin{cases} \dfrac{dB_t}{dt} = rB_t\left(1-\left(\dfrac{B_t}{K_t}\right)^{m-1}\right) - \sum_{i=1}^{n-1} q_{i,t} f_{i,t} B_t - C_{n,t} \\ \dfrac{dC_{i,t}}{dt} = q_{i,t} f_{i,t} B_t \quad 1 \le i < n \end{cases} \quad (2)$$

With n-1, the total number of fleets for which fishing effort is available; $q_{i,t}$, the catchability coefficient for fleet i at time t, $f_{i,t}$ the mesured nominal fishing effort for fleet i at time t and $C_{i,t}$, the catches for fleet i at time t. $C_{n,t}$ represents the catches for all the fleets non documented in term of effort.

The biomass equation (equation 2) is an ordinary differential equation. It is integrated using a first order in time semi-implicit numerical approximation to have a better numerical stability than with a fully explicit scheme. This provides a time serie of predicted catches given a set of parameters (including biomass at time 0) :

$$\begin{cases} \dfrac{dB_t}{dt} = rB_t\left(1-\left(\dfrac{B_t}{K_t}\right)^{m-1}\right) - \sum_{i=1}^{n} q_{i,t} f_{i,t} B_t - C_{n,t} \\ \quad \approx \dfrac{B_{t+dt}-B_t}{dt} = rB_t - rB_{t+dt}\left(\dfrac{B_t}{K_t}\right)^{m-1} - \sum_{i=1}^{n-1} q_{i,t} f_{i,t} B_{t+dt} - C_{n,t} \\ \dfrac{dC_{i,t}}{dt} = q_{i,t} f_{i,t} B_{t+dt} \quad 1 \le i < n \end{cases}$$

$$\Leftrightarrow \begin{cases} B_{t+dt} = \dfrac{B_t(1+r\,dt) - dt\,C_{n,t}}{1+\left(r\left(\dfrac{B_t}{K_t}\right)^{m-1} + \sum_{i=1}^{n} q_{i,t} f_{i,t}\right)dt} \\ C_{i,t+dt} = q_{i,t} f_{i,t} B_{i,t+dt}\,dt \quad 1 \le i < n \end{cases}$$

To take into account potential fluctuations of the carrying capacity due to environmental fluctuations or to modifications of the fishery configuration such as stock surface (process errors), the parameter K is assumed to be dependent of time. We assume that the parameters log(K_t) has the structure of a random walk which allows to model slow variations over time (Fournier, 1996) :

$$K_{t+1} = K_t\, e^{J_t - \frac{\sigma_{q_i}^2}{2}} \qquad J \sim N(0, \sigma_J)$$

The local catchability by fleet is also supposed to vary slowly each year to take into account potential fluctuations of fishing power for each fleet (process errors). We assume a random walk structure to the catchability time series for each fleet (Fournier et al., 1998):

$$q_{i,t+1} = q_{i,t}.e^{\varepsilon_{i,t} - \frac{\sigma_{\varepsilon_i}^2}{2}} \qquad \text{with } \varepsilon \in N(0, \sigma_{\varepsilon_i})$$

To address high-frequency variability of the catchability coefficient, a lognormal process-error structure is assumed for the fishing mortality. Then, the fishing mortality of fleet k at time t is written Concerning the catchability coefficient, the fishing mortality error structure is assumed to be lognormal. Then, the fishing mortality of fleet i in year t is written

$$F_{i,t} = q_{i,t} f_{i,t} e^{\eta_{i,t} - \frac{\sigma_i^2}{2}}$$

where the η_i are robustified normally distributed random variables with mean 0.

To estimate the parameters in a bayesian context, we use the method of the maximum of posterior distribution (Bard, 1974) by maximizing the sum of the log-likelihood of the data plus the log of the prior density function. Then, given the data, the bayesian posterior distribution function for the model parameters has 4 components (one for the likelihood of the catch by fleet estimates L_C, one for the process errors for the carrying capacity L_K, one for the process errors concerning the effort-fishing mortality relationship L_q, and one for prior assumptions on the parameters r, m, and B_0).

Then, the posterior distribution is equal to L:

$$L = L_C \times L_K \times L_q \times L_{prior}$$

Catch component

We assume that the log of the predicted catches are the expected values of a random variable with a normal distribution:

$$L_C = \prod_{i=1}^{n-1}\prod_{t=0}^{t_{\max}}\left[\frac{1}{C_{i,t}\,\sigma_{C_i}\sqrt{2\pi}}\, e^{-\frac{\left(\log(C_{i,t}) - \log(\hat{C}_{i,t})\right)^2}{2\sigma_{C_i}^2}}\right]$$

With $\hat{C}$, the observed catches and C, the predicted catches.

Carrying capacity process error component

This component corresponds to the log-normal structured random walks for carrying capacity over time:

$$L_K = \prod_{t=0}^{t_{\max}}\left[\frac{1}{\sigma_J\sqrt{2\pi}}\, e^{-\frac{J^2}{2\sigma_J^2}}\right]$$

Catchability process error component

This component combines the log-normal structured random walks for fishing power trends for each fleets and the effort/fishing mortality process error which has a robustified normal structure. This robustified normal distribution assumes a probability p for unlikely events (events which are more than e times the variance from the mean) and 1-p for the standard normal distribution (Fournier et al., 1996) (Fig.1):

$$L_q = \prod_{i=1}^{n-1}\prod_{t=0}^{t_{\max}}\left[\frac{1}{\sigma_{\varepsilon_t}\sqrt{2\pi}}\, e^{-\frac{\varepsilon_{i,t}^2}{2\sigma_{\varepsilon_i}^2}}\right] \times \prod_{i=1}^{n-1}\prod_{t=0}^{t_{\max}}\left[(1-p)\left(\frac{1}{\sigma_{\eta_i}\sqrt{2\pi}}\, e^{-\frac{\eta_{i,t}^2}{2\sigma_{\eta_i}^2}}\right) + p\left(\frac{\sqrt{2}}{\pi\,\sigma_{\eta_i} e\left(1+\frac{\eta_{i,t}^4}{(\sigma_{\eta_i} e)^4}\right)}\right)\right]$$

Priors and penalties

Informative priors can be added to the likelihood to take into account potential external informations concerning the parameters r, m and B_0. In the present version of the software, these three parameters are assumed to follow either a normal distribution, either a lognormal distribution either a beta distribution.

Alternatively, priors can be added to the likelihood for MSY and fMSY, the fishing effort at MSY. Here, uniform priors where used for all the parameters and normal priors where used for both MSY and fMSY. Those priors indirectly provide information concerning the parameters r, K and m.

Estimating at the same time the variances for observation and process errors often lead to very unstable behaviors of the estimation process. In PROCEAN, only the standard errors σ_C for the catches by fleet observation errors and the standard errors for the carrying capacity process errors σ_θ can be estimated simultaneously. The standard errors for the catchability process errors, σ_ε and σ_η are considered to be proportional to σ_C with fixed proportionality coefficients p :

$$\begin{cases} \sigma_{\varepsilon_i} = p_1 \sigma_{C_i} \\ \sigma_{\eta_i} = p_2 \sigma_{C_i} \end{cases} \quad \forall i \in [1, n[$$

Thus, important additional information is provided through the use of the coefficients p which fix the strength of the constraints on the catchabilities variability.

The parameters of the model are estimated by finding the values of the parameters which minimize the opposite of log(L). This minimization is performed with a quasi-Newton numerical function minimizer using exact derivatives with respect to the model parameters with the AD model builder software (ADMB © 1993-1996 by Otter Research Ltd). ADMB calculates the exact derivatives with a technique named automatic differentiation (Griewank and Corliss, 1991) and provides the variance of the parameter estimates by computing the Hessian matrix, **H**, the elements of which are:

$$H_{i,j} = \frac{\partial^2(-\log L)}{\partial q_i . \partial q_j}$$

Where θ_i and θ_j are any two model parameters. Covariance matrix of the model parameters are estimated by computing the inverse of the hessian at the minimum.

RESULTS

In a one way trip situation, the shape parameter m is very poorly determined. In this paper, we keeped m fixed and tested 3 different values for it : m=1.1, m=1.5 and m=2.

In the three cases considered, data are well fitted by the model. The fishery seems to be just below the fMSY, catches being in a desequilibrium situation just over the MSY value.

The estimated fishing mortality is increasing slowly during the first historical period of the fishery before the purse seine fishery appearance in the early eighties, then it increases dramatically until the present days with a slight slow down or even a plateau in the late nineties.

Estimated catchability time series for both longliners and purse seiners exhibit a very typical shape which is robust to the value of m. A strong decrease at the beginning of the time serie folowed by a very stable plateau characterizes longliners catchability and a continuous increase characterizes the purse-seiners.

The robust catchability process error can be interpreted as residuals. According to the assumptions of the model, it does not exhibit any trend and enables to take into account extreme data values such as the extremely low first year CPUE for the french purse seiners without biasing the estimation.

DISCUSSION

MCMC exploration of the posterior density function should be undertaken during the meeting to estimate the impact of the priors used on the values of MSY and fMSY.

A strong decrease at the beginning of the time serie characterizes longliners catchability and a continuous increase characterizes the purse-seiners.This may well be interpreted in an age-structured context taking into account the strong increase of fishing efficiency which has been experienced at least by the purse seiner fleets.

Consider for instance two typical fisheries : a longline fishery fishing only for old large fish and a purse seine fishery fishing only for young small fish. For longliners, fishing will lead to a reduction of the stock relatively to the whole population and then a decrease of the catchability of the entire population. For purse seiners, fishing will have the opposite effect and then will lead to an increase of the catchability of the entire population (fig. 8).

This age structured dynamics can be characterized in simulations (Maury and Chassot, 2001) by defining the catchability of the whole population as the ratio CPUE/population biomass which increases when effort increases for longliners and decreases for purse seiners (Fig. 9).

Surplus production models are based on very simple equations where the whole population is represented with a single state variable : the biomass of the population. This simplicity's counterpart is that surplus production models cannot produce dynamics as complex as age structured model's dynamics. In particular, surplus production models are not designed to treat explicitly the linkage between population dynamics, biomass productivity and the age structure. They are not able to distinguish the fished stock (the exploited fraction of the population) from the whole population which includes non fished age class.

This age structured processus is not deterministically taken into account in PROCEAN. But PROCEAN enables process error on catchability to be modelled with a random walk. This allows the model to be able to take implicitely into account the trend in catchability due to the effect of age-structure on fish population availability and then to estimate an unbiased population biomass (Maury and Chassot, 2001).

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m=1.1

Table 1: main population dynamics parameter estimates

r	m	K	σ_{jp_ll}	σ_{es_ps}	σ_{fr_ps}
15,008	1.1 (fixed)	609625	0.111	0.060	0.084

MSY	320505
f_{2000} / fMSY	0.66

m=1.5

Table 1: main population dynamics parameter estimates

r	m	K	σ_{jp_ll}	σ_{es_ps}	σ_{fr_ps}
1.51	1.5 (fixed)	1315890	0.129	0.070	0.097

MSY	292423
f_{2000} / fMSY	0.87

m=2

Table 1: main population dynamics parameter estimates for m=2

r	m	K	σ_{jp_ll}	σ_{es_ps}	σ_{fr_ps}
0.82	2 (fixed)	1774990	0.112	0.057	0.082

MSY	282885
f_{2000} / fMSY	0.87

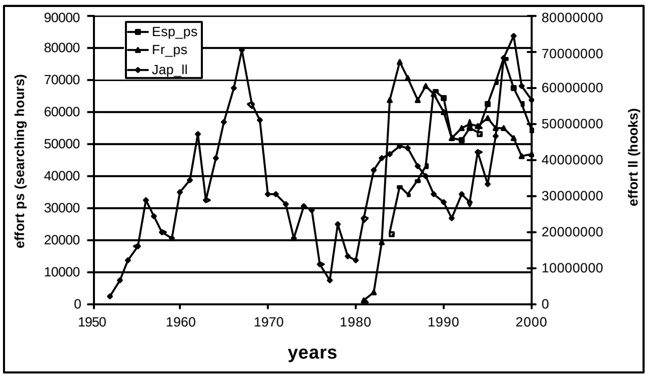

Fig. 1: Fishing effort series used in the present work.

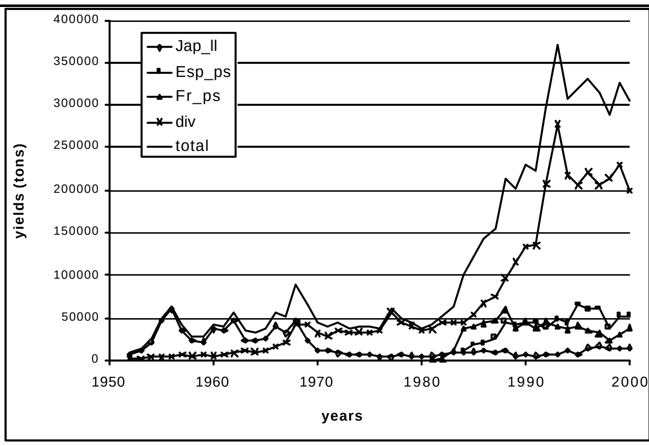

Fig. 2: Yield series used in the present work.

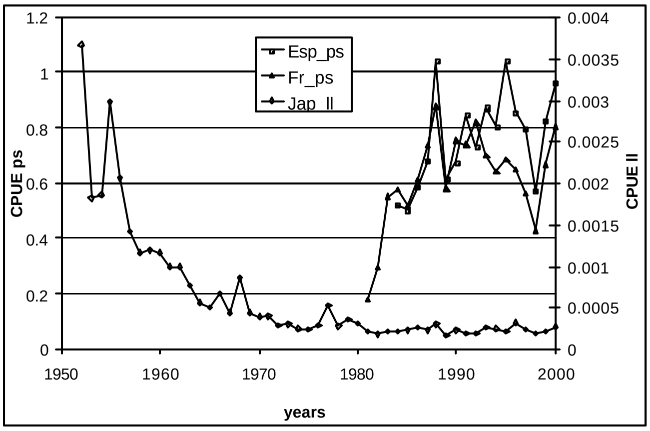

Fig. 3: CPUE series calculated from yields and effort.

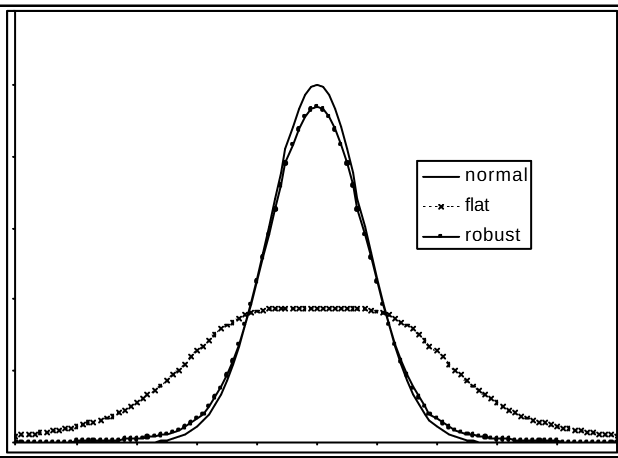

Fig. 4: the robust distribution function used is a combination of a flat and a normal distribution function. Here, e=3 and p=0.1.

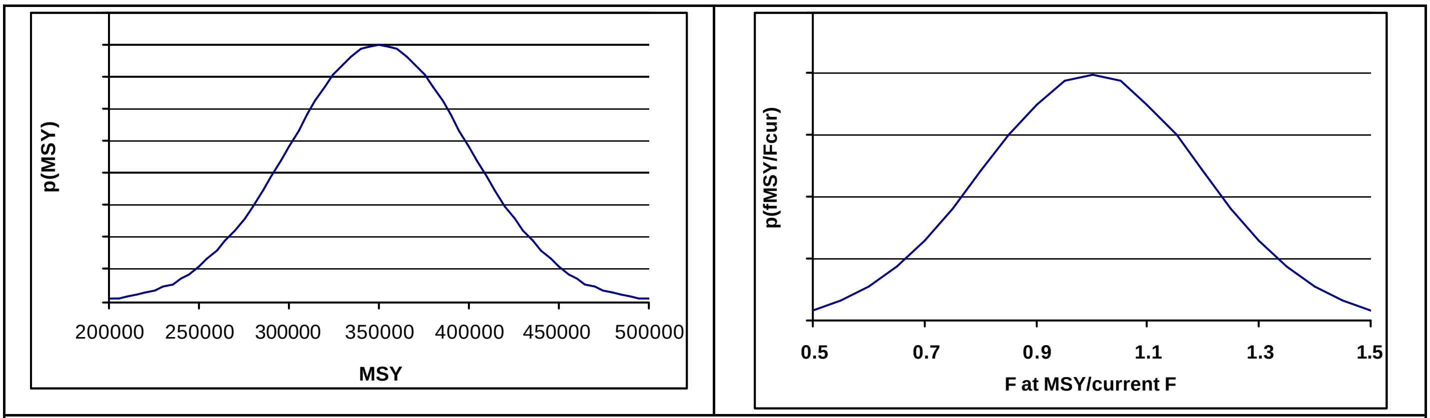

Fig. 5 : Left : the prior distribution used for MSY (mean=350000tons, sigm=50000tons). Right : the prior distribution used for the ratio of fishing mortality at MSY over the current fishing mortality (mean=1, sigm=0.2).

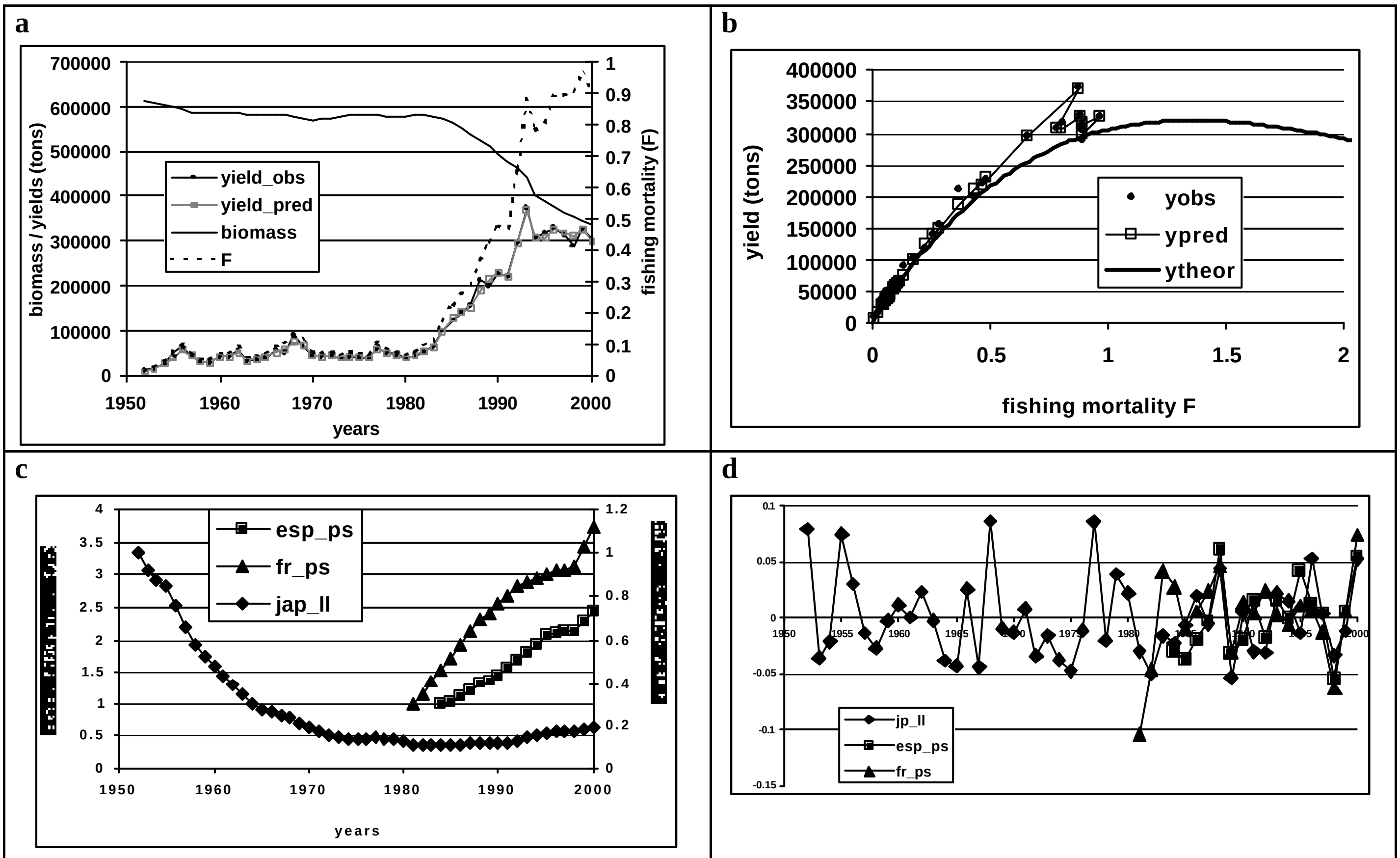

Fig. 5 : PROCEAN results for m=1.1 : a) observed and predicted total yield, estimated biomass and fishing mortality time series ; b) observed, predicted and equilibrium yield versus fishing mortality ; c) estimated catchability time trends for the three fleets ; d) robust catchability process error.

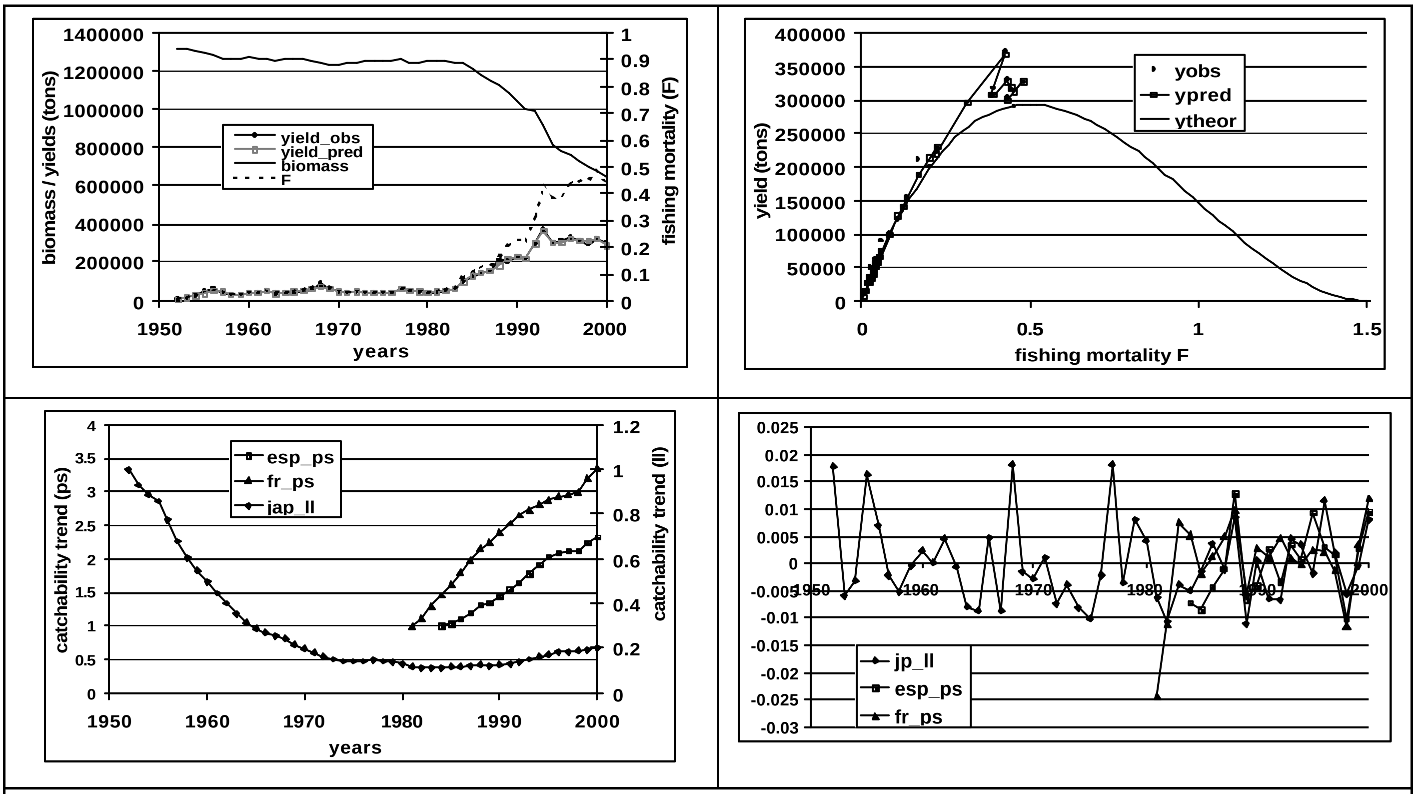

Fig. 6 : PROCEAN results for m=1.5 : a) observed and predicted total yield, estimated biomass and fishing mortality time series ; b) observed, predicted and equilibrium yield versus fishing mortality ; c) estimated catchability time trends for the three fleets ; d) robust catchability process error.

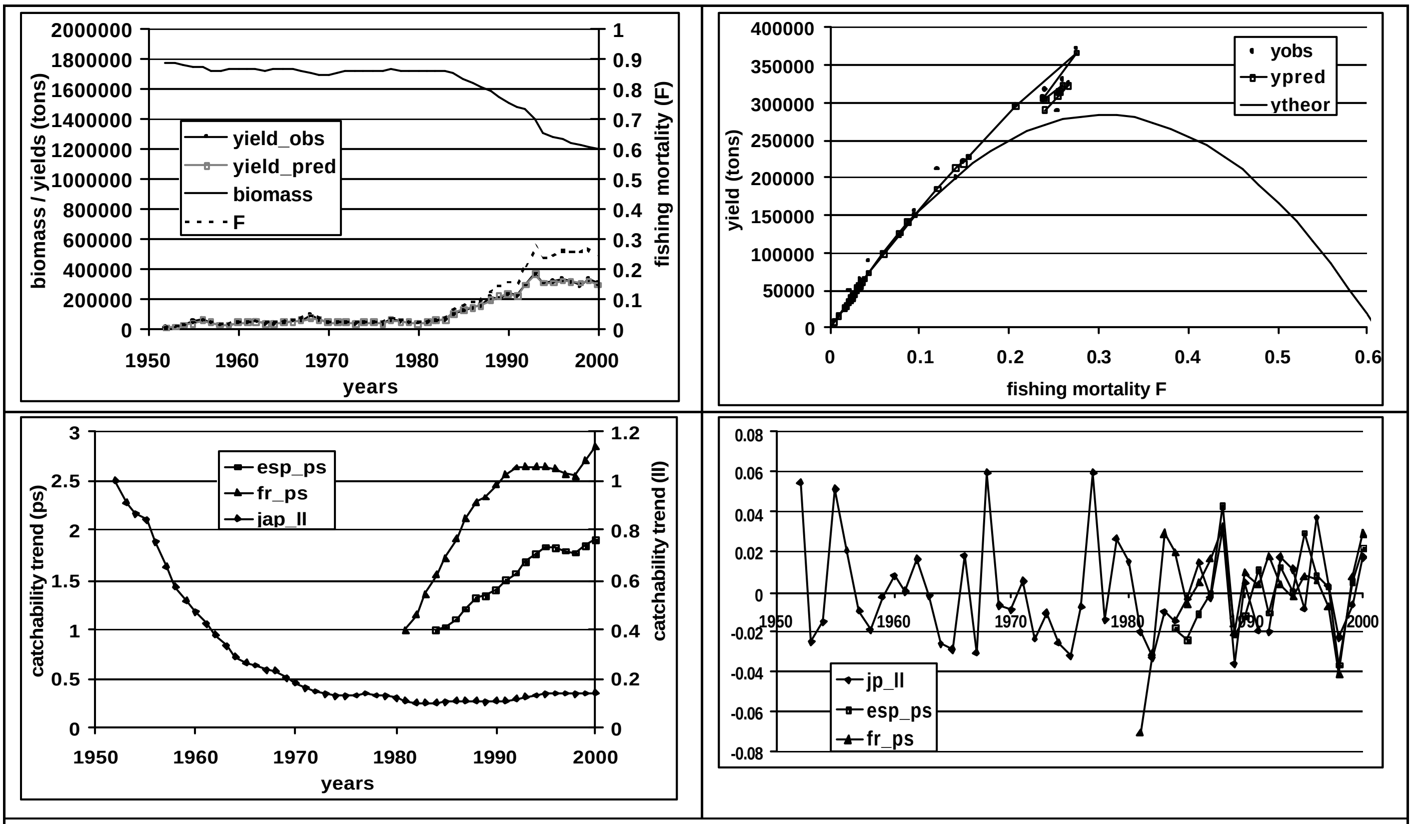

Fig. 7 : PROCEAN results for m=2.0 : a) observed and predicted total yield, estimated biomass and fishing mortality time series ; b) observed, predicted and equilibrium yield versus fishing mortality ; c) estimated catchability time trends for the three fleets ; d) robust catchability process error.

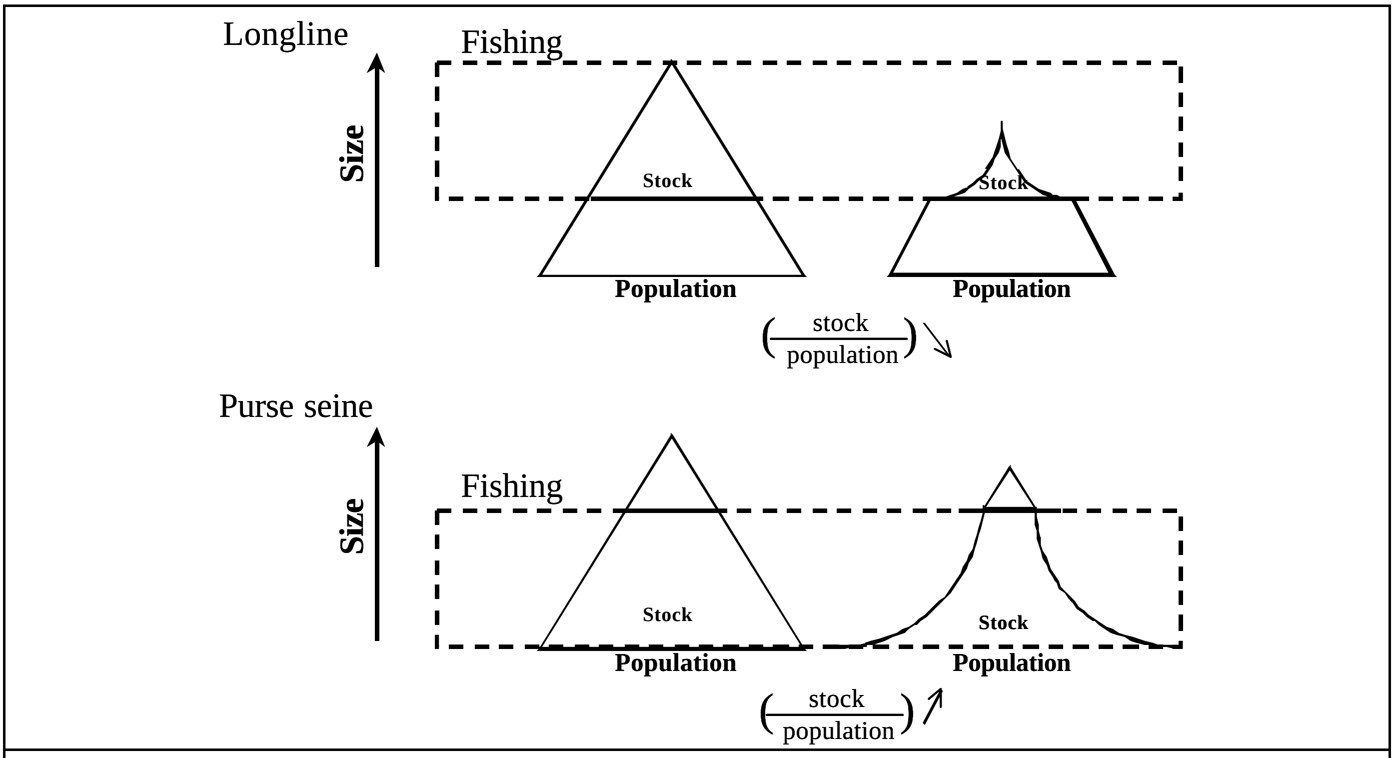

Fig.8: Schematic population size structure for a typical longline fishery (top) and for a typical purse seine fishery (bottom). When the fishing pressure increases (right), the ratio stock/population decreases for the longliner fishery and it increases for the purse seiner fishery.

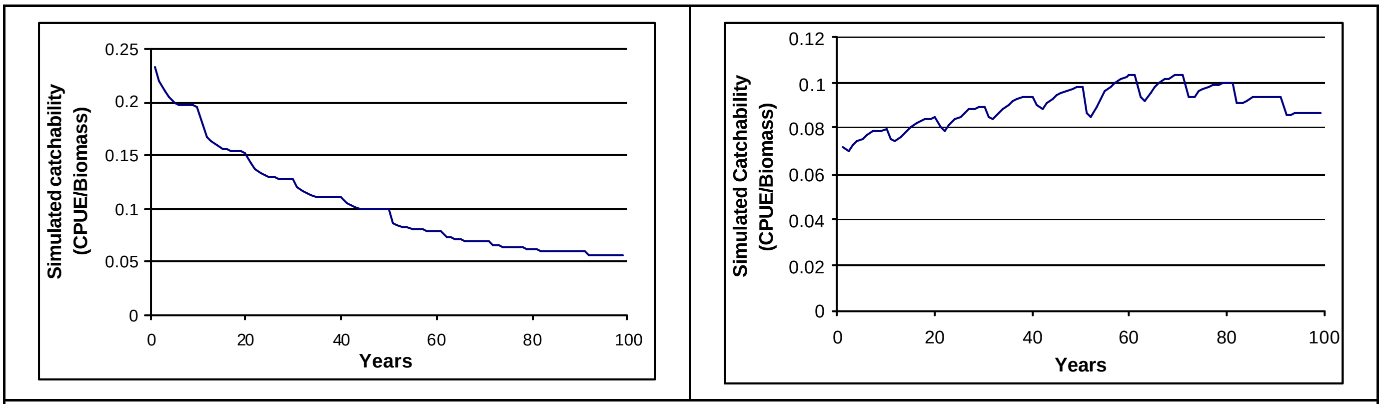

Fig.9: Simulated population catchability calculated as the ratio stock/population. Left : longline fishery. Right : purse seine fishery. from Maury and Chassot, 2001.