The Earth’s Tuna System: The past, the future and the missing link

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Earth System Model (ESM)

- for AR5 (2014)
- ESM closes the carbon cycle (in green)

It's time to think about Earth's Tuna System modeling!

From R.J. Stouffer et al.

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IPCC ESM models can help us to reconstruct the past of tuna stocks and to forecast projections, a key issue for management.

This next generation of models should provide better prediction of oceanic environment (physics and biogeochemistry), at higher resolution, with more realistic interannual and decadal variability.

We need to identify our needs and communicate with ESM community.

PFRP, with SPC and CLS supported the development of ecosystem and tuna models that can be linked to ESM.

IPCC (2007). *Time series of global annual ocean heat content for the 0 to 700 m layer (observations).*
PFRP Tuna and climate project

3-year project finishing in June 2010

Objectives:

- calibrate SEAPODYM in the Pacific for 3 species (SKJ, YFT, BET) and APECOSM in the Indian O. using several environmental forcings to get an envelope of prediction

- run the models in the other Oceans with the same parameterization and evaluate the predictive skills of the model

- Support the development of a global tuna database (SARDARA) at IRD.
General scheme of SEAPODYM

**Environmental forcing**
- Epipelagic data: SST, PP
- Surface MTL forage biomass

**3-layer data:**
- temperature, oxygen, currents
- MTL forage biomass

**Anthropogenic forcing**
- Data by fishing fleets: Pole-and-line, Purse-seine, Long-line

**Biological information***
- Conventional tagging
- Archival tagging

**ADR model**
- Initial conditions
  - 0-3 month juveniles model
  - K-cohorts Pre-mature and adults model

**Output**
- Computing predictions
- Cost function

**Resetting model parameters**
- Quasi-Newton convergence?
  - yes
  - no

**Reverse model**: Computing derivatives of cost function

**“Optimal” parameterization**

*Preliminary work has been initiated for including tagging data into the optimization process*
### Parameters

#### Pre-defined parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SKJ</th>
<th>YFT</th>
<th>BET</th>
<th>SP alb.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Population structure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of larvae cohorts (month)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of juvenile cohorts (month)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Age at 1&lt;sup&gt;st&lt;/sup&gt; autonomous displacement</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Number of young cohorts (3 mo; 6 mo; 12 mo)</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Age at 1&lt;sup&gt;st&lt;/sup&gt; maturity (month)</td>
<td>9</td>
<td>15</td>
<td>27</td>
<td>57</td>
</tr>
<tr>
<td>Number of adult cohorts (3 mo; 6 mo; 12 mo)</td>
<td>12</td>
<td>12</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td><strong>Growth</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l_a$ Predator' size of cohort $a$</td>
<td>cm</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>$w_a$ Predator' weight of cohort $a$</td>
<td>kg</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* from independent studies (Langley et al., 2005; Hampton et al., 2006; Langley et al. 2007; Hoyle et al. 2008)

#### Parameters estimated by the model

<table>
<thead>
<tr>
<th>Parameters estimated by the model</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_s$ Optimum of the spawning temperature function</td>
<td>°C</td>
</tr>
<tr>
<td>$\sigma_s$ Std. Err. of the spawning temperature function</td>
<td>°C</td>
</tr>
<tr>
<td>$\alpha$ Larvae food-predator trade-off coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$T_a$ Optimum of the adult temperature function at maximum age</td>
<td>°C</td>
</tr>
<tr>
<td>$\sigma_a$ Std. Err. of the adult temperature function at maximum age</td>
<td>°C</td>
</tr>
<tr>
<td>$\dot{O}$ Oxygen value at $\Psi_O=0.5$</td>
<td>ml·l&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>$\gamma$ Curvature coefficient of the oxygen function</td>
<td>-</td>
</tr>
<tr>
<td>$V_M$ Maximum sustainable speed</td>
<td>B.L.·s&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>$c$ Coefficient of diffusion habitat dependence</td>
<td>-</td>
</tr>
<tr>
<td>$\eta$ Coefficient of diffusion density dependence</td>
<td>-</td>
</tr>
<tr>
<td>$R_s$ Coefficient of larvae recruitment (Beverton-Holt function)</td>
<td>-</td>
</tr>
<tr>
<td>$M_{p_{\max}}$ Maximal mortality rate due to predation</td>
<td>mo&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>$M_{s_{\max}}$ Maximal mortality rate due to senescence</td>
<td>mo&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>$\beta_p$ slope coefficient in predation mortality</td>
<td>-</td>
</tr>
<tr>
<td>$\beta_s$ slope coefficient in senescence mortality</td>
<td>-</td>
</tr>
<tr>
<td>$A_{0.5}$ Age at which $\frac{1}{2}M_{s_{\max}}$ occurs</td>
<td>Mo</td>
</tr>
<tr>
<td>$\epsilon$ Coefficient of variability of tuna mortality with food requirement index</td>
<td>-</td>
</tr>
<tr>
<td>$q_f$ Catchability coeff. of fishery $f$</td>
<td>-</td>
</tr>
<tr>
<td>$d_f$ Target fish length of fishery $f$</td>
<td>cm</td>
</tr>
<tr>
<td>$s_f$ Selectivity slope coeff. (if sigmoid function) or width (if Gaussian function) of fishery $f$</td>
<td>-</td>
</tr>
</tbody>
</table>

Only 17 parameters (2 optional) for the entire life cycle spatial population dynamics! + 3 by fishery

But high sensitivity to oceanic environment…
Ocean model configurations used for optimization experiments with four Pacific tuna species at the date of Oct 1st 2009.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>SKJ</th>
<th>YFT</th>
<th>BET</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESSIC (1948-2004; 2deg; monthly)</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>NCEP-ORCA2- PISCES (1948-2003; 2deg; monthly)</td>
<td>Ongoing</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>ERA40-ORCA2- PISCES (1955-2001; 2deg; monthly)</td>
<td>Ongoing</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Fishing events used in optimization (catch-effort / size frequencies)</td>
<td>174,221 / 1,571</td>
<td>352,160 / 9,534</td>
<td>362,424 / 1,492</td>
</tr>
<tr>
<td>Hindcast and validation</td>
<td>1950-2004</td>
<td></td>
<td>1978-2004</td>
</tr>
<tr>
<td>Nb fisheries (cf. appendix 2)</td>
<td>WCPO: 4 EPO: 2 PS</td>
<td>WCPO: 15 EPO: 3 PS &amp; 2 LL (MFCL)</td>
<td>26 (MFCL)</td>
</tr>
</tbody>
</table>

Solution = ensemble simulation with different forcings
Pacific Skipjack tuna

- **Monthly catch data**
  4 purse-seine
  2 pole-and-line fisheries

- **Quarterly length frequencies data**
  for each fishery by 5, 10 or 20 degree squares


- General agreement between SEAPODYM & MFCL
- Major difference between the 2 models during post-El Niño ecosystem conditions
- Direct relationship between ENSO events (SOI) and skipjack recruitment
- The general trend in abundance of the adult stock is predictable 8 months in advance simply using the SOI
- Due to current El Nino, biomass is expected to increase peaking in the second half of 2010

Biomass of young (3 month to 3 quarter of age) skipjack and 8-month lagged SOI
Pacific yellowfin tuna

- **Monthly catch data**
  - 4 purse-seine in WCPO
  - 1 pole-and-line fisheries
  - 3 purse-seine in EPO
  - 9 longline fisheries
  - 3 fisheries Phil. And Ind.

- **Quarterly length frequencies data**
  - by fishery by 5, 10 or 20 degree squares
    - No data for Japanese PS subtropical fishery
    - Only one region for EPO

  Problem to fit the data
Pacific yellowfin tuna

Biomass of Recruitment

Biomass of adult

NCEP

ERA40
Pacific yellowfin tuna

Comparison of biomass estimates between MULTIFAN-CL and SEAPODYM

Region 3 & 4:
- Same range of biomass for adult
- Less total biomass (i.e., less young fish) in SEAPODYM

BUT, much higher biomass predicted by SEAPODYM in subtropical regions 1, 2, 5 and 6 influenced by Kuroshio and East Austr. Cur., i.e., regions of intense mesoscale activity

Red: MULTIFAN-CL (right axis); grey SEAPODYM-NCEP; black: SEAPODYM-ERA40 (left axis)
In absence of mesoscale activity, the model cannot fit the peaks (low/high) of catch and thus tends to increase biomass and diffusion in region of intense activity.
Pacific Bigeye tuna

• **Monthly catch data**
  4 purse-seine in WCPO; 1 pole-and-line fisheries
  3 purse-seine in EPO; 9 longline fisheries
  3 fisheries Phil. And Ind.

  **Quarterly length frequencies data**
  by fishery by 5, 10 or 20 degree squares

✓ Results will be published in Lehodey P., Senina I., Sibert J., Bopp L, Calmettes B., Hampton J., Murtugudde R. (*accepted*). Preliminary forecasts of population trends for Pacific bigeye tuna under the A2 IPCC scenario. *Progress in Oceanography. CLIOTOP Special Issue*

The “easiest” optimization experiment, that quickly provided a good fit to data and plausible set of biological parameter

- A lot of information (fishing data) for both juvenile to adult over a very large geographical extension, i.e., all the Pacific Basin, including temperate regions
- The influence of both seasonal and interannual signals can be captured by the model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Bigeye</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>0.073</td>
<td>0.0005</td>
</tr>
<tr>
<td>$\beta_p$</td>
<td>0.25</td>
<td>0.003</td>
</tr>
<tr>
<td>$M_{max}$</td>
<td>-0.097</td>
<td>0.008</td>
</tr>
<tr>
<td>$A$</td>
<td>80.6</td>
<td>0.008</td>
</tr>
<tr>
<td>$\sigma_0$</td>
<td>0.82</td>
<td>0.012</td>
</tr>
<tr>
<td>$T_0$</td>
<td>26.2</td>
<td>0.013</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.63</td>
<td>0.02</td>
</tr>
<tr>
<td>$BH_a$</td>
<td>0.0045</td>
<td>6e-4</td>
</tr>
<tr>
<td>$\sigma_a$</td>
<td>2.16</td>
<td>0.004</td>
</tr>
<tr>
<td>$T_a$</td>
<td>13</td>
<td>0.004</td>
</tr>
<tr>
<td>$\delta$</td>
<td>0.46</td>
<td>0.0006</td>
</tr>
<tr>
<td>$D_{max}$</td>
<td>0.22</td>
<td>0.002</td>
</tr>
<tr>
<td>$V_{max}$</td>
<td>0.32</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Fishing parameters: catchabilities & selectivities

st.dev; * fixed
The model suggests that ENSO has an impact on larvae recruitment and spatial dynamics of young fish, but not really on spatial dynamics of adult fish.

Adult fish rely on deep forage organisms and seasonal production in subtropical regions that are less strongly impacted by ENSO than epipelagic equatorial and tropical forage.
Pacific Bigeye tuna

Optimization

WCP

EP

WCPO adult bigeye

Biomass (10^6 mt)


0.15 0.20 0.25 0.30 0.35 0.40 0.45

Hindcast

Optimization

Forecast

EPO adult bigeye

Biomass (10^6 mt)


0.30 0.32 0.34 0.36 0.38

Hindcast

Optimization

Forecast

Black: SEAPODYM

Red: MULTIFAN-CL (right axis)

les vivre demain
Pacific Bigeye tuna

Loop animation Jan 1985- Dec 94

Semi-isolated south-west sub-stock?

Larvae (age 1 month)

Juvenile (2-3 month)

Young immature (age 4-27 month)

Adult fish and LL cpue (circles)
Next Steps

- Comparative analyses between species, models, and oceans (last objective of PFPR tuna & climate model + CLIOTOP WGs).

- Past Fishing and Climate impacts

- Future Climate (and Fishing) impacts

- The missing Link: Sensitivity to Mid-Trophic Level?
Assimilating *in situ* bioacoustic data in a mid-trophic level model, and its impact on predicted albacore feeding habitat in the American Samoa waters (R Domokos & P Lehodey)

A new PFRP project

Matrix of Energy transfer coefficients used for the 3-layer 6-components mid-trophic levels model, according to the depth and the number of corresponding layers

<table>
<thead>
<tr>
<th>Nb of Layers</th>
<th>epi</th>
<th>meso</th>
<th>m-meso</th>
<th>bathy</th>
<th>m-bathy</th>
<th>hm-bathy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.34</td>
<td>0.27</td>
<td>0.39</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0.17</td>
<td>0.10</td>
<td>0.22</td>
<td>0.18</td>
<td>0.13</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Thank you!
Despite low resolution of data (5 deg) and little information for juveniles and young fish, we got reasonable 1st estimation:

- A good fit to data (both total catch and spatial correlation)

- A natural separation of the south Pacific albacore population emerged due to constraints associated to the definition of thermal, feeding and spawning habitats.

- A plausible dynamical distribution of larvae

- A clear seasonal migration pattern of adult:
  - Concentration of adult north of 25°S peaking in Oct-Nov
  - fish moving to the feeding grounds in the southern convergence during austral summer (January to May)
  - Northern migration starting in June-July