Adjoint-based parameter estimation for the spatially explicit model of large pelagics (with application to skipjack tuna).

1 Pelagic Fisheries Research Program, JIMAR, UH, Honolulu, USA

2 Marine Ecosystems Modeling and Monitoring by Satellites, CLS, Toulouse, France.
General scheme of the SEAPODYM model with optimization approach

**Physical environment**
- NPZD Chlorophyll
- 3-layer data: Temperature (GCM), currents (GCM), Oxygen (Levitus)

**Biological input**
- Six forage components:
  - epi-pelagic
  - Migrant and non-migrant meso-pelagic
  - Migrant, non-migrant and highly migratory bathypelagic

**Fishing data**
- Pole-and-line: tropical and sub-tropical gears
- Purse seine: WCPO associated and unassociated fleets

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**TADR tuna model**
- Eqns for 0-3 month old juveniles: spawning, foraging, passive transport, survival, mortality, cannibalism
- Eqns for 1-16 quarter old adults: recruitment, foraging, migrations, ageing, natural and fishing mortality

**Predictions**
- Tuna spatial distributions, catches and length frequencies time series

**Optimization:**
- Preliminary sensitivity analysis
- Constructing cost function according to data distribution
- Minimization, parameter estimation and errors.

**Estimates of model parameters**
- Management applications

I. Senina, J. Sibert, P. Lehodey
Tuna habitat description

- **3 types of habitats:**
  
  - **Spawning habitat:** SST, product of primary production (*food*), forage biomasses (*predators*)
  
  - **Juvenile habitat:** SST, biomass of adults tuna (*cannibals*)
  
  - **Movement (feeding) habitat:** forage biomass (*epipelagic, mesopelagic, bathypelagic, migrant mesopelagic, migrant bathypelagic and highly migratory bathypelagic species*), temperature and oxygen concentration at 3 layers (0-100m, 100-400m and >400m).

- **Seasonality effect**
  
  - at high latitudes feeding habitat is computed as spawning habitat (obeying continuity of habitat distribution)

- **Food requirement index**
  
  - index influencing the mortality rate of young tuna mostly imposing starvation penalty on their natural mortality rate.
Adult’s habitat definition and migrations as a response to environmental heterogeneity

**Habitat parameters:**

1. optimal temperature for spawning;
2. tolerance interval for spawning temperature;
3. optimal temperature for foraging/migrations;
4. tolerance interval for foraging temperature;
5. slope coefficient (response on food abundance);
6. critical concentration of oxygen;
7. slope coefficients in sigmoid function.

**Movement parameters:**

8. maximal diffusion coefficient;
9. slope coefficient in dependence on habitat index $\gamma$;
10. taxis coefficient $\chi$;

Temperature functions for different ages

Oxygen functions
Movement habitat II

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Parameter estimation in Seapodym
Natural and fishing mortality

- (11) maximal predation mortality;
- (12) slope coefficient in predation mortality function;
- (13) maximal senescence mortality;
- (14) slope coefficient in senescence mortality;
- (15) threshold age for senescence;
- (16) variability with habitat index;
- (17-22) target size for fleet, \( \hat{l} \);
- (23-28) fish size range, \( \sigma \);
- (29-34) right asymptote, \( \rho \);
- (35-40) catchability coefficients;
Model domain
Catch data (1980-2005)

SEAPODYM

Materials and methods
Parameter estimation in Seapodym
Summary

Data and simulation set-up
Maximal likelihood approach
Adjoint method keynotes

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Parameter estimation in Seapodym
Length frequencies data (1980-2005)

LF data available for 7 regions
Objective function

- Model predictions

\[
C_{t,f,i,j}^{\text{pred}} = q_f E_{t,f,i,j} \sum_{a=1}^{K} s_{f,a} w_a N_{a,i,j} \Delta x \Delta y,
\]

\[
Q_{t,f,a,r}^{\text{pred}} = \frac{s_{f,a} \sum_{i,j,r} E_{f,i,j} N_{a,i,j} \Delta x \Delta y}{\sum_{a=1}^{K} \sum_{i,j,r} E_{f,i,j} N_{a,i,j} \Delta x \Delta y}
\]

- The task of finding the optimal parameterization of the numerical model by fitting its prediction to observations consists in maximizing the likelihood function (or commonly, minimizing negative log-likelihood).

  - Catch likelihood:

\[
- \ln L(\theta | C^{\text{obs}}) = \sum_t \sum_f C_{t,f}^{\text{pred}} - \sum_t \sum_f C_{t,f}^{\text{obs}} \ln C_{t,f}^{\text{pred}} + \sum_t \sum_f \ln(\Gamma(C_{t,f}^{\text{obs}} + 1))
\]

  - LF likelihood:

\[
-L_{LF} = \sum_{t,f,a,r} \frac{1}{2\sigma_f^2} (Q_{t,f,a,r}^{\text{obs}} - Q_{t,f,a,r}^{\text{pr}})^2
\]

  - Boundary penalties.

- Quasi-Newton minimization method being used requires evaluation of the gradient of cost function with respect to control parameters.
Adjoint method keynotes

- Adjoint method consists in constructing the reverse model in order to compute derivatives of objective function derivatives with respect to model parameters:

\[ \nabla \alpha \mathbf{L} = \begin{pmatrix} \frac{\partial L^-}{\partial \theta_1} \\ \vdots \\ \frac{\partial L^-}{\partial \theta_n} \end{pmatrix} \]

- Efficacy of the adjoint method is determined by:
  - exact evaluation of derivatives
  - low computational cost, which does not depend on the dimension of the parametric space

- One of the methods of verification of adjoint model is comparison of exact derivatives with first order finite difference approximation:

\[ \frac{\partial L^-}{\partial \theta_k} \approx \frac{L^- (\theta_k + \varepsilon \delta \theta_k) - L^- (\theta_k)}{\varepsilon \delta \theta_k}, \quad k = 1..n \]
Pre-optimization

- Preliminary sensitivity analysis
  - Based on gradient of model predictions function
  - Based on the change of likelihood relative to the parameter bounds

  ✓ *exclusion of non-observable parameters from optimization*

- Create appropriate initial conditions (climatology spin-up) using optimization approach

- Validation of the model approach on another data set and with simplified model
  - Application to tagging data for skipjack
Application to tag recaptures data

Tag recaptures summarized over period 1977–1982

Observed (black) vs. predicted (red) tag returns

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Parameter estimation in Seapodym
A list of calibrated model parameters with their estimated optimal values and uncertainties *(experiment 1980-1990)*

<table>
<thead>
<tr>
<th>N</th>
<th>$\theta$</th>
<th>Description</th>
<th>$\bar{\theta}$</th>
<th>$\theta^0$</th>
<th>$\theta^*$</th>
<th>St.dev. uncertainty</th>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\beta_p$</td>
<td>slope coefficient in predation mortality</td>
<td>0</td>
<td>2</td>
<td>0.35</td>
<td>1.66</td>
<td>0.0134</td>
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<tr>
<td>2</td>
<td>$\beta_s$</td>
<td>slope coefficient in senescence mortality</td>
<td>-0.5</td>
<td>0</td>
<td>-0.05</td>
<td>-0.028</td>
<td>0.0004</td>
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<tr>
<td>3</td>
<td>$\sigma$</td>
<td>standard deviation in temperature function</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1.929</td>
<td>0.0025</td>
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<tr>
<td>4</td>
<td>$\gamma$</td>
<td>slope coefficient in oxygen function</td>
<td>0</td>
<td>1</td>
<td>0.1</td>
<td>0.0003</td>
<td>0.0018</td>
</tr>
<tr>
<td>5</td>
<td>$V_{max}$</td>
<td>maximal sustainable speed</td>
<td>0</td>
<td>2</td>
<td>1.5</td>
<td>1.78</td>
<td>0.0085</td>
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<tr>
<td>6</td>
<td>$c$</td>
<td>coefficient of diffusion variability</td>
<td>0</td>
<td>0.5</td>
<td>0.25</td>
<td>0.275</td>
<td>0.0054</td>
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<td>7</td>
<td>$q_1$</td>
<td>catchability for PLTRO fishery</td>
<td>0</td>
<td>0.1</td>
<td>0.005</td>
<td>0.0047</td>
<td>0.0068</td>
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<tr>
<td>8</td>
<td>$q_2$</td>
<td>catchability for WPSASS fishery</td>
<td>0</td>
<td>0.1</td>
<td>0.007</td>
<td>0.0064</td>
<td>0.0018</td>
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<tr>
<td>9</td>
<td>$q_3$</td>
<td>catchability for WPSUNA fishery</td>
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<td>0.1</td>
<td>0.0035</td>
<td>0.0026</td>
<td>0.0034</td>
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<tr>
<td>10</td>
<td>$s_0$</td>
<td>target fish length, PLSUB fleet</td>
<td>25</td>
<td>75</td>
<td>44.5</td>
<td>43.13</td>
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<tr>
<td>11</td>
<td>$d_1$</td>
<td>selectivity slope coefficient, PLTRO fleet</td>
<td>0</td>
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<td>0.0028</td>
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<td>12</td>
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<td>select. width of Gaussian, WPSASS fleet</td>
<td>1</td>
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<td>75</td>
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<tr>
<td>14</td>
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<td>selectivity slope coefficient, PLSUB fleet</td>
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<td>15</td>
<td>12.25</td>
<td>11.88</td>
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<tr>
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<td>25</td>
<td>75</td>
<td>53.8</td>
<td>51.9</td>
<td>0.006</td>
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</tbody>
</table>
The correlation coefficients between optimal parameters

(experiment 1980-1990)

|    | $\beta_F$ | $\beta_S$ | $\sigma$ | $\gamma$ | $V_{max}$ | $c$ | $q_1$ | $q_2$ | $q_3$ | $s_0$ | $d_1$ | $d_2$ | $s_2$ | $d_3$ | $s_3$ |
|----|-----------|-----------|----------|----------|-----------|-----|-------|-------|-------|-------|-------|-------|-------|-------|
| $\beta_F$ | 1 | 0.88 | -0.03 | 0 | 0.06 | 0.11 | 0.62 | 0.14 | 0.17 | -0.48 | 0.08 | -0.05 | 0.03 | -0.01 | -0.02 |
| $\beta_S$ | 0.88 | 1 | -0.15 | 0.01 | 0.1 | 0.21 | 0.75 | 0.16 | 0.19 | -0.58 | 0.09 | -0.06 | 0.02 | -0.02 | -0.03 |
| $\sigma$ | -0.03 | -0.15 | 1 | -0.04 | -0.34 | -0.11 | -0.06 | 0.03 | 0.02 | -0.08 | -0.02 | 0.01 | -0.02 | 0.02 | 0.01 |
| $\gamma$ | 0 | 0.01 | -0.04 | 1 | 0.03 | -0.03 | 0.03 | 0 | 0.01 | 0 | 0 | 0 | -0.01 | 0 | 0.01 |
| $V_{max}$ | 0.06 | 0.1 | -0.34 | 0.03 | 1 | 0.69 | -0.04 | -0.06 | -0.04 | -0.16 | -0.01 | -0.09 | 0.07 | -0.11 | -0.06 |
| $c$ | 0.11 | 0.21 | -0.12 | -0.03 | 0.69 | 1 | 0.12 | -0.04 | -0.04 | -0.15 | 0.03 | -0.08 | 0.08 | -0.15 | -0.13 |
| $q_1$ | 0.62 | 0.75 | -0.05 | 0.03 | -0.04 | 0.12 | 1 | 0.13 | 0.17 | -0.44 | 0.53 | -0.04 | 0.03 | 0 | -0.01 |
| $q_2$ | 0.14 | 0.16 | 0.03 | 0 | -0.06 | -0.04 | 0.13 | 1 | 0.07 | -0.1 | 0 | -0.88 | -0.61 | -0.01 | 0.01 |
| $q_3$ | 0.17 | 0.19 | 0.02 | 0.01 | -0.04 | -0.04 | 0.17 | 0.07 | 1 | -0.13 | 0.01 | -0.05 | 0 | 0.17 | 0.62 |
| $s_0$ | -0.48 | -0.58 | -0.08 | 0 | -0.16 | -0.15 | -0.44 | -0.1 | -0.13 | 1 | -0.05 | 0.05 | -0.03 | 0.02 | 0.01 |
| $d_1$ | 0.08 | 0.09 | -0.02 | 0 | -0.01 | 0.03 | 0.53 | 0 | 0.01 | -0.05 | 1 | 0.01 | 0.02 | -0.01 | -0.02 |
| $d_2$ | -0.05 | -0.06 | 0.01 | 0 | -0.09 | -0.08 | -0.04 | -0.88 | -0.05 | 0.05 | 0.01 | 1 | 0.25 | -0.01 | -0.03 |
| $s_2$ | 0.03 | 0.02 | -0.02 | -0.01 | 0.07 | 0.08 | 0.03 | -0.61 | 0 | -0.03 | 0.02 | 0.25 | 1 | 0.06 | 0.03 |
| $d_3$ | -0.01 | -0.02 | 0.02 | 0 | -0.11 | -0.15 | 0 | -0.01 | 0.17 | 0.02 | -0.01 | -0.01 | 0.06 | 1 | 0.86 |
| $s_3$ | -0.02 | -0.03 | 0.01 | 0.01 | -0.06 | -0.13 | -0.01 | 0.01 | 0.62 | 0.01 | -0.02 | -0.03 | 0.03 | 0.86 | 1 |
Predicted with estimated parameters and observed catch data

- Observed vs. Predicted for $C_{skj}$ PLSUB, $R^2 = 0.801$
- Observed vs. Predicted for $C_{skj}$ PLTRO, $R^2 = 0.633$
- Observed vs. Predicted for $C_{skj}$ WPSASS, $R^2 = 0.846$
- Observed vs. Predicted for $C_{skj}$ WPSUNA, $R^2 = 0.932$
- Observed vs. Predicted for $C_{skj}$ EPSASS, $R^2 = 0.604$
- Observed vs. Predicted for $C_{skj}$ EPSUNA, $R^2 = 0.536$
Twin experiments
(simulation 1980-1990)
Projections? Need environmental data forecast
(based on parameter estimated for 1980-1990)

Possible management applications:
— Reduction of fishing effort (for chosen fisheries)
— Area closures
— Estimate of the impact of fishing
Results and further plans

- The efficient computational tool developed for estimating model parameters, that allows to improve fit of the model predictions to observations;

- Optimization experiments showed that such an explicit spatial model is able to adequately predict spatial distribution of catch with small number of control parameters;

- Improvements in the model made as a result of optimization experiments:
  - Topographic indices, preventing tuna dispersal to shallow regions (with usually high habitat index);  
  - Removing variability of mortality of adults, adding starvation penalty on mortality of young tuna  
  - Adding Beverton-Holt stock-recruitment relationship.

- Still need improvement:
  - Model predictions for EPO fisheries data

- Upcoming work:
  - Publishing current results;
  - Parameter estimation in the tuna-forage coupled model;
  - Application of parameter estimation to other tuna species (bigeye and yellowfin)
  - Projections based on different management scenarios.

Thank you...
Spatial correlations between predicted and observed catch and number of data points

- $n$ and $r_{PLSUBSkj}$, $R_1 = 0.768$
- $n$ and $r_{WPSUNASkj}$, $R_1 = 0.782$
- $n$ and $r_{PLTROSkj}$, $R_1 = 0.903$
- $n$ and $r_{EPSASSkj}$, $R_1 = 0.691$
- $n$ and $r_{WPSASSkj}$, $R_1 = 0.844$
- $n$ and $r_{EPSUNASkj}$, $R_1 = 0.718$
SEAPODYM and MULTIFUN-CL predicted population biomasses

Adults biomass predicted with Seapodym (black) and Multifun-CL (red)

Total biomass predicted with Seapodym (black) and Multifun-CL (red)