Transport and pre-recruitment of sardine and anchovy ichthyoplankton in the Canary Upwelling System: an individual-based modelling approach

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Science and the challenge of Managing Small Pelagic fisheries on shared stocks in Northwest AFRICA, *Casablanca, March 11th -14th , 2008*

0. PLAN OF THE TALK

- Introduction
- Background
- Part 1 : Mathematical Modelling of larval stage and recruitment
  - Aims of modelling
  - life cycle description (sardine)
  - model equations and recruitment probability estimates
- Part 2 : IBM modelling approach
  - Aims of the work
  - Modelling tools
  - Preliminary results and discussions
- Ongoing and fututre research
- Challenges

1. INTRODUCTION

Small pelagic fish are of key importance in upwelling ecosystems due to their role in the food web and socio-economical rules (food, industry, jobs,…etc.).

These species are subject to large interannual fluctuations due to :

1) Increase of fishing effort
2) but, mainly to environmental effects affecting early life history stages. (1997 : sardine collapse due to all but fishing...natural regulation, warm waters,…)

Case of study :

Sardina Pilchardus **(most abundant and studied species in Morocco)**
Engraulis Encrasicolus **(comparaison with other upwelling systems)**

But, can be easily extended to others species taking into account thier own traits.

1) Mathematical Modelling :

PNDR Project (Projet National de Déterminisme de Recrutement)

Arino O., C.Koutsikopoulos and A.Ramzi (1996), Elements of mathematical modelling of evolution in number of a sole population. *Journal of Biological Systems*, Vol. 4, p.p. 445-458.

Ramzi A., Arino O., Koutsikopoulos C., Boussouar A. and Lazure P. (2001), Modelling and numerical simulations of larval migration of the sole (*Solea solea (L.)*) of the Bay of Biscay. Part 1 : modelling. *Oceanologica acta*, vol. 24, pp 101-112.

Ramzi A., Arino O., Koutsikopoulos C., Boussouar A. and Lazure P. (2001), Modelling and numerical simulations of larval migration of the sole (*Solea solea (L.)*) of the Bay of Biscay. Part 2 : numerical simulations. *Oceanologica acta*, vol. 24,, pp 113-124.

Ramzi A., M.L. Hbid and **O. Ettahiri *(2006),* Larval dynamics and recruitment modelling of the Moroccan Atlantic coast sardine (*Sardina pilchardus*), *Ecological Modelling, 197 (2006) pp : 296–302.***

2) An IBM simulation model

Modelling the biophysical dynamics of sardine and anchovy ichthyoplankton in the Canary Current System *(Submitted)*

Collaborators :

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PART I .   MATHEMATICAL MODELLING

2. EARLY LIFE HISTORY AND RECRUITMENT

Literature :

-Hjort (1913) (*Critical period hypothesis*)
- Cushing (1975, 1990) *(Match/ mismatch)*
- C. Roy et P. Cury 1989 *(Environmental Optimal Window)*
- Bakun (1996, 1998) *(Bakun's Triad : Enrichment, concentration, larval retention).*

- Latest Benguela Upwelling System studies (Mullon, Fréon, Lett, Prada, …) show that Transport play an important role in recruitment processes.

Case of Canary : filaments transported sardine larvae (Rodriguez et al. (2006)

3. AIMS OF MODELLING

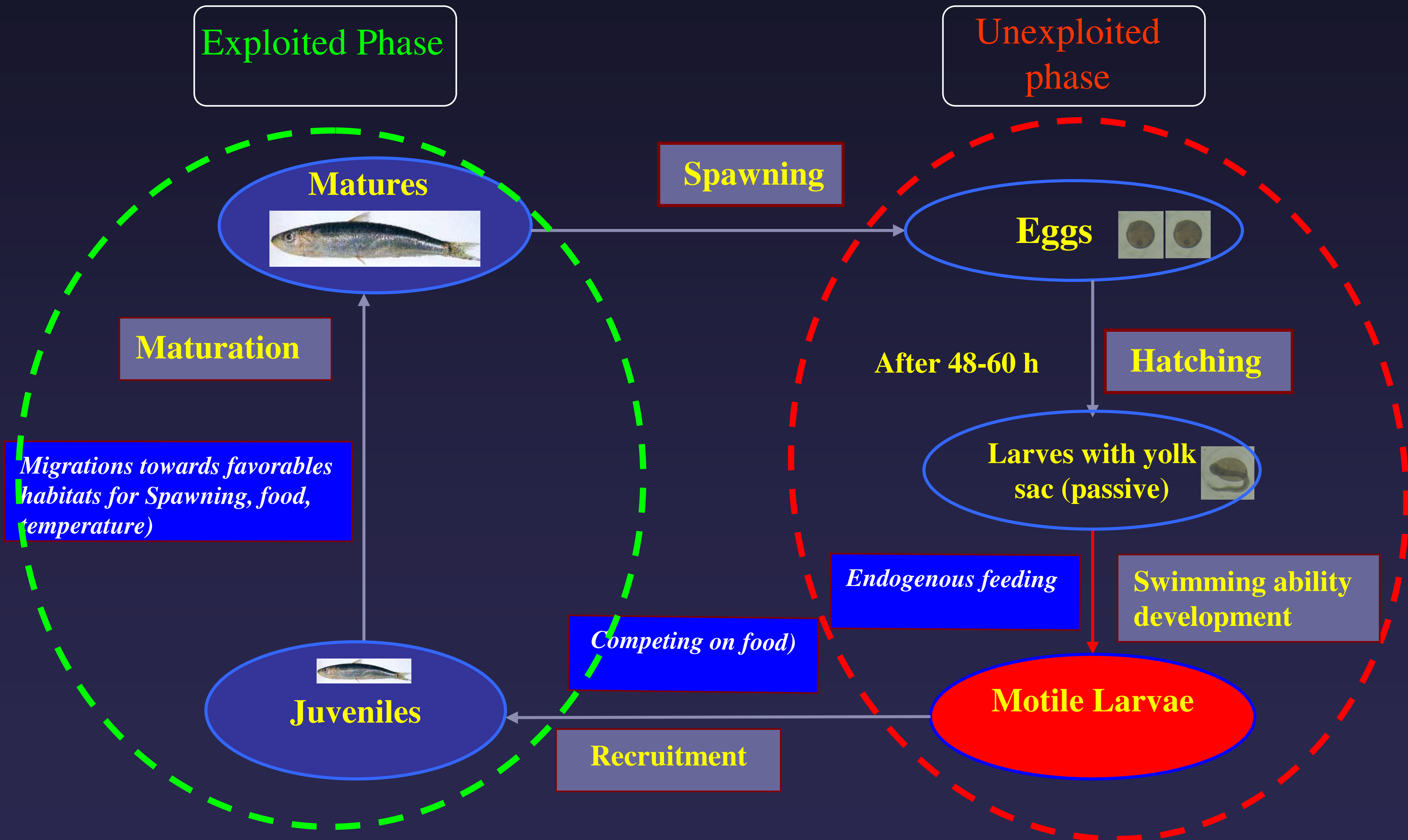
- Modelling and comprehension of larval spatio-temporal dynamics and quantifying the recruitment probability taking into account :

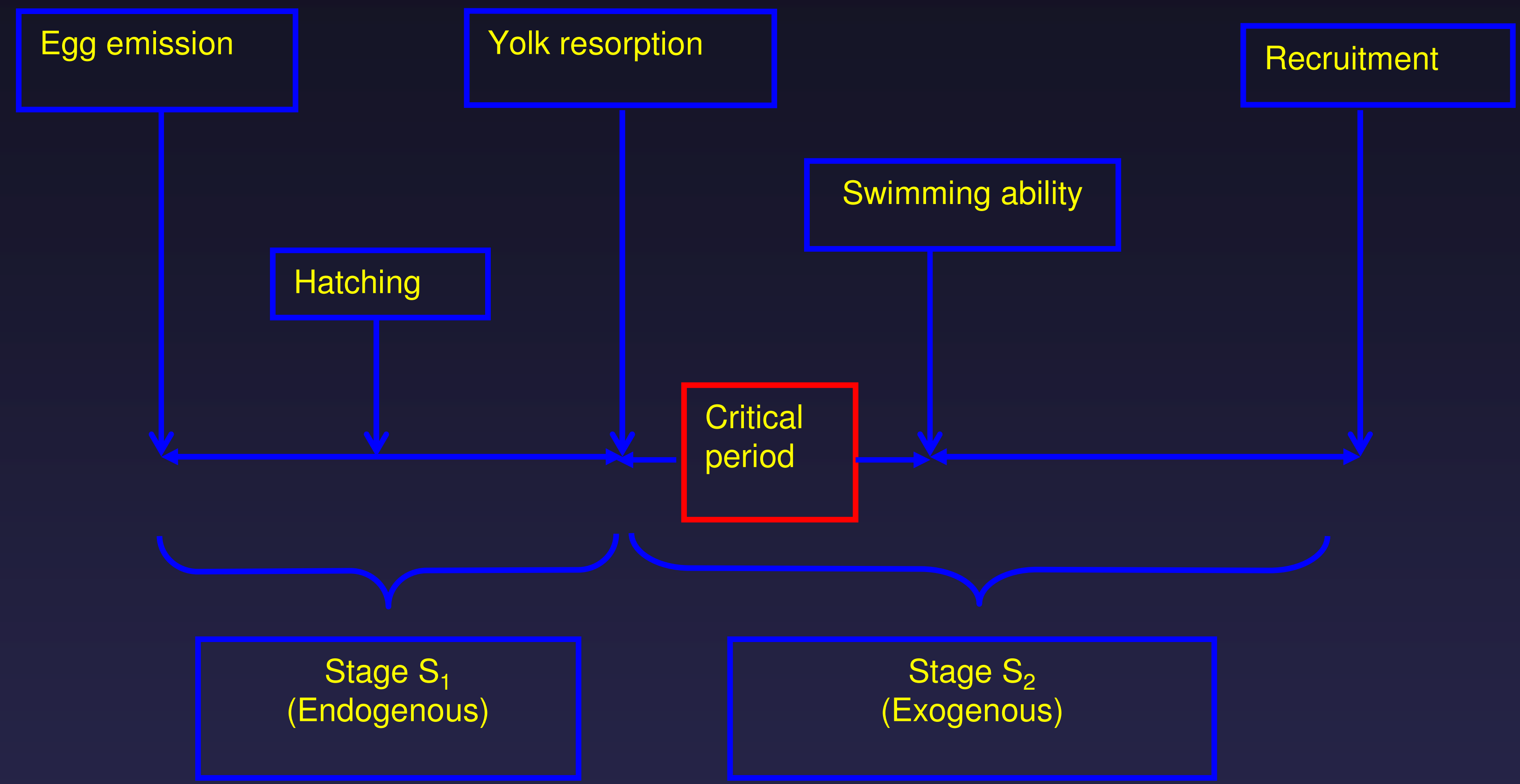
  - Transport during passive stage

  - Density dependance effects: feeding, competition, growth and mortality,…)

  - Environmental Effects (Climate change and physical processes effects : temperature, water masses circulations, upwellings).

SARDINE LIFE CYCLE





Egg emission
Yolk resorption
Recruitment
Swimming ability
Hatching
Critical period
Stage S_1 (Endogenous)
Stage S_2 (Exogenous)

4. MODEL EQUATIONS

3.1. Reproduction equation

$$B(t,X) = \int_0^{a_{max}} \beta(a,t,X)\, e(a)\, M(a,t,X)\, da$$

$\beta(a,t,X)$: spawning females proportion.

$e(a)$: spawning rate eggs/ female aged a.

$B(t,X)$: density of the eggs production rate.

3.2. Populations dynamics modeling of stage S_1

$$\begin{aligned}\left(\frac{\partial}{\partial t} + \frac{\partial}{\partial a}\right) l_1(t,a,X) &= \nabla.[K \nabla l_1(t,a,X)] \\ &\quad - \nabla.(U l_1(t,a,X)) \\ &\quad - \mu_1(a)\, l_1(t,a,X)\end{aligned}$$

$$l_1(t,0,X) = B(t,X).$$

K : diffusion matrix S.P.D (constant)

U : advection vector (constant)

$\mu_1(a)$: mortalité rate at age a

$M(t,a,X)$ density of matures aged a.

3.2. Pre-recruitment probability estimate

$$PR(t) = \frac{\pi_1(a_1^*(t)) \sum_{i=1}^{n} \int_{\Omega_i} \left(\int_{\Omega} k_L(a_1^*(t), X, Y; U)\, B(t - a_1^*(t), Y)\, dY \right) \omega(t,X)\, dX}{\int_{\Omega} B(t - a_1^*(t), Y)\, dY}$$

$\omega(t,X)$ is a weighting function depending on nurseries hospitality and habitat conditions (food abundance, temperature,turbulence, retention,...)

Competition on food (density dependance) :

$$\left(\frac{\partial}{\partial t}+\frac{\partial}{\partial a}\right) l_2^i(t,a) \quad = \quad -\mu_2\left(a, \frac{L_2^i(t)}{C^i(t)}\right) l_2^i(t,a)$$

$\mu_2(a,.)$ is an increasing function

Phytoplankton ingestion equation :

$$\left(\frac{\partial}{\partial t}+\frac{\partial}{\partial a}\right) q_2^i(t,a) = \frac{\kappa_2(a)}{1+\delta\left(\frac{L_2^i(t)}{C^i(t)}\right)} q_2^i(t,a)$$

$q_2^i(t,a)$: amount of food ingested by a larva aged a.

The recruitment threshold condition :

$$Q = \int_{t-a_2^*(t)}^{t} \frac{\kappa_2(s-(t-a_2^*(t)))}{1+\delta\left(\frac{L_2^i(s)}{C^i(s)}\right)} ds$$

$C^i(t)$: phytoplankton density in patch i
λ_i : phytoplankton proliferation rate.
$\kappa_2(a)$: maximum ingestion rate by a larva of age a.
A_2 : life span in stage S_2
$L_2^i(t)$: total number of larvae in stage S_2 :

$T(t)$ is the mean temperature at time t.

Phytoplankton dynamics :

$$\frac{d}{dt}C^i(t) = \lambda_i(T(t))C^i(t) - \frac{1}{1+\delta\left(\frac{L_2^i(t)}{C^i(t)}\right)} \int_0^{A_2} \kappa_2(a) l_2^i(t,a)da$$

$$L_2^i(t) = \int_0^{A_2} l_2^i(t,a)da$$

Ongoing and future research :

Modeling Juvenile and Adult stages to acheive modelling the whole life cycle, taking into account :

- density dependent effects and their impact on Adult and Juvenile migration towards preferendums either for trophic or reproduction reasons : (temperature, food availibility, homing, …etc.).

- Harvesting.

PART II. INDIVIDUAL BASED MODELLING (IBM)

Aims of IBM modelling

- Study the effect of transport on the pre-recruitment succes.
- Test the hypothesis of optimal spawning strategy of sardine and anchovy along the Moroccan Atlantic coasts.
- Determine the main model parameters affecting the pre-recruitment.

Area of study **:**

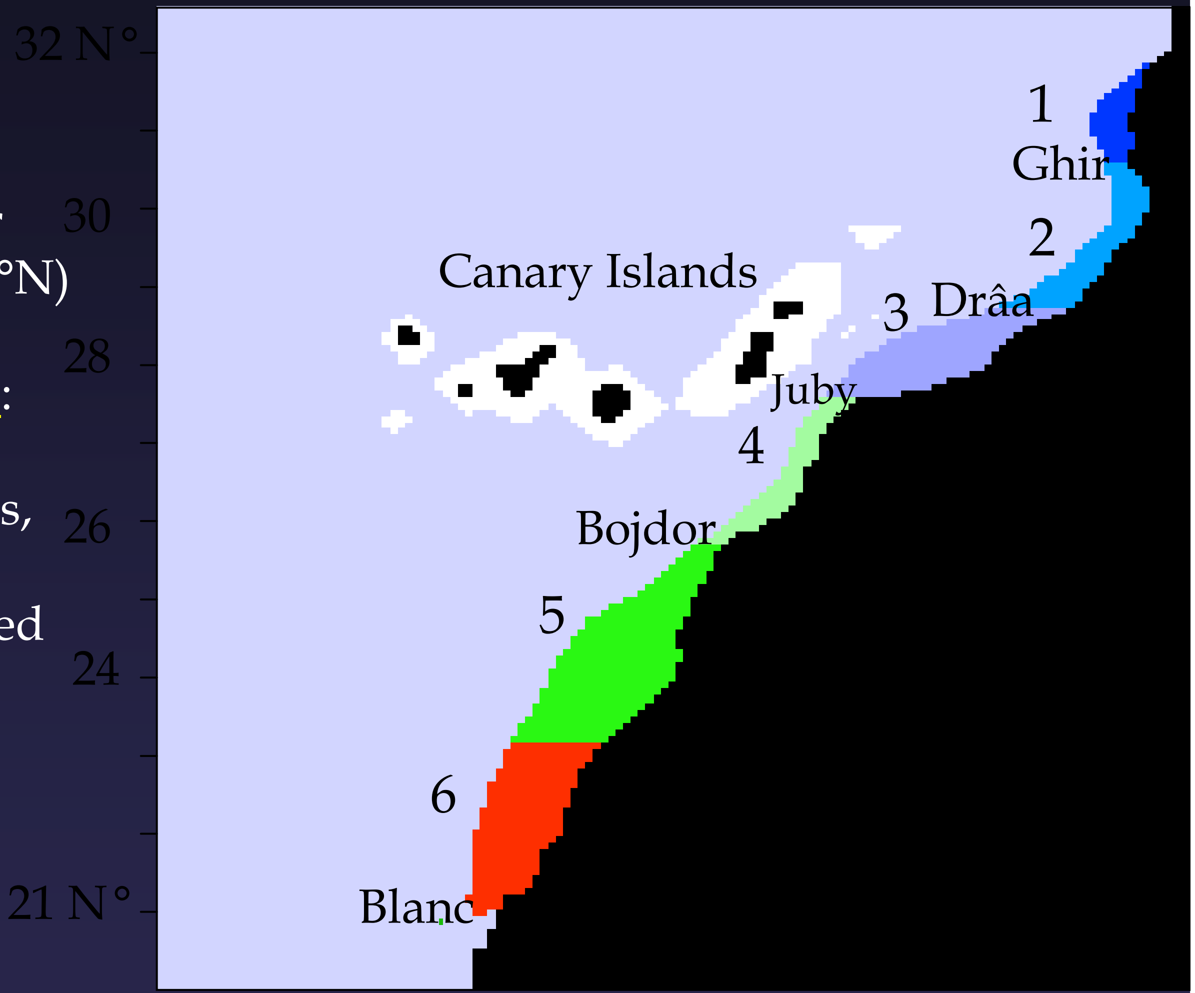
Extending from North Cape Ghir to North of cape Blanc (32°N - 21°N)

Spawning grounds and nurseries :

The coast is subdivided to 6 zones, considered as both spawning grounds and nurseries, delimitated by capes and 200m isobaths

Period of study **:**

Years : 1998, 1999, 2000.

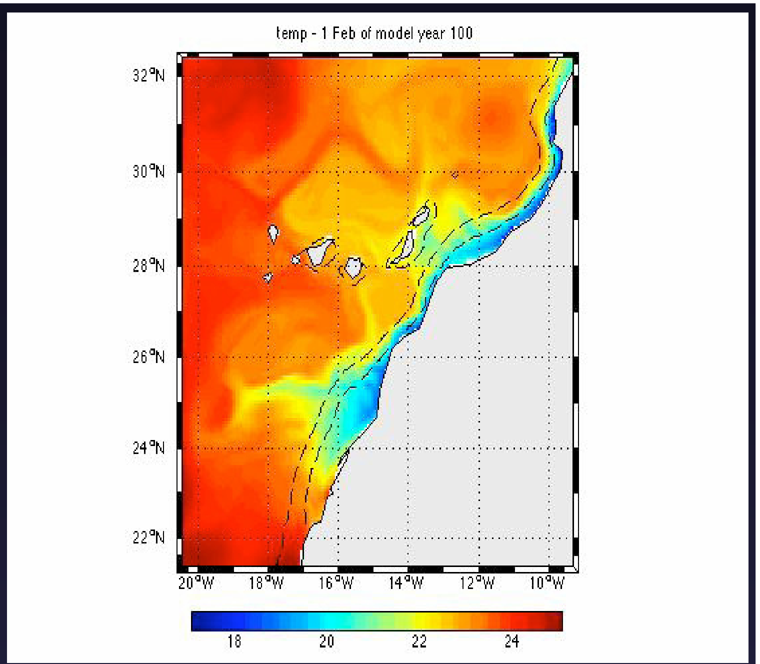


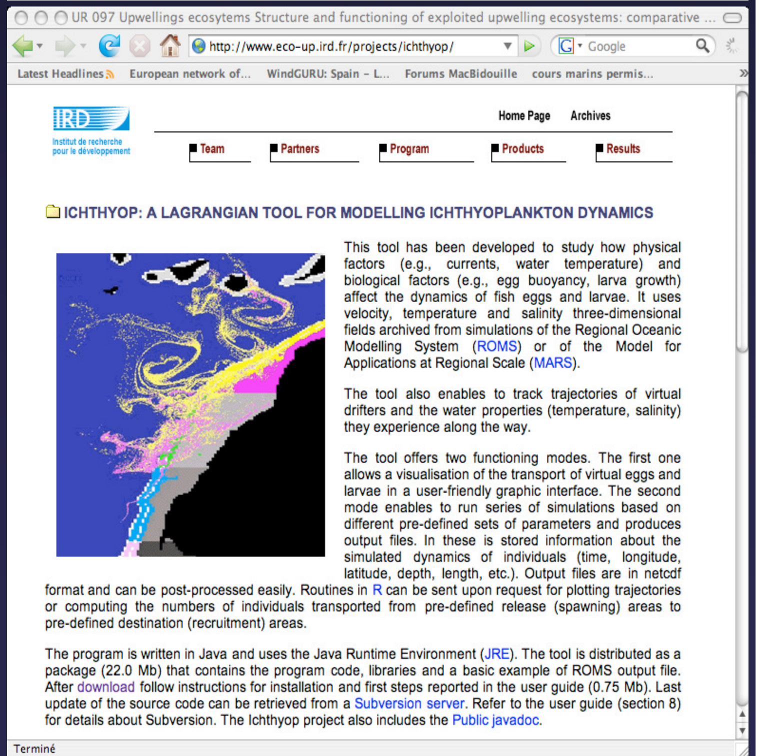
Modelling Tools

ICHTHYOP, an IBM (Individual Based Model) (Lett, Brochier, Ramzi, Verley) Coupled with ROMS (Regional Oceanic Model System) with resolution 1/12° (≈ 8km) and 32 sigma-levels (E. Machu)

downloadable from : http://www.eco-up.ird.fr/projects/ichthyop/

Methodology : Each year, monthly passive particles are released from the different zones, different depth classes, and are considered to be pre-recruited when reaching one of the nurseries at the critical age.

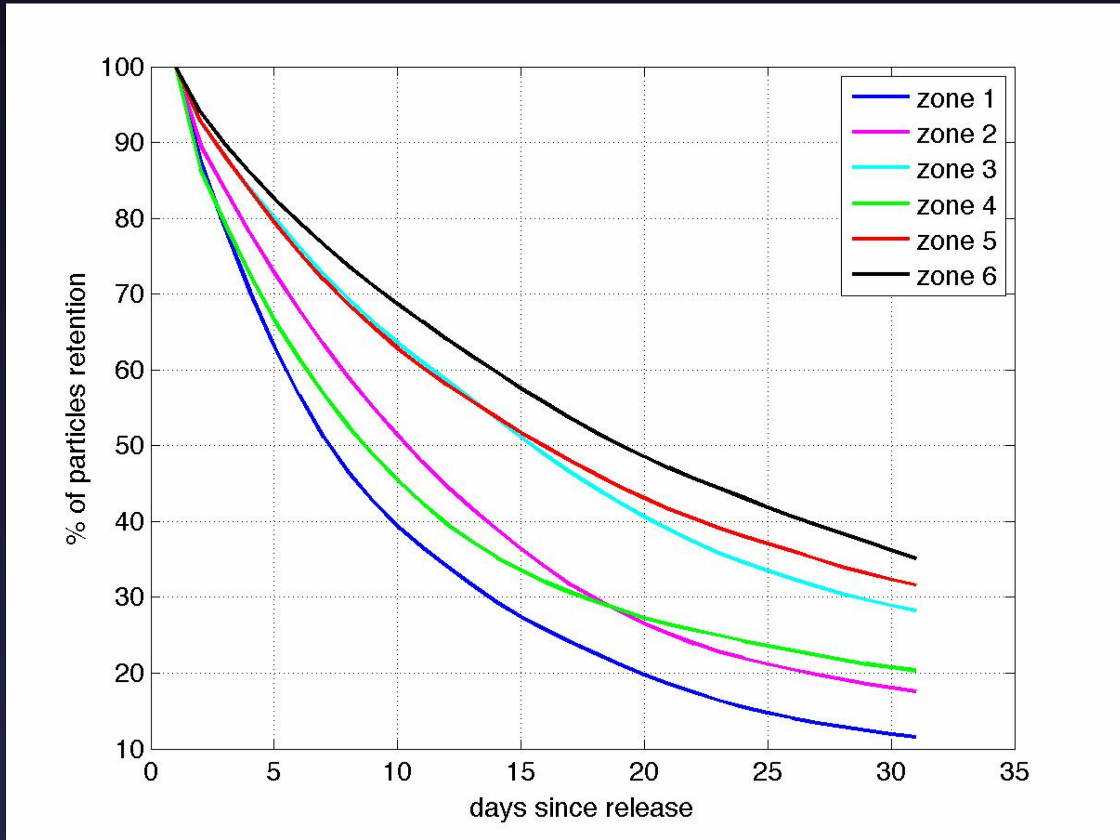




PRLIMINARY RESULTS

Analyse Of Variance

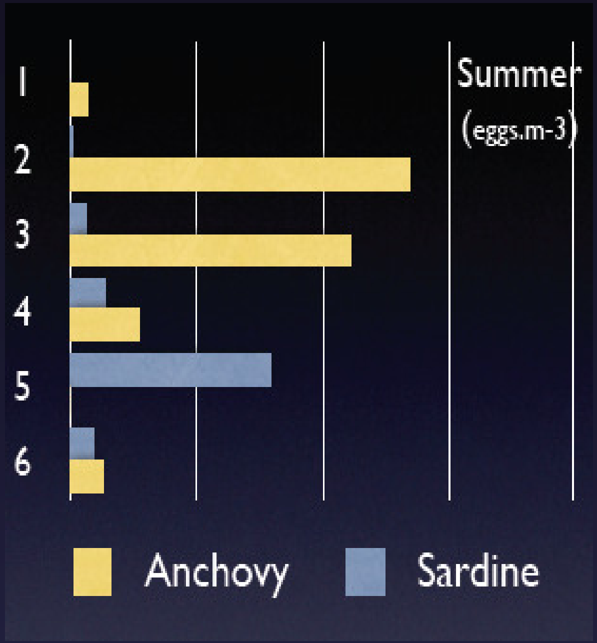
	Df	Sum Sq	% expl.	Mean Sq	F value	Pr(>F)
Depth	2	1833407	13,0	916704,0	8971,4	<2e-16
Month	11	1543986	10,9	140362,0	1373,7	<2e-16
ReleaseArea	5	204933	1,4	40987,0	401,1	<2e-16
Year	2	21075	0,1	10538,0	103,1	<2e-16
Replicate	2	31	0,0	15,0	0,2	0,9
Depth:Month	22	2462204	17,4	111918,0	1095,3	<2e-16
Depth:ReleaseArea	10	292252	2,1	29225,0	286,0	<2e-16
Depth:Year	4	38290	0,3	9573,0	93,7	<2e-16
Month:ReleaseArea	55	3157447	22,3	57408,0	561,8	<2e-16
Month:Year	22	480185	3,4	21827,0	213,6	<2e-16
ReleaseArea:Year	10	164214	1,2	16421,0	160,7	<2e-16
Residuals	38734	3957850	28,0	102,0		
Total		14155874	100,0			



100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
% of particles retention
days since release
zone 1
zone 2
zone 3
zone 4
zone 5
zone 6

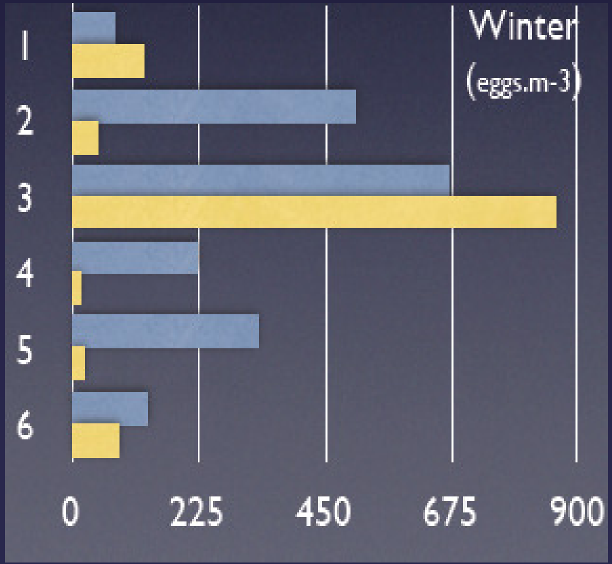
Spring+summer

spawning.area	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Total
1	7%	40%	20%	0%	0%	0%	67%
2	1%	16%	53%	2%	0%	0%	72%
3	0%	1%	26%	21%	13%	0%	63%
4	0%	0%	1%	11%	45%	1%	59%
5	0%	0%	0%	0%	35%	16%	51%
6	0%	0%	0%	0%	16%	35%	51%
	8%	58%	100%	35%	109%	52%	

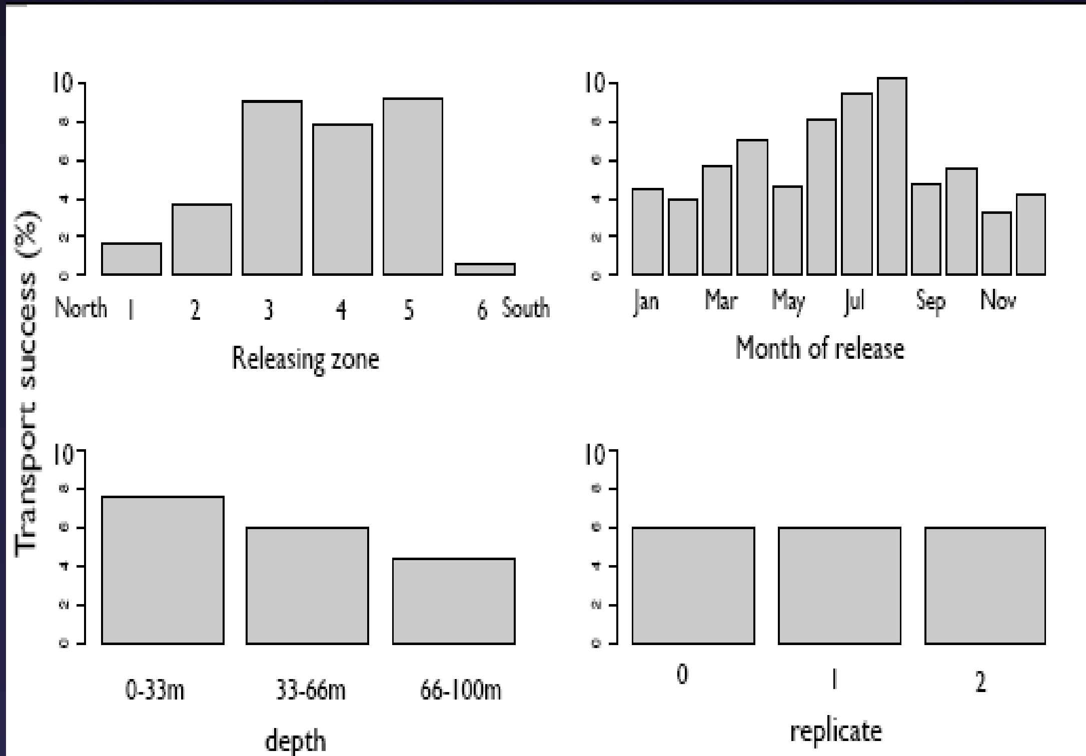


Automn_winter

spawning.area	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Total
1	25%	33%	6%	0%	0%	0%	64%
2	4%	34%	29%	1%	0%	0%	68%
3	0%	5%	42%	13%	3%	0%	64%
4	0%	0%	8%	27%	35%	0%	71%
5	0%	0%	0%	1%	51%	9%	61%
6	0%	0%	0%	0%	8%	51%	59%
	29%	72%	85%	43%	98%	60%	



Transport to the Canary islands



DISCUSSIONS

Simulations results show that :

- month, zone, and depth classes of releases are main model parameters affecting the pre-recruitment also the period of transport (exogenous stage).
- The transport is generally southward (Canary Current) but may be northward (zone 6) when upwelling generates filaments and offshore transport north Cape Boujdor (Barton, 1989).
- More retention in the same area in near bottom classes than in surface depth classes.
- Zone 2, 3 and 5 are zones of maximum retention and concentration in agreement with high density of eggs and larvae are found during surveys.

ONGOING & FUTURE RESEARCH

Couple the IBM to biogeochemical models (N,P,Z) to :

1. Take into account interactions of larvae with primary and secondary production and habitat preferences (temperature, feeding, swimming food availability,…etc.).

2. Elaborate favourabilitiy map : determine the locations of best habitat for reproduction and recruitment success.

3. Enhance comprehension of biological and environmental forcing factors interactions (upwelling, food, predation, temperature,…).

4. Adult stage (Migration, Reproduction, Exploitation, bioeconomy,…etc.)

5. Multi-specific Interactions towards an ecosystem approach for fisheries management (Couple IBM, NPZD with EwE or Ecospace).

CHALLENGES

- Improve modelling ecosystemic approach and ecosystemic management of fisheries taking into account inter-specific interactions.

- Improve bilogical and ecological studies and to reduce the gap between biologie, ecology & models :
 (Analytical models and ecosystemic models should start…!!!)

- Need of interdisciplinary collaboration and Investment in collecting adequate and qualitative data

Thank You !