Forecasting populations trends of tuna under climate change scenarios

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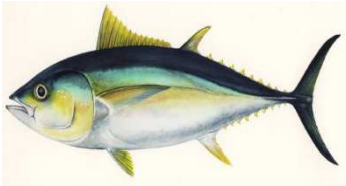
Outline

- **End-to-end ecosystem modeling approach**
  - **Bridging the gap: a simple model of micronekton**
  - **Habitats and Spatial dynamics**
- **Parameters**
  - **Optimization**
  - **Evaluation**
- **IPCC A2 projection**
- **Conclusion**



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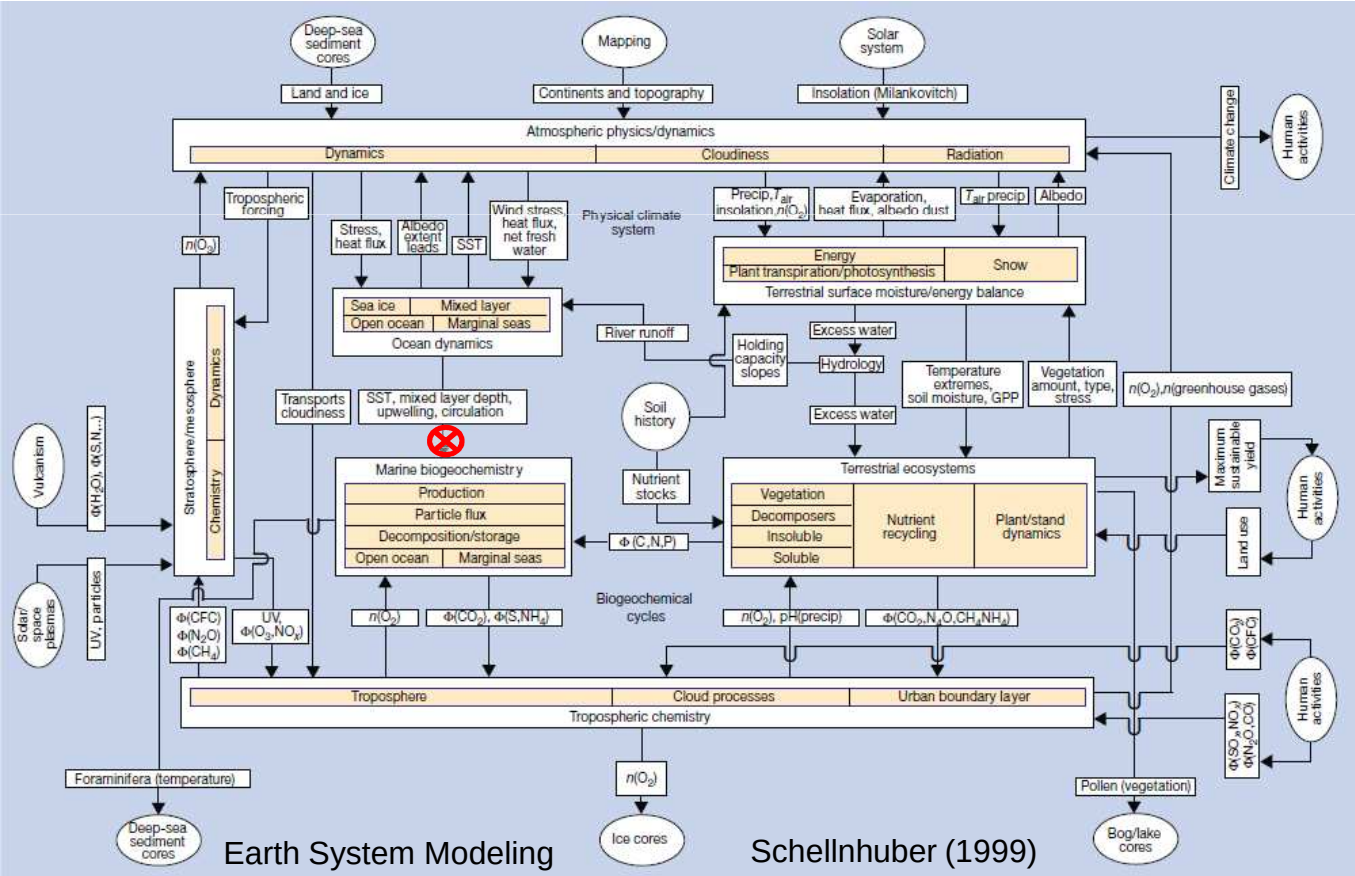
⊗ Marine life is (should be) here

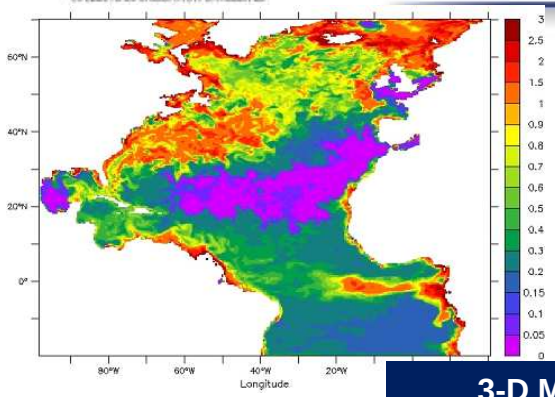
Modelling approach



Earth System Modeling

Schellnhuber (1999)

ECOSYSTEM MODEL



3-D Models

Ocean Biogeochem.

Primary Production from satellites

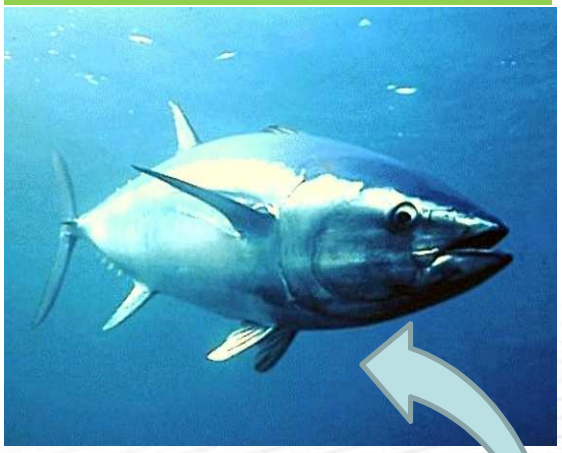
Ocean Physics

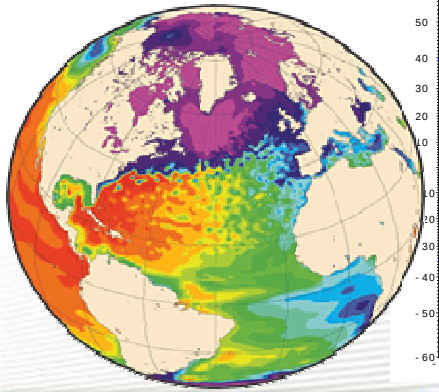
3-D models

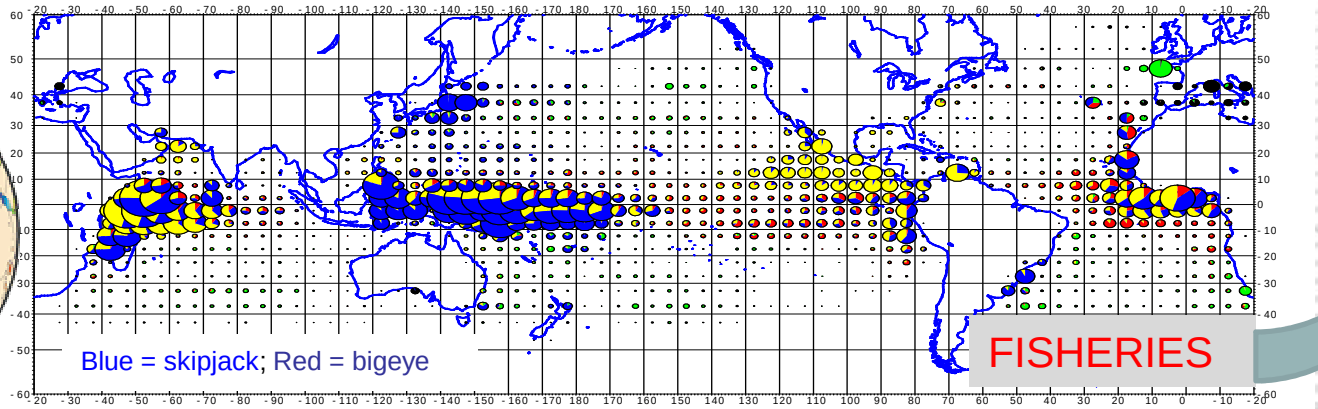
SEAPODYM

Prey model

Predator's population dynamics model







FISHERIES

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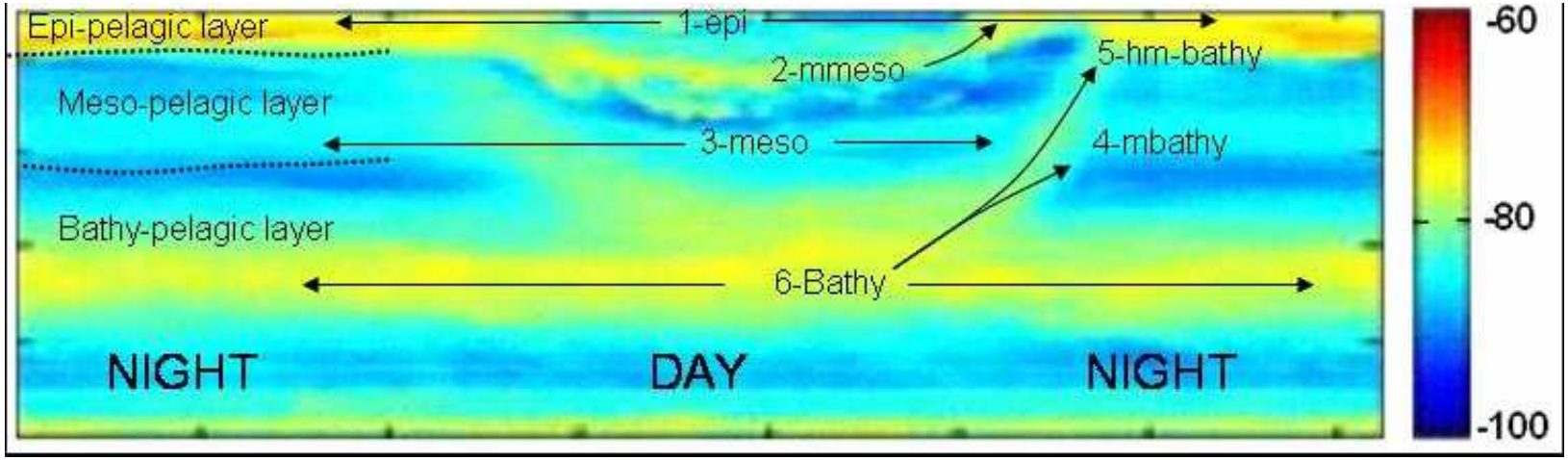
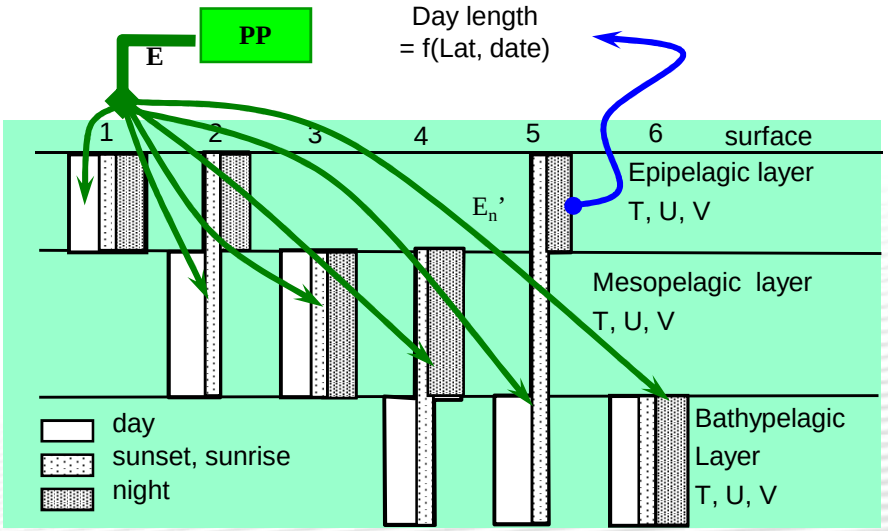
First step: predicting the distribution of prey

Mar-ECO station North Atlantic, (IMR, Bergen Norway) showing acoustic detection of micronekton





We have developed a model of micronekton, (small prey organisms)

The MODEL: 6 functional groups in 3 vertical layers. Several components exhibit diel vertical migrations, transferring energy from surface to deep layers. The biomass of each component is computed with an energy transfer coefficient directly from the observed or modelled vertically integrated primary production

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Functional group = multi-species population

Lindeman (1942), Schaeffer (1965), Ryther (1969), and Iverson (1990):

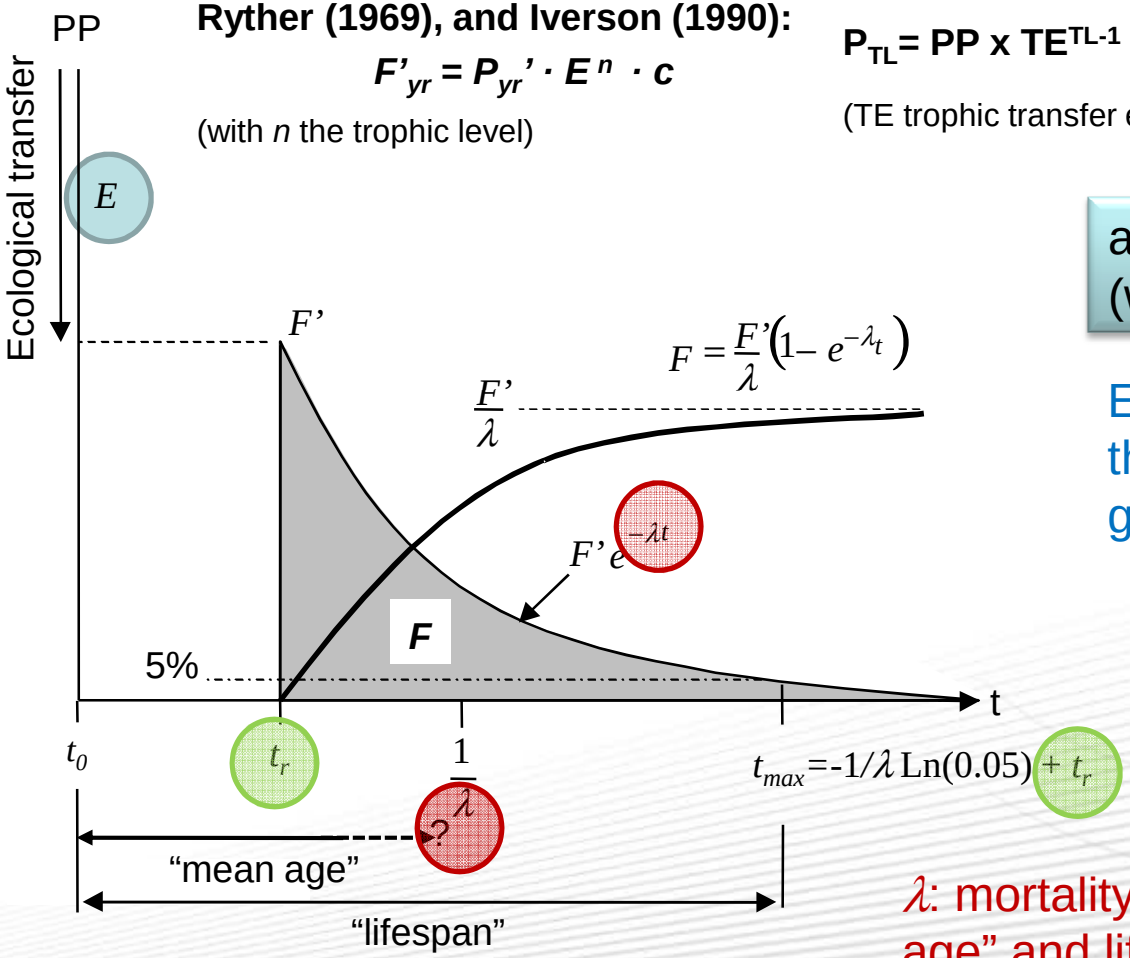
$$F'_{yr} = P_{yr}' \cdot E^{n} \cdot c$$

(with *n* the trophic level)

Jennings (2005):

$$P_{TL} = PP \times TE^{TL-1}$$

(TE trophic transfer efficiency; TL trophic level)



Lehodey (2001)

a window in the biomass size (weight) spectrum defined by:

E: energy transfer from PP to the functional micronekton group (trophic level ~2.5)

t_r: time of development for reaching the minimum size (weight), linked to temperature

λ: mortality coefficient, control the "mean age" and lifespan, (i.e. the turn over) of the population, also linked to temperature.

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Parameterizing λ

Can we link λ to meaningful biological parameters that are used to characterize the turnover of a population, i.e., generation time (~age at maturity t_m or lifespan t_{max})?

substituting t_{max} by previous definition of lifespan (i.e., $-1/\lambda \, \mathrm{Ln}(0.05) + t_r$), we obtain:

$$t_m^{0.957} = -\frac{\ln(x)}{10^{0.5496} \cdot \lambda} + \frac{1}{10^{0.5496}} \cdot t_r$$

that, given the range of standard error of the original regression, can be simplified as:

$$t_m = 1/\lambda + 1/3\, t_r$$

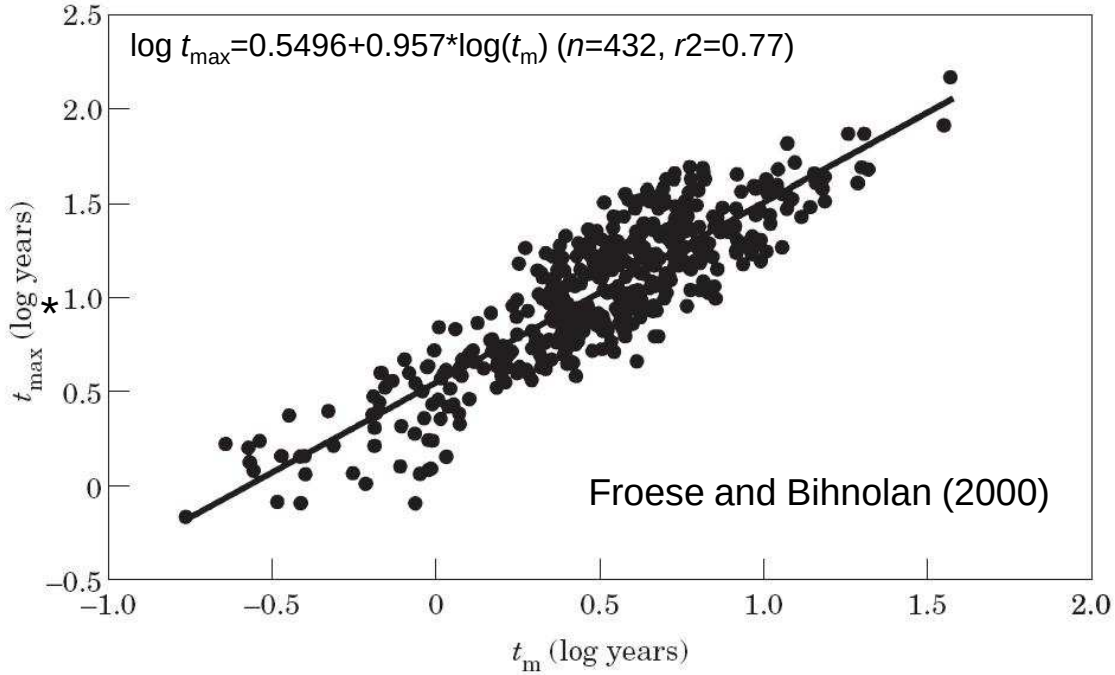

FIG. 4. Relationship between life span (t_{max}) and length at first maturity (t_m).

* t_{max} = age at L_∞*0·95 (Taylor, 1958)

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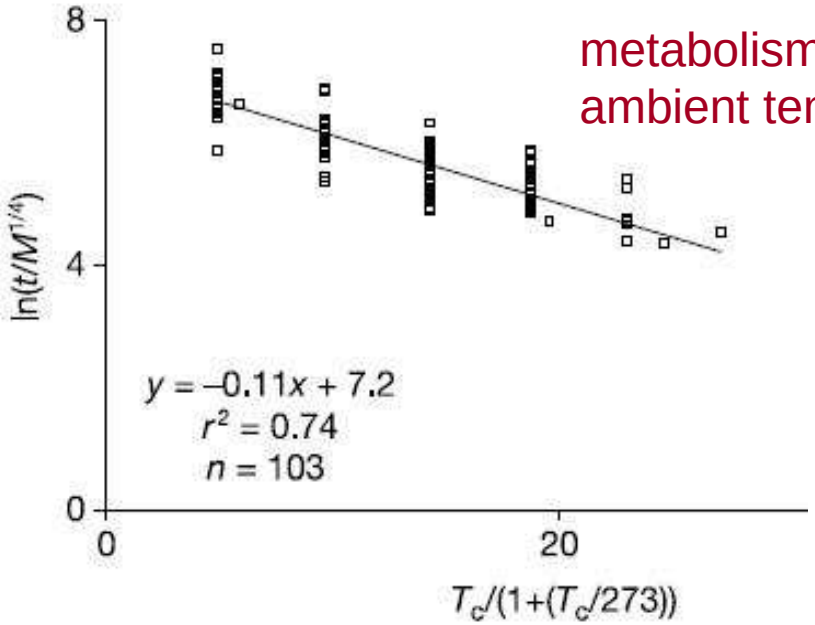
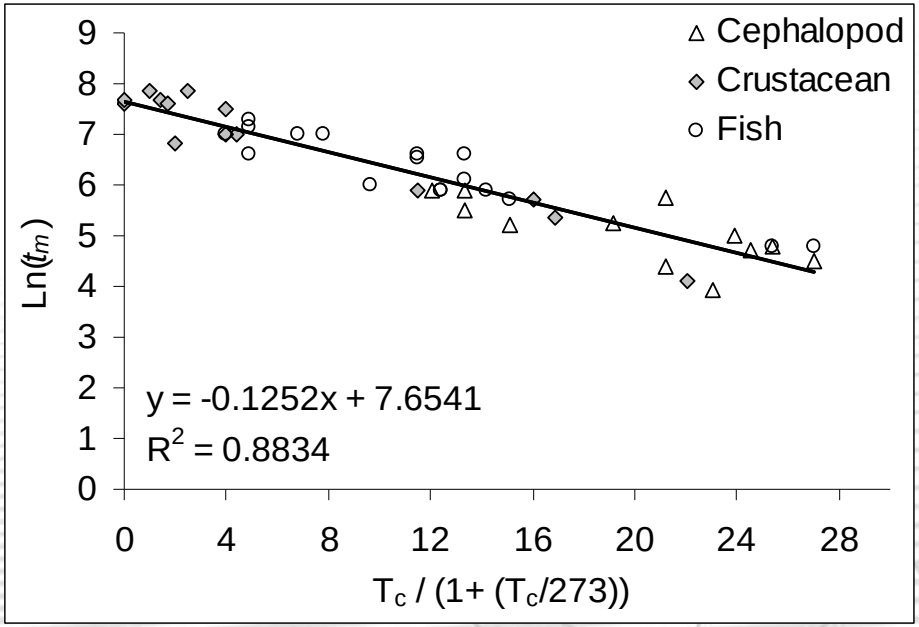
Temperature and development

metabolism of ectotherm animals is linked to ambient temperature



we obtain similar result using age at maturity and ambient temperature of micronekton species

Gillooly et al. (2002) propose a model explaining relation between temperature and development time of post-embryonic (hatching to adult) zooplankton species (rotifers, copepods and cladocerans) incubated at different constant temperatures ranging from 5 to 30°C



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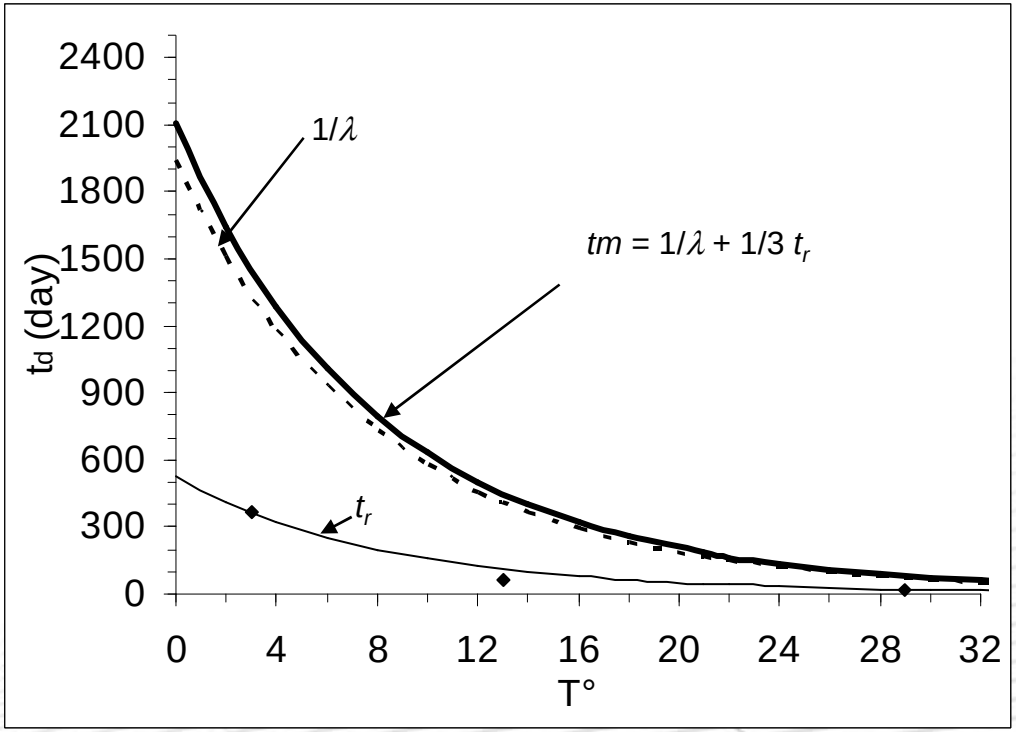
Dynamic of a MTL component

λ is the mortality coefficient that control the turn over of the MTL (Mid-Trophic Level) component, ~ the time of development to the age at maturity

λ is linked to temperature

t_r is the recruitment time, i.e. the minimum time between "birth" coinciding with the apparition of PP and the age at which organisms reach a size large enough to be included ("recruited") in the MTL



based on a few obs., we fixed t_r to the development time needed to reach a weight of 1g, which is also linked to temperature (with same slope) and lead to $t_r \sim 1/4\ t_m$)

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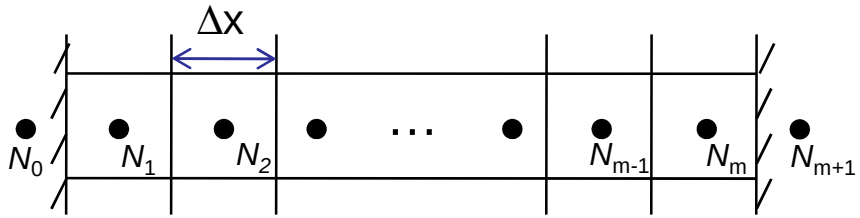
Model = numerical solution of PDEs

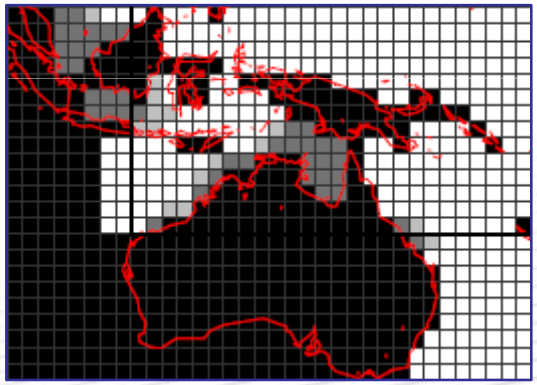
Computational GRID



3-layer ocean MASK (etopo2 data)

Finite difference approximation:

- upwind differencing for advection terms
- two-point centered-space differences



Closed boundaries

Initial conditions (climatological “spin-up”)

ADI numerical solver (unconditional convergence)

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Spatial Dynamics

Mid-trophic Production (= recruitment)

$$\frac{\partial S_n^m}{\partial t} = D\left(\frac{\partial^2 S_n^m}{\partial x^2} + \frac{\partial^2 S_n^m}{\partial y^2}\right) - \frac{\partial}{\partial x}(\hat{u} S_n^m) - \frac{\partial}{\partial y}(\hat{v} S_n^m), \quad n = 1 \ldots 6, m = 1 \ldots t_{r\max}$$

$$S_n^m = S_n^{m-1}, \text{for } 1 \le m \le \lfloor t_{r\,ij} \rfloor$$

Initial condition: $S_{nij}^0 = cE_n P_{ij}$

Neumann boundary conditions (impermeability):

$$\hat{u}_{ij} = \hat{v}_{ij} = \frac{\partial S_{ij}}{\partial x} = \frac{\partial S_{ij}}{\partial y} = 0, \quad \forall (i,j) \in \partial\Omega$$

Mid-trophic biomass

$$\frac{\partial F_n}{\partial t} = D\left(\frac{\partial^2 F_n}{\partial x^2} + \frac{\partial^2 F_n}{\partial y^2}\right) - \frac{\partial}{\partial x}(\hat{u} F_n) - \frac{\partial}{\partial y}(\hat{v} F_n) - \lambda F_n + F_n'$$

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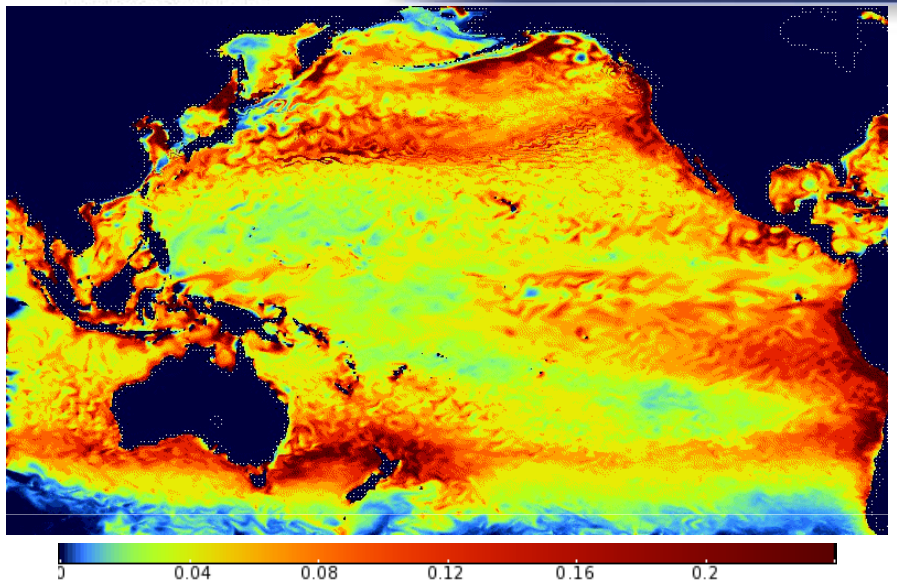
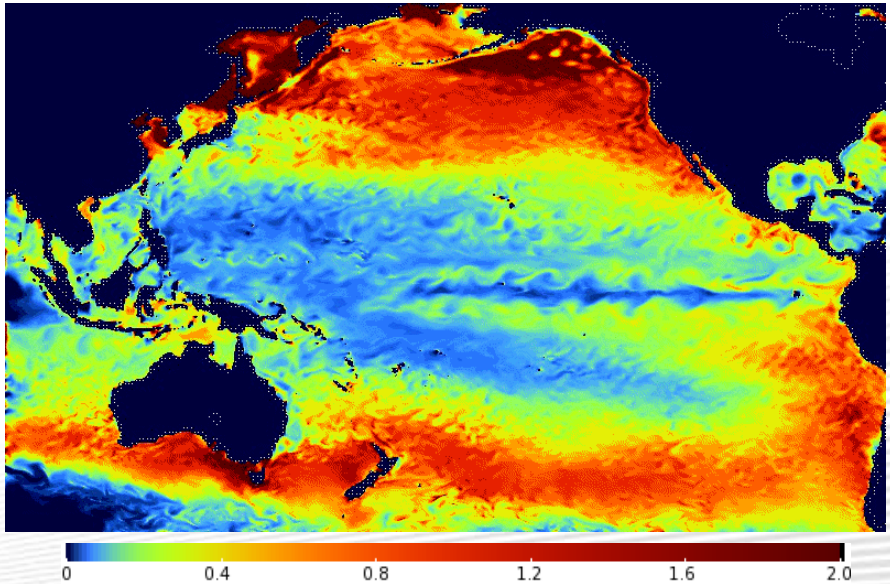
Results: P/B epipelagic micronekton



Epipelagic (daytime) micronekton (2005)

Production (g m^{-2} d^{-1})



Biomass (g m^{-2})

¼ deg x 6 day

Physical fields from MERCATOR (http://www.mercator-ocean.fr/)
Satellite derived Primary production

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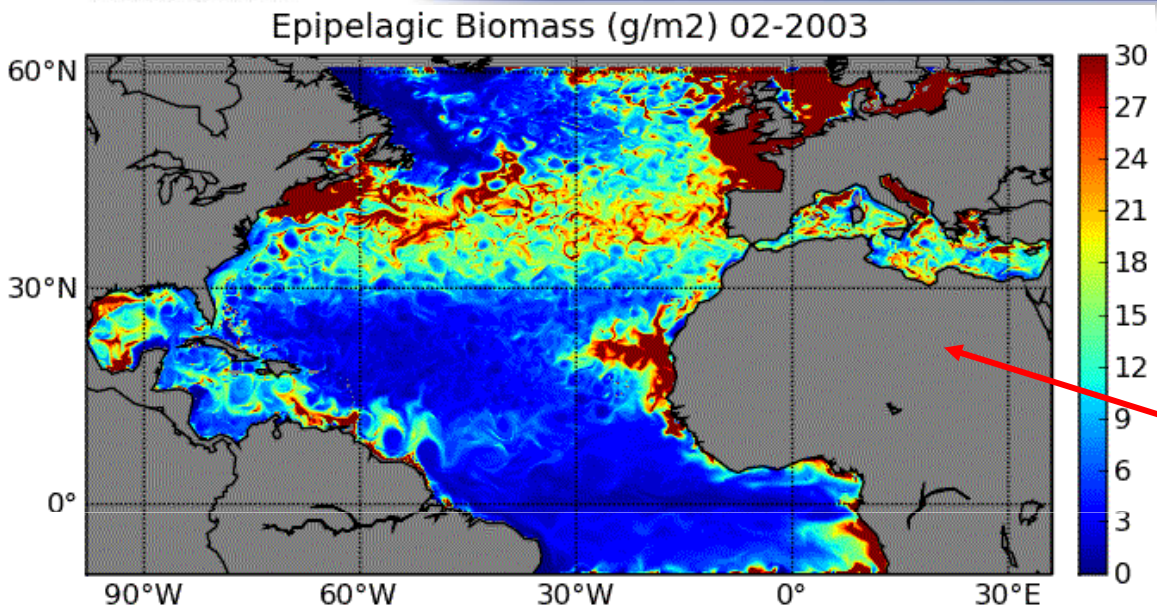
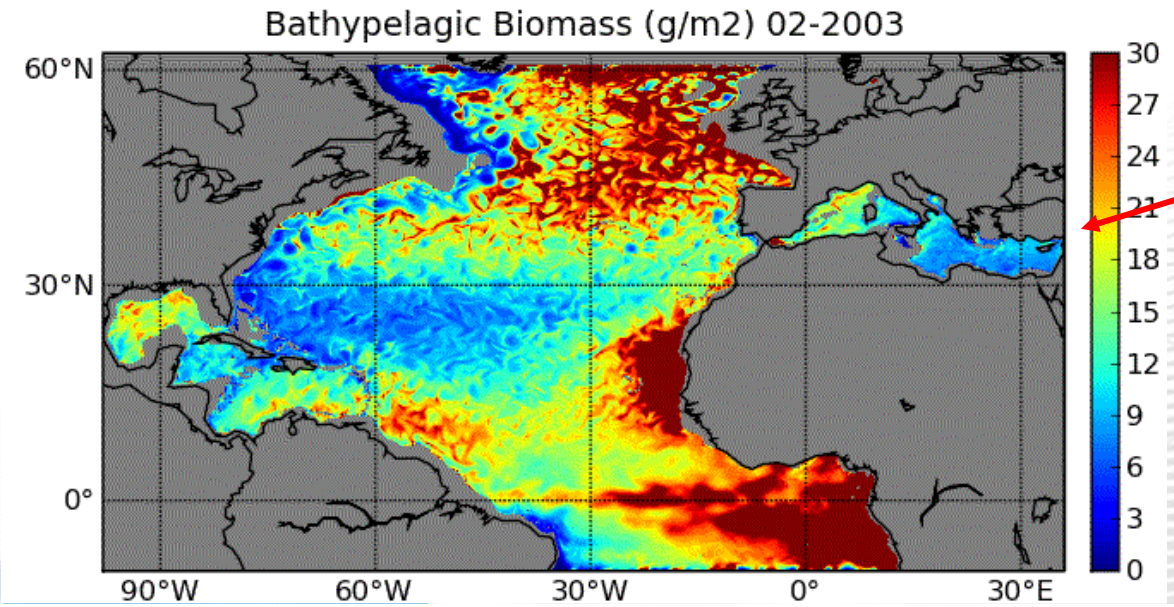
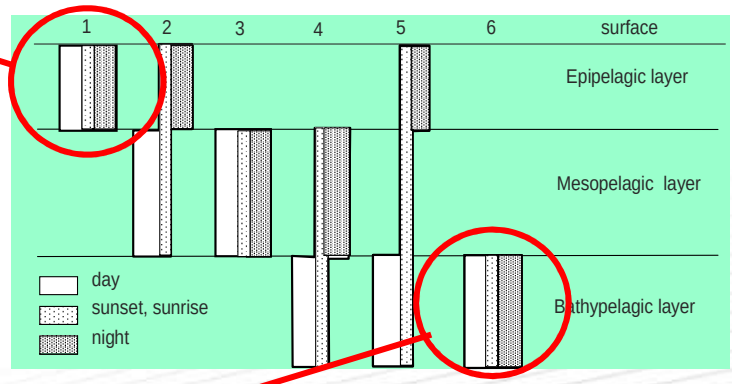
Results: day/night epipelagic biomass





1/12th deg x 6 day

Physical fields from MERCATOR (http://www.mercator-ocean.fr/)
Satellite derived Primary production



References:
Lehodey et al. (1998). *Fish. Oceanog.*
Lehodey, (2001). *Prog. Oceanog.*
Lehodey et al. (*accepted*) *Prog. Oceanog.*

2nd step: evaluation … either direct …

Hidaka et al. (2003):

micronekton biomass (Jan-Feb 1998) in the upper 200 m
Day: <1 mg WW m^{-3} during the day (0.001-0.07 mg WW m^{-2}) notable exception of large anchovy schools (-> 23.3 mg WW m^{-3})
Night: 3-38.8 mg WW m^{-3} = 0.3-3.88 mg WW m^{-2}

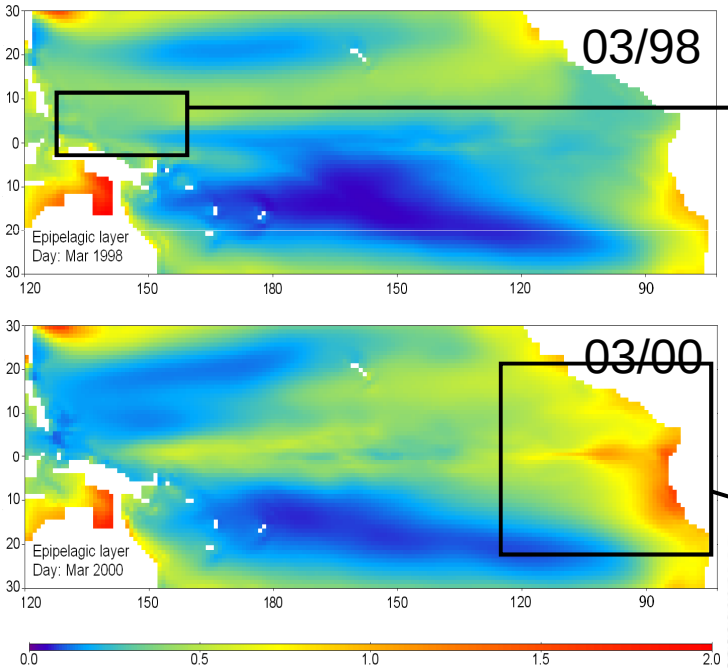
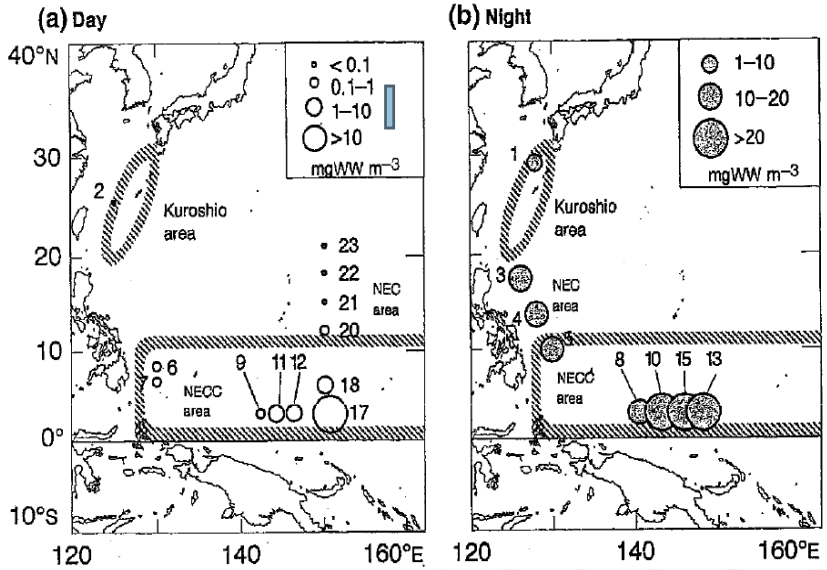
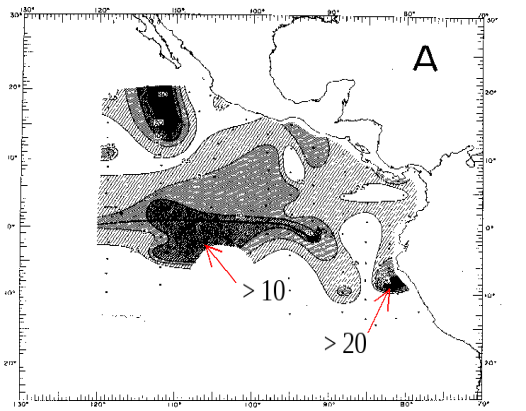


Figure 5. Total micronekton biomass in the upper 200 m layer of the western tropical–subtropical Pacific in January to February 1998. Number indicates station number referable to the station number in Table 1.





EASTROPAC cruises 1967-1968 (Blackburn and Laurs, 1972):

distributions of micronekton in the EPO in the upper 200m showing an increase in biomass between day and night from ~1-8 to 10-20 ml/1000 m^3, and still some higher concentration near the coast of Peru.

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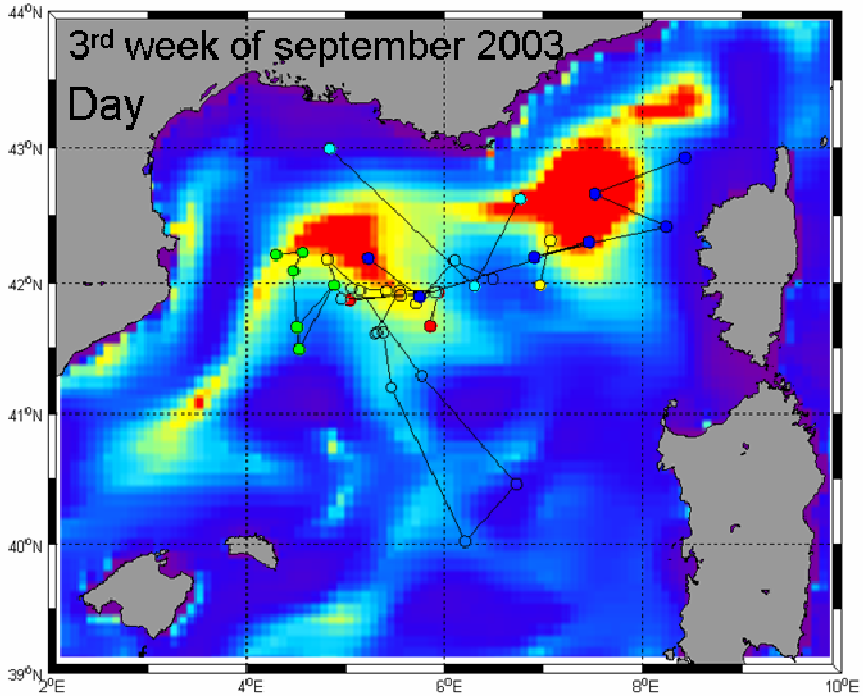
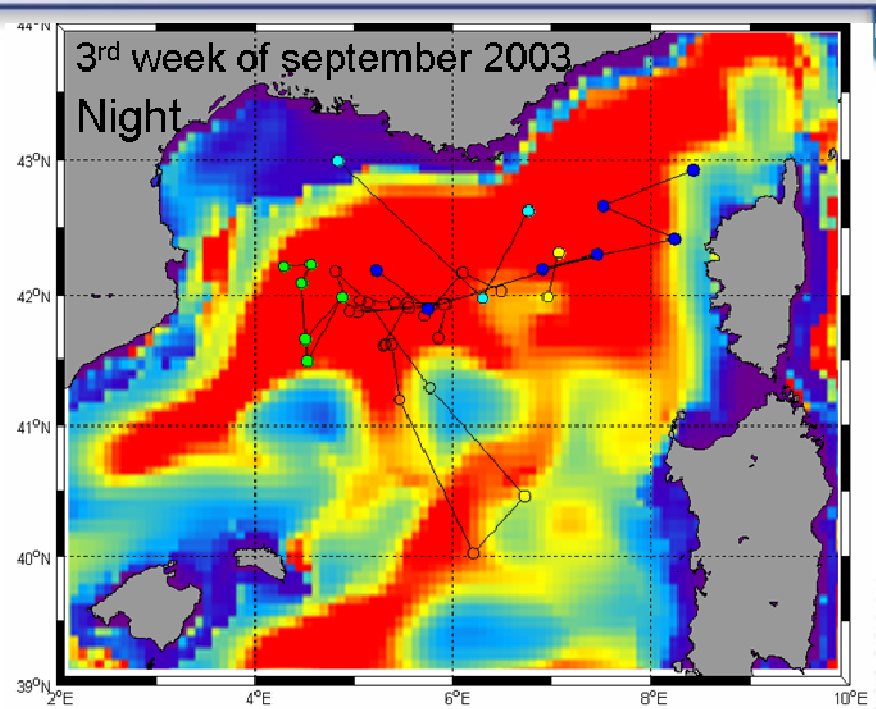
… or indirect

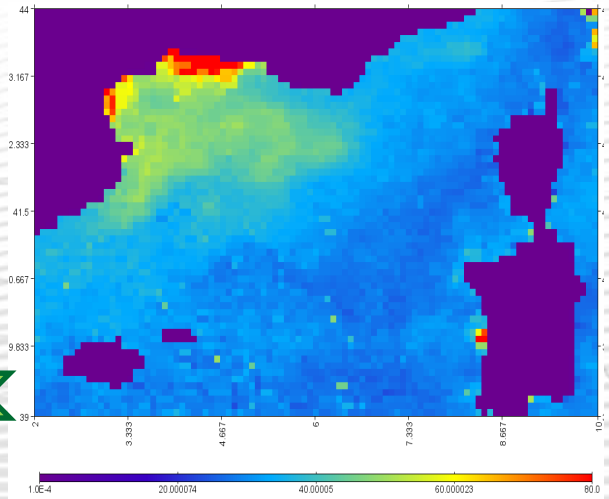




Positions of whales (*Balaenoptera physalus)* (one color by individual) tracked with satellite tags (Cédric Cotté, CEBC) superimposed on predicted micronekton in the surface layer during day and night for the 3rd week of Sep 2003.

Prey sp.: small fish, squids and crustaceans (Mysids and krill).

Primary production (Seawifs derived) for the same week decoupled !



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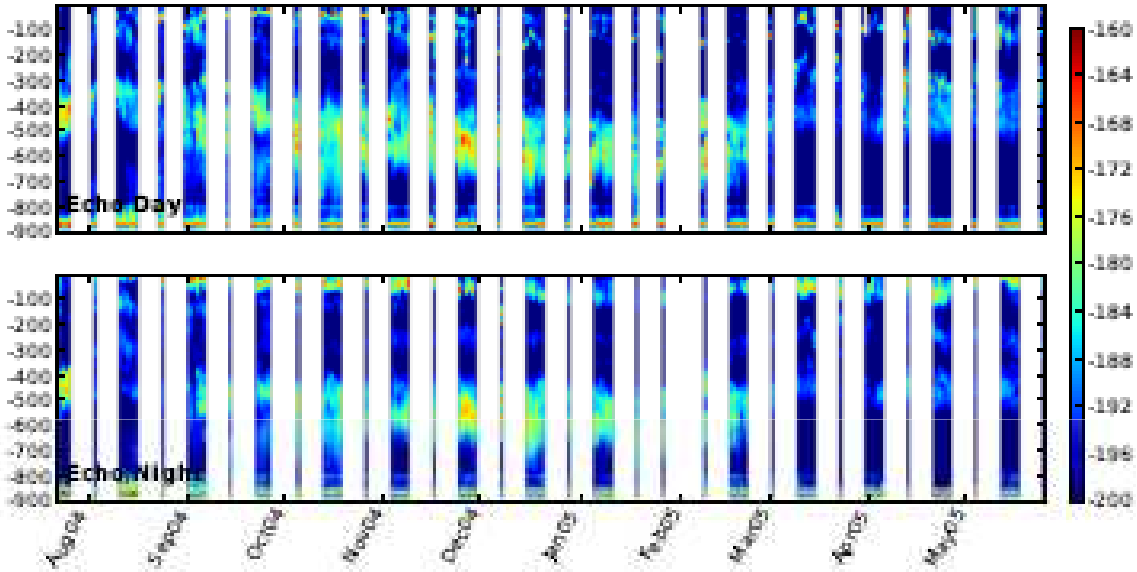
Next step: optimization with data assimilation

MarEco lander

IMR, Bergen

Kindly from N. O. Handegard.



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

	Mid-trophic functional groups					
Nb of Layers	epi	meso	m-meso	bathy	m-bathy	hm-bathy
0	0	0	0	0	0	0
1	1	0	0	0	0	0
2	0.34	0.27	0.39	0	0	0
3	0.17	0.10	0.22	0.18	0.13	0.20

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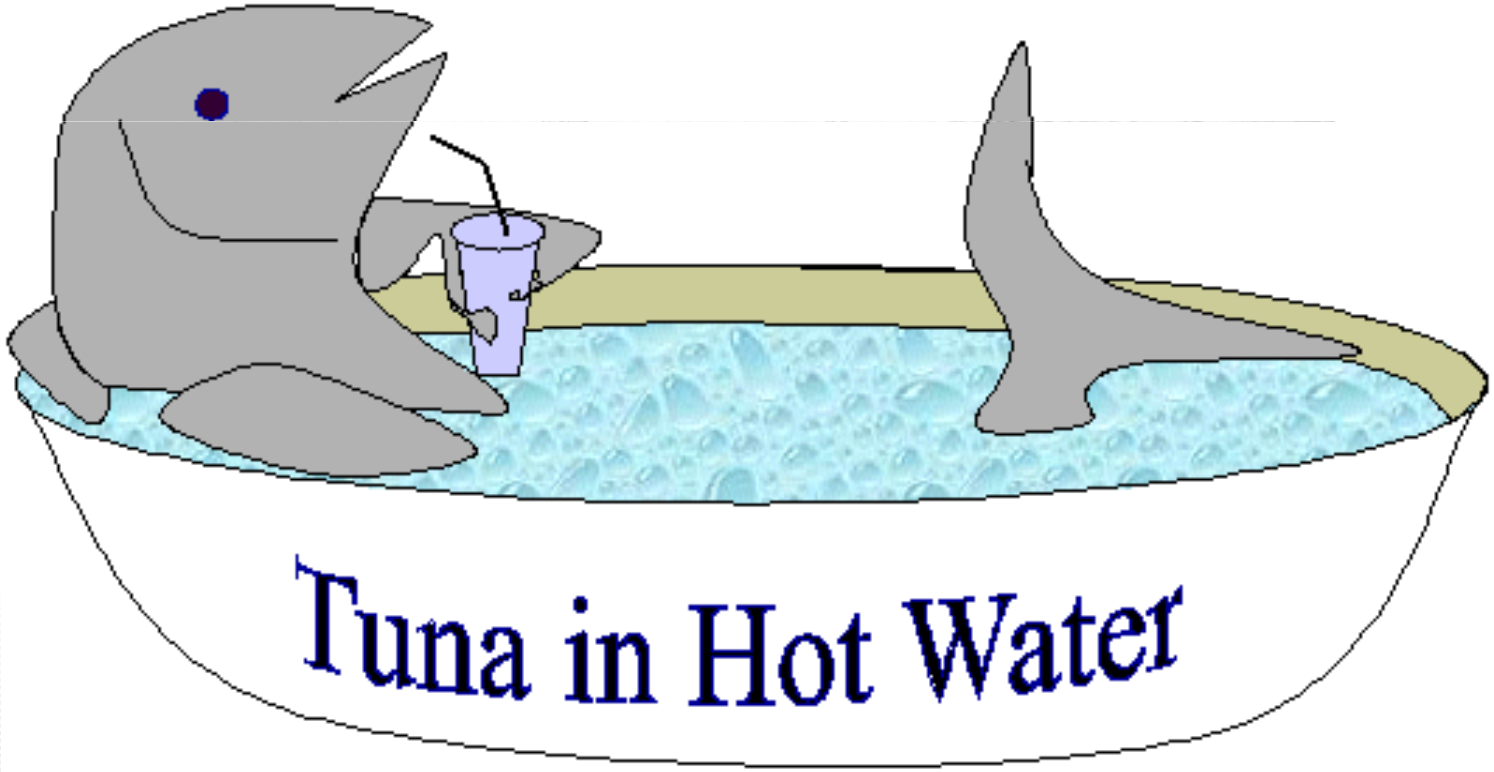
Predicting habitat and dynamics of large oceanic predators



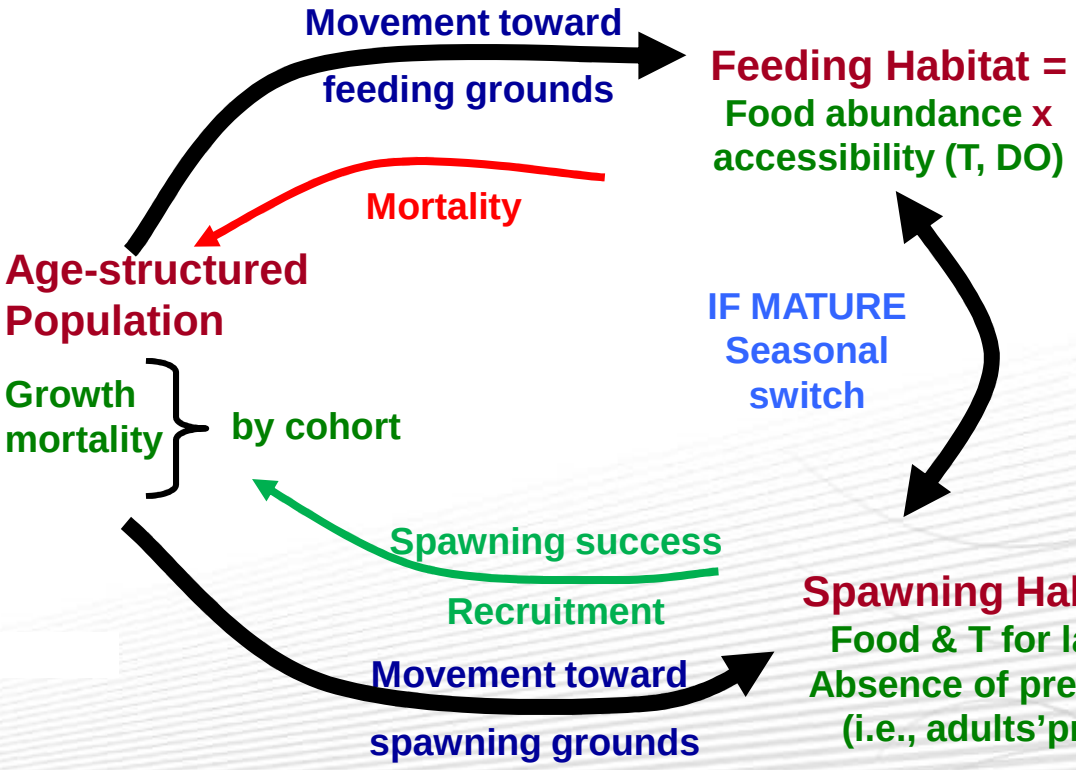
Predator model

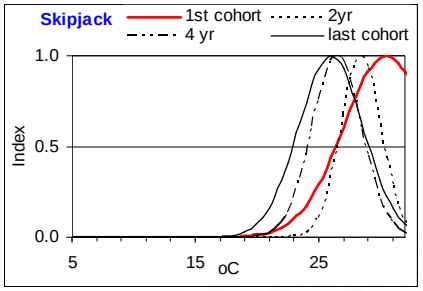
EULERIAN AGE-STRUCTURED POPULATION DYNAMICS MODEL

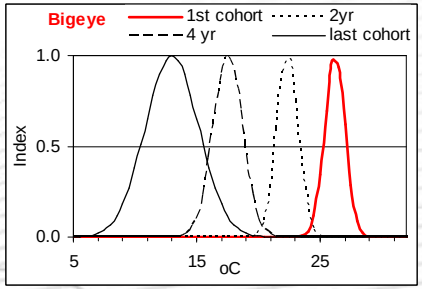
❑ Advection-diffusion equation for each cohort with source/sink terms (reproduction/ageing/natural mortality/fishing)

HABITAT-DRIVEN MOVEMENT

❑ Animals move towards favorable habitats (feeding or spawning)







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SEAPODYM underlying equations

A system of ADR equations with Neumann boundary conditions:

$$\partial_t N_a = \begin{cases} -\mathrm{div}(\mathbf{v}_0 N_a) + \delta \Delta N_a - m_a N_a + S_a, \ a = 0,..,(k_L + k_J - 1); \\ -\mathrm{div}(\mathbf{V}_a N_a) + \mathrm{div}(D_a \nabla N_a) - (m_a + f_a) N_a + S_a, a = (k_L + k_J),..,K. \end{cases}$$

$$\mathbf{n} \cdot \mathbf{V}_a \big|_{\mathbf{x} \in \partial\Omega} = \mathbf{n} \cdot \nabla N_a \big|_{\mathbf{x} \in \partial\Omega} = 0 \qquad S_o = \Lambda(\mathrm{PP}, F, N_{a>kL+kJ})$$

Velocity **V** and diffusion **D** are linked to the habitat index H∈ [0, 1]

$$U_a = \hat{u} + \chi_a \frac{\partial H_a}{\partial x}, \ V_a = \hat{v} + \chi_a \frac{\partial H_a}{\partial y}, \qquad D_a = \overline{D}_a \left(1 - \frac{H_a}{(c + H_a)}\right)\left(1 - \rho \left|\nabla H_a\right|\right)$$

The feeding habitat index is the function of micronekton F and environmental factors: temperature T and oxygen O in the layer z :

$$H_a = \sum_{z=1}^{3} \Theta_{a,z} \left(F_{zz} + \tau \sum_{k \neq z} F_{zk} + (1 - \tau) \sum_{k \neq z} F_{kz} \right)$$

$$\Theta_{a,z} = P(O_z; \boldsymbol{\theta}_{O,a}) \cdot G(T_z; \boldsymbol{\theta}_{T,a})$$

$$\begin{pmatrix} F_{11} & 0 & 0 \\ F_{21} & F_{22} & 0 \\ F_{31} & F_{32} & F_{33} \end{pmatrix} \begin{matrix} \text{epi} \\ \text{meso} \\ \text{bathy} \end{matrix}$$

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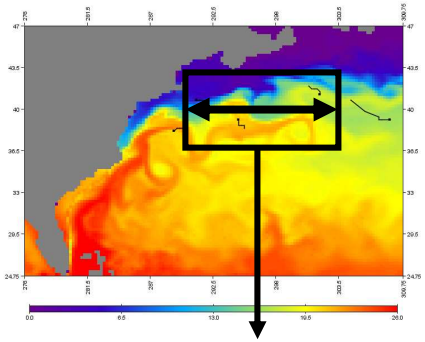
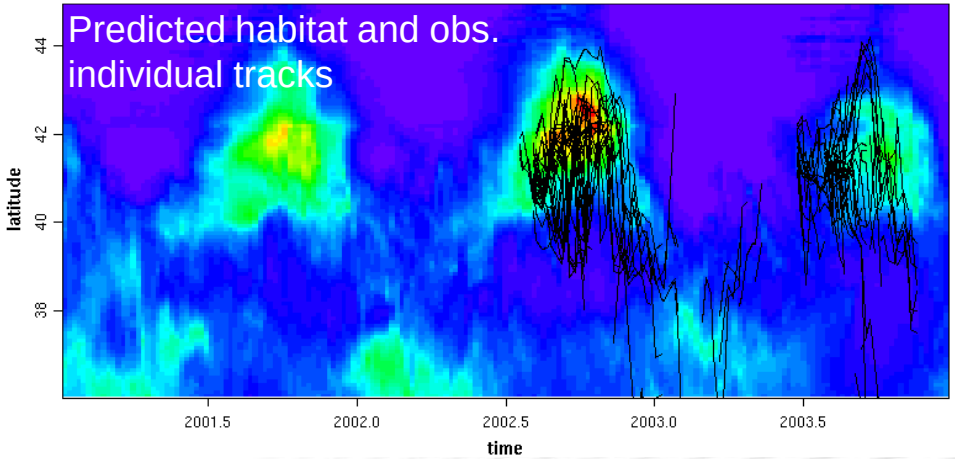
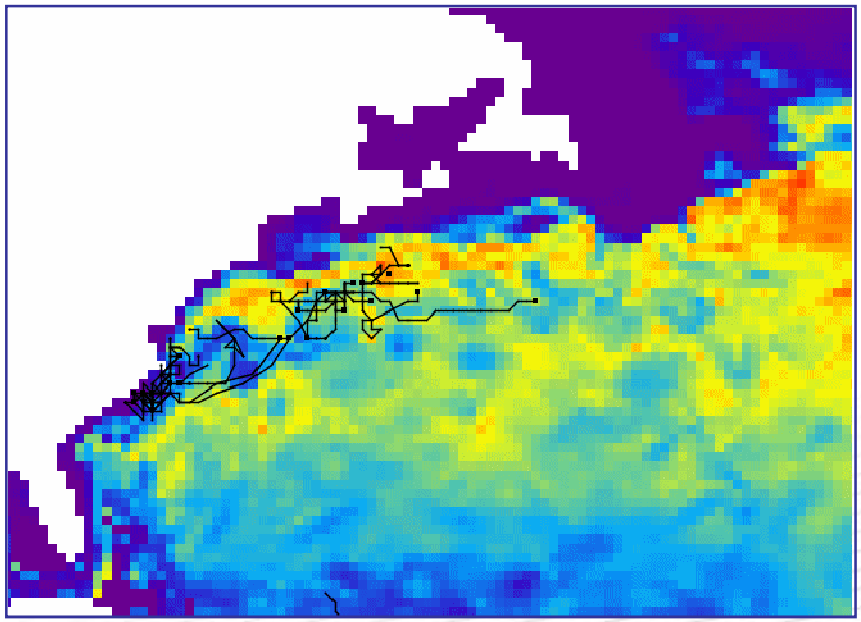
Example of feeding habitat (Atlantic bluefin)

UNH LPRC project: ABFT habitat (Tagging data kindly from M. Lutcavage)



Atlantic bluefin tuna





Observed individual tracks (satellite tags) superimposed on the feeding habitat

Low resolution simulation (1/2 deg x month) based on SODA and satellite-derived PP

temperature x prey = habitat

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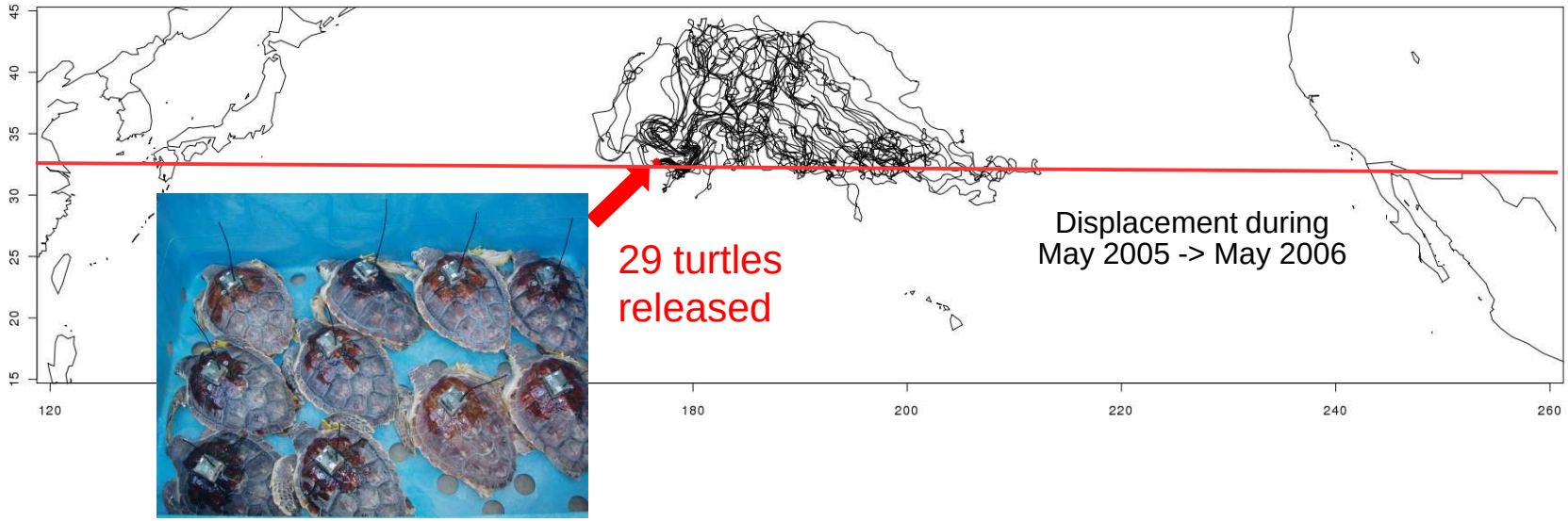
Ex. of movement: Loggerhead turtle



Ongoing project in collaboration with NMFS Hawaii
(Jeff Polovina and Mélanie Abecassis)

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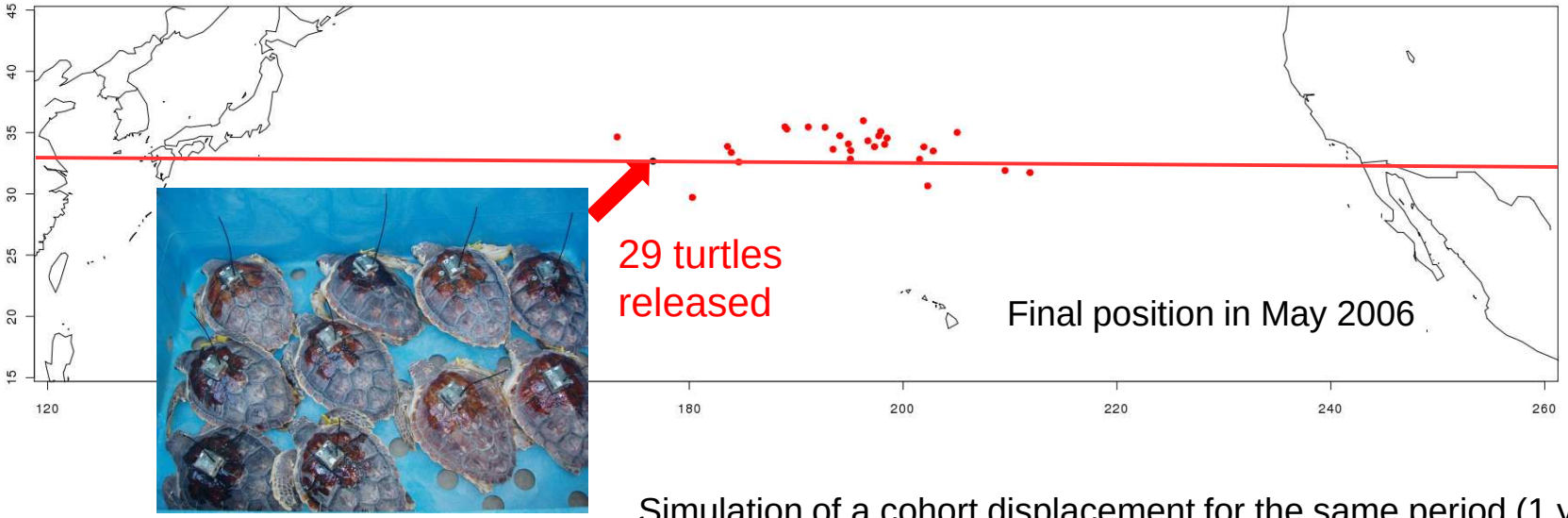
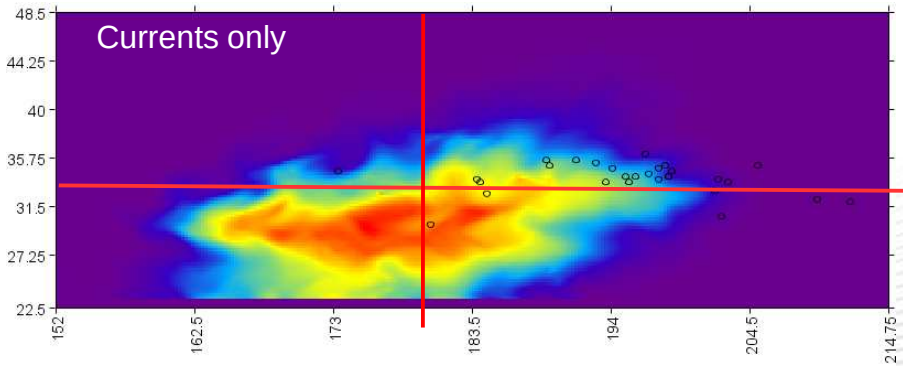
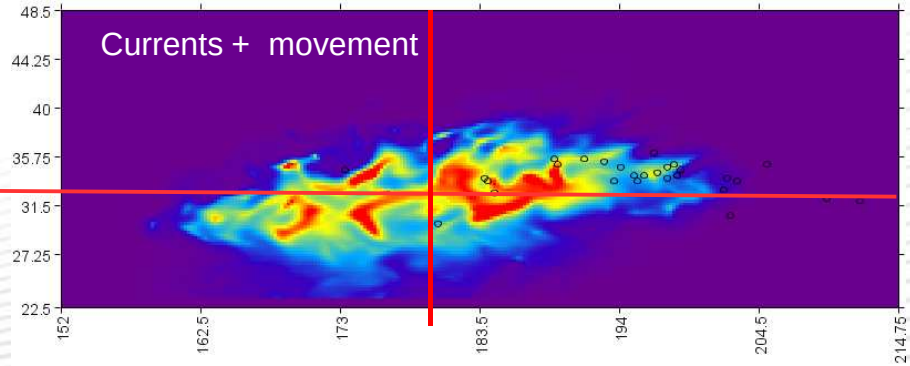
Ex. of movement: Loggerhead turtle



Simulation of a cohort displacement for the same period (1 year)
<u>First try without data assimilation in the physics</u>



Simply drifting with currents



Currents + active swimming controlled by habitat = temperature preference x available prey in first 100 m

Ongoing project in collaboration with NMFS Hawaii (Jeff Polovina and Mélanie Abecassis)

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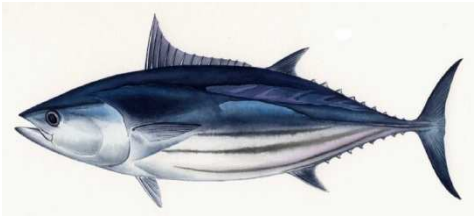
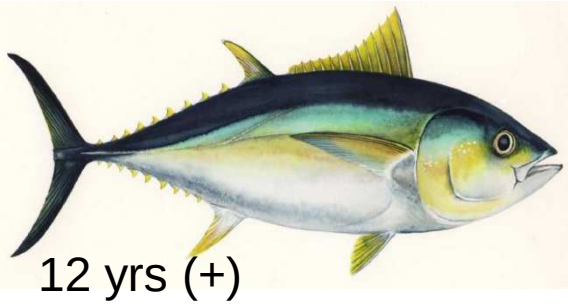
Application to 2 tuna species

Skipjack (*Katsuwonus pelamis*) vs Bigeye (*Thunnus obesus*)





Biology

4 yrs +	← Lifespan →	12 yrs (+)
75 cm / 20 kg	← Max size / weight →	180 cm / 225 kg
10-12 months	← Age at maturity →	2.5 years
Very high	← Fecundity →	Very high
~0.4 per month	← Natural mortality →	~0.1(-) per month
Micronekton	← Food →	Micronekton

Ecology

Warm 20 – 30 °C	← Thermal habitat →	Large 10-30 °C
Low! >3-4 ml l^{-1}	← Oxygen tolerance →	Good! >1.5 ml l^{-1}
0-200 m	← Vertical habitat →	0-1000 m
Tropical	← Spatial distribution →	Tropical to sub-temperate

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MODEL CALIBRATION & VALIDATION

1) Optimal estimation of parameters over the period 1985-2000 (Senina et al, 2008) using fishing data and ocean state from a coupled BGCM (ESSIC, U. Maryland, USA) forced by the NCEP 1948-2005 atmospheric reanalysis
2) Verification of coherence of parameters estimates and model realism with present knowledge
3) Check of model skill outside of the optimization period

4) Repeat the 3-step approach using the Climate Model ocean state (SRES A2, IPSL model) to account for different environment (and biases!)
5) Compare
6) Run the full simulation (1860-2100) with optimal parameterization

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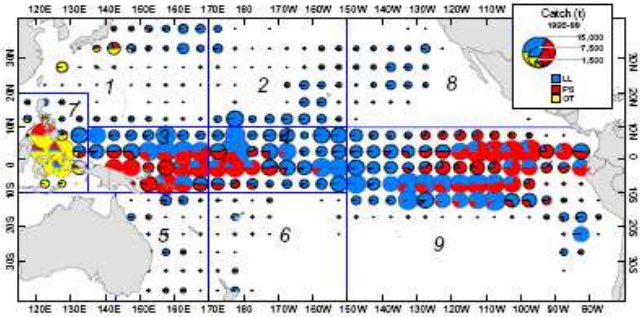
MODEL CALIBRATION & VALIDATION

Fishing data (Pacific)



- **Monthly catch data** (spatially-distributed)

  Skipjack = **4** purse-seine and **2** pole-and-line fisheries

  Bigeye = idem skipjack + **15** long-line fisheries (original data on 5-deg resolution)

- **Quarterly length frequencies data**

  for each fishery by 5, 10 or 20 degree squares

Ex. Bigeye: 360,720 fishing events and 1,499 size frequency distributions

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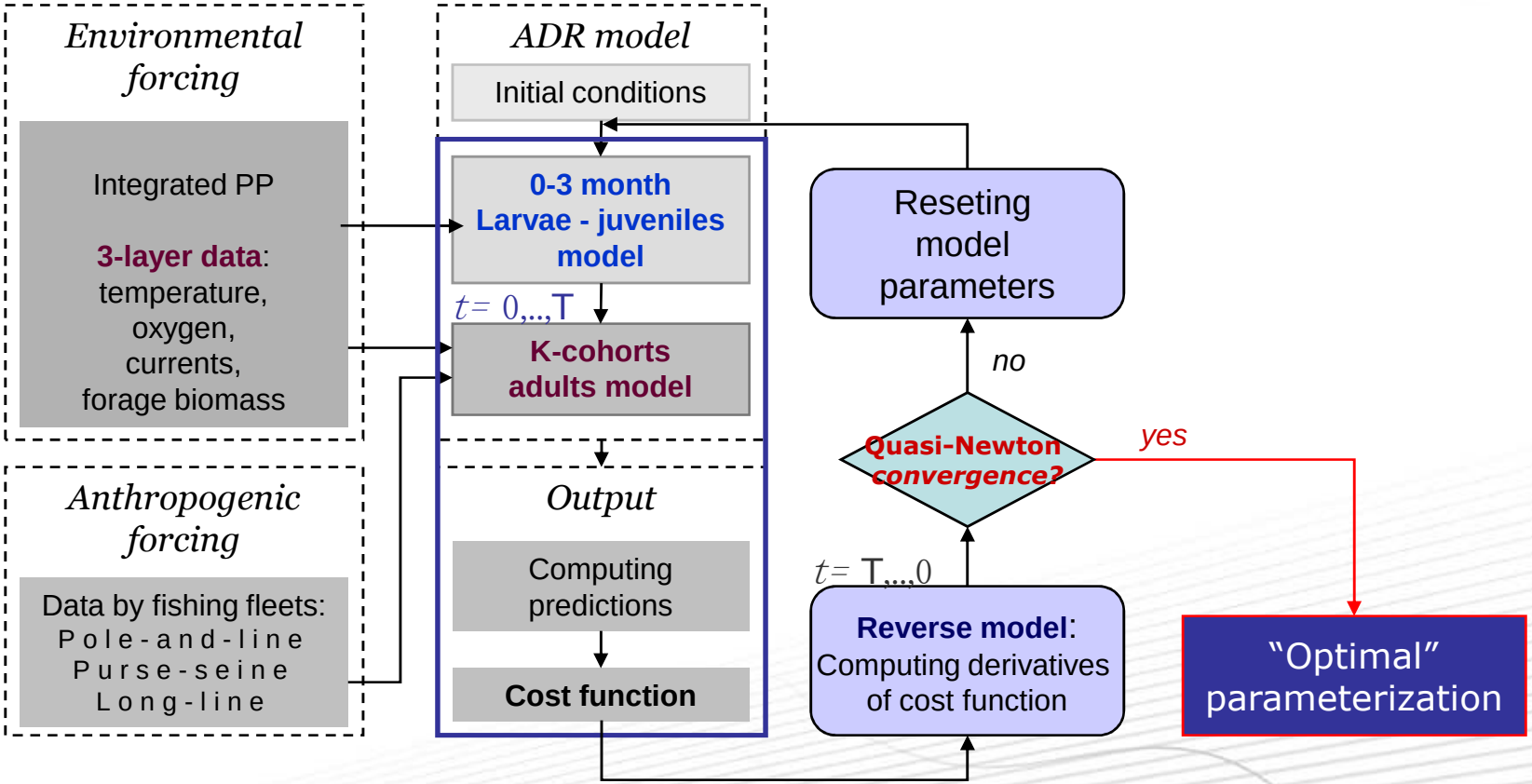
Implementation



Advantages: relatively low computational cost (doesn't depend on the dimension of parameter space), fast method convergence (~100 iterations)

Drawbacks: detection of local minima; depending on the model dimension may require large RAM size (>16Gb), otherwise temporal files will be written;

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Optimization method

Maximum likelihood approach

- Model predictions:

$$C^{pred}_{t,f,i,j} = q_f E_{t,f,i,j} \sum_{a=1}^{K} s_{f,a} w_a N_{a,i,j} \Delta x \Delta y, \quad Q^{pred}_{t,f,a,r} = \frac{s_{f,a} \sum_{i,j \in r} E_{f,i,j} N_{a,i,j} \Delta x \Delta y}{\sum_{a=1}^{K} {}_{f,a} \sum_{i,j \in r} E_{f,i,j} N_{a,i,j} \Delta x \Delta y}$$

- are being fit to observations by maximizing the likelihood function (or commonly, minimizing negative log-likelihood).

Catch likelihood:

$$-\ln L\left(\boldsymbol{\theta} \middle| C^{obs}\right) = \sum_t \sum_f C^{pred}_{t,f} - \sum_t \sum_f C^{obs}_{t,f} \ln C^{pred}_{t,f} + \sum_t \sum_f \ln(\Gamma(C^{obs}_{t,f} + 1))$$

LF likelihood:

$$-L_{LF} = \sum_{t,f,a,r} \frac{1}{2\sigma_f^2} \left(Q^{obs}_{t,f,a,r} - Q^{pr}_{t,f,a,r}\right)^2$$

Parameter scaling:

$$\theta_k = \underline{\theta_k} + \left(\overline{\theta_k} - \underline{\theta_k}\right)\left(1 + \sin\frac{\pi\theta'_k}{2}\right)$$

- **Quasi-Newton** minimization method being used requires evaluation of the gradient of cost function (*adjoint* variables) with respect to control parameters

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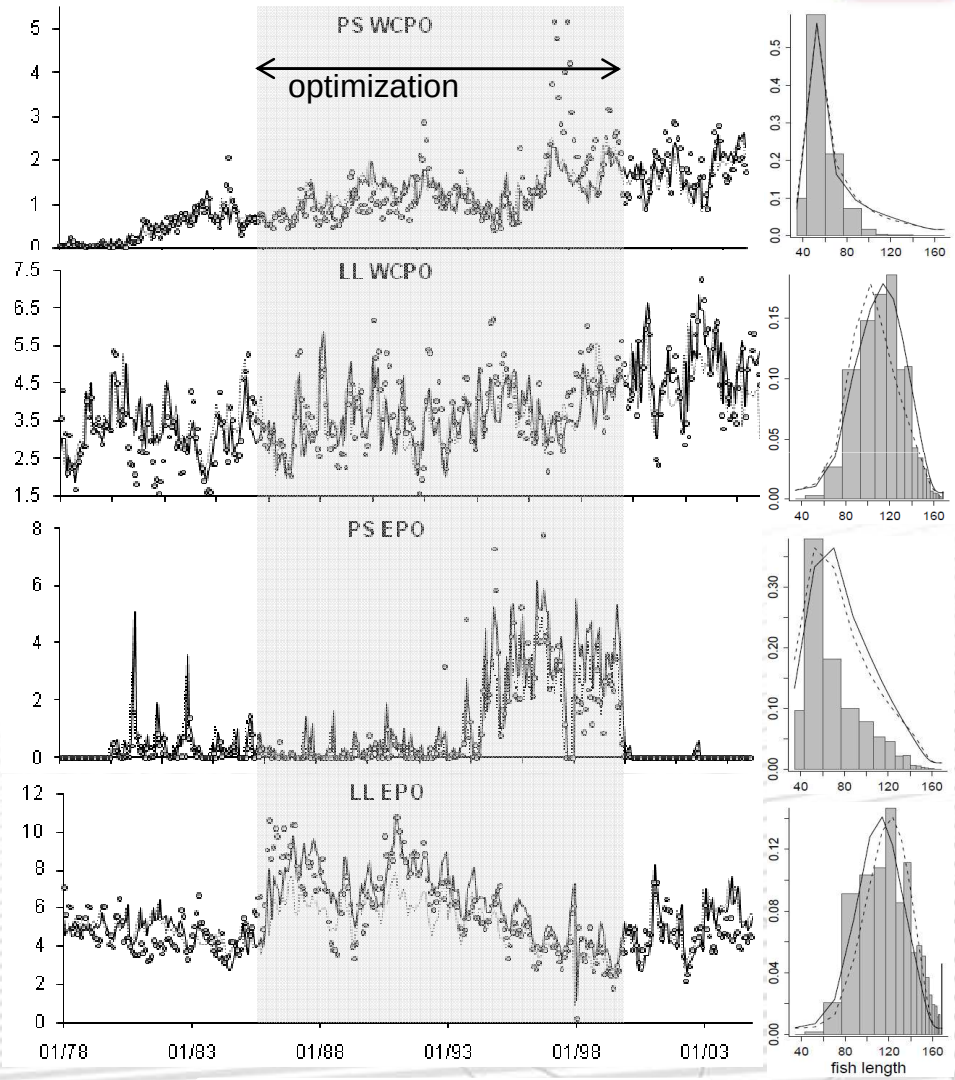
Optimal estimation of parameters

Estimated parameters (ESSIC reanalysis)

	θ	Skipjack	Bigeye
Natural mortality	β_p	0.296 ± 0.0018	0.073 ± 0.0005
	M_{max}	0.5*	0.25 ± 0.003
	β_s	-0.044 ± 0.0015	-0.097 ± 0.008
	A	31*	80.6 ± 0.008
Spawning habitat	σ_0	3.5*	0.82 ± 0.012
	T_0	30.5 ± 0.0047	26.2 ± 0.013
	α	0.1*	0.63 ± 0.02
	BH_a	0.5*	0.0045 ± 6e-4
Adult habitat	σ_a	2.62 ± 0.0015	2.16 ± 0.004
	T_a	26*	13 ± 0.004
	$\hat{O}$	3.86 ± 0.0009	0.46 ± 0.0006
	D_{max}	0.4 ± 0.005	0.22 ± 0.002
	V_{max}	1.3 ± 0.006	0.32 ± 0.002
Fishing parameters: catchabilities & selectivities			

± st.dev; * fixed



Fitting Prediction vs observation

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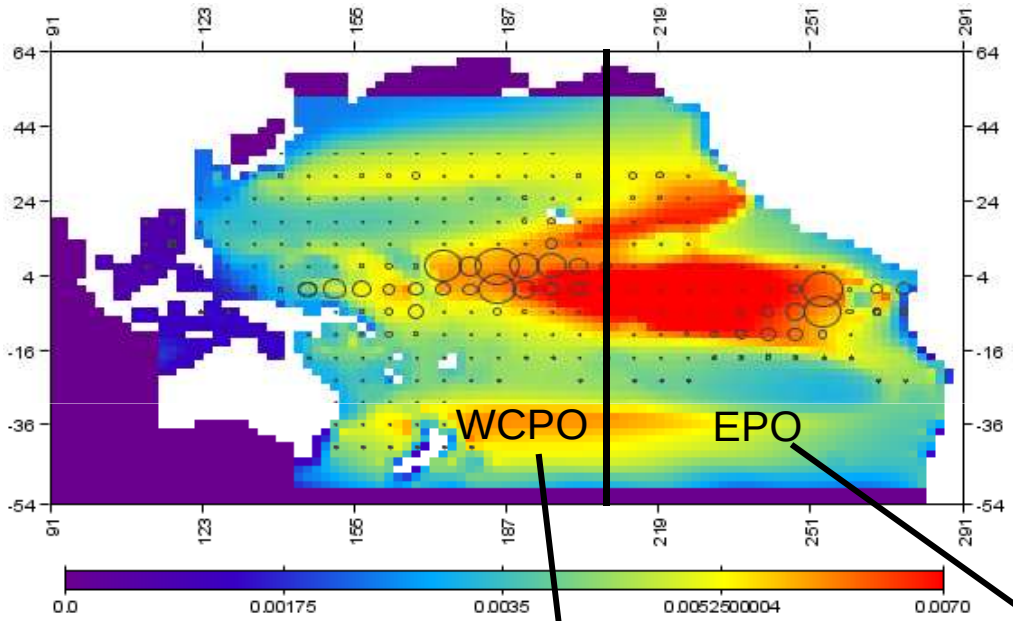
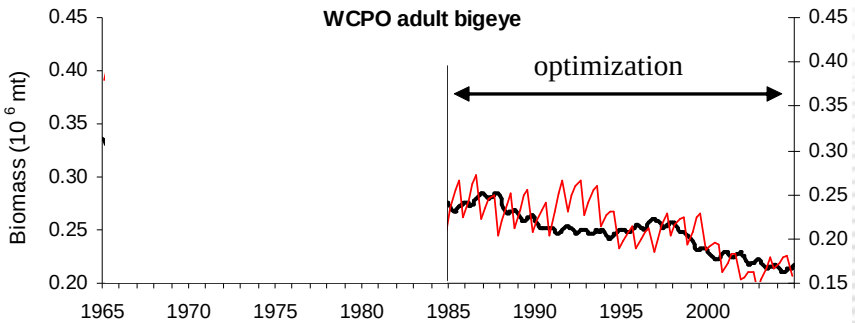
Hindcast and comparison with other estimates

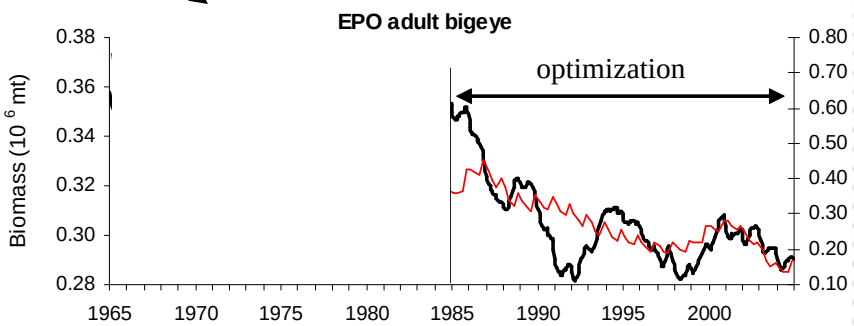
Pacific bigeye



- Predicted distribution of adult biomass and observed (circles) longline catch

Black curve: SEAPODYM
Red curve: Statistical Stock-recruitment model (MULTIFAN-CL) used by the Western Central Pacific Fisheries Commission





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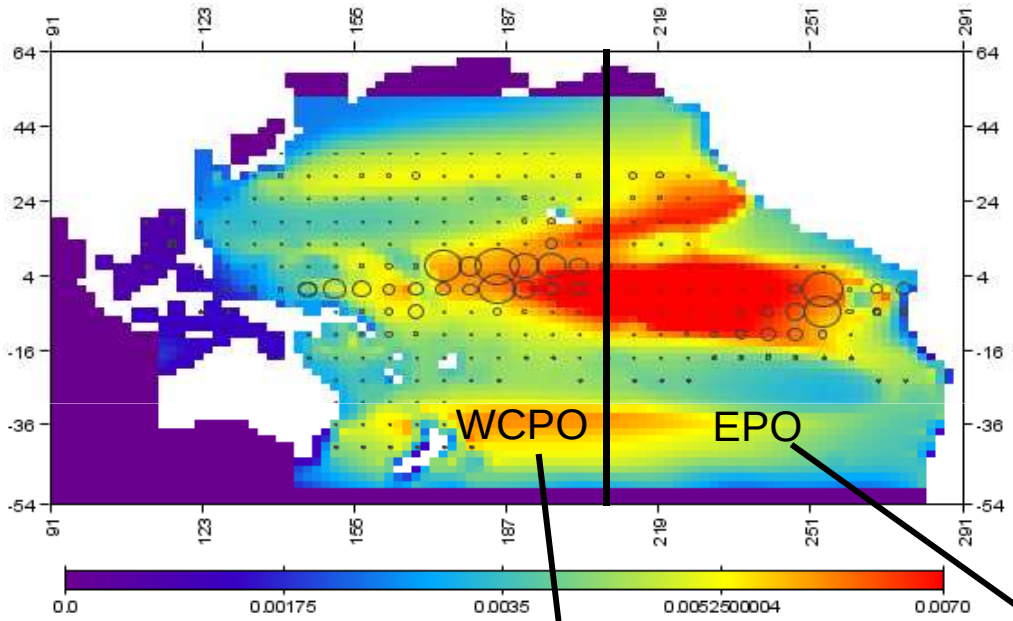
Hindcast and comparison with other estimates

Pacific bigeye



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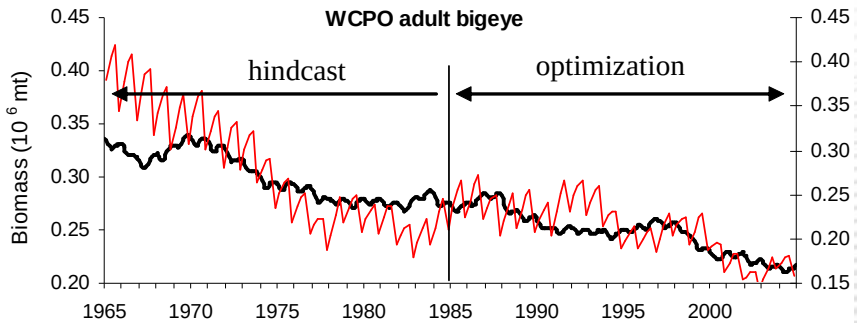

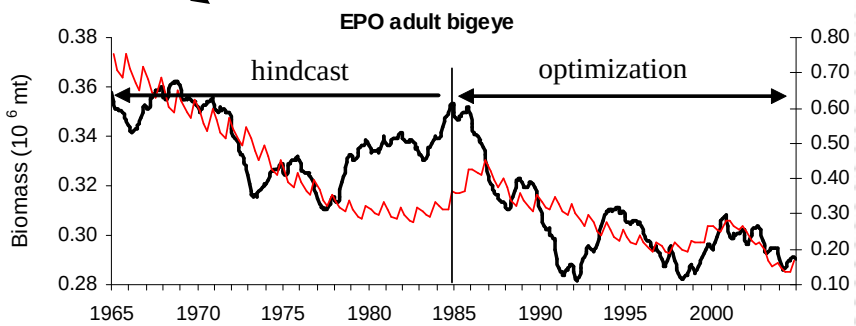

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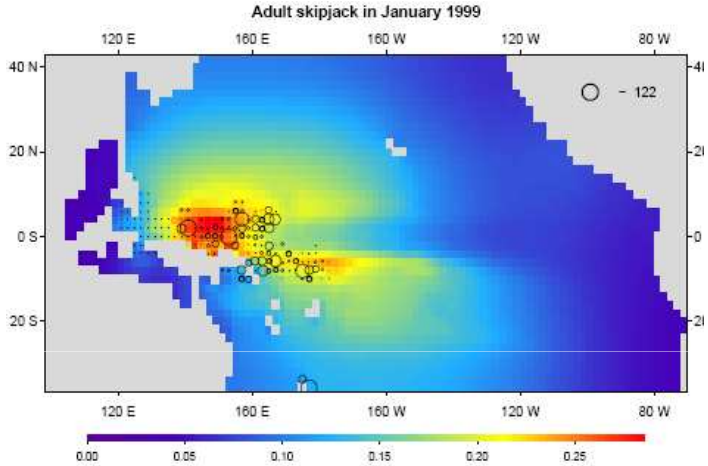
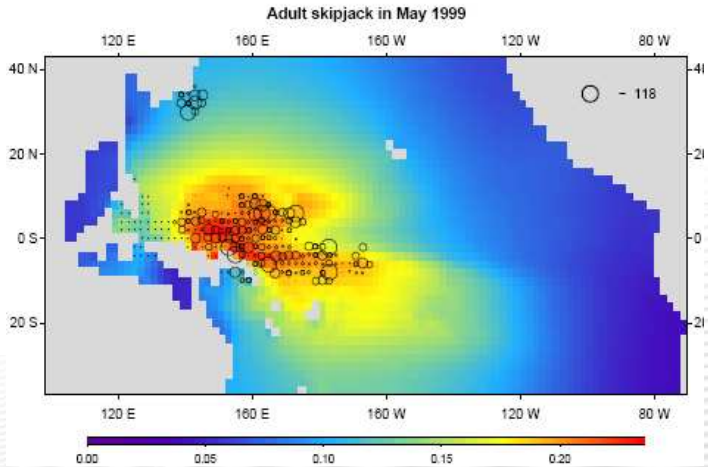
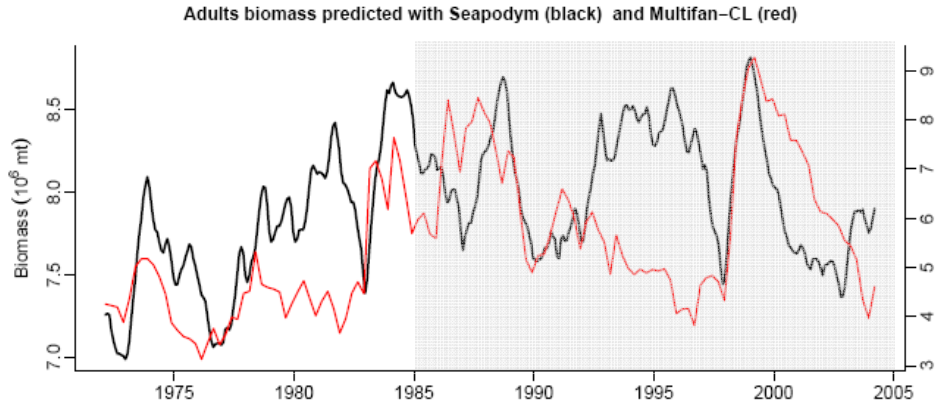
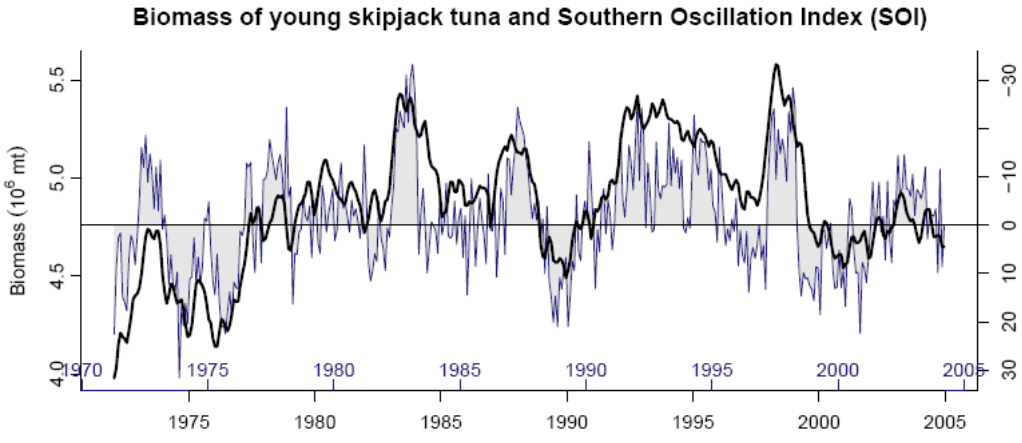
Hindcast and comparison with other estimates

Pacific Skipjack









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

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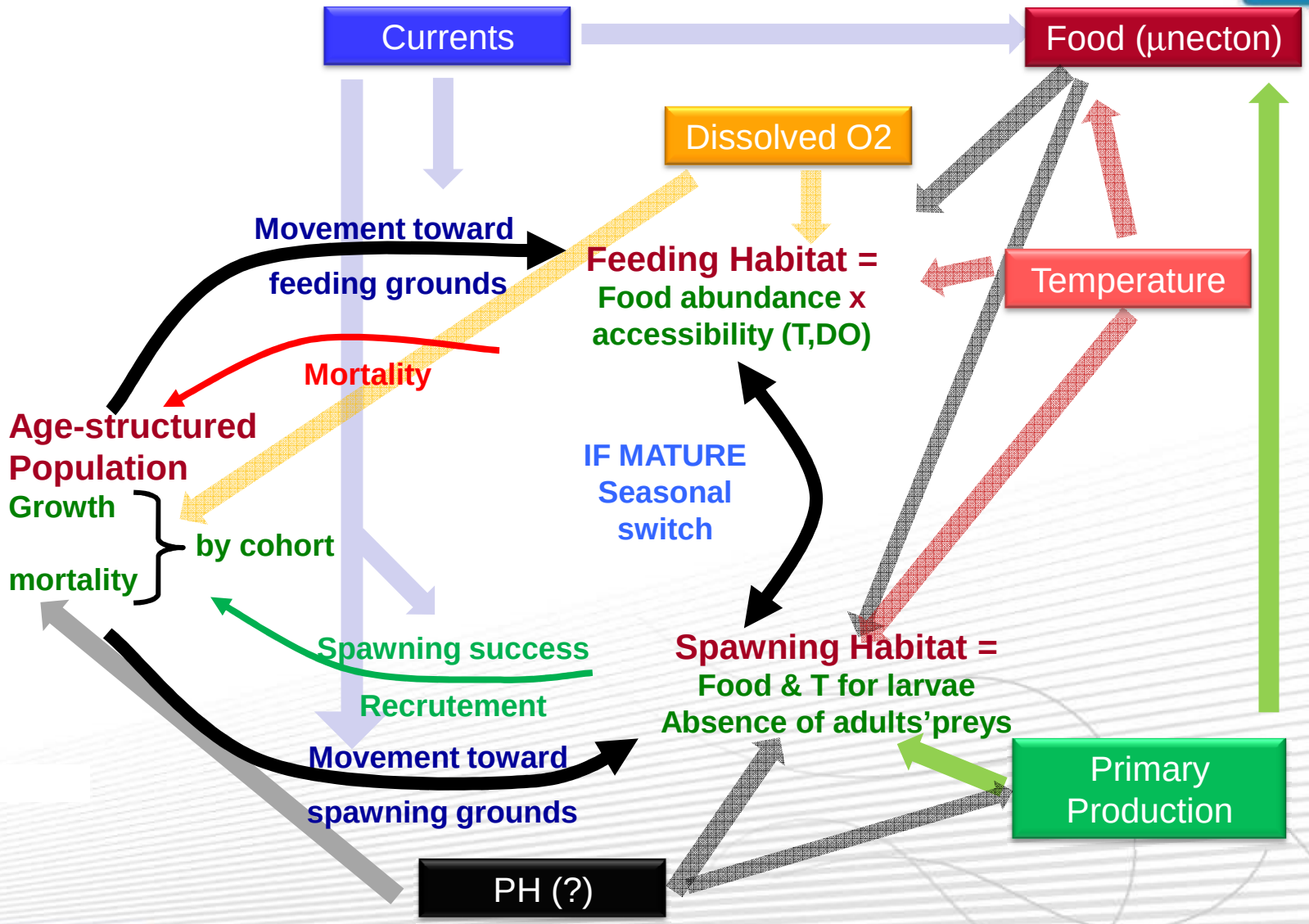
Impacts of Climate Change?



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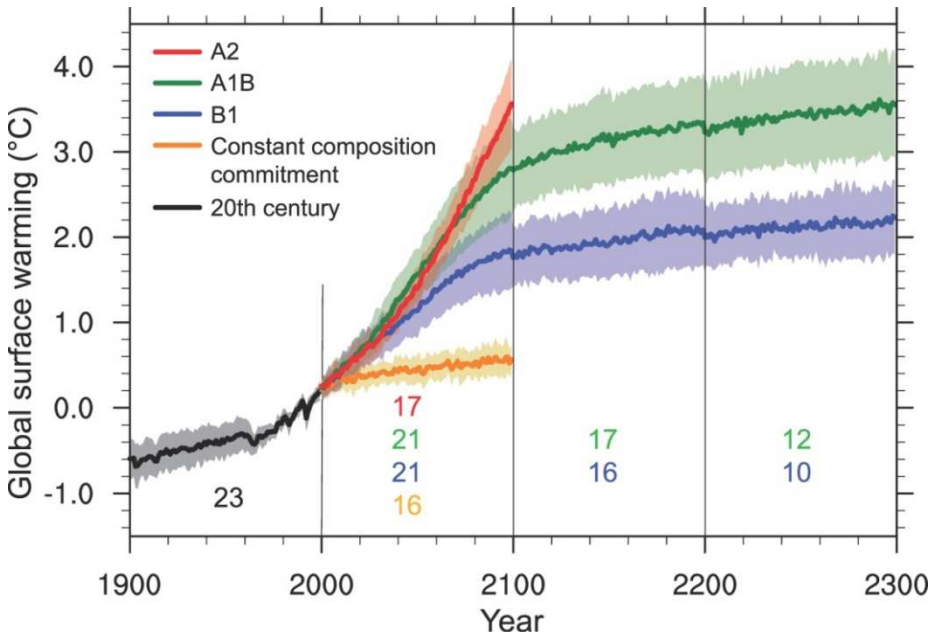
Forecast under IPCC A2 scenario



A2 scenario : PCO_2 reaches 850 ppm in 2100

IPSL Earth Climate Model

Atmospheric CO2 concentration
1860-2000 : Measured
2000-2100 : IPCC A2 scenario

Atmospheric model (*LMDZ*)

Land surface Model *(ORCHIDEE)*

Coupler (OASIS)

Ocean General circulation Model *(OPA)*

Sea-ice model (*LIM*)

Ocean Biogeochemical (NPZD) Model

This model simulates realistic seasonal, interannual and decadal variability in a **statistical sense**

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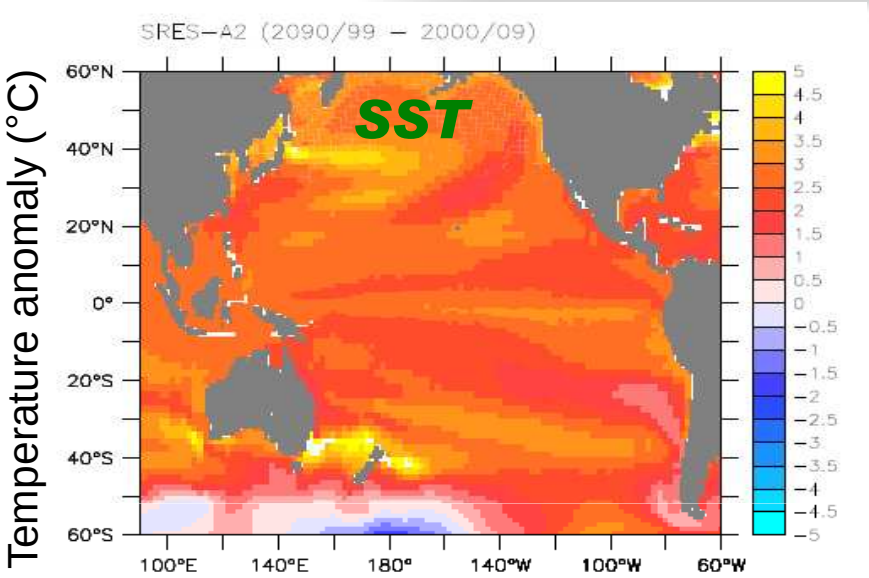
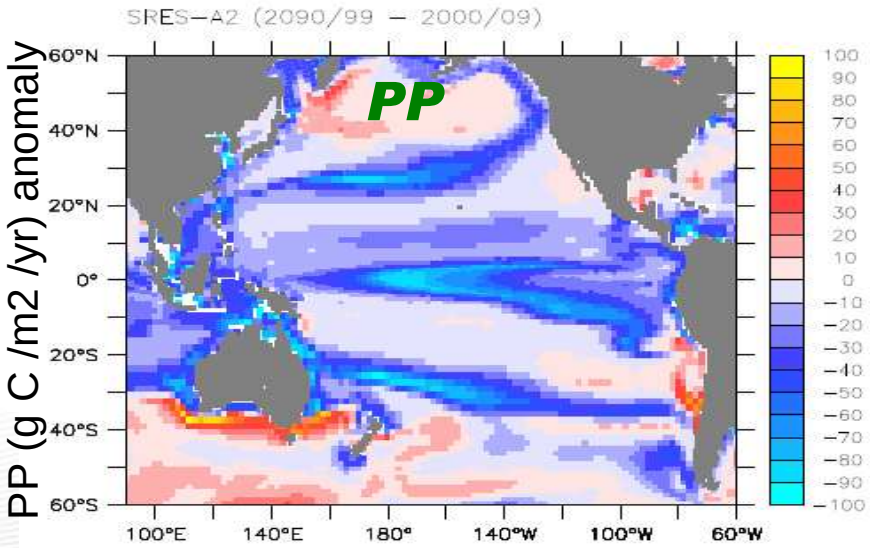
Effects of Climate Change

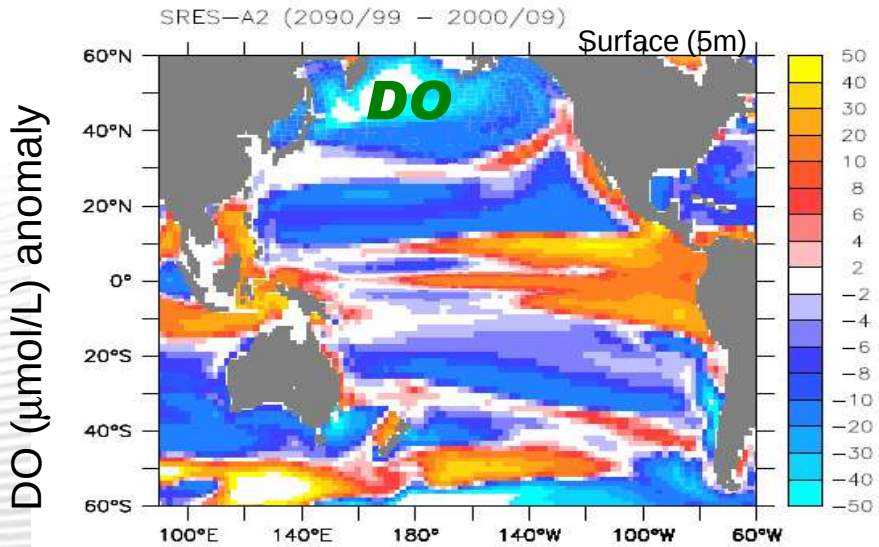


Simulated change in

SST, PP & DO

[2090/99] - [2000/09]





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Effects of Climate Change

Revising parameters optimization

Bigeye

θ	F	ESSIC	IPSL
β_p	Natural mortality	0.073	0.083
M_{max}		0.25	0.3
β_s		-0.097	-0.11
A		80.6	75.8
σ_0		0.82	**0.21**
T_0	Spawning habitat	26.2	26.5
α		0.63	0.69
BH_a		0.0045	0.009
σ_a	Adult habitat	2.16	2.74
T_a		13	**9.94**
$\hat{O}$		0.46	**1.05**
D_{max}	Movement	0.22	0.11
V_{max}		0.32	0.4
Fishing parameters			

Skipjack

θ	F	ESSIC	IPSL
β_p	Natural mortality	0.296	0.1
M_{max}		0.5*	0.5*
β_s		-0.044	-0.1
A		31*	31*
σ_0	Spawning habitat	3.5*	3.5*
T_0		30.5	29.5
α		0.1*	0.1*
BH_a		0.5*	0.5*
σ_a	Adult habitat	2.62	2.1
T_a		26*	26*
$\hat{O}$		3.86	**5.46**
c	Movement	0.4	0.27
V_{max}		1.3	0.95
Fishing parameters			

The estimated biology reflects the environment

Bigeye has a long life span and extended habitat strongly influenced by seasonal variability, facilitating the revision of parameters with CC simulation

Skipjack has a short life-span, with equatorial core habitat influenced by ENSO variability: it is more difficult to revise parameters optimisation with CC simulation

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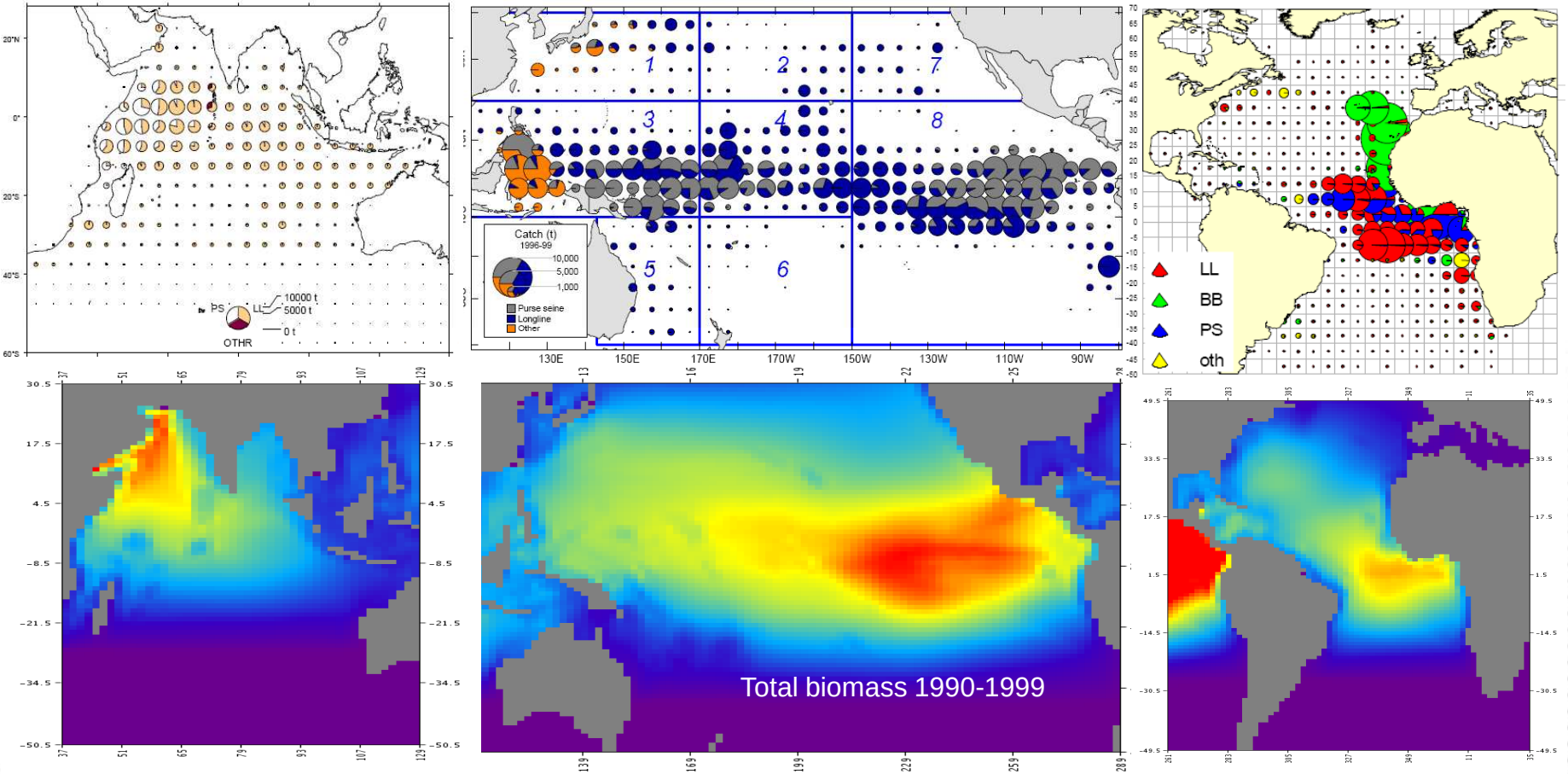
Effects of Climate Change

BIGEYE: Global average predicted distribution



model gives superficially realistic predictions in other oceans using parameters estimated from Pacific populations

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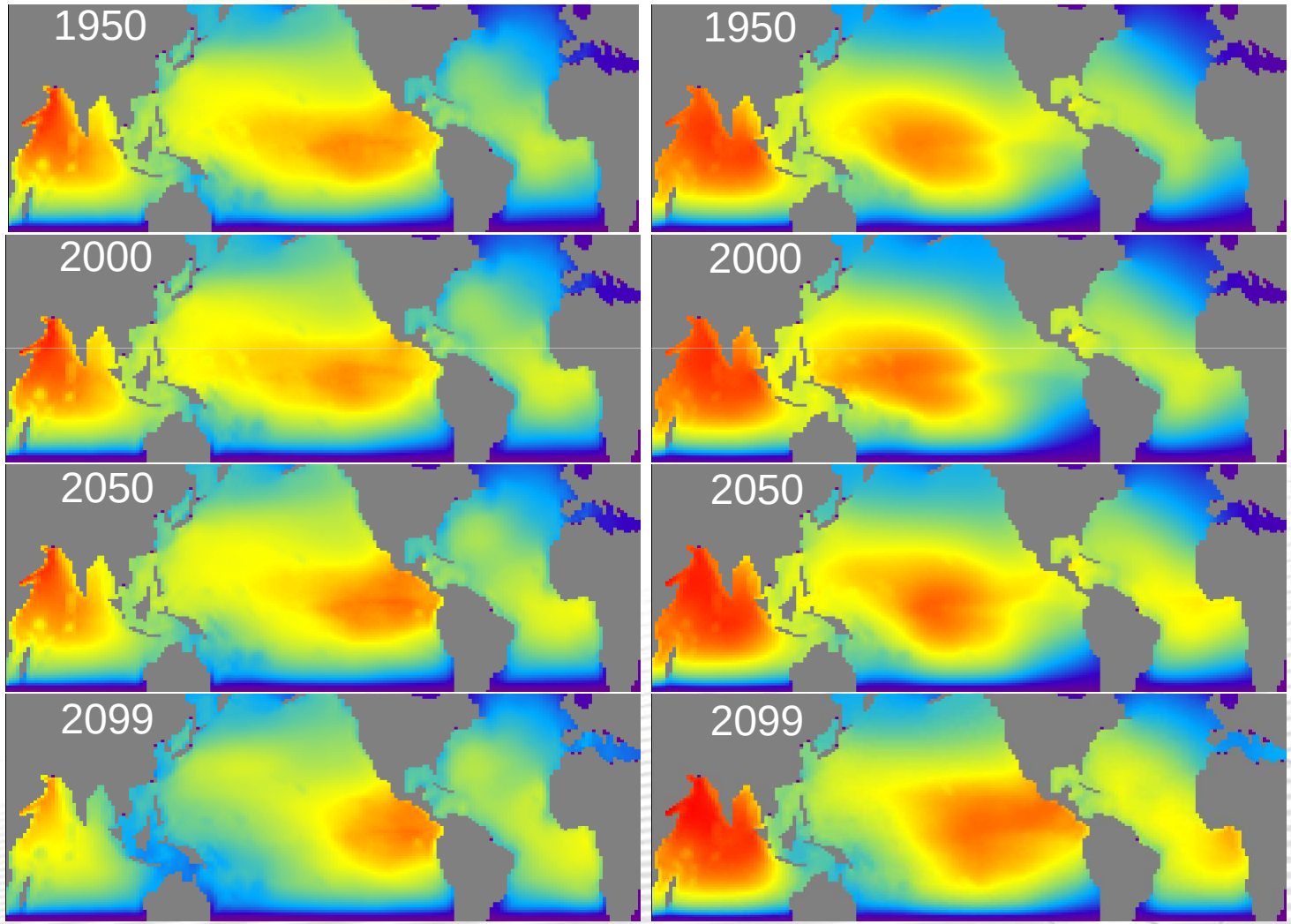
Forecast using IPSL forcing

Bigeye

Skipjack

Adults biomass distribution



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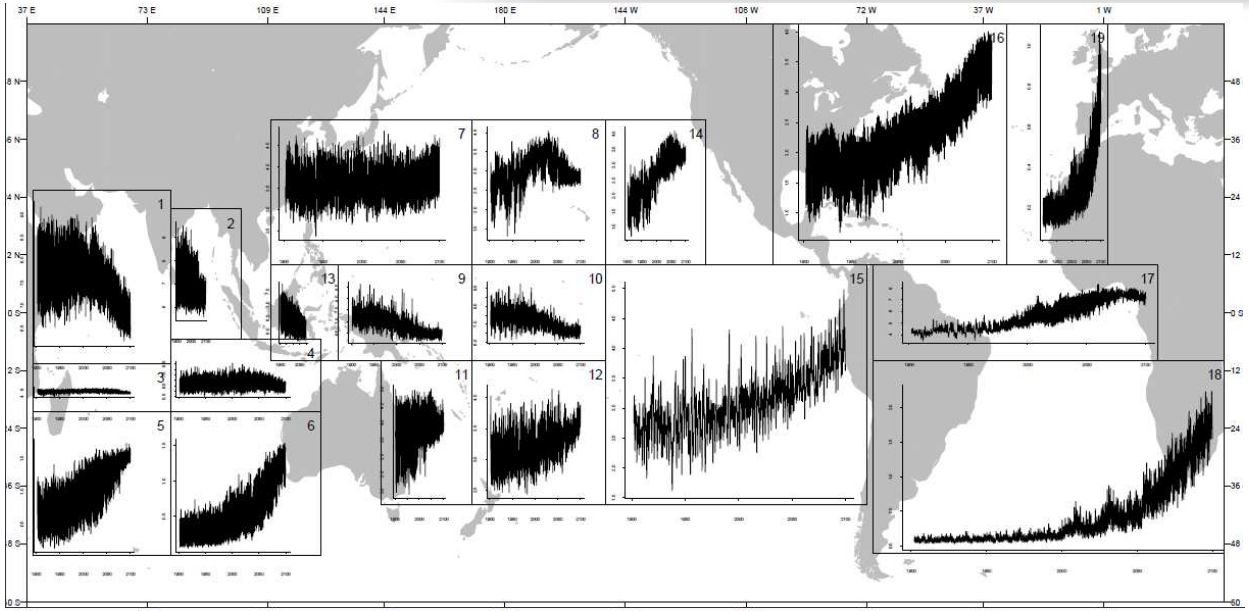
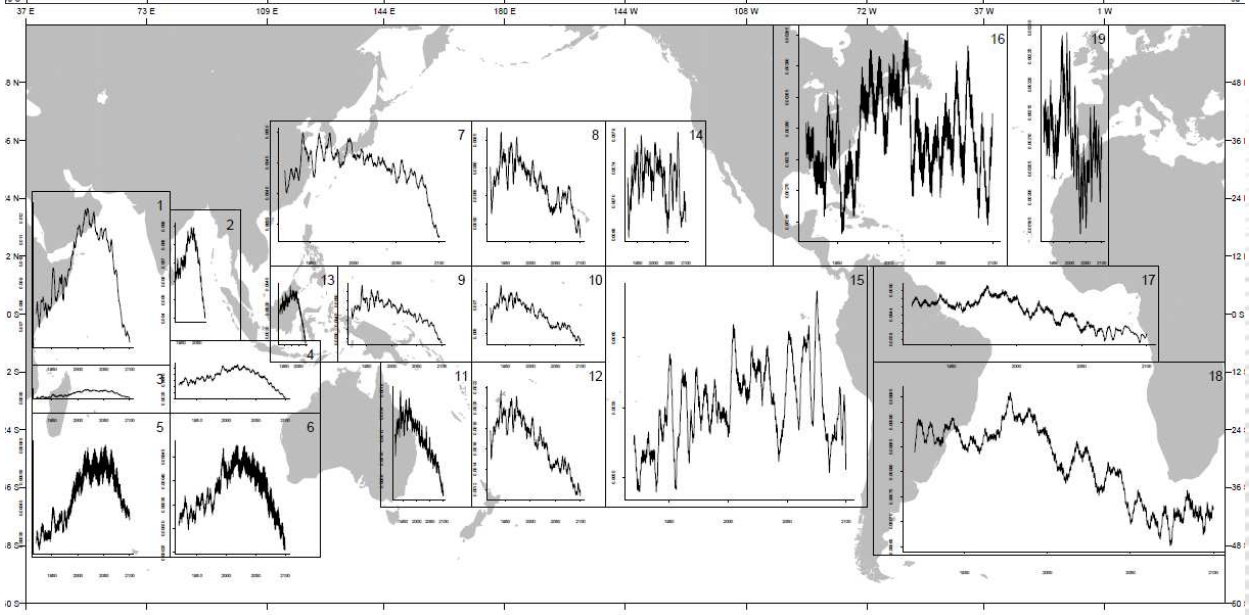
Forecast using IPSL forcing



Larvae biomass

Bigeye

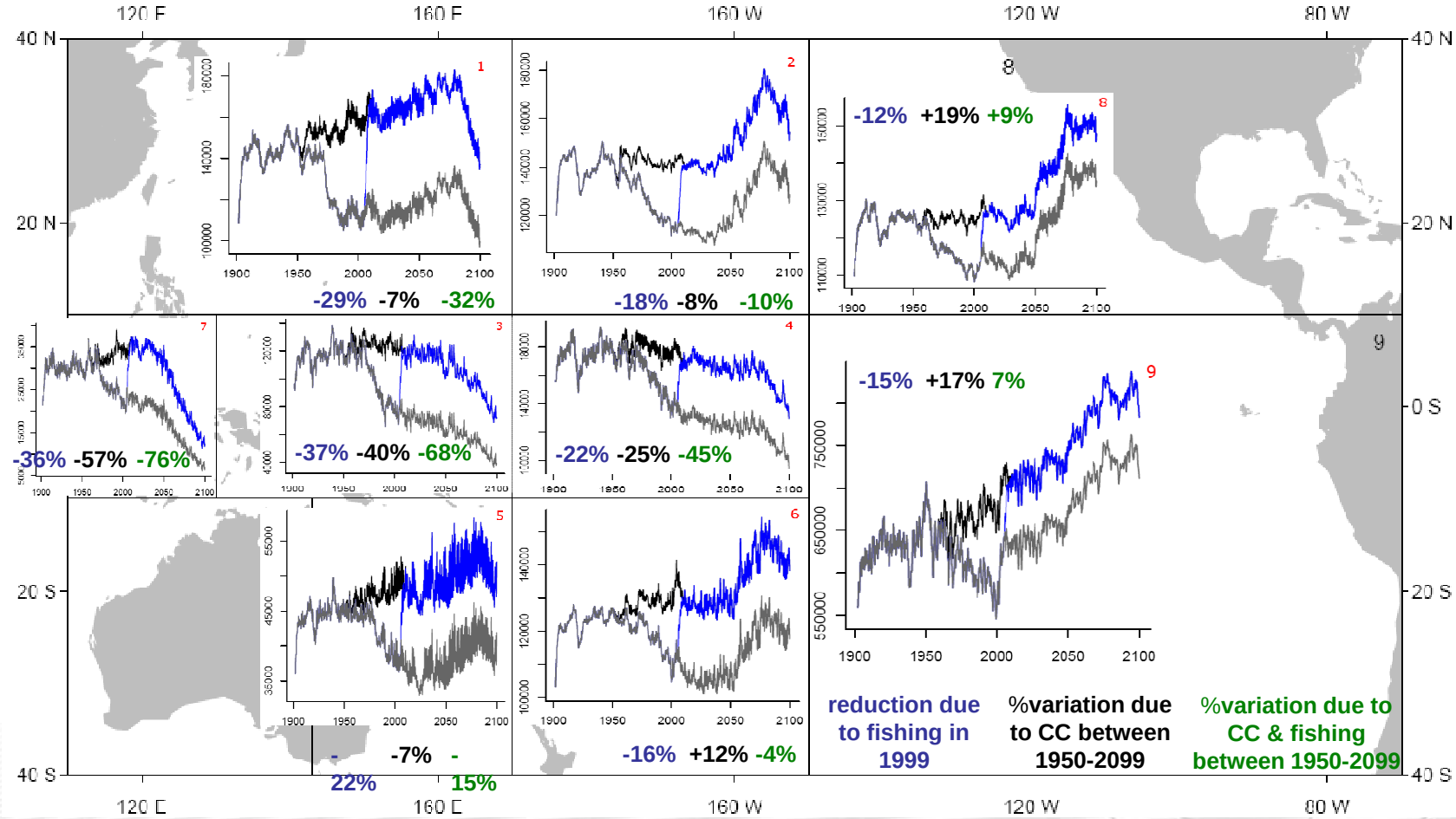


Adult biomass

NO FISHING !!

Climate vs (wrong) fishing impact

Projection with average 1995-2000 fishing effort



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Conclusion: Model

- ✓ An end-to-end marine ecosystem & stock assessment model (ESAM?) has been developed and validated
- ✓ It is ready to use for various applications for tuna species (from stock management to impact studies, seasonal forecast & climate change simulations)
- ✓ Within an ongoing project (French ANR PEPS: Peru Ecosystem Projection Scenarios), we are developing a version for small pelagics (i.e., sardine and anchovy) based on ROMS+PISCES
- ✓ Though it is a multi-species model, optimization with several species and higher resolution requires code parallelization
- ✓ Possible evolution of the model with a fitness index, based on physiology & energy budget, associated to each cohort and varying in time and space
- ✓ Coupling NPZD and M (mid-trophic level) to investigate the feedback (zooplankton mortality, detritus)?

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Conclusion: Mechanisms (ex. Bigeye)

CC simulation suggests:

• Change in spawning habitat. Improving both in subtropical latitudes and in the eastern tropical Pacific (ETP) where the surface temperature becomes optimal for bigeye tuna spawning.

• Change in feeding habitat. Also improving in the ETP due to the increase of dissolved oxygen concentration allowing adults to access deeper forage.

• Conversely, in the Western Equatorial Pacific the temperature becomes too warm in the equatorial region for bigeye spawning.

• This is compensated by an increase of larvae biomass in subtropical regions, but …

• … increasing mortality of older stages due to lower habitat values (too warm temperature in surface, decreasing oxygen concentration in sub-surface, and less food), and displacement of surviving fish to the eastern region led to stable (without fishing!) then declining adult biomass at the end of the Century.

• Each Ocean has its own response!

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Conclusion: data and forcing fields

• Data assimilation! Fishing data but also: Acoustic data for the Mid-Trophic level model or for biomass estimates of the focus species, archival and conventional tagging data, larvae density (e.g. small pelagics)

• Field studies and lab experiments for independent validation of key parameter values, testing genetic plasticity, and new CC issues (pH).

• As realistic as possible reanalyses of physical and biogeochemical environment .

• More realistic CC model outputs with higher resolution. Ideally, CC runs should combine a realistic historical period (forced with atmospheric reanalysis ??) to help in data assimilation process and evaluation, and then forcing with IPCC scenarios

•Realistic projection of fishing effort (fleets dynamic + economical models)

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Thank you for the invitation to attend this workshop

More details in :

Lehodey P., Senina I., & Murtugudde R. (2008). A Spatial Ecosystem And Populations Dynamics Model (SEAPODYM) - Modelling of tuna and tuna-like populations. *Progress in Oceanography,* 78: 304-318.

Senina I., Sibert J., & Lehodey P. (2008). Parameter estimation for basin-scale ecosystem-linked population models of large pelagic predators: application to skipjack tuna. *Progress in Oceanography*, 78: 319-335.

Lehodey P., Murtugudde R., Senina I. (*accepted*). Bridging the gap from ocean models to population dynamics of large marine predators: a model of mid-trophic functional groups. *Progress in Oceanography.* Special issue of the EUR-OCEANS conference "Parameterisation of Trophic Interactions in Ecosystem Modelling", 20-23 March 2007, Cadiz, Spain.

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.* Special issue of the 1st international CLIOTOP Symposium, La Paz, Mexico, 3-7 Dec 2007

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