A spatially-explicit population dynamics and stock assessment model driven by environmental variables

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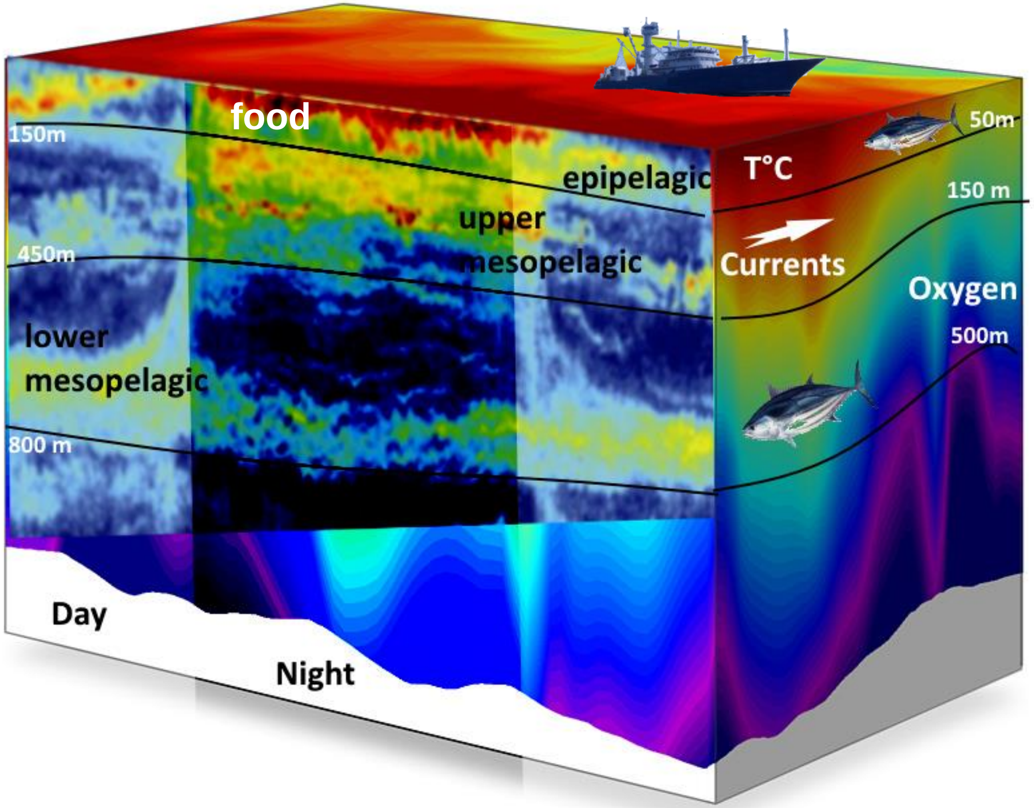
SEAPODYM introduction

Spatial Ecosystem And Population Dynamics Model



An hybrid modeling framework to combine:

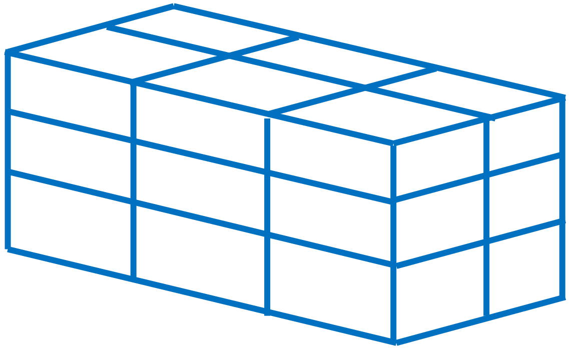
- the progress in ecological sciences to describe ocean pelagic ecosystem and species habitats and behaviour;
- The progress in ocean (physical and biogeochemical) modeling;
- the progress achieved in stock assessment models for quantitative estimation of population dynamics parameters models (MLE).

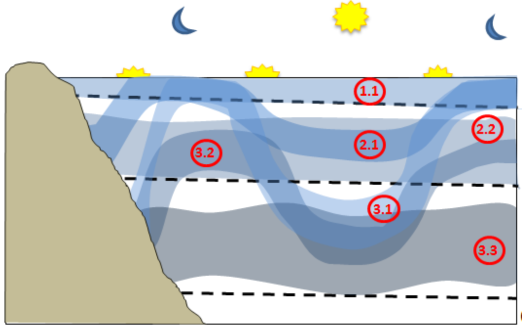
SEAPODYM introduction

Spatial Ecosystem And Population Dynamics Model

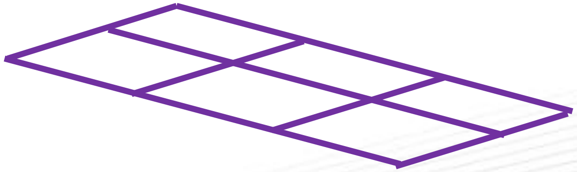
2D - 3-layer environment:

T°, U&V, PP, Zeu, O2, Zoo, μnekton





habitats + movements
Integrated over
day-night conditions
in the 3 vertical layers

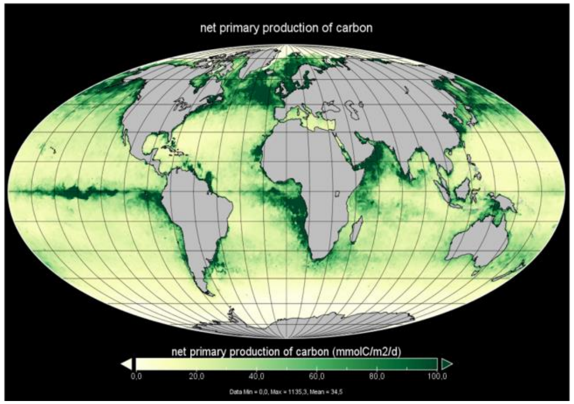


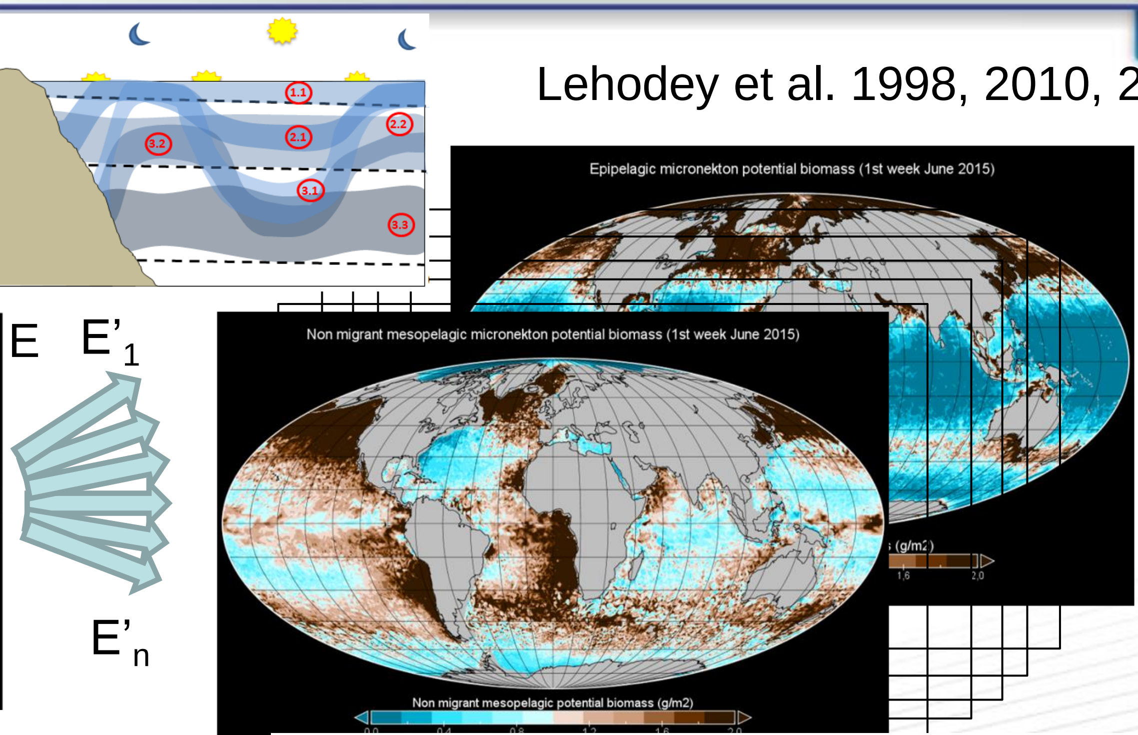
2D – fish population dynamics (ADR)
+ fisheries & parameter estimation
(spatial resolution from 2° to 9 km)

Micronekton (forage)

Lehodey et al. 1998, 2010, 2015

Temperature; currents
Primary production

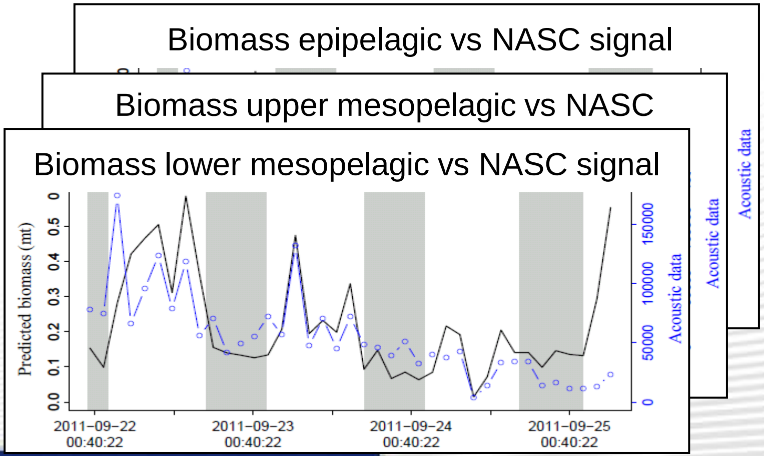


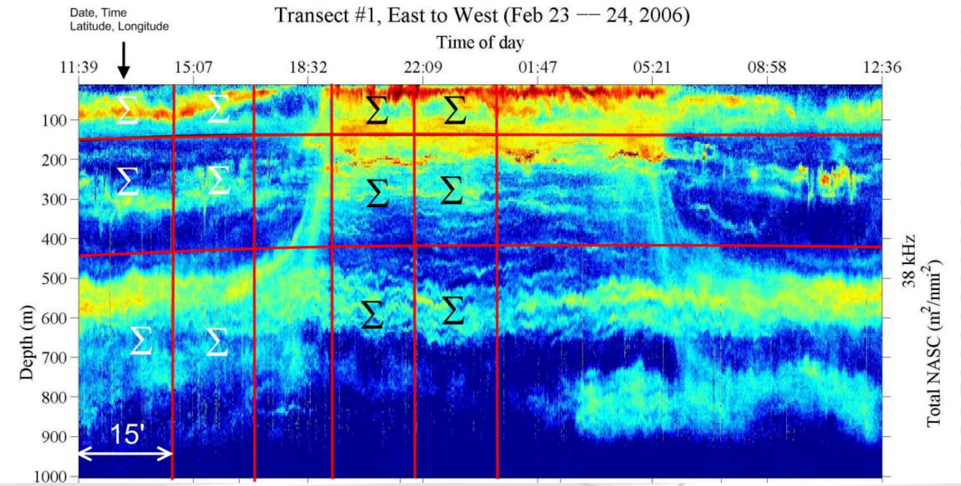


Biomass epipelagic vs NASC signal

Biomass upper mesopelagic vs NASC

Biomass lower mesopelagic vs NASC signal





Outline

I - SEAPODYM Fish spatial dynamics modelling

- Feeding Habitat
- Movement
- Spawning habitat and recruitment

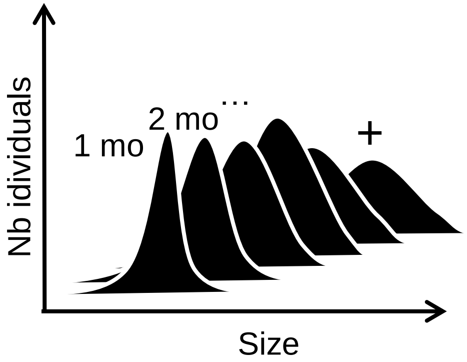
II - Applications to tuna

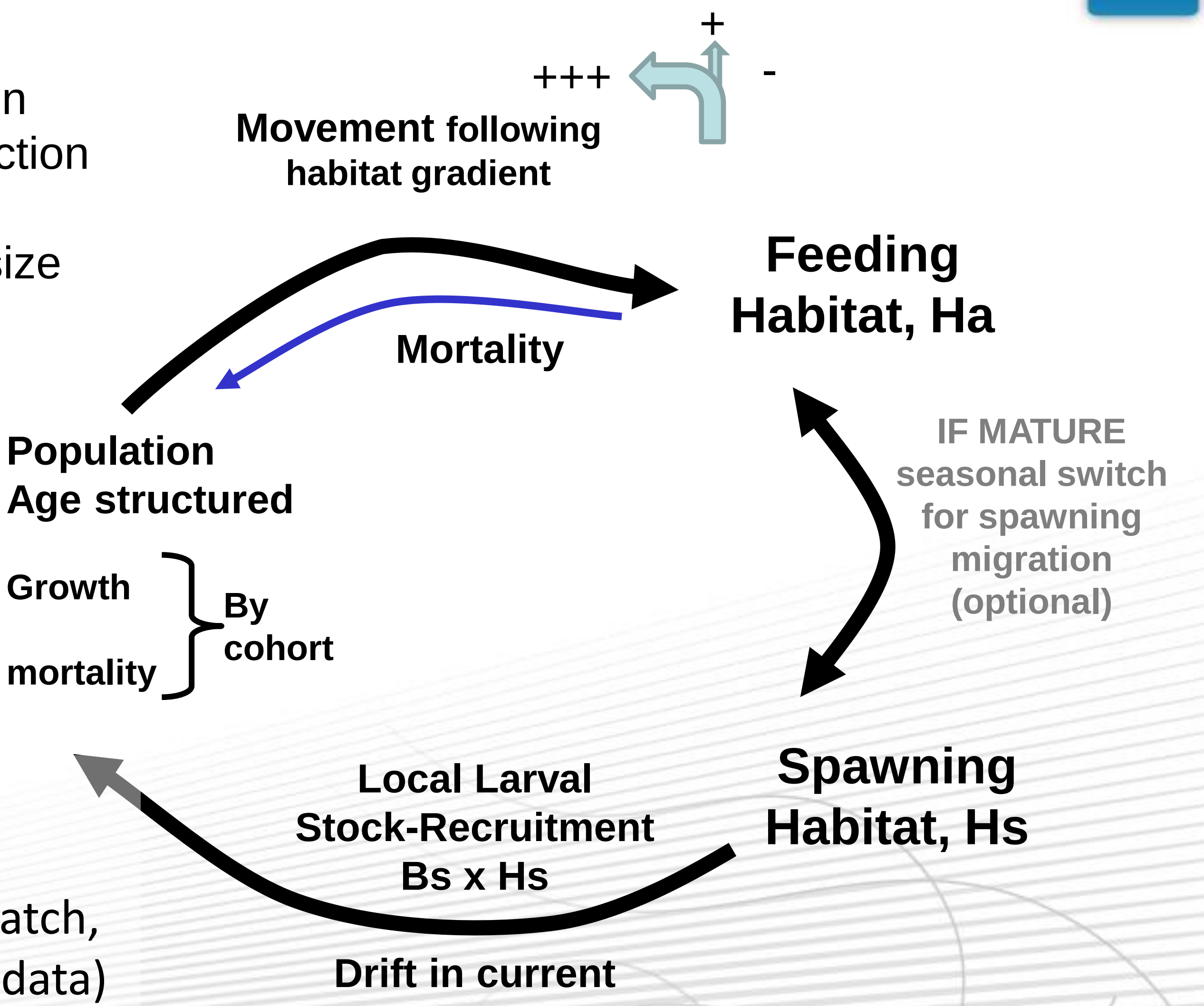
- Parameters and stock estimates
- Environmental variability
- Impact of Climate change

SEAPODYM-Fish

ADR (*Da*,*Ua*, *R*, *Za*)

Spatial dynamics based on advection - diffusion - reaction equations
with movement ∝ to fish size and habitat





+++
+
-

Movement following habitat gradient

Feeding Habitat, Ha

Mortality

Population Age structured

Growth

mortality

By cohort

IF MATURE seasonal switch for spawning migration (optional)

Spawning Habitat, Hs

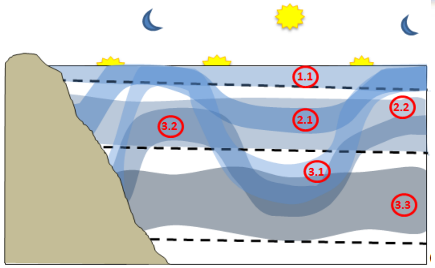
Local Larval Stock-Recruitment Bs x Hs

Drift in current

Model parameter Estimation (MLE)
(spatially-disaggregated catch, size, acoustic and tagging data)

SEAPODYM-Fish Feeding Habitat

Ha= index accounting for the abundance of different groups of forage and their accessibility in the vertical layer inhabited (day and night changes)



Biomass in layer *z* due to non-migrant group

Biomass in layer *z* due to migrant groups present during the day (τ)

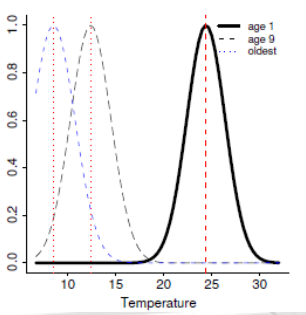
Biomass in layer *z* due to migrant groups present during the night (1-τ)

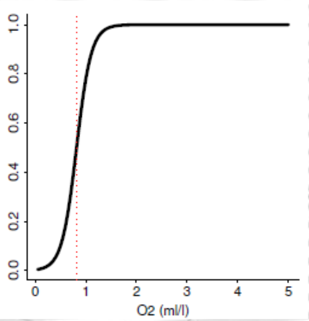
$$H_a = \sum_{z=1}^{3} \Theta_{a,z} \left(F_{zz} + \tau \sum_{k \neq z} F_{zk} + (1-\tau) \sum_{k \neq z} F_{kz} \right)$$

$$\begin{pmatrix} F_{11} & 0 & 0 \\ F_{21} & F_{22} & 0 \\ F_{31} & F_{32} & F_{33} \end{pmatrix}$$

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

Coefficient of accessibility in the concerned layer as a function of oxygen and temperature

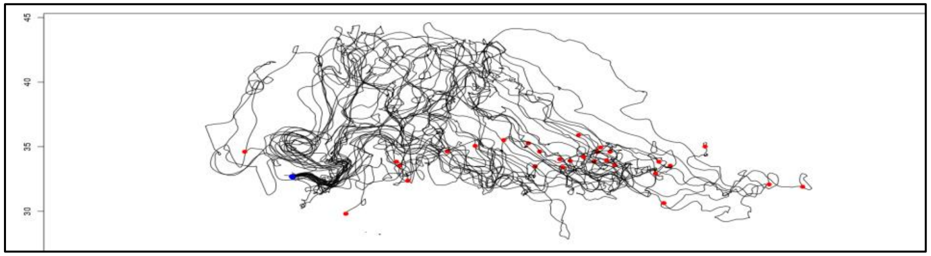




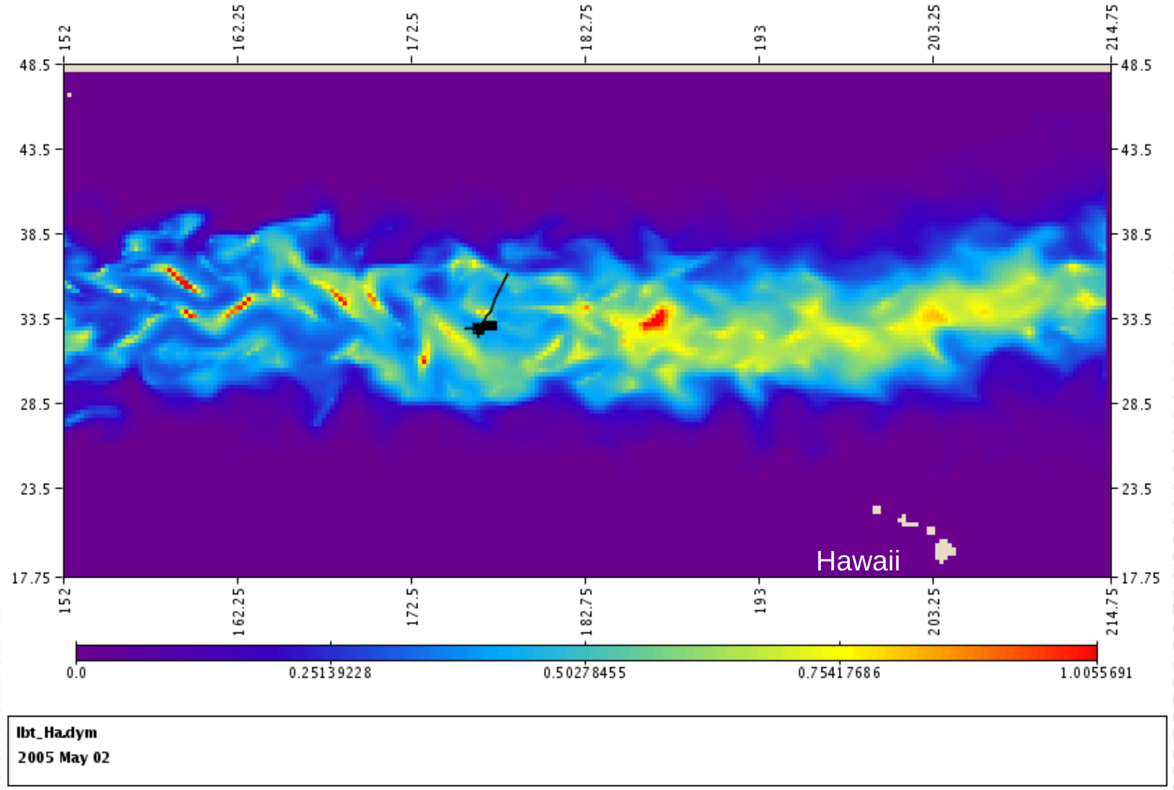
SEAPODYM-Fish Feeding Habitat

Feeding habitat of loggerhead turtles

One-year displacements of 29 ind. released in May 2005 (final position = red dots)



(Abécassis et al 2013)

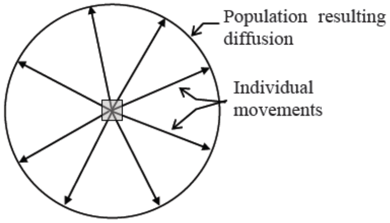


SEAPODYM - Fish Movement

Rules of movements (D_a, U_a V_a) based on H_a

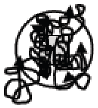
Habitat is null (no gradient)

Diffusion rate is maximum
Advection minimum



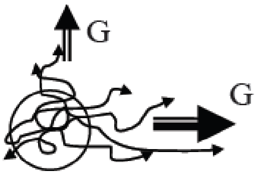
Habitat is high (no gradient)

Diffusion rate is minimum
Advection minimum



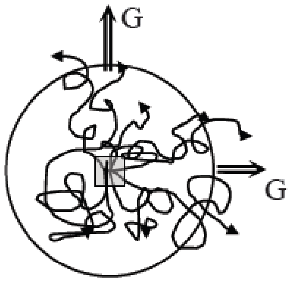
Habitat is low (high gradient)

Diffusion rate is low
Advection is high

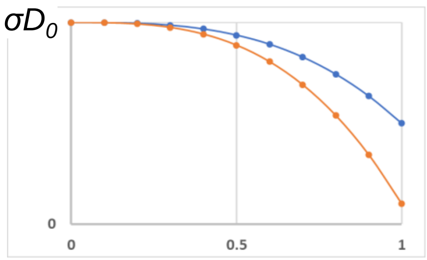


Habitat is medium (gradient)

Diffusion % with Habitat value
Advection % with Habitat gradient



Diffusion: $D_a = \sigma D_0(1 - cH_a^3)$



D_0: mean theoretical diffusion rate for a null habitat

D_0(a)= $\bar{V}_a^2 \frac{\Delta t}{4}$ $\quad \bar{V}_a = L_a s^{-1}$

2 parameters: σ and c

Advection: Passive (currents) + active (swimming)

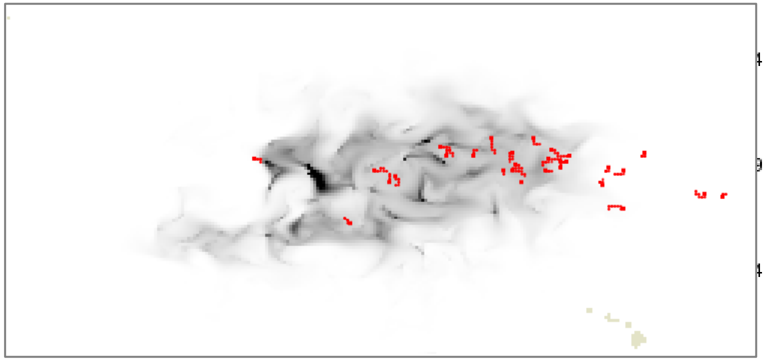
$$U_a = \hat{u} + \chi_a \frac{\partial H_a}{\partial x}, \; V_a = \hat{v} + \chi_a \frac{\partial H_a}{\partial y},$$

$$\chi_a = V L_a{}^A$$

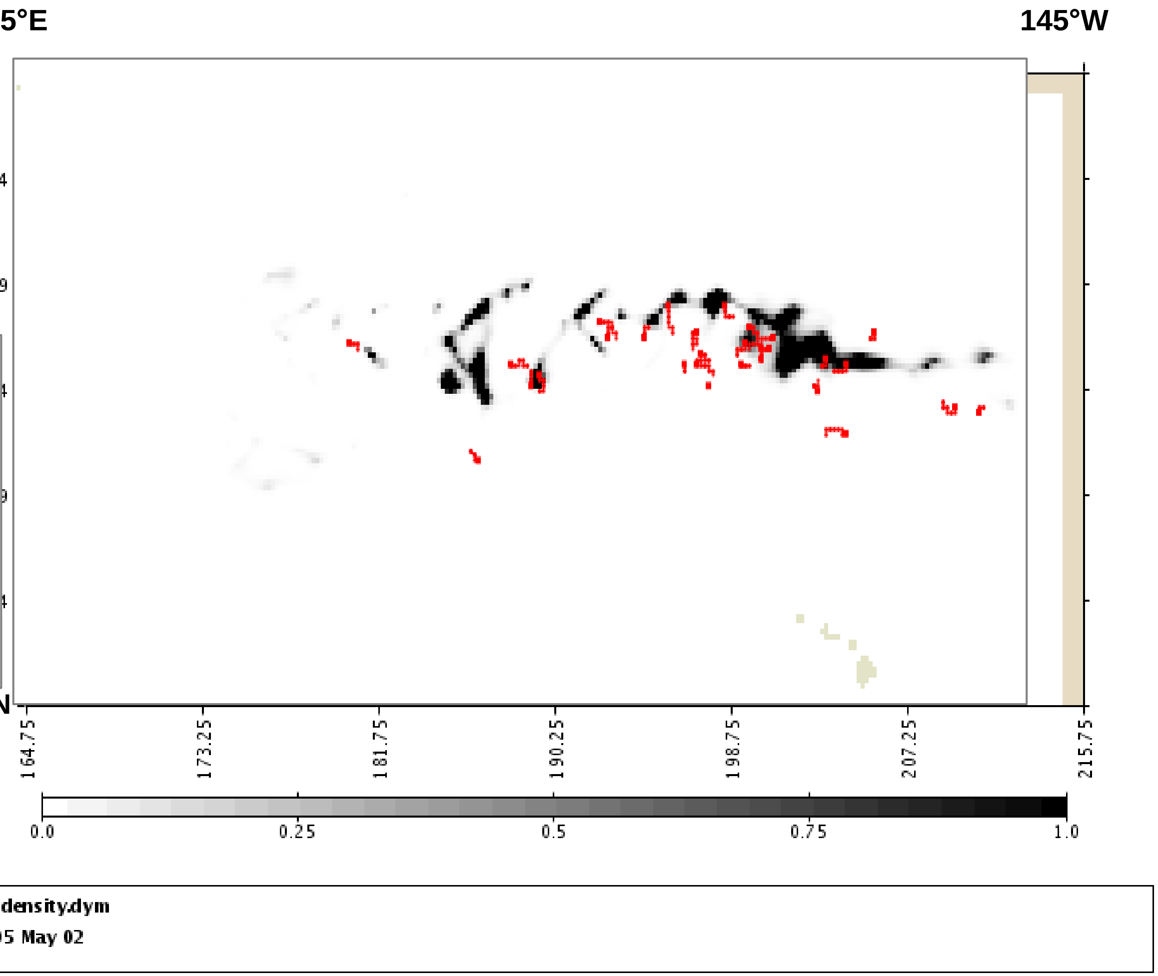
2 parameters
- V: velocity (BL/s) at maximal habitat gradient
- A: slope coefficient

ONLY 4 parameters to define the movement of all cohorts

SEAPODYM - Fish Movement



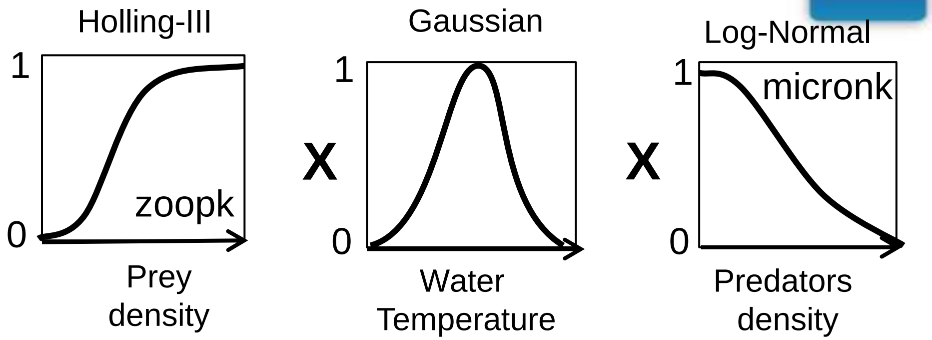
Predicted distribution after one year using passive drift with currents only



SEAPODYM Fish - Spawning & Recruits

Spawning habitat H_s

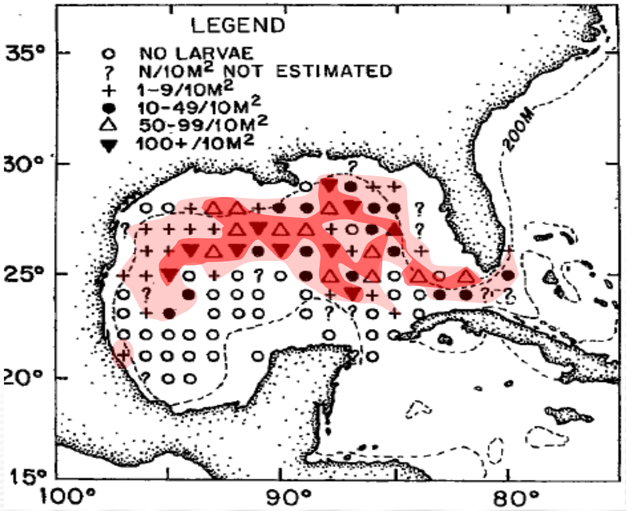
$$H_s = f_1(prey)\ f_2(T°)\ f_3(predator)$$



Larvae recruits $N(0,t,x)$

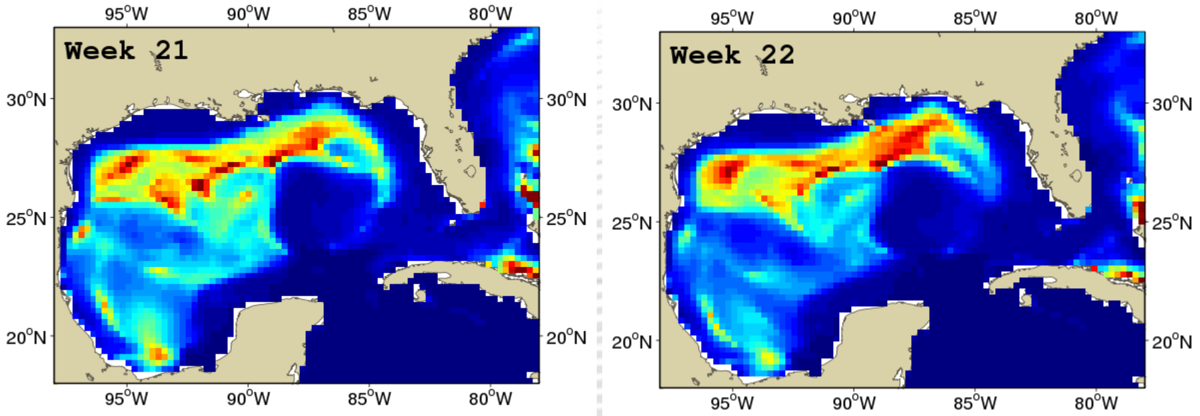
$$N(0,t,x) = H_s \frac{R\hat{N}}{1+b\hat{N}}$$ with $\hat{N}$ Number of mature fish

Then recruited larvae drift with currents; Average mortality coefficient + a range of variability ∝ Hs

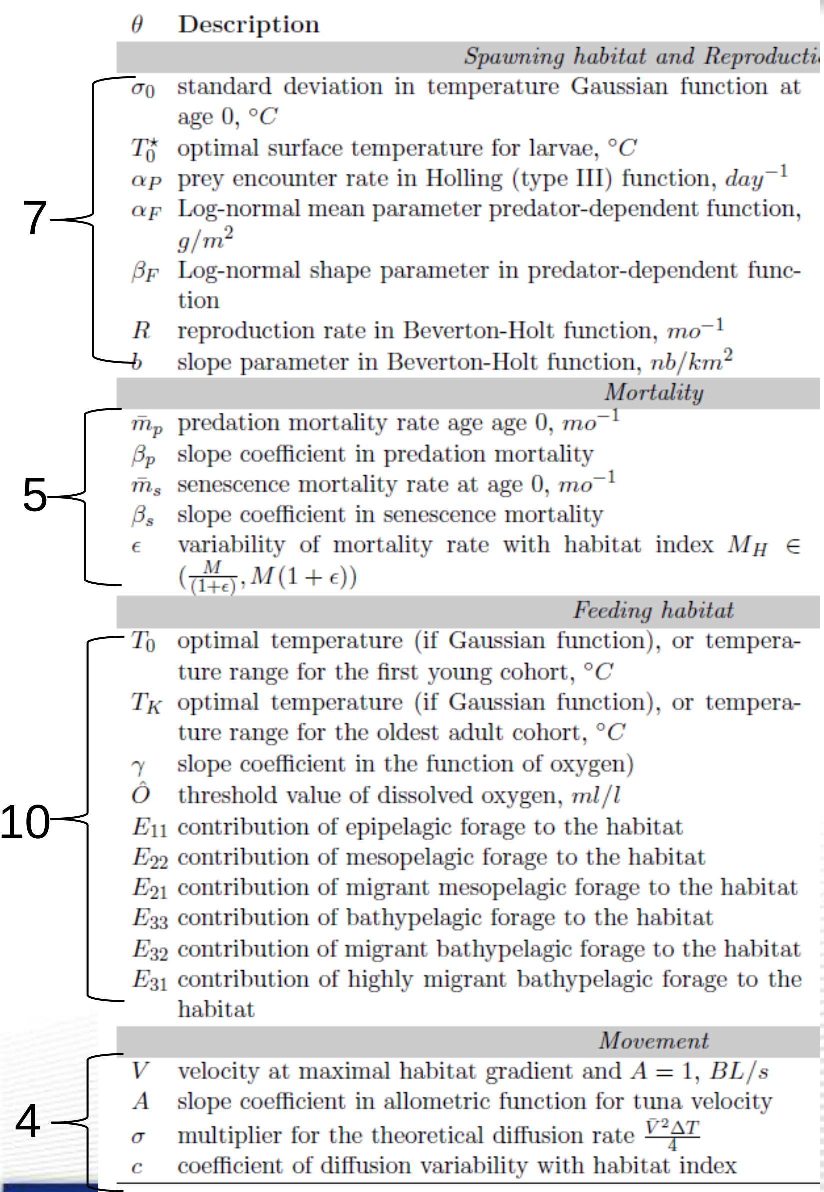


Density of Atl. Bluefin tuna larvae (5-30 d)

end of May 2010



Applications: Param. Estimation



	θ	**Description**
		Spawning habitat and Reproducti
7	σ_0	standard deviation in temperature Gaussian function at age 0, $°C$
	$T_0^\star$	optimal surface temperature for larvae, $°C$
	α_P	prey encounter rate in Holling (type III) function, day^{-1}
	α_F	Log-normal mean parameter predator-dependent function, g/m^2
	β_F	Log-normal shape parameter in predator-dependent function
	R	reproduction rate in Beverton-Holt function, mo^{-1}
	b	slope parameter in Beverton-Holt function, nb/km^2
		Mortality
5	$\bar{m}_p$	predation mortality rate age age 0, mo^{-1}
	β_p	slope coefficient in predation mortality
	$\bar{m}_s$	senescence mortality rate at age 0, mo^{-1}
	β_s	slope coefficient in senescence mortality
	ϵ	variability of mortality rate with habitat index $M_H \in (\frac{M}{(1+\epsilon)}, M(1+\epsilon))$
		Feeding habitat
10	T_0	optimal temperature (if Gaussian function), or temperature range for the first young cohort, $°C$
	T_K	optimal temperature (if Gaussian function), or temperature range for the oldest adult cohort, $°C$
	γ	slope coefficient in the function of oxygen)
	$\hat{O}$	threshold value of dissolved oxygen, ml/l
	E_{11}	contribution of epipelagic forage to the habitat
	E_{22}	contribution of mesopelagic forage to the habitat
	E_{21}	contribution of migrant mesopelagic forage to the habitat
	E_{33}	contribution of bathypelagic forage to the habitat
	E_{32}	contribution of migrant bathypelagic forage to the habitat
	E_{31}	contribution of highly migrant bathypelagic forage to the habitat
		Movement
4	V	velocity at maximal habitat gradient and $A = 1$, BL/s
	A	slope coefficient in allometric function for tuna velocity
	σ	multiplier for the theoretical diffusion rate $\frac{\bar{V}^2 \Delta T}{4}$
	c	coefficient of diffusion variability with habitat index

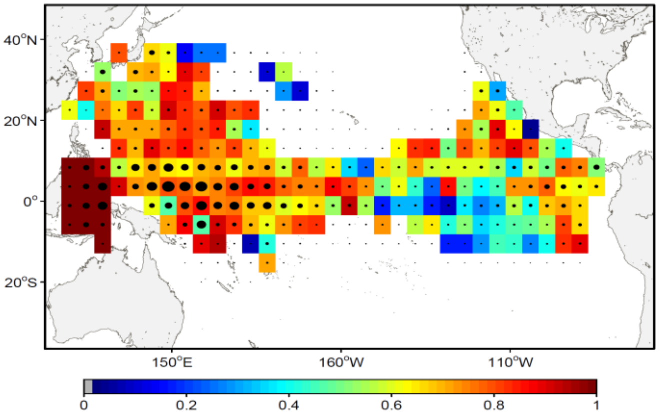
26 parameters + 3 or 4 par by fishery (growth, age at maturity from independent studies).

The Maximum Likelihood Estimation approach has been implemented in SEAPODYM to include:

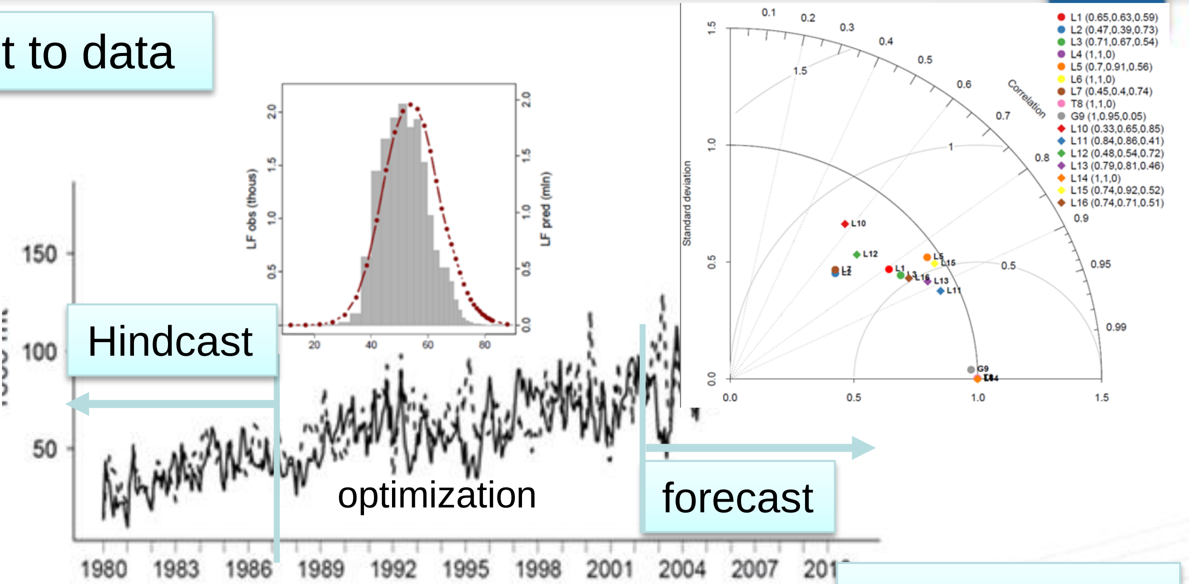
- spatially disaggregated catch and size frequency data (Senina et al. 2008)
- Spatially disaggregated catch (Senina et al 2016)
- Acoustic biomass estimates, by analogy to a pseudo fishery without mortality (Dragon et al. 2015)
- Tagging data (Senina et al 2017; in rev.)

Applications: Param. Estimation

Evaluation



Fit to data

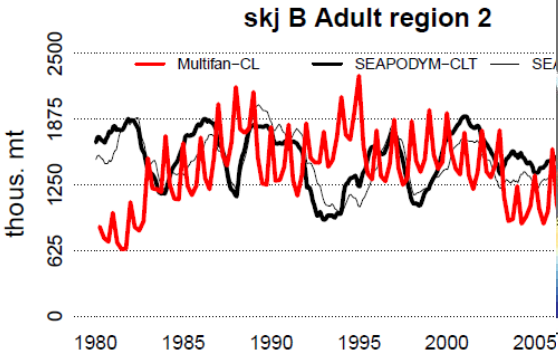


Hindcast

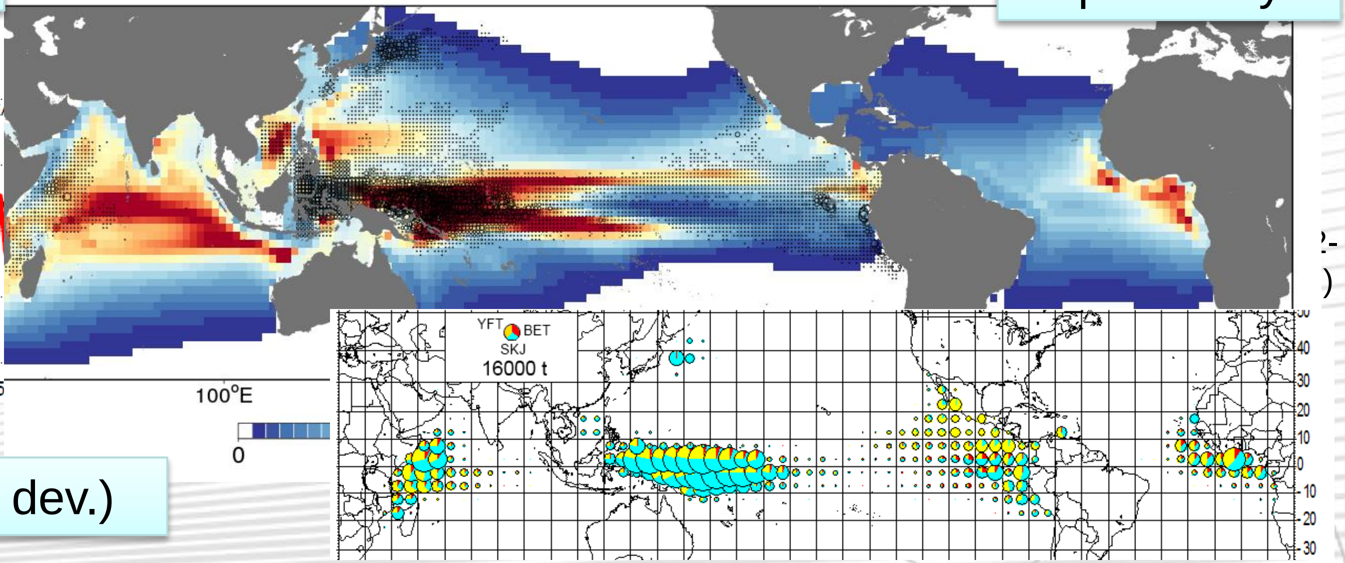
optimization

forecast

Model inter-comparison



‘exportability’



Sensitivity analyses (in dev.)

Applications: Param. Estimation

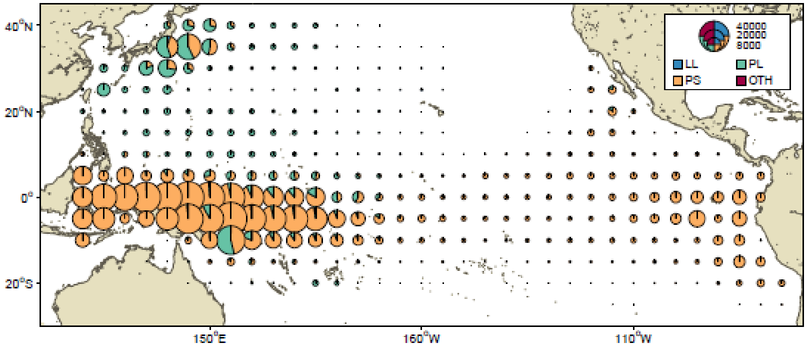
For tagging data

- the choice was to use only data from recaptures to be independent of fisheries
- this information contributes mainly to the estimation of movement and habitats parameters
- Data are aggregated by time strata, e.g. quarter, and distributions smoothed using Gaussian kernels to reduce the errors related to recapture date and positions.
- More weight to longer time of liberty at sea
- The same model of A&D is used without considering mortality.

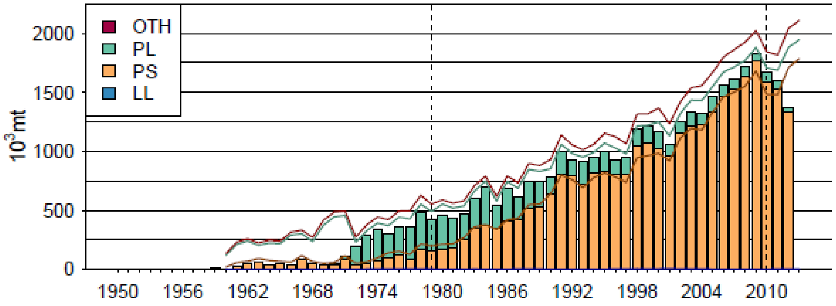
Senina I., Lehodey P., Calmettes B., Nicol S., Caillot S., Hampton J. and P. Williams (2016). Predicting skipjack tuna dynamics and effects of climate change using SEAPODYM with fishing and tagging data. WCPFC, 12th Regular Session of the Scientific Committee, Bali, Indonesia 3–11 August 2016, WCPFC-SC12-2016/EB WP-01: 71 pp. http://www.wcpfc.int/node/27443

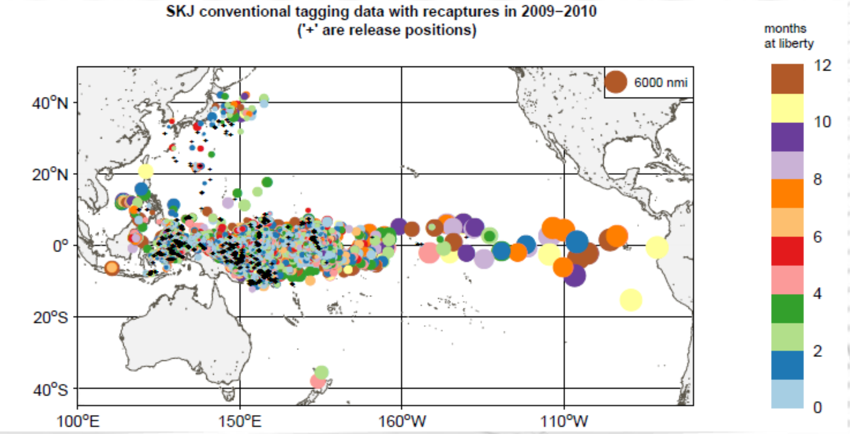
Applications: Stock estimates

Pacific Skipjack



Total spatially distributed catch of skipjack tuna
(dashed lines mark simulation time period, solid lines – total landings)





SKJ conventional tagging data with recaptures in 2009–2010
('+' are release positions)

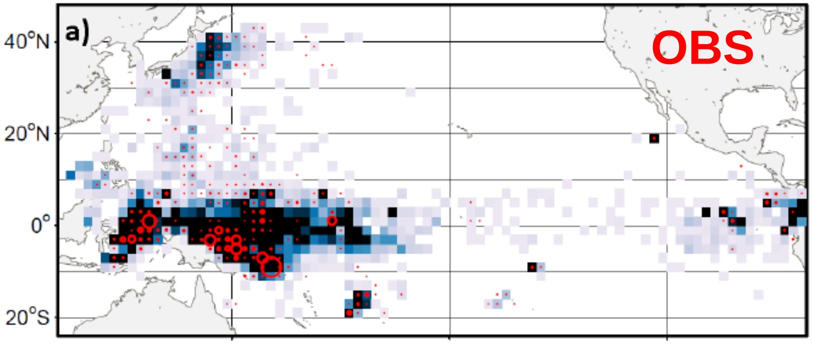
Physical & biogeochemical forcing:
NEMO-PISCES **2° x month** driven by atmospheric reanalysis INTERIM **1979-2010**

Age structure:
36 monthly cohorts + one (age+).
Age-length and age-weight from MULTIFAN-CL estimate (Rice et al., 2014).

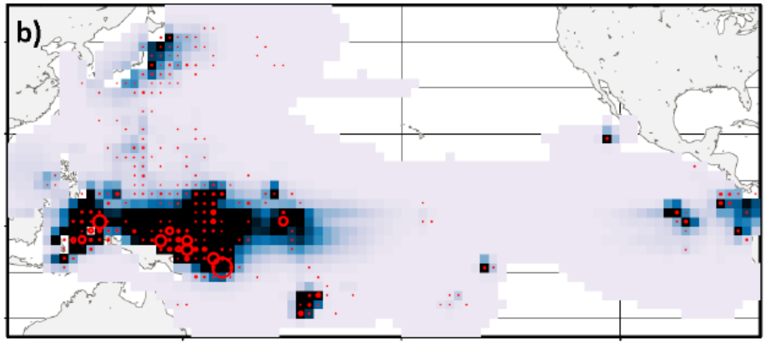
Fishing:
Revised SPC + IATTC (2013) datasets
(6 pole-and-line, 9 purse-seine and 2 longline fisheries)

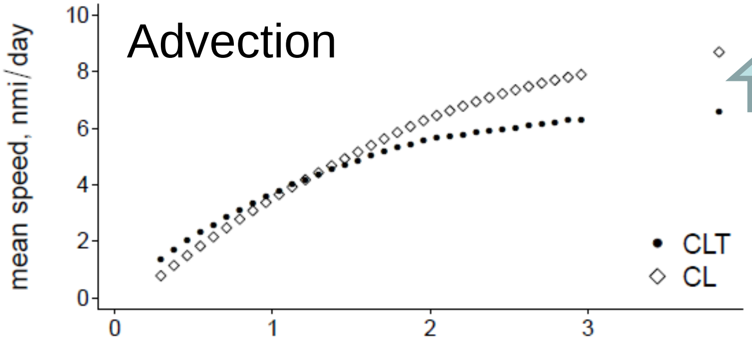
Tagging data:
Tags recaptured between May 2008 and Dec 2010

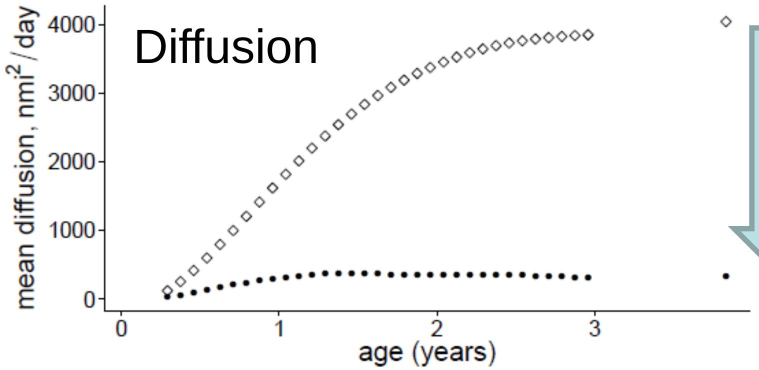
Applications: Stock estimates



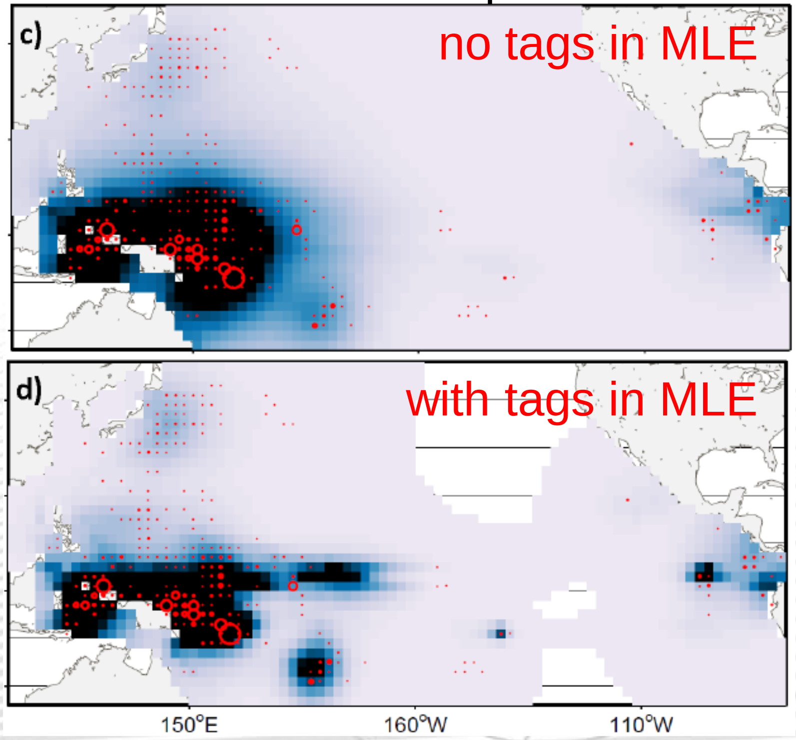
Kernel







Predicted recaptures

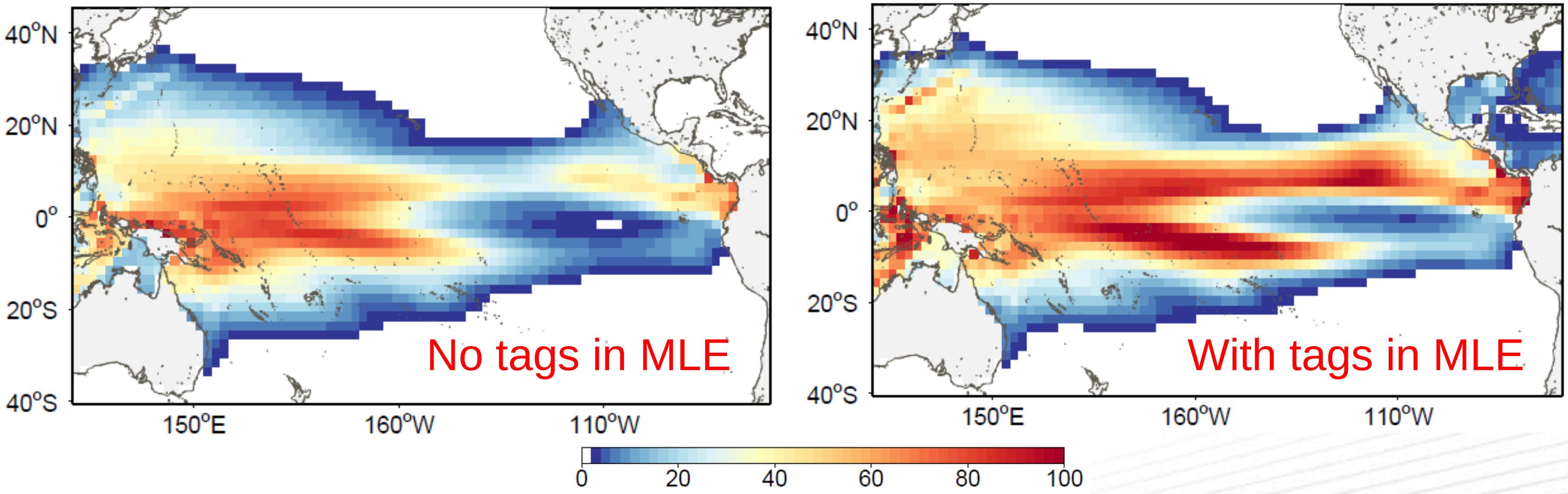


Applications: Stock estimates

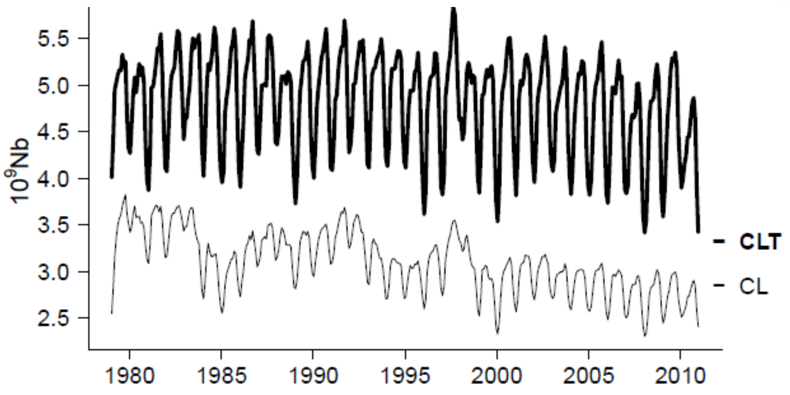
Pacific Skipjack

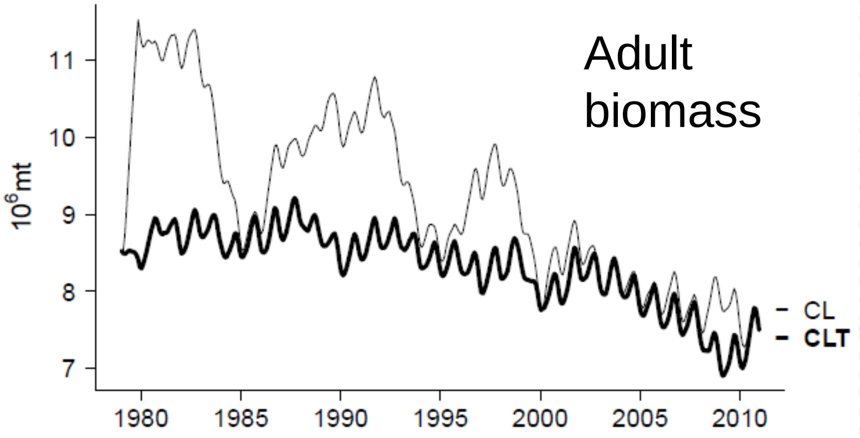
Impact on habitats & dynamics

Recruited larvae (nb/ km²) 1980-2010



Recruitment time series

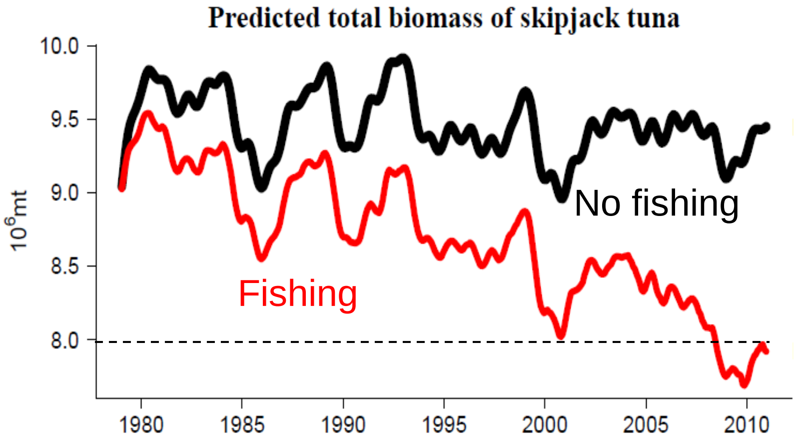


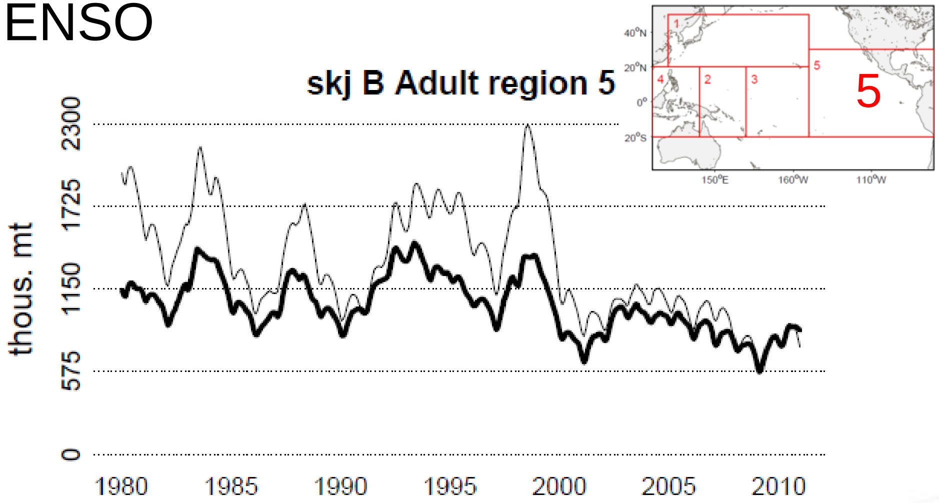


Adult biomass

Applications: Environmental Var.

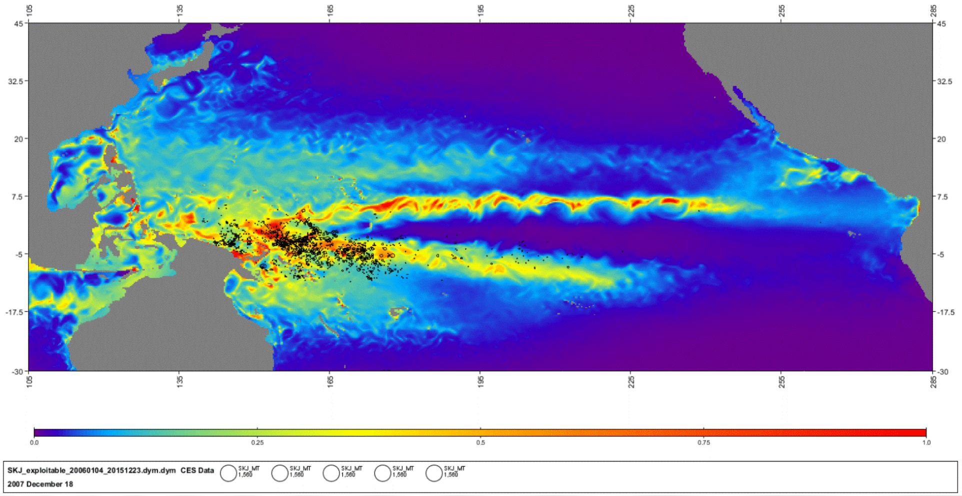
Skipjack & ENSO

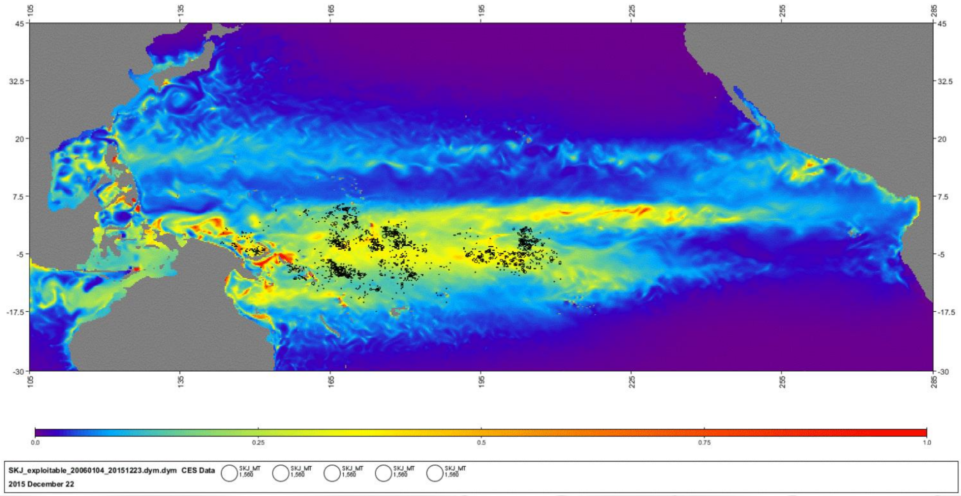




2011: La Niña

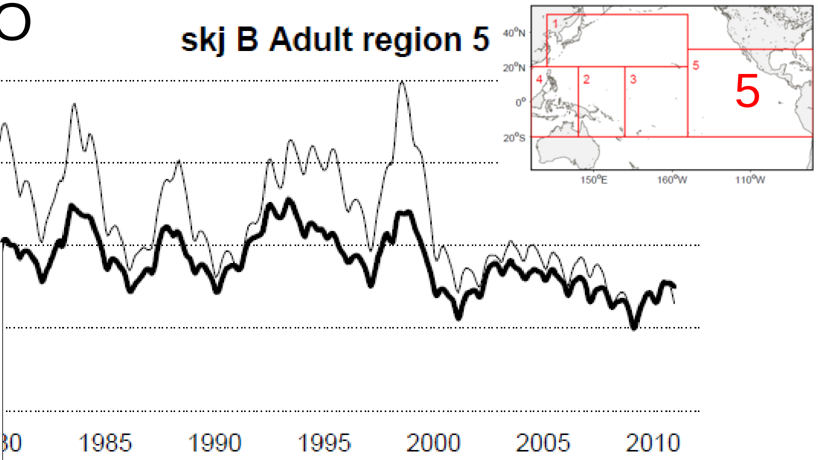
2015 : El Niño

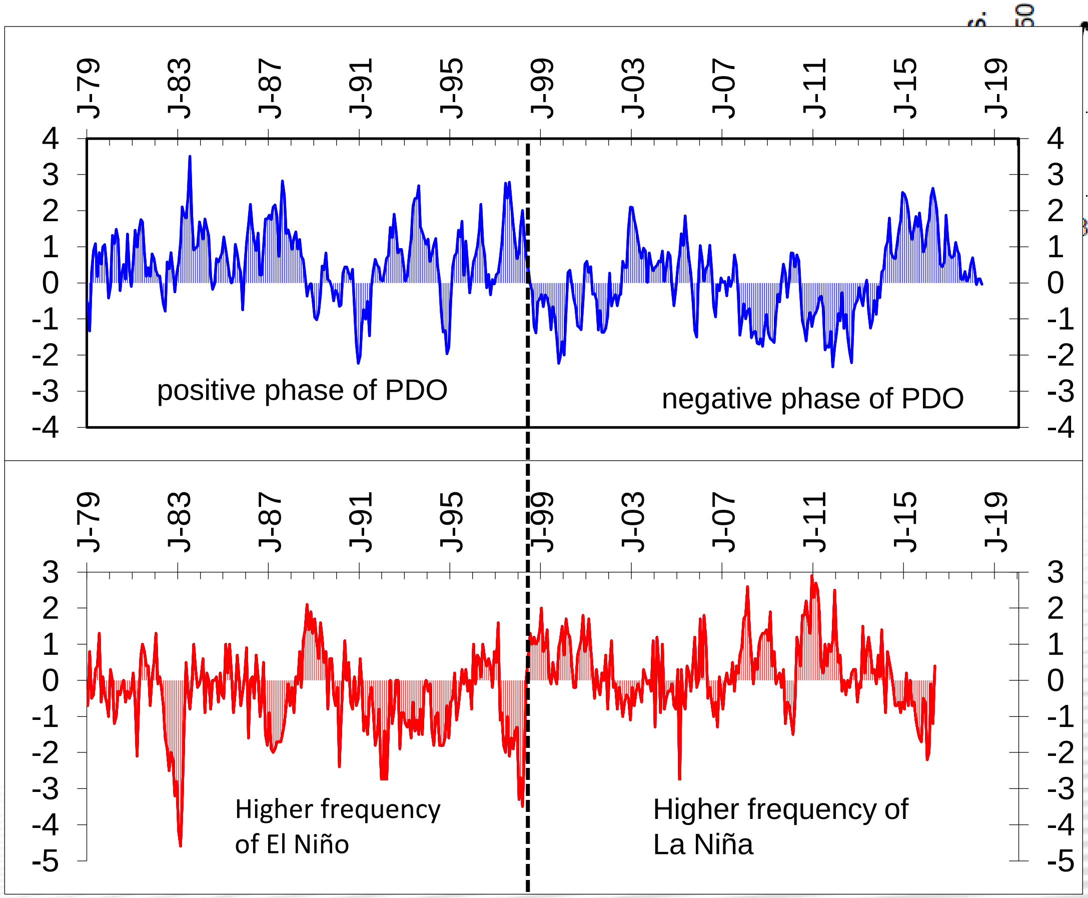




Applications: Environmental Var.

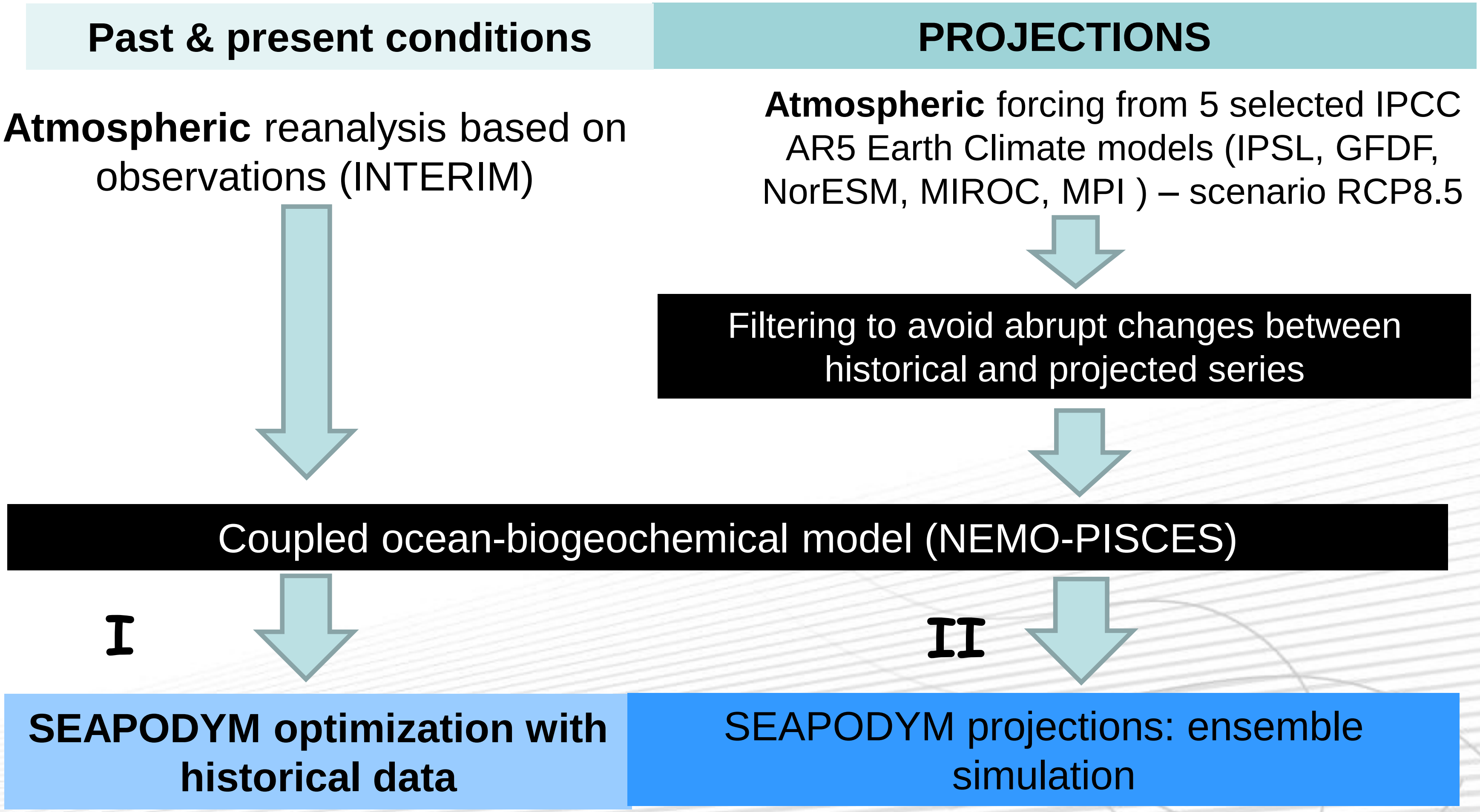
Skipjack & ENSO





Applications: Climate Change

CC projections: Ensemble simulation to account for uncertainty



Past & present conditions

PROJECTIONS

Atmospheric reanalysis based on observations (INTERIM)

Atmospheric forcing from 5 selected IPCC AR5 Earth Climate models (IPSL, GFDF, NorESM, MIROC, MPI) – scenario RCP8.5

Filtering to avoid abrupt changes between historical and projected series

Coupled ocean-biogeochemical model (NEMO-PISCES)

I

II

SEAPODYM optimization with historical data

SEAPODYM projections: ensemble simulation

Applications: Climate Change

I - Optimization

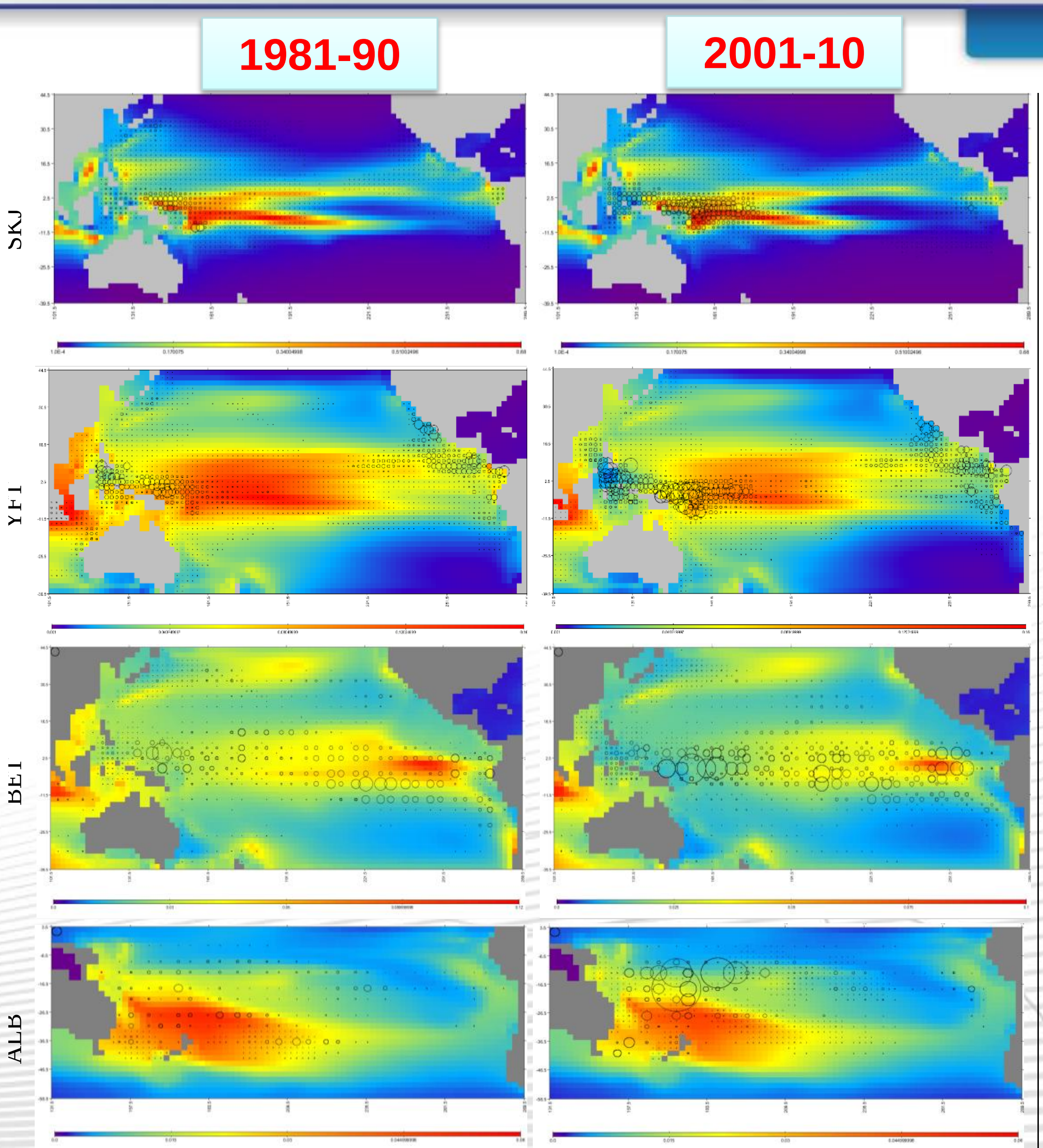
Comparison of predicted distributions for 1st and last decade of the historical time series. Total observed catches are shown with catch proportional to circles (same scales between decades).

Skipjack: WCPFC SC12 & Senina et al. (sub.)

Yellowfin: WCPFC SC13

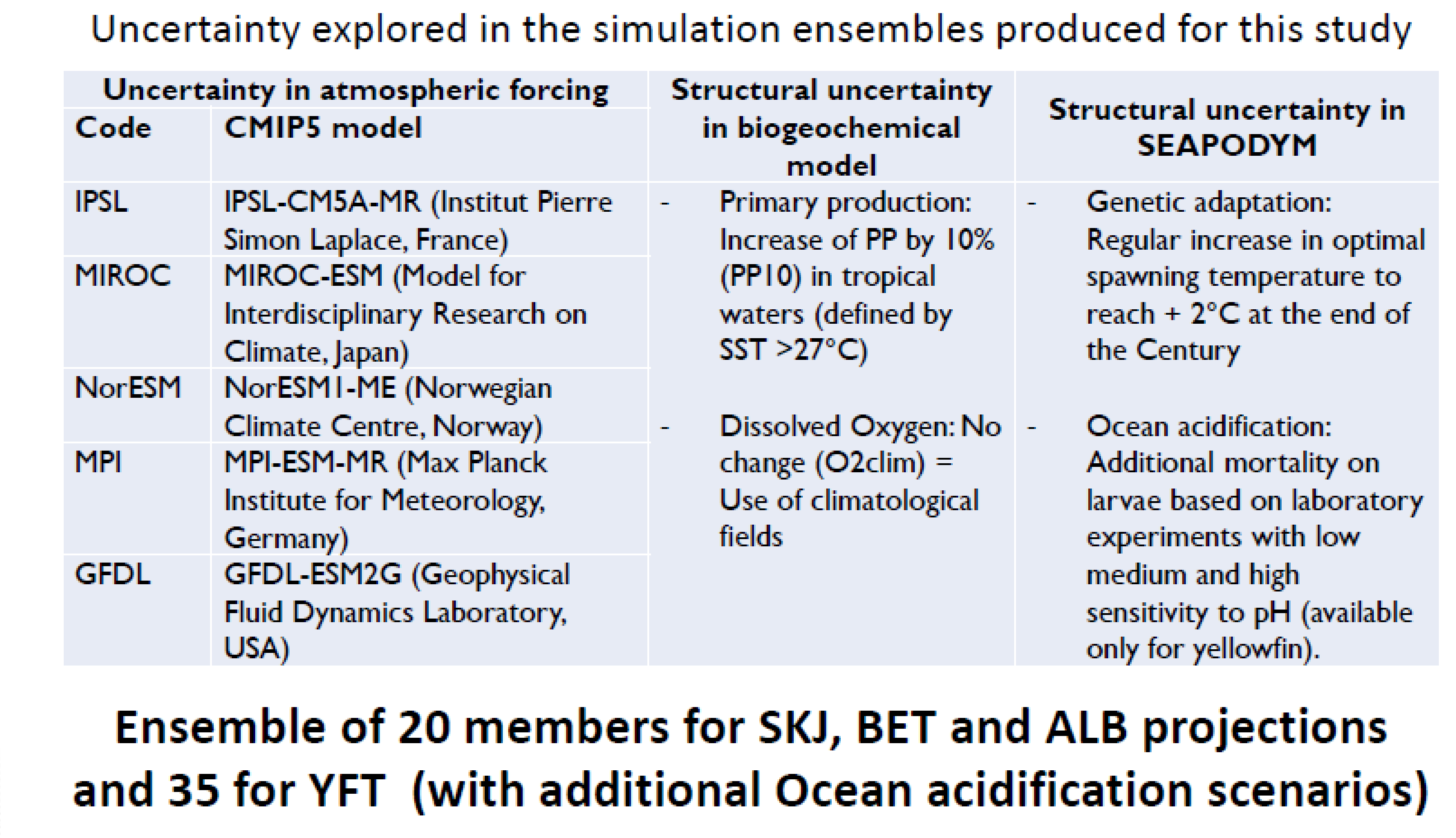
Bigeye: WCPFC SC 14

South Pacific Albacore: WCPFC SC14



Applications: Climate Change

II – Ensemble simulation



Uncertainty explored in the simulation ensembles produced for this study

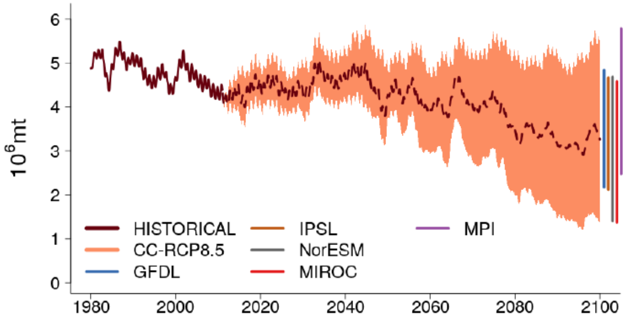
Uncertainty in atmospheric forcing		**Structural uncertainty in biogeochemical model**	**Structural uncertainty in SEAPODYM**
Code	**CMIP5 model**		
IPSL	IPSL-CM5A-MR (Institut Pierre Simon Laplace, France)	- Primary production: Increase of PP by 10% (PP10) in tropical waters (defined by SST >27°C) - Dissolved Oxygen: No change (O2clim) = Use of climatological fields	- Genetic adaptation: Regular increase in optimal spawning temperature to reach + 2°C at the end of the Century - Ocean acidification: Additional mortality on larvae based on laboratory experiments with low medium and high sensitivity to pH (available only for yellowfin).
MIROC	MIROC-ESM (Model for Interdisciplinary Research on Climate, Japan)		
NorESM	NorESM1-ME (Norwegian Climate Centre, Norway)		
MPI	MPI-ESM-MR (Max Planck Institute for Meteorology, Germany)		
GFDL	GFDL-ESM2G (Geophysical Fluid Dynamics Laboratory, USA)		

Ensemble of 20 members for SKJ, BET and ALB projections and 35 for YFT (with additional Ocean acidification scenarios)

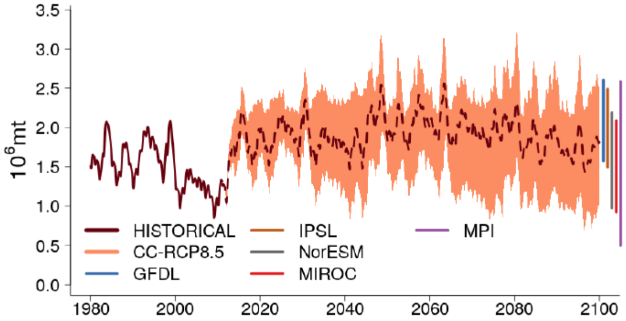
Applications: Climate Change

II – Ensemble simulation (skipjack)

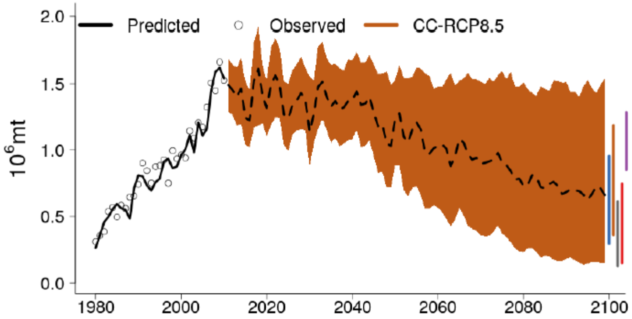
Biomass,WCPO



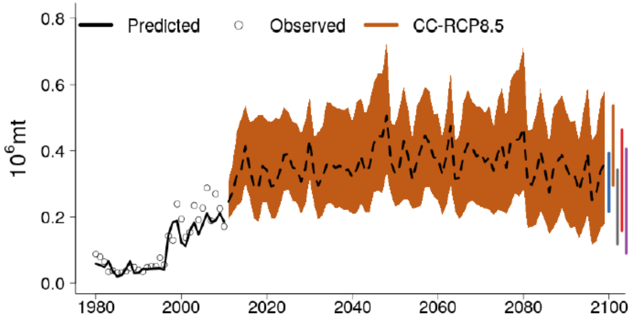
Biomass, EPO

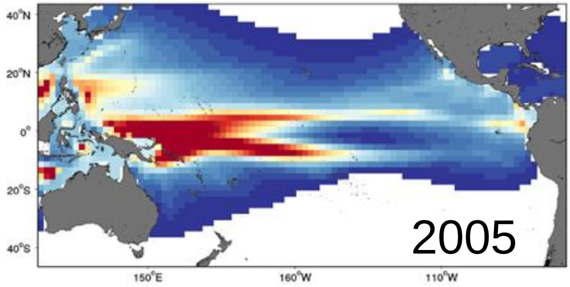


Catch, WCPO

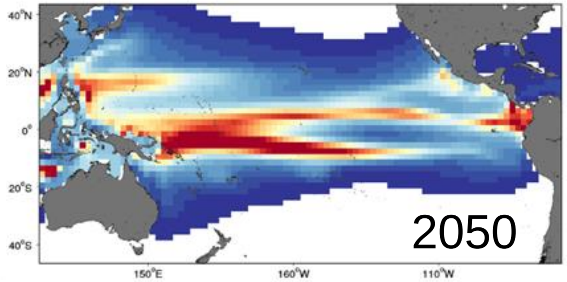


Catch, EPO

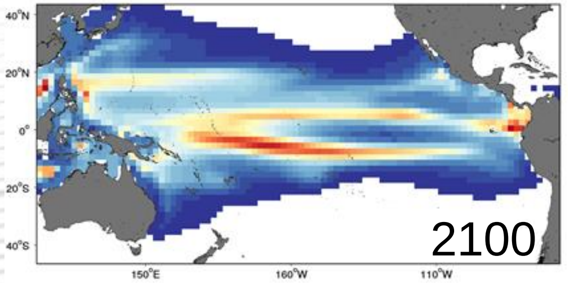




2005



2050



2100

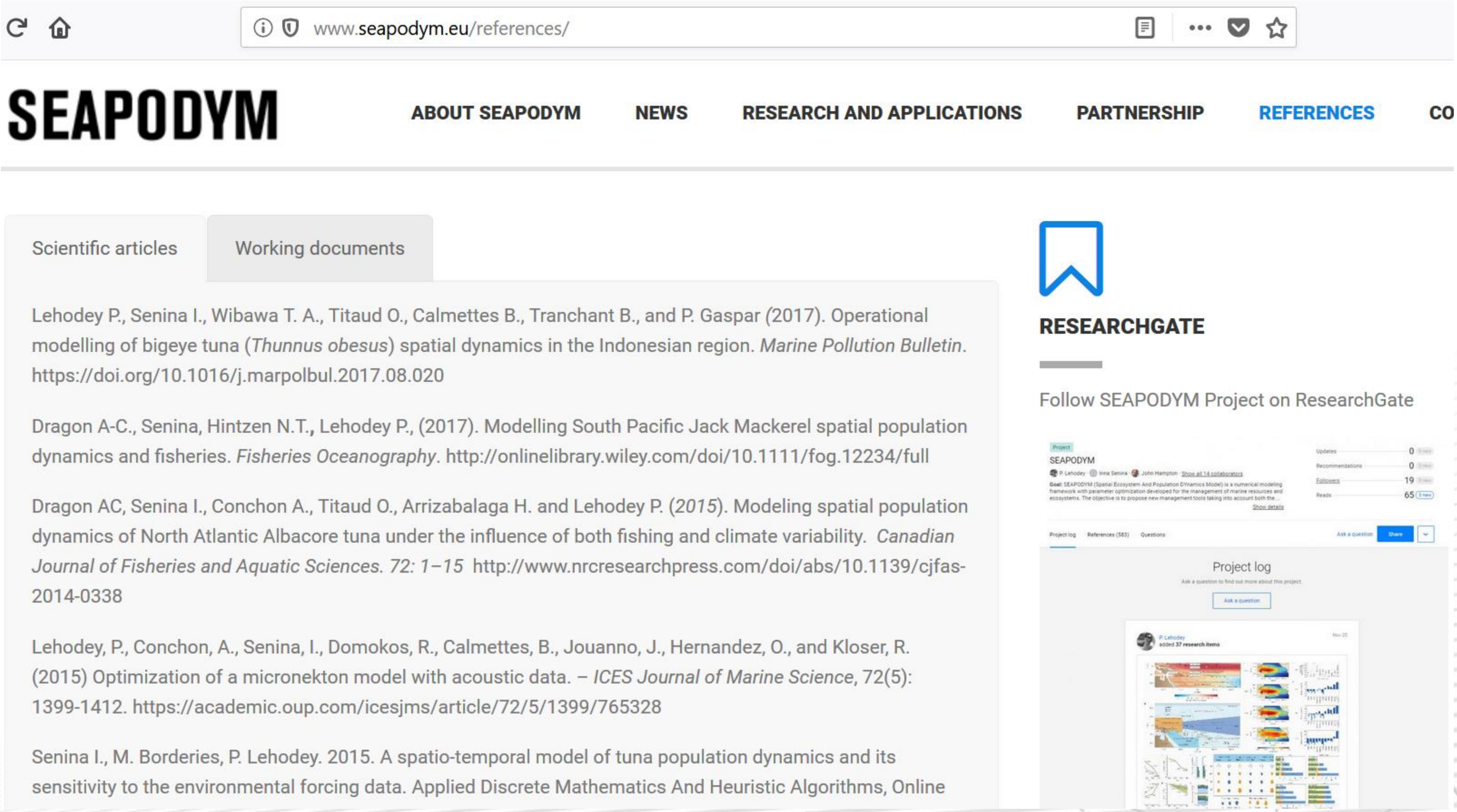
Senina et al. (2018) Impact of climate change on tropical tuna species and tuna fisheries in Pacific Island waters and high seas areas 14th Scientific Committee of the WCPFC, Busan, South Korea, 8-16 Aug. 2018. **WCPFC-SC14-2018/ EB-WP-01,** 44 pp. https://www.wcpfc.int/node/30981

Conclusions

- SEAPODYM simulates spatial structure & spatial dynamics of exploited pelagic fish species
- MLE approach at the resolution of the model => hundred thousands of data are assimilated
- Recent integration of tagging data in the MLE has greatly improved skipjack optimization
- With fish dynamics driven by environmental variables, the model can help to understand (forecast?) natural climate variability (e.g., ENSO) and impacts of climate change
- The results are sensitive to the quality of environmental forcings
- Ensemble simulations help to account for uncertainty
- Multiple possible applications, spatial management, connectivity study, operating model, …

References

www.seapodym.eu



SEAPODYM

Lehodey P., Senina I., Wibawa T. A., Titaud O., Calmettes B., Tranchant B., and P. Gaspar (2017). Operational modelling of bigeye tuna (*Thunnus obesus*) spatial dynamics in the Indonesian region. *Marine Pollution Bulletin*. https://doi.org/10.1016/j.marpolbul.2017.08.020

Dragon A-C., Senina, Hintzen N.T., Lehodey P., (2017). Modelling South Pacific Jack Mackerel spatial population dynamics and fisheries. *Fisheries Oceanography*. http://onlinelibrary.wiley.com/doi/10.1111/fog.12234/full

Dragon AC, Senina I., Conchon A., Titaud O., Arrizabalaga H. and Lehodey P. (*2015*). Modeling spatial population dynamics of North Atlantic Albacore tuna under the influence of both fishing and climate variability. *Canadian Journal of Fisheries and Aquatic Sciences. 72: 1–15* http://www.nrcresearchpress.com/doi/abs/10.1139/cjfas-2014-0338

Lehodey, P., Conchon, A., Senina, I., Domokos, R., Calmettes, B., Jouanno, J., Hernandez, O., and Kloser, R. (2015) Optimization of a micronekton model with acoustic data. – *ICES Journal of Marine Science*, 72(5): 1399-1412. https://academic.oup.com/icesjms/article/72/5/1399/765328

Senina I., M. Borderies, P. Lehodey. 2015. A spatio-temporal model of tuna population dynamics and its sensitivity to the environmental forcing data. Applied Discrete Mathematics And Heuristic Algorithms, Online

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Thank you.