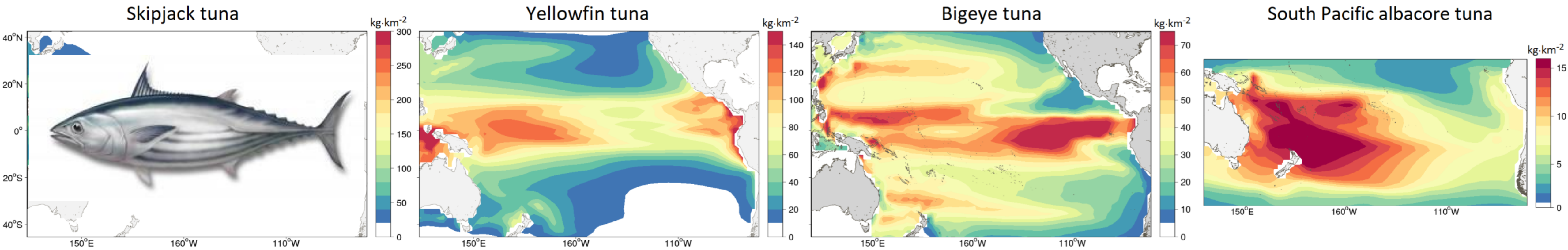
DTU Workshop

12-16th May 2025

Pacific Community
Communauté du Pacifique

SEAPODYM model and DATA

With examples for SKIPJACK tuna



Inna Senina

PART 1. THE MODEL

- Simplifying the reality: view of the ecosystem and tuna environment, tuna life cycle and population dynamics;
- Modelling habitats;
- Modelling tuna movements.

SEAPODYM: continuous equations and numerical model

Modelled dynamic processes: ***reproduction, mortality, and movement***

$N(a,t,\mathbf{x})$ - density of fish population at age $a \in [0,\bar{a}]$,

time $t \in [t_0, t_{\text{fin}}]$, and $\mathbf{x} = (x,y) \in \Omega \in \mathbf{R}^2$

$$\partial_t N + \partial_a N = -\text{div}(\mathbf{v}N) + \nabla(D\nabla N) - MN$$

$$N(a,t_0,\mathbf{x}) = N_0(a,\mathbf{x})$$

$$N(0,t,\mathbf{x}) = S(t,\mathbf{x})$$

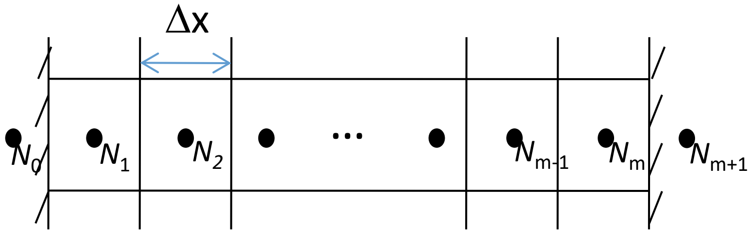
$$\mathbf{n}\cdot\mathbf{v}\Big|_{\mathbf{x}\in\partial\Omega} = \mathbf{n}\cdot\nabla N\Big|_{\mathbf{x}\in\partial\Omega} = 0$$

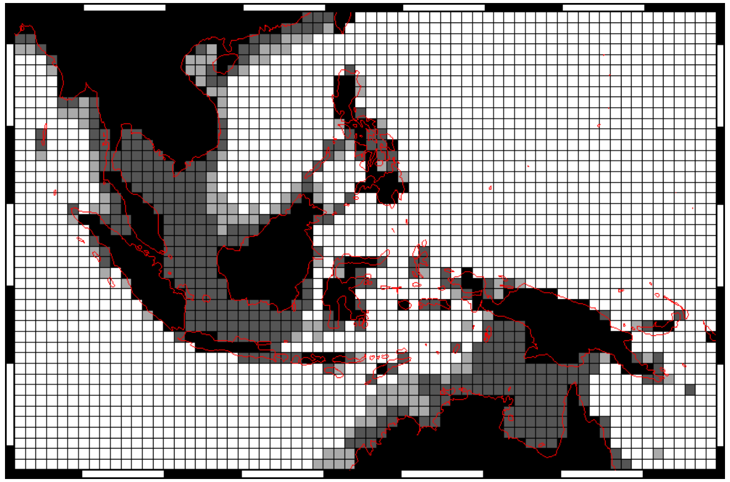
where $\mathbf{v}(a,t,\mathbf{x})$, $D(a,t,\mathbf{x})$ - advection ($\mathbf{v}_c + \mathbf{v}_N$) and diffusion rates;

$M(a,t,\mathbf{x})$ - mortality rate ($m_N + m_F$)

$S(t,\mathbf{x})$ - tuna larvae survived after spawning

ADI numerical solver





J. Sibert and D. Fournier, 1994, FAO report

Modelling movement: directional and non-directional

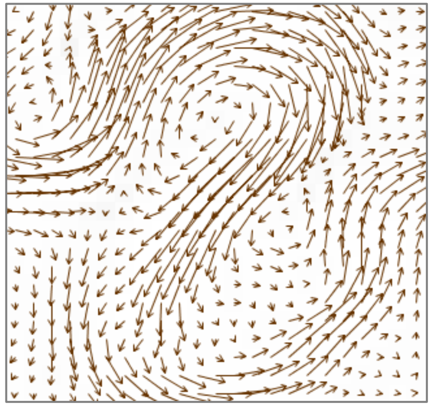
passive

active

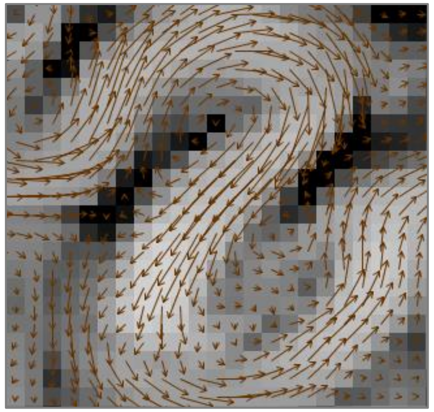
directional

non-directional

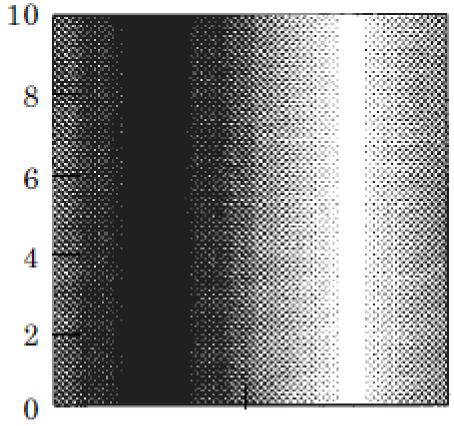
Ocean currents



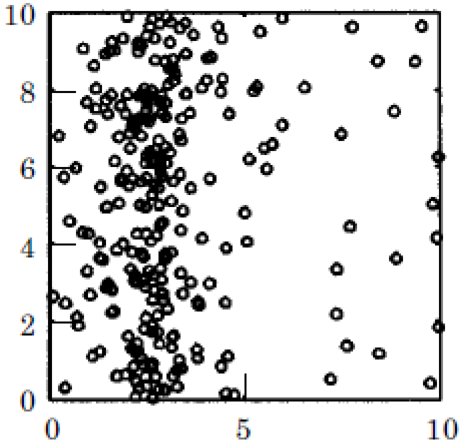
Biomass distribution



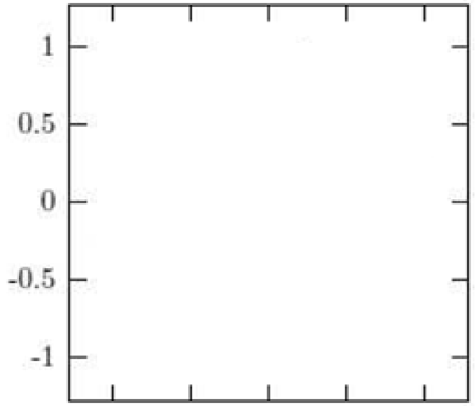
Habitat



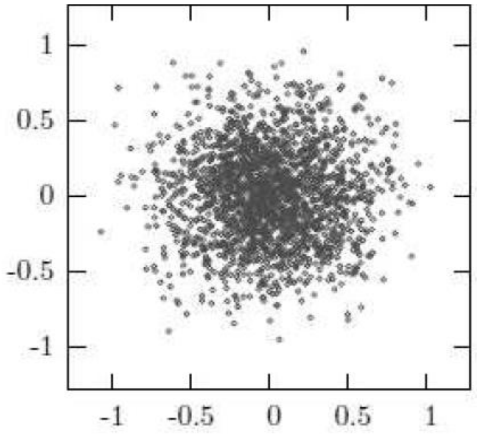
Resulting distribution of fish



Habitat



Resulting distribution of fish



From: Grunbaum, 1999; Flierl et al., 1999; Fougeras et Maury, 2007

Tuna movement as the response to environmental heterogeneity

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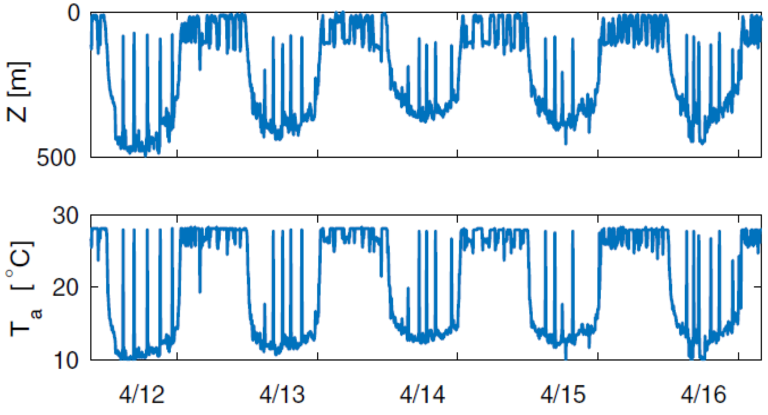
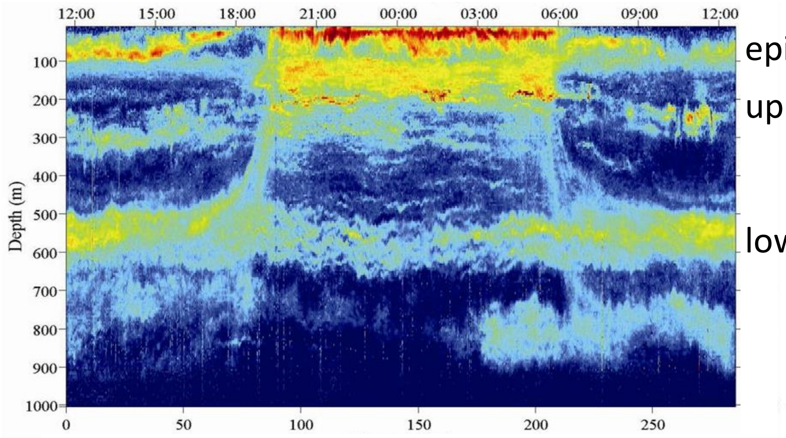
Bigeye tuna in Western Coral Sea, 04-2002
(From: Thygesen et al., 2016; Evans et al., 2008)



Prey of tuna (micronekton)



Credit: Réka DOMOKOS (NOAA)

Feeding habitat index is an ***accessible micronekton density***

$$H_a(a) = \mathbf{\Theta}(a) \times \left(\tau \mathbf{F}\delta + (1-\tau)\mathbf{F}^\mathsf{T}\delta\right)$$

$$\Theta = f_2(T; T^*, \sigma^*) \times f_4(O_2; O_2^*, \gamma)$$

Active movement rates depend on habitat index

$$\mathbf{v}_N(a) = \chi(a)\left(\frac{\partial H_a}{\partial x}, \frac{\partial H_a}{\partial y}\right)^\mathrm{T}$$

$$D(a) = \sigma D_0\left(1 - cH_a^p(a)\right)$$

All parameters must be estimated from data!

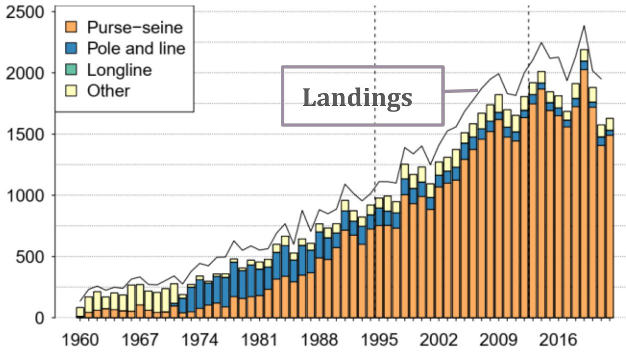
PART 2. LEARNING FROM DATA

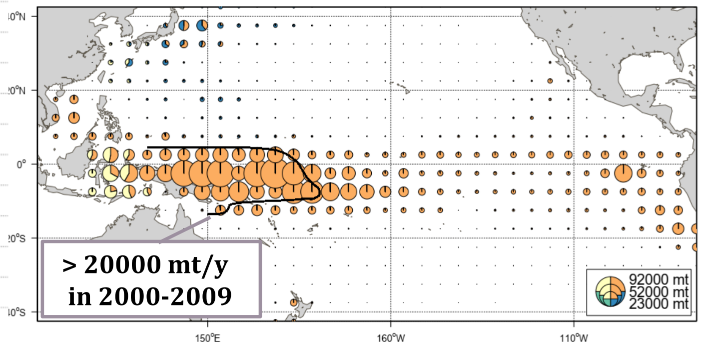
- Data overview for parameter estimation;
- Parameter estimation methods;
- Integration of tagging data;
- Integration of early life data;

Data inform modelled processes

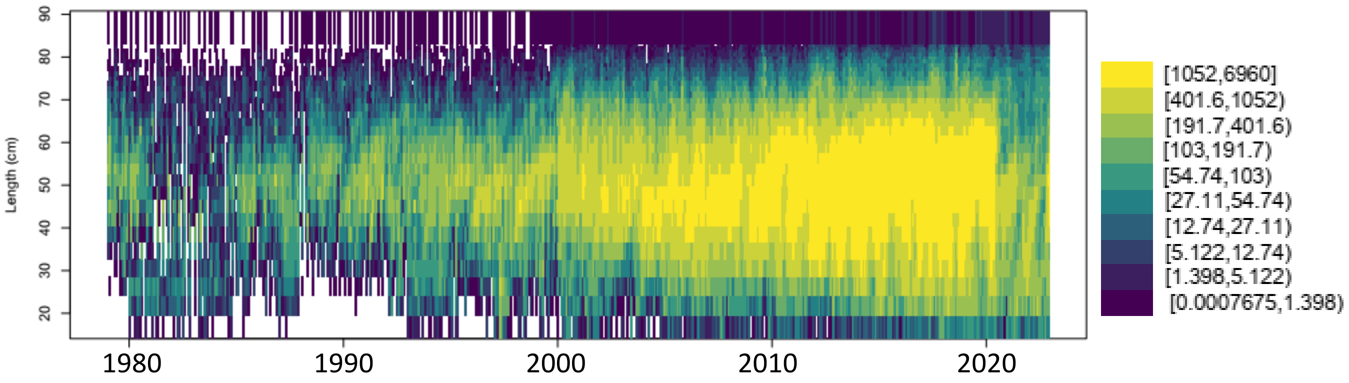
Industrial fishing

1 – EC data:





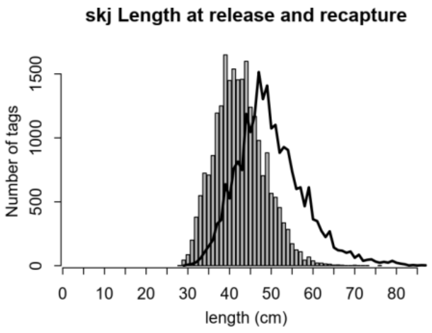
2 – LF data:

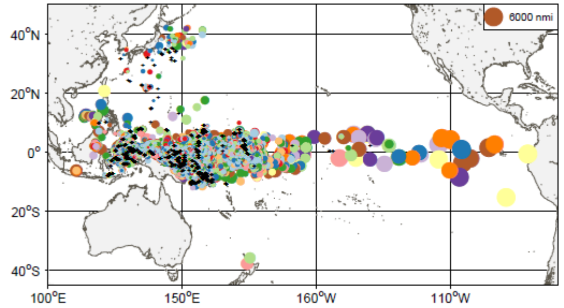


Good: reproduction and mortality rates, spatial extent
Poor: spatial distributions, movements

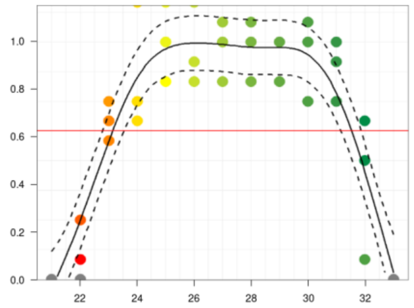
Scientific surveys

3 – Conventional tagging data:

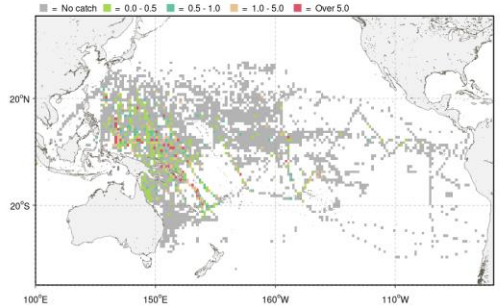




4 – Eggs survival data:



5 – Larval sampling data:

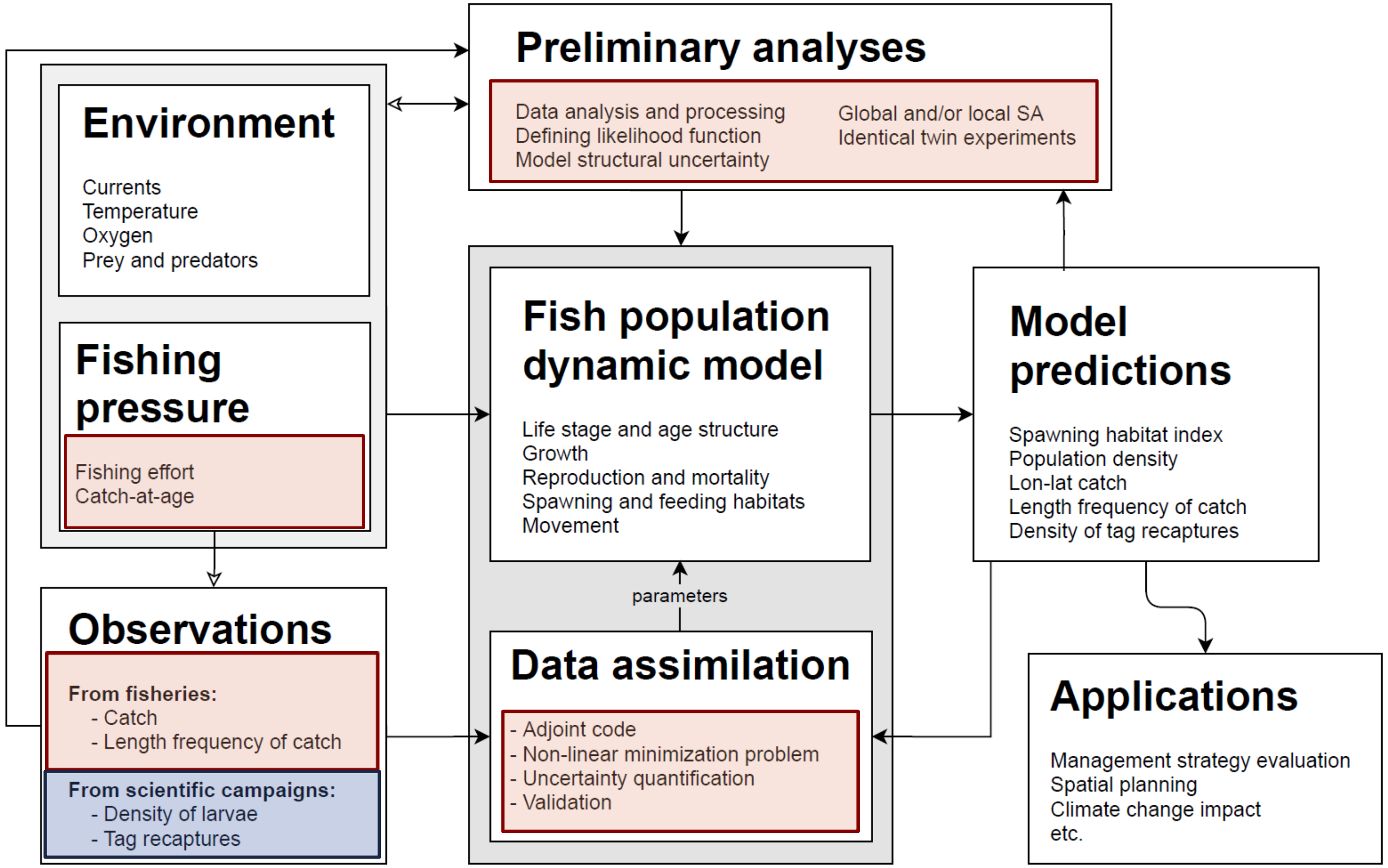


Good: reproduction, spawning and feeding habitats, movement rates, spatial distribution of spawning stock

Parameter estimation in SEAPODYM

Workflow for data processing, sensitivity analysis, parameter estimation and validation

- SEAPODYM parameters control the dynamic processes and links to environmental variables which define *spawning* and *feeding* habitats;
- Environmental variables can be viewed as **fixed parameters**;
- The dynamic processes explicitly described by a biophysical and highly dimensional model can be governed by a limited number of parameters (up to 30):
  - 2 reproduction of Beverton-Holt function,
  - 5 parameters of natural mortality function,
  - 5 parameters in spawning habitat,
  - 12 parameters in feeding habitat,
  - 4 parameters to define movement rates
  - 2 for seasonal spawning migrations
- Fisheries parameters (catchability and selectivity) for each fishery are estimated given the species spatial distributions at age and time.



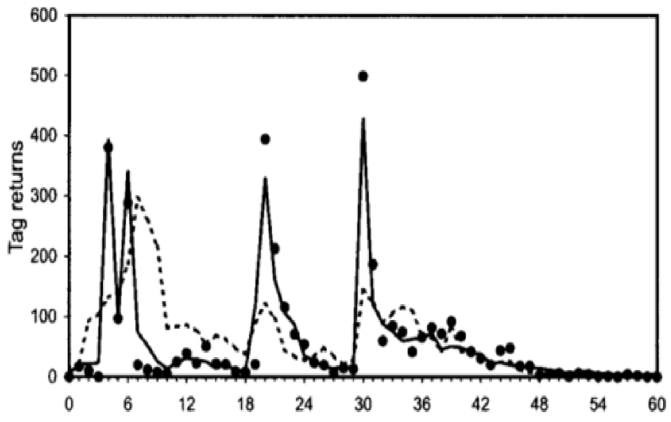
Sibert etal., 1998 ‘TAGEST’ approach implementation in SEAPODYM

$$N_{xyt} = \sum_{c=1}^{C_t} \tilde{N}_{xytc}$$

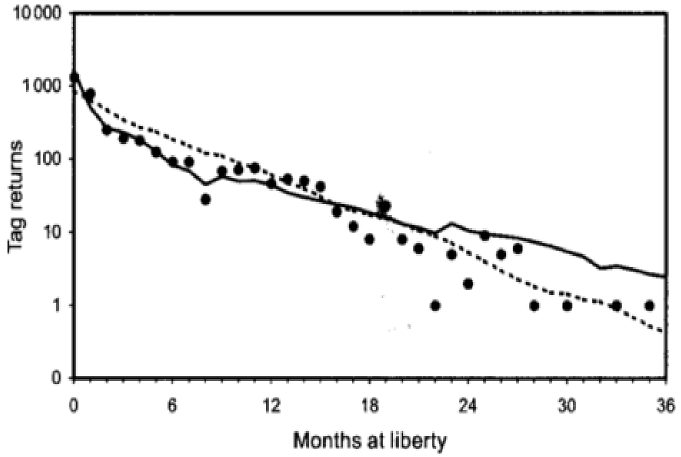
$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial N}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial N}{\partial y}\right) - \frac{\partial}{\partial x}(uN) - \frac{\partial}{\partial y}(vN) - ZN$$

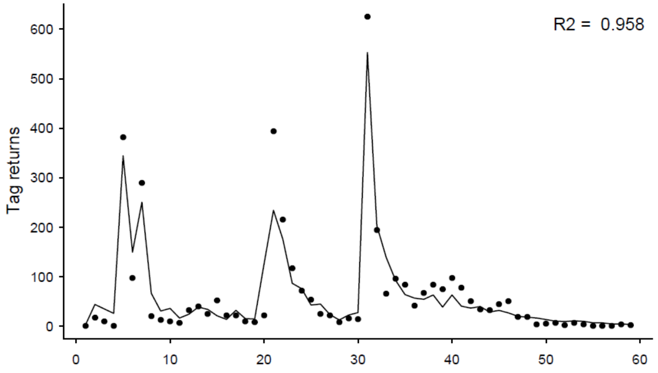
N_{xyt} – the aggregate density of tagged tunas from all cohorts released up to time t

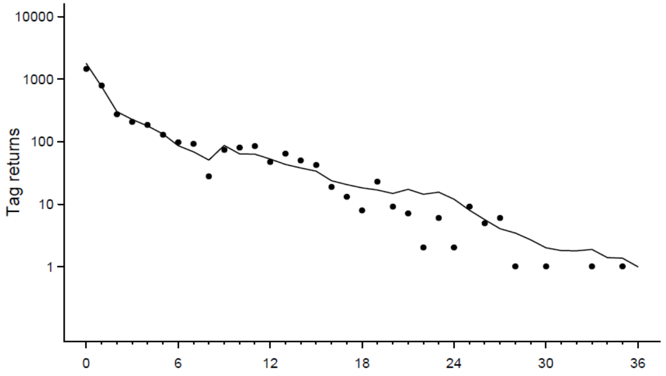
SEAPODYM: *ADRE with age structure and movement driven by habitat*: $\partial_t N + \partial_a N = -\mathrm{div}(\mathbf{v}N) + \nabla(D\nabla N) - MN$



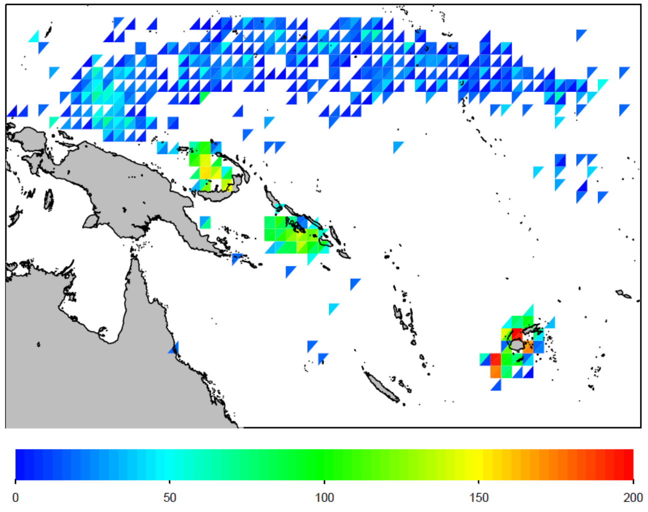
Observed (solid circles) and predicted (line) tag returns







Tag recaptures summarized over 1977-1982 **(lower triangles – model predictions)**



Sibert etal., 1998 'TAGEST' approach implementation in SEAPODYM

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Lessons learned:

- Compared to the original model with 36 parameters, a better fit to the data was achieved by SEAPODYM with only six dynamic parameters and five catchabilities. However, when varying parameters over two seasons, the model of Sibert et al. (1999) with 66 estimated parameters fits better to the data ($\chi^2[55]$ = 348.4 with a p value < 0.001);
- **Estimation of mortality depends on reporting rates. Calibrating the reporting rates within the parameter estimation is difficult because of their variation in space and time**;
- **Prediction of tag recaptures in this model depends on the quality of georeferenced fishing effort and gear information;**
- As a result of above uncertainties, significant differences obtained for mortality estimates from the TAGEST and the full population dynamics model: 0.0891 mo^{-1} in seapodym_tagest vs. 0.171 mo^{-1} in the full population dynamics model for the same ages.

Integration of tagging data: alternative approach to TAGEST

$$\{t_{rel}, x_{\text{rel}}, y_{\text{rel}}, \ell_{\text{rel}}; t_{\text{rec}}, x_{\text{rec}}, y_{\text{rec}}, \ell_{\text{rec}}\} \xrightarrow{\ell^{-1}(a)} \{t_{rel}, x_{\text{rel}}, y_{\text{rel}}, a_{\text{rel}}; t_{\text{rec}}, x_{\text{rec}}, y_{\text{rec}}, a_{\text{rec}}\} \rightarrow \begin{array}{l} (t_{rel}, x_{\text{rel}}, y_{\text{rel}}, a_{\text{rel}}; \boldsymbol{t_1}, x_{\text{rec}}, y_{\text{rec}}, a_{\text{rec}}) \\ (t_{rel}, x_{\text{rel}}, y_{\text{rel}}, a_{\text{rel}}; \boldsymbol{t_2}, x_{\text{rec}}, y_{\text{rec}}, a_{\text{rec}}) \\ \ldots \\ (t_{rel}, x_{\text{rel}}, y_{\text{rel}}, a_{\text{rel}}; \boldsymbol{t_m}, x_{\text{rec}}, y_{\text{rec}}, a_{\text{rec}}) \end{array}$$

$$N^{obs}(t_{\text{rec}}, a_{\text{rec}}, x, y) = \frac{1}{2\pi\sigma_x\sigma_y\Delta x\Delta y} e^{-\frac{(x-x_{\text{rec}})^2}{2\sigma_x^2} - \frac{(y-y_{\text{rec}})^2}{2\sigma_y^2}}$$

- density of tagged fish at the <u>time of recapture</u> accounting for uncertainty of recapture position

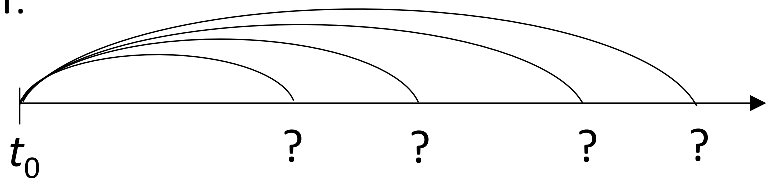
$$R_k^{obs}(x, y) = \sum_{a_{\text{rec}}=\underline{a}_k,..,\bar{a}_k} N^{obs}(t_{\text{rec}}, a_{\text{rec}}, x, y)$$

- density of group of tagged fish all recaptured at time $t_{\text{rec}} = t_k$, aged between $\underline{a}_k$ and $\bar{a}_k$, and released at $\forall t_{\text{rel}} \in [t_0, t_k - \Delta t]$

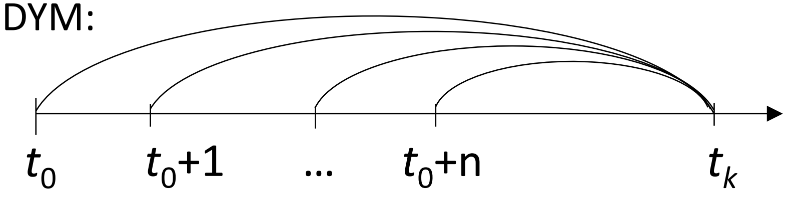
Let's also denote $r_k(a, t, \mathbf{x})$ the density of tagged fish of group $k=1,..,m$ of age a <u>released at time t</u>.

Then, let's model dynamics of $R_k(x, y)$ through $[t_0, t_k]$ (*inverse* design of the problem compared to TAGEST)

TAGEST:



SEAPODYM:



Underlying continuous equations of SEAPODYM and TAG movement model

To inform model parameters from tagging data, **simultaneously solve**

$N(a, t, \mathbf{x})$ - density of fish population at age *a*, time *t* and position *(x, y)*

$$\partial_t N + \partial_a N = -\mathrm{div}(\mathbf{v}N) + \nabla(D\nabla N) - MN$$
$$N(a, \mathbf{x}, t_0) = N_0(a, \mathbf{x})$$
$$N(0, \mathbf{x}, t) = S(t, \mathbf{x})$$
$$\mathbf{n}\cdot\mathbf{v}\Big|_{\mathbf{x}\in\partial\Omega} = \mathbf{n}\cdot\nabla N\Big|_{\mathbf{x}\in\partial\Omega} = 0$$

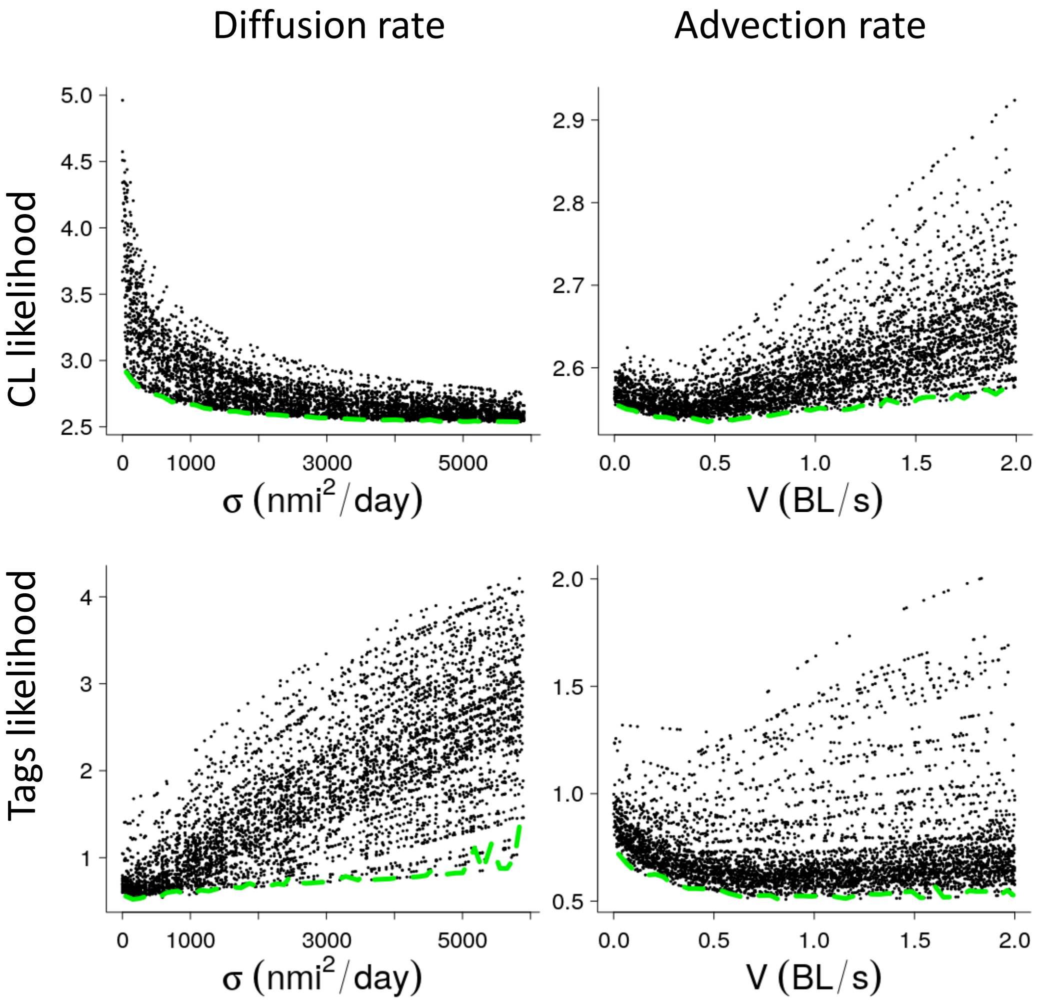
$+ \; m \times$

$R_k(a, t, \mathbf{x})$ - density of k-th group of tagged fish of age $a \in [a^0_{k,\mathrm{rel}}, .., a_{k,\mathrm{rec}}]$, time $t \in (t_0, k)$ and position *(x, y)*

$$\partial_t R_k + \partial_a R_k = -\mathrm{div}(\mathbf{v}\cdot R_k) + \nabla(D\nabla R_k) + r_k$$
$$R_k(a, t_0, \mathbf{x}) = 0$$
$$R_k(a_0, t, \mathbf{x}) = N^{obs}(a^0_{k,\mathrm{rel}}, t, \mathbf{x})$$
$$\mathbf{n}\cdot\mathbf{v}\Big|_{\mathbf{x}\in\partial\Omega} = \mathbf{n}\cdot\nabla R_k\Big|_{\mathbf{x}\in\partial\Omega} = 0$$

with shared movement parameters!

How different data inform model dynamics



1. Fisheries data inform the model demographic parameters, which control local densities and population temporal dynamics.

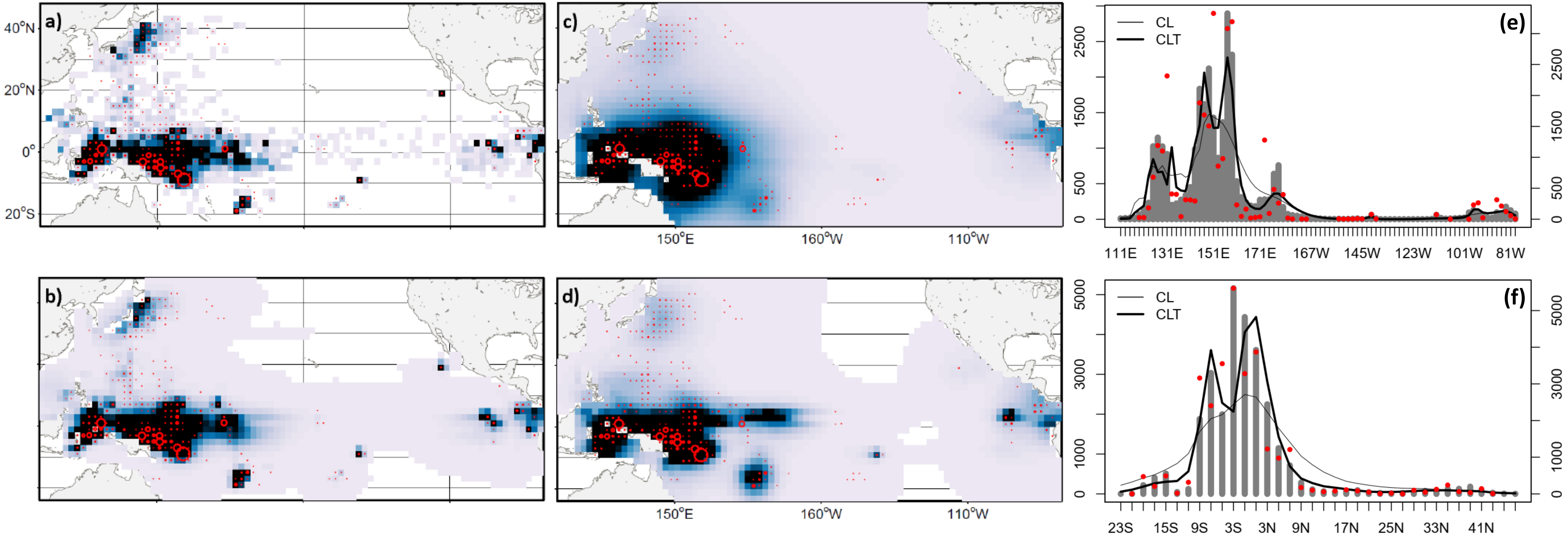
2. Fisheries data often provide biased information on movement and hence lead to a wrong estimation of movement parameters.
   Reasons depend on fisheries types:

   H1) fishermen "samples" locations where there is fish;
   H2) the data (positions, effort, catches) are noisy or erroneous

3. In above-described cases tagging data are essential in estimating habitats and movement parameters.

Improvements of skipjack movement modelling with the use of tagging data

Tag recaptures from 1979 to 2010 releases



a) Observed distribution; **b)** observed, smoothed by Gaussian kernel function; **c)** predicted by the model without tag likelihood (CL); **d)** predicted with the full likelihood (CLT); **e)** number of observed releases (right axis) and recaptures (left axis, bars) vs. predicted tag recaptures (solid line) by longitude; **f)** number of observed releases and recaptures vs. predicted recaptures by latitude.

Integration of larval data. Credit: Lucas Bonnin

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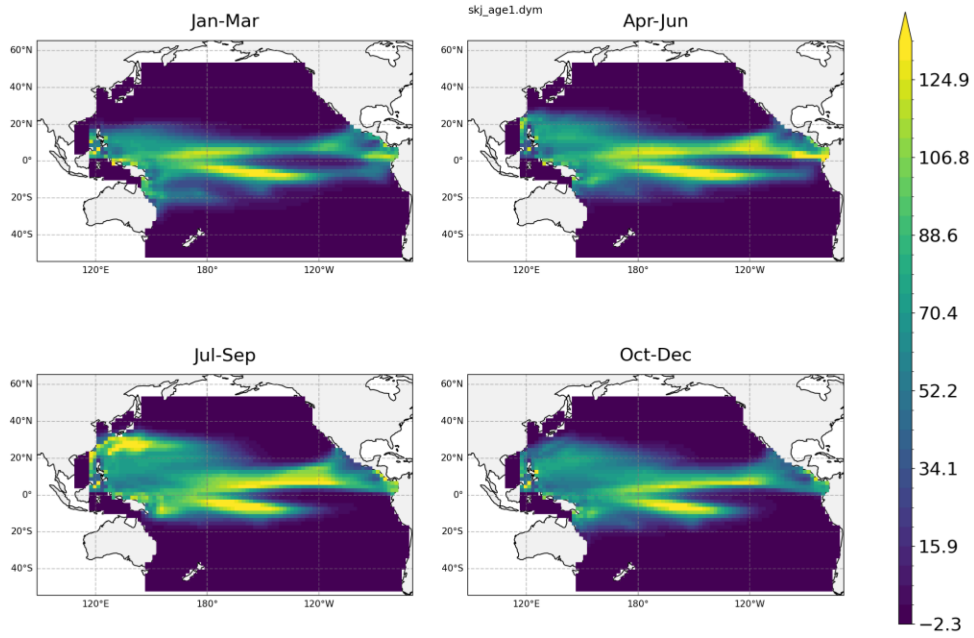
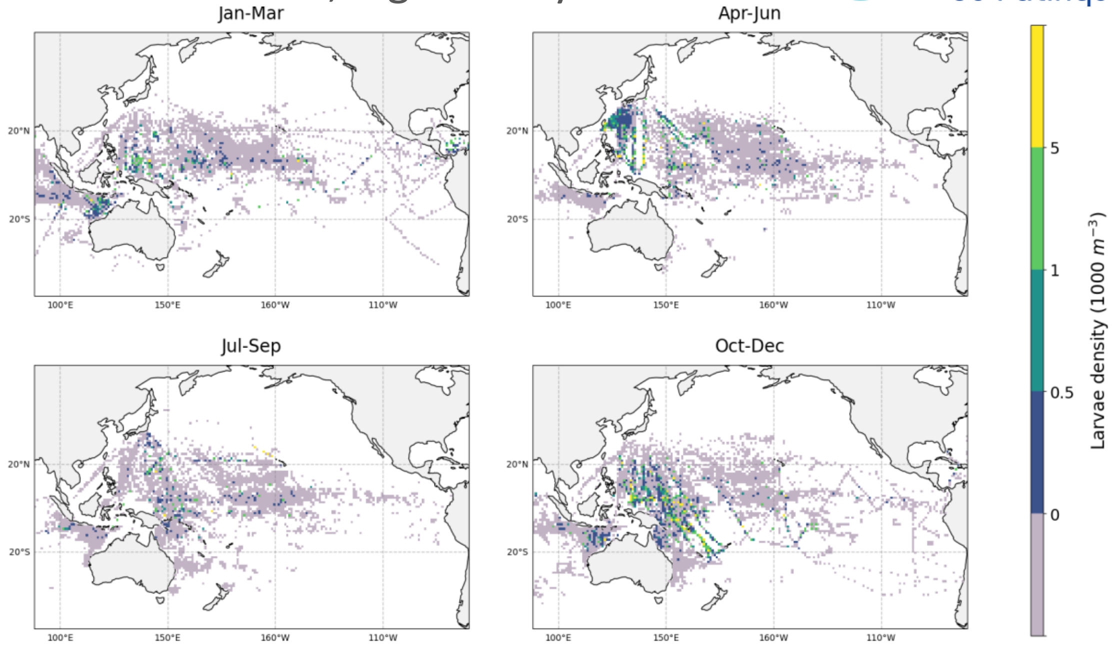
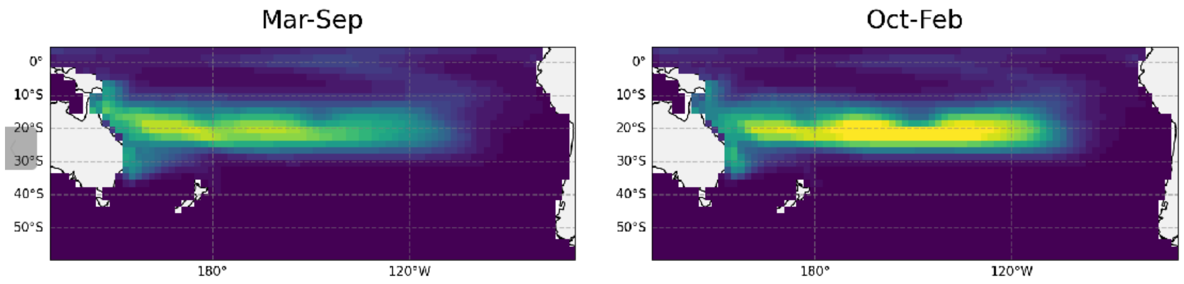


SEAPODYM skipjack tuna larval density

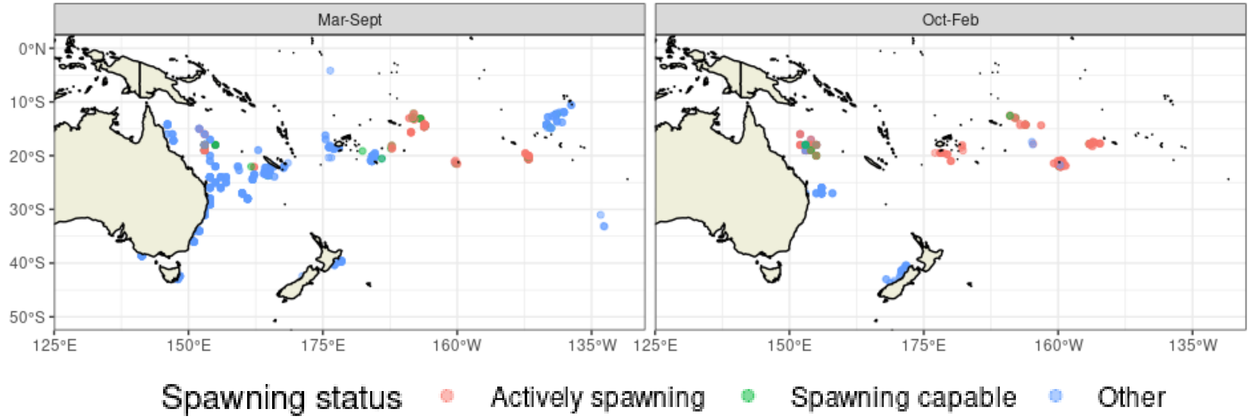
Nishikawa Atlas, digitized by Kristine Buenafe



Skipjack tuna larval CPUE (Buenafe et al. 2022, *Scientific Data*)



SEAPODYM albacore tuna larval density



Albacore tuna female gonad histological data (Farley et al. 2013, *Plos One*)

Larval model revision

Previous model

For a given t and at age 0, the density of larvae N_0 = N(0) is computed as

$$N(0) = H_s \frac{r\hat{N}}{1 + b\hat{N}}$$, where

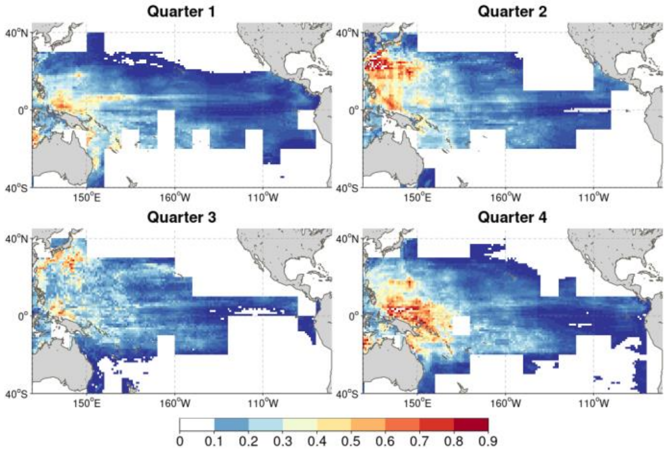
$$H_s = f_1(SST; T^*, \sigma) \times f_2(\Lambda, \alpha) \times f_3(F_1, \alpha_F, \beta_F)$$

$$\hat{N} = \int_{a_J}^{\bar{a}} \mu(a) N(a) da$$

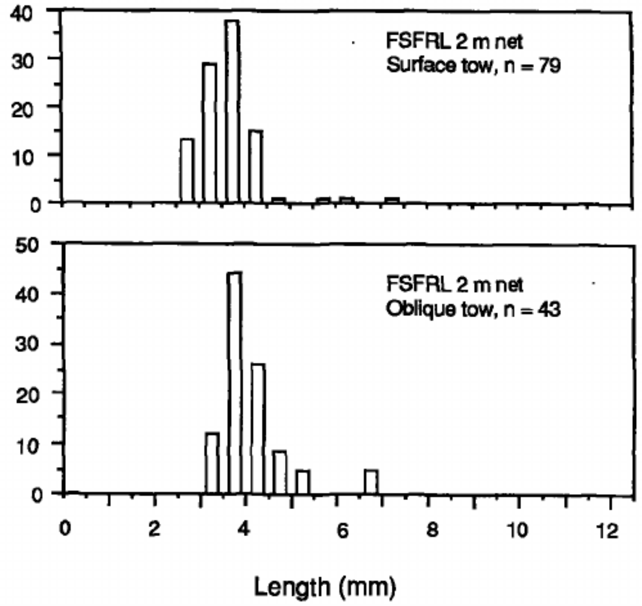
At t = t+30, density of larvae, N_0, is obtained as a solution of

$$\partial_t N_0 = -\mathrm{div}(\mathbf{v}N_0) + \nabla(D\nabla N_0) - MN_0$$, with $M = m_p\,(1+\epsilon)^{(1-H_s)}$

1. *Sizes of larvae caught by plankton nets are about 4mm on average, with 2-3mm being the size of the newly hatched larvae. Fast growing tuna larvae exceed 1cm at about 14 days.*
2. *Conditions for eggs hatching and survival evolve quickly at early development stage.*



Observed larvae are 4-6mm big!



Larval model revision

Revised model

For a given t and at age 0, the density (Nb/sq.km) of eggs $N(0)$ is computed as

$$N(0) = \frac{r\hat{N}}{1 + b\hat{N}}$$, where $$\hat{N} = \int_{a_J}^{\bar{a}} \mu(a)N(a)da$$

At t = t+[max.obs.age], density of early larvae, N_0, is obtained as a solution of

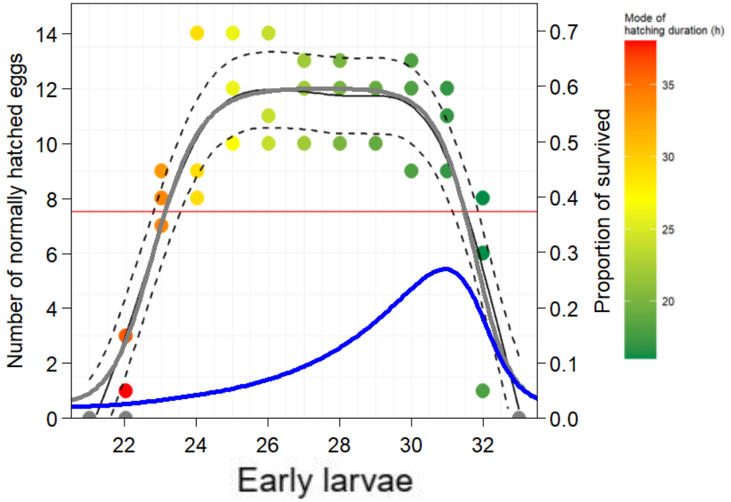
$$\partial_t N_0 = -\mathrm{div}(\mathbf{v}N_0) + \nabla(D\nabla N_0) - MN_0$$, where

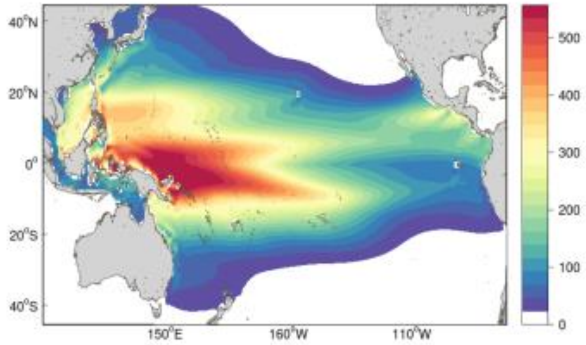
$$M = 0.5 + 3.3822 * \left(1 - \left(\frac{1}{1+0.2442^{T_0 - 21.8322}} - \frac{1}{1+0.1858^{32.5599 - T_0}} - 1\right) f_1(T_0)\right)$$

At t = t+30, density of early monthly larvae is obtained as a solution of

$$\partial_t N_0 = -\mathrm{div}(\mathbf{v}N_0) + \nabla(D\nabla N_0) - MN_0$$, where $$M = m_p\,(1+\epsilon)^{(1-H_s)}$$

Fujioka et al., 2024. Experimental study on eggs hatching success





PART 3. REFERENCE MODEL OF SKIPJACK TUNA

- Configuration;
- Assumptions and fixed parameters;
- Validation for early life data;
- Validation for tagging data;
- Validation for fisheries data;
- Estimated stock structure and size, fishing impact, environmental impact on recruitment and movement.

Model configuration for skipjack tuna

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$N(a,t,\mathbf{x})$ - density of fish population at age *a*, time *t* and position $\mathbf{x} = (x,y) \in \Omega \in \mathbf{R}^2$

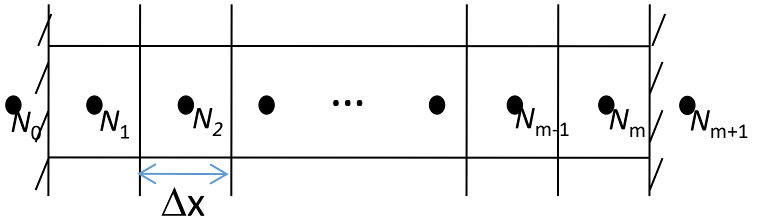
$$\partial_t N + \partial_a N = -\mathrm{div}(\mathbf{v}N) + \nabla(D\nabla N) - MN$$

$$N(a,\mathbf{x},t_0) = N_0(a,\mathbf{x})$$

$$N(0,\mathbf{x},t) = S(t,\mathbf{x})$$

$$\mathbf{n}\cdot\mathbf{v}\Big|_{\mathbf{x}\in\partial\Omega} = \mathbf{n}\cdot\nabla N\Big|_{\mathbf{x}\in\partial\Omega} = 0$$

SEAPODYM - *a numerical solution of underlying continuous equations in a discretised space*



OCEAN INPUTS

Physical (T, u, v) and biogeochemical variables (P, O_2)

NEMO-ERA5-ORCA1, NEMO-JRA55-ORCA1

Biological variables ($F_{1..6}$): **SEAPODYM-LMTL** 1° x 30d

SKIPJACK MODEL

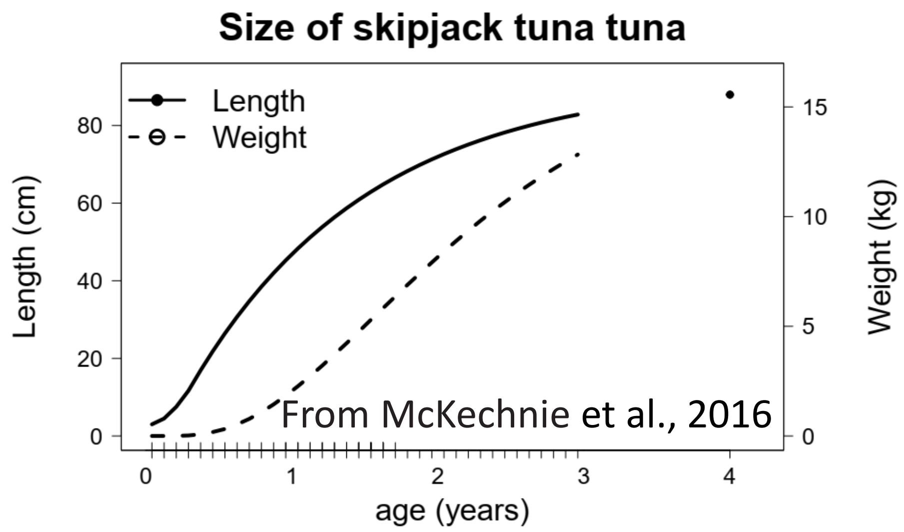
OPTIMIZATION : 2° x 30d x 30d & 1° x 30d x 30d;

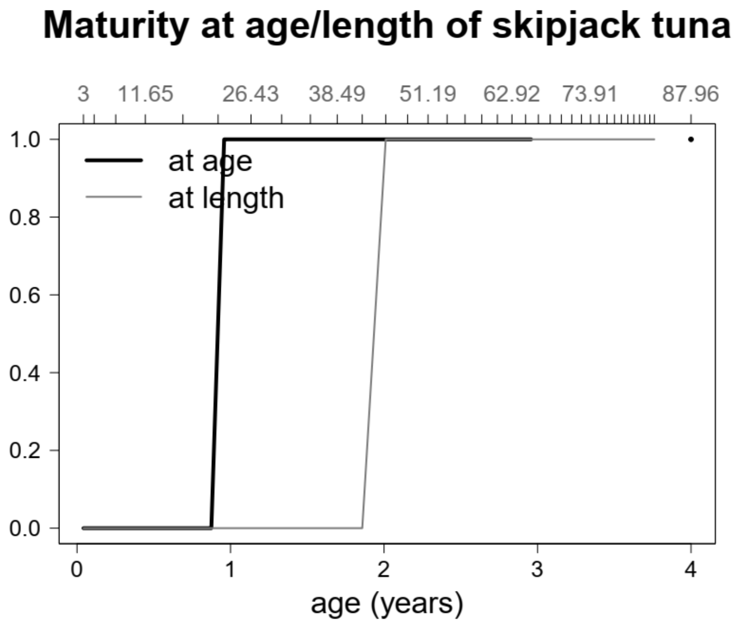
C, LF 1995-2012; EL 1995-2000, T 1994-2012
(12241 tags from 46 WCPO tag groups)

MLE with Catch (PL/EC, PS/CR), Length, Tagging and Early Life Data and **26-35 parameters to estimate**

SIMULATION/VALIDATION : 1° x 30d x 30d & 2° x 30d x 30d; **1960-2022.**

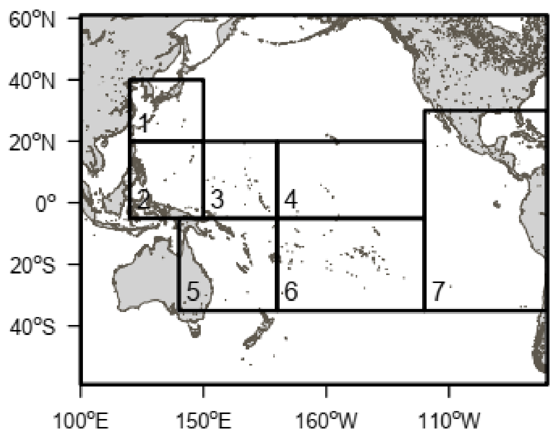
Fixed parameters and assumptions

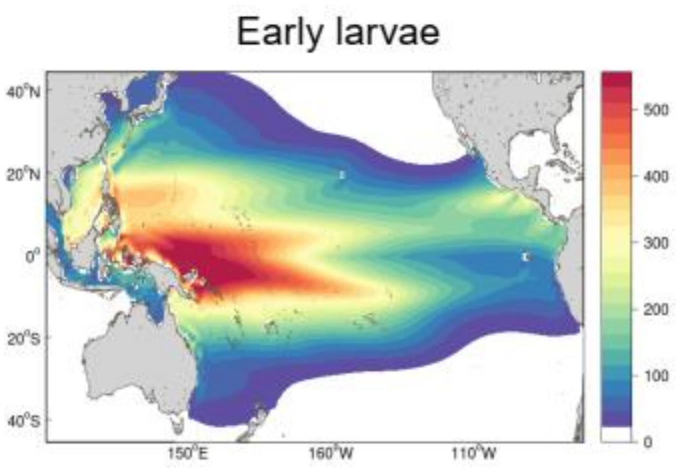




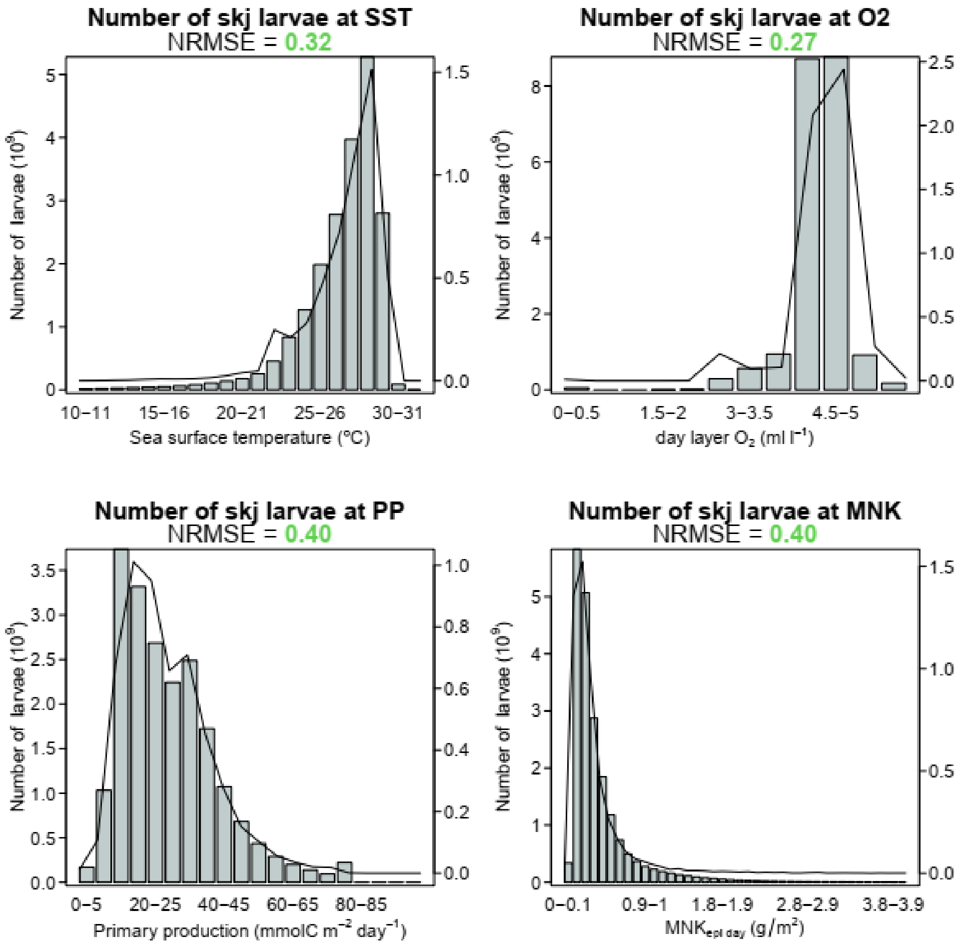
1. The model structure is suitable to describe skipjack population dynamics;
2. Skipjack does not undertake seasonal migrations for spawning;
3. Maturity can be approximated by a “knife-edged” function;
4. The average Pacific Ocean stock did not exceed 9Mt over 1995-2012;
5. Individual fisheries, as defined in the model, can be assumed to have constant (across space) catchability and selectivity;
6. Catchability of pole-and-line fisheries (JPPL split in 1981 and 1990) wasn’t increasing in time;
7. Fixed values of some parameters (correlated with other parameters or poorly observed from available data) do not influence the optimal solution;

Early life data validation scores





Spatial fit to observed densities (BRTMs)



Seasonality of spawning

Reg	HS model	CLT-JRA	CLTE-JRA
1	0.59	0.3	0.66
2	0.07	-0.07	0.24
3	-0.11	0.36	0.33
4	0.68	0.76	0.58
5	0.8	0.74	0.92
6	0.75	-0.08	0.69
7	0.9	0.93	0.96

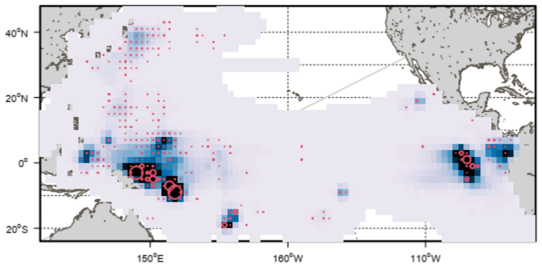
Validation of tag distributions

Statistical scores for ***Independent Data***

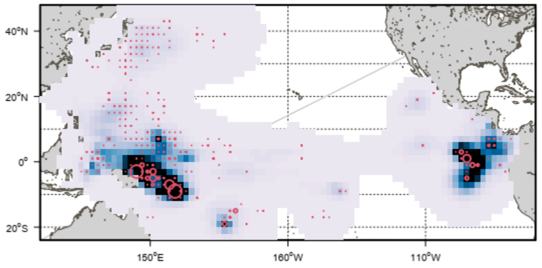
	1979-2008, 2x30d		*All but MLE obs (14t)*	
Metric	**INTERIM**	**CLTE-JRA**	**CLT-JRA-2**	**CLTE-JRA-1**
Exp. var	0.53	**0.82**	**0.59**	**0.72**
Var. ratio	0.59	**0.73**	**0.86**	**0.73**
NMSE	0.69	**0.43**	**0.66**	**0.53**

Tag recaptures
(all but MLE observations)

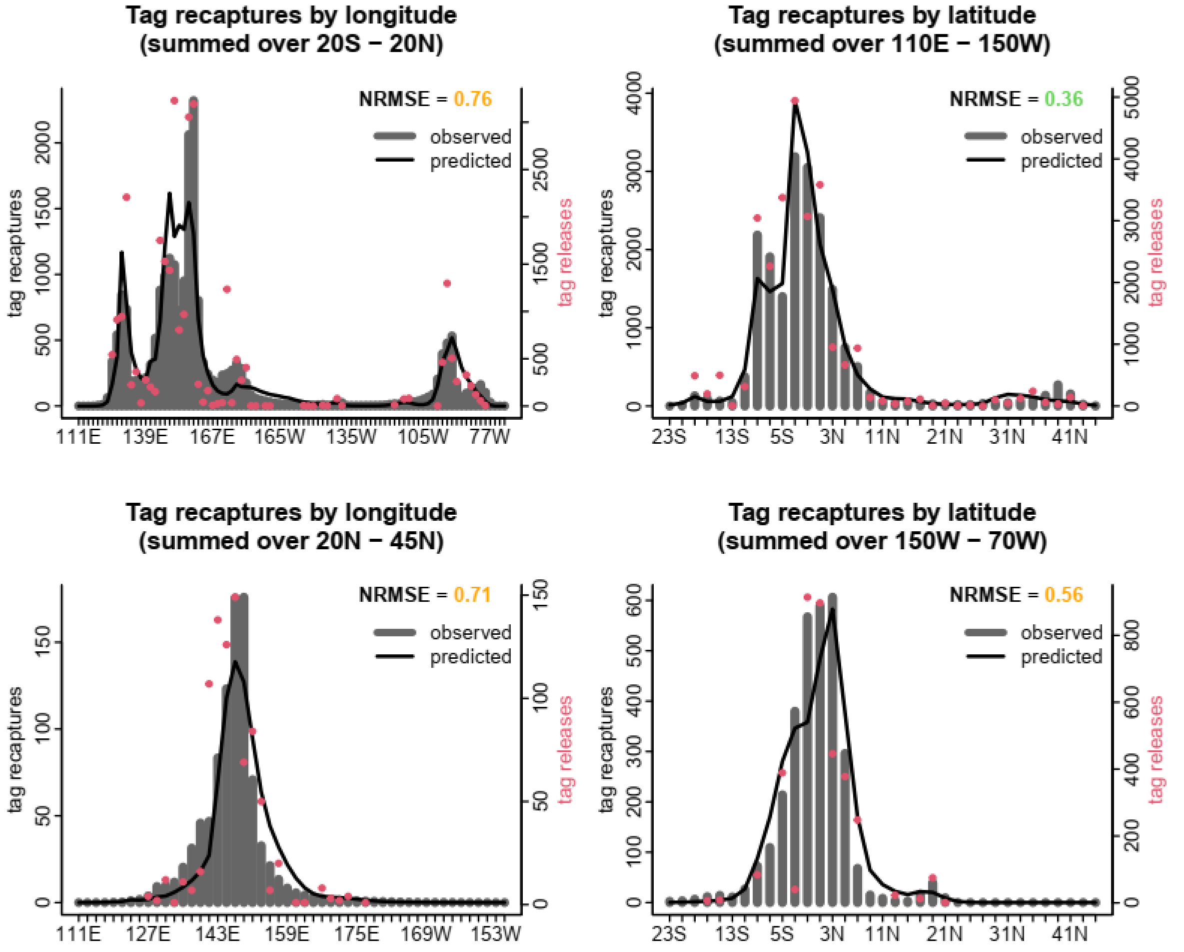
observed



predicted



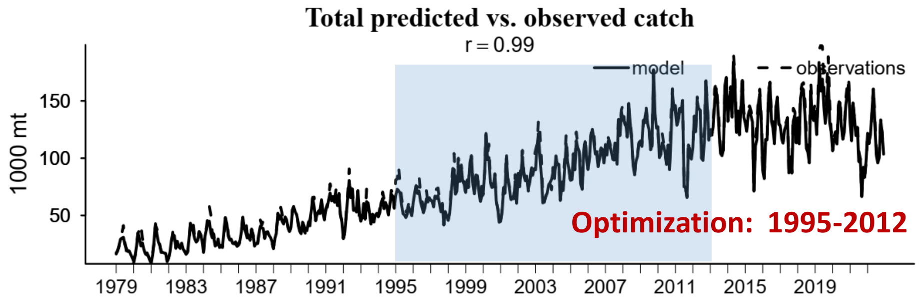
1D profiles: all tags vs all but MLE observations



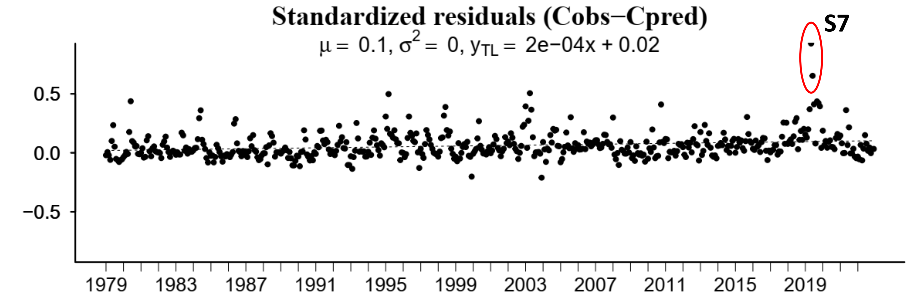
EPO data provided by Dan Fuller

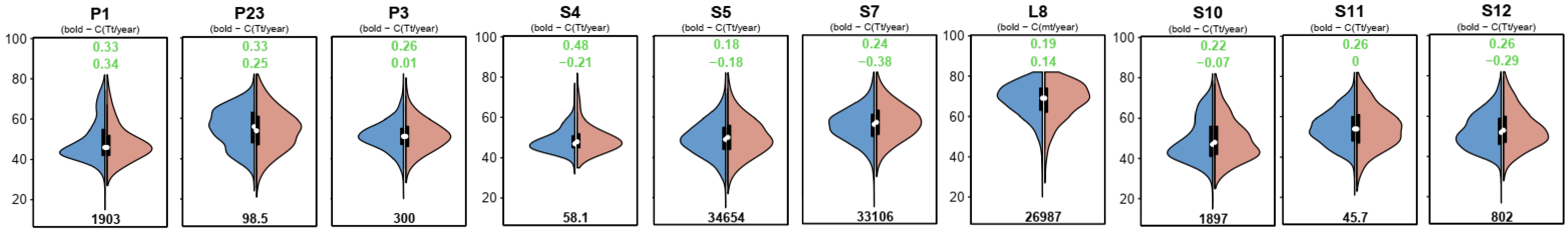
Validation scores for catch and length frequency data

Metric	CLTE JRA55-NP	CLTE JRA55-NP
Catch	**1995-2012**	**1979-2022**
Expl. variance	0.85	0.85
Variance ratio	0.74	0.72
NMSE	0.39	0.39
Length		
NRMSE PL WCPO	0.34, 0.32, 0.43	0.33, 0.33, 0.26
NRMSE PS WCPO	0.19, 0.3, 0.36,0.48	0.18, 0.26, 0.24,0.48
NRMSE PS EPO	0.28, 0.27, 0.28	0.22, 0.26, 0.26
NRMSE LL	0.2	0.18

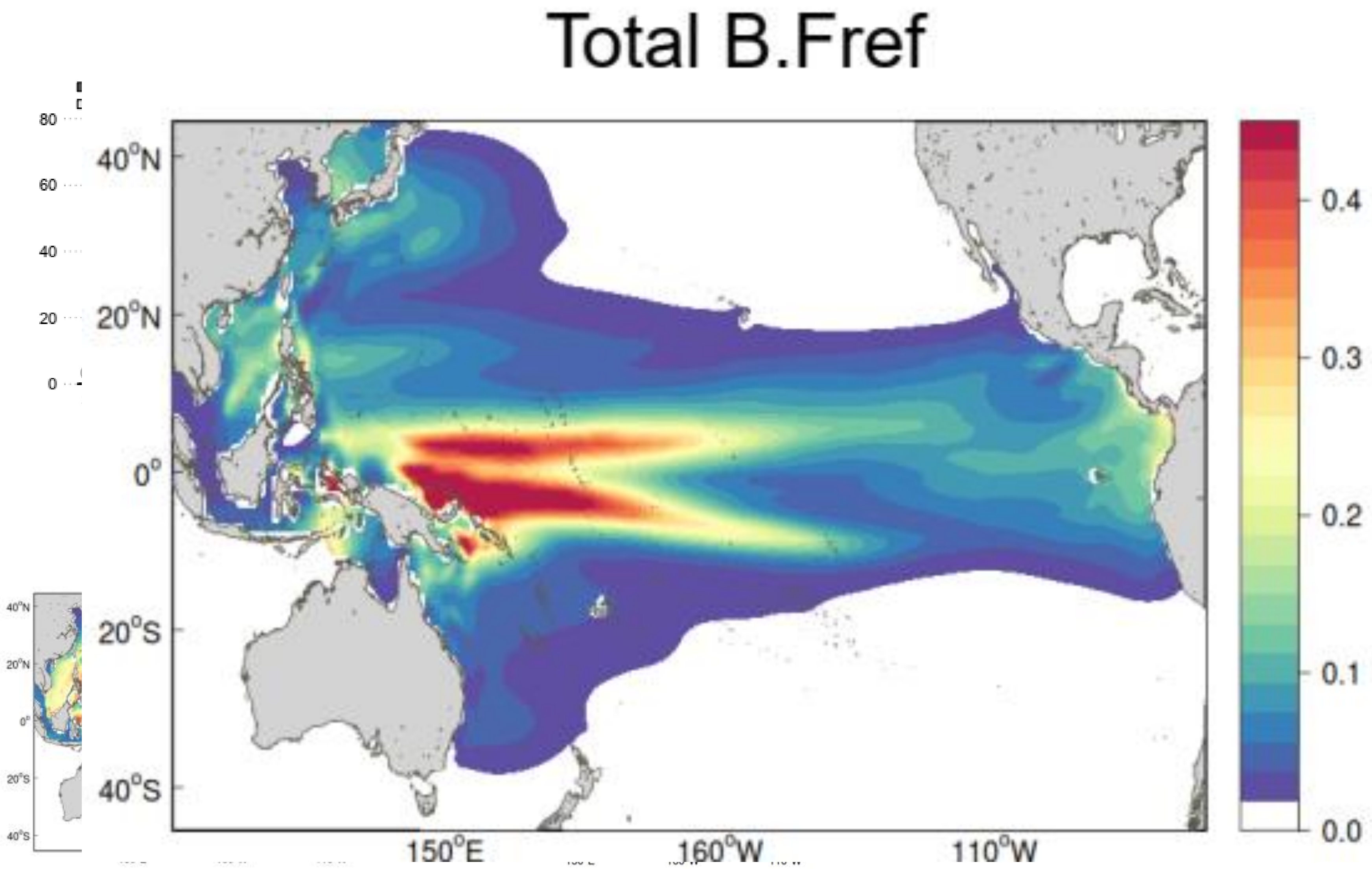


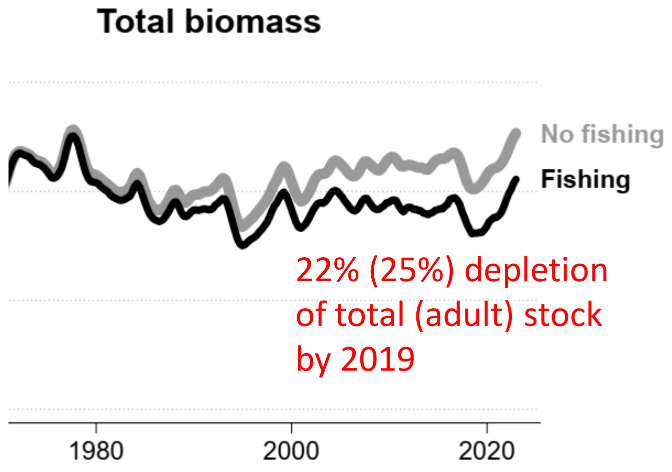
! *PS catches computed with catch removal method*



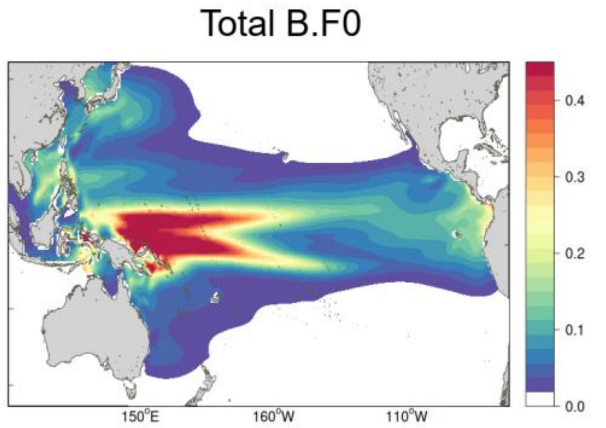


Estimated stock structures and size





22% (25%) depletion of total (adult) stock by 2019

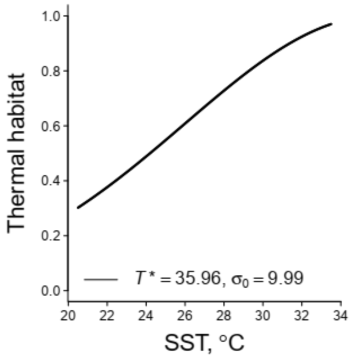


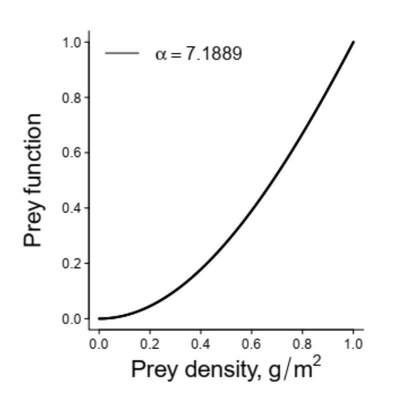
PART 4. SKIPJACK MODEL ANALYSES

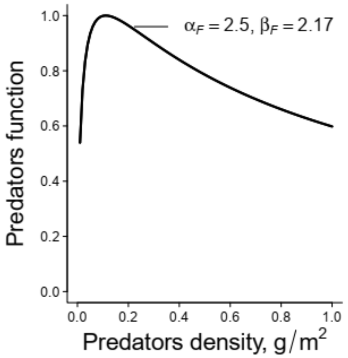
- Impact of environmental variability on recruitment and movement;
- Movement alone: age and interannual spatial variability;
- Comparison with Multifan-CL
- Effort creep estimation for Japanese pole-and-line fisheries

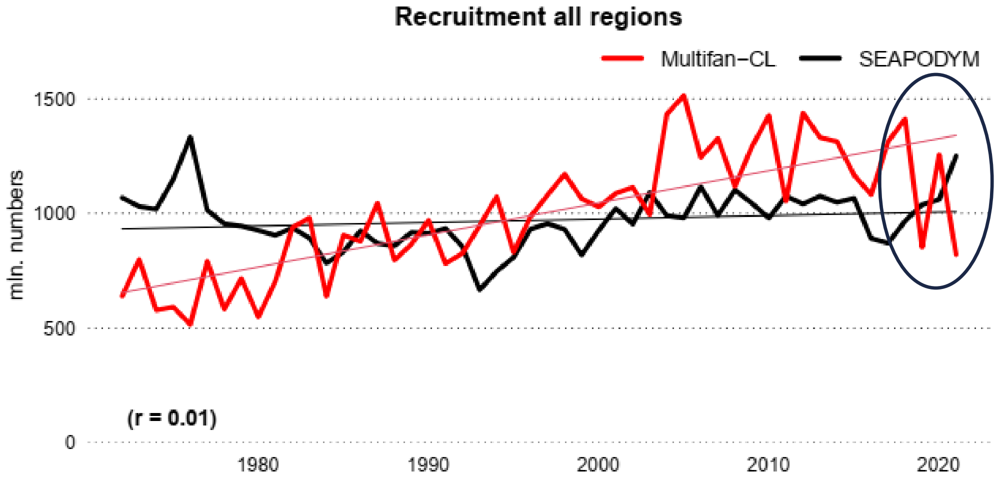
Impact of environmental variability on recruitment

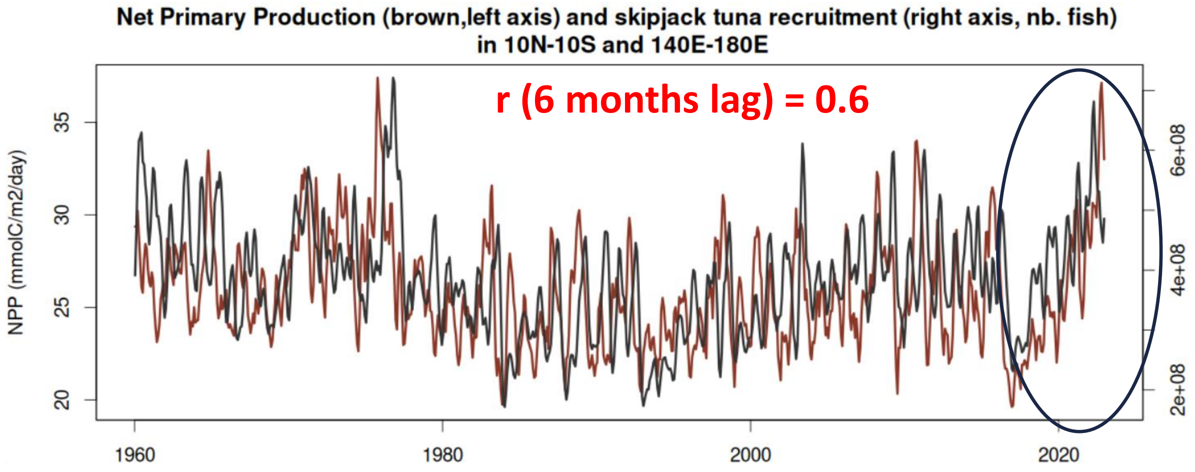
Ocean productivity – main environmental driver of skipjack recruitment

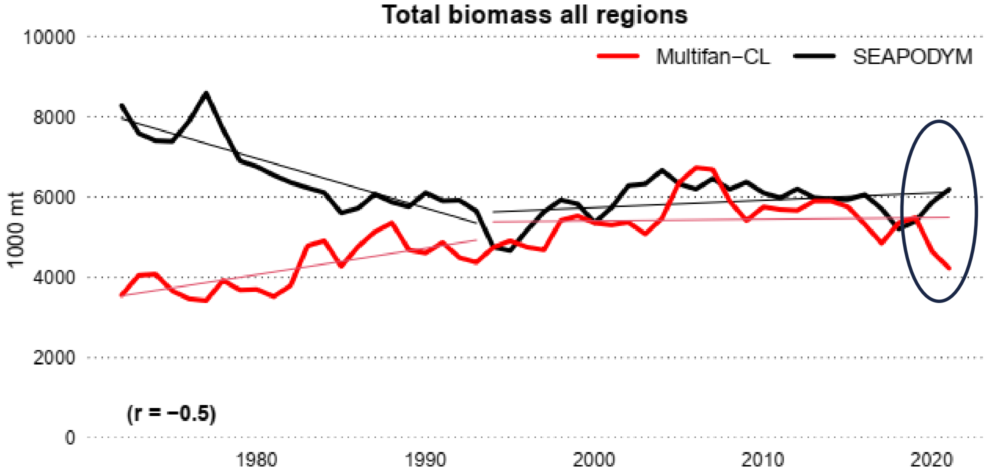




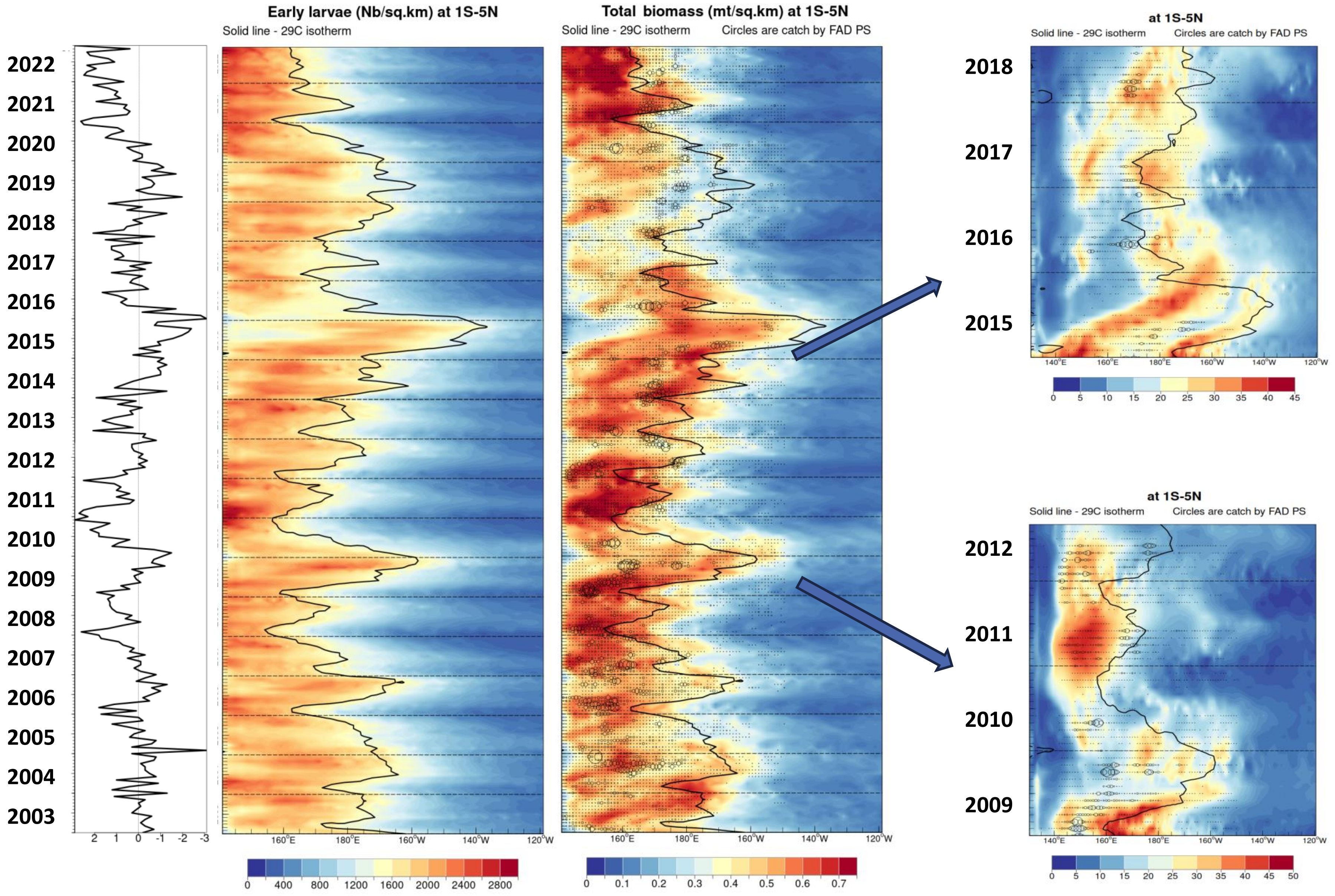








Impact of environmental variability on recruitment and movement

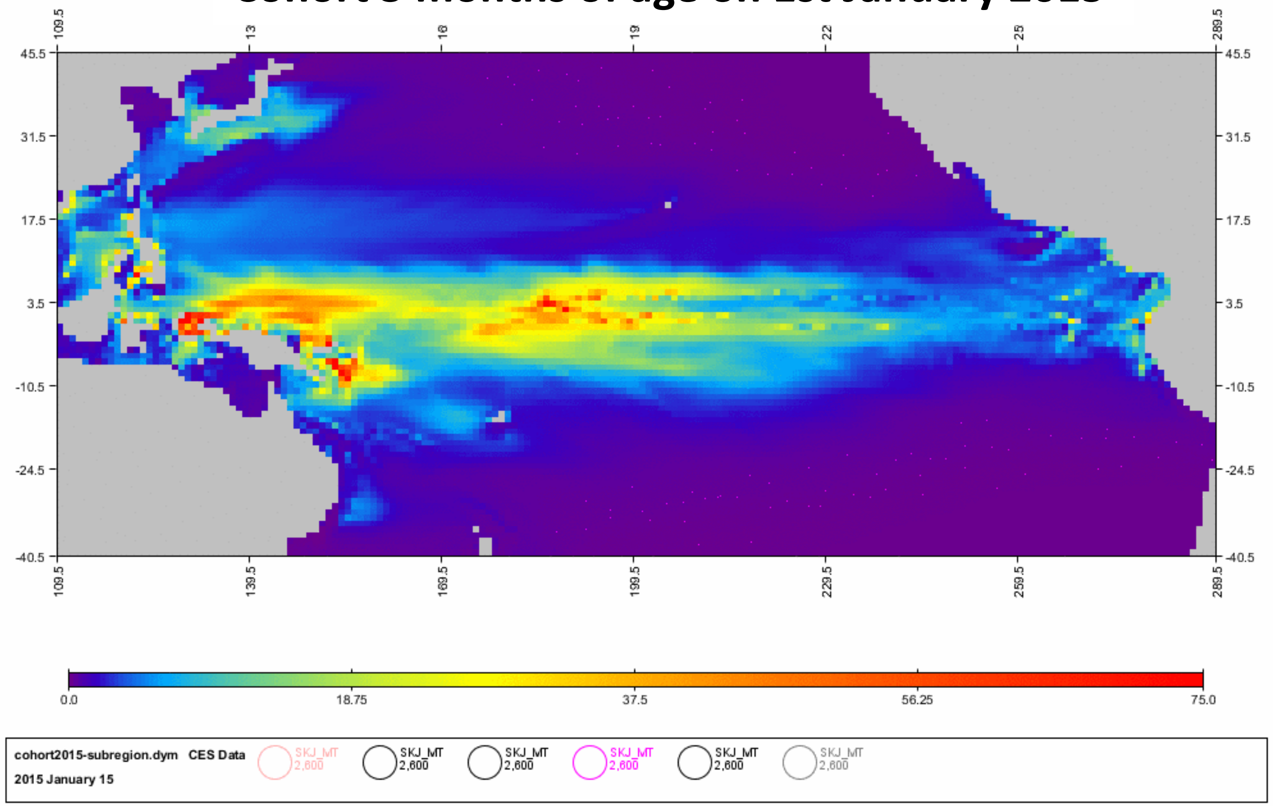


Movement only,
No mortality

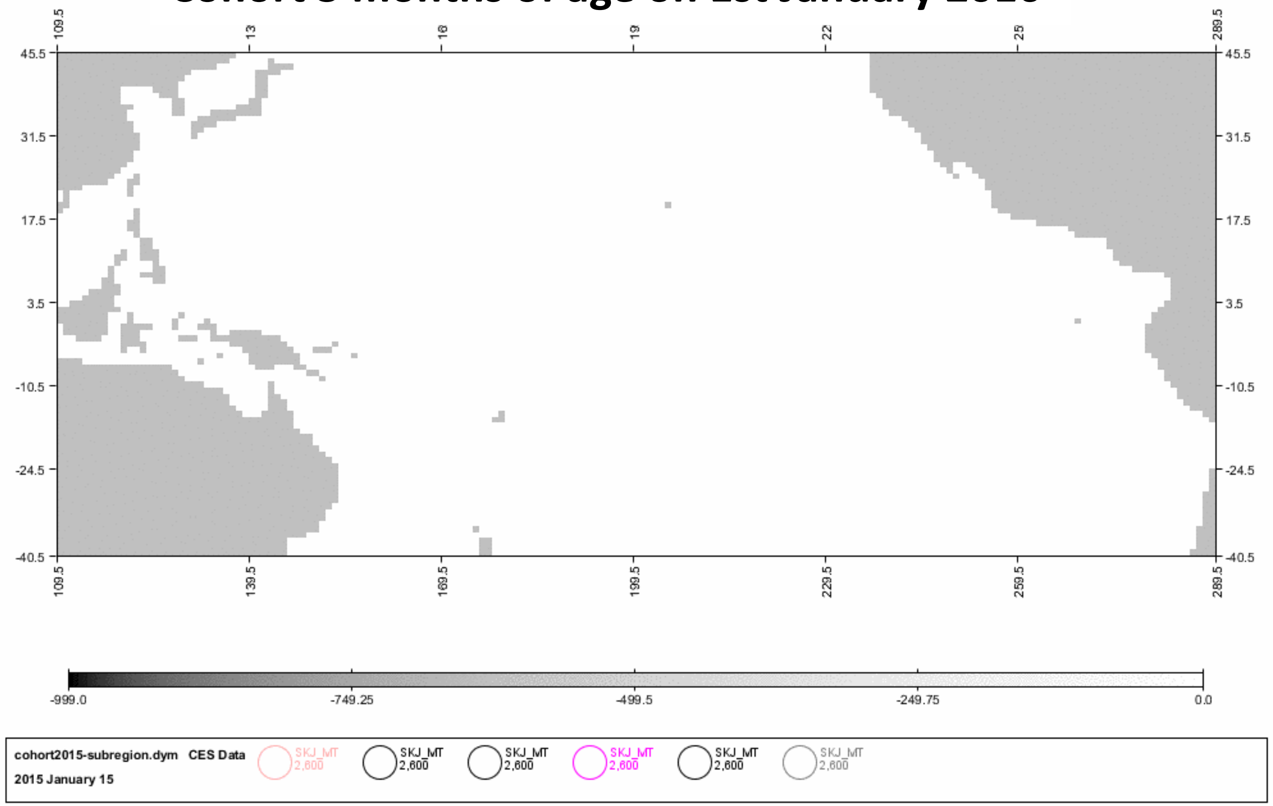
Impact of environmental variability on recruitment and movement

Movement only, No mortality: same times, different age (1 year difference)

Cohort 3 months of age on 1st January 2015

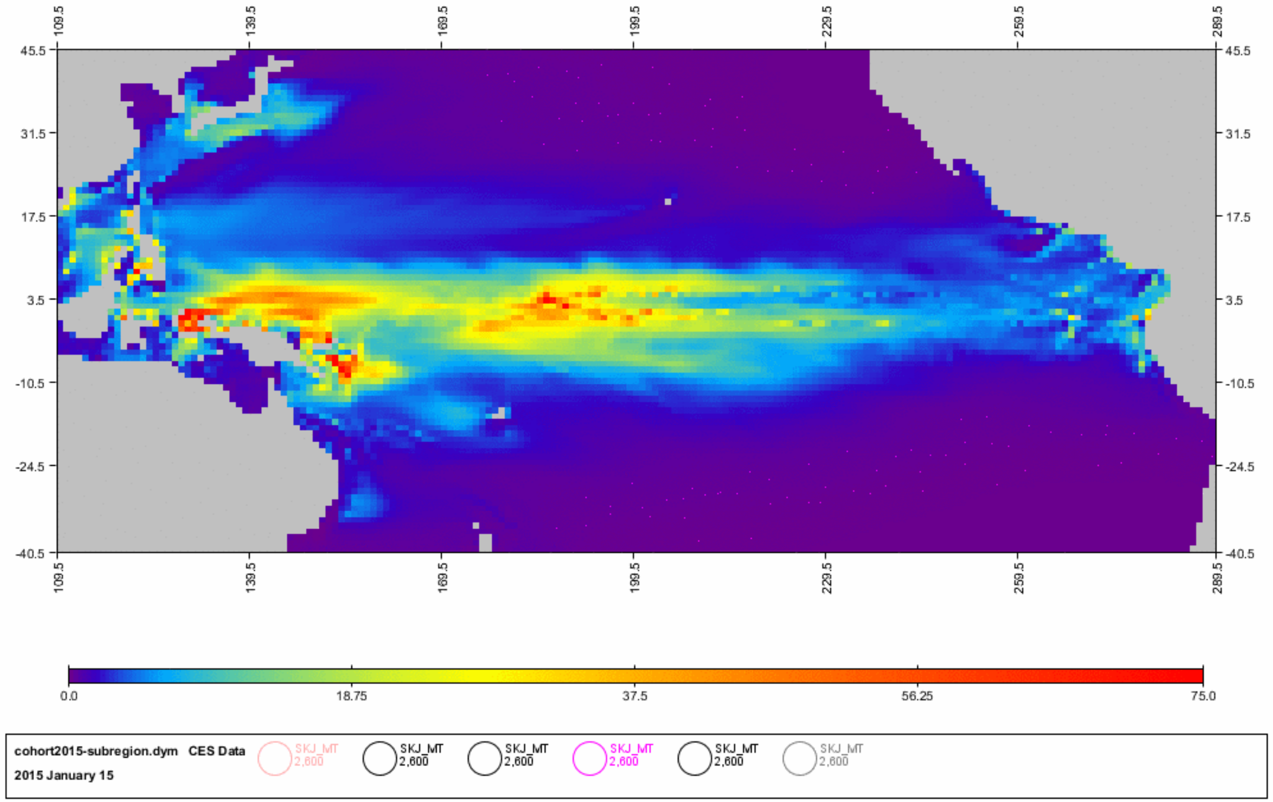


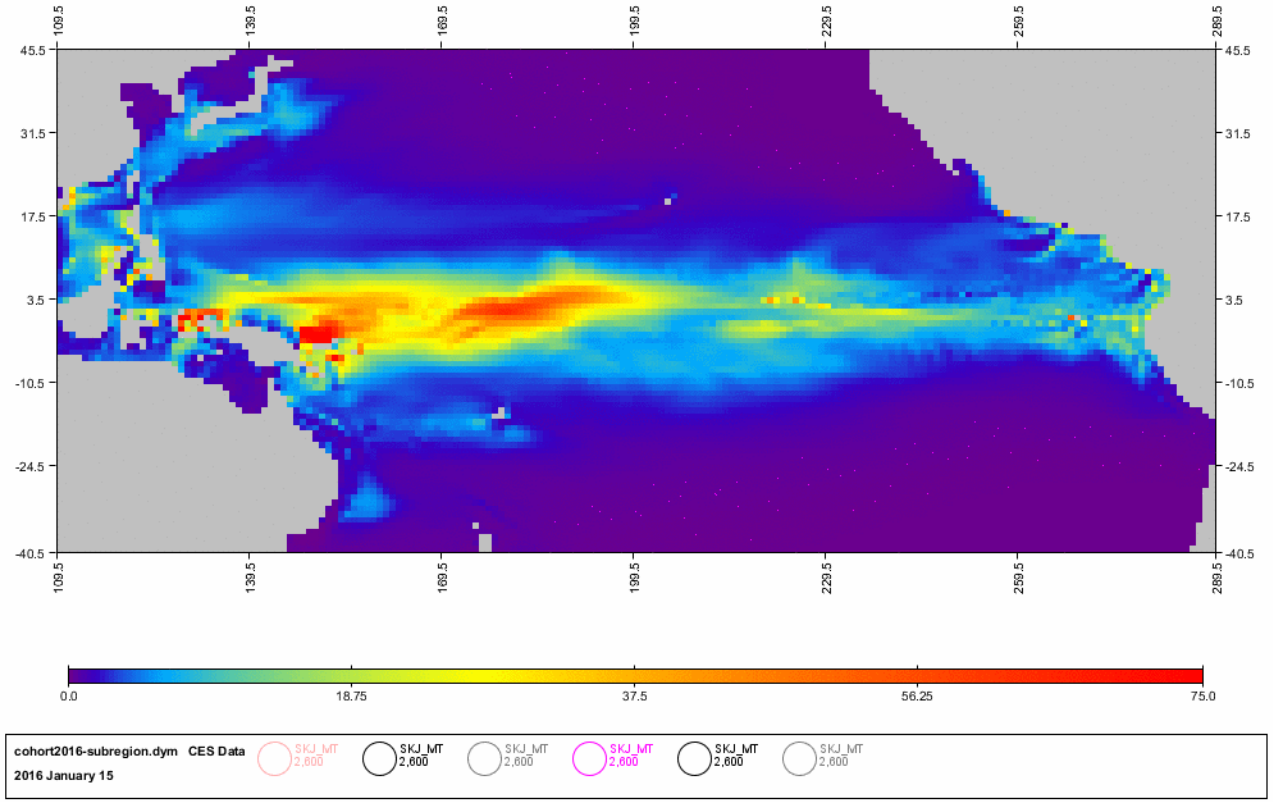
Cohort 3 months of age on 1st January 2016



Impact of environmental variability on recruitment and movement

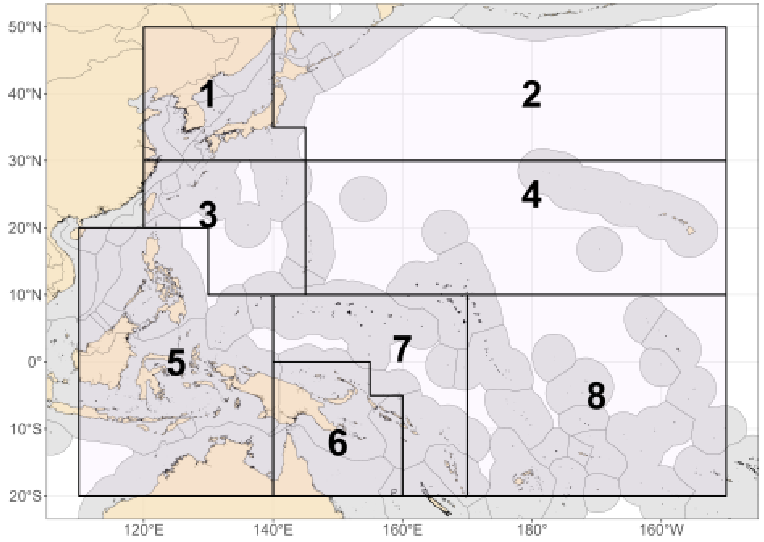
Movement only, No mortality: same age, different times



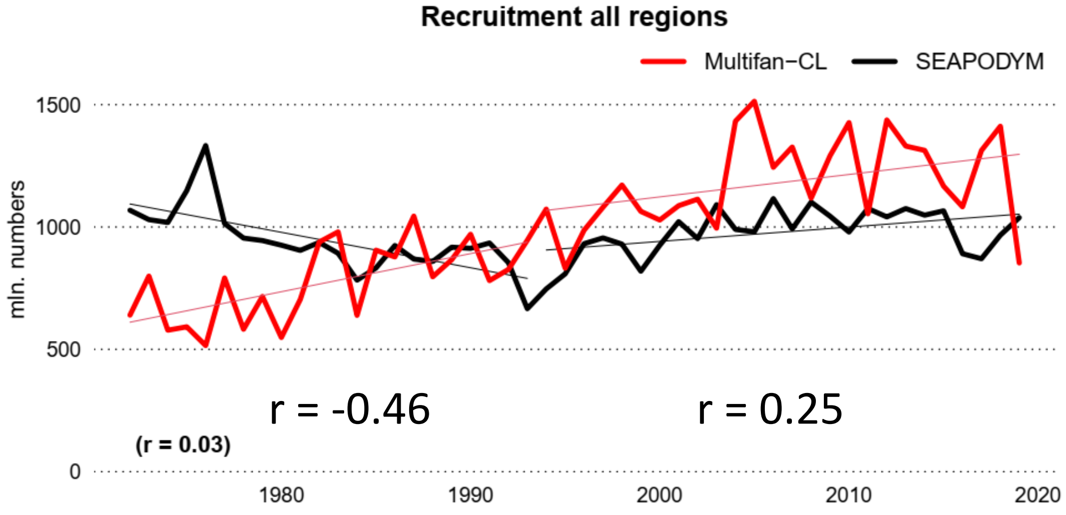


Need to use IKAMOANA to trace the density!

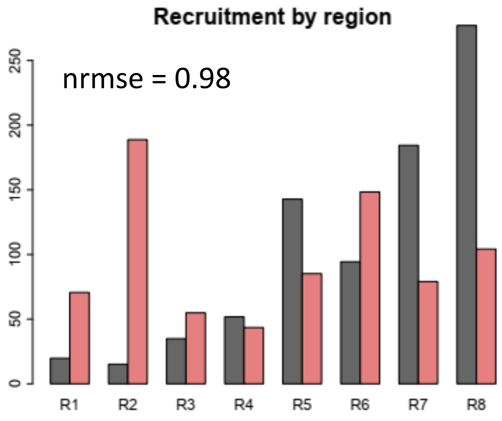
SEAPODYM and MULTIFAN-CL: why they are diverging before mid-nineties?



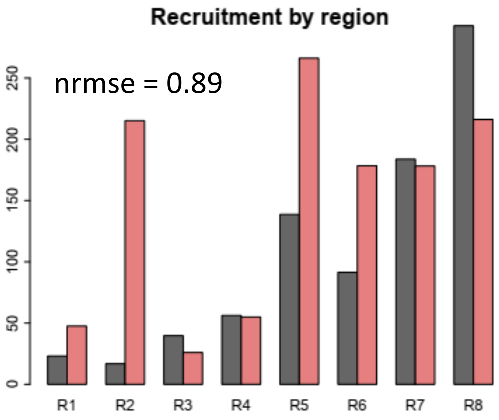
1. The break in correlations between models coincide with the development of the PS gear;
2. Positive trends after 1994

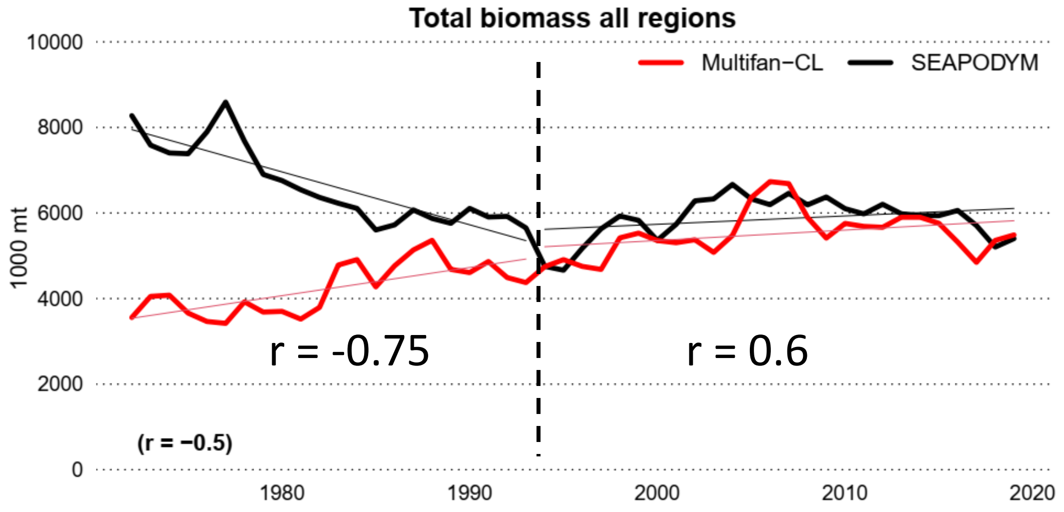


1960 – 1993



1994 - 2019

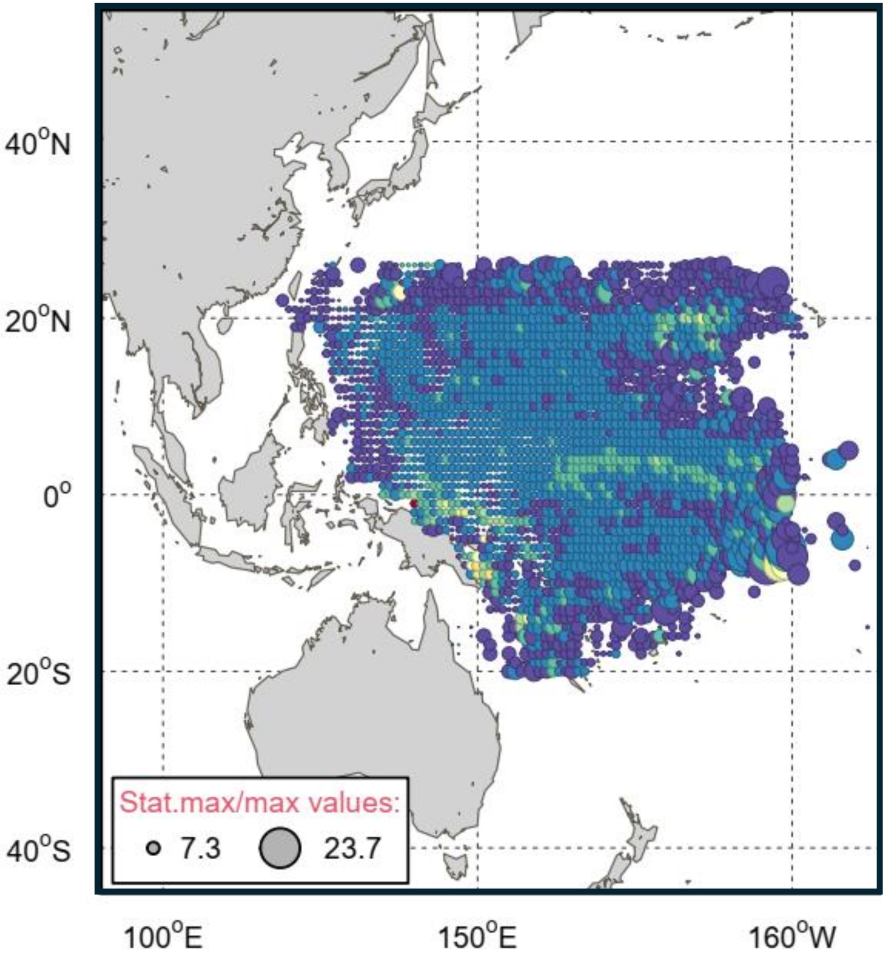


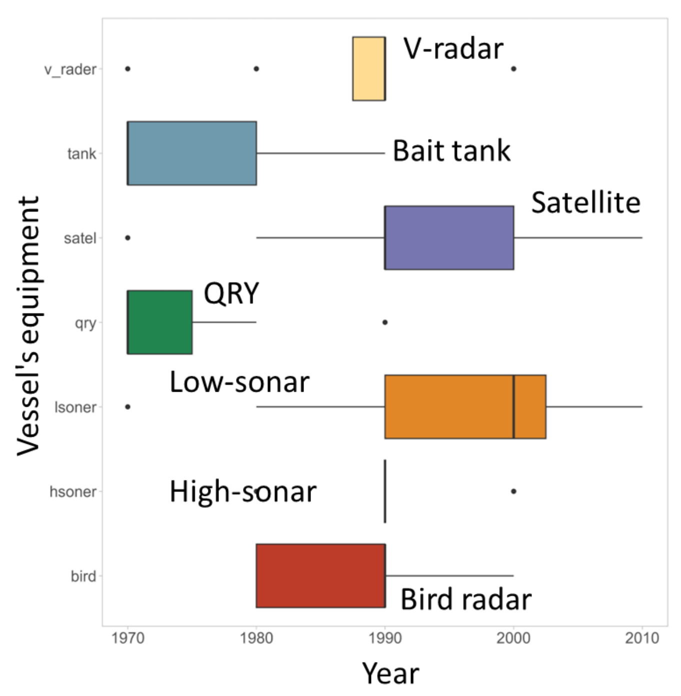


JP-PL effort creep estimation in SEAPODYM

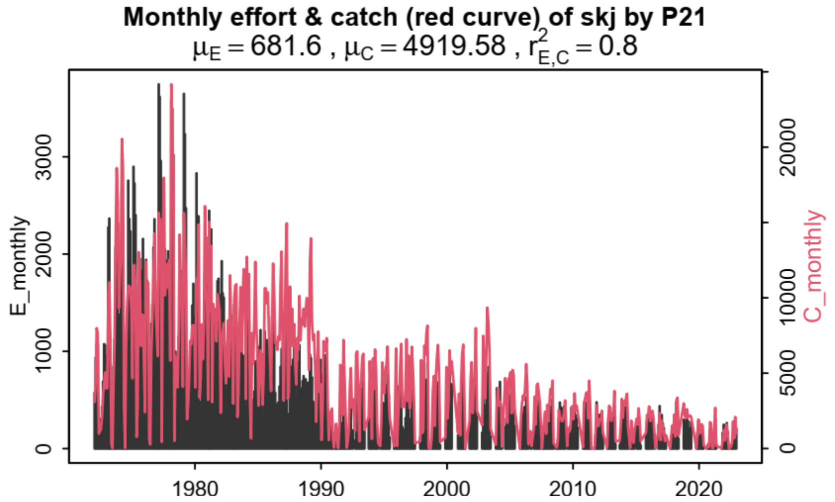
- *Evolution of Japanese tropical pole-and-line fishery from 1972 to 2022*

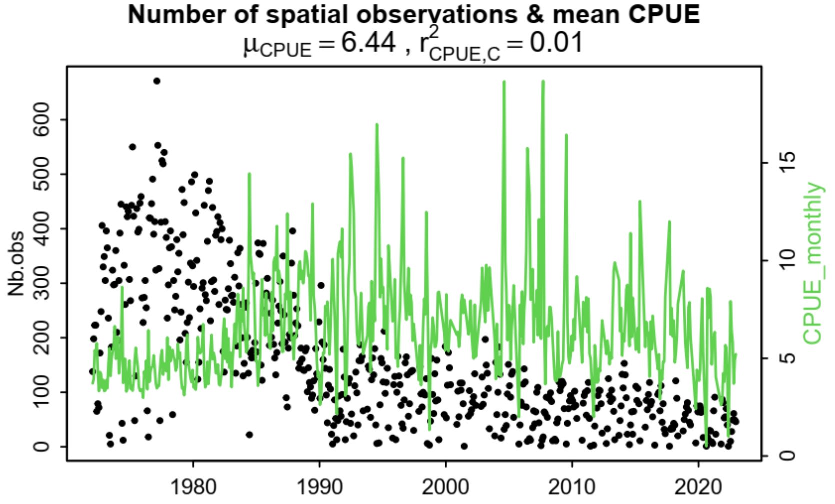
Mean CPUE (circle size) and effort (color)





Credit: Nishimoto et al., 2023
Hamer et al., 2024

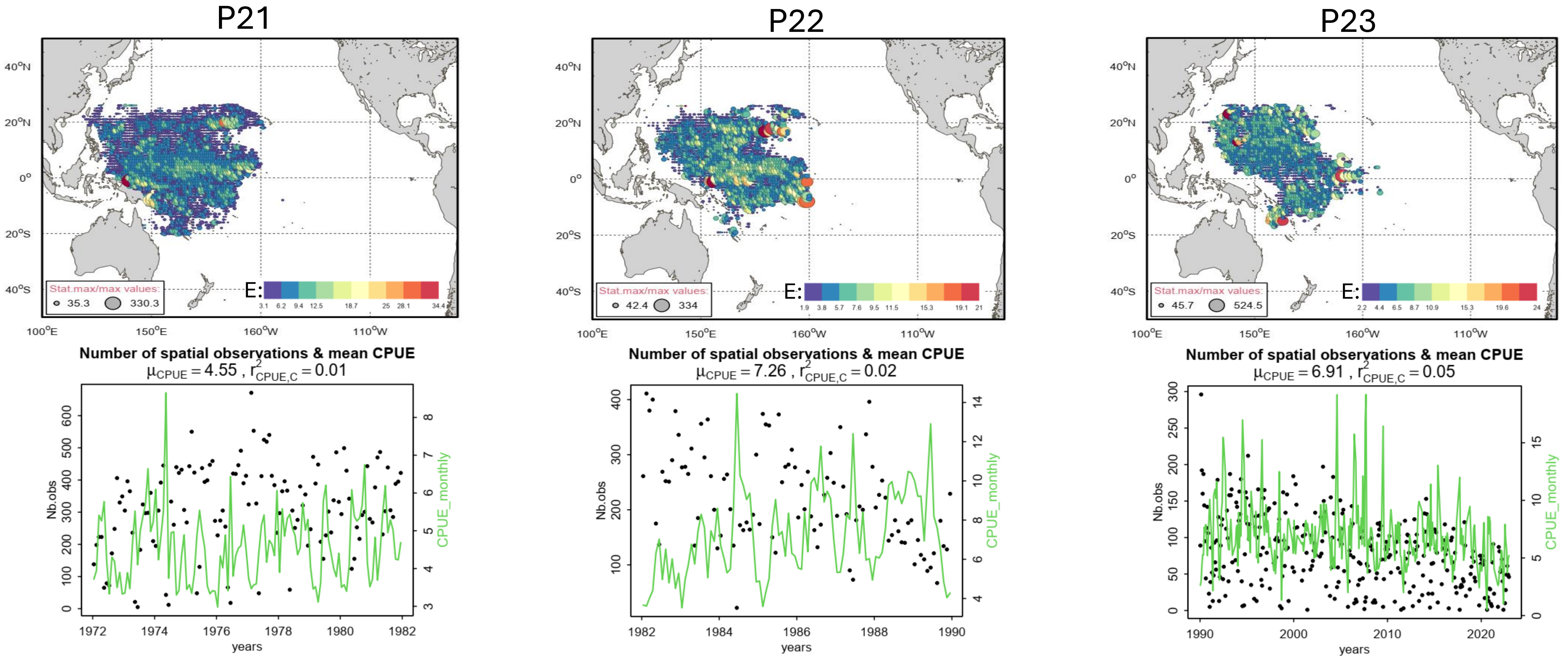




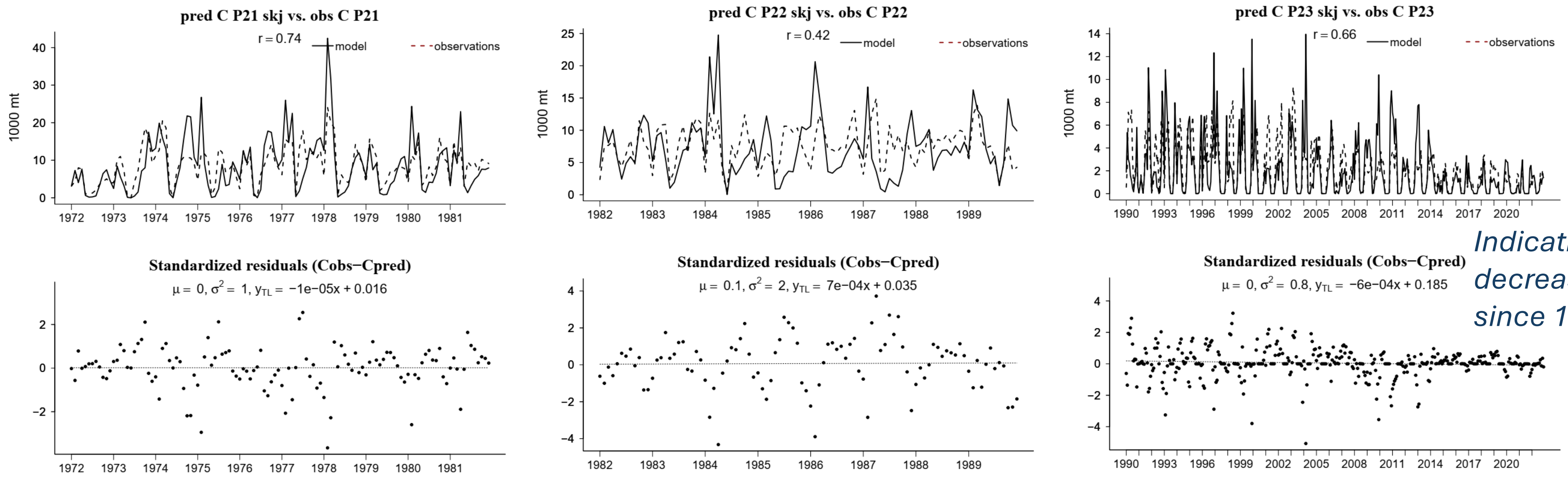
JP-PL effort creep estimation in SEAPODYM

- *<u>Effort creep is an emergent property in SEAPODYM</u>, since the model state is driven by environmental variability and not the fisheries CPUE. To fit to the pole-and-line data, given the model state variable, the fishery was split in three parts, P21 in 1972-1981, P22 in 1982-1989 and P23 in 1990-2022 and catchability with their linear slopes were estimated and calibrated (for now), respectively.*

Mean catches (circle size) and effort (color)

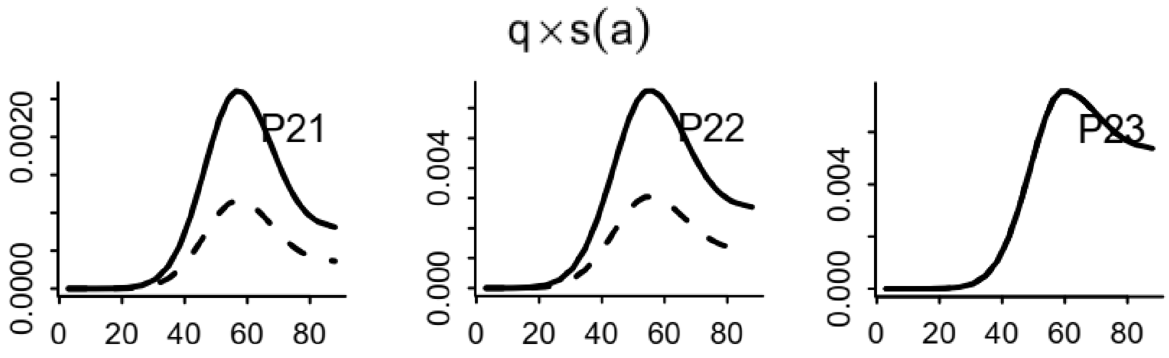


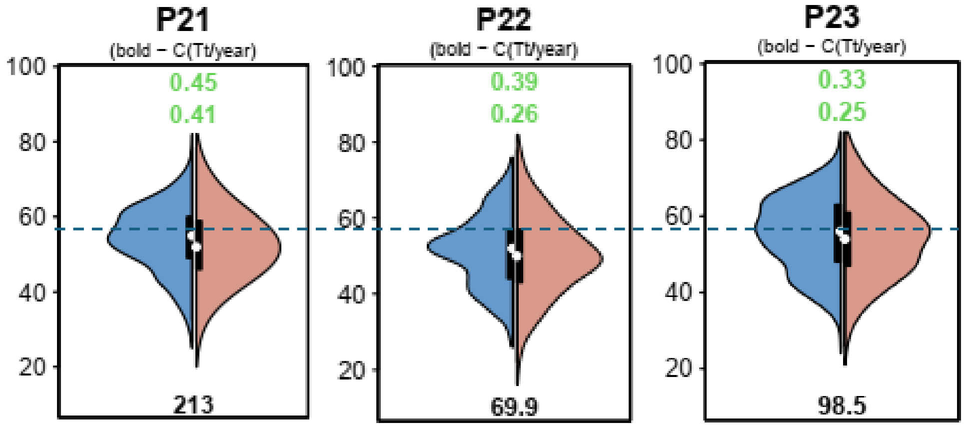
JP-PL effort creep estimation in SEAPODYM



Indication of decreasing trend since 1990.

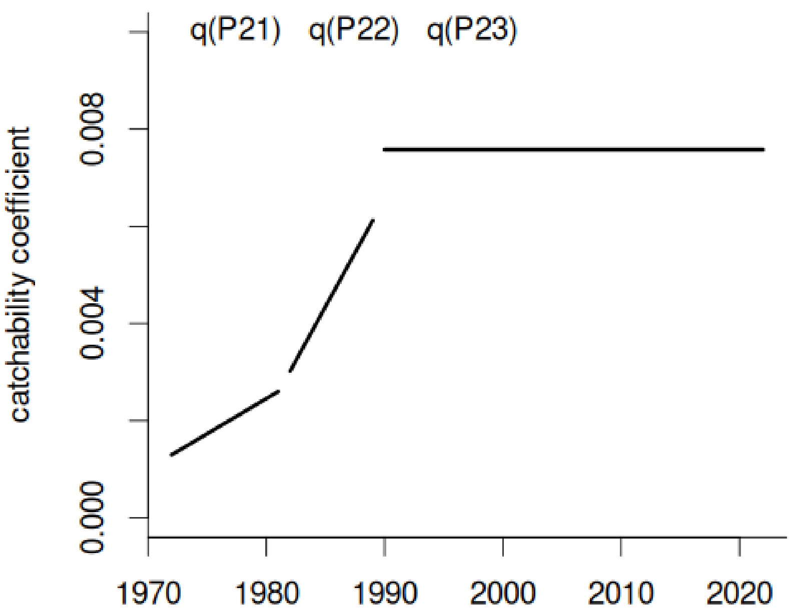
- *Note, after 1990 PL fishery seems to catch wider size ranges, with larger skipjack in catches.*

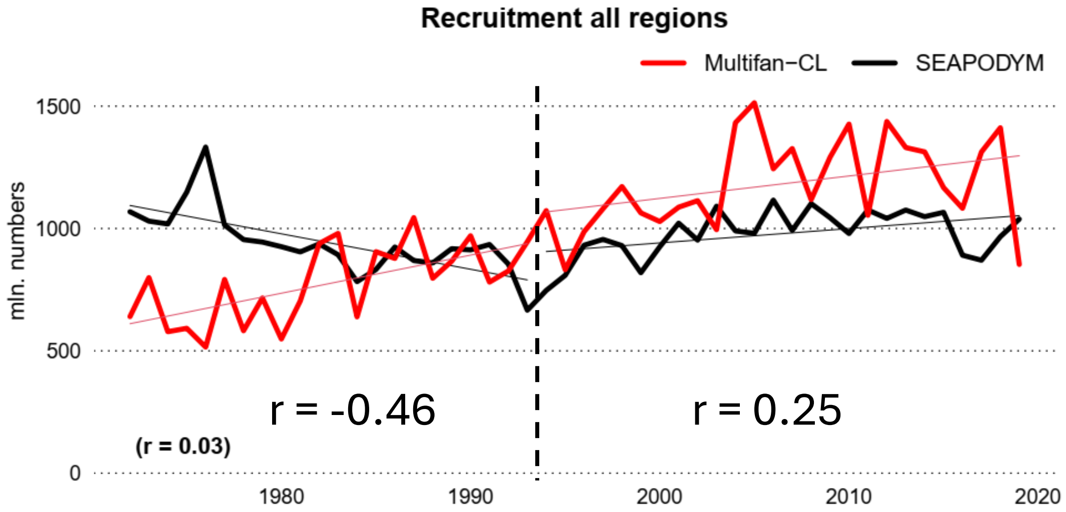


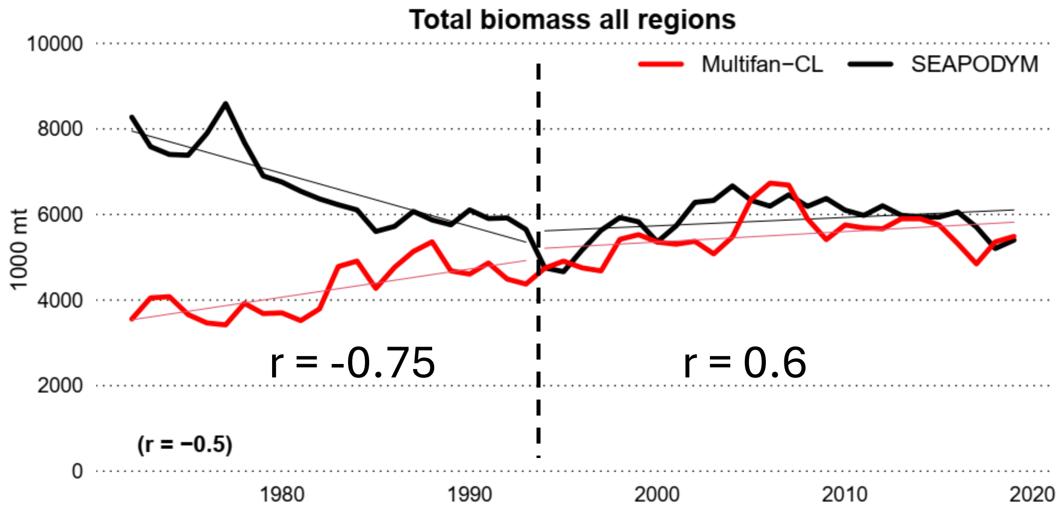


JP-PL effort creep estimation in SEAPODYM

- *Estimating* ***6.5 (4)-fold increase of catchability from 1972 (1976) to 2022***





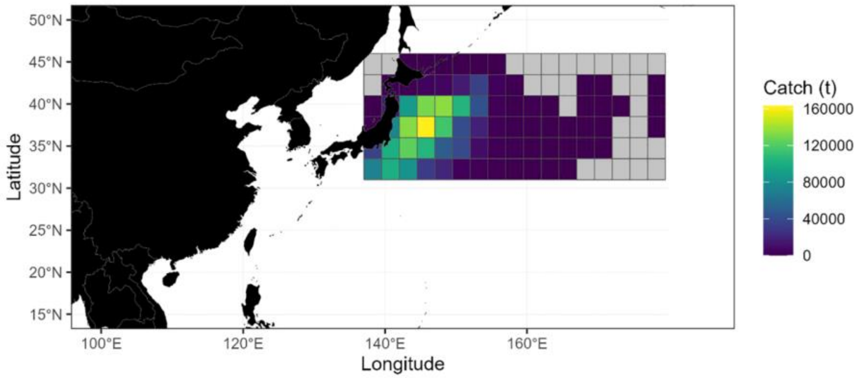


- *Not including the PL effort creep in the MULTIFAN-CL model likely is responsible for estimating a persistent increasing trend in recruitment and total biomass, which are not present in SEAPODYM estimation.*

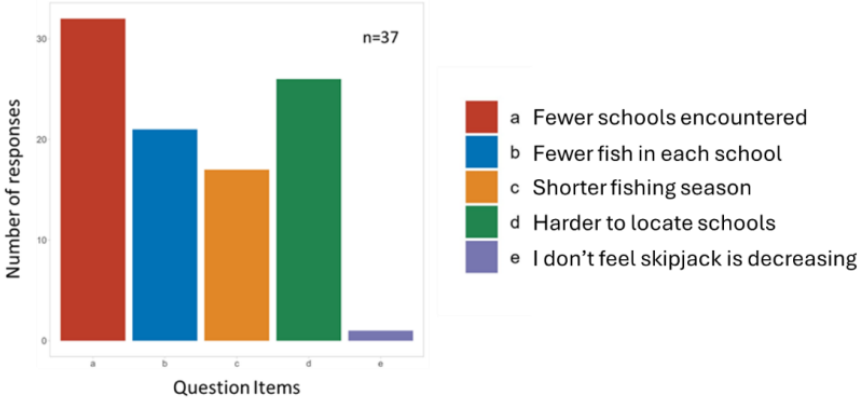
JP-PL effort creep estimation by Bayesian state-space models

- *<u>Results from recent study by Makoto Nishimoto et al., Frontiers in Marine Science, 2024</u>*

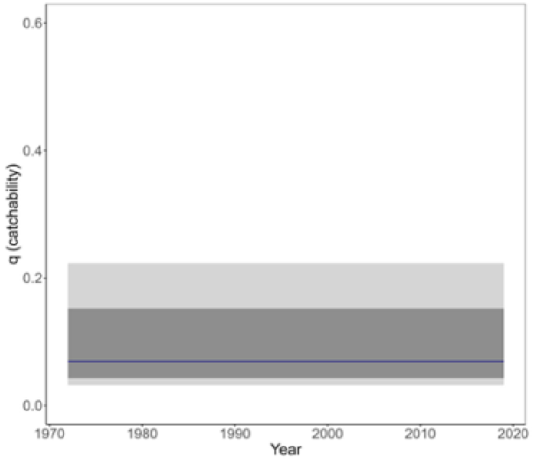
Study area of the PL fleet, 1972-2019

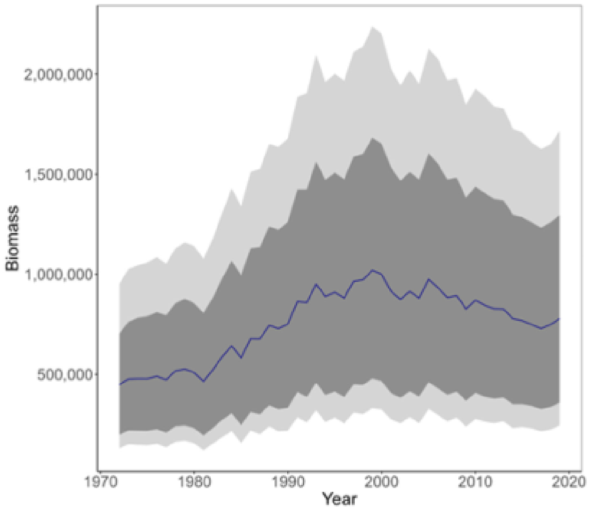


Survey: fishers about skipjack stock changes



Ricker model & constant q





Ricker model & S-shaped q