SCIENTIFIC COMMITTEE

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SEAPODYM review with an update about ongoing developments and preliminary results

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1. Introduction

The development and application of the Spatial Ecosystem And POpulation DYnamics Model (SEAPODYM) is the objective of WCPFC Scientific Committee Project 62. At SC10 a scientific peer review of SEAPODYM was requested by the WCPFC Scientific Committee to assist with guiding the WCPFC in evaluating potential model applications and its future work program (Anon 2014). The review was tasked to include the data inputs, model assumptions, the criteria for establishing reference models and identifying new sensitivity tests. In this context the review provides advice to WCPFC on the current status of the SEAPODYM project; the immediate and medium term applications of SEAPODYM; how SEAPODYM can be modified in order to improve the quality of the science; and priorities for Project 62's work plan.

The Terms of Reference for the review and the participants in the review are given in Appendix I. The review was undertaken thanks to the financial support of ISSF.

2. SEAPODYM in brief

SEAPODYM has been developed over many years (e.g. Lehodey, 2004a; Lehodey, 2004b; Lehodey et al. 2009; Senina et al., 2015). SEAPODYM is a model developed for investigating spatiotemporal dynamics of fish populations under the influence of both fishing and environment (see www.seapodym.org). The model is based on advection-diffusion-reaction equations describing dynamic processes (spawning, movement, mortality), which are constrained by environmental data (temperature, currents, primary production and dissolved oxygen concentration) and distributions of mid-trophic (micronektonic tuna forage) functional groups. The model simulates tuna age-structured population dynamics with length and weight relationships obtained from independent studies. Different life stages are considered: larvae, juveniles, immature and mature adults. At larvae and juvenile phases fish drift with currents, later on they become autonomous, i.e., in addition to the currents velocities their movement has additional component linked to their size and the habitat quality. From the pre-defined age at first maturity fish start spawning and their displacements are controlled by a seasonal switch between feeding and spawning habitats, effective outside of the equatorial region where changes in the gradient of day length are marked enough and above a threshold value. The last age class is a "plus class" where all oldest individuals are accumulated. The model takes into account fishing and predicts total catch and size frequencies of catch by fishery when spatially distributed fishing data are available. A Maximum Likelihood Estimation approach is used to estimate model parameters. Conventional release-recapture tagging data were recently integrated within MLE to allow better observability of movement and habitat parameters.

3. Review overview and discussions

The review meeting took place between 25 and 27 January 2016 at SPC, Noumea, New Caledonia, and was chaired by Dr Simon Nicol. Patrick Lehodey gave a presentation on the structure, assumptions, input data and current applications of SEAPODYM and responded to questions from the review participants on the first day of the review. Dr Inna Senina joined the review via tele-conference for the morning of the second day. A summary of key points from the discussions follows.

3.1 Model Assumptions

1. Growth is an external input to the model and currently modelled as a constant through space. There is evidence for longitudinal and latitudinal variation in growth across the Pacific Ocean (albacore and bigeye). Testing the influence of different growth curves and ideally growth variability should be considered.
2. Primary production as proxy for zooplankton. The assumption is difficult to relax with the SEAPODYM framework but WCPFC is encouraged to support independent research cruises that may address this assumption.

3. Diffusion in the model does not commence until 3 months of age. A sensitivity analyses to test the influence of diffusive movement by larvae and juveniles would be beneficial.
4. The inclusion of temperature in the calculation of several independent parameters of SEAPODYM. Does this generate overfitting of the temperature effect?
5. The current configuration to simulate seasonal migration for spawning is age based. The evidence for albacore (Farley et al. 2014) suggests that this may be more appropriately triggered by size.

3.2 Model Validation and sensitivity tests

6. Replicating the revisions to Multifan-CL should be implemented by applying a modified multinomial approach for the length and weight data that is self-scaling.
7. Including the sensitivity of the model to environmental data would be useful as part of the standard diagnostics. This could be done by holding each environmental variable constant or by sequentially flattening each environmental variable in some other way.
8. There is a need to compute maximum lifetime displacement and compare with fish speed estimates in the model.
9. When comparing Multifan-CL output and SEAPODYM output ensure the data mask only includes spatial cells where catch comes from.
10. Profiling the likelihood for key parameters would aid with comparison of similar variables estimated by Multifan-CL.
11. Is spatial distribution related to abundance or related catchability. A sensitivity analyses to test this should be a priority.
12. Each fishery in SEAPODYM is currently weighted the same. Weighting each fishery in an equivalent manner to Multifan-CL would assist the comparison between models.
13. Consider the inclusion of spatially explicit catchabilities.
14. Consider running the full population dynamics model for the tagging data to estimate tag recaptures and mortality rates.
15. Consider altering output scripts to generate each cohort on month-by-month and habitat indices values.
16. SPC to advise CLS when Multifan-CL spatial structures change to ensure appropriate changes made in SEAPODYM.
17. Ensure that fleet definitions for Multifan-Cl are provided to CLS each time they are changed.
18. Compare catchability/selectivities between SEAPODYM and Multifan-Cl.
19. Need to plot advection and diffusion spatially as a diagnostic.
20. Explore different examples of spawning habitat (especially with respect to Beverton-Holt relationship changes).
21. Consider using standardised CPUE experiment data in SEAPODYM.
22. Time period for optimisation results in stronger correlation (see Senina, 2008 Tables 4 and 5) – producing this correlation matrix as a routine diagnostic is useful.
23. Sensitivity analyses plots quite useful for identifying which parameters are most sensitive to various data sources – this might be sufficient to avoid the profiling.

3.3 Input Data

24. Assimilate ADCP data for micronekton estimation.
25. CLS and SPC to coordinate data exchange to ensure that SEAPODYM team has the same catch and effort data as used in stock assessments.
26. Consider the inclusion of Japan and IATTC tagging data (conventional and electronic) where available.

3.4 Applications

27. Can SEAPODYM be used to estimate the Stock Recruitment relationship for other models?
28. Density dependent movement may be a way to explore range contraction.
29. Errors around biomass estimates – model, temporal and spatial and how to present that. Use a grid to evaluate model parameter uncertainty based on likelihood profiles/sensitivity analyses.
30. Plausible alternative states of nature for MSE. Noting that the ability to replicate Multifan-CL will be important for this application in future.
31. Improve our understanding of ENSO and other oceanographic cycles on tuna.

3.5 General Comments

32. Consider revising terminology used to describe SEAPODYM juveniles (1-3 months old) as this differs from most other uses of the term in WCPO.
33. Table of model descriptions including anomalies in forcing data would aid with interpreting each reference model.
34. The single biggest area of improvement would be to increase the speed of model runs through to optimization. There are several potential approaches to achieving this. Irrespective of the option selected, this work is a matter of priority as it will allow many other items in the work plan to be achieved more rapidly.

4. General conclusions

The review concluded:

1. SEAPODYM is ready for application by WCPFC to assist its decision making. By design the model is particularly suited to addressing questions of spatial distribution and the influence of environmental processes on tuna population dynamics. SEAPODYM would be a useful complementary model to Multifan-CL for MSE work that includes spatial management. Similarly, the capacity of SEAPODYM to include alternate oceanographic states (e.g. ENSO phases and climate change projections) would allow climate proofing to be a consideration in the MSE work undertaken by WCPFC.
2. WCPFC should encourage and where feasible support (through Project 62) the continual development of diagnostic to evaluate the fit of the model to data, the validity of underlying assumptions, and allow comparison with alternate population dynamics models.
3. An annual review meeting, similar to the pre-assessment workshop held annually to guide the development of the WCPFC stock assessments, would benefit SEAPODYM applications in the WCPO. This would foster additional collaboration between the modelling team focussed on Multifan-CL applications and development and those focussed on SEAPODYM which would result in more regular sharing of ideas and peer review of models than currently occurs.

An option for WCPFC would be resourcing CLS to attend the pre-assessment workshop with potentially an additional day added for the workshop to also discuss any applications of SEAPODYM to WCPFC fisheries that require presentation at the scientific committee of that year.

4. WCPFC and other sub-regional organisations should consider options for industry support for research and data that would enhance SEAPODYM's forage component. Acoustic data provided opportunistically by fishing vessels would allow for optimisation routines to be applied to the estimation of the forage biomass.
5. SEAPODYM could be used as a tag simulator to test assumptions and/or provide priors or fixed values for the inclusion of the PTTP data in Multifan-CL applications.
6. A detailed technical document which describes reviews to date, developments implemented and developments planned should be developed to support future SEAPODYM work (including for example criteria for reference models).

5. Ongoing developments and preliminary results

Subsequent to the review in January 2016, additional work has commenced on aspect of the review and general development of SEAPODYM. This work includes inclusion of additional information on micronekton (tuna forage), operational modelling developments, preliminary revised results for yellowfin and bigeye tuna, and climate change related developments including multi-model ensemble simulation and on ocean acidification. The state of this work and the preliminary results are described in detail in Appendix II.

6. References

Anon. 2014. Report of the Tenth Regular Session of the Scientific Committee of the Commission for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean. 6–14 August 2014, Majuro, Republic of the Marshall Islands. Western and Central Pacific Fisheries Commission, Pohnpei, Federated States of Micronesia.

Farley J.H., S.D. Hoyle, J.P. Eveson, A.J. Williams, C.R. Davies, S.J. Nicol. 2014. Spatial Variation in Maturity of South Pacific Albacore Tuna (*Thunnus alalunga*). *PLoS ONE*, 9(1): e83017. doi:10.1371/journal.pone.0083017

Lehodey, P. 2004a. A Spatial Ecosystem and Populations Dynamics Model (SEAPODYM) for tuna and associated oceanic top-predator species: Part I Lower and intermediate trophic components. 17th meeting of the Standing Committee on Tuna and Billfish, Majuro, Republic of Marshall Islands, 9-18 Aug. 2004, Working Paper: ECO-1: 26 pp.

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Lehodey, P., Senina, I., and 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., and 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.

Senina, I., Lehodey, P., Calmettes, B., Nicol, S., Caillot, S., Hampton, J., and Williams, P. 2015. SEAPODYM applications for yellowfin tunas in the Pacific Ocean. 11th Regular Session of the Scientific Committee of the Western Central Pacific Fisheries commission, WCPFC-SC11-2015/EB-IP- 01.

Appendix I

Terms of reference

The review is a science peer review of SEAPODYM v3.0 and amendments made since July 2015 (see Senina et al. 2015) through until December 2015. The workshop will be chaired by Dr. S. Nicol (ABARES, Australia). Reviewers will utilise supporting documentation for the current SEAPODYM model (Senina et al. 2008; Lehody et al. 2008) and the most recent report on SEAPODYM implementation available (Senina et al. 2015). During the workshop the model structure, assumptions, input data and current applications will be presented by CLS (Lehody, Senina). Presenters will respond to questions from the review participants and the review included detailed discussion dedicated to the terms of reference.

The specific terms of reference for the review of the spatial ecosystem and population dynamics model (SEAPODYM) project were to:

- review the parameter and structural assumptions of the model;
- review the suitability of standard diagnostics applied;
- identify other diagnostics to evaluate model performance;
- provide advice on priority sensitivity analyses;
- document the biases associated with different model resolutions;
- provide a description of the current reference models for each species
- provide advice on how SEAPODYM can be modified in order to improve its quality and utility;
- identify immediate practical applications of SEAPODYM;
- identify practical applications of SEAPODYM which are achievable with the post v3.0 implementation; and
- provide advice on components of a future spatial ecosystem and population dynamics work plan.

Reviewers

The participants in the review included the lead researchers for Project 62, staff of the SPC OFP and staff from IRD:

Steven Hare, Graham Pilling, Tom Peatman, Rob Scott, Laura Tremblay-Boyer, Peter Williams, Stephen Brower, Valerie Allain, Christophe Menkes (IRD), Sylvain Caillot, Fabrice Bouyer, Simon Nicol (ABARES), Neville Smith, John Hampton, Patrick Lehodey (CLS), and Inna Senina (CLS).

APPENDIX II

SEAPODYM ongoing developments and preliminary results

Content

Micronekton (tuna forage)

The modeling of micronekton functional groups provides a key biological forcing to understand and model the dynamics of large predators like tunas. To improve the modeling of these ocean ecosystem components a method is developed to optimize the model parameters (energy transfer coefficients and temperature-related time of development) using acoustic data (Lehodey et al. 2015). These data are also used to revise the definition of the vertical layers used in SEAPODYM (Fig. A1). This task is supported by several European research projects (AtlantOS, MESOPP, GREENUP), with the objective of building a large network of acoustic samples.

Any institute willing to contribute by providing existing 38 kHz acoustic transects is very welcome and should contact Patrick Lehodey at plehodey@cls.fr.

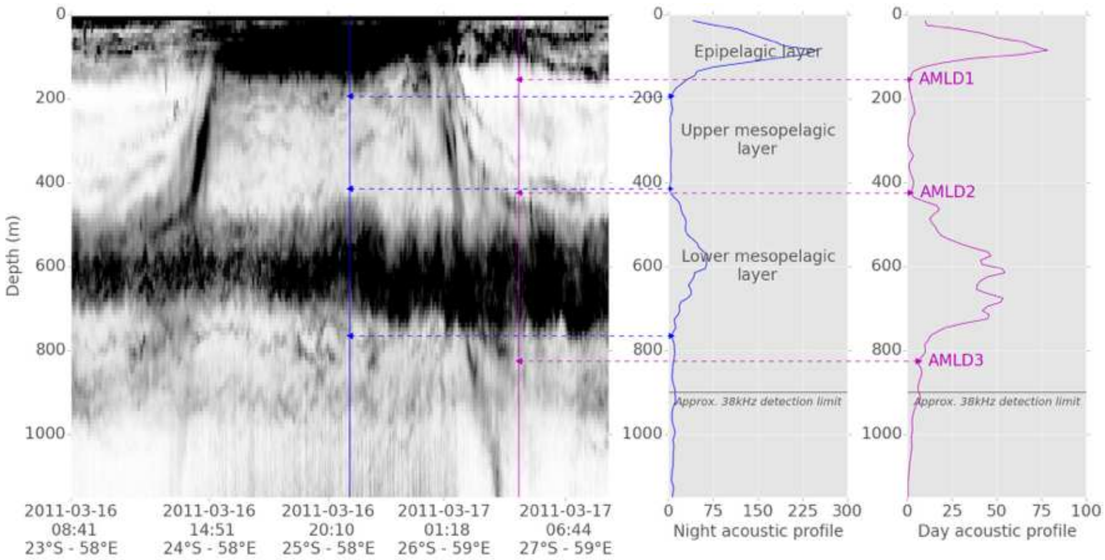

Figure A1. An automatic detection of vertical layer boundaries is developed based on acoustic data profiles (Conchon et al., submitted).

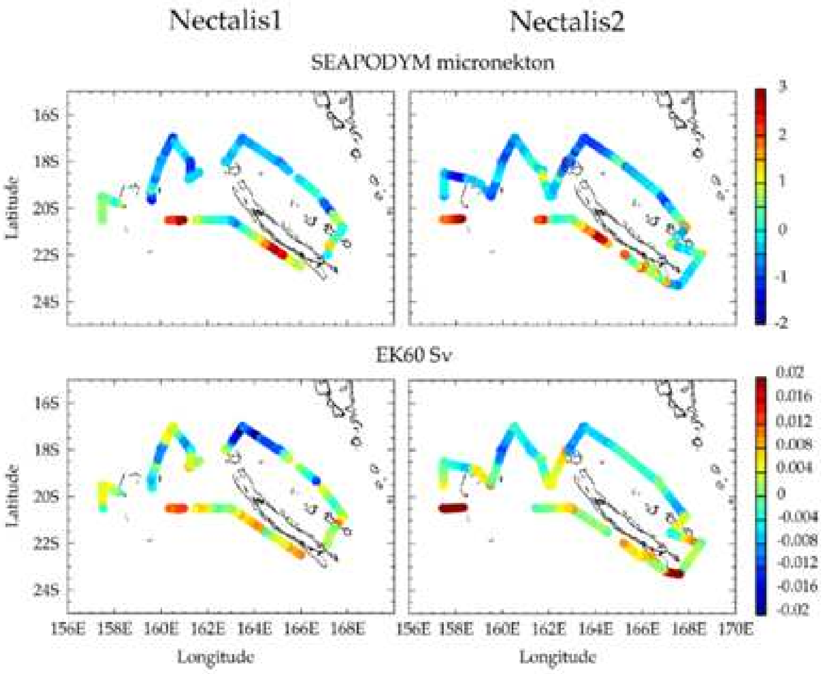

Figure A2. Comparison of 38 kHz acoustic signal collected during a research cruise around New Caledonia with predicted micronekton biomass (from Menkes et al 2015).

Operational modeling

With the project INDESO for the Government of Indonesia, CLS has implemented an operational configuration of SEAPODYM to provide real-time and forecast of three tropical tuna species dynamics: skipjack, yellowfin and bigeye. The high resolution regional model required to develop also a larger basin scale configuration at coarser resolution to provide boundaries conditions at the regional level. The approach requires several steps:

1- One first series of optimization experiment using long hindcast simulations with forcing from coupled physical–biogeochemical model at coarse resolution (2°x month) and historical catch data in the Pacific Ocean.

2- The downscaling of parameters to the operational configuration at ¼°x week.

3- The downscaling of parameters to the regional INDESO configuration at 1/12°x day.

The last improvements achieved with the new skipjack parameterization presented in this working document have not yet been released in the operational chain of production. Nevertheless, the current version shows clearly the expected westward shift of abundance distribution associated with the ending El Niño event (Fig A3) and the development of neutral conditions.

Based on NOAA ENSO bulletin, there is about a 75% chance of La Niña development during the fall and winter 2016.

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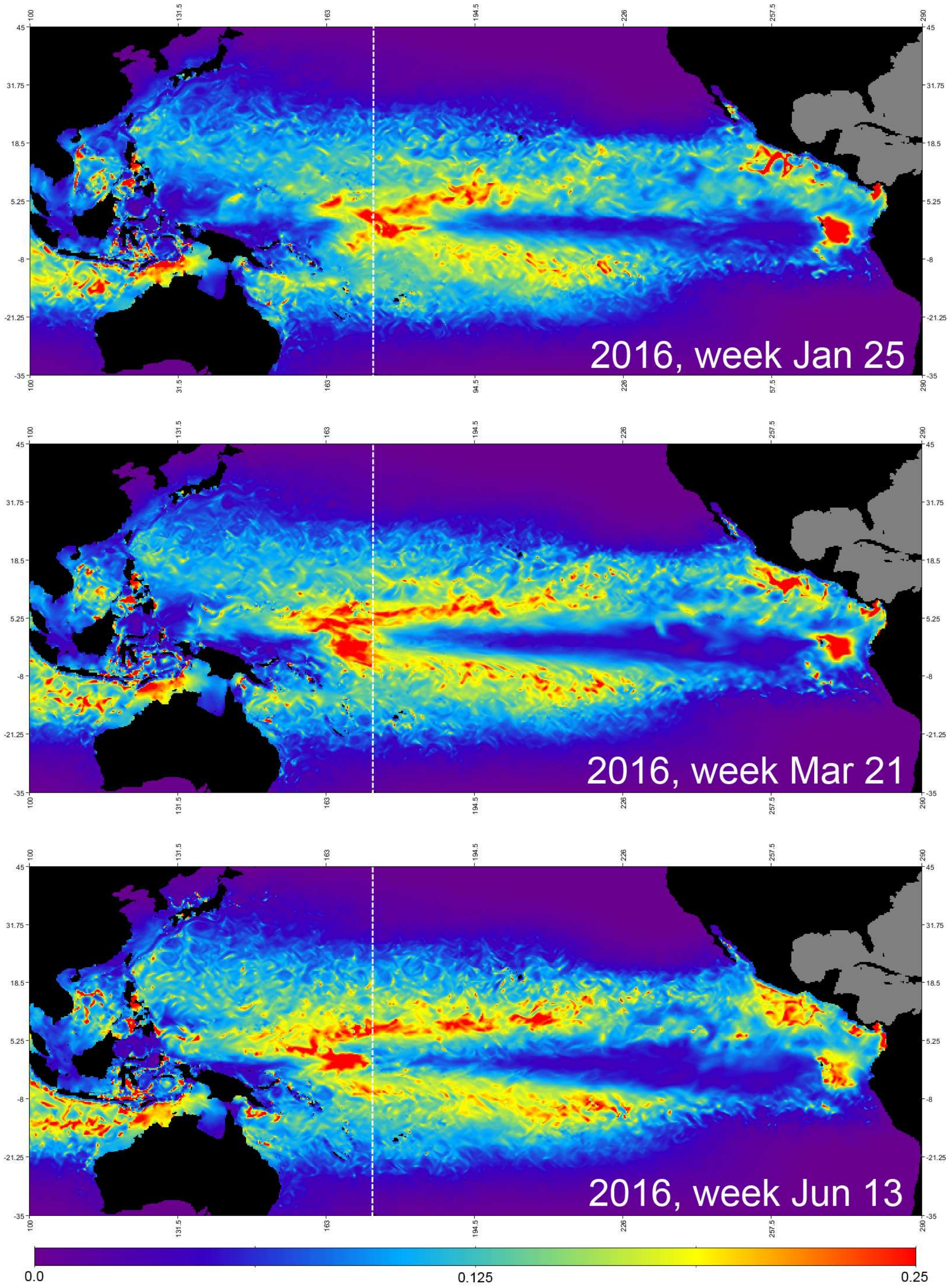

Figure A3. Skipjack biomass distributions predicted by SEAPODYM operational model showing the change in 2016 associated to the end of El Nino event (dotted line indicates the longitude 170°E). It should be noted that in absence of fishing data, an average distribution of fishing effort is used to avoid a too strong bias due to absence of fishing mortality.

The horizontal currents of both the ocean GLORYS reanalysis and the PSY3R3v3 operational ocean model outputs were corrected in the Pacific equatorial region due to the presence of anomaly impacting the major fishing ground in the western equatorial Pacific Ocean. The correction (Fig.

A4) consists to extract the signal variability from the (wrong) mean state in the equatorial band and to add it to a more satisfying mean state (computed from ECCO reanalysis). A relaxation function is used to smooth the transition between the two mean states on the border of the corrected area. The correction was implemented in 2015 and the impact on the stock distribution is starting to be integrated in the simulated stock dynamics. A new GLORYS reanalysis is in preparation and will be used with the most recent reference parameterisation to update tuna hindcast simulations with the operational configuration and to provide better initial conditions.

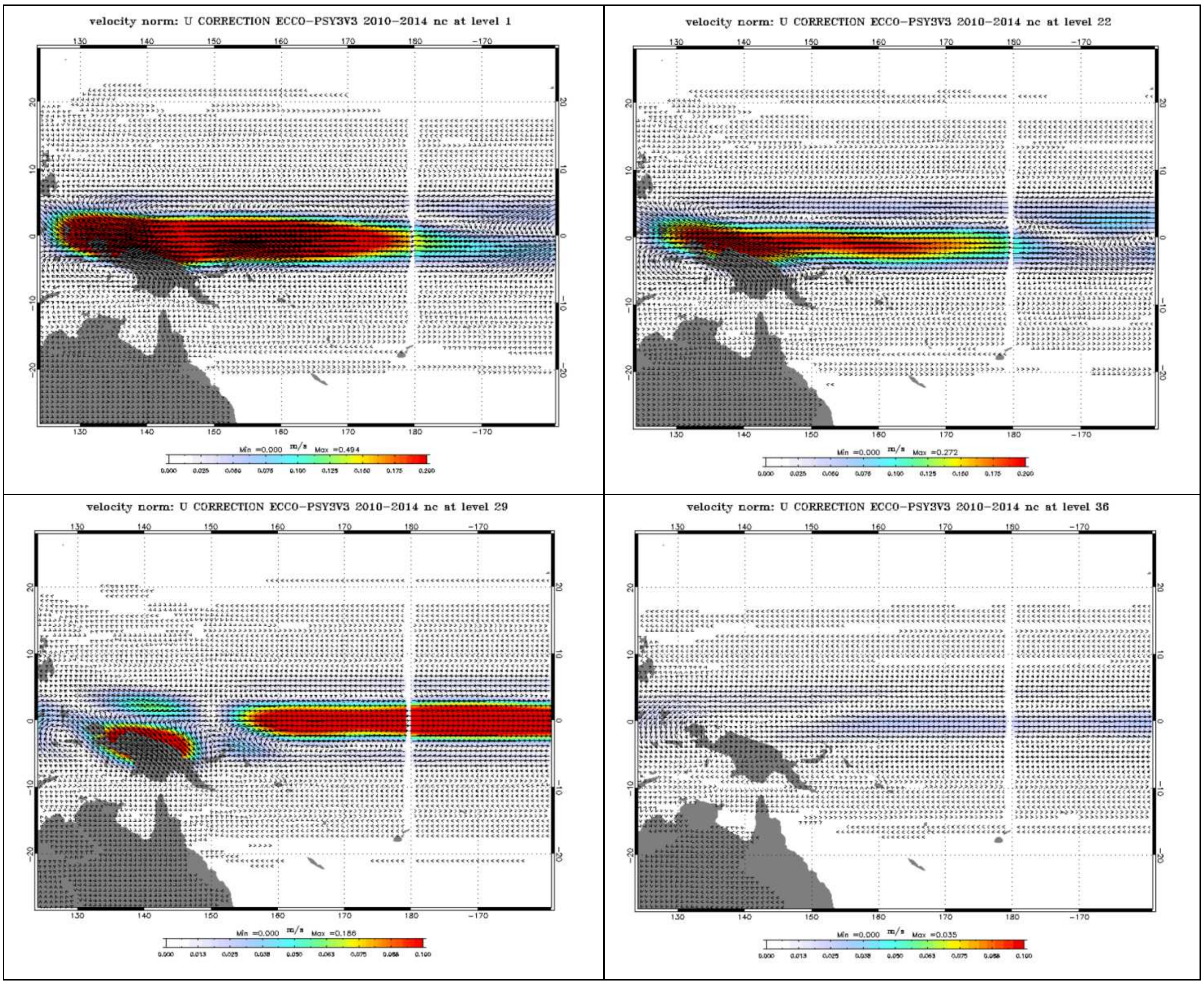

Figure A4. Difference in zonal currents between PSY3V3 and ECCO reanalysis at 0, 100, 300 and 1000m for the period 2010-14 in the Western equatorial Pacific.

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Yellowfin tuna

The SEAPODYM application to yellowfin was presented at the last scientific committee of the WCPFC (Senina et al 2015). However, the optimization of the model was conducted using a geo-referenced fishing dataset that was not fully raised to the total nominal catch. It represented between 60-75% of total landings during the last two decades.

Since then, a revised fishing dataset was provided by SPC and used in new optimization experiments. Initial values of habitat and movement parameters were defined from the same independent optimization experiments using tagging data as described in Senina et al. (2015). Therefore, the only change from this previous study is the updated (raised) fishing data set (Fig. A5) that required conducting a new optimization study. Note that in the optimization with the updated fishing data the primary production series were replaced by satellite-derived variables (1998-2010) in order to fit the huge catches by purse-seine fleets following the strong 1997-1998 ENSO event.

The new fishing dataset (catch and associated size frequencies) generated a new solution with the main changes in the temperature habitat both for spawning (Fig. A6) and feeding (Table A1). The result in larvae distribution (Fig. A7) is a stronger contrast with less dense concentrations in the central equatorial region but higher densities in the eastern and western regions.

The overall fit to catch data increased with this new solution (Fig. A8). The comparison with MULTIFAN-CL estimate by region (Fig. A9) shows major difference in region 2 where the previous biomass estimate is divided by a factor 10 then the region 6 (divided by 2). There is slighter decrease of biomass in region 7 and 4.

However, in the main fishing ground areas 3 and 4 of the WCPO, the two models provide close solution. In the region 7, they are also quite close if we omit the peak of biomass predicted in 2001 by MULTIFAN-CL. This discrepancy has been investigated and it appears that the biogeochemical model did not predict a strong enough increase in primary production during this period in the eastern-central equatorial Pacific. When replacing the primary production from the biogeochemical model by the satellite derived primary production the peak of biomass is much well reproduced (Fig A.10).

The predicted impact of fishing is well visible by comparison of simulation with and without fishing mortality (Fig A11 and A12). The fishing impact is particularly strong on the adult population with a biomass reduced to 40 or less than 30% of the unfished biomass in the EPO and the western equatorial fishing grounds.

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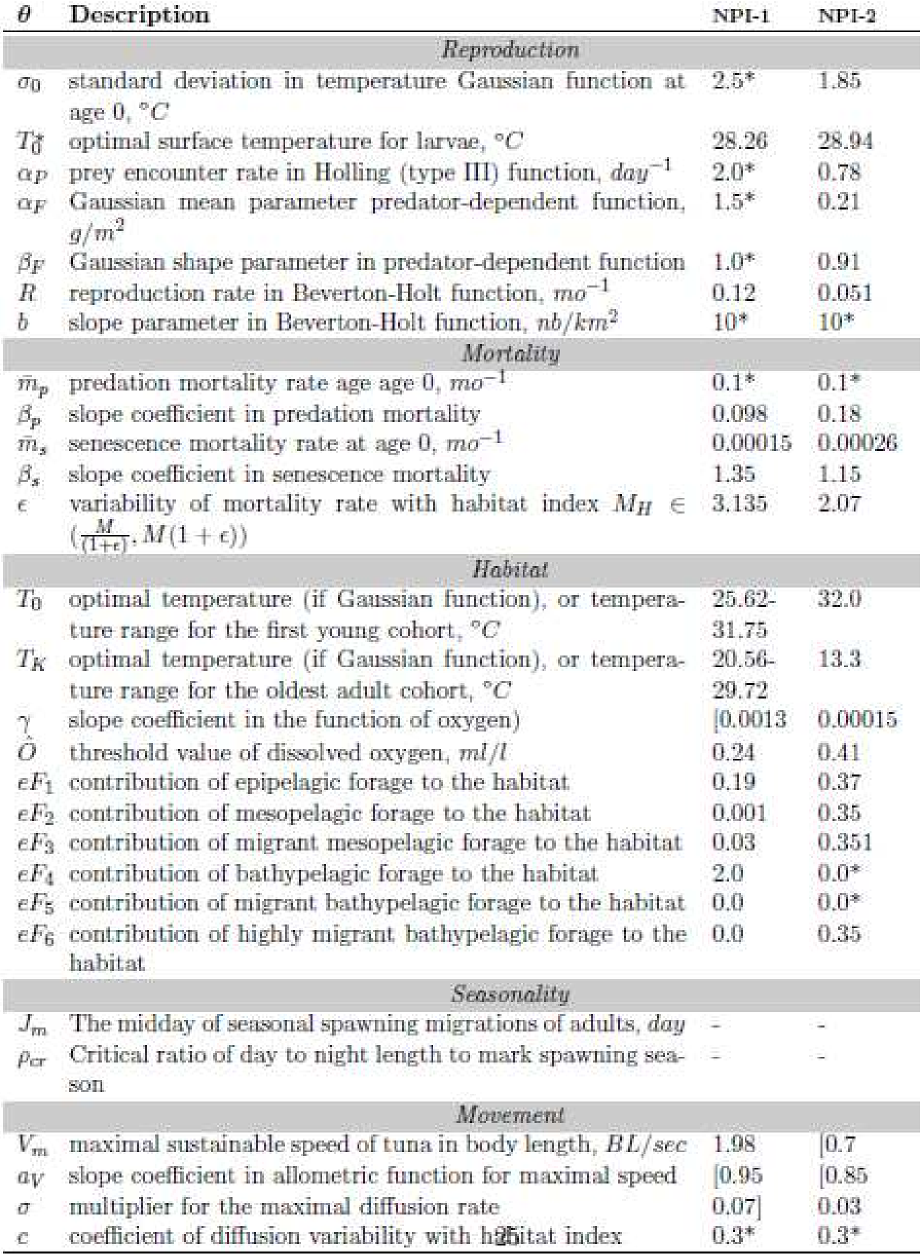
Table A1. Parameter estimates from three model configurations. NPI-1: NEMO-PISCES-INTERIM forcing with incomplete fishing dataset in the likelihood (Senina et al., 2015); NPI-2: complete fishing dataset and same forcing as NPI-1 prior to 1998 but satellite PP and respective micronekton fields after. Parameter with [or] were estimated at their lower or upper boundary correspondingly. The dash indicates that the parameter is not effective and could not be estimated.



θ	**Description**	**NPI-1**	**NPI-2**
	Reproduction		
σ_0	standard deviation in temperature Gaussian function at age 0, °C	2.5*	1.85
T_0^*	optimal surface temperature for larvae, °C	28.26	28.94
α_P	prey encounter rate in Holling (type III) function, day^{-1}	2.0*	0.78
α_F	Gaussian mean parameter predator-dependent function, g/m^2	1.5*	0.21
β_F	Gaussian shape parameter in predator-dependent function	1.0*	0.91
R	reproduction rate in Beverton-Holt function, mo^{-1}	0.12	0.051
b	slope parameter in Beverton-Holt function, nb/km^2	10*	10*
	Mortality		
$\bar{m}_p$	predation mortality rate age age 0, mo^{-1}	0.1*	0.1*
β_p	slope coefficient in predation mortality	0.098	0.18
$\bar{m}_s$	senescence mortality rate at age 0, mo^{-1}	0.00015	0.00026
β_s	slope coefficient in senescence mortality	1.35	1.15
ϵ	variability of mortality rate with habitat index $M_H \in (\frac{M}{(1+\epsilon)}, M(1+\epsilon))$	3.135	2.07
	Habitat		
T_0	optimal temperature (if Gaussian function), or temperature range for the first young cohort, °C	25.62-31.75	32.0
T_K	optimal temperature (if Gaussian function), or temperature range for the oldest adult cohort, °C	20.56-29.72	13.3
γ	slope coefficient in the function of oxygen)	[0.0013	0.00015
$\hat{O}$	threshold value of dissolved oxygen, ml/l	0.24	0.41
eF_1	contribution of epipelagic forage to the habitat	0.19	0.37
eF_2	contribution of mesopelagic forage to the habitat	0.001	0.35
eF_3	contribution of migrant mesopelagic forage to the habitat	0.03	0.351
eF_4	contribution of bathypelagic forage to the habitat	2.0	0.0*
eF_5	contribution of migrant bathypelagic forage to the habitat	0.0	0.0*
eF_6	contribution of highly migrant bathypelagic forage to the habitat	0.0	0.35
	Seasonality		
J_m	The midday of seasonal spawning migrations of adults, day	-	-
ρ_{cr}	Critical ratio of day to night length to mark spawning season	-	-
	Movement		
V_m	maximal sustainable speed of tuna in body length, BL/sec	1.98	[0.7
a_V	slope coefficient in allometric function for maximal speed	[0.95	[0.85
σ	multiplier for the maximal diffusion rate	0.07]	0.03
c	coefficient of diffusion variability with habitat index	0.3*	0.3*

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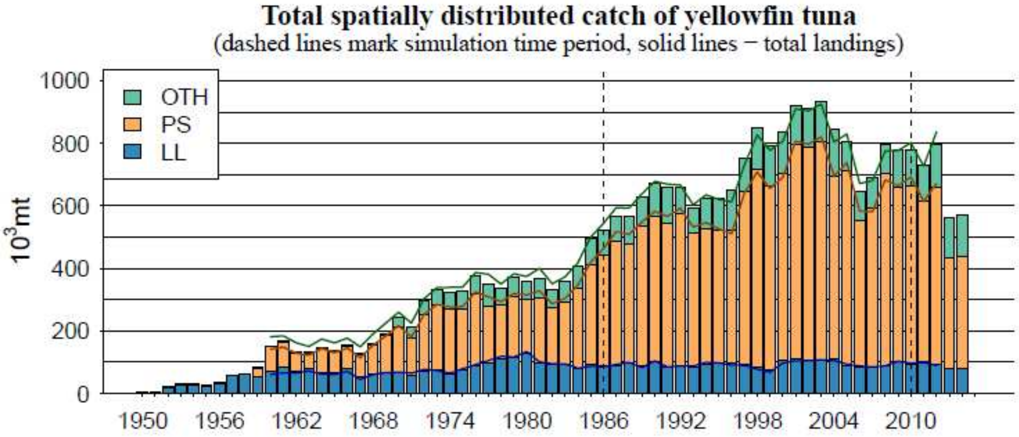

Figure A5. Total spatially-distributed catch of yellowfin population (Pacific-wide) being used in SEAPODYM analyses. Solid lines show total annual catches from declared port landings (SPC Year Book, 2012).

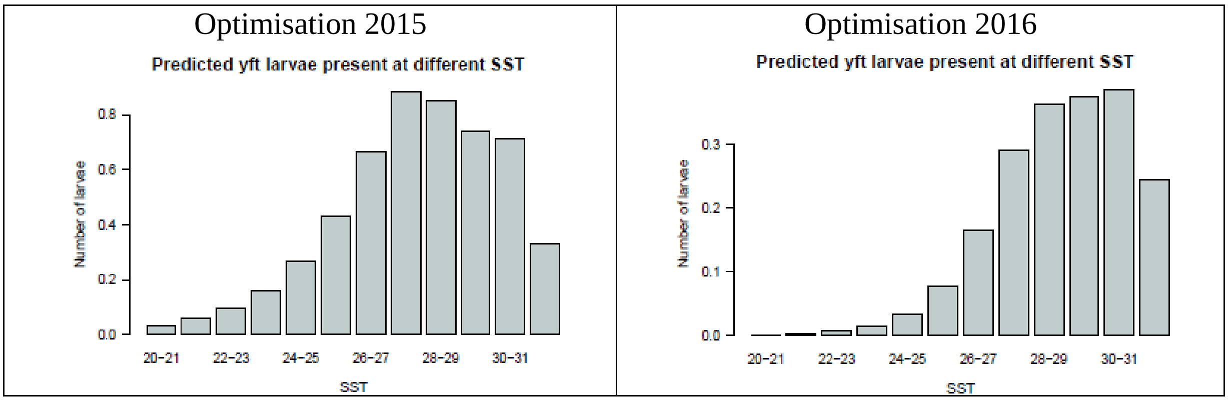

Figure A6. Comparison of predicted distribution of larvae at sea surface temperature between 2015 and revised INTERIM optimisations.

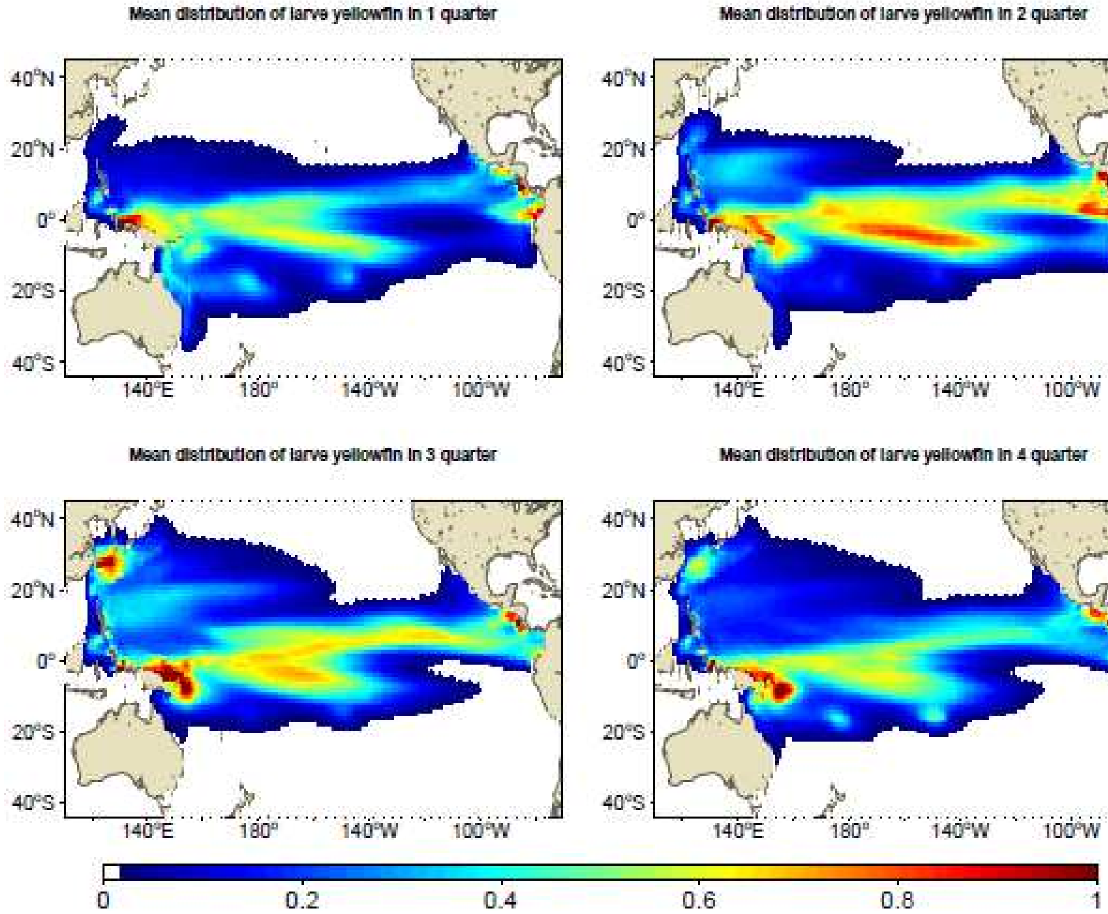

Figure A7. Predicted seasonal distributions of yellowfin larvae (decadal average) with revised INTERIM optimization.

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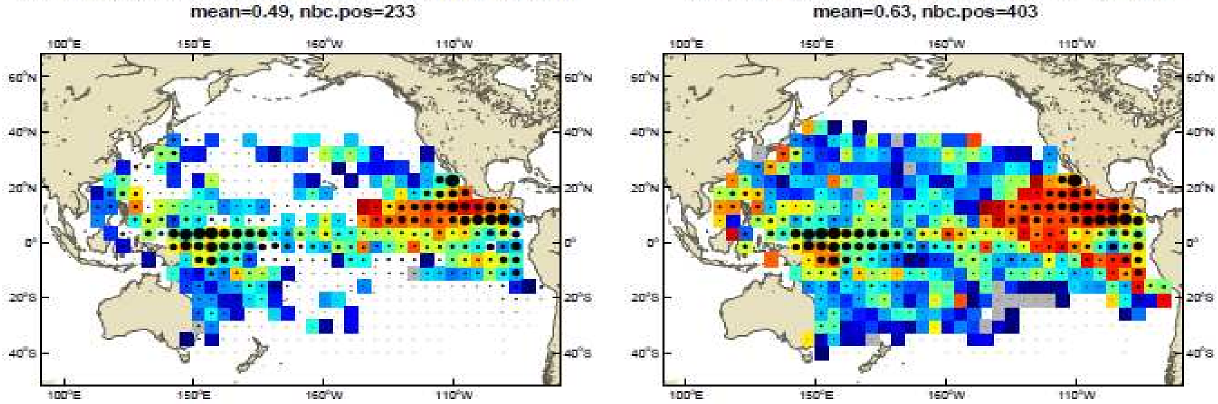
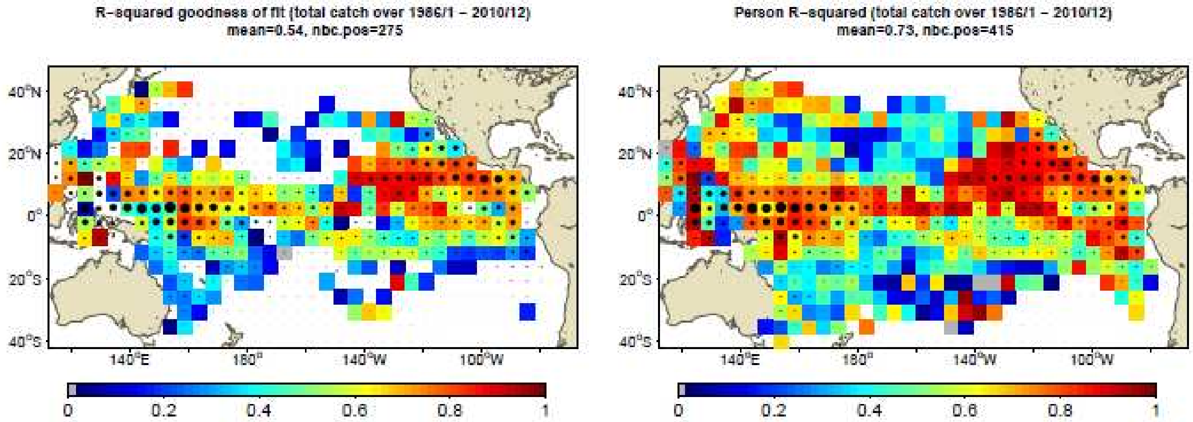
Optimisation 2015



R–squared goodness of fit (total catch over 1980/1 – 2010/12)
mean=0.49, nbc.pos=233

Person R–squared (total catch over 1980/1 – 2010/12)
mean=0.63, nbc.pos=403

Optimisation 2016



R–squared goodness of fit (total catch over 1986/1 – 2010/12)
mean=0.54, nbc.pos=275

Person R–squared (total catch over 1986/1 – 2010/12)
mean=0.73, nbc.pos=415

Figure A8. Comparison of spatial maps of validation metrics between tow optimization experiments for yellowfin: (left) R-squared goodness of fit and (right) squared Pearson correlation coefficient.

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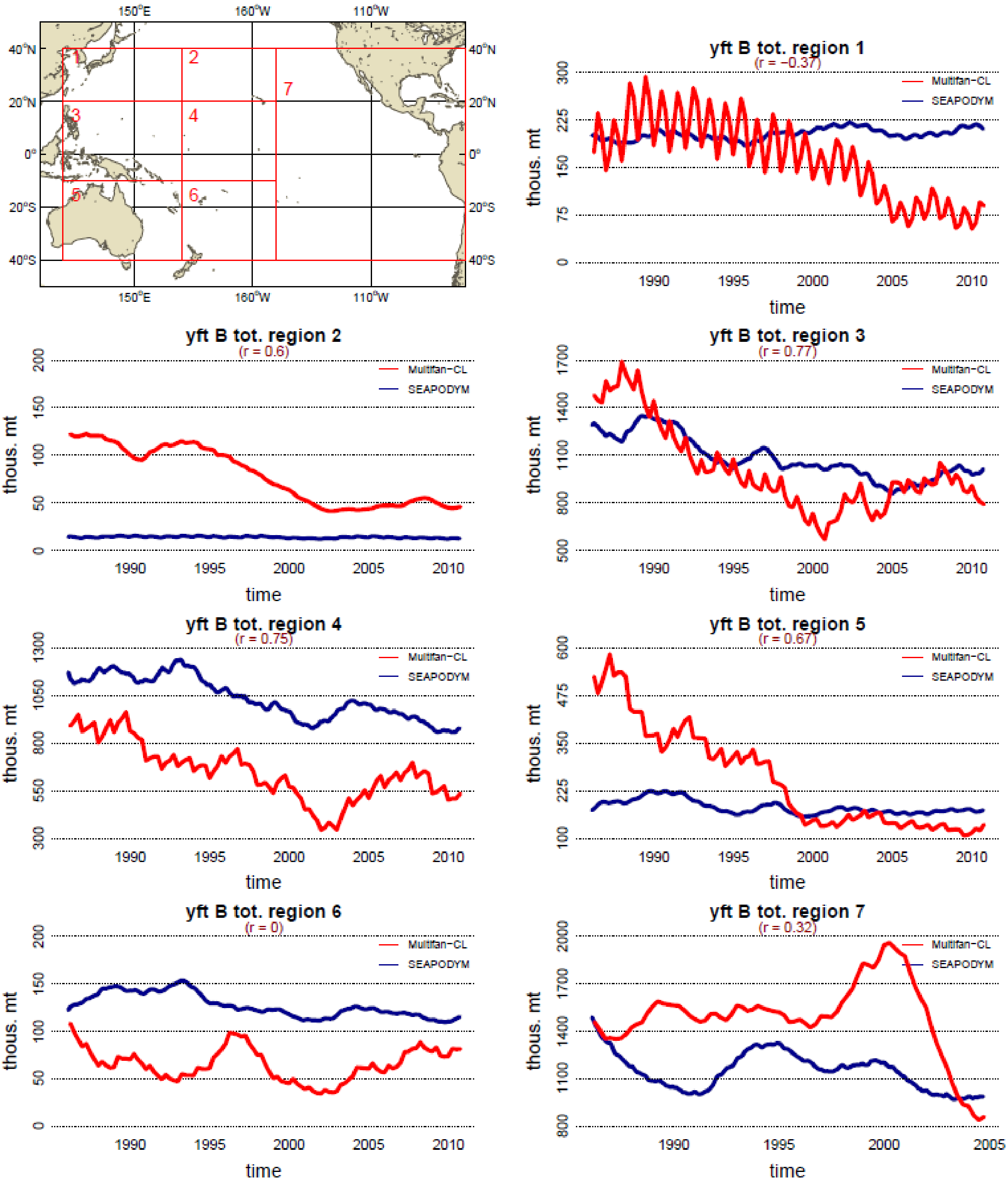

Figure A9. Regional comparison between SEAPODYM and Multifan-CL model predictions for total (immature and mature) biomass with the revised INTERIM optimization

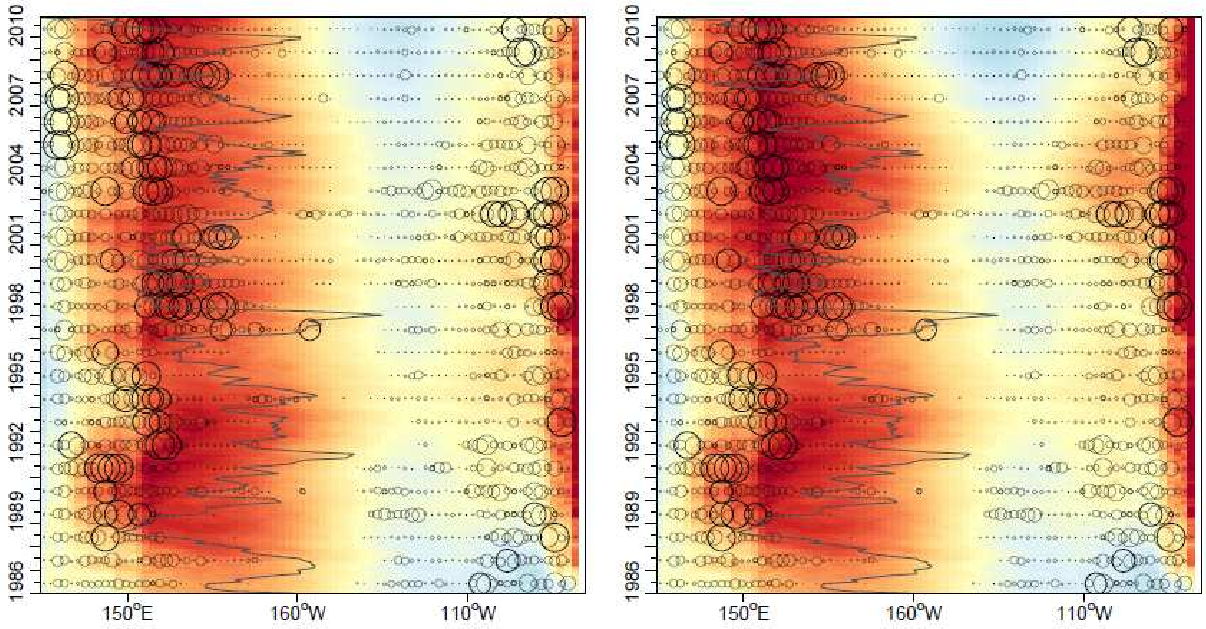

Figure A10. Variability of tropical (average over 10°S-10°N) total biomass of yellowfin tuna with PS catches (proportional to circles) and Southern Oscillation Index. The result from the revised INTERIM optimization (left) is compared to the result (right) with a simulation using satellite derived primary production. Note the peak in biomass predicted in the EPO with satellite primary production in 2001-2004.

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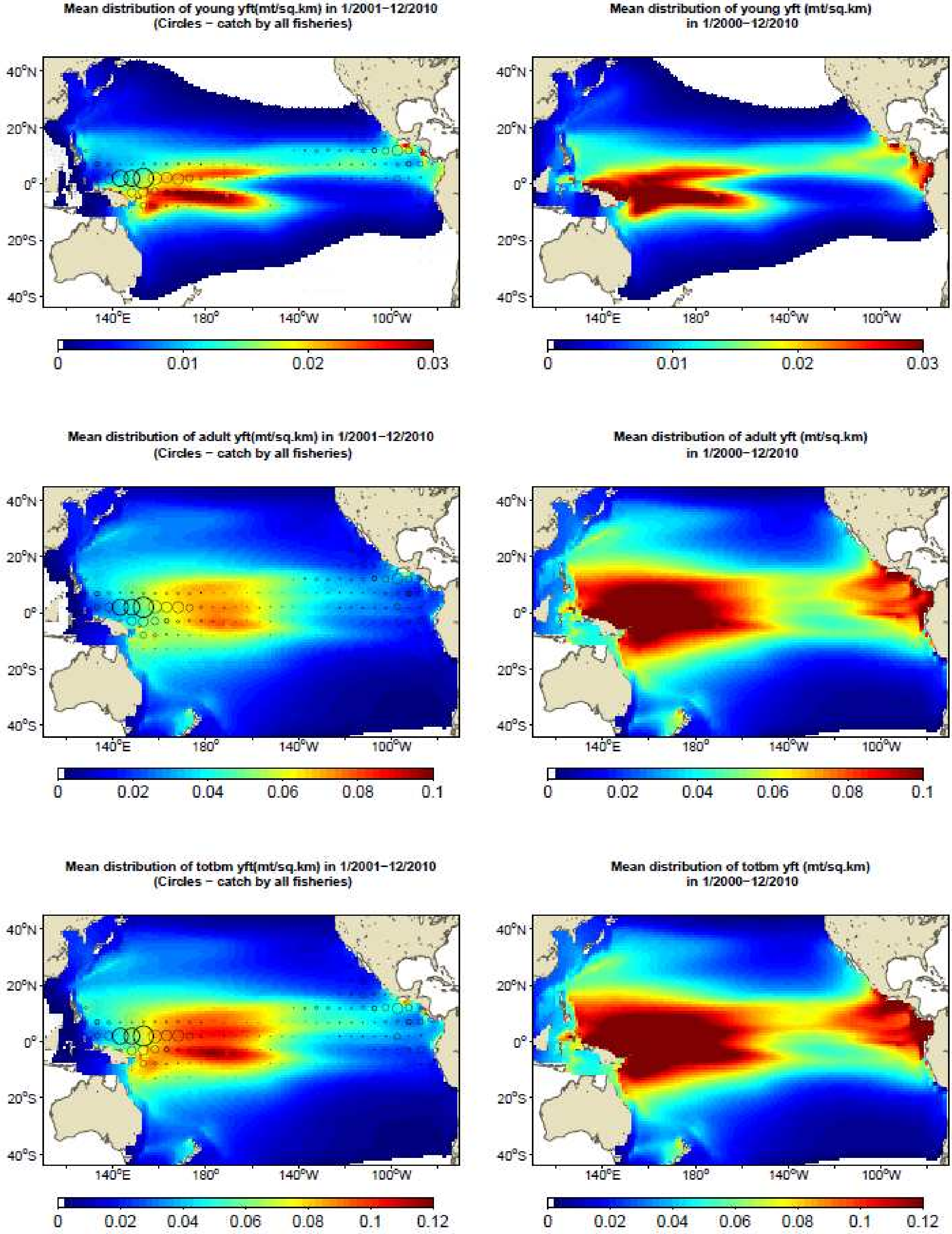

Figure A11. Yellowfin average spatial distributions of (from top to bottom) young, adult and total biomass with (left) and without fishing (right) predicted with revised INTERIM optimization.

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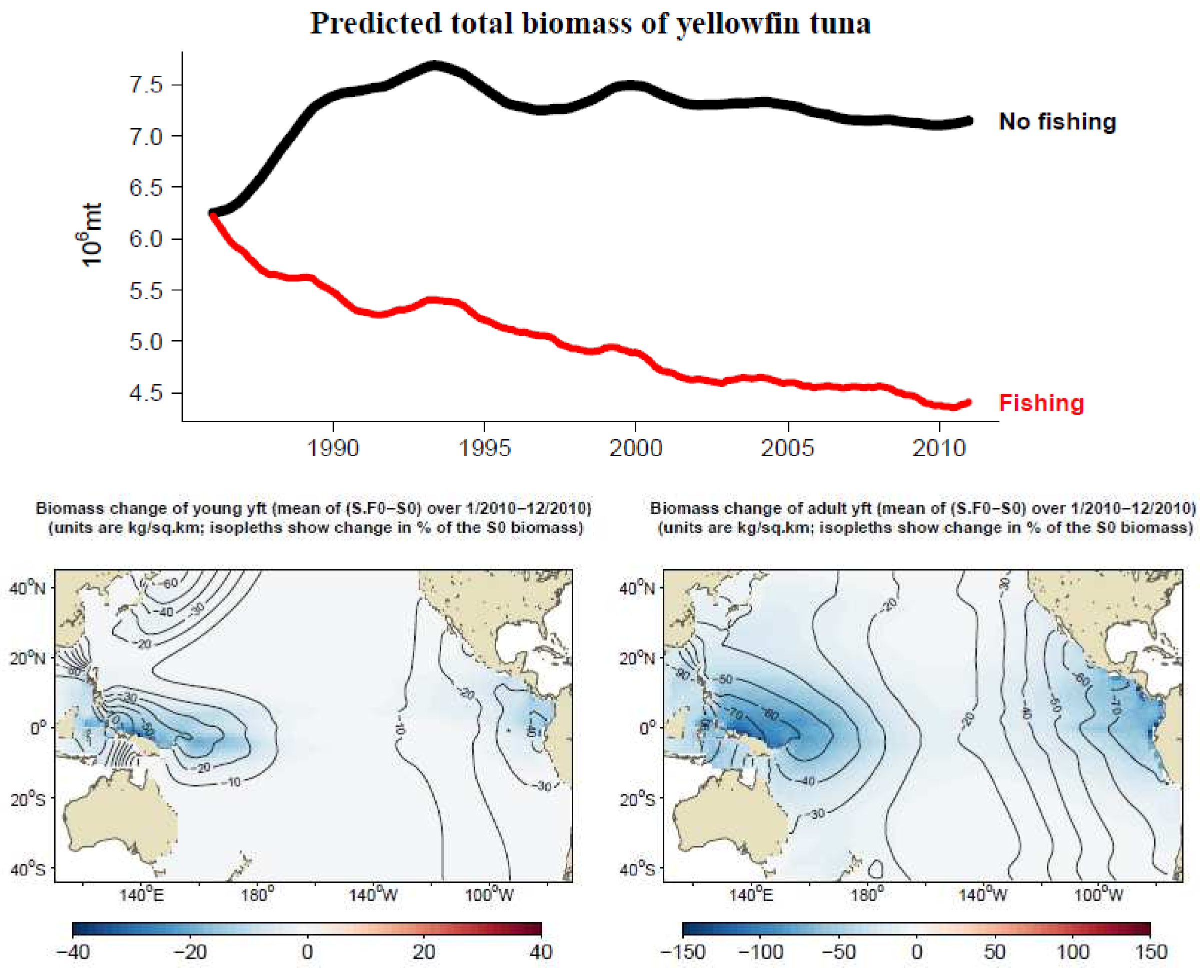

Figure A12. Quantification of the fishing impact of Pacific yellowfin tuna. Spatial fishing impact on young and adult population stages is shown with contour lines of the index $(B_{F0}-B_{Ref}) / B_{F0}$ and color background indicating the average biomass reduction due to fishing (kg /km^2).

Bigeye tuna

Preliminary optimization experiments with SEAPODYM have been conducted for the Pacific wide bigeye population. A revised fishing dataset was provided by SPC with geo-referenced catch data raised to the level of nominal catch (Fig. A13). As for yellowfin a first optimization with tagging data and the ECCO 1° x month ocean reanalysis was used to get a first estimate of habitat and movement parameters. The optimal solution achieved with this preliminary study predicts a large central equatorial spawning ground (Fig. A14). The fit to catch data is good in the main fishing ground, roughly 20°N-10°S (Fig. A15) but less in the subtropical regions. While the juvenile and young immature fish are predicted to be concentrated mainly in the equatorial and tropical central Pacific (Fig. A16), the adult distribution extends to the more temperate latitudes following the Kuroshio extension and the Eastern Australian Current.

The comparison with MULTIFAN-CL estimates by region (Fig. A17 & A18) shows that the SEAPODYM estimates of adult biomass are always higher. However, the difference is relatively small for the main central fishing ground (region 4). The same comparison of biomass estimate for the total of immature and mature fish shows better convergences in 4 of the 7 regions. The difference therefore coming likely from the natural mortality estimated with the model (Fig A19).

The predicted impact of fishing can be seen on figures A16 and A20. The predicted decrease in biomass relatively to the unfished simulation is very strong. Overall the decrease is predicted to be almost 50% from the unfished biomass at the end of the time series, i.e. end of 2010. The exploitation level certainly increased since this year. The level of exploitation is estimated to be above 60% in the far western equatorial region.

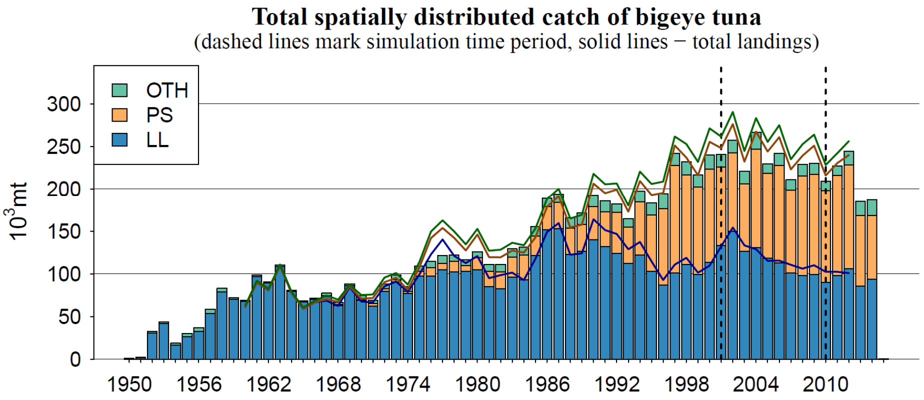

Figure A13. Total spatially-distributed catch of bigeye population (Pacific-wide) being used in SEAPODYM analyses. Solid lines show total annual catches from declared port landings (SPC Year Book, 2012).

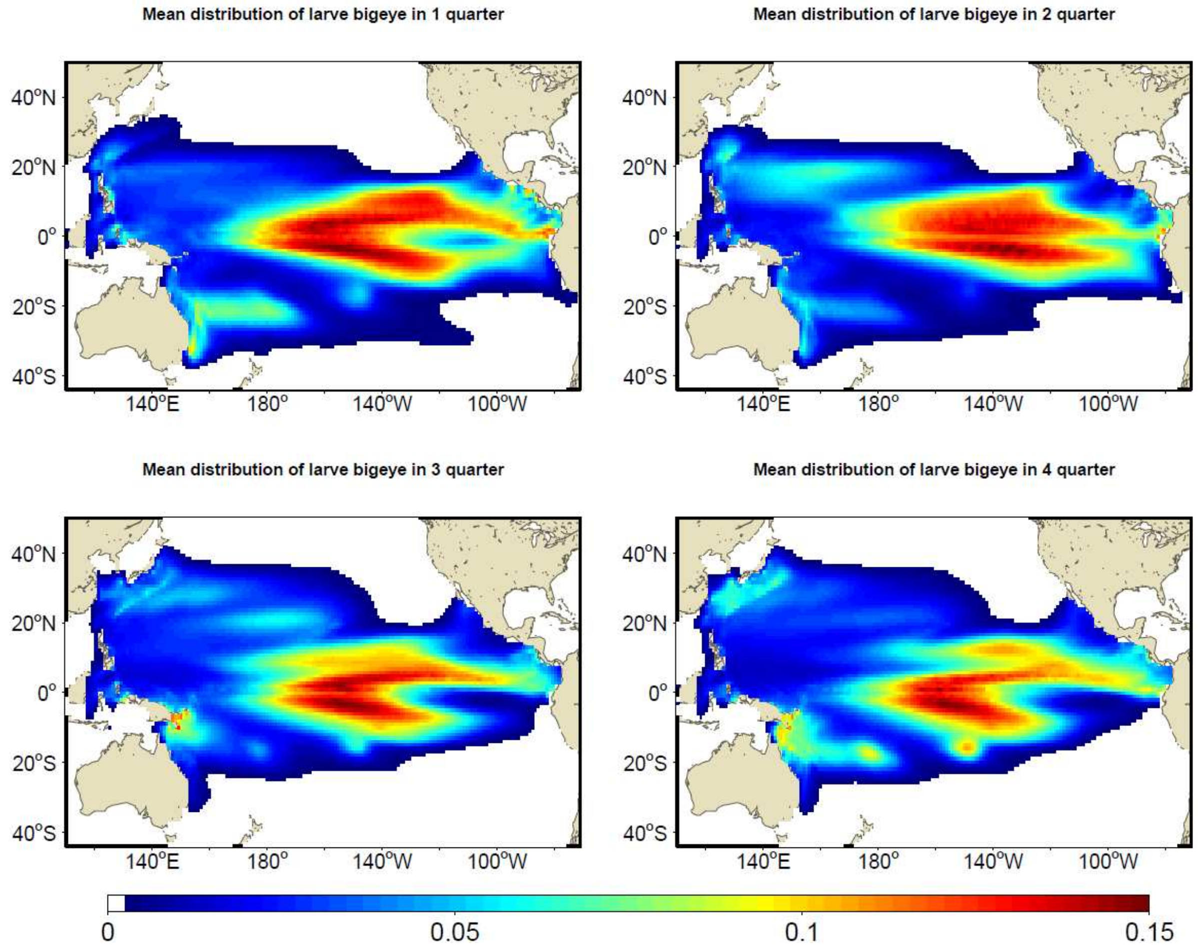

Figure A14. Predicted seasonal distributions of bigeye larvae (decadal average) with first INTERIM optimisation.

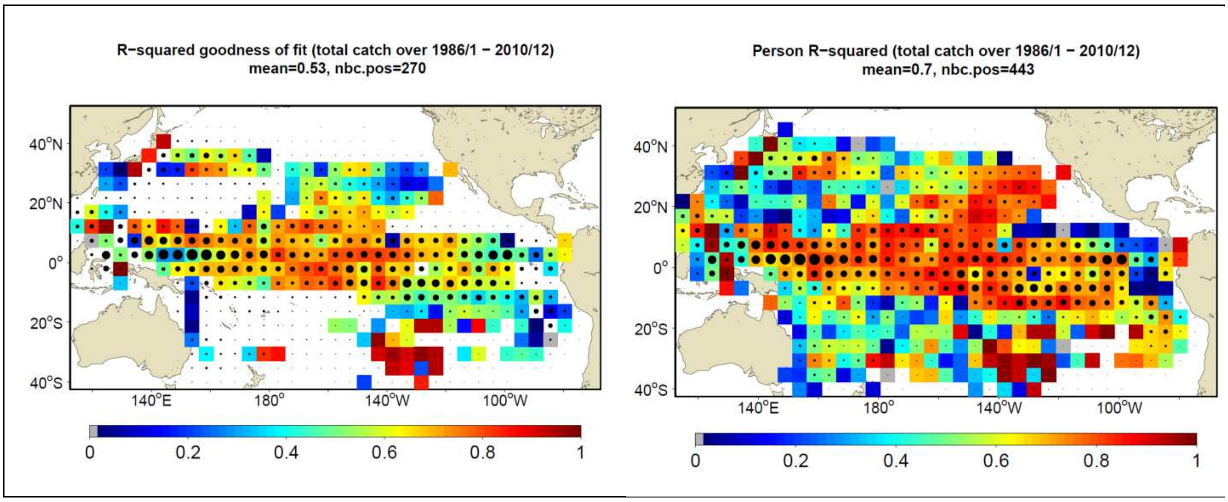

Figure A15. Spatial maps of validation metrics for bigeye: (left) R-squared goodness of fit and (right) squared Pearson correlation coefficient.

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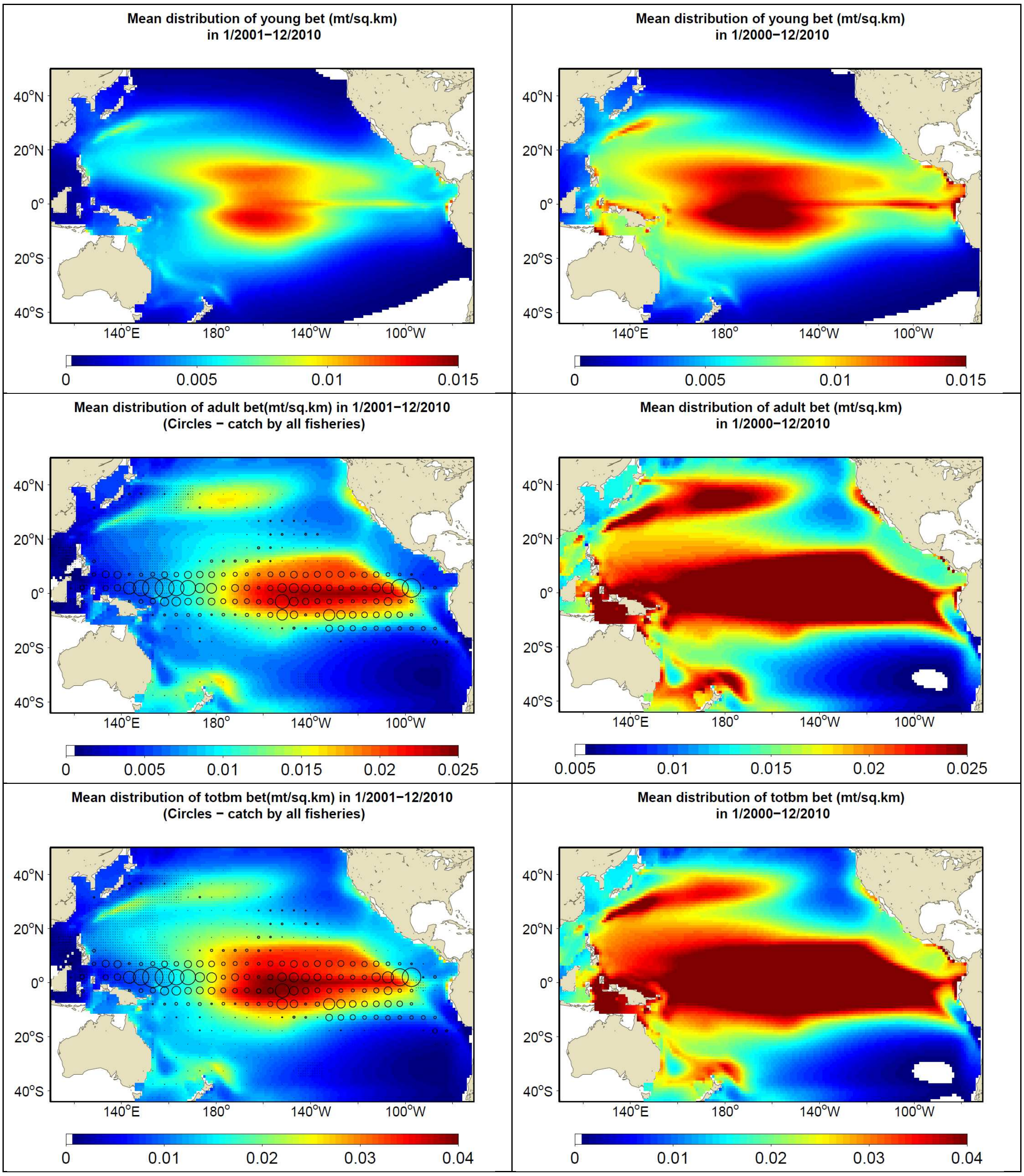

Figure A16. Bigeye average spatial distributions of (from top to bottom) young, adult and total biomass with (left) and without fishing (right) predicted with first INTERIM optimization.

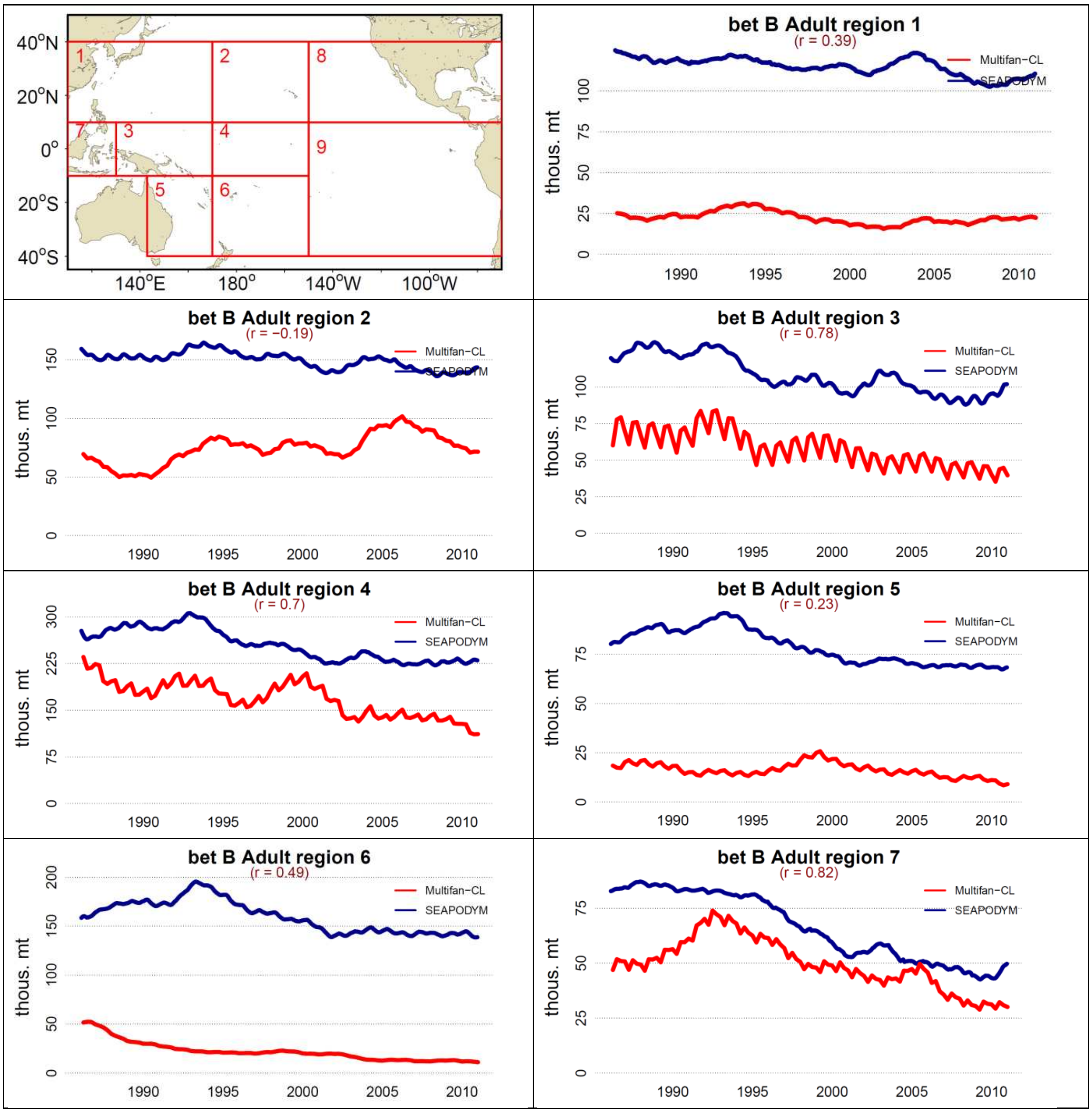

Figure A17. Regional comparison between SEAPODYM and Multifan-CL model predictions for adult (mature) bigeye tuna biomass

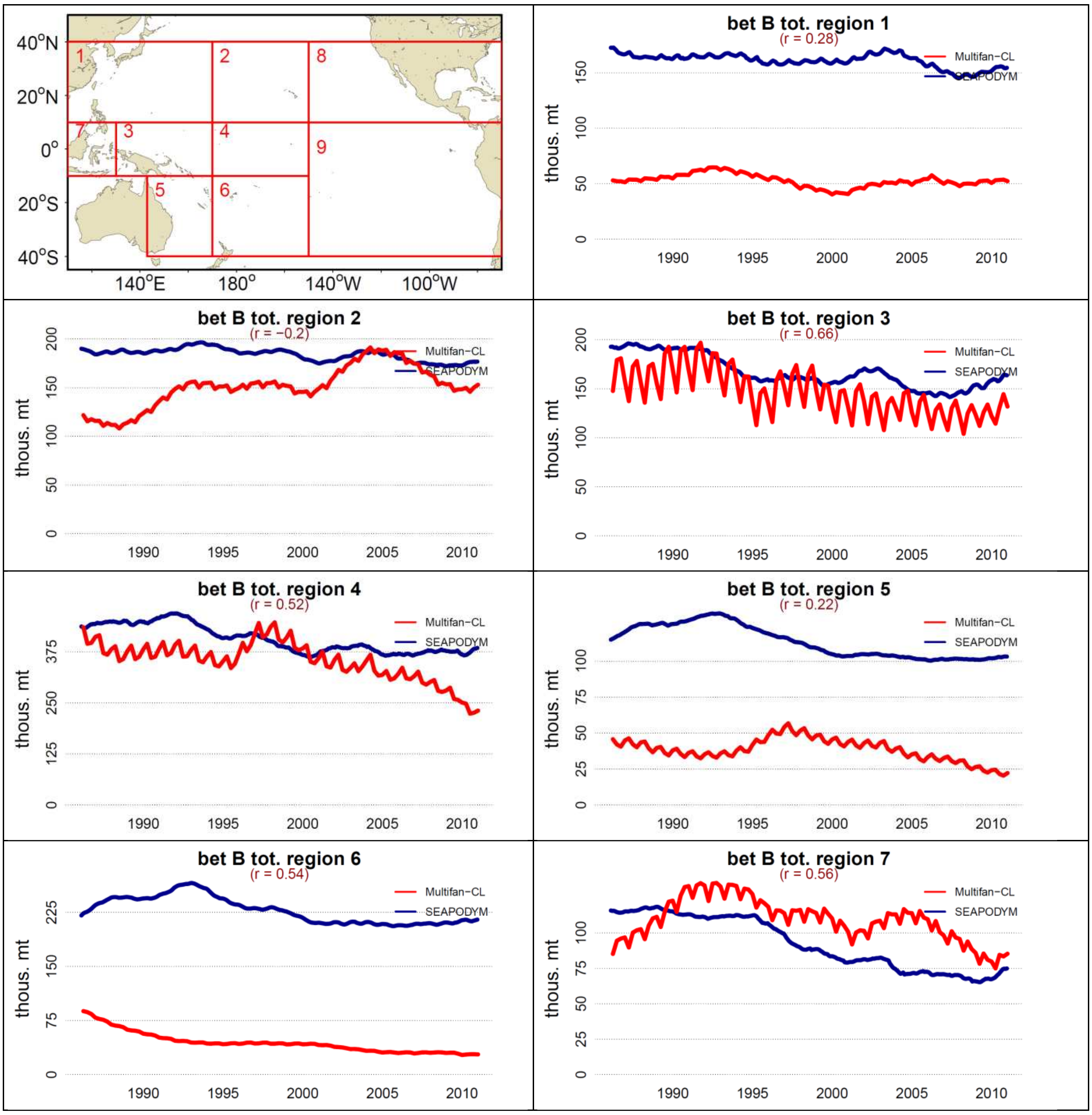

Figure A18. Regional comparison between SEAPODYM and Multifan-CL model predictions for total bigeye tuna biomass.

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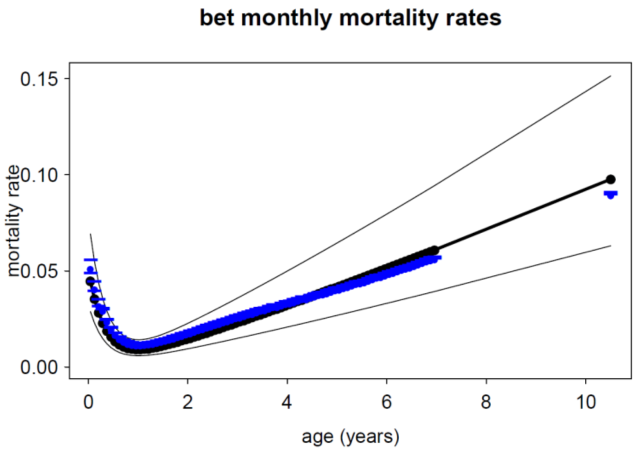

Figure A19. Average natural mortality coefficient at age estimated with SEAPODYM optimization experiment for bigeye.

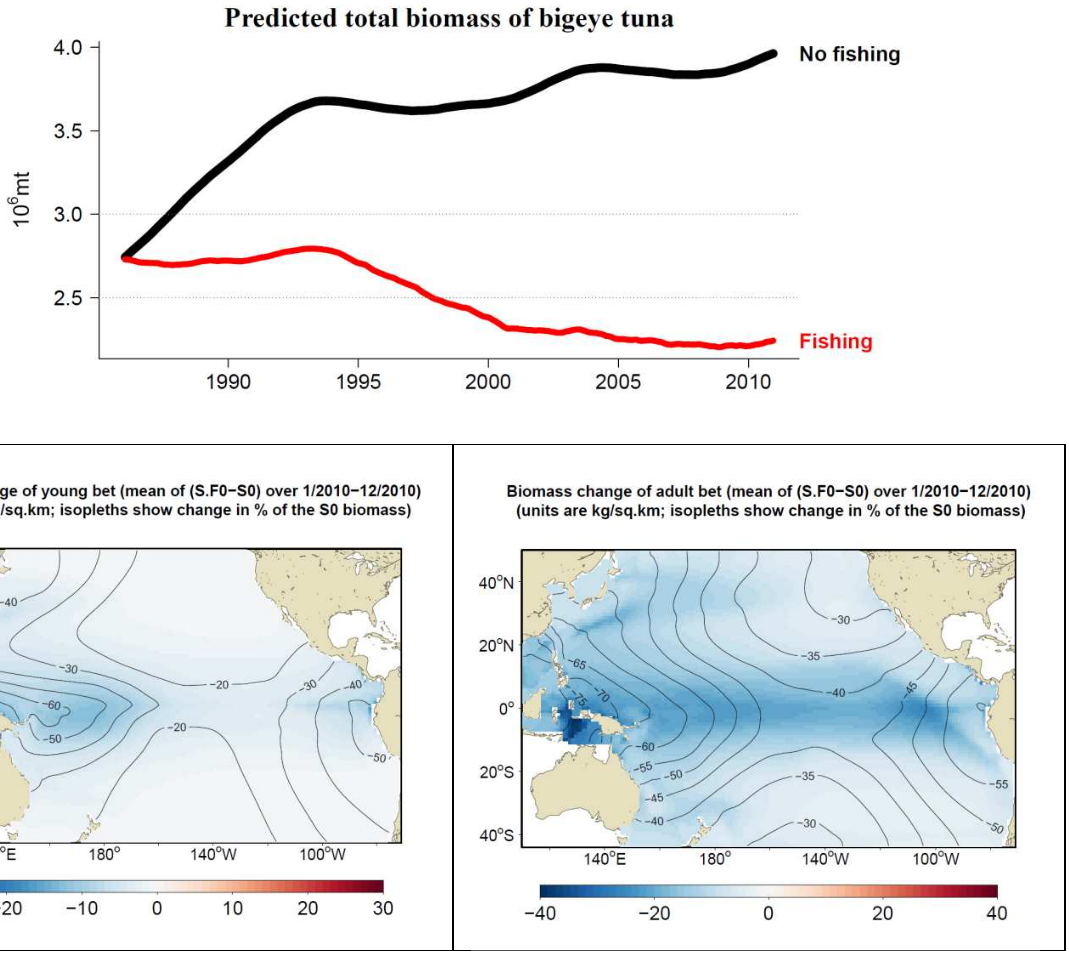

Figure A20. Quantification of the fishing impact of Pacific bigeye tuna. Spatial fishing impact on young and adult population stages is shown with contour lines of the index (B_{F0}-B_{Ref}) / B_{F0} and color background indicating the average biomass reduction due to fishing (kg /km^2).

APPENDIX II

Climate change

The gradual warming and acidification of the ocean due to anthropogenic greenhouse gas emissions impact the distributions and population dynamics of tuna populations. The model SEAPODYM has been used to explore these potential impacts over the coming Century under the worst IPCC scenarios (Lehodey et al 2013, 2015). In addition to the classical uncertainties associated to the mechanisms and parameterization of SEAPODYM, these climate change projections add a few more challenges. A first critical one is the uncertainty on the physical and biogeochemical Earth Climate models, and the need to adapt the SEAPODYM tuna parameterization to each Climate Model environment provided by these models, since they have all their own biases and errors. Then, environmental variables and mechanisms that are not considered critical today for the modelling of tuna biology and population dynamics may become limiting factors in the future. This is certainly the case concerning the ocean acidification and its potential effects.

Multi-model ensemble simulation

The well established approach to deal with uncertainty between models is to run a multi-model ensemble simulation, allowing to get a mean trend with a quantified range of uncertainty. However, in the case of SEAPODYM, this would mean time consuming series of optimisation experiments of SEAPODYM for each Earth Climate Model forcing. Therefore, it was decided to use a single realistic hindcast of the past history driven by an atmospheric reanalysis (i.e. observations interpolated on a regular grid) to get the optimal solution for each tuna species based on the historical fishing datasets. Then, the projections following IPCC scenarios are produced but with the same coupled physical-biogeochemical ocean model and using only the atmospheric variables predicted from the multiple Climate Models. A preliminary filtering to avoid abrupt changes between the historical series and the projections is necessary. This work has been achieved with three earth climate model projections (cf Senina et al 2015; 2016) and will be complemented with three others. Also, since coupled physical-biogeochemical outputs may include a “drift”, i.e., a trend in the outputs due to unachieved equilibrium state in the initial conditions, control runs need to be used to remove these trends.

Ocean acidification

A workshop was held in January 2016 to review the current status of information on the effects of ocean acidification on pelagic fisheries in the Pacific Ocean and to examine options for assessing the impact on tuna resources. Previously, one study investigated how ocean acidification may affect tuna eggs and larvae (Bromhead et al., 2015). The conclusions that can be drawn from the workshop are that there is some support for ocean acidification directly resulting in increased mortality of eggs and larvae (Baumann et al., 2012; Chambers et al., 2014), but at high pCO2 levels (above 1000 µatm, i.e. at concentrations that are on average higher than that predicted by 2100), and that these impacts maybe dampened with parental acclimation (Miller et al., 2012).

- If tuna larvae mortality increases due to unfavourable changes in their prey conditions, the Holling-III function used in SEAPODYM to describe the number of prey consumed relatively to the density of prey can be modified to increase the density of prey before the function asymptotes with increasing acidity.
- Similarly, the impacts of acidification on the life history of tuna could be incorporated by adding a 3rd dimension (an acidification effect) to the natural mortality curve. In this case the mortality would increase with increasing acidity.
- Movement in SEAPODYM is modelled as a Eulerian process based on the definitions of habitats indices, the gradients of which influence the advection parameters. It may be

possible to add an acidity component to the spawning and habitat indices to investigate other subtle effects of ocean acidification on the population dynamics.

The fields of pH projected by three Earth climate models until the end of this Century have just been processed and the first test simulations will start in the second half of 2016.

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