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SEAPODYM.V2: A SPATIAL ECOSYSTEM AND POPULATION DYNAMICS MODEL WITH PARAMETER OPTIMIZATION PROVIDING A NEW TOOL FOR TUNA MANAGEMENT

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Abstract

An enhanced version of the spatial ecosystem and population dynamics model SEAPODYM is presented to describe spatial dynamics of tuna and tuna-like species in the Pacific Ocean. It includes the modelling of mid-trophic organisms of the pelagic ecosystem with several pelagic mid-trophic functional groups. Parametrization of the dynamics of these components is based on an allometric relationship. Then, a simple energy transfer from primary production is used, justified by the existence of constant slopes in log-log biomass size spectrum relationships. Impacts of vertical behaviour of the organisms and horizontal currents are considered through a system of advection-diffusion equations. Dynamics of tuna populations have been revised. This new version of SEAPODYM includes expanded definitions of habitat indices, movements, and natural mortality based on empirical evidences and first biological principles. A thermal habitat of tuna species is derived from an individual heat budget model. The feeding habitat is computed according to the accessibility of tuna predator cohorts to different vertically migrating and non-migrating micronekton (mid-trophic) functional groups. The spawning habitat is based on temperature and the coincidence of spawning fish with presence or absence of predators and food for larvae. The successful larval recruitment is linked to spawning stock biomass. Larvae drift with currents, while immature and adult tuna can move of their own volition, in addition to being advected by currents. A food requirement index is computed to adjust locally the natural mortality of cohorts based on food demand and accessibility to available forage components. Together these mechanisms induce bottom-up and top-down effects, and intra- (i.e. between cohorts) and inter-species interactions. The model is now fully operational for running multi-species, multi-fisheries simulations, and the structure of the model allows a validation from multiple data sources. In particular, the model includes a rigorous mathematical parameter optimization using catch data and size frequency of catch. Examples of applications are presented to illustrate the interest of the model for management of tuna stocks in the context of climate and ecosystem variability, and to investigate potential changes due to anthropogenic activities including global warming and fisheries pressures and management scenarios.

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1. Introduction

SEAPODYM is a model developed initially for investigating spatial tuna population dynamics, under the influence of both fishing and environmental effects. This modelling effort started in 1995 at the Secretariat of the Pacific Community in Noumea, New Caledonia, under two consecutive EU-funded projects: SPR-TRAMP (1995-2000) and PROCFISH (2002-2005). The model development also benefited of a grant from the PFRP (Pelagic Fisheries Research Program) of the University of Hawaii, allowing the implementation of irregular grids and initiating the work for parameter optimization (2004-05). Since 2006, the development has continued within the MEMMS section (Marine Ecosystem Modeling and Monitoring by Satellites) of the Spatial Oceanography Division of CLS, a subsidiary of the French CNES and IFREMER Institutes. Collaboration with SPC continues, with funding support from a new EU-funded SPC project, SCIFISH.

An enhanced version of the model (SEAPODYM.v2) is now ready for use. It includes revised mechanisms for the modelling of mid-trophic organisms of the pelagic ecosystem with several pelagic mid-trophic functional groups. Dynamics of tuna populations have been also revised with expanded definitions of habitat indices, movements, and natural mortality. The code for parameter optimization has been completed and tested. A second PFRP grant (2006-09) and the SPC – CLS collaboration via SCIFISH should lead to parameterized models for the main tuna species in the Pacific Ocean (skipjack, yellowfin, bigeye and south Pacific albacore), using catch, size frequency and possibly tagging data for the parameter optimization, and based on single-species basin-scale simulations at monthly 2x2 degree resolution. Examples of applications are presented in this document to illustrate the potential utility of the model for management of tuna stocks in the context of climate and ecosystem variability, and to investigate potential changes due to anthropogenic activities including global warming, fishing and management intervention.

2. Model summary

The SEAPODYM model has been continuously enhanced to provide a general framework allowing integration of the biological and ecological knowledge of tuna species, and potentially other oceanic top-predator species, within a comprehensive description of the pelagic ecosystem (Bertignac et al., 1998; Lehodey et al., 1998; Lehodey, 2001; Lehodey et al., 2003). It has been upgraded to include more detailed relationships between population dynamics and basic biological and ecological functions, including a more realistic representation of the vertical oceanic habitat, both in terms of physical and foraging conditions. The model includes a forage (prey) sub-model describing the transfer of energy of stored biomass through functional groups of mid-trophic levels and an age-structured population sub-model of tuna predator species and their multi-fisheries. The dynamics of forage and predators are driven by environmental forcing (temperature, currents, oxygen and primary production) that can be predicted from coupled physical-biogeochemical models. The model also includes a rigorous mathematical parameter optimization using catch data and size frequency of catch (Figure 1). We attempted to keep the minimal number of parameters to facilitate a formal optimization procedure required for assessment analyses.

Because the model is driven by the bio-physical environment of the ecosystem, it was possible to reduce the number of parameters that describe the complete spatially-explicit population dynamics of a species to twenty-one (cf. appendix), i.e., a small number relative to the number of variables described in the model. A few more parameters should be added to include the growth function that is still provided by independent studies in this version. Other parameters concern the description of fisheries (selectivity and catchability).

The model is parameterized through assimilation of commercial fisheries data, and optimization is carried out using maximum likelihood estimation approach. For parameter optimization, we implemented adjoint methodology to obtain an exact, analytical evaluation of the likelihood gradient. The approach to select the “best parameter estimate” is based on a series of computer experiments in order i) to determine model sensitivity with respect to variable parameters and, hence, investigate their observability, ii) to estimate observable parameters and their errors, and iii) to justify the reliability of found solution.

The new version of the model is fully detailed in recent papers (Lehodey et al., *in press*; Lehodey et al., *in revision*; Senina et al., *in press*).

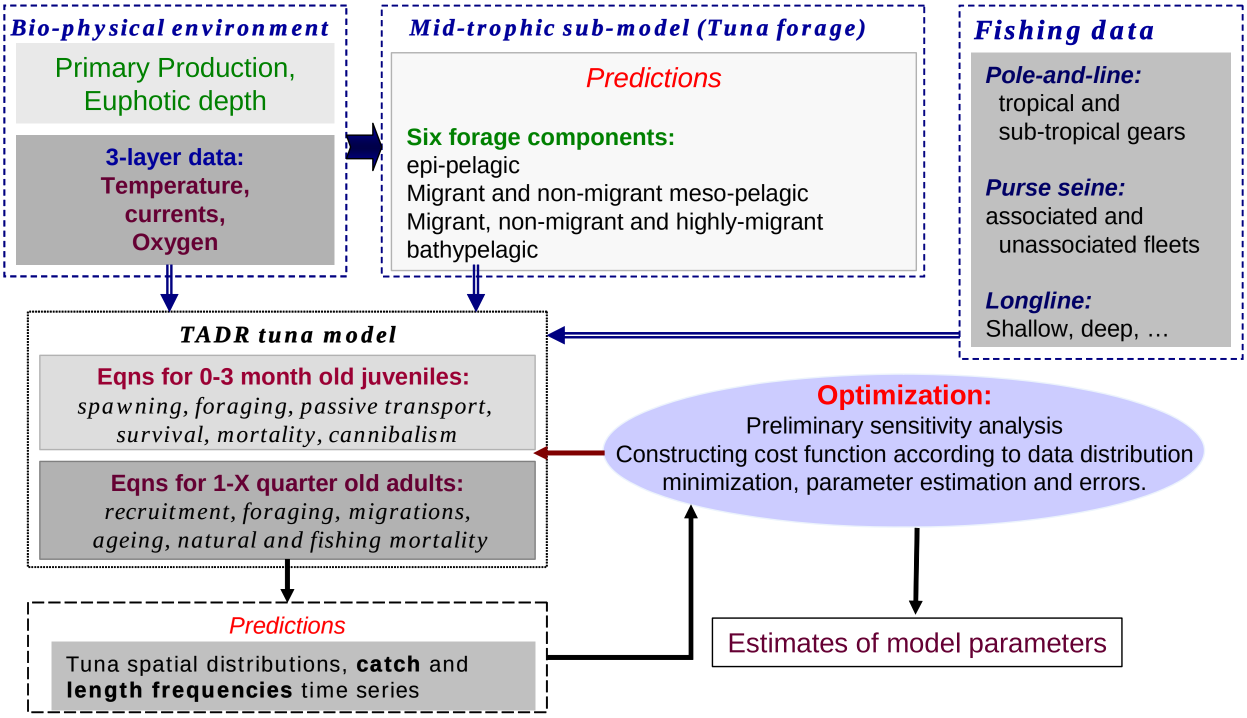

Figure 1: General scheme of the SEAPODYM model with optimization approach.

3. Applications

3.1. Stock assessment

A preliminary parameterization has been obtained with SEAPODYM for skipjack and bigeye Pacific tuna, using an oceanic physical environment predicted by an independent Ocean General Circulation Model with biogeochemical input predicted by a nutrients-phytoplankton-zooplankton-detritus model developed at ESSIC, University of Maryland. Table 1 summarizes the fishing data used for parameter estimation for each species. Parameters describing recruitment, movement, habitat preferences, and the natural and fishing mortality of the population are presented in Table 2. Figures 2 and 3 provide examples of outputs, e.g., comparison between SEAPODYM and MULTIFAN-CL estimates or comparison between predicted and observed catch. It is worth noting that parameter optimization is carried out over the recent period (1985-2004) and the remainder of the time series hindcast using the parameterized model.

Future tasks:

- Run optimization experiments with multiple forcing data sets to provide an envelope of prediction and to investigate sensitivity of the model and the optimization approach to the forcing fields (since the population dynamics in the model are strongly linked to the environmental conditions).
- Investigate independent measures or estimates of some of these parameters, for example using electronic tagging data, should assist in the evaluation of model predictions.
- Add the conventional and archival tagging data to the parameter estimation to provide additional key information for estimating several critical parameters (e.g., movements, habitats, recruitment and mortality).
- Apply to other species (yellowfin, albacore, swordfish, …)
- Run parameter optimization with multi-species simulations
- Compare with simulation experiments in Atlantic and Indian Ocean.

Table 1. Definition of fisheries for the Pacific skipjack and bigeye tuna SEAPODYM parameters optimization experiments.

Fishery Number	Nationality	Gear	Sub-region	Code
1	Japan, Korea, Chinese Taipei	Longline	1	LLI
2	Japan, Korea, Chinese Taipei	Longline	2	LL2
3	United States (Hawaii)	Longline	2	LL3
4	All	Longline	3	LL4-5
5	Papua New Guinea	Longline	4	LL6
6	Japan, Korea, Chinese Taipei and China	Longline	4	LL7-8
7	United States (Hawaii)	Longline	4	LL9
8	All excl. Australia	Longline	5	LL10
9	Australia	Longline	5	LL11
10	Japan, Korea, Chinese Taipei	Longline	6	LL12
11	Pacific Island Countries/Territories	Longline	6	LL13
12	All excl. Chinese Taipei & China	Longline	7	LL21
13	Chinese Taipei and China	Longline	7	LL22
14	Japan, Korea, Chinese Taipei	Longline	8	LL23
15	Japan, Korea, Chinese Taipei	Longline	9	LL24
16	All	Purse seine, log/FAD sets	3	WPSASS
17	All	Purse seine, school sets	3	WPSUNA
18	All	Purse seine, log/FAD sets, nearshore and central area	8	EPSASS
19	All	Purse seine, school, dolphin sets, log/FAD sets, offshore area	8	EPSUNA
20	Japan	Pole-and-line	1,2	PLSUB
21	All	Pole-and-line	3,4	PLTRO
22	Philippines, Indonesia	Handline (large fish)	3	COMMHL
23	Philippines, Indonesia	Miscellaneous (small fish)	3	ARTSURF

Table 2: Estimated values of model parameter based on optimization with ESSIC reanalysis.

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

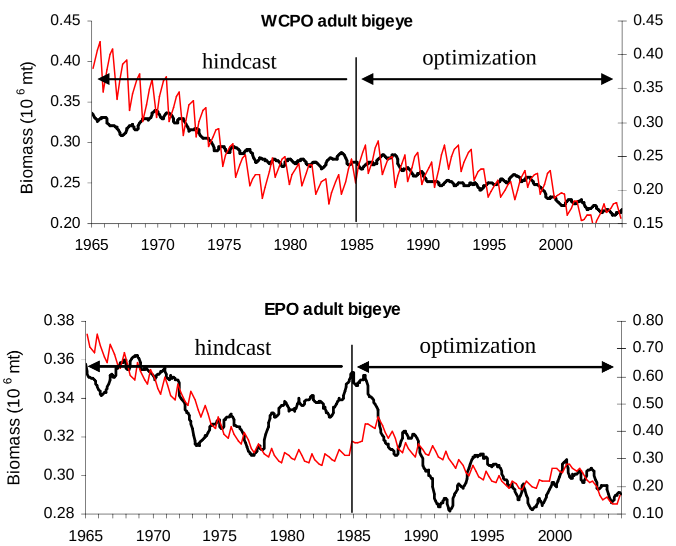

Figure 2: Trends in Pacific bigeye tuna population predicted in WCPO and EPO with optimization (1985-2004) and hindcast prediction to 1965 for experiment based on ESSIC (black thick line) forcing fields. The trends for adults are compared to estimates (thin red line) from stock-assessment model MULTIFAN-CL (Hampton et al. 2006, Sibert et al. 2006).

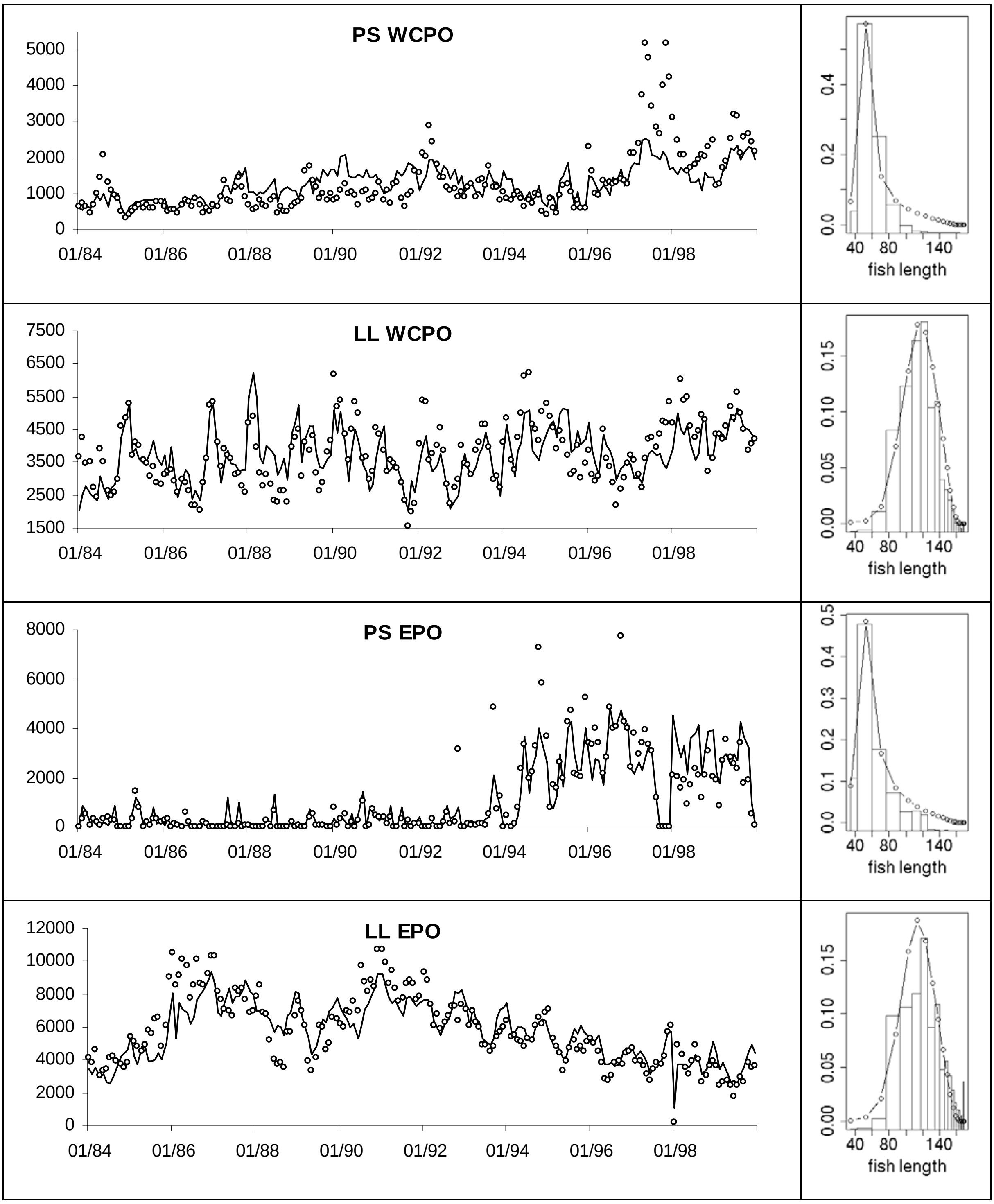

Figure 3: Comparison of observed (circles) and predicted (lines) catch series and size frequency distributions aggregated by main categories of fleets (PS = purse seine, LL = longline) in the western central (WCPO) and eastern Pacific Ocean (EPO).

3.2. Impacts of climate variability

Previous studies have shown the influence of climate variability on tuna (e.g., Lehodey et al. 1997, Fournier et al., 1998; Lehodey et al 2003). The new simulation experiments with parameter optimization using data assimilation confirm the strong influence of interannual ENSO variability on both the spatial dynamics and the recruitment of skipjack.

During El Nino, the skipjack population moves eastward (Figure 4), and the biomass in the Central and Eastern Pacific increases, while it decreases in the Western Pacific ocean correspondingly. These spatial changes very likely affect the catch and can lead to a discrepancy between SEAPODYM-APE and MULTIFAN-CL biomass estimates. The latter might "interpret" a sudden drop of catches in the WCPO due to an eastward displacement of a large fraction of the stock as either a decrease in stock abundance or a decrease in catchability. Conversely, SEAPODYM has the additional flexibility to model environmentally-induced time-series changes in movement, and can therefore explicitly predict catch decline due to short-medium term eastward movement of the population.

Comparison of predicted biomass time series of young tuna and the Southern Oscillation Index (SOI) shows an evident direct relationship between ENSO events and changes in the population dynamics (Figure 4). The maximum correlation between the two series (-0.63) is obtained with a SOI series lagged by 8 months, a time lag approximately matching the age of recruits, and thus suggesting that the ENSO impact occurs directly on the early life history of the species (i.e. spawning index). This result can have important application in the real-time management of the fishery, with the general trend in abundance of the adult stock being predictable 8 months in advance simply using the SOI.

<u>Future tasks:</u>

- Investigate climate variability impacts on other tuna species (and in other oceans)
- Explore management and economic repercussions of climate linked forecasts
- Develop ENSO-phase (El Nino; La Nina; Neutral) fisheries scenarios and run projections
- Develop a fleet dynamics model that could integrate ENSO forecasting and that could be coupled to SEAPODYM

Note that in order to develop useful climate-based projections, e.g., at 6 months, it would be essential to reduce to a minimum the delay in the update of fishing databases. The use of VMS is a promising way to provide near real-time estimates of fishing effort.

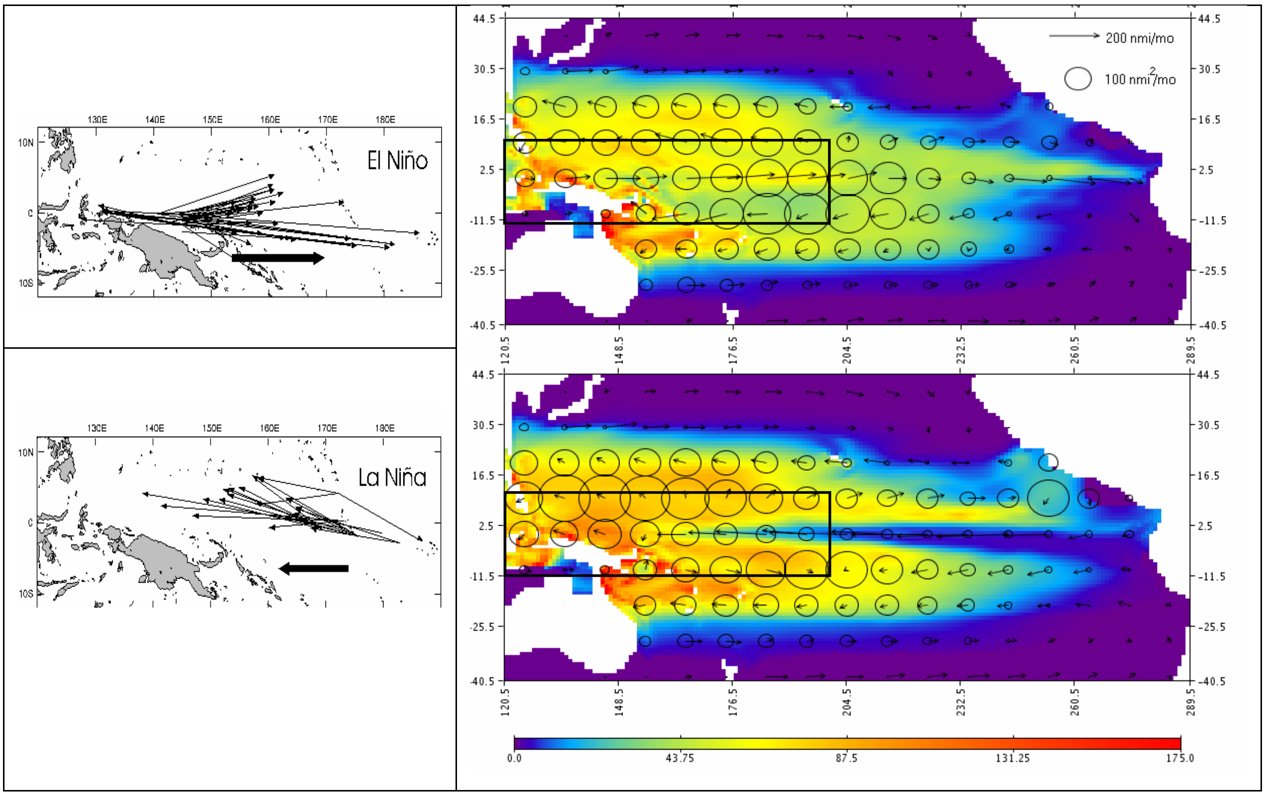

Figure 4: Distribution of biomass of a skipjack cohort at the first month after the age of maturity in November 1997 (El Niño phase) and November 1998 (La Niña phase) in the Pacific Ocean. Circles and arrows represent random (diffusion) and directed (advection) movements of population density, respectively, and are averaged by 10 degree squares. Black rectangles show the region where tags have been released and recaptured during the earlier corresponding ENSO phases (redrawn from Lehodey et al., 1997).

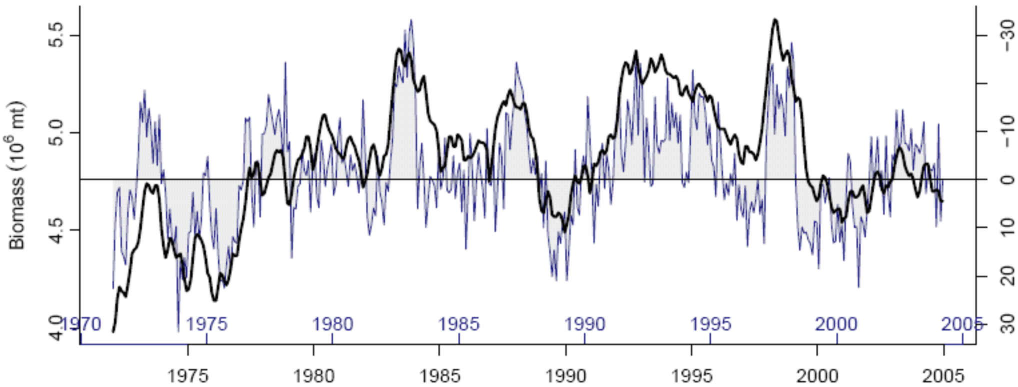

Figure 5: Biomass of young skipjack tuna (sum of ages from 3 month to 3 quarter) and eight month lagged Southern Oscillation Index (notice that y axis is inverted) as an indicator of El-Nino event (Redrawn from Senina et al., *in press*).

3.3. *Impacts of Global warming*

It is possible to investigate the impact of global warming on tuna populations with SEAPODYM using forcing datasets of oceanic conditions under IPCC scenarios for the 21th Century. A preliminary study has been carried out for skipjack and bigeye using the SRESA2 IPCC scenario, i.e, atmospheric CO2 concentrations reaching 850 ppm in the year 2100, and historical data between 1860 and 2000. The simulation is driven by physical-biogeochemical fields predicted from a global Earth system simulation (IPSL, L. Bopp, pers. comm.).

The projection of this IPSL climate simulation under the A2 scenario for the 21th century shows a decline in primary productivity and an increase in temperature in both equatorial and sub-tropical regions correlated to an increase in the euphotic depth. The decline of productivity in the tropical region is compensated by an increase in higher latitudes where the greater vertical stability increases the length of the growing season of phytoplankton in the euphotic depth. The dissolved oxygen concentration, a critical variable constraining tuna habitat, is also predicted to decrease under this A2 scenario almost everywhere. The primary reason for the simulated decrease in oxygen is the reduction of transport to depth due to increased vertical stability and solubility changes due to warmer waters. The decrease in primary productivity predicted during the 21st Century is particularly strong in the western tropical Pacific.

The parameterization based on the IPSL predictions over the period 1985-2000 was used for the whole climate simulation (1860-2100), without fishing effort, to investigate the general trends of biomass (Figure 6) and spatial distributions (Figure 7) associated with environmental changes under the increasing forcing of atmospheric CO2. The result is a clear expansion of the spawning habitat and density of larvae for both species, especially in the eastern tropical Pacific (see Figure 7). This phenomenon occurs in correlation with ocean warming but also the changes in productivity and circulation that interact through the larvae prey-predator interactions in the model. In the eastern tropical Pacific, enhanced adult habitat leads to an increase in the adult biomass with a direct effect on the local spawning through the assumed Beverton-Holt relationship. Despite the large increase in larvae density, the ensuing adult biomass of both species is predicted to decrease in the western Pacific and to remain stable or increase slightly in the eastern Pacific (Figures 6 and 7).

<u>Future tasks:</u>

- Compare fishery and climate effects during historical period
- Apply to other tuna species
- Test the sensitivity to mid-trophic parameterization
- Run optimization using other reanalyses and simulation products
- Test other IPCC scenarios
- Run optimization with multi-species for testing species-interaction (need parallel coding)
- Forecast fishing effects into the future (needs model of fishery dynamics)

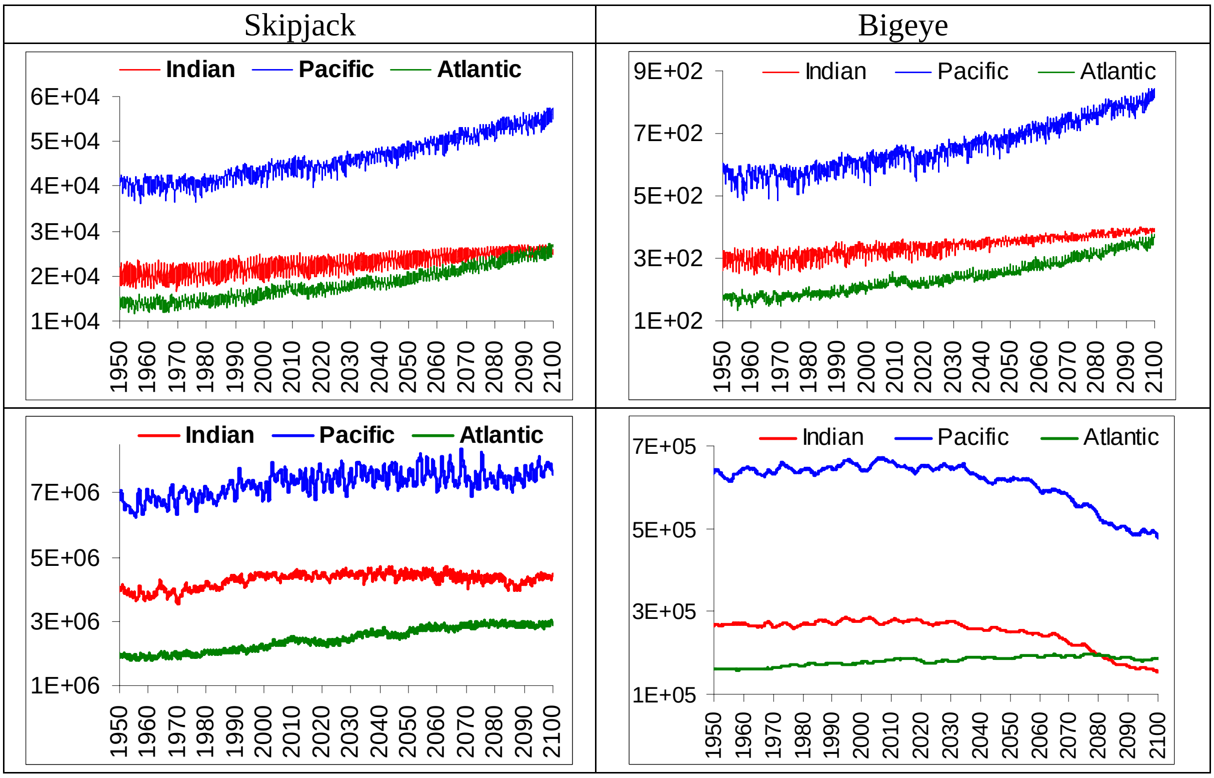

Figure 6. Trends by ocean of bigeye and skipjack larvae (top) and adult (bottom) biomass (million tonnes) estimated by SEAPODYM under the IPCC SRESA2 scenario.

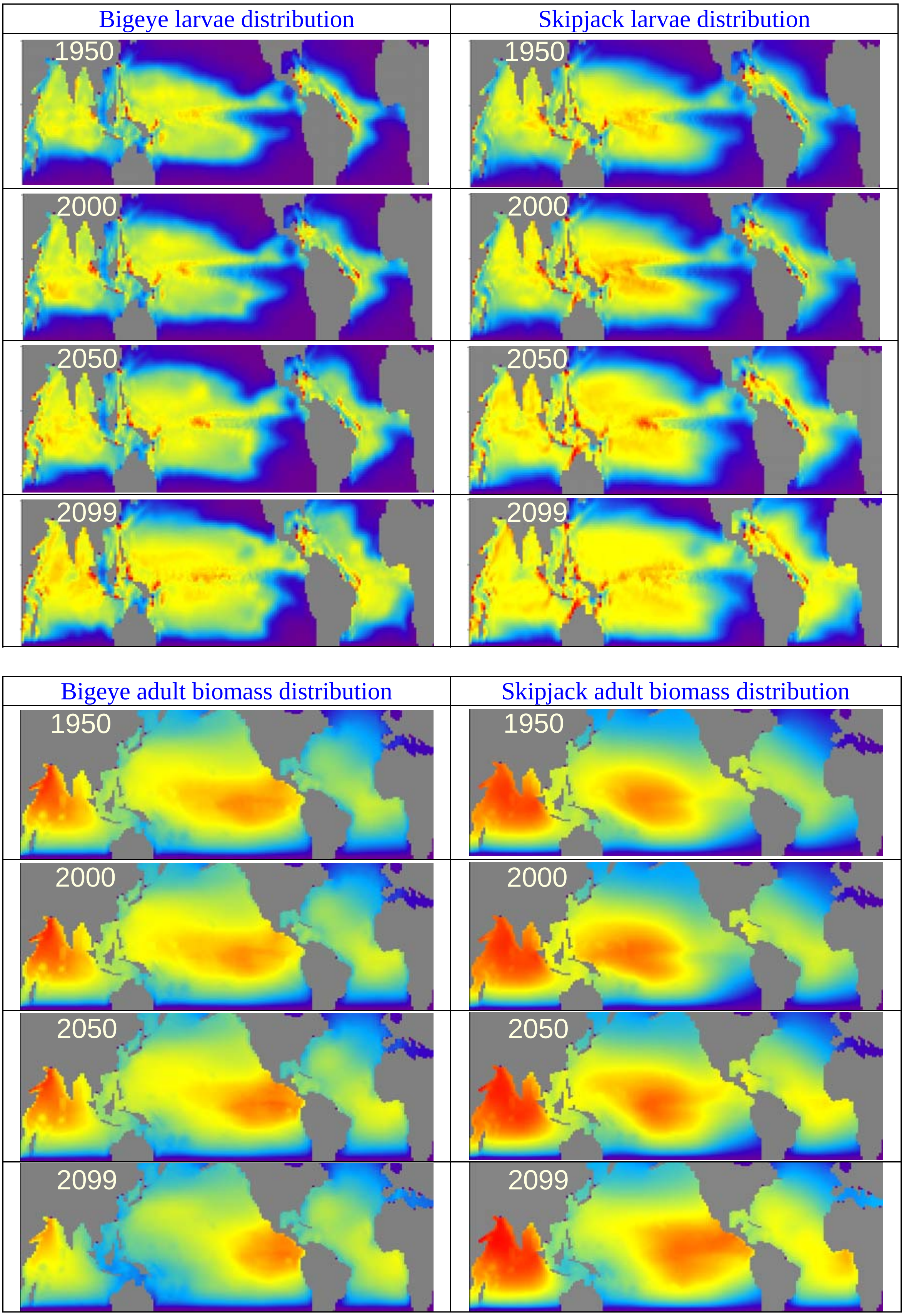

Figure 7. Change in spatial distribution of bigeye and skipjack larvae and adult biomass under the IPCC (SRES A2) scenario. Note that parameter optimization is carried out in the Pacific Ocean for the period 1985-2004). Fishing impact is not included in this simulation.

3.4. Management Scenarios

Once the best parameterization of the model is obtained and the predicted results fully evaluated, it becomes possible to use the model for many different management scenarios taking advantage of its spatial multi-species multi-fisheries structure. There are many types of potential applications. In a first attempt to estimate the mobility of tropical tunas, Sibert and Hampton (2003) suggested that semi-isolated high-seas enclaves of the WCPO could provide potential conservation zones. One preliminary analysis is presented here to examine the potential interest of establishing marine protected areas (MPAs) on these high-sea enclaves as a new tool and strategy for tuna fisheries management.

MPAs are recognized as appropriate tools to implement ecosystem-based fisheries management in the context of scientific uncertainty, but have been designed in coastal domain mainly. High Seas MPAs requires identification of pelagic areas that are key zones for ensuring the sustainability of tuna stocks and fisheries and the resilience of by-catch marine species. The relevance of establishing High Seas MPAs in the WCPO leads to a set of questions: Can it contribute to a better sustainable management of tuna resources and conservation of marine biodiversity? What could be the impact on the catch rates in adjacent EEZs? Would the MPA implementation benefit all fleets, i.e. is it a win-win option?

This preliminary analysis used an optimal parameterization that has been obtained for skipjack using the maximum likelihood approach and function minimization method outlined above. Two scenarios corresponding to the closure of the 3 IW MPAs shown in Figure 8 were tested: the total monthly effort released from MPAs was redistributed within the same fishery either equally over other areas (S3) or (more realistically) proportionally to the current effort distribution (S4). MPA closures have more limited impact in scenario S4 (annual reduction of catch <3%) due to more efficient use of released effort. In this case purse seine fleets targeting free schools (i.e. WPSUNA) obtain smaller losses than those fishing on associated sets (WPSASS).

This preliminary result highlights the interest of using spatially-disaggregated catch data to investigate MPA effects and demonstrates how simple management measures can produce complex responses on stock dynamics and fisheries. It indicates that redistribution of fishing effort displaced by the imposition of MPAs will be a critical factor that will determine whether high-seas MPAs will be successful in achieving stock conservation objectives.

<u>Future tasks:</u>

- Run multi-species multi-fisheries simulations
- Include economic criteria in the scenarios of redistribution of the fishing effort.

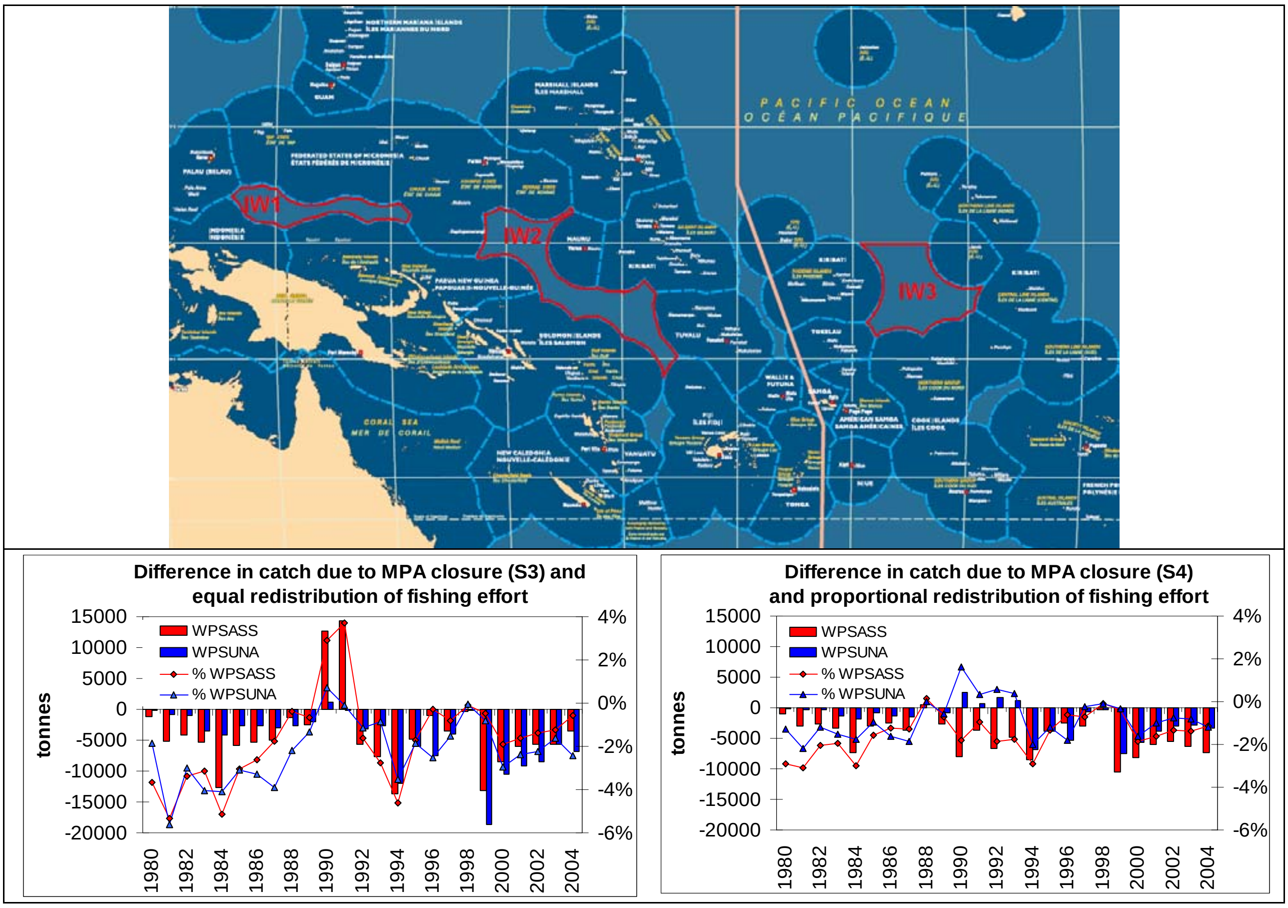

Figure 8: Location of the three MPAs considered in the simulation and results showing the difference in skipjack catch by purse seine fleets due to the MPA closures and two different scenarios dealing with released fishing effort – either to redistribute the effort equally among other enclaves (S3) or proportionally to the existing distribution (S4).

4. Conclusion

The new version of SEAPODYM with a parameterization achieved by a rigorous optimization approach can now be considered sufficiently mature to be proposed and used as a new approach for tuna stock assessment studies and developing spatial management strategies. It can help us investigate the impact of fishing under various management scenarios, and also forecast the spatial dynamics of stocks in the context of environmental variability and climate change.

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