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Project 62: SEAPODYM applications in WCPO

WCPFC-SC10-2014/EB-WP-02

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1. EXECUTIVE SUMMARY

Recommendations

The SC acknowledge the projects and donors that are continuing to contribute to the development and application of SEAPODYM to the work programme of the WCPFC-SC and to endorse the inclusion of all presented projects within the scope of Project 62.

The SC notes the 2014-2015 work plan for Project 62.

Introduction

SEAPODYM is a model developed for investigating spatial tuna population dynamics, under the influence of both fishing and environmental effects. In addition to fisheries data the model utilises environmental data in a manner that allows high resolution prediction. SEAPODYM complements the Scientific Committee's MULTIFAN-CL models by providing additional information on how tuna distributions are structured in space and time. The continued development and application of the SEAPODYM model to the work of the WCPFC Scientific Committee is facilitated through Project 62. The project affiliates the independently funded work on SEAPODYM into the SC's work programme.

Code Development

Three modifications to the SEAPODYM code have been completed since SC9. The two most significant modifications are the capability to compute the fluxes of fish density between several pre-defined geographical areas and testing of a new definition of the function used to describe the thermal habitat. Four additional diagnostic routines have been developed to facilitate the analysis and validation of simulation outputs.

Physical Forcing of reference fits

A new reference fits using OMEGA 1 degree physical forcing has been completed for skipjack (SKJ3.0). A new reference fit using ECCO 1 degree has been completed for bigeye (BET 3.0). These optimisations include the PTTP tagging data. A new reference fits using NCEP 2 degree physical forcing has been completed for yellowfin (YFT1.1) with optimisation based on fishing data only.

Current and Future Work Plan

1. Optimisation of the micronekton model using acoustic data transects to estimate the energy transfer from primary production to micronekton functional groups.
2. Given the sensitivity analysis suggesting that changes either in the parameterization of the micronekton (prey) model or the accessibility to its components could drastically improve the fit to tagging data, it will be necessary to revise skipjack, bigeye and yellowfin reference fits using updated parameterisation of micronekton (cf. 1) and new definition of thermal habitat functional relationship.

3. Upgrade of operational Basin scale modelling configured at a weekly ¼° resolution, for skipjack, yellowfin and bigeye tuna with new reference fits and fishing effort climatology in the Indian Ocean.
4. Evaluation of the regional operational (realtime) high resolution SEAPODYM model (1/12° x day) in the far western Pacific.
5. Revision of the software SeapodymView which provides for easy display of SEAPODYM outputs to allow use on non-Linux operating systems and to provide improved visualisation options.
6. Optimisations using the new physical forcing for climate change (see SC10-EB-IP-02).
7. Updating the SEAPODYM manual to include a description of commonly applied diagnostics to assist the Scientific Committee in evaluating SEAPODYM optimisations as reference fits.

Acknowledgements and Donors

Project 62 is currently supported by 6 projects with financial support provided by Secretariat of the Pacific Community, Collecte Localisation Satellites, Australian Government Overseas Aid Program (AUSAID), 10th European Development Fund (EDF), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Western Pacific Regional Fishery Management Council, Government of Indonesia, Agence Francaise de Developpement, and Pelagic Fisheries Research Program. The Inter American Tropical Tuna Commission has provided access to non-public domain data for the purposes of progressing the work programme of the WCPFC-SC.

Content

2. INTRODUCTION

SEAPODYM is a model developed for investigating spatial tuna population dynamics, under the influence of both fishing and environmental effects. The model is based on advection-diffusion-reaction equations, and population dynamics (spawning, movement, mortality) are constrained by environmental data (temperature, currents, primary production and dissolved oxygen concentration) and simulated distribution of mid-trophic (micronektonic tuna forage) functional groups. The model simulates tuna age-structured populations with length and weight relationships obtained from independent studies. Different life stages are considered: larvae, juveniles and (immature and mature) adults. After juvenile phase, fish become autonomous, i.e., they have their own movement (linked to their size and habitat) in addition to be transported by oceanic currents. Fish are considered immature until pre-defined age at first maturity and mature after this age, i.e., contributing to the spawning biomass and with their displacements controlled by a seasonal switch between feeding and spawning habitat, effective outside of the equatorial region where changes in the gradient of day length is marked enough and above a threshold value. The last age class is a "plus class" where all oldest individuals are accumulated. The model includes a representation of fisheries and predicts total catch and size frequency of catch by fleet when fishing data (catch and effort) are available. A Maximum Likelihood Estimation approach is used to optimize the model parameters. Integration of conventional tagging data has been achieved recently.

3. AFFILIATED PROJECTS

The continued development and application of the SEAPODYM model to the work of the WCPFC Scientific Committee is facilitated through Project 62. The project affiliates the independently funded work on SEAPODYM into the SC's work programme.

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 (# 651438) from the PFRP (Pelagic Fisheries Research Program) of the University of Hawaii. Since 2006, the development has continued within the Space Oceanography Division of CLS, a subsidiary of the French CNES and IFREMER Institutes in collaboration with SPC (under the EU SCIFISH and SCICOFISH projects, a grant from the Australian Department of Climate Change and Energy Efficiency and the SPC-Australian Climate Change Support Programme 2011-2013) and PFRP (project number 657425, 659708 and 661551). Current projects are described in Table 2.1.

Table 3.1: Current projects and donors affiliated with Project 62.

Title	Purpose	Donor
Scientific Support for the Management of Coastal and Oceanic Fisheries in the Pacific Islands Region (SciCOFish)	Develop reference fits for the historical period for skipjack, bigeye and south pacific albacore. Develop reference fit for the IPSL CMIP4 model and provide first simulation of Climate Change Impacts for skipjack, bigeye and south pacific albacore	10^{th} European Development Fund
SPC-Australian Climate Change Support Programme 2011-2013	Analysis of climate change impacts for skipjack, bigeye, yellowfin and south pacific albacore to assist national and regional policy formation	Australian Government Overseas Aid Program (AUSAID)
Enhanced estimates of climate change impacts on WCPO tuna, including estimates of uncertainty	Application of a model ensemble approach to capture the uncertainty in climate change forecasts for Pacific tuna populations	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)
Skipjack resource assessment for the Mariana Islands	High resolution modelling to estimate the skipjack resource status in the Mariana Islands	Western Pacific Regional Fishery Management Council
Integrating conventional and electronic tagging data into the spatial ecosystem and population model SEAPODYM	Modify the code of SEAPODYM to incorporate tagging data	Pelagic Fisheries Research Program
Infrastructure Development of Space Oceanography for IUU Fishing and Coral Monitoring (INDESO Project)	Modify the code to allow operational and sub-regional modelling	Government of Indonesia, Agence Française de Développement

4. CODE DEVELOPMENT

The code of SEAPODYM is continually enhanced to improve the model skills and to facilitate its use by non-developers. Changes since those reported at SC9 include:

a) The spawning habitat has been slightly modified to estimate separately the different effects between temperature, food and predation on larvae. A condition in dissolved oxygen concentration for the accessibility by the adults has been added.
b) The code has been developed to compute the fluxes of fish density between several pre-defined geographical areas.
c) new definition of the function used to describe the thermal habitat has been tested

Additional diagnostic routines are developed to facilitate the analysis and validation of simulation outputs:

d) Production of Taylor plot providing three aggregated metrics of model fit to the data: standard deviation (distance from (0,0) point depicts the ratio between model and data standard deviation), correlation (angular coordinates) and normalized mean squared error (concentric circles with the green bullet being the centre).

e) Observed (grey) and predicted (red) length frequencies distribution and mean length in catches.
f) Script to produce multiple simulations with increasing fishing effort to compute MSY over long time series and resulting Kobe plot.
g) The visualization software SeapodymView allowing to visualize, manipulate and analyze the SEAPODYM outputs files in their native (.dym) format is currently entirely revised.

5. OCEANIC FORCINGS

SEAPODYM uses spatially explicit estimates of ocean and biological properties such as temperature, current speed, oxygen, phytoplankton concentration and euphotic depth from physical-biogeochemical ocean models to constrain tuna population dynamics. The outputs of SEAPODYM are therefore strongly dependent on the quality of its forcing.

The physical variables (temperature and currents) are outputs of ocean circulation models, either from hindcast simulations or reanalyses. They both provide the same outputs but in the first case the ocean model is forced by atmospheric variables (eg. surface winds) only. In reanalyses, the simulation also includes observations of oceanic variables (e.g. Argo profilers, satellite altimetry) that are assimilated in the model to correct the model and produce more realistic circulation patterns, especially at mesoscale resolution.

The biogeochemical variables (primary production, dissolved oxygen concentration and euphotic depth) can be obtained from a biogeochemical model that is coupled to the physical model or from satellite ocean color sensors from which chlorophyll a, euphotic depth and vertically-integrated primary production are estimated. However, in that case the dissolved oxygen concentration is not available and needs to be replaced by a climatology (i.e., monthly average based on all available observations). All physical reanalyses are used with biogeochemical variables derived from satellite ocean color data.

A list of forcings and their characteristics used for SEAPODYM applications are listed in Table 5.1 Two new physical forcings (ECCO and OMEGA) have been used in the references fits presented in this document. They are both reanalyses and at 1° x month resolution.

ECCO is based on the MIT general circulation model (MITgcm), a numerical model designed for study of the atmosphere, ocean, and climate. It is forced by the atmospheric reanalysis ERA-INTERIM. The model state is mainly constrained by sea surface temperature (SST) and subsurface upper ocean thermal XBT (Expendable Bathythermograph) and MBT (Mechanical Bathythermograph) measurements, supplemented by a spatially sparse tide gauge data set that covers much of the last 50 years.

OMEGA is a reanalysis of the ocean circulation built from historical data on temperature (T) and salinity (S) and a generalized hydrodynamic adjustment method (GHDAM) developed by Ivanov et al (1997). It is based on a model of the ocean general circulation and allows the reconstruction of T- and S-fields in unobserved areas and their retention in the initial form for the areas statistically provided with observations. To obtain balanced fields of temperature, salinity, and currents in the overall area of the ocean, model computations are performed within the adjustment regime until the system arrives at a quasi-stationary state.

Table 5.1. Description of forcings used in SEAPODYM applications for historical and operational simulations

Code	Forcing Type (H/R/D) Hindcast/ Reanalysis/Data	Models features /sources	Resolution	Period used
Physical Forcings				
GLORYS	Ocean reanalysis Glorys v2.1 –PSY3 (R)	NEMO ORCA025; Mercator-Ocean	¼ deg x 1 week	1998-2014
OMEGA	Ocean reanalysis (R)	Generalized Hydrodynamic Adjustment Method (GHDAM) Ivanov et al (1997)	1 deg x 1 month	1998-2012
ECCO	Ocean reanalysis ECCO (R)	http://ecco.jpl.nasa.gov/ http://ecco.jpl.nasa.gov/datasets/dr080/	1 deg x 1 month	1998-2012 (Jul)
NCEP2	Ocean Hindcast NCEP v2 (H)	NEMO ORCA2 forced with 2nd atmospheric reanalysis NCEP	2 deg x 1 month	1960-2008
SODA	Ocean reanalysis SODA (R)	http://www.atmos.umd.edu/~ocean/	1 deg x 1 month	1998-2008
NCEP1	Ocean Hindcast NCEP v1 (H)	NEMO ORCA2 forced with atmospheric 1st reanalysis NCEP	2 deg x 1 month	1979-2003
Biogeochemical Forcings				
PISCES	Biogeochemical model (H)	Coupled to NEMO-ORCA2 in NCEP1 and NCEP2	Same as the coupled physical model (NEMO)	
VGPM	satellite data (D)	Primary production and euphotic depth derived from ocean color	1/12°x day	1998-present
EPPLEY	satellite data (D)	Primary production and euphotic depth derived from ocean color	1/12°x day	1998-present

6. CONFIGURATIONS OF REFERENCES FITS

In this document we report the results concerning the reference fits achieved for skipjack, yellowfin and bigeye tuna with the configurations detailed in Table 6.1.

Table 6.1. Configurations of reference fits achieved for 3 tuna species.

	Skipjack	**Yellowfin**	**Bigeye**
Physical forcing	OMEGA	NCEP v1	ECCO
Biogeochemical forcing	VGPM	PISCES	EPPLEY
Domain and resolution	Pacific O.; 1°x month	Pacific O.; 2°x month	Pacific O.; 1°x month
Period of simulation	2003-2012	1980-2003	1998-2011
Period of optimisation	2004-2012	1985-2003	2008-2011
Initial conditions	Initially used interpolated IC from previous SODA reference solution. Then updated in optimization experiments using current estimated parameters.	Subsequently updated in optimization experiments using estimated parameters, by re-running the simulation from 1948	Initially used interpolated IC from previous NCEP reference solution. Then updated in optimization experiments using current estimated parameters.
Data used in the likelihood	CPUE, Size frequencies, conventional tagging data (SPC database)	Catch, Size frequencies	CPUE, Size frequencies, conventional tagging data (SPC database)
Additional likelihood terms	Average stock estimate from MFCL (2013)	Average stock estimate from MFCL	Average stock estimate from MFCL
Data used in validation	ALL conventional tagging data (SPC database)	Fisheries data not being used in optimization, i.e 1980-1984	Fisheries data not being used in optimization, i.e. 1998-2007

7. REFERENCE FIT FOR PACIFIC SKIPJACK

Fishing data

The fishing dataset used for skipjack fisheries in the Pacific Ocean, ie covering both the WCPFC and IATTC convention areas was revised (Table 7.1). Except for the Philippine-Indonesia fishery and the longline fishery, all catch and effort fishing data were at a resolution of 1°x1°x month. Philippines and Indonesia fleets have been combined and not used in the optimization approach due to a lack of accuracy.

Table 7.1. SKJ fisheries and data availability for SEAPODYM (DS2013).

ID	Gear	Region	Description	Nation	Time	Nb. obs	Res	Nb. LF obs
P1	PL	120E-162W; 20N-47N	Sub-tropical pole-and-line	Japan	1972-01-15 - 2012-11-15	55704	1x1	2733
P2	PL	120E-150W; 20S-47N	Pole-and-line	Japan	1972-01-15 - 2012-11-15	129223	1x1	1360
P3	PL	141E-177W; 20S-0N	Tropical pole-and-line	Pacific Islands	1970-03-15 - 2012-03-15	9426	1x1	1237
S4	PS	120E-151W; 20N-50N	Sub-tropical purse-seine	Japan	1970-07-15 - 2013-01-15	17434	1x1	172
S5	PS	130E-150W; 20S-20N	FAD and LOG	ALL	1967-12-15 - 2013-03-15	96339	1x1	2539
S6	PS	120E-160E; 8N-14N	Purse seine	Philippines, Indonesia	1970-01-15 - 2011-12-15	9540	1x1	2660
S7	PS	130E-150W; 20S-20N	Free schools	ALL	1967-12-15 - 2013-03-15	57908	1x1	1292
L8	LL	120E-150W; 20S-50N	Traditional YFT&BET target	ALL	1950-06-15 - 2012-12-15	70918	5x5	3274
L9	LL	120E-130E; 0N-15N	Domestic fisheries	Philippines, Indonesia	1970-01-15 - 2011-12-15	6123	5x5	3055
S10	PS	150W-71W; 25S-25N	Anchored and Drifting FADs	ALL	1996-12-15 - 2013-01-15	46541	1x1	3516
S11	PS	150W-72W; 22S-31N	LOGs	ALL	1996-12-15 - 2012-12-15	5103	1x1	216
S12	PS	149W-72W; 19S-33N	Animal association	ALL	1996-12-15 - 2012-12-15	11124	1x1	638
S13	PS	150W-72W; 21S-33N	Free schools	ALL	1996-12-15 - 2013-01-15	12362	1x1	859
S14	PS	150W-71W; 24S-34N	Unknown Log	ALL	1996-12-15 - 2013-01-15	13481	1x1	2659

Tagging data

Tagging data are used through a definition of cohorts in which all individuals, tagged with conventional method, are recaptured at the same time period (month – quarter, depending on the time scale chosen for the age structure). According to this definition, only the tags which were recaptured are integrated into the model and hence drive the maximum likelihood estimation. Each population of tags has the same age structure as the actual population of modeled species; and the spatial and temporal dynamics are described using advection-diffusion equations with the reaction term set to zero (i.e., no recruit nor mortality). The ADR equations are only used to account for the change of the density due to the tag releases within the cohort. The life span of each cohort of tags is defined according to the age of youngest and oldest tagged individuals in a given cohort.

The cohorts of tags were defined using compiled tagging datasets provided by NIFSF and SPC PTTP tagging programme. Twenty-five monthly cohorts were defined from tagged fish released and recaptured during the time series 2004-2012 and used in the optimisation.

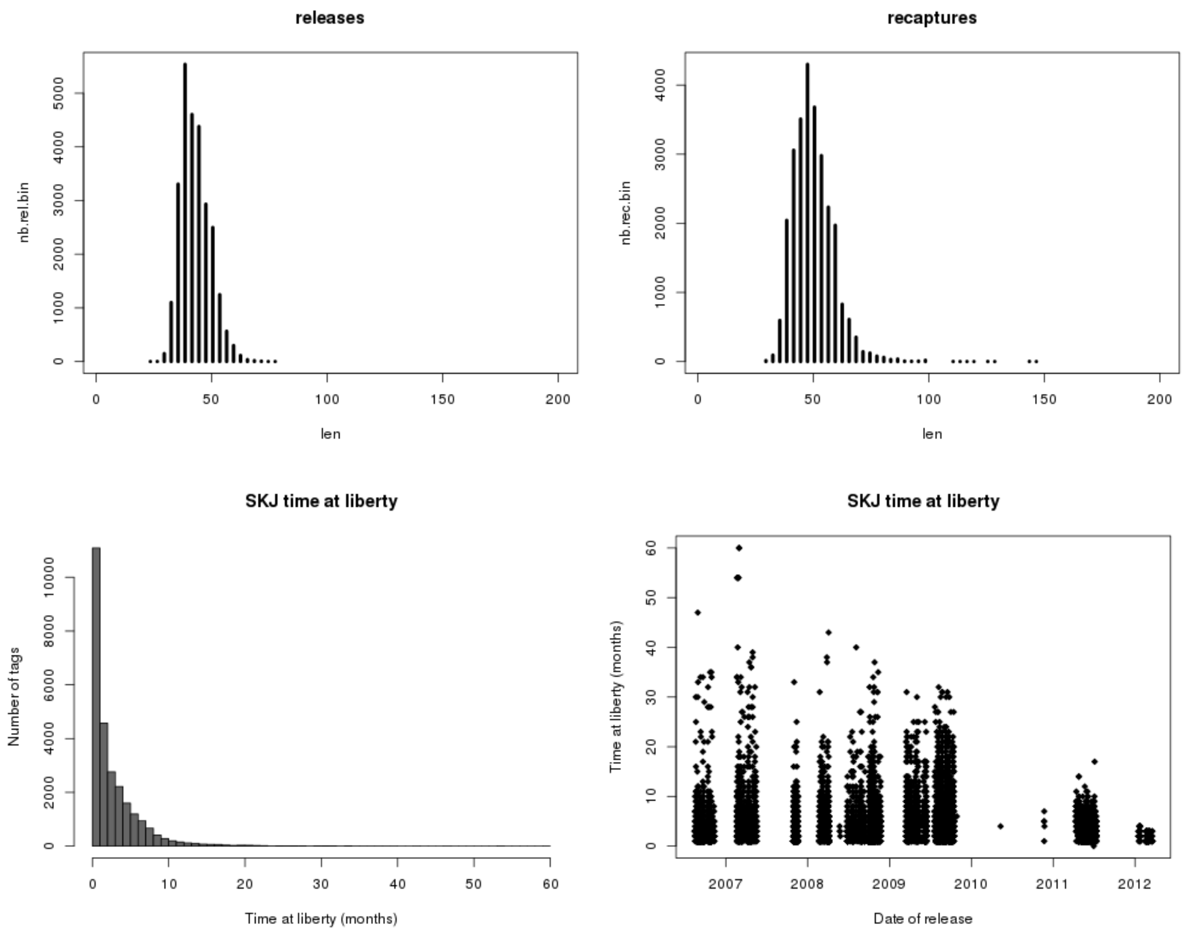

Figure 7.1. (top) Fish size distribution at release and recapture of skipjack conventional tagging data used in optimization; (bottom) Time at liberty histogram of tagged skipjack and time at liberty as a function of date of release.

Skipjack population structure

The structure of the population is similar to the one used in previous reference fit (SODA-SKJ2.1). It was defined by age (cohorts) with variable time unit to save computation time. There is 1-month cohort for larvae life stage, one 2-month cohort for juvenile stage, five 1-month and one 2-month cohorts for young fish (before age at maturity) and 9 cohorts for adult stages (two of 2 months, two of 3 months and the last five of 4, 5, 6, 7, 9 months correspondingly). The last "+ cohort" accumulates older fish. Age at maturity is set to 10 months. Age-length and age-weight relationships (Figure 7.2) are derived from the last MULTIFAN-CL estimate (Hoyle et al., 2011).

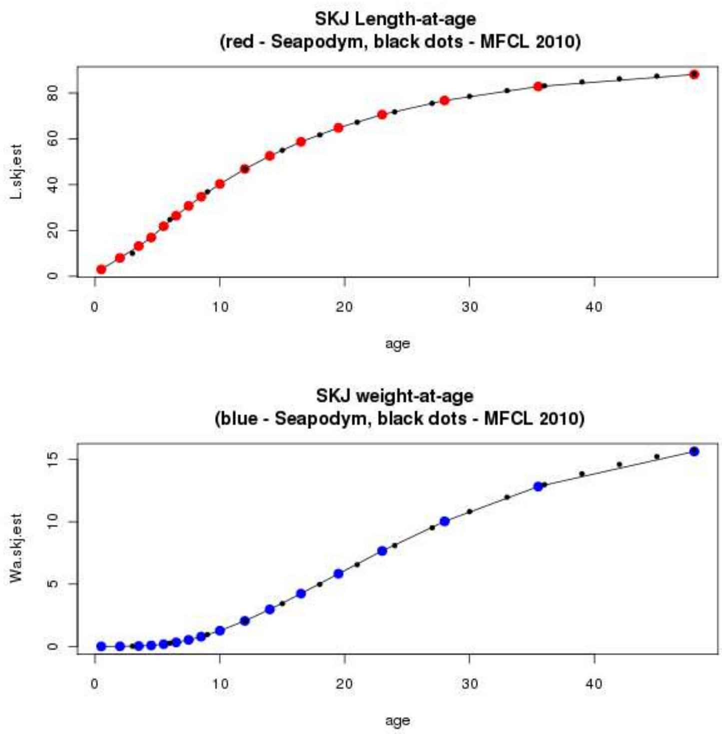

Figure 7.2. Skipjack size (FL in cm) at age (month) and weight (kg) at age functions used in SEAPODYM simulation, based on MULTIFAN-CL 2010 and 2011 estimates (Hoyle et al, 2011)

Optimization experiments

The focus of this new optimization experiment was mainly on the integration in the optimisation approach of the recent conventional tagging data collected by SPC/OFP. Thus, a realistic forcing covering the recent period was sought. This likelihood optimization was performed over the 2004-2012 time period with the physical reanalysis OMEGA and the VGPM satellite derived primary production and euphotic depth. The optimization was conducted using both fishing and tagging data. The Multifan-CL estimated stock size in WCPO area was used as prior information to constrain the likelihood function.

The introduction of additional information with tagging data in the likelihood produces antagonistic effects, especially through the estimation of movement parameters. In previous experiments without tagging data, the model had a tendency to increase diffusion and decrease advection parameters estimates while with tagging data the model has an opposite tendency. This first series of experiments with tagging data indicate that a realistic description of currents in 3D is of paramount importance to use tagging data in a model like SEAPODYM, because they both control the prey distribution and contribute directly in the movement of fish.

Fit to catch data

The model results were validated using the whole time series, i.e. 2004-2012. The details of fit for all fisheries separately are provided in **appendix 1** while a summary is provided below.

In addition to the spatial CPUE (541,226 observations) and length-frequencies (26,210 observations) data, as in previous experiment SODA-SKJ2.1, this new optimization (OMEGA-SKJ3.0) also includes the conventional tagging data from the recent SPC sampling cruises in the total likelihood function (see last year report: Lehodey et al 2013). The two experiments used different time series and cannot be compared directly. Nevertheless, overall spatial fit to predicted catch seems slightly degraded at basin scale (Figure 7.3) though very close to the previous solution with SODA reanalysis.

Catchability by fishery was estimated to increase since 2004 for the western purse seine fisheries (Table 7.2) with the largest annual increase for the FAD and LOG fisheries (+3.6%) followed by the free school fishery (+3.0%). Conversely, in the eastern Pacific the catchability of the purse seine fisheries both on LOG or on free school are estimated to have decreased since 2004 with an annual decrease of 1.8% and 1.2% respectively, but it has increased for the fishery on FAD by 1.2% per year.

Selectivity coefficients were obtained with all parameters being estimated within their bounds. These selectivity estimates allowed a good fit with size frequency data for all fisheries (Appendix 1). The fit to length frequency data is reasonable for all fisheries with fisheries P1 (Japanese small pole-and-line boats) and S10 (eastern Pacific FAD-associated sets) and S11 (eastern Pacific LOG-associated sets) showing a mode peaking in the smallest sizes.

The catch is reasonably well predicted for all fisheries (Figure 7.4 and appendix 1 for details). There are however some exceptional high peaks of catch in the purse seine fishery S14 (PS EPO unknown LOG) that cannot predicted (Appendix 1).

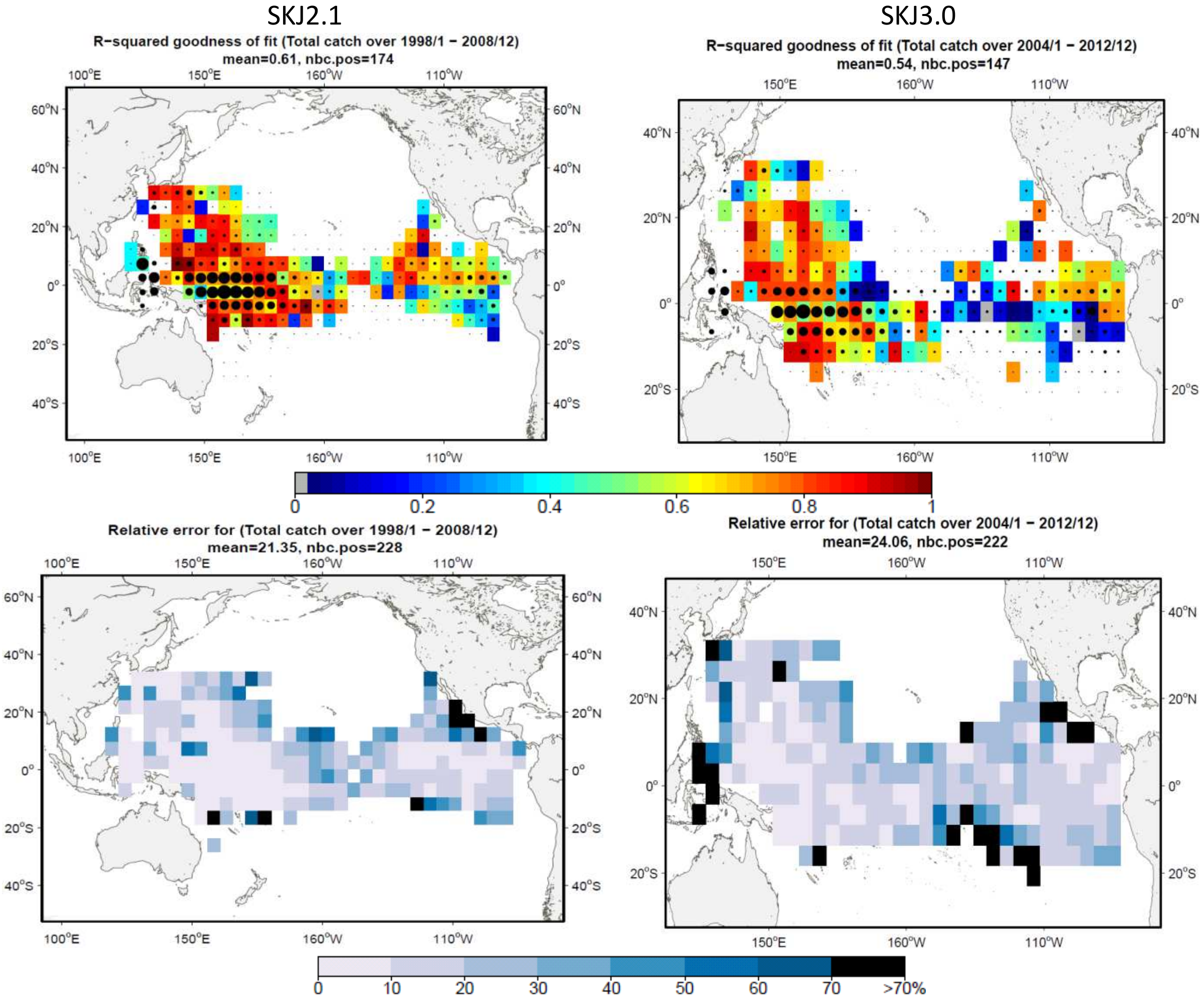

Figure 7.3. Comparison of fit to fishing data between previous (Lehodey et al. 2013) and new optimization experiments over the period 1998-2008 for SODA-SKJ2.1 and 2004-2012 for OMEGA-SKJ3.0 experiments. Top: R-squared goodness of fit representing the spatial fit over the period used for optimization (white squares indicate negative correlation between observations and predictions; Black circles are proportional to the level of catch. Bottom: relative error in predicted catch for all fisheries.

Table 7.2. Estimates of catchability by fishery and annual change (%) since 2003.

Fishery		q	annual % change since 2003
P1	PL small boats Japan	0.00767	0.00
P2	PL large boats Japan	0.00643	0.00
P3	Tropical Pole and line	0.00415	0.00
S4	PS subtropical	0.07750	0.00
S5	PS on LOG and FAD	0.02076	3.60
S6	PS Phil-Ind	0.00400	0.00
S7	PS on free school	0.01880	3.00
L8	LL Traditional YFT&BET target	0.00993	0.00
L9	LL domestic fisheries Phil-Ind	0.00400	1.20
S10	PS EPO Anchored and drifting FAD	0.29996	1.20
S11	PS EPO on LOG	0.09309	-1.80
S12	PS EPO animal association	0.01571	0.00
S13	PS EPO on free school	0.00781	-1.20
S14	PS EPO unknown LOG	0.07580	0.00

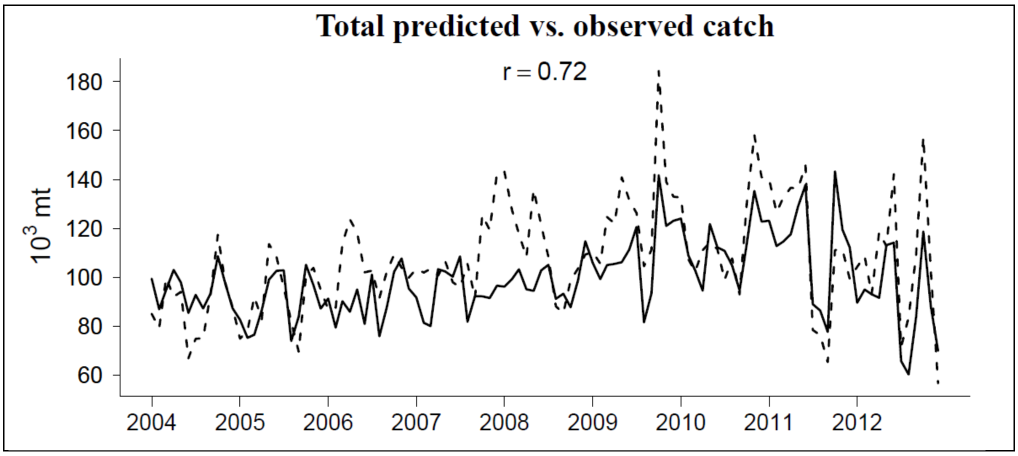

Figure 7.4. Total Pacific skipjack catch observed (dotted line) and predicted (continuous line).

Fit to tagging data

There is a reasonable agreement between final observed and predicted distribution of tagged fish in the WCPO from where all tags were released, but the model cannot predict the long distance displacements along the equator to the EPO (Figure 7.5).

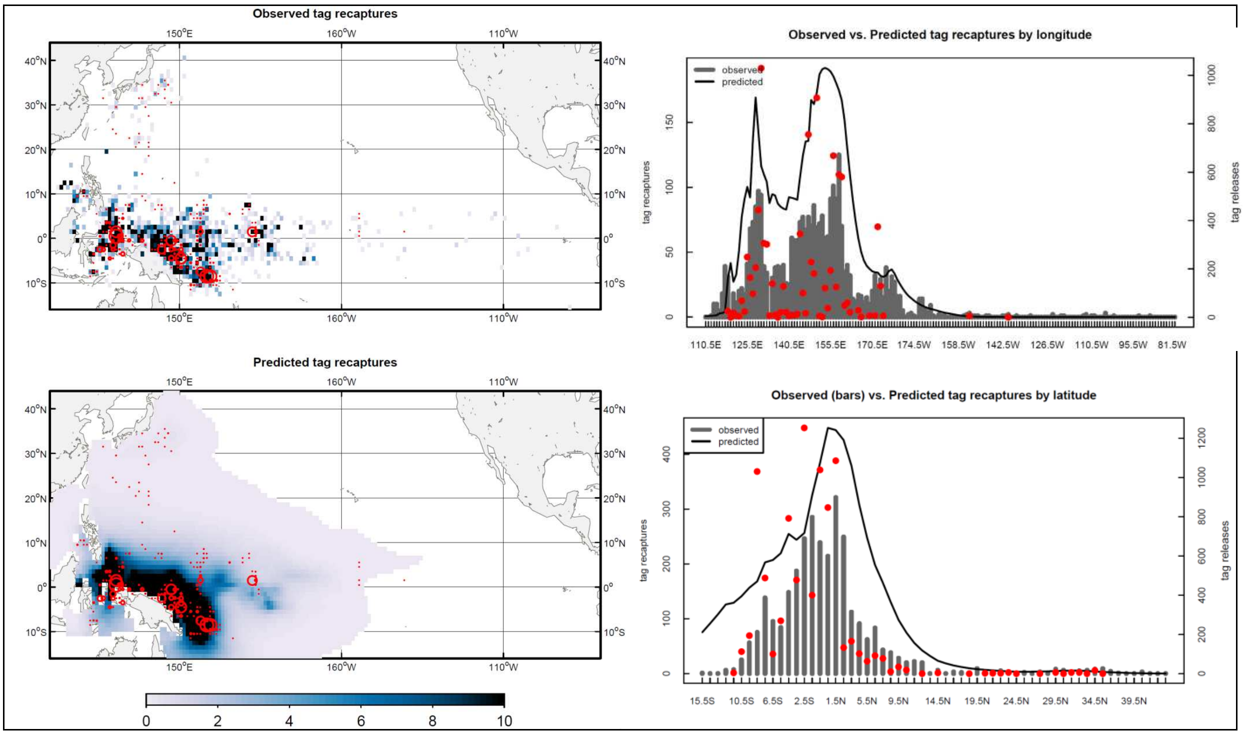

Figure 7.5. Observed and predicted skipjack recaptures. Left: All releases and recaptures between Apr 2007 and June 2010. Red circles are releasing sites and proportional to the number of released fish. The colour background gives the predicted density of fish. Right: observed and predicted number of tag recapture by longitude and latitude.

Optimal Parameterization

The use of tagging data in the likelihood function allowed estimating the advection parameter (maximum sustainable speed) to 1.105 body length per second. However, to fit the tagging data the model had a tendency to decrease drastically the diffusion parameter estimate. To achieve optimisation diffusion it was fixed to its minimum value (Table 7.3). The optimal spawning temperature was estimated but with a standard error reaching the maximum boundary value. A major difference with previous optimisation experiments are for the parameterization of feeding habitat that is predicted to occur in a much warmer range of temperature even for adults, and with a higher threshold in oxygen tolerance. Also, given the lower diffusion and higher advection estimates the large fish have higher capacity to quickly move along the habitat gradients towards better habitat values. As a consequence the difference increases with age between the mean mortality coefficients estimated from theoretical functions and those weighted by the cohort density (Figure 7.6).

Table 7.3: Habitats and movement parameter estimates for skipjack application

Parameters estimated by the model			**Unit**	**SODA 1° v1**	**SODA 1° v2**	**OMEGA**
T_s	Spawning	Optimum of the spawning temperature function	°C	28.67	29.5*	28.62
σ_s		Std. Err. of the spawning temperature function	°C	0.75*	3.0*	3.0]
α		Larvae food-predator trade-off coefficient	-	1.03	0.51	60] [1]
T_a	Feeding habitat	Optimum of the adult temperature function at maximum age	°C	20.64	20	28]
σ_a		Std. Err. of the adult temperature function at maximum age	°C	4.5]	3.5]	3]
$\hat{O}$		Oxygen threshold value at Ψ_O =0.5	$mL \cdot L^{-1}$	2.47	2.2	4.5]
D_{max}	Move-ment	Diffusion parameter		0.065*	0.08*	0.07*
V_{max}		Maximum sustainable speed	$B.L.\ s^{-1}$	[0.9	[0.75	1.105

*Fixed; [val = value close to minimum boundary value; val] = value close to maximum boundary value
[1] cannot be compared to previous experiments due to changes in model formulation

<table>
<tr><th>SODA-SKJ2.1</th><th>OMEGA-SKJ3.0</th></tr>
<tr><td>

a Mean ambient temperature of skj

NA

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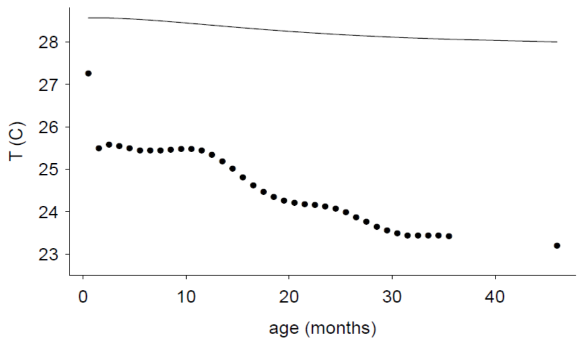
a Mean ambient temperature of skj



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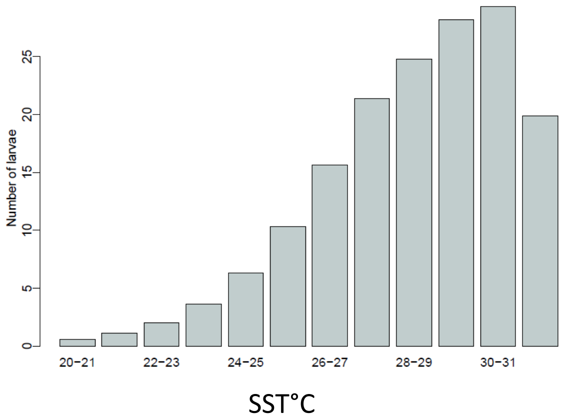
b Predicted larvae density with SST



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b Predicted larvae density with SST

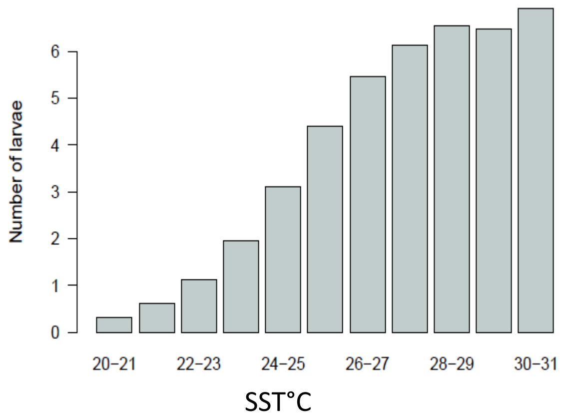

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Figure 7.6 : see next page

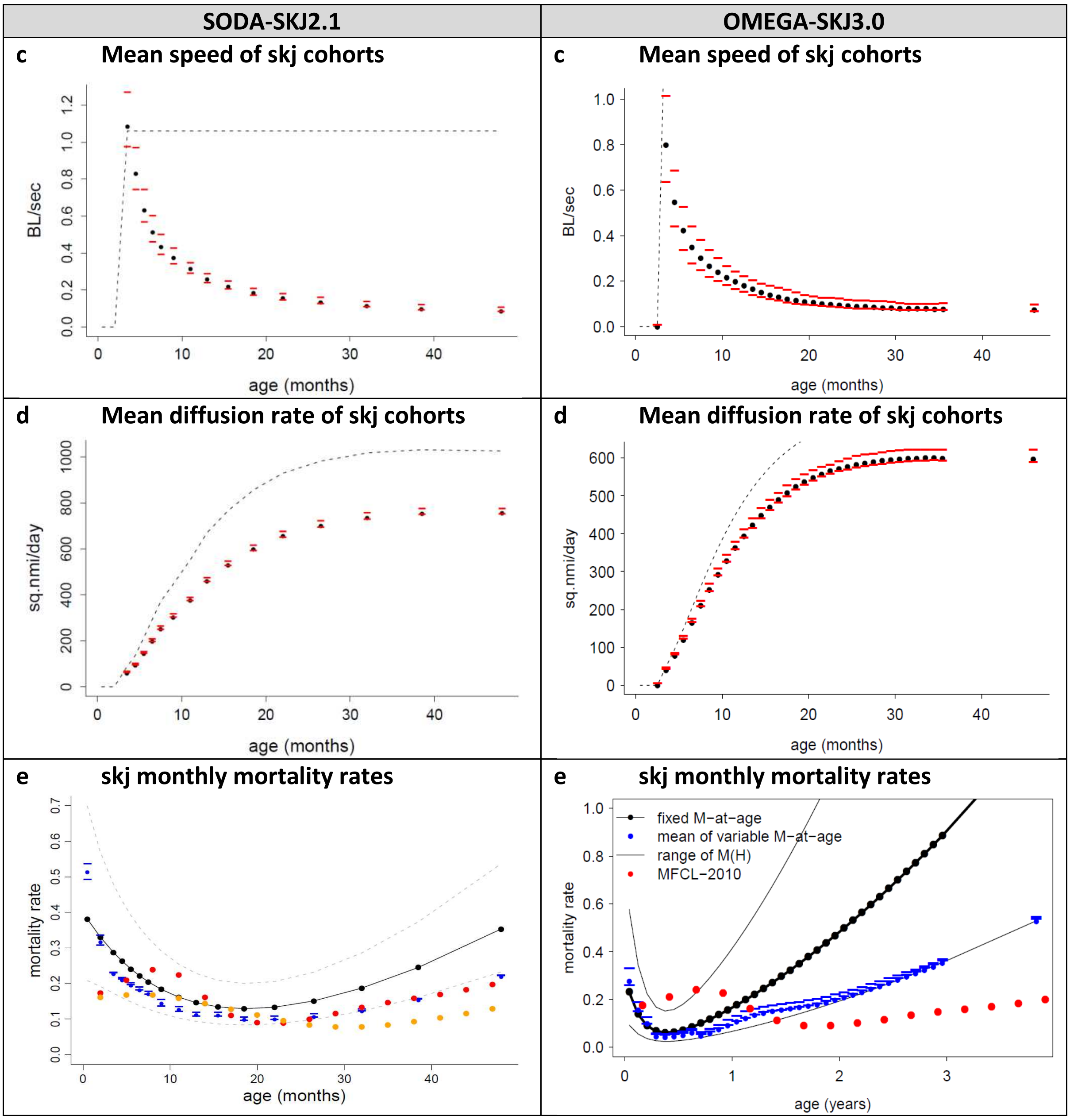


Figure 7.6: Comparisons between previous (SKJ2.1) and new (SKJ3.0) optimal parameterization. **a**: change with age (size) of optimal temperature of thermal habitat. **b**:distribution of larvae according to SST and the estimated parameters of spawning index. **c, d**: Maximum sustainable speed and diffusion rates by cohort (depending of age/size and habitat value / gradient) based on SEAPODYM parameterization (dotted lines) and predicted means weighted by the cohort density (black dots) with one standard error (red bars). **e**: natural mortality rates (month^{-1}) estimated from SEAPODYM optimization experiments. Black dotted line corresponds to the theoretical average mortality curve whereas blue dots indicate the mean mortality rates weighted by the cohort density and orange and red dots are the MUTLTIFAN-CL estimates for 2010 and 2011 assessments.

Biomass estimates and population dynamics

In comparison to the last reference fit achieved with the SODA-VGPM configuration (SEAPODYM progress report 2013), the new OMEGA reference fit shows:

1. Lower total biomass estimate (~7-8.5 instead of ~9-10 million tonnes) with higher range of interannual variability at the Pacific basin scale (Figure 7.8).
2. More contrast between PNA region and the rest of the Ocean with higher concentration of fish in PNA region relatively to other regions.
3. Despite the lower biomass estimates predicted for the entire Pacific Ocean and WCPFC area, the predicted skipjack densities in the main fishing grounds, including PNG and Solomon I. EEZs, are higher in the revised simulation using OMEGA forcing (Figure 7.10).
4. Like in previous estimate, the total biomass in the WCPO is close to the one estimated with MFCL, but with regional differences especially in region 1 and 2 (Figure 7.9); in both models the lowest biomass occurs in region 1 (north west Pacific) with MFCL estimate roughly 50% below the SEAPODYM estimate. The highest biomass is estimated in region 3 (central equatorial region) for MFCL but region 2 for SEAPODYM.

As a consequence, the overall fishing impact is lower in the revised solution (Figure 7.11). The strong fishing pressure in the western equatorial region led to a depletion of biomass of larger cohorts resulting in an average decrease (over 2008-12) of the spawning (adult) biomass of skipjack that can reach 50% of the unfished biomass locally in the Papua New Guinea EEZ (Figure 7.11).

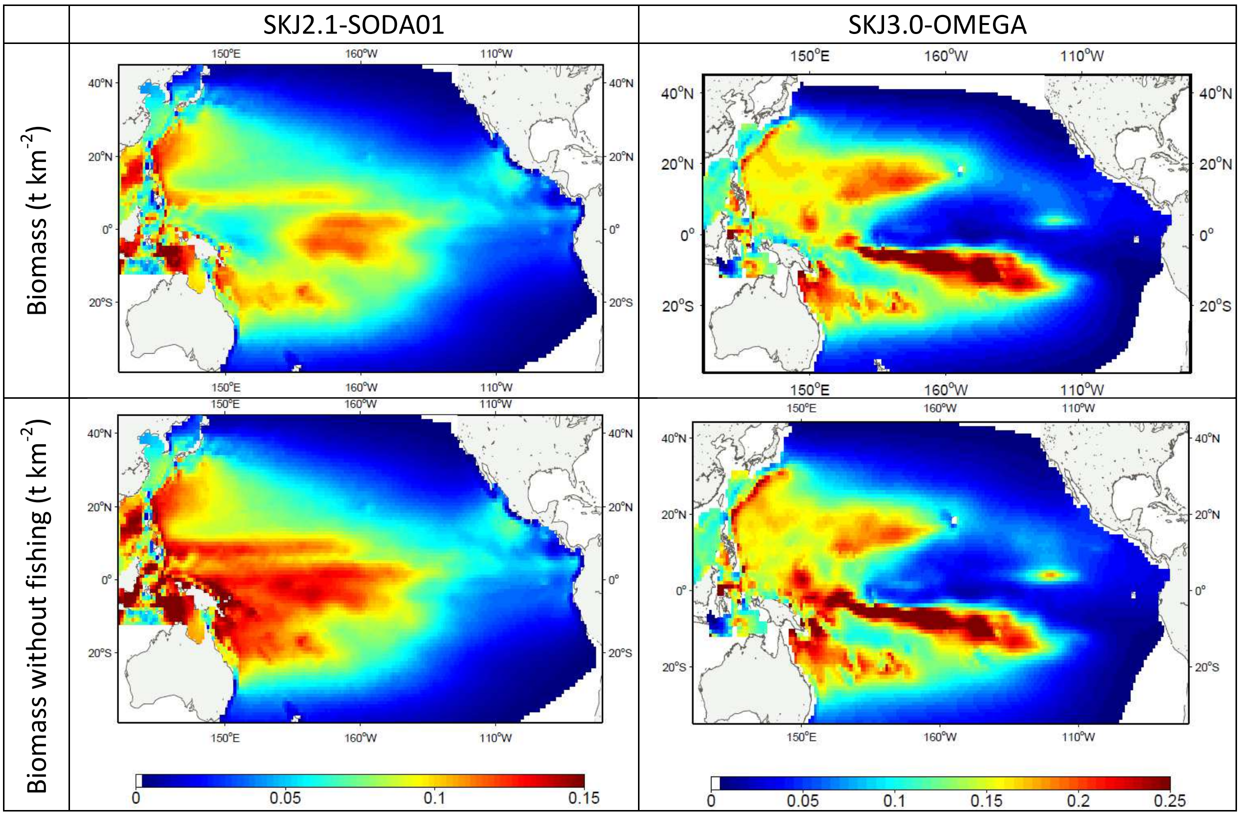


Figure 7.7. Change in five year average (2004-2008) total biomass distribution between first (SKJ2.0) and new (SKJ3.0) reference model solutions (top: with fishing, bottom - without fishing).

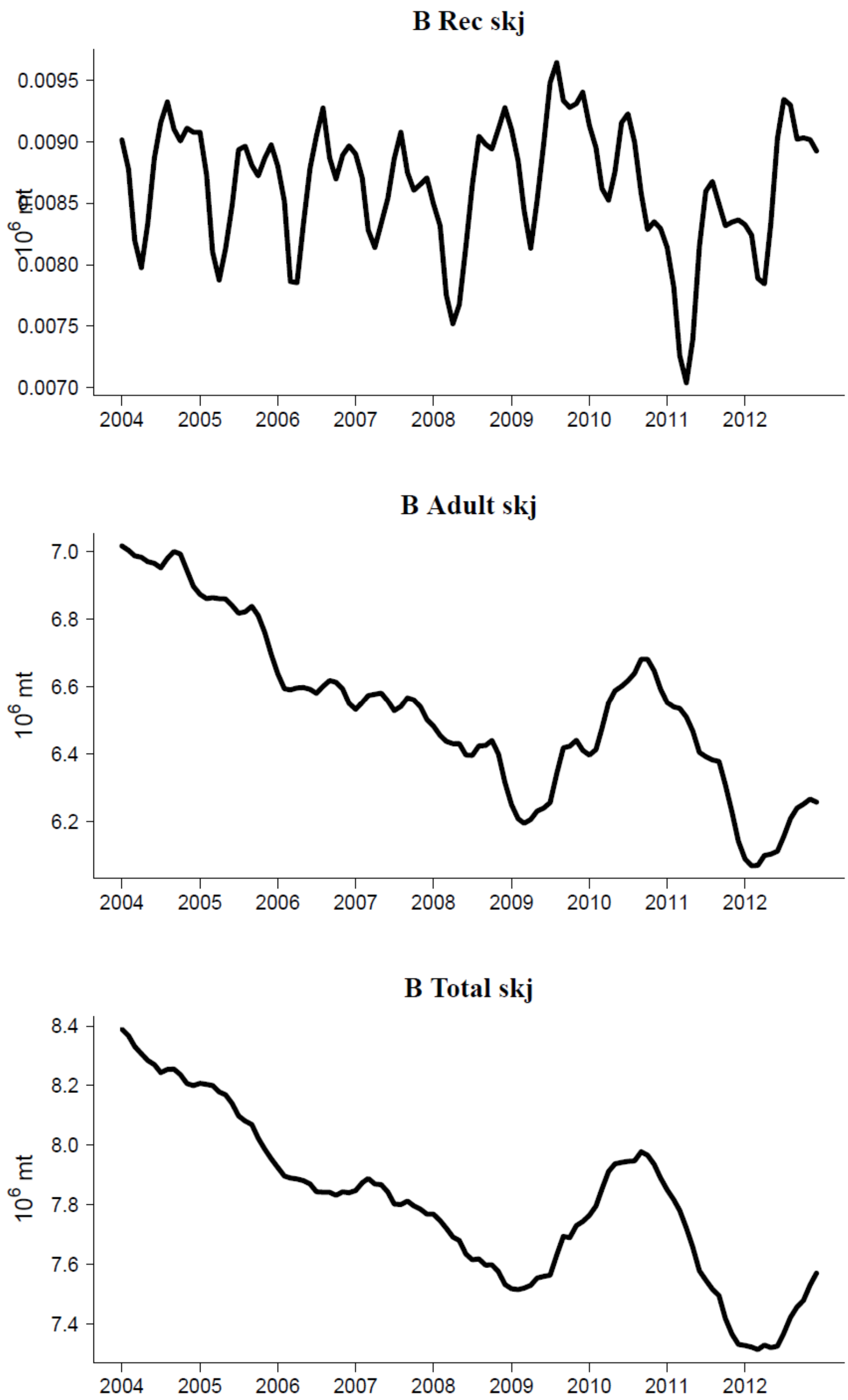


Figure 7.8. Time series of (from top to bottom) skipjack recruits, adults and total biomass estimated with the new optimization experiment SKJ3.0 for the Pacific Ocean.

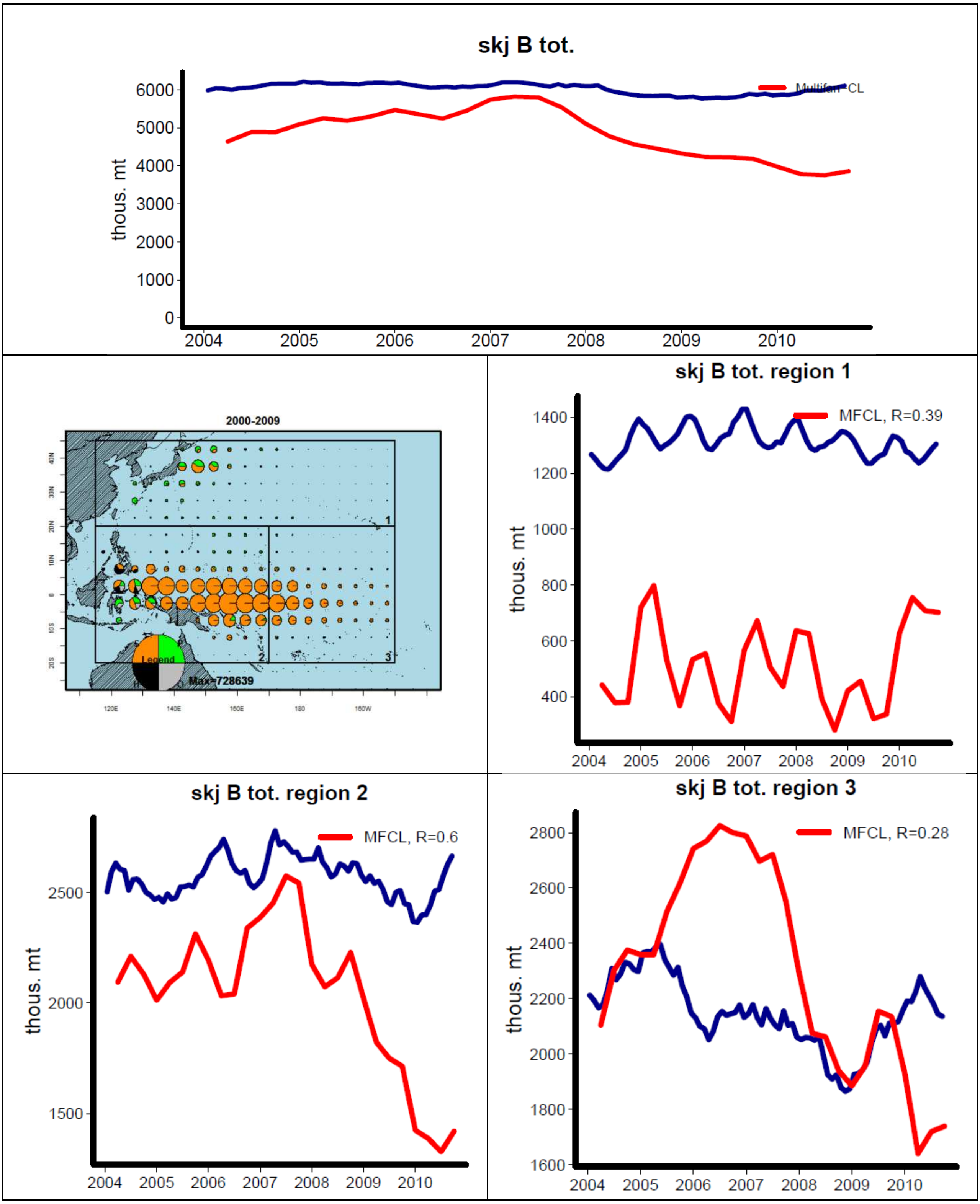


Figure 7.9. Comparison between SEAPODYM SKJ3.0 and MULTIFAN-CL (red curves) total skipjack biomass estimates for WCPO (top) and by region 1 to 3.

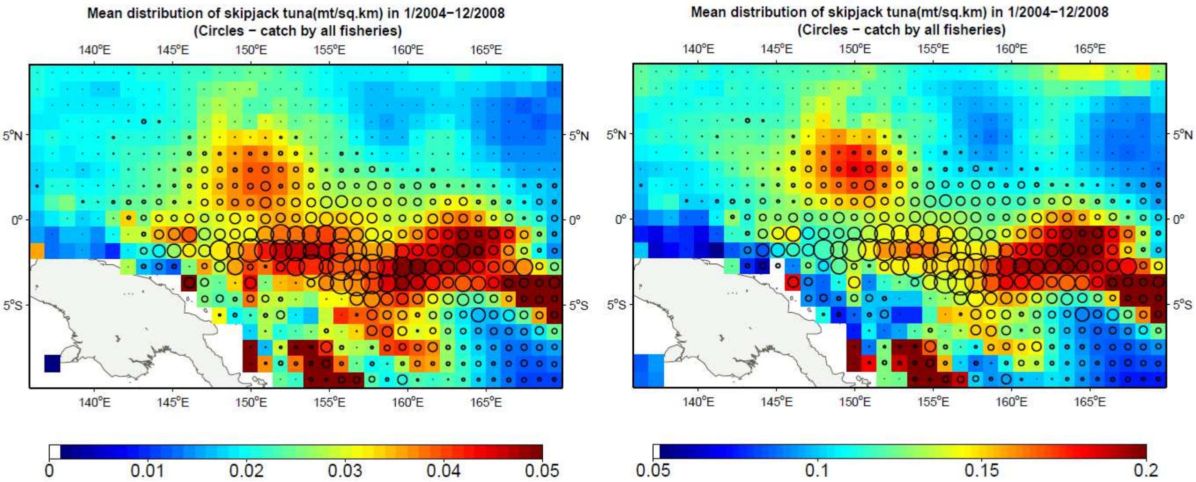


Figure 7.10. Mean distribution of young and adult skipjack tuna in SKJ 3.0 reference model. Circles are mean skipjack catches over the same period.

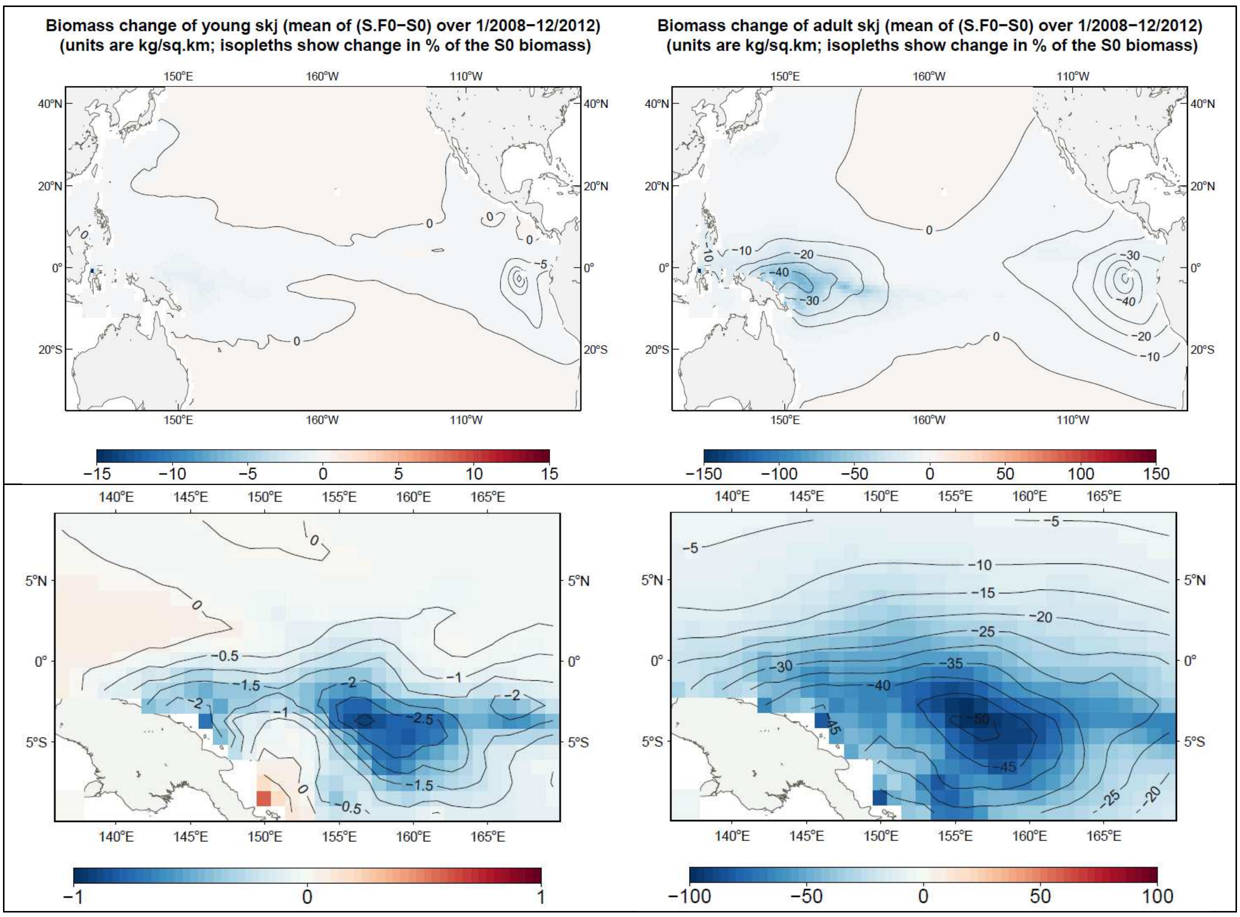


Figure 7.11. Fishing impact on young and adult skipjack with reference fit SKJ3.0 at the scale of the Pacific Ocean and in the western equatorial region. Contour lines show the index $\frac{B_{F0} - B_{ref}}{B_{F0}}$ and color shows the average biomass reduction due to fishing.

8. REFERENCE FIT FOR PACIFIC BIGEYE

Fishing data

The definition of fisheries for Pacifc bigeye tuna is provided in Table 8.1. All longline catch and effort fishing data are at a resolution of 5° x 5° x month while for surface gears (purse seine and pole-and-line) the resolution is 1°x 1° x month, excepted for Philippine and Indonesia fisheries. Size frequency data are at a resolution of 5°x 5° (WCPO purse seine) 10°x 20°, or aggregated over a region for the EPO. A major revision of fisheries definition has been realized since the last optimization experiment, with all fisheries organised by nation and careful data screening procedure to i) remove outliers using a method based on the computation of CPUE variance and 2) convert the fishing effort of EPO purse seine fisheries in fishing days when only total effort in days and number of sets by fishery was available.

Table 8.1. Bigeye Fishing Dataset 2014. Definition of SEAPODYM fisheries in Pacific Ocean

f	Description	Nationalities	Dataset	Time period	C unit	Res
L1	LL BET&YFT	Japan	SPC	1950-2012	Nb	5x5
L2	LL BET&YFT	Korea	SPC	1962-2012	Nb	5x5
L3	LL BET&YFT	China, Chinese Taipei, Vanuatu	SPC	1964-2012	Nb	5x5
L4	LL BET&YFT	USA	SPC	1991-2012	Nb	5x5
L5	LL BET&YFT	Pacific Islands	SPC	1991-2012	Nb	5x5
L6	LL Shallow night	China, Chinese Taipei	SPC	1958-2012	Nb	5x5
L7	LL ALB	Japan	SPC	1951-2011	Nb	5x5
L8	LL ALB	Korea	SPC	1962-2011	Nb	5x5
L9	LL ALB	China, Chinese Taipei	SPC	1958-2012	Nb	5x5
L10	LL ALB	USA	SPC	1994-2012	Nb	5x5
L11	LL ALB	Pacific Islands	SPC	1982-2012	Nb	5x5
L12	LL Australia East Coast	Australia	SPC	1985-2011	Nb	5x5
L13	LL PH_ID	Philippines, Indonesia	SPC	1970-2011	Nb	5x5
L14	LL BFT	All	SPC	1955-2012	Nb	5x5
S15	PS on drifting FAD & log	All	SPC	1967-2012	mt	1x1
S16	PS on anchored FAD	All	SPC	1979-2012	Mt	1x1
S17	PS on free school	All	SPC	1967-2012	Mt	1x1
S18	PS Sub-tropical, all sch. types	Japan	SPC	1970-2011	Mt	1x1
S19	PS PH_ID	Philippines, Indonesia	SPC	1970-2012	Mt	5x5
S20	PS type 'O' – other, WCPO	All	SPC	1967-2012	Mt	1x1
S21	PS YFT, free schools	All	IATTC	1958-2011	Mt	1x1
S22	PS YFT FO	All	IATTC	1959-2011	Mt	1x1

Tagging data

The cohorts of tags were defined using compiled tagging datasets provided by SPC from the PTTP tagging programme. There are four different release positions. Forty-four monthly tagged cohorts were defined from tagged fish released and recaptured during the time series 2004-2012 and used in the optimisation (Figure 8.1).

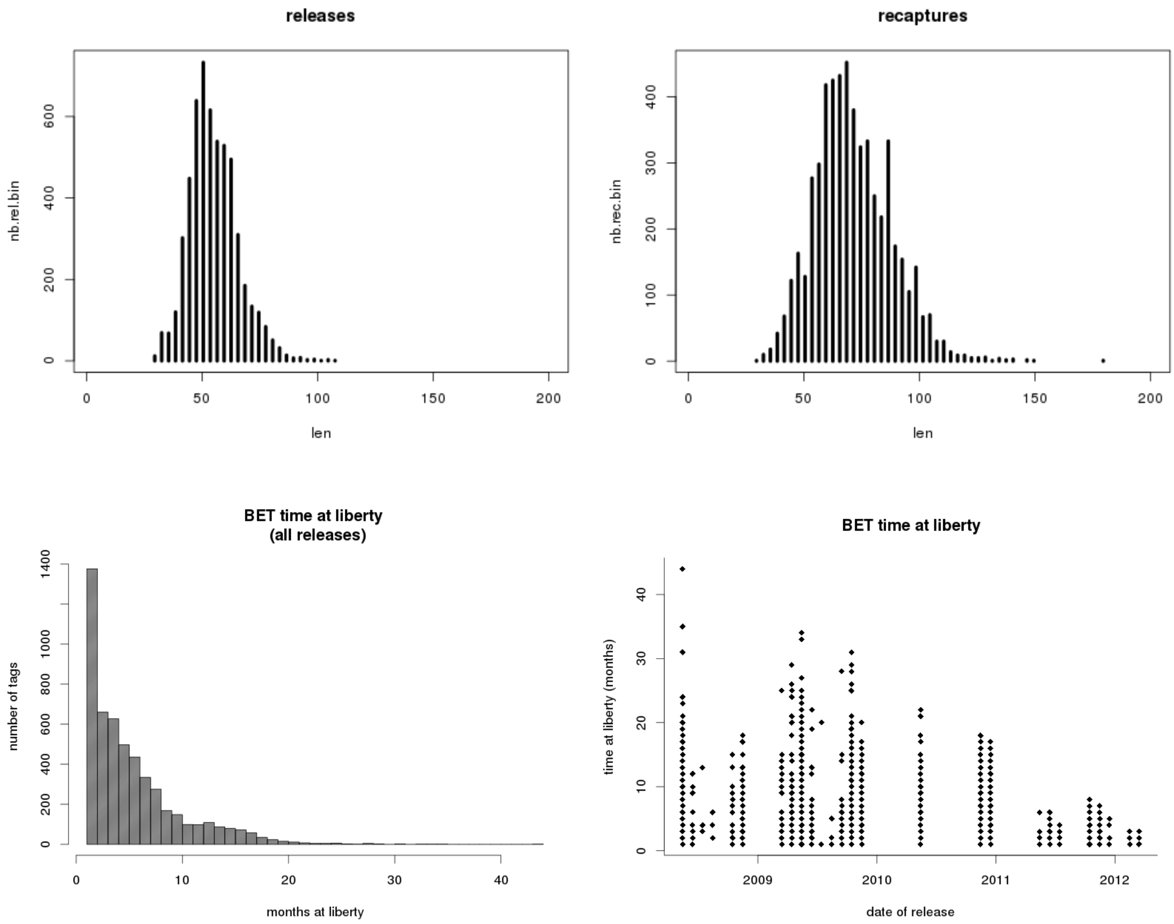


Figure 8.1. Bigeye conventional tagging data used in optimization: (top) size distribution at release and recapture; (bottom) time at liberty histogram and time at liberty of the tags released at different time.

Bigeye population structure

The structure of the population is similar to the one used in previous reference fit (SODA-BET2.0). There is 1-month cohort for larvae life stage, two 1-month cohort for juvenile stage, two 2-month and five 3-month cohorts for young fish (before age at maturity) and 11 cohorts for adult stages (three of 4 months, two of 5 months and the last six of 6, 8, 9, 11, 15, and 60 months correspondingly). The last "+ cohort" accumulates older fish. Age at first maturity was set to age 3 yr. Age-length and age-weight relationships (Figure 8.2) are derived from the last MULTIFAN-CL estimate (Davies et al., 2011).

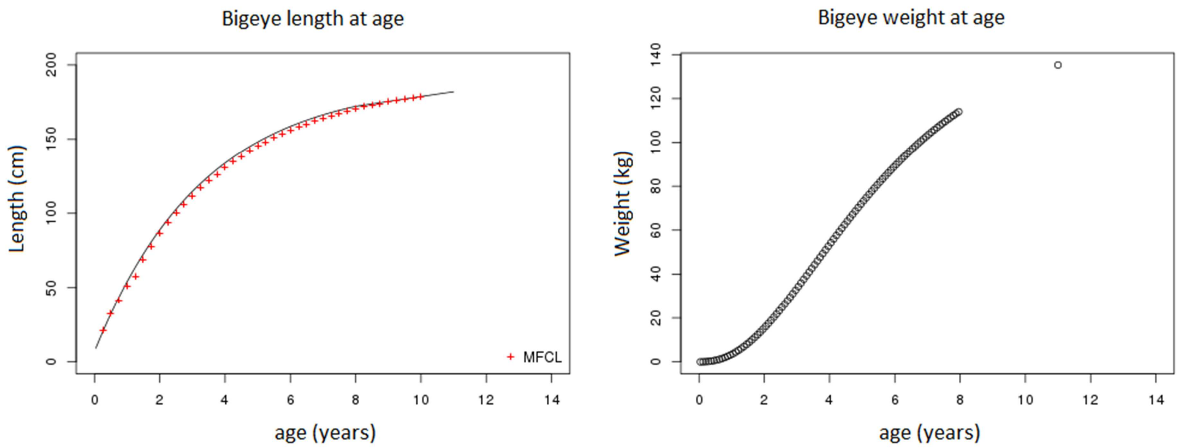


Figure 8.2: Bigeye size (FL in cm) and weight at age functions used in SEAPODYM simulation (left), based on MULTIFAN-CL estimates (Davies et al., 2011).

Optimization experiments

The optimization was conducted using both fishing and tagging data. Philippine and Indonesia fishing data are not used in the optimization due to a lack of accuracy.

As for skipjack the objective was to test the first optimization using conventional tagging data as an additional contribution to the Likelihood function. Due to the longer life span of bigeye and the need for a realistic simulation of currents, we used the ECCO reanalysis which extended the time-series back to 1998, ie the beginning of ocean color monitoring with SeaWiFS, and thus providing a time-series of 15 years. The primary production and euphotic depth are derived from satellite ocean color data using the VGPM-EPPLEY model. Due to the use of conventional tagging data in the optimization experiments that leads to greater memory demands the maximal duration of simulation period could be set no more than 7 years. The time series is hence too short for a good estimation of initial conditions and the Multifan-CL estimated stock size in WCPO area was used as prior information to constrain the likelihood function (*a priori* on average total biomass = 1,300,000 mt in the geographical box 120°E-150°W; 45°N-20°S).

Fit to catch data

The model results were validated using the whole time series, i.e., 1998-2012. The details of fit for all fisheries separately are provided in **appendix 2** while a summary is provided below.

Results for this new optimization (ECCO-BET3.0) are compared to the previous reference fit (SODA-BET2.0; last year report). However, the results are not fully comparable due to the different time series used. Nevertheless, it is clear that this new optimisation experiment provide much better fit to catch data (Figure 8.3). Especially the relative error on the catch has been drastically reduced and the R2 increased, not only in the main fishing grounds but also in the subtropical gyres where the catch is usually low.

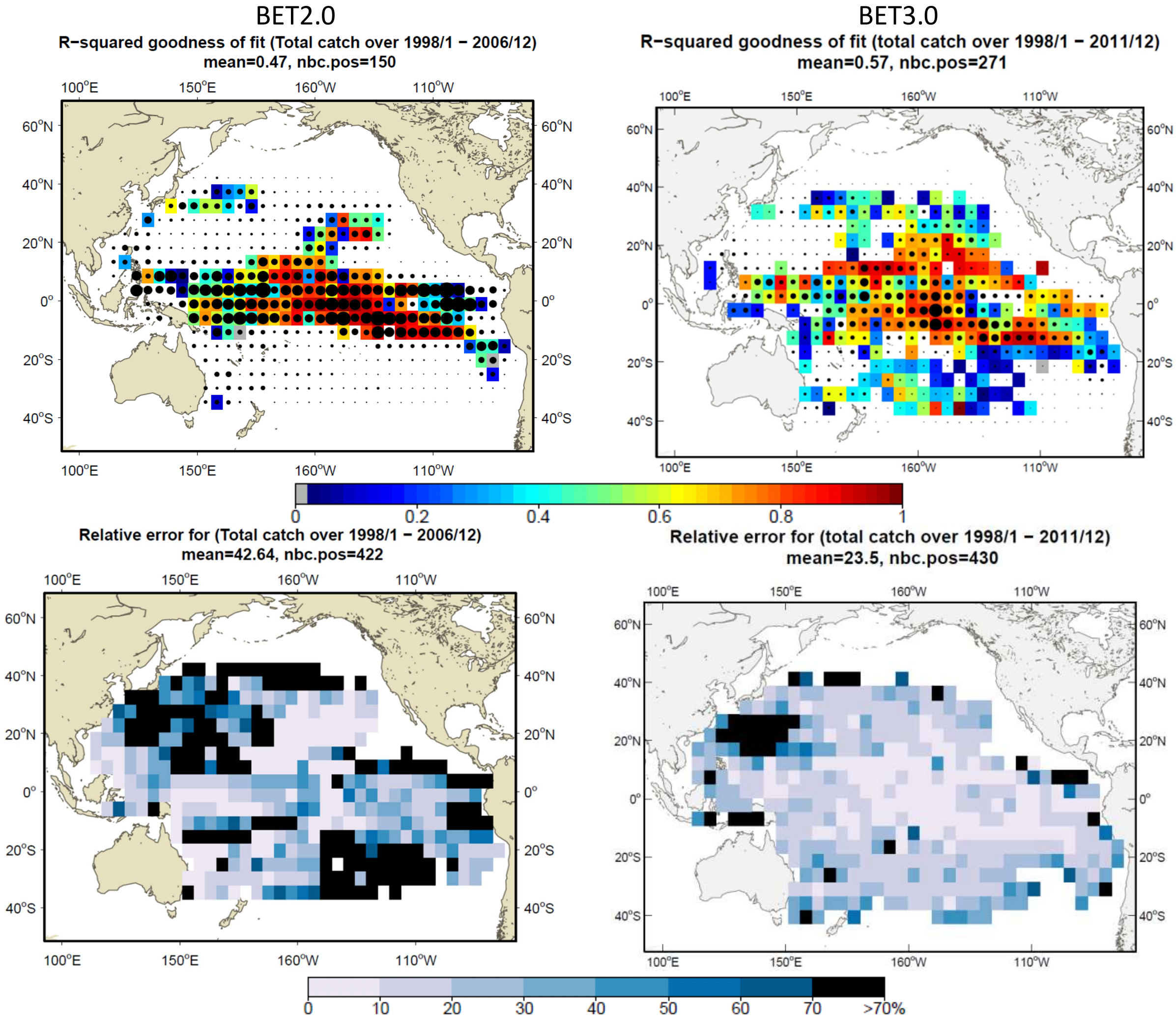


Figure 8.3. Comparison of fit to fishing data between previous (Lehodey et al. 2013) and new optimization experiments over the period 1998-2008 for SODA-BET 2.0 and 1998-2012 for ECCO-BET3.0 experiments. Top: R-squared goodness of fit representing the spatial fit over the period used for optimization (white squares indicate negative correlation between observations and predictions; Black circles are proportional to the level of catch. Bottom: relative error in predicted catch for all fisheries.

Total catch is well predicted (Figure 8.4). Especially, the predicted catch fit very well the catch of the three main Asian longline fisheries (L1, L2, L3) targeting bigeye and yellowfin (cf Appendix 2). The fit is lower for several fisheries with much higher range of observed variability than predicted. This is the case for longline fisheries L4 (USA), L7 (Japan targeting albacore), L12 (East Coast Australia) and for purse seine fisheries S15 (drifting FADs), S16 (anchored FAD) and S21 (free school targeting yellowfin). The catch by the two latter being an order of magnitude lower than the former. Trends in catchability over the time series 1998-2012 (Table 8.2) suggest a clear annual decrease in the Chinese-Taiwan longline fishery targeting albacore (-6%), and also in the purse seine fishery fishing on anchored FAD (-3.6%).

Given the single size coefficient-at-age used by cohort and the single parameterisation of the selectivity function by fishery, the model cannot output a detailed representation of size variability in catch. Nevertheless, it is useful to check the overall fit to size frequencies samples and its change over the time series (Appendix 2). One major discrepancy in the fits for longline fisheries appears in longline fishery L2 (Korea) with a shift in size of catch samples from ~100 cm in average during 1998-2003 to ~130-140 cm in the following years. Smaller sizes also appears during the same period in longline fisheries L8 (Korea targeting albacore) and L9 (China and Taiwan-ROC targeting albacore).

Table 8.2. Estimates of bigeye catchability by fishery and annual % change (%) since 1998.

Fishery		q	annual % change since 1998
L1	LL BET&YFT	0.0001700	0.00
L2	LL BET&YFT	0.0002100	0.00
L3	LL BET&YFT	0.0000709	0.00
L4	LL BET&YFT	0.0000367	0.00
L5	LL BET&YFT	0.0001080	1.20
L6	LL Shallow night	0.0000588	0.00
L7	LL ALB	0.0000655	0.00
L8	LL ALB	0.0001110	0.00
L9	LL ALB	0.0000484	-6.00
L10	LL ALB	0.0000100	0.00
L11	LL ALB	0.0000222	0.00
L12	LL Australia East Coast	0.0000600	0.00
L13	LL PH_ID	0.0000200	0.00
L14	LL BFT	0.0000150	0.00
S15	PS on drifting FAD & log	0.0448400	0.00
S16	PS on anchored FAD	0.4547600	-3.60
S17	PS on free school	0.0056300	0.00
S18	PS Sub-tropical, all sch. types	0.1524000	0.00
S19	PS PH_ID	0.0150000	-2.40
S20	PS type 'O' – other, WCPO	0.0020000	0.00
S21	PS YFT, free schools	0.0015790	0.00
S22	PS YFT FO	0.1303700	0.00

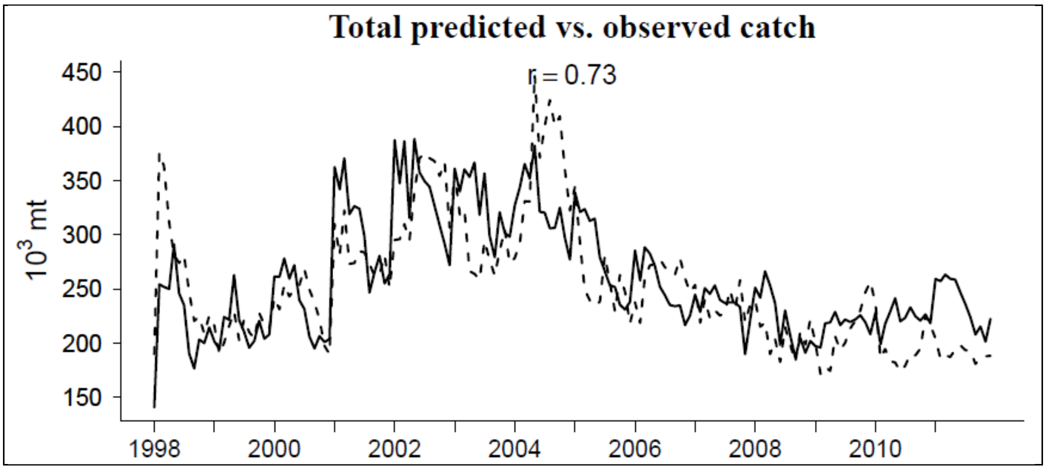


Figure 8.4. Fit between observed (dotted line) and predicted (continuous line) Total Pacific bigeye tuna catch. Note this is the sum of catch by fishery, which are given in different units (PS – in metric tons, LL – in number of fish).

Fit to tagging data

Observed recapture of tagged fish occurred mainly in a longitudinal band between 10°N-10°S over all the Pacific Ocean from the coast of Papua New Guinea to the coast of South America, far from their sites of release mainly in the central equatorial Pacific. The fit between observed and predicted tag recaptures achieved by optimizing the full likelihood (CPUE, LF and Tags) is shown on Figure 8.5 and Figure 8.6. Predicted recaptures show also a concentration in the equatorial band 10°N-10°S and are consistent with observations showing the longitudinal separation of tags at 160W. However, there is much less longitudinal extension either east or west and obviously too strong diffusion to higher latitudes in comparison to observations. The distant longitudinal movements are not well represented as diffusion movements seem to be prevailing over directed movements. To investigate this bias, a sensitivity analysis was conducted using tagging data only in the optimisation (cf. next section).

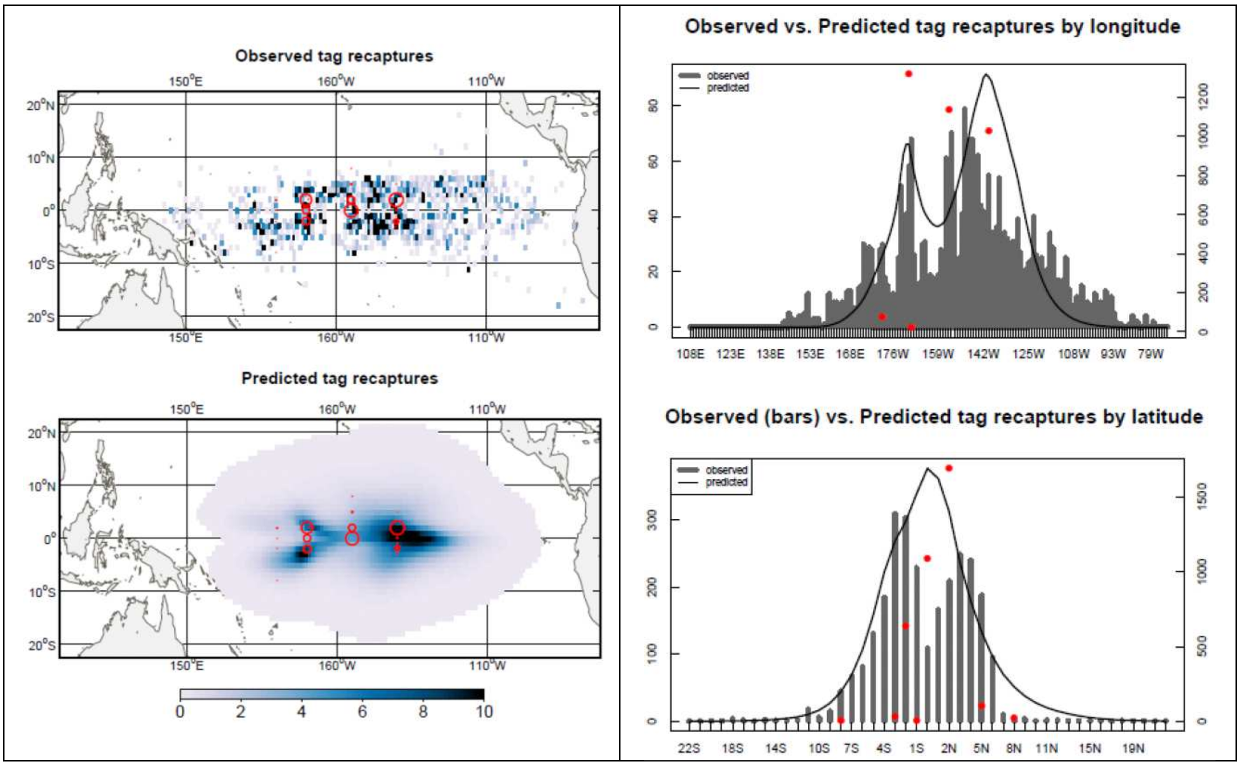


Figure 8.5. Observed and predicted bigeye recaptures after introducing flexibility in parameterization estimates of energy transfer or accessibility to micronekton functional groups. All releases and recaptures between May 2008 and May 2012. Red circles are releasing sites and proportional to the number of released fish.

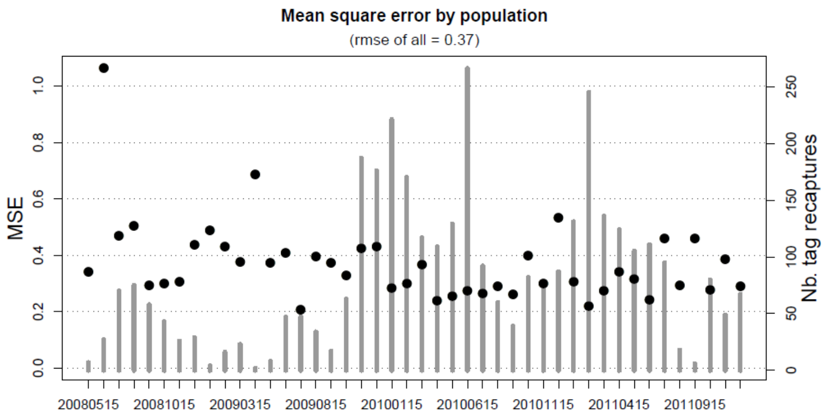


Figure 8.6. RMSE for the number of tag recaptures on 5-deg square resolution grid in observational space. Each circle corresponds to the cohort of tags, which were recaptured at the same month.

Optimal Parameterization

The use of tagging data in the likelihood function produced antagonistic effect with the CPUE term of the likelihood. The inclusion of tagging data resulted in decreased estimate of diffusion and also estimated the advection term at its lower boundary value (Table 8.3). The optimal spawning temperature was estimated (24.8°C) but still with a standard error that had to be fixed (2°C). The optimal temperature for feeding habitat of adults was estimated but also with a standard error that reached the upper boundary value. In comparison to previous reference fit, this parameterization led to a warmer feeding habitat (Figure 8.7) and much wider distribution of larvae relatively to SST, with no change in oxygen threshold. The mean natural mortality coefficients estimated from theoretical functions as well as those weighted by the cohort density (Figure 8.7) is close to the previous one with values rapidly decreasing in the early life stages to values around 0.04 mo^{-1} (0.48 yr^{-1}) for cohorts older than 1.5 year.

Table 8.3: Estimates of habitats and movement parameters of previous simulations and the new one using environmental forcings from SODA and IPSL-CM4 before and after correction of temperature fields.

Parameters estimated by the model			**Unit**	**NCEP-ORCA2**	**SODA**	**ECCO**
T_s	Spawning	Optimum of the spawning temperature function	°C	26.13	28.29	24.83
σ_s		Std. Err. of the spawning temperature function	°C	2*	1*	2*
α		Larvae food-predator trade-off coefficient	-	0.33	4.93	0.01*
T_a	Feeding habitat	Optimum of the adult temperature function at maximum age	°C	[6.5	[8	11.69
σ_a		Std. Err. of the adult temperature function at maximum age	°C	4.5]	2.8	4.2]
$\hat{O}$		Oxygen threshold value at Ψ_O =0.5	$mL \cdot L^{-1}$	0.89	0.61	0.604
D_{max}	Move-ment	Diffusion parameter		0.06*	0.02*	0.0091
V_{max}		Maximum sustainable speed	B.L. s^{-1}	0.834	0.32	[0.2

Biomass estimates and population dynamics

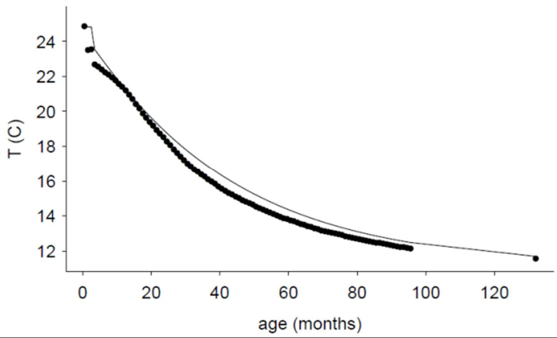
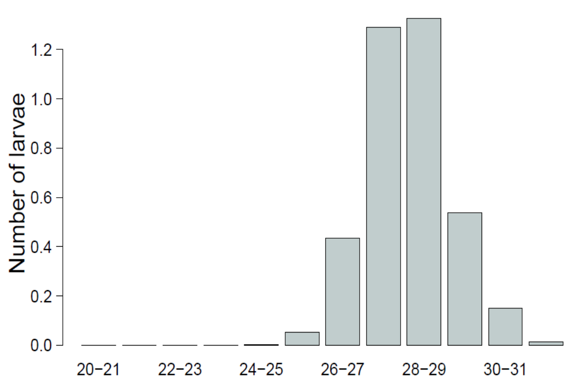
In comparison to the last reference fit achieved with the SODA-VGPM configuration (SEAPODYM progress report 2013), this new optimisation (BET3.0) shows:

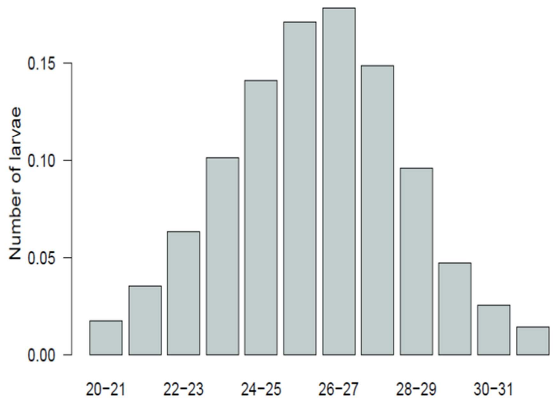
1. Higher biomass in the WCPO relatively to the EPO, with larger increase in the north-west Pacific, the Coral Sea and the Indonesia region (Figure 8.8; Figure 8.9).
2. At Pacific basin scale better recruitment conditions in 1999-2001 leading to a peak in total biomass in 2006 (Figure 8.10).
3. Largest concentration of juvenile fish in the central Pacific.
4. Higher total biomass estimate (~3 million tonnes instead of ~1.5) at the Pacific basin scale (Figure 8.10).

5. The total biomass in the WCPO is also much higher than the previous one and the estimate with MFCL (2011), especially in regions north and south of the tropical regions 3 and 4 corresponding to the main fishing grounds.

The overall higher biomass estimates as well as the likely overestimated biomass in higher latitudes can be due to the problem of movement parameters estimates resulting in high diffusion and low advection. This problem was investigated through a sensitivity analysis detailed in the next section.

<table>
<tr><th>SODA-BET2.0</th><th>ECCO-BET3.0</th></tr>
<tr><td>a Mean ambient temperature of bet

NA</td><td>a Mean ambient temperature of bet

</td></tr>
<tr><td>b Predicted larvae density with SST


SST°C</td><td>b Predicted larvae density with SST


SST°C</td></tr>
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Figure 8.7: see next page

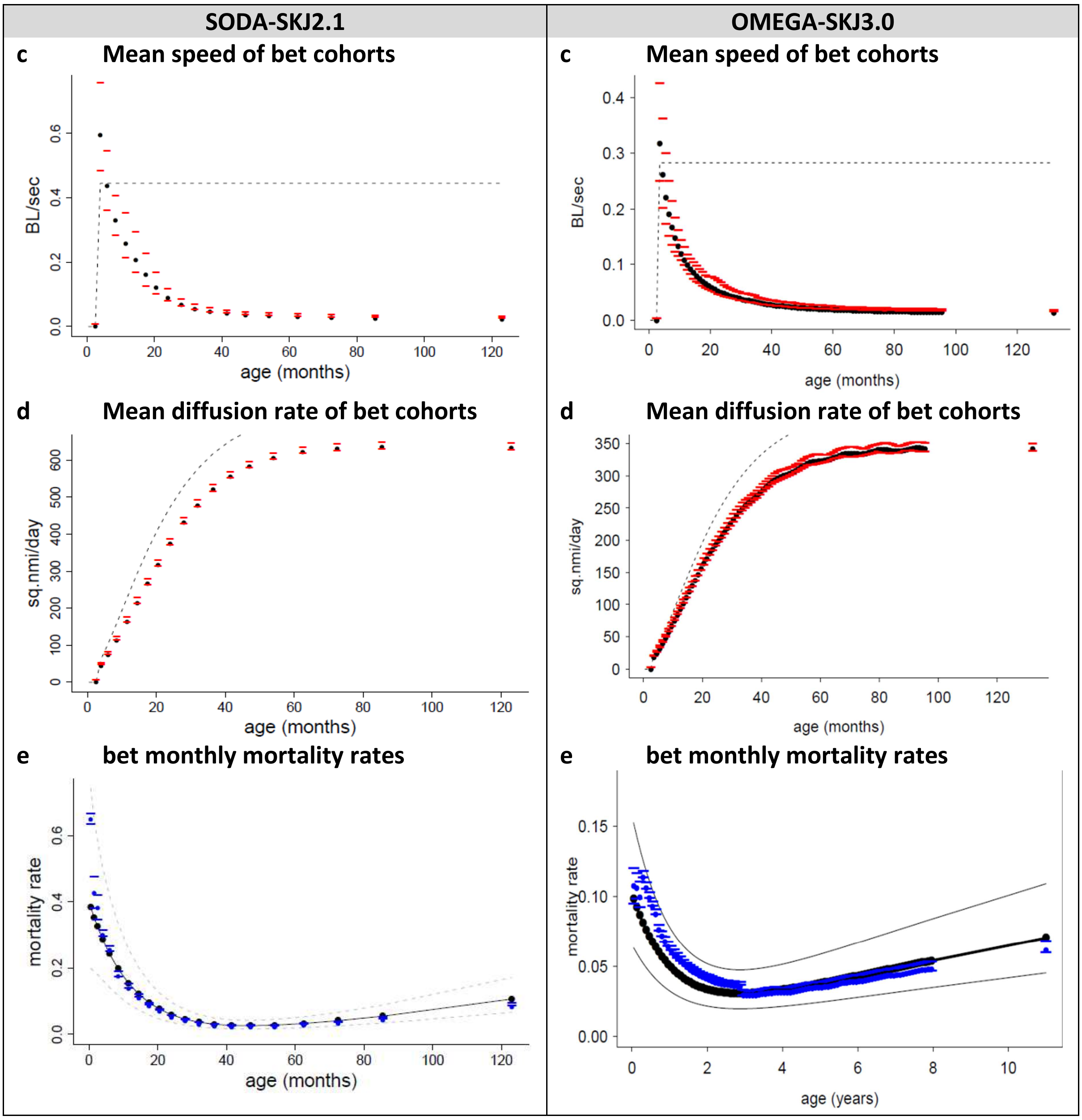

Figure 8.7: Comparisons between previous (BET2.0) and new (BET3.0) optimal parameterization. **a**: change with age (size) of optimal temperature of thermal habitat. **b**:distribution of larvae according to SST and the estimated parameters of spawning index. **c, d**: Maximum sustainable speed and diffusion rates by cohort (depending of age/size and habitat value / gradient) based on SEAPODYM parameterization (dotted lines) and predicted means weighted by the cohort density (black dots) with one standard error (red bars). **e**: natural mortality rates (month^{-1}) estimated from SEAPODYM optimization experiments. Black dotted line corresponds to the theoretical average mortality curve whereas blue dots indicate the mean mortality rates weighted by the cohort density.

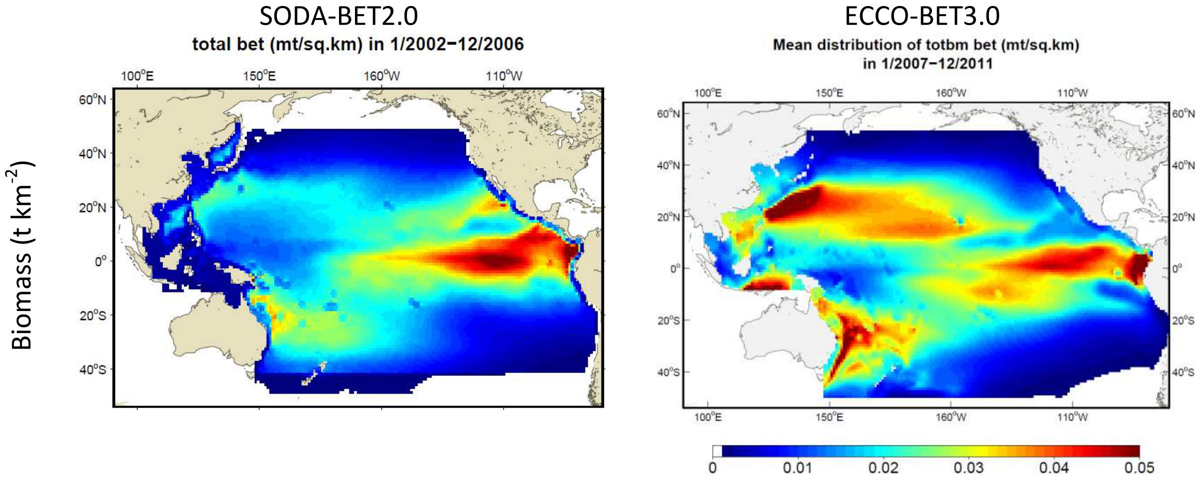

Figure 8.8. Total biomass distribution between first (BET2.0) and new (BET3.0) reference model solutions.

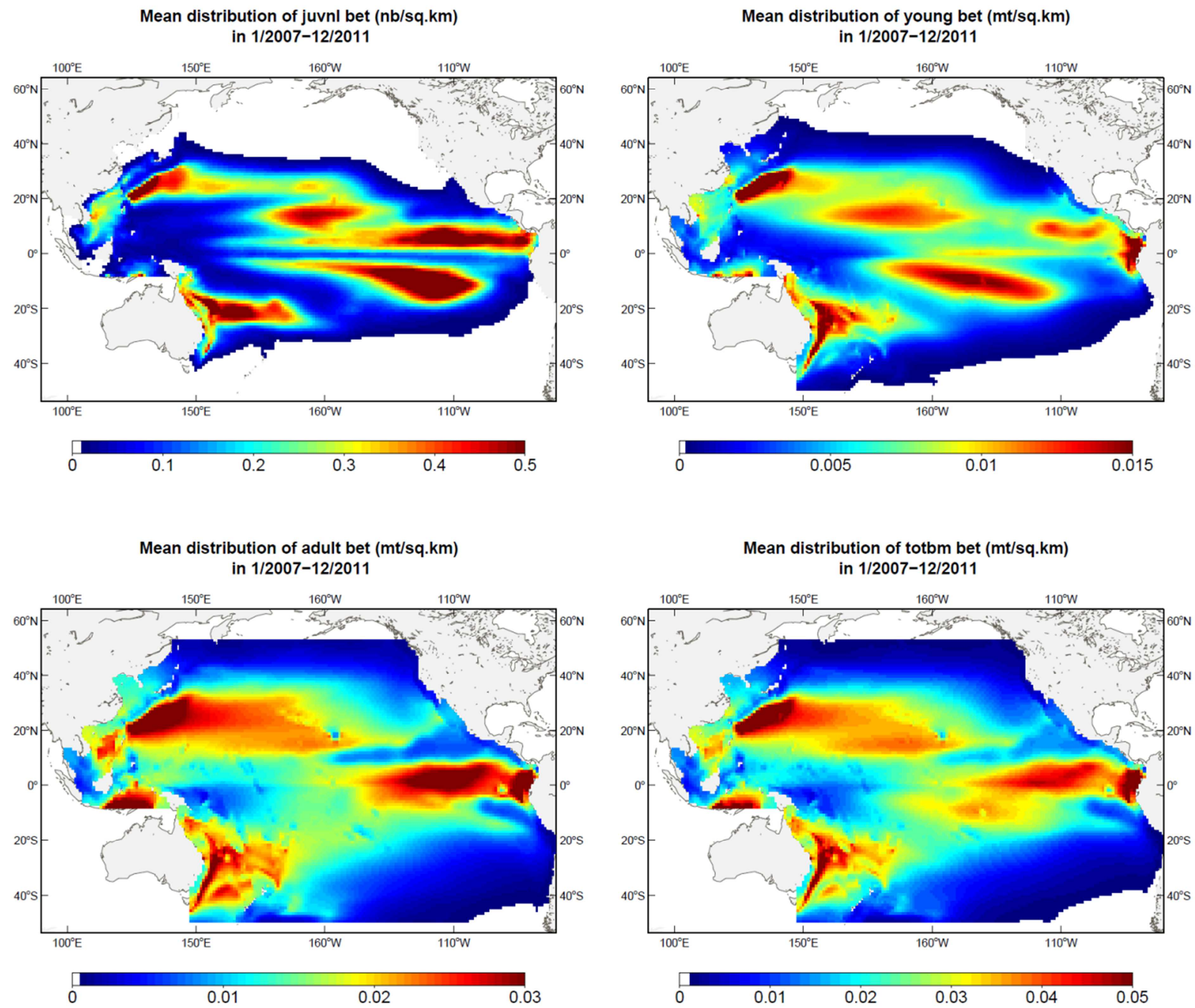

Figure 8.9. Average spatial distributions of Bigeye juveniles, young, adult and total biomass with reference fit BET3.0.

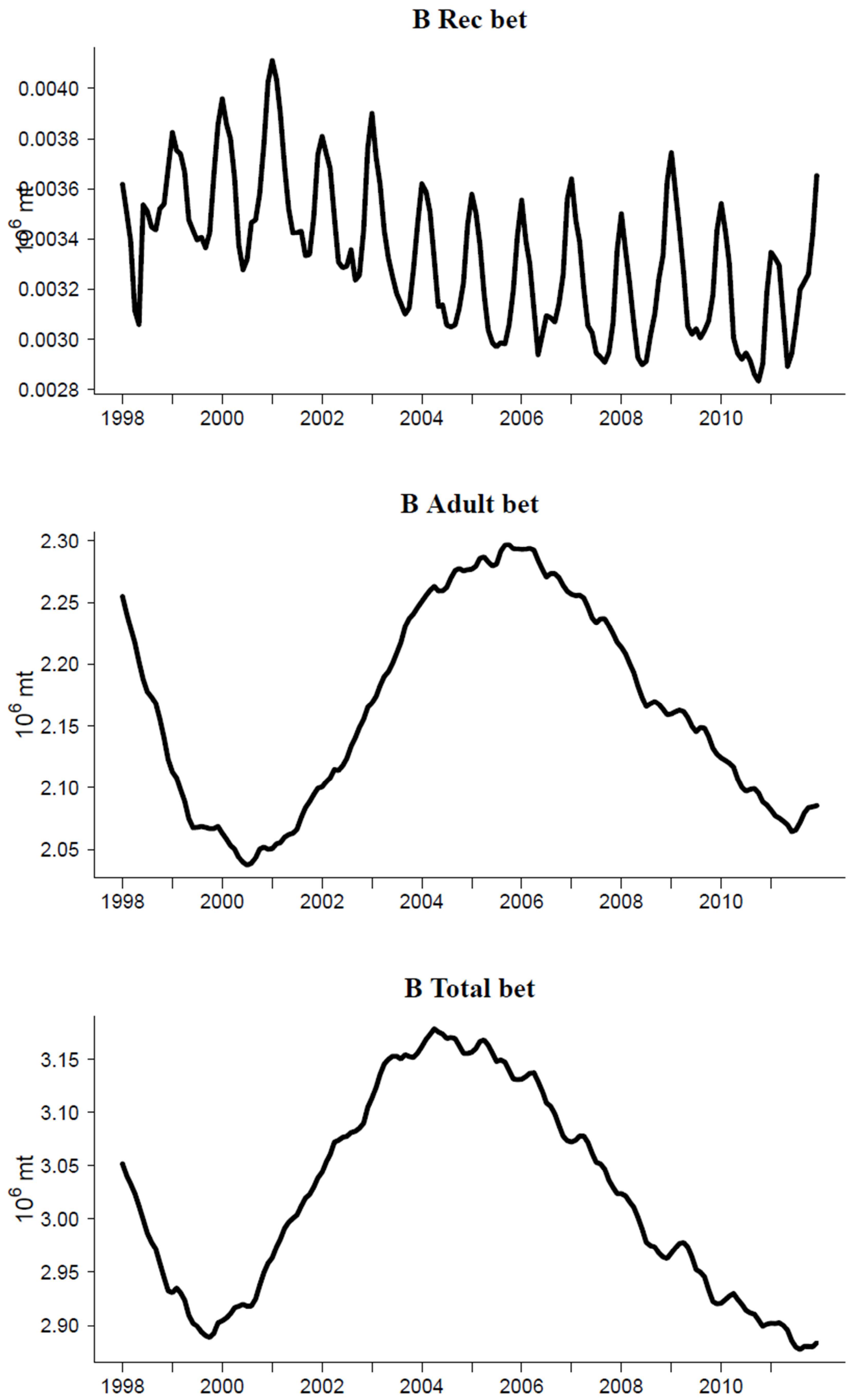

Figure 8.10. Time series of (from top to bottom) bigeye recruits, adults and total biomass estimated for the Pacific Ocean with the new optimization experiment BET3.0.

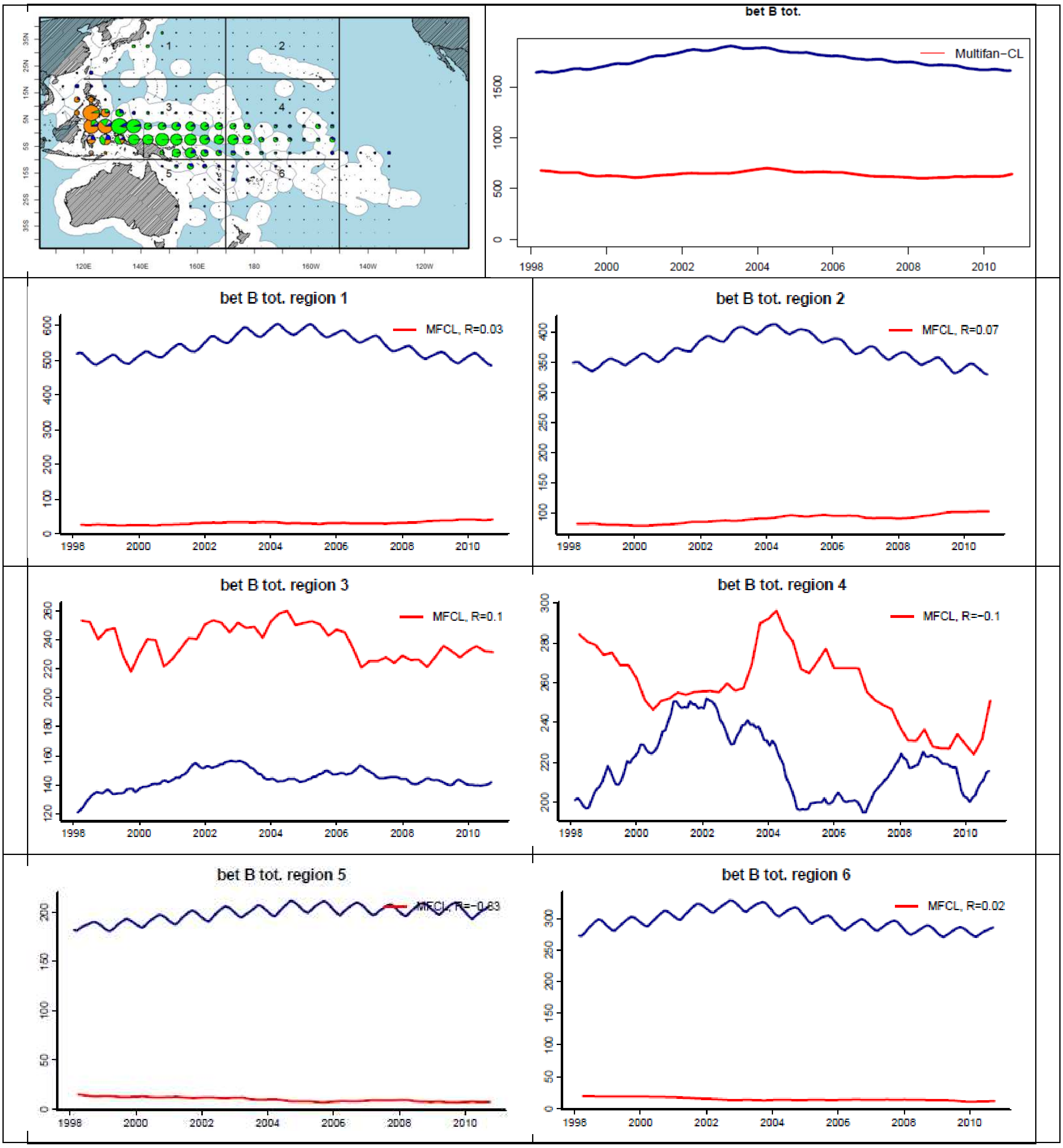

Figure 8.11. Comparison between SEAPODYM BET3.0 and MULTIFAN-CL (red curves; Davies et al., 2011) total bigeye biomass estimates for WCPO (regions 1 to 6).

Optimization of tagging data likelihood

Given the unsatisfactory results achieved using tagging data in the full likelihood function, a study was conducted by modelling only the tagged cohorts and minimizing the cost function including only tagging data. It was concluded that the lack of improvement in the fit was due to the poor representation of feeding habitat index distributions, which are used in the model to stipulate the directed movements of fish. Adding six additional parameters to the feeding habitat allowed testing the sensitivity to the vertical distribution of micronekton biomass functional groups and/or to their accessibility. Much better fit to the observed tag recapture was achieved and the advection parameter was well estimated (1.36 body length per second compared to 0.2 BL/sec being estimated at its lower boundary). In addition to the longitudinal separation of tag recaptures at 160°W (Figure 8.12), the long-distance longitudinal movements are much better represented, predicting more tags recaptured east of the release position.

The latitudinal movements are rather weak, resulting in high concentrations of tags around the equator, however the range of predicted latitudes is much more consistent with observations in comparison with the experiment with full likelihood function, where considerable amount of tags were predicted north of 10°N. This result suggests that changes either in the parameterization of the micronekton (prey) model or/and the accessibility to its components could drastically improve the distributions of habitat gradients and the fit to tagging data (Figure 8.12). The estimated values for the additional coefficients (Table 8.4) indicate that it would be necessary to drastically increase the accessibility to the deep non migrant micronekton to obtain a better representation of fish movements. The current limited accessibility is likely due to the thermal habitat. It is possible to include more flexibility in the form of the functional relationship used to define the thermal habitat with a wider optimal range of temperature to reflect a better thermoregulation capacity of fish. This hypothesis will be tested in the future work for bigeye and verified in the skipjack and yellowfin applications.

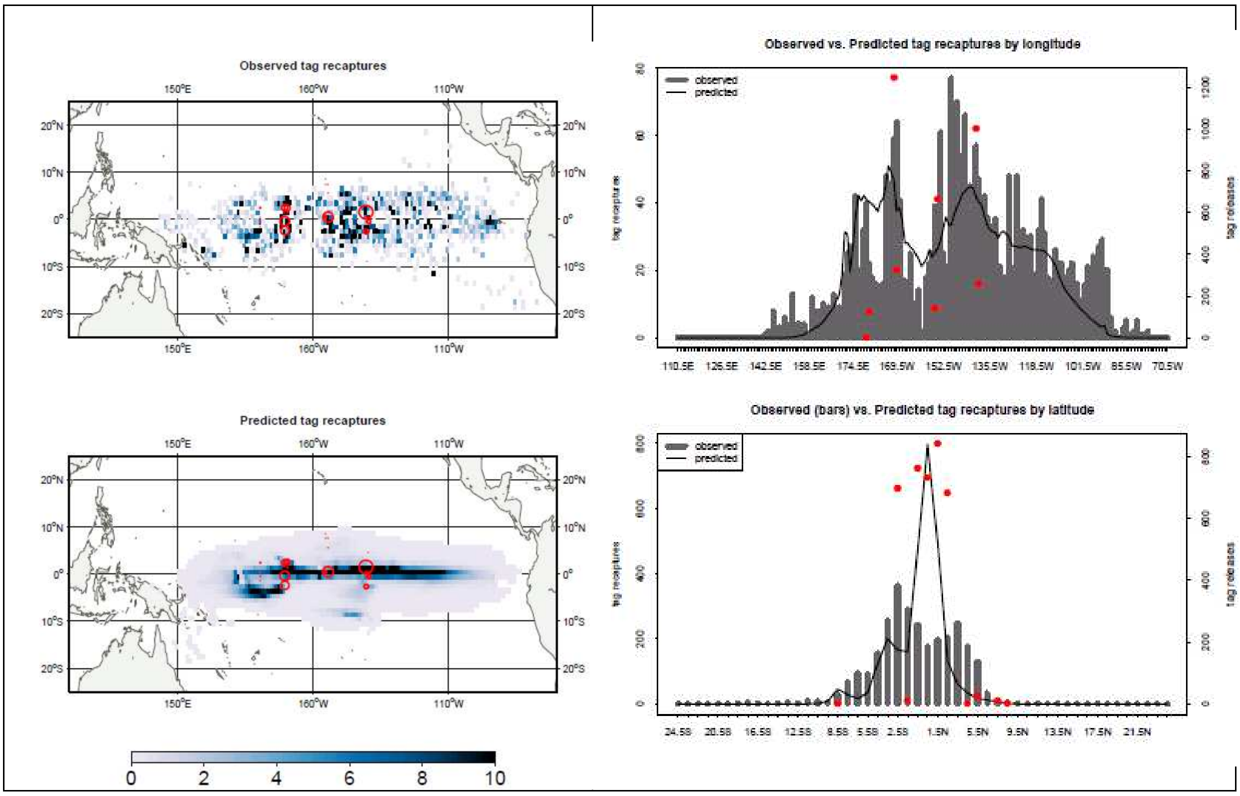

Figure 8.12. Observed and predicted bigeye recaptures after introducing flexibility in parameterization estimates of energy transfer or accessibility to micronekton functional groups. All releases and recaptures between May 2008 and May 2012. Red circles are releasing sites and proportional to the number of released fish.

Table 8.4. Parameter estimates from the sensitivity analysis with tag releases between 05/2008 and 05/2012. In grey are the non-observable parameters (seasonal migrations).

N	Parameter	Min	Max	Init	Est
4	b_sst_spawning	26	32	25.4865	30.713
5	a_sst_habitat	0.4	4.5	2.36148	4.5
6	b_sst_habitat	5	17	10.7874	14.1778
7	a_oxy_habitat	1e-05	0.1	0.000113197	1e-05
8	b_oxy_habitat	0	4.5	0.799602	0.710891
9	sigma_species	0	0.02	0.00418584	0.000597843
10	MSS_species	0.1	3	0.993299	1.36131
11	c_diff_fish	0	1	0.764346	5.51759e-10
12	spawning_season_peak	0	90	89.1636	2.00974e-07
13	spawning_season_start	0.95	1.2	1.00211	1.19871
14	e_Fepi	0.1	1000	0.3	0.1047748
15	e_Fmeso	0.1	1000	1	5.129941
16	e_Fmmeso	0.1	1000	0.5	0.2329335
17	e_Fbathy	0.1	1000	0.3	105.3145
18	e_Fmbathy	0.1	1000	1	0.1000004
19	e_Fhmbathy	0.05	1000	0.3	0.05

9. REFERENCE FIT FOR PACIFIC YELLOWFIN

Fishing data

The definition of fisheries for Pacific yellowfin tuna is provided in Table 9.1. As for bigeye tuna, all longline catch and effort fishing data are at a resolution of 5° x 5° x month while for surface gears (purse seine and pole-and-line) the resolution is 1°x 1° x month, excepted for Philippine and Indonesia fisheries. Size frequency data are at a resolution of 5°x 5° (WCPO purse seine) 10°x 20°, or aggregated over a region for the EPO.

Table 9.1. Yellowfin Fishing Dataset 2014. Definition of SEAPODYM fisheries in Pacific Ocean

	Description	Nationality	Resolution	Time period
L1	LL targeting BET and YFT	Japan	5x5, monthly	1950 - 2011
L2	LL targeting BET and YFT	Korea	5x5, monthly	1962 - 2011
L3	LL targeting BET and YFT	China, Chinese Taipei, Vanuatu	5x5, monthly	1964 - 2011
L4	LL targeting BET and YFT	China, Chinese Taipei	5x5, monthly	1958 - 2011
L5	LL targeting South and North Pacific Albacore, with specific fleet ID : DW, OS and SP	ALL	5x5, monthly	1964 - 2012
L6	LL targeting South and North Pacific Albacore, with specific fleet ID : JP and OD	Japan, Taiwan	5x5, monthly	1952 - 2012
L7	LL targeting South Pacific Albacore	ALL	5x5, monthly	1982 - 2012
L8	LL targeting BET and YFT	ALL	5x5, monthly	1970 - 2012
L9	Longline Australia East Coast	Australia	5x5, monthly	1985 - 2011
L10	Hawaii Longline	USA	5x5, monthly	1991 -2011
L11	LL targeting Pacific Bluefin operating west of 145°E	ALL	5x5, monthly	1955 - 2011
L12	LL targeting BET and YFT	ID, ID-ID	5x5, monthly	1958 - 2012
S13	PS sub-tropical	Japan	1x1, monthly	1972 – 2008
S14	PS Anchored FADs, WCPO	ALL	1x1, monthly	1979 – 2010
S15	PS Animal, WCPO	ALL	1x1, monthly	1986 – 2010
S16	PS Drifting FADs, WCPO	ALL	1x1, monthly	1982 – 2010
S17	PS Natural Fads, WCPO	ALL	1x1, monthly	1979 – 2010
S18	PS Free swimming school, WCPO	ALL	1x1, monthly	1979 – 2010
P19	PL WCPO	ALL	1x1, monthly	1972 – 2008
S20	PS Floating objects	ALL	1x1, monthly	1996 – 2013
S21	PS Animal, EPO	ALL	1x1, monthly	1996 – 2013
S22	PS Free swimming school, EPO	ALL	1x1, monthly	1996 – 2013

Yellowfin population structure

The population is structured with 2-month cohorts and a last “+ cohort” that accumulates older fish. The age at maturity occurs after cohort 15, i.e., at age 2.5 yr. Age-length and age-weight relationships are derived from the 2011 MULTIFAN-CL estimate (Langley et al., 2011).

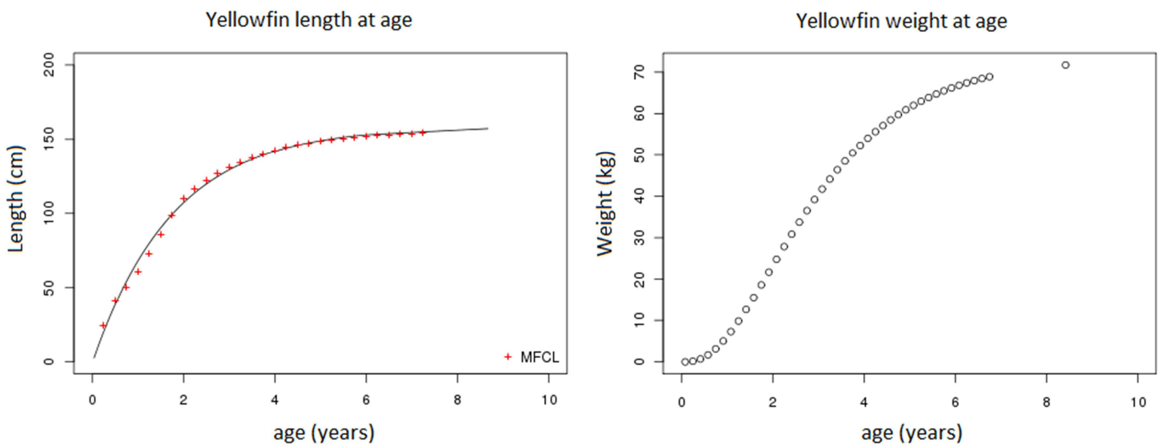

Figure 9.1: Yellowfin size (FL in cm) and weight at age (yr) functions used in SEAPODYM simulation based on MULTIFAN-CL estimates (Langley et al. 2011).

Optimization experiments

This optimization for yellowfin (YFT.1.1) was conducted with fishing data only (i.e., catch effort and size frequencies). Philippine and Indonesia fishing data are not used in the optimization due to a lack of accuracy. This optimization was conducted after the bigeye tuna tagging data sensitivity (cf. above), and thus included the change in the form of the functional relationship for the thermal habitat. The long historical hindcast provided by the coupled models NEMO-PISCES forced by the atmospheric reanalysis time series was used to achieved this first estimate. Prior information to constrain the likelihood function (*a priori* average total biomass =3,900,000 mt in the geographical box 120°E-150°W; 45°N-20°S), based on previous stock estimates with Multifan-CL.

Fit to catch data

The model results were validated using the whole time series, i.e., 1980-2004. The details of fit for all fisheries separately are provided in **appendix 3** while a summary is provided below.

The spatial fit to observed catch is fairly good in the main fishing grounds, in particular the equatorial EPO but decreasing towards the central gyres and higher latitudes where catch become more occasional (Figure 9.2).

Total catch is well predicted, showing a regular increasing trend since the early 1980s (Figure 8.4). The detail by fishery (appendix 3) shows a difficulty to simulate the high variability observed in catch of longline fisheries L2 (Korea), L9 (East Coast Australia), L10 (Hawaii) and L11 (targeting albacore west of 145°). The fit is high for all purse seine fisheries, the lowest (r = 0.67) being for S22 (free school). Trends in catchability over the time series 1980-2003 (Table 9.2) suggest annual decrease in L4 (China and Taipei) and L12 (East Australia) longline fisheries. Many purse seine fisheries in WCPO and EPO showed an annual increase in a range of 1.2-2.4%.

The overall fit to size frequencies samples are generally good (Appendix 3) with the exception of purse seine fishery S18 (WCPO, sets on logs) where a lot of small size fish in observed catch are not predicted by the model. Interestingly, the model predicted significant variability in mean size of catch over time in the purse seine fisheries S20, S21 and S22 in the EPO.

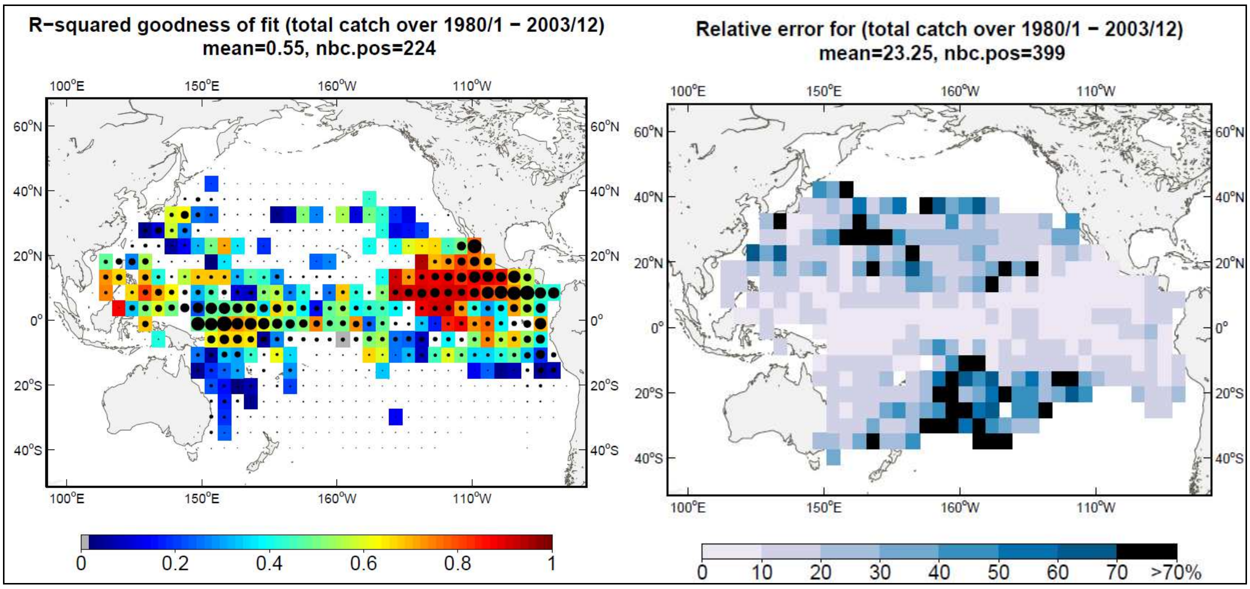

Figure 9.2. Comparison of fit to fishing data over the period 1980-2003 for NCEP-YFT2.0. Left: R-squared goodness of fit representing the spatial fit over the period used for optimization (white squares indicate negative correlation between observations and predictions; Black circles are proportional to the level of catch. Right: relative error in predicted catch for all fisheries.

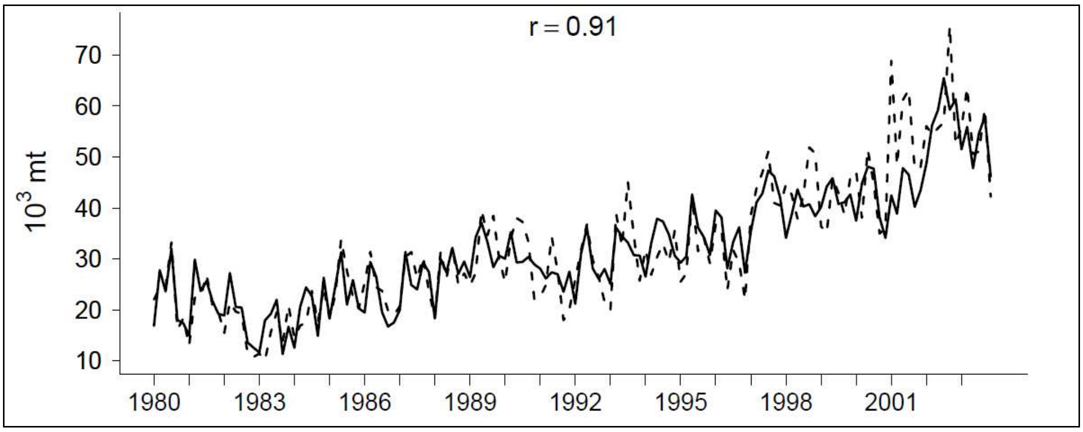

Figure 9.3. Fit between total observed (dotted line) and predicted (continuous line) Pacific yellowfin tuna catch. Note that series represent the sum of catches by fisheries having different units, i.e. longline catch is provided in numbers of fish, the purse-seine and pole-and-line are given in metric tons.

Table 9.2. Estimates of yellowfin catchability by fishery and annual change (%) since 1980.

Fishery		q	annual % change since 1980
L1	LL BET&YFT	0.007667	0.00
L2	LL BET&YFT	0.009220	0.00
L3	LL BET&YFT	0.004727	0.00
L4	LL BET&YFT	0.017616	-2.40
L5	LL BET&YFT	0.008062	0.00
L6	LL Shallow night	0.003084	0.00
L7	LL ALB	0.005289	0.00
L8	LL ALB	0.008889	0.00
L9	LL ALB	0.010000	0.00
L10	LL ALB	0.002280	0.00
L11	LL BFT	0.002000	0.00
L12	LL SP-ALB	0.015000	-2.40
S13	PS sub-tropical	0.001380	0.00
S14	PS Anchored FADs, WCPO	0.004871	0.00
S15	PS Animal, WCPO	0.004000	0.00
S16	PS Drifting FADs, WCPO	0.008736	0.00
S17	PS Natural Fads, WCPO	0.002343	1.20
S18	PS Free swimming school, WCPO	0.002638	1.20
P19	PL	0.000499	-1.20
S20	PS type ‘O’ – other, WCPO	0.007964	1.80
S21	PS EPO, FO	0.005534	2.40
S22	PSEPO free school	0.008611	1.80

Optimal Parameterization

The optimal spawning temperature was estimated (29.3°C) with a standard error reaching the upper boundary value (2°C) (Figure 9.4). As a result larvae mainly concentrate in waters with SST above 26°C with a peak in the range 28-31°C (Table 9.3). The optimal temperature for feeding habitat of adults was estimated and gives a thermal habitat decreasing with size/age from 28°C to 14°C. The value of the oxygen threshold parameter was estimated to 0.6 mL/L which is surprisingly low for yellowfin. The movement parameters cannot be estimated correctly even with fixed diffusion, the advection coefficient reached its lower boundary value. The mean natural mortality coefficients are estimated between 0.05 and 0.7 mo^{-1} (0.60-0.84 yr^{-1}) for cohorts older than 1 year.

Table 9.3: Estimates of habitats, movement and mortality function parameters for yellowfin tuna based on NCEP-NEMO-PISCES forcing. The values marked with ‘[’ or ‘]’ were estimated at their minimal or maximal boundary value correspondingly

Parameters estimated by the model			Unit	NCEP-YFT2.0
T_s	Spawning	Optimum of the spawning temperature function	^oC	29.31
σ_s		Std. Err. of the spawning temperature function	^oC	2]
r		Maximal number of recruits per adult	Nb	137.5
T_a	Feeding habitat	Optimum of the adult temperature function at maximum age	^oC	[14
σ_a		Slope coefficient in sigmoid function describing tolerance to oxygen	^oC	1.13
$\hat{O}$		Oxygen threshold value at Ψ_O =0.5	$mL \cdot L^{-1}$	0.60
D_{max}	Movement	Diffusion parameter		0.025*
V_{max}		Maximum sustainable speed	B.L. s^{-1}	[0.1
e_p	Mortality	Slope in exponential decrease of predation mortality with age	-	0.114
M_s		Senescence mortality at age 0	mo^{-1}	0.005
e_s		Increase of senescence mortality with age	-	0.65
ε		variability of mortality due to food requirement index	%	29

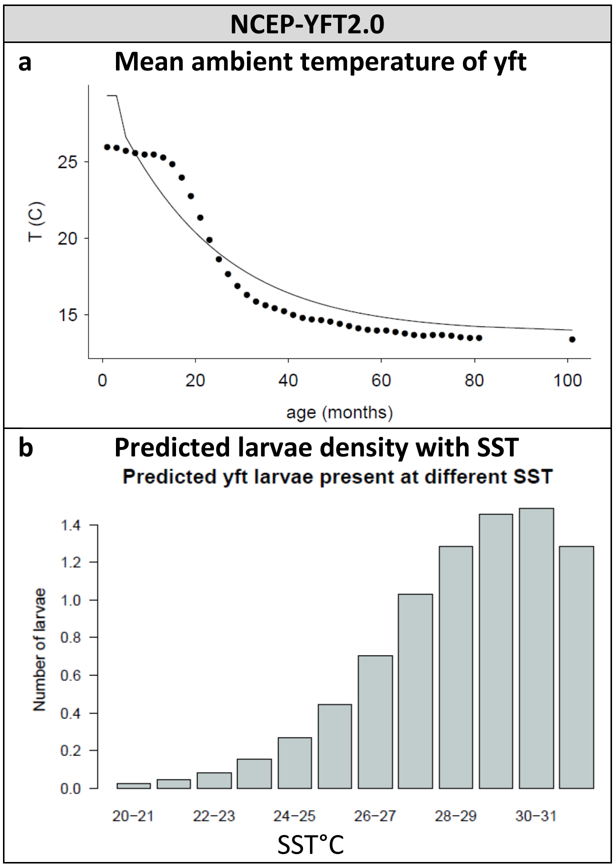

Figure 9.4: see next page

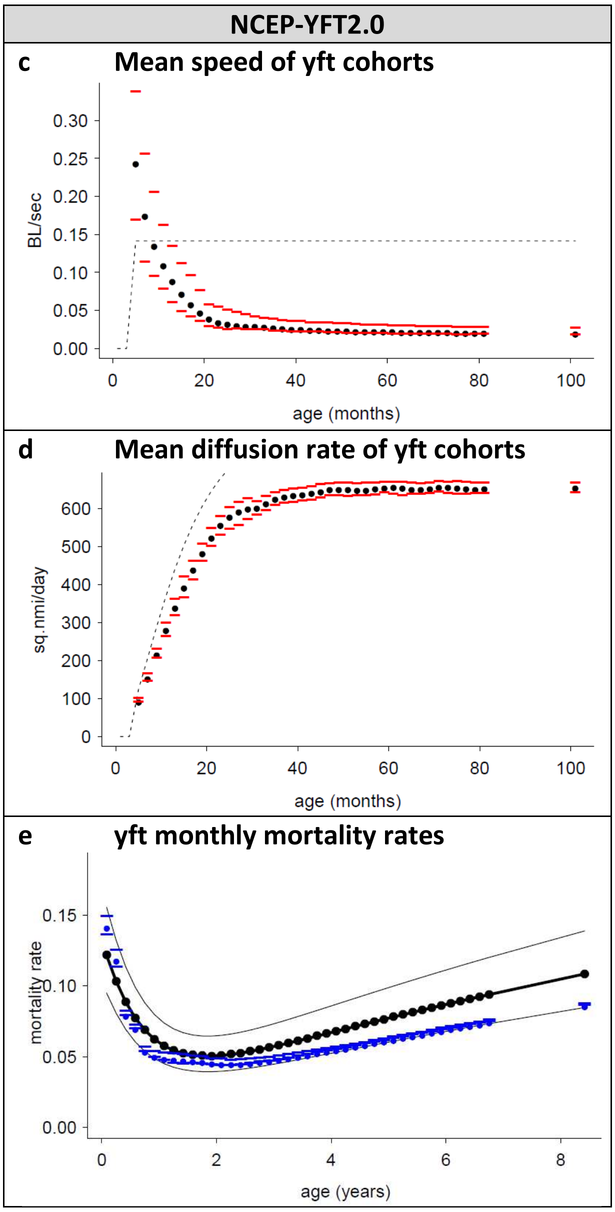

Figure 9.4: Optimal parameterization for yellowfin tuna. **a**: change with age (size) of optimal temperature of thermal habitat. **b**:distribution of larvae according to SST and the estimated parameters of spawning index. **c, d**: Maximum sustainable speed and diffusion rates by cohort (depending of age/size and habitat value / gradient) based on SEAPODYM parameterization (dotted lines) and predicted means weighted by the cohort density (black dots) with one standard error (red bars). **e**: natural mortality rates (month^{-1}) estimated from SEAPODYM optimization experiments. Black dotted line corresponds to the theoretical average mortality curve whereas blue dots indicate the mean mortality rates weighted by the cohort density.

Biomass estimates and population dynamics

This parameterization produce a biomass distribution with a core area associated to the warm waters of the warm pool and the Philippine-Indonesia region, and the warm currents moving north (Kuroshio), south (East Australian Current) and east (north equatorial counter current) with a strong diffusing pattern from these core areas while fish cohorts are getting older (Figure 9.5). The total biomass estimate for the Pacific fluctuates between 7 and 8 million metric tonnes since the 1980s with a rapid decline to 6.5 Mt after 2001 due to the large increase of catch by longline fisheries and the purse seine fishery S21 (EPO floating objects fishery). In the WCPO, the total biomass is estimated between 5 and 4 Mt (3.5-1.5 for MFCL; Langley et al. (2011)). The largest regional discrepancies between SEAPODYM and MFCL biomass estimates are from outside the main fishing regions 2 and 3, with a biomass higher by a factor ~6 in region 6 and a factor ~3 in regions 1 and 2.

Though the fit to catch data is reasonable, the movement parameters are poorly constrained and the introduction of tagging data in the future optimization experiment should be useful to improve the modelling of spatial distribution for this species.

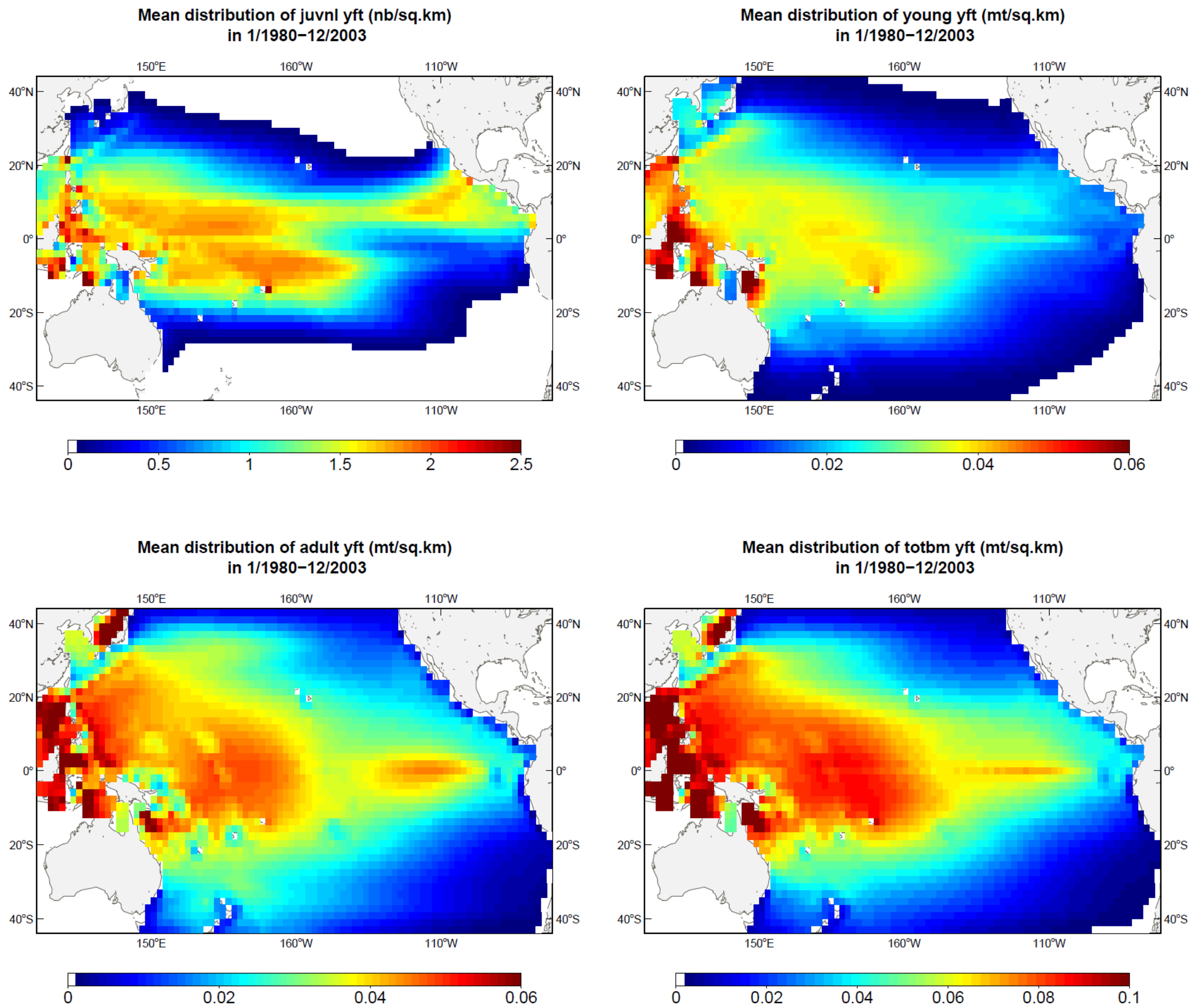

Figure 9.5. Average spatial distributions of yellowfin larvae, young, adult and total biomass

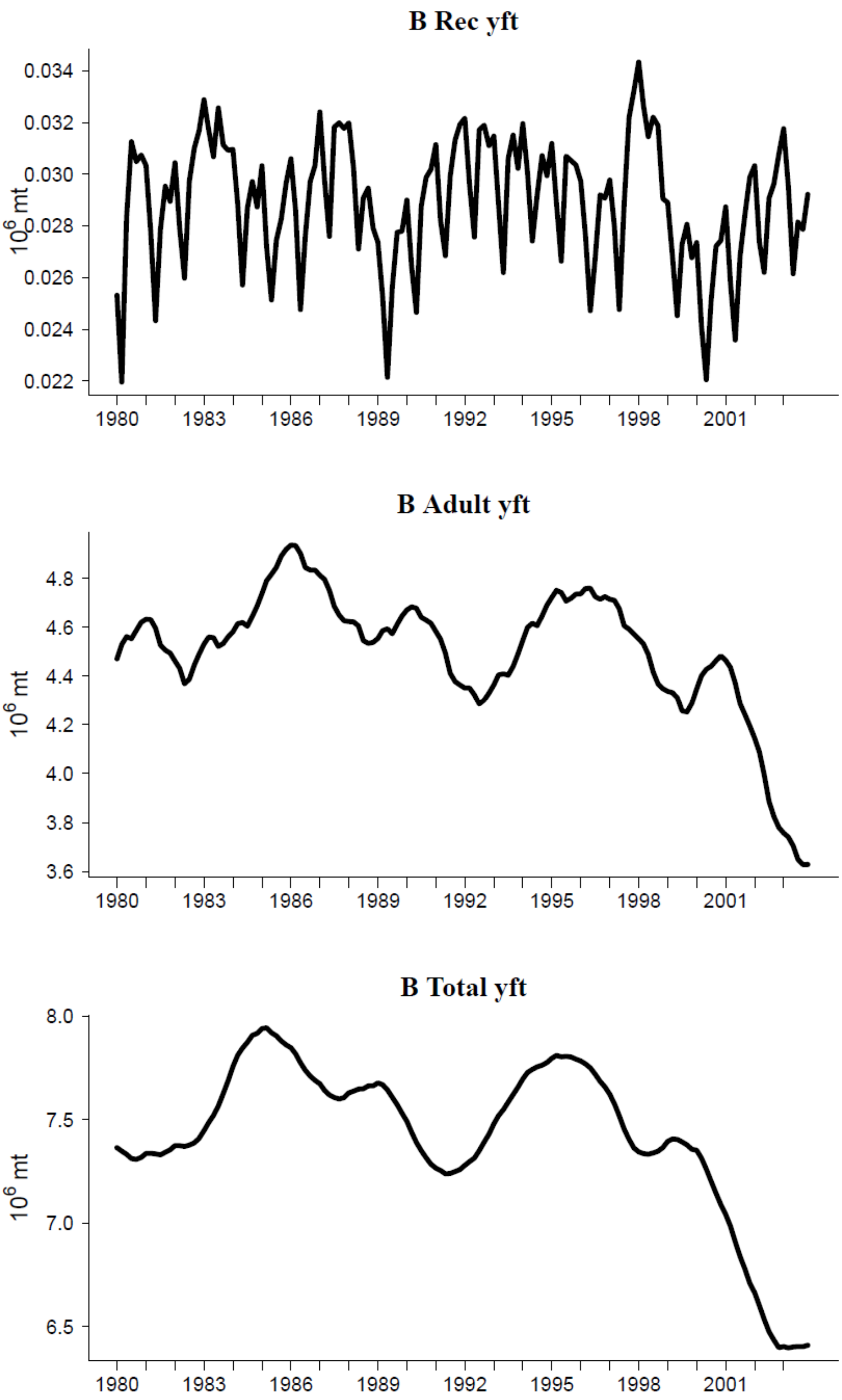

Figure 9.6. Time series of (from top to bottom) yellowfin recruits, adults and total biomass estimated for the Pacific Ocean with the new optimization experiment YFT1.0.

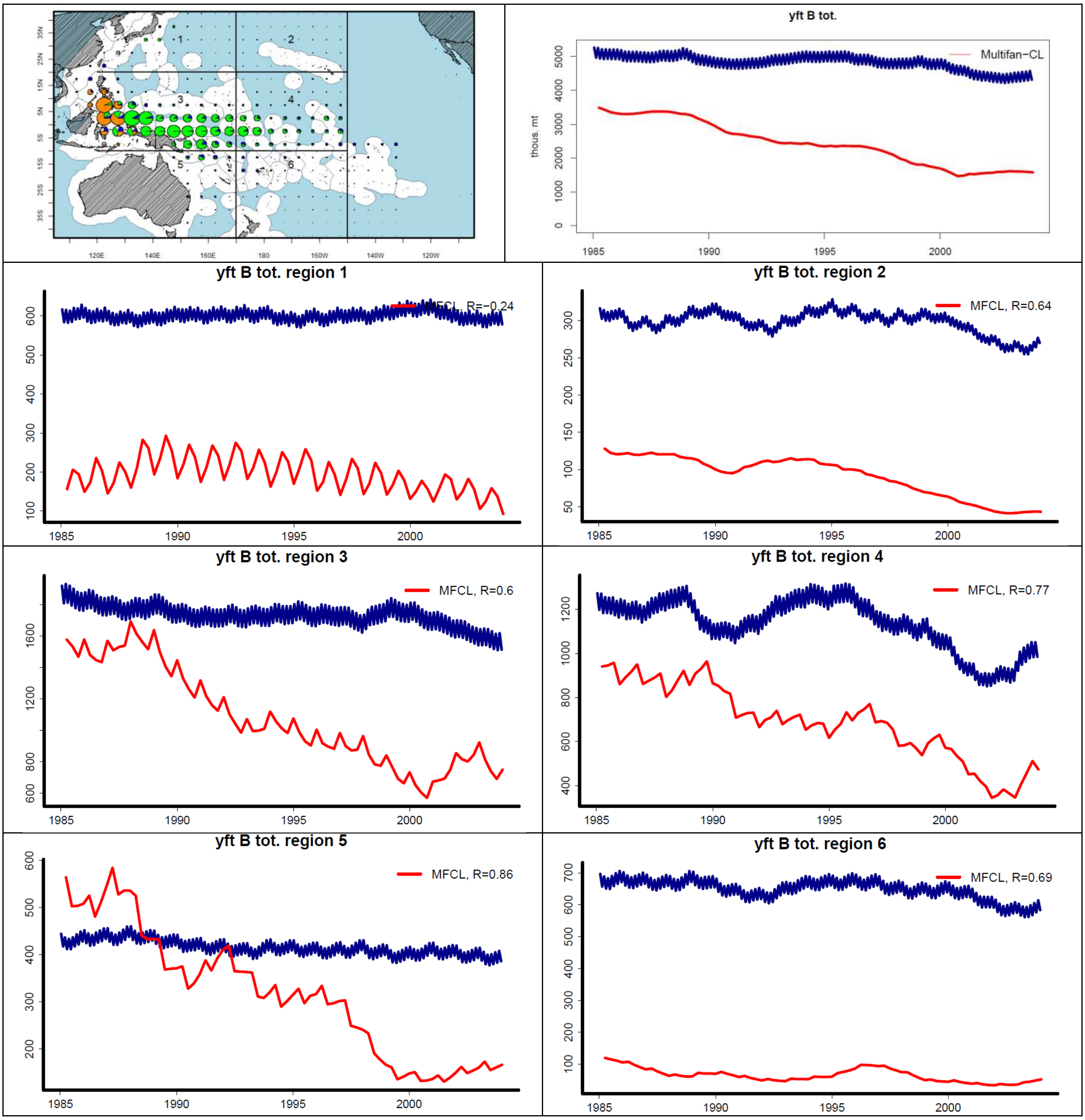

Figure 9.7. Comparison between SEAPODYM YFT2.0 and MULTIFAN-CL (red curves) total yellowfin biomass estimates for WCPO and by region 1 to 6.

10. CURRENT AND FUTURE WORK PLAN 2014-15

Impact of tagging data in optimisation

The use of conventional tagging data in the optimisation framework of SEAPODYM remains one priority for 2014-15 to improve the modelling of spatial tuna population dynamics. The current results for the reference fit SKJ3.0 and BET 3.0 should be revised. Preliminary sensitivity analyses have been conducted and suggest that changes either in the parameterization of the micronekton (prey) model or the accessibility to its components could drastically improve the fit to tagging data (Figure 8.12). In parallel, the optimisation of the micronekton model will continue with the objective of using acoustic data transects to estimate the energy transfer from primary production to micronekton functional groups. Optimization using both fishing data and tagging data still needs to be conducted for yellowfin tuna.

Operational Basin scale model

SEAPODYM progress and applications in 2013-2014 have been strongly linked to the development of an operational model for the INDESO project. The operational model configuration has been developed at weekly ¼° resolution, for skipjack, yellowfin and bigeye tuna based on the reference fits presented in this document. A climatology (monthly average over the last 5 years) of fishing effort is used in the Pacific to include fishing mortality. In 2014-15, a special focus will be given to the Indian Ocean to define similarly the tuna fisheries and produce fishing effort climatologies and better initial conditions for the operational model.

Regional Modelling

A regional operational (realtime) high resolution SEAPODYM model is developed for the Indonesian Government (INDESO project) and will be delivered in the 4th quarter of 2014 in the Perancak Center, Bali. The regional model provides higher resolution (1/12° x day) with a much detailed bathymetry and thus more accurate ocean circulation estimates than the global model (1/4° x week). Once the operational regional model started from initial conditions provided by the global model, outputs begin to diverge due to different slightly environmental conditions, especially a more accurate circulation near the coast of Islands in the regional model. Therefore it is useful to compare similar outputs from both global and regional models. For example, the global model seems to produce spurious concentration of fish in several cells adjacent to the coast (Figure 10.1). These concentrations (red cells) disappear in the regional model, likely due to more accurate circulation. Thus, the comparisons of both model outputs should help to improve the estimates of tuna biomass both at regional and global scales. Efforts are also developed to compare in real time total tuna catch by administrative fishing areas with model outputs.

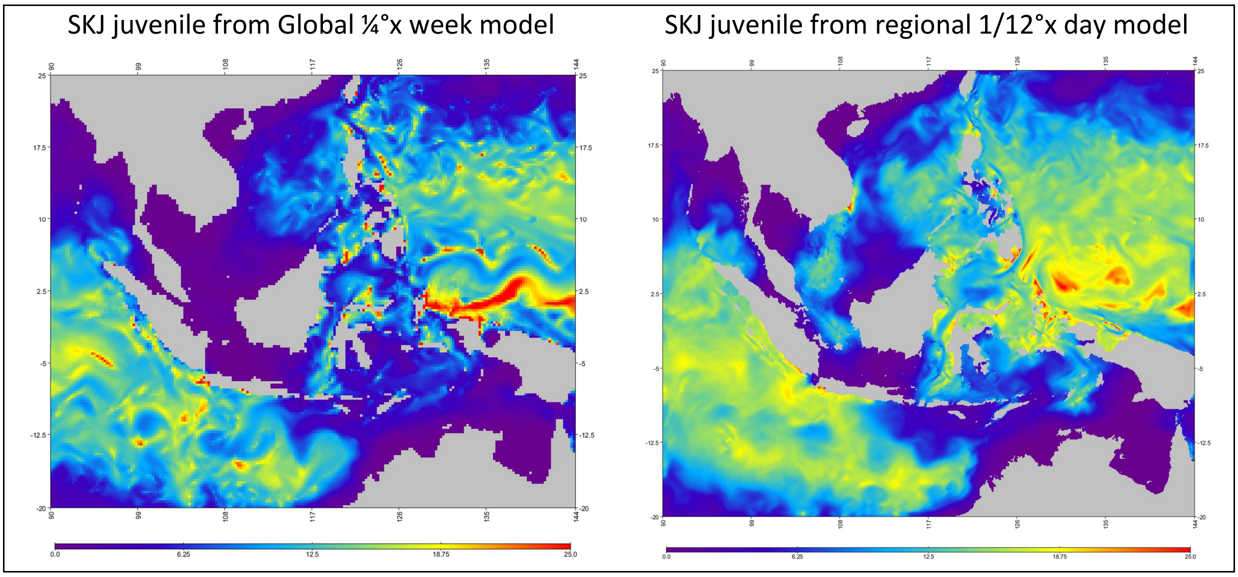

Figure 10.1. Comparison between juvenile skipjack biomass distributions from global (top) and regional (bottom) model for the week of 02-06-2014. Note that regional outputs were averaged over the week for comparison with the weekly outputs of the global model.

SeapodymView

The software SeapodymView which provides for easy display of SEAPODYM output is currently being revised to allow use on non-Linux operating systems and to provide improved visualisation options. The new version will be released in October 2014.

11. REFERENCES

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Hoyle S, Kleiber P, Davies N, Langley A, Hampton J (2011) Stock assessment of skipjack tuna in the Western and Central Pacific Ocean. Seventh Regular Session of the Scientific Committee, 9–17 August 2011, Pohnpei, Federated States of Micronesia, WCPFC-SC7-2011/SA-WP-04, 134 pp.

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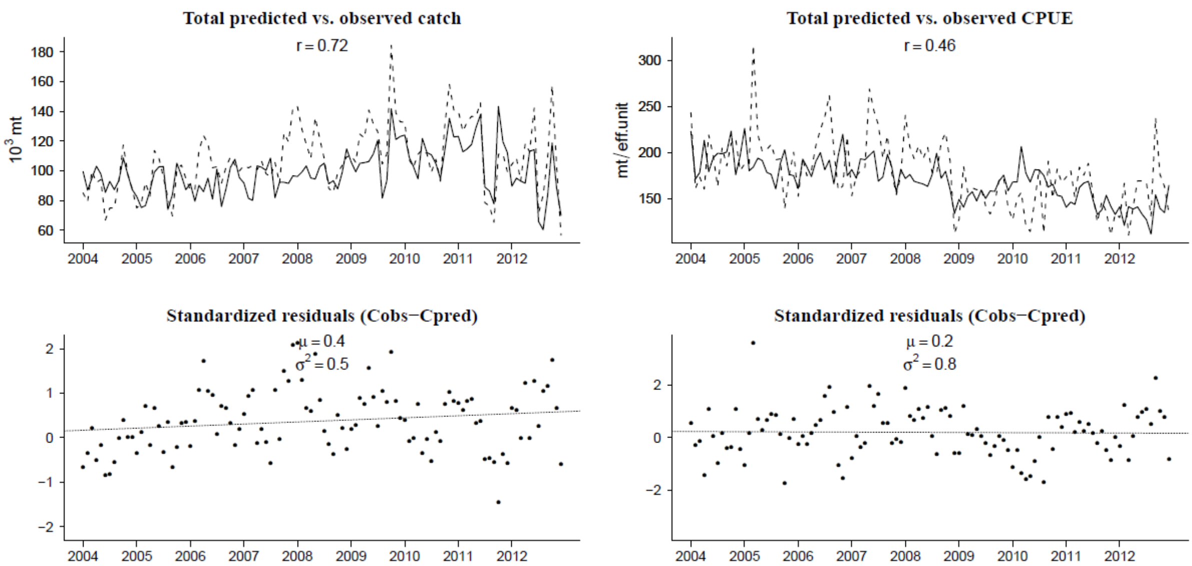
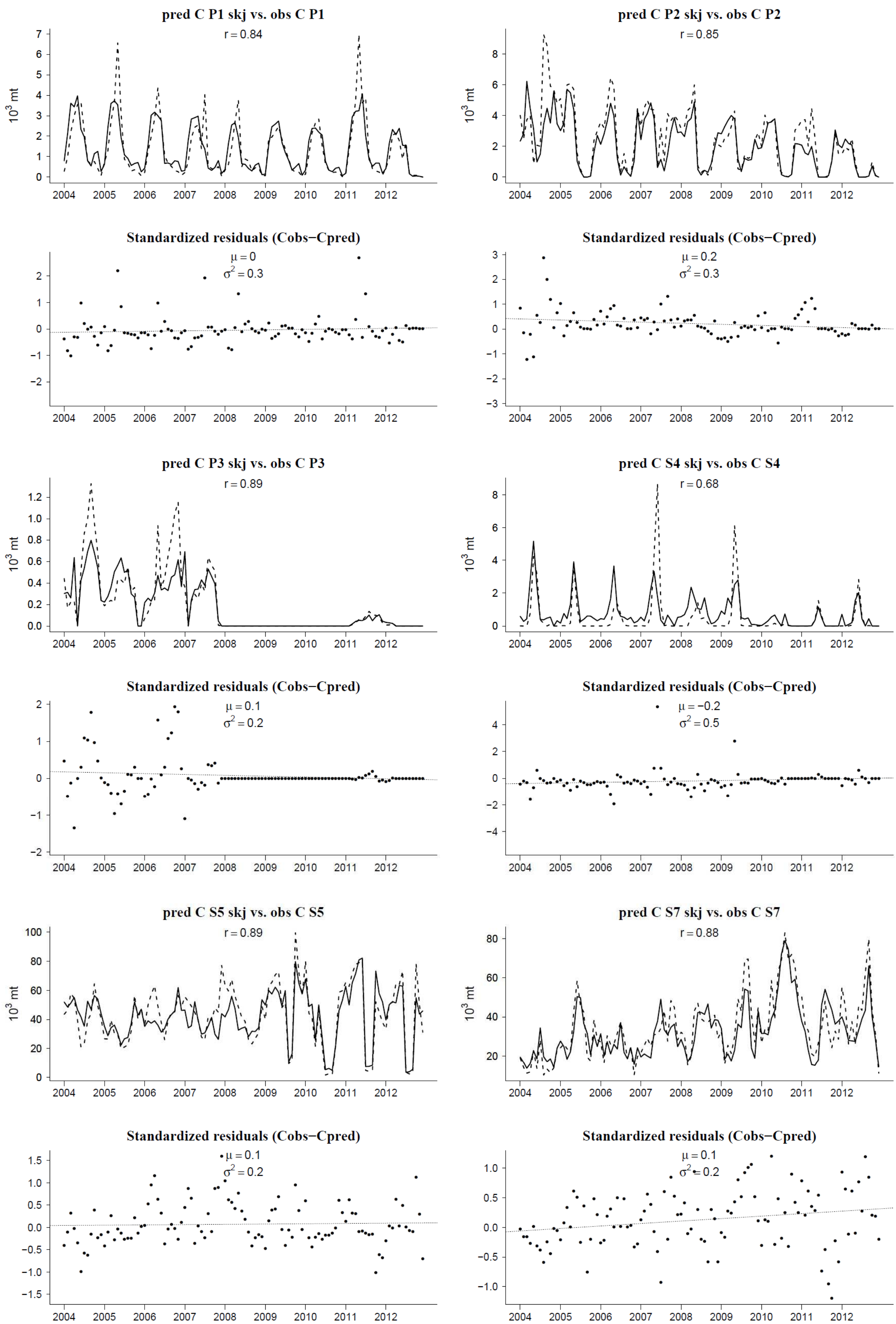
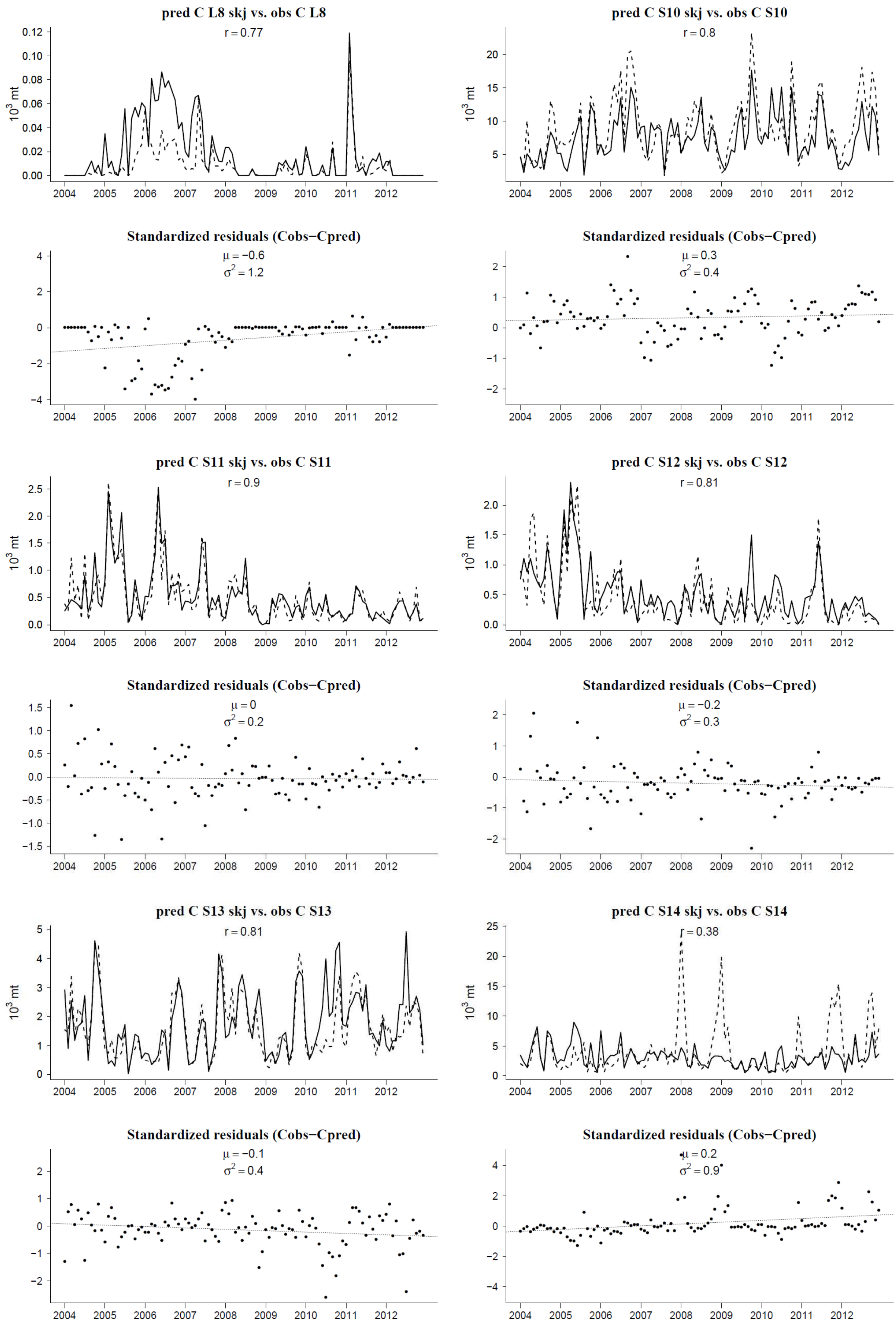
12. APPENDIX 1 – SKIPJACK



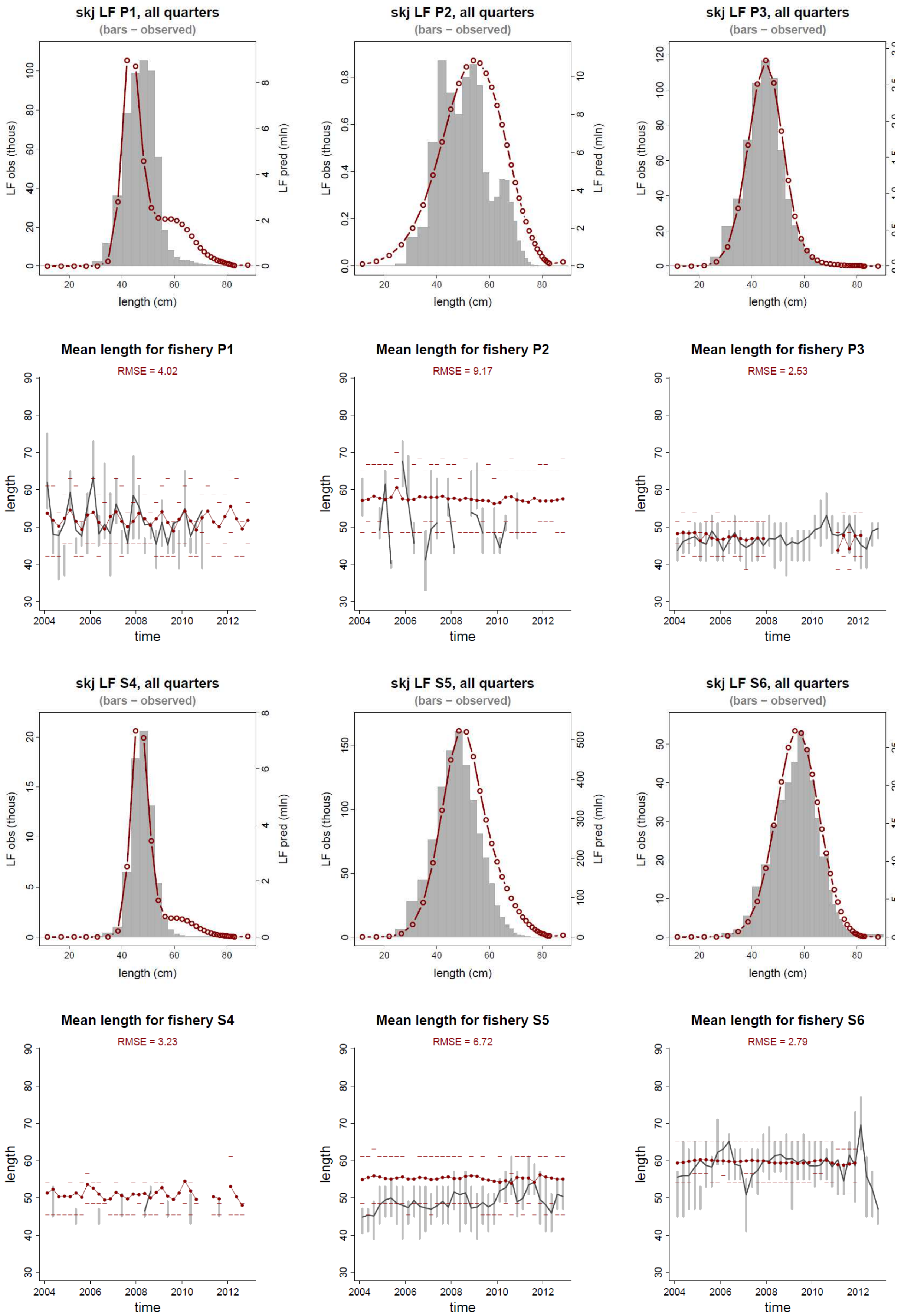
Time series of total observed and predicted catch (left) and CPUE (right)



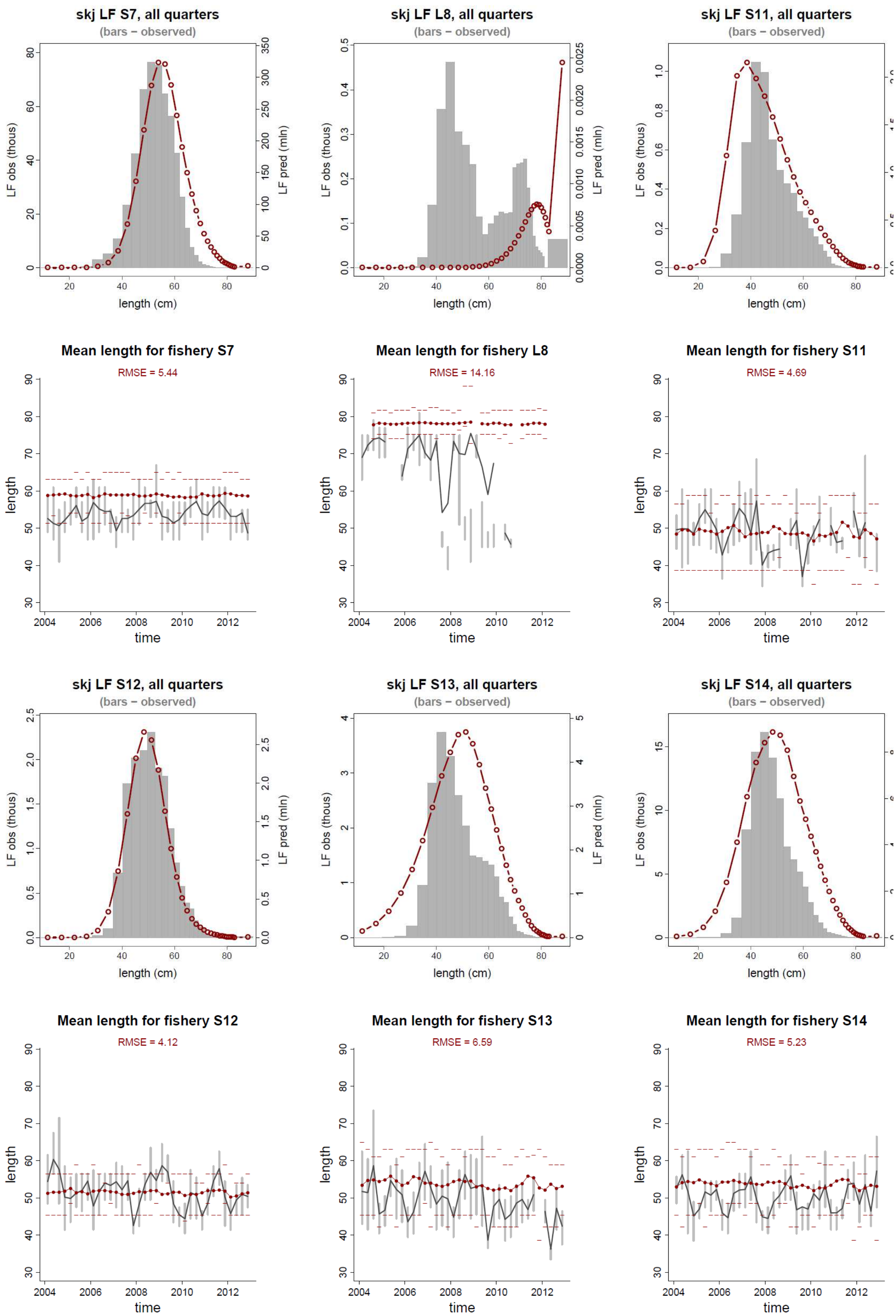
Time series of observed and predicted catch by fishery



Time series of observed and predicted catch by fishery (cont.)

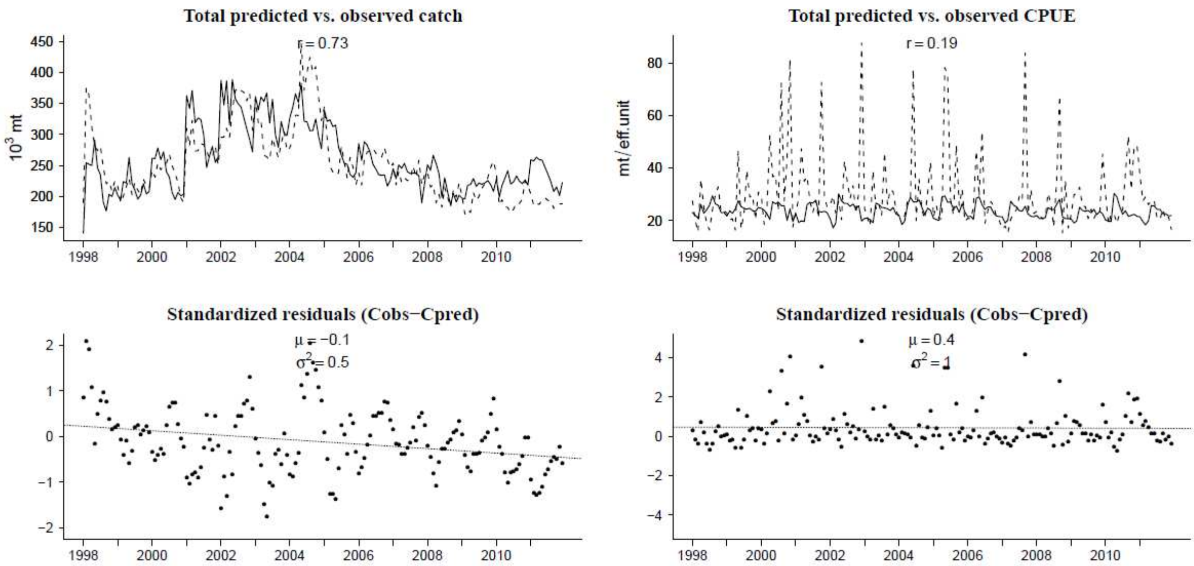


Observed (grey) and predicted (red) length frequencies distribution and mean length in catches.

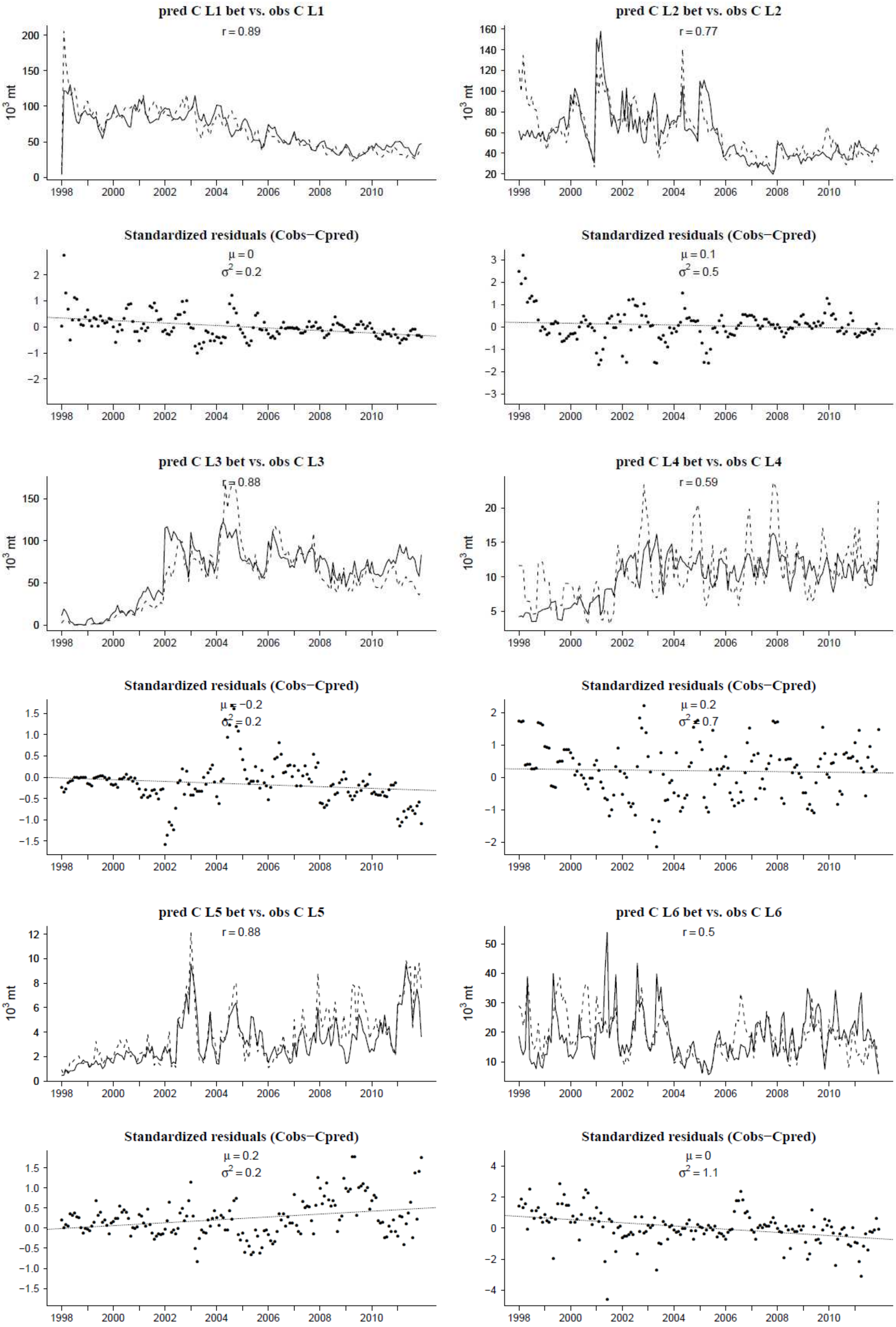


Observed (grey) and predicted (red) length frequencies distribution and mean length in catches (cont.)

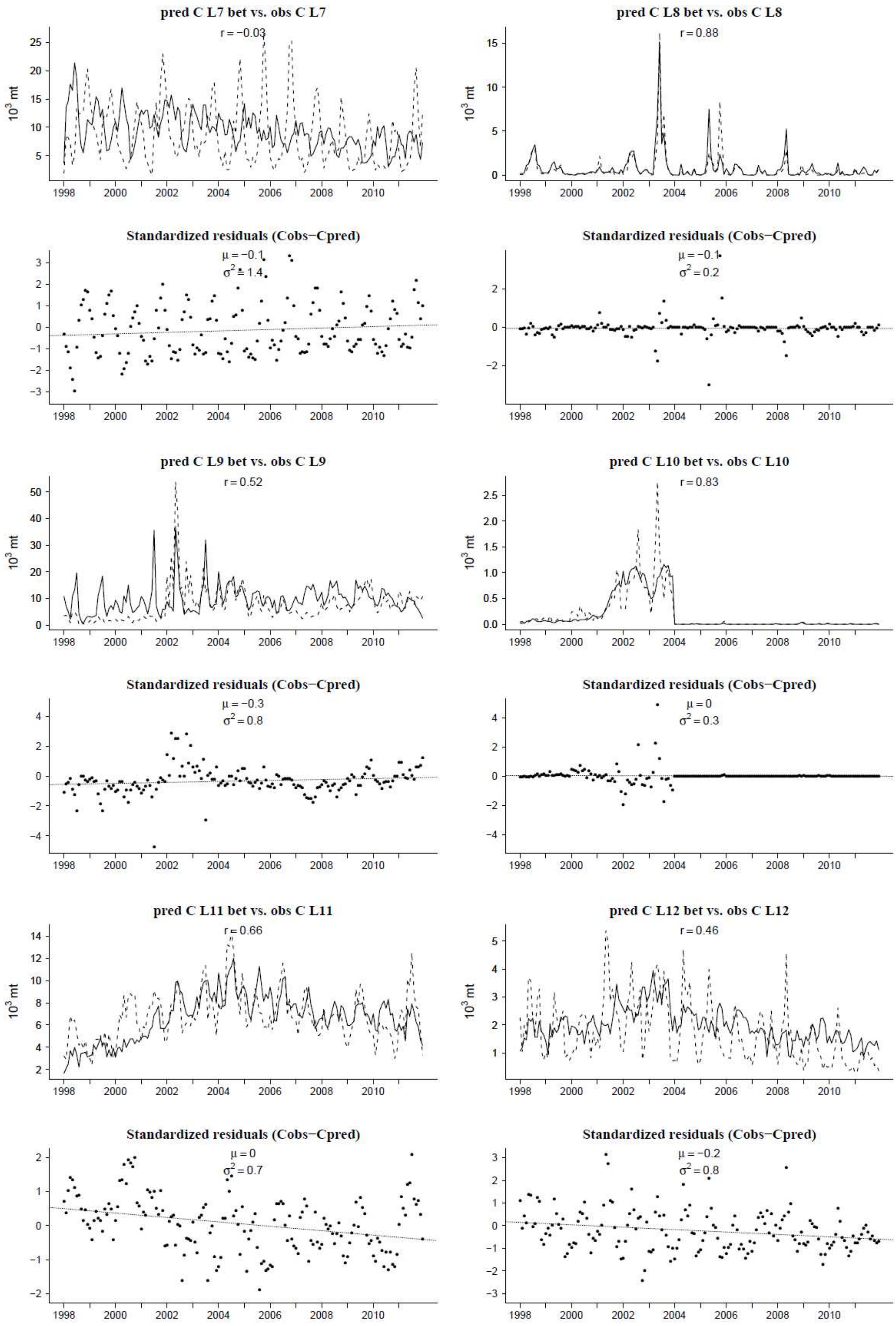
13. APPENDIX 2 – BIGEYE



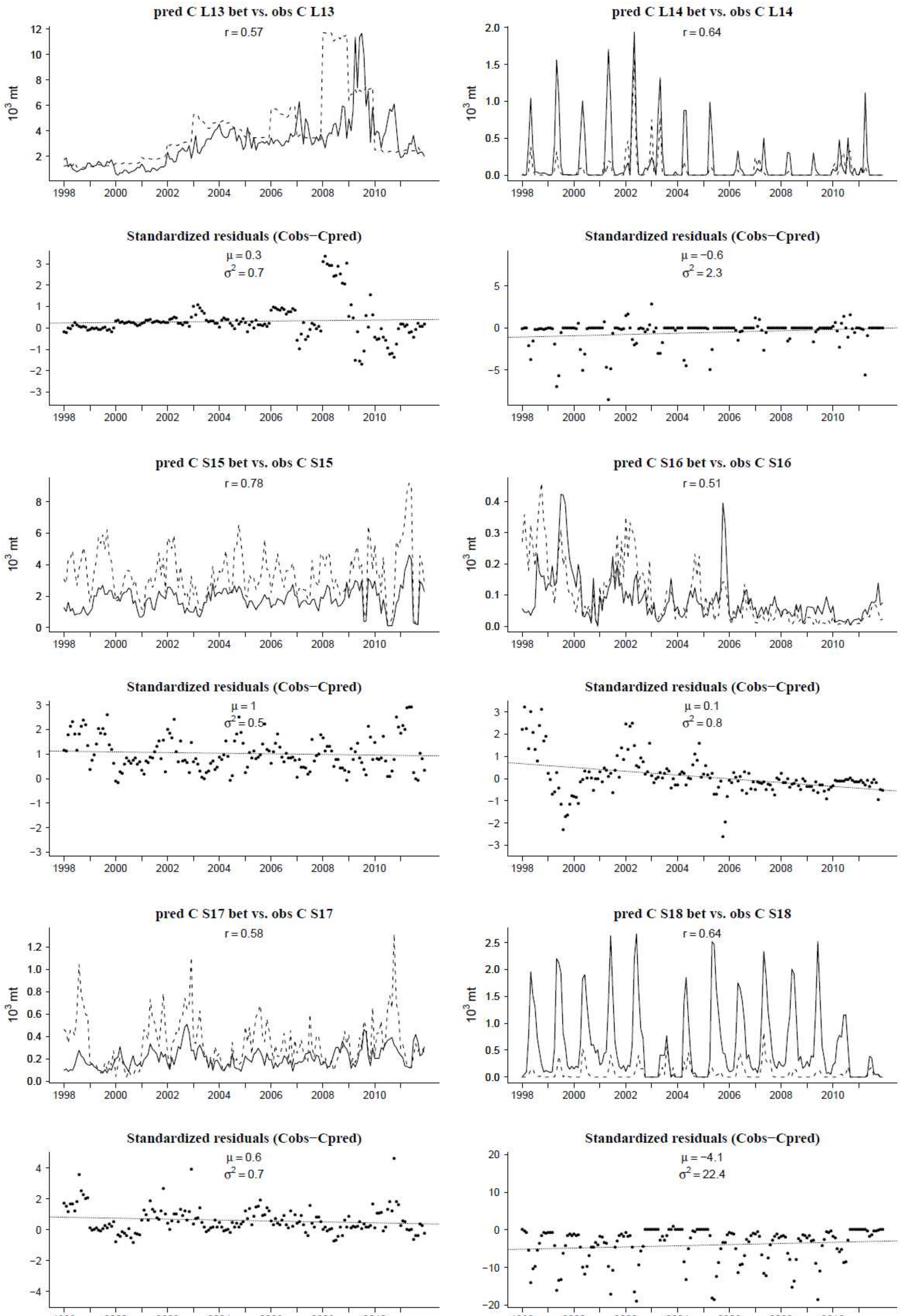
Time series of total observed and predicted catch (left) and CPUE (right)



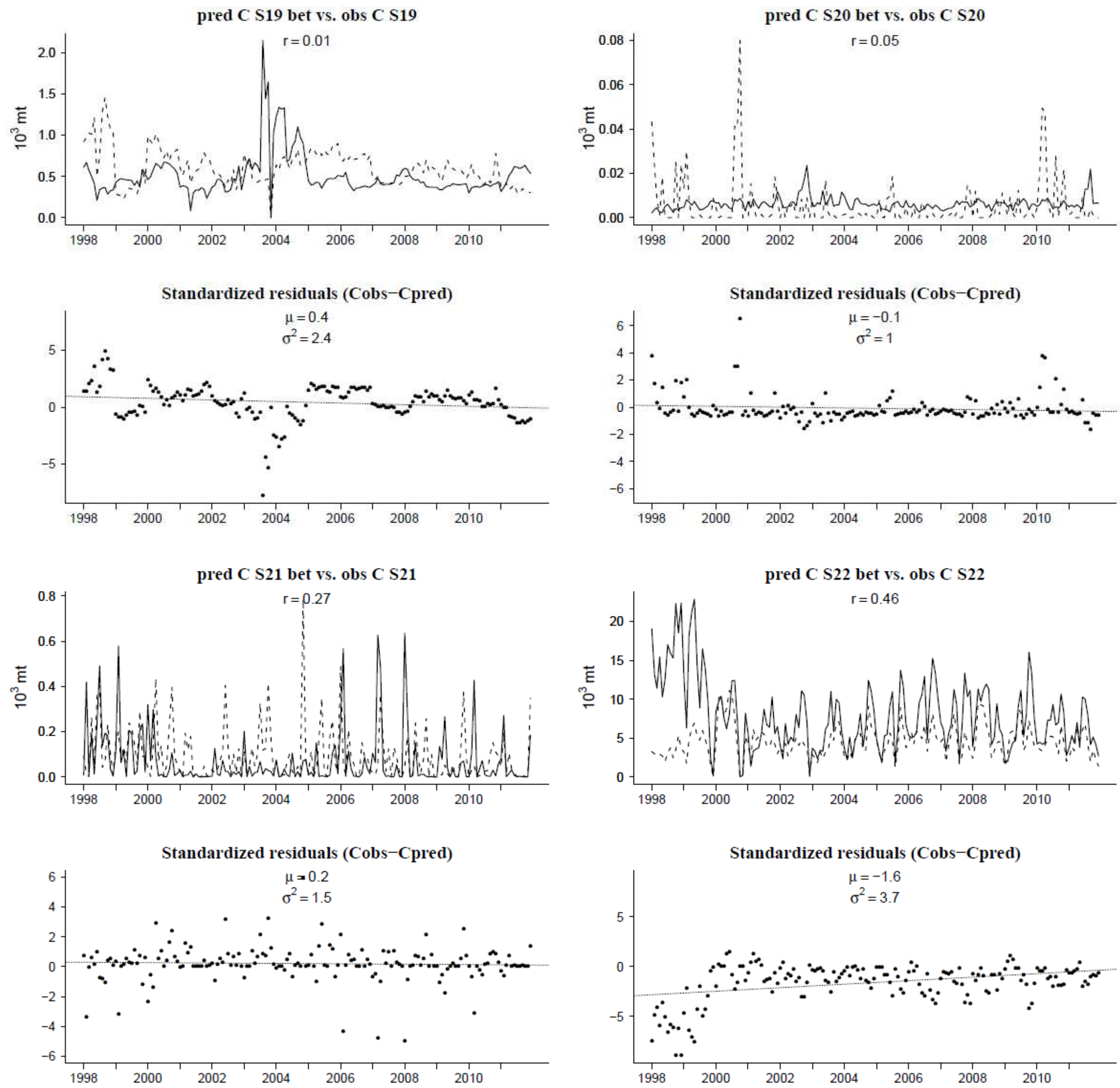
Time series of observed and predicted catch by fishery



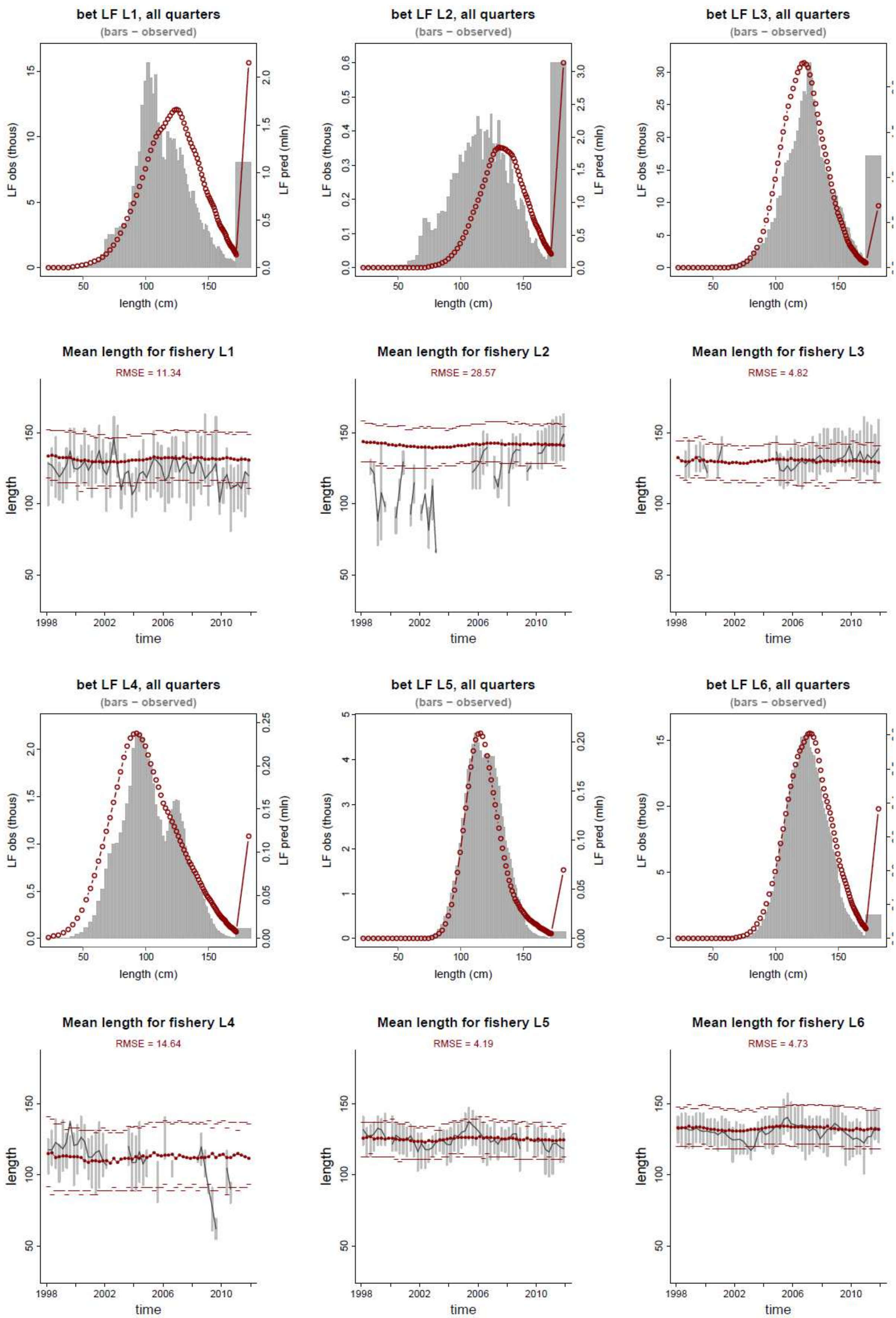
Time series of observed and predicted catch by fishery (Cont.)



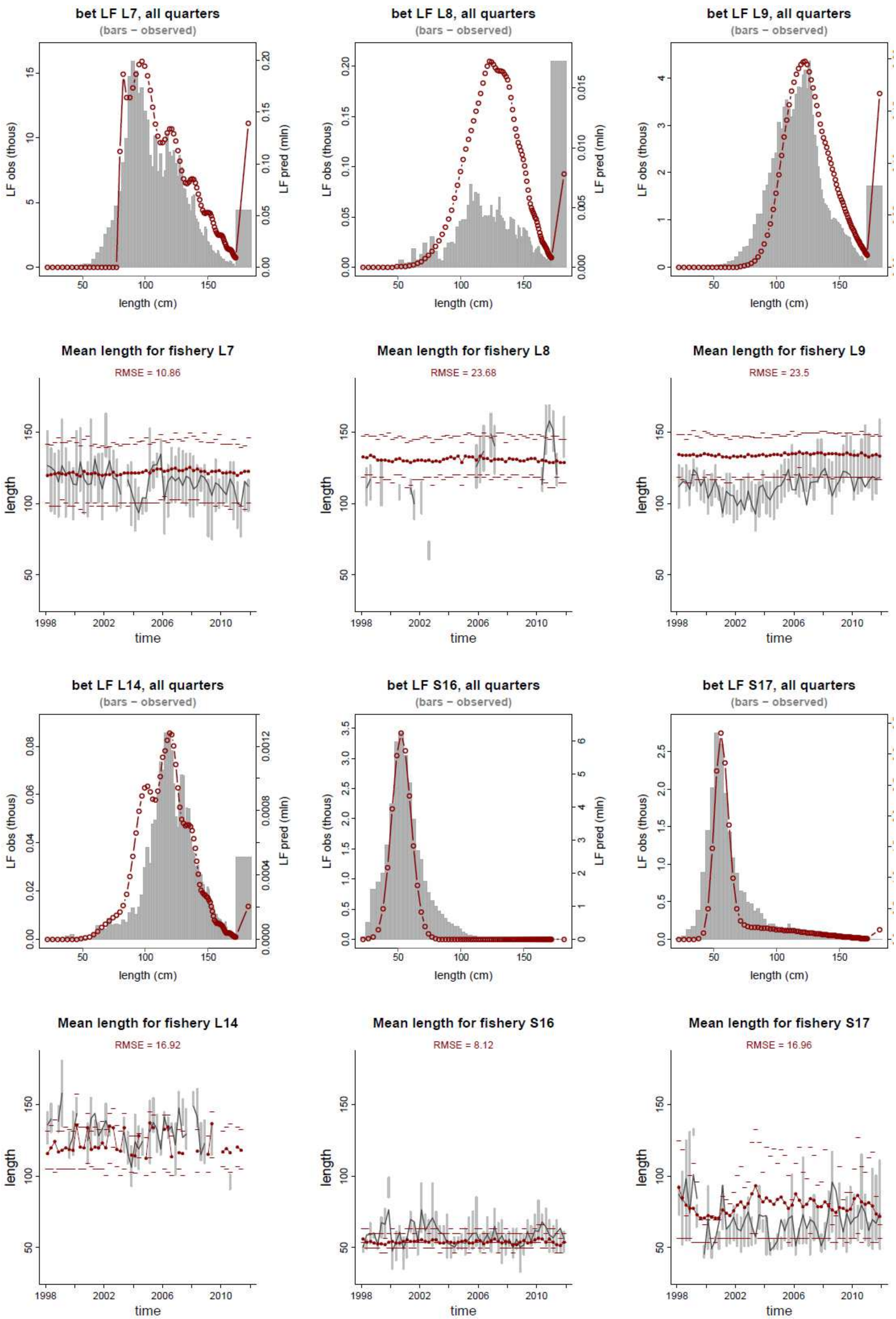
Time series of observed and predicted catch by fishery (Cont.)



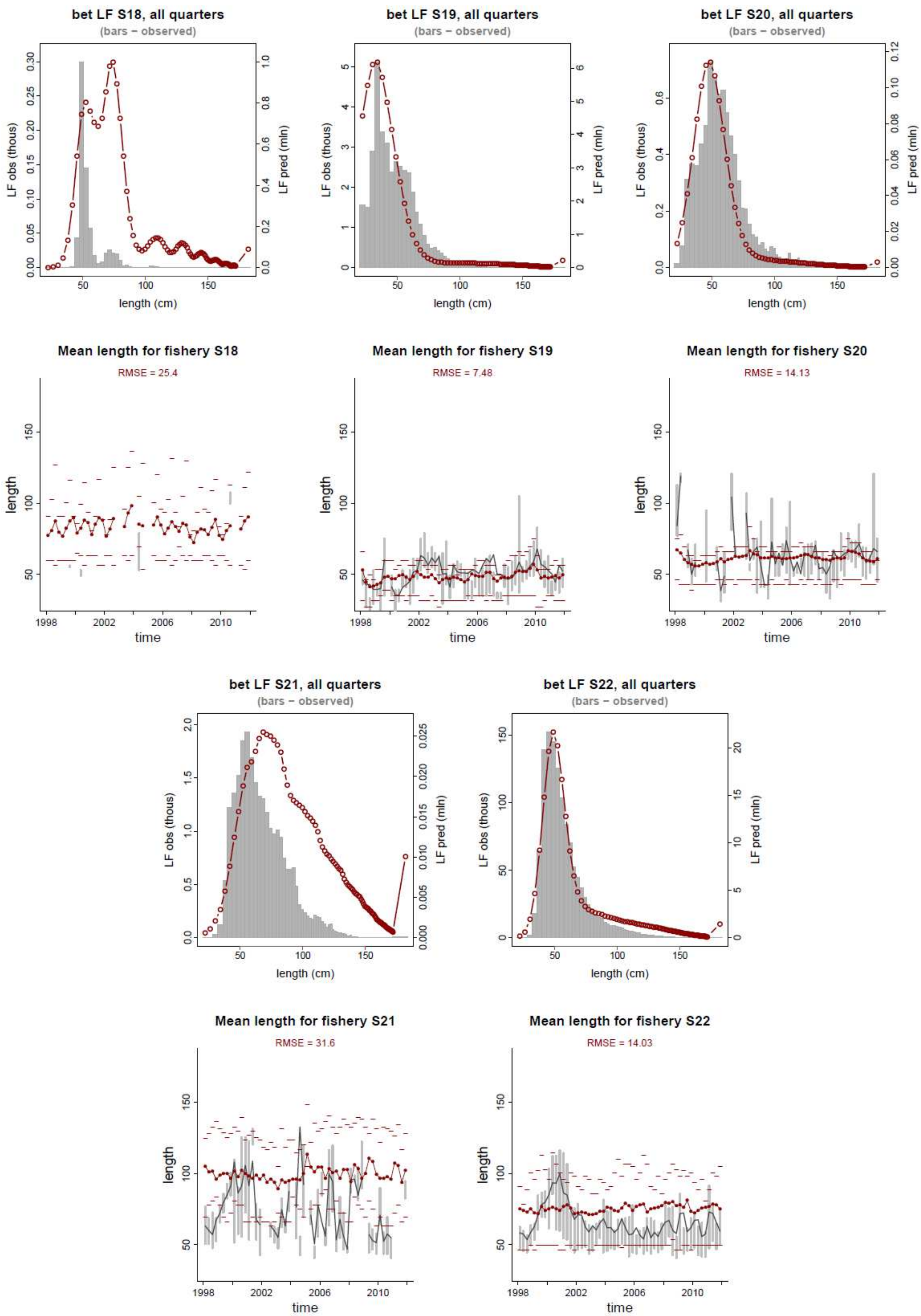
Time series of observed and predicted catch by fishery (Cont.)



Observed (grey) and predicted (red) length frequencies distribution and mean length in catches.

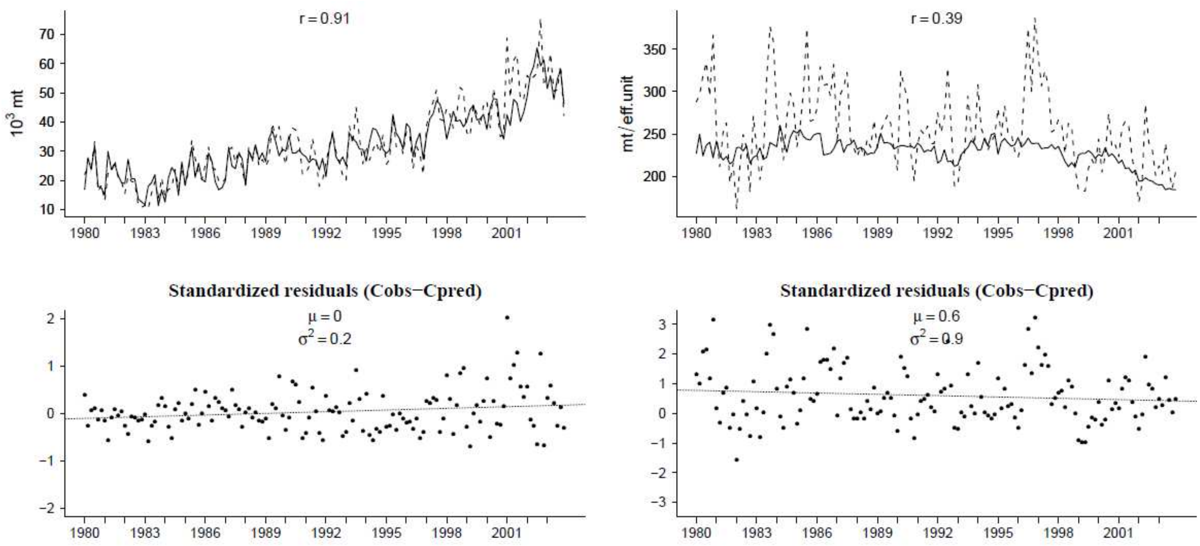


Observed (grey) and predicted (red) length frequencies distribution and mean length in catches (cont.)

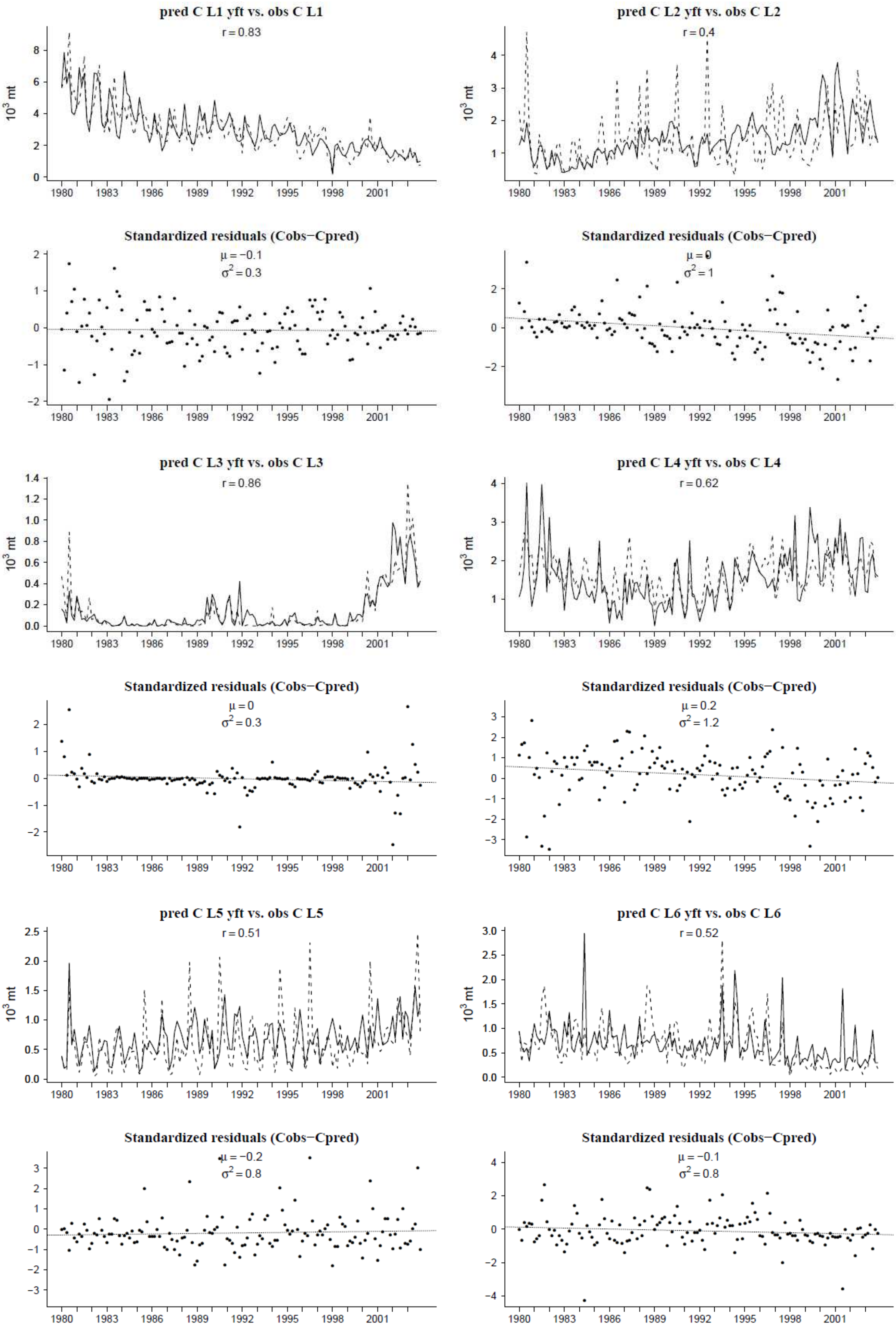


Observed (grey) and predicted (red) length frequencies distribution and mean length in catches (cont.)

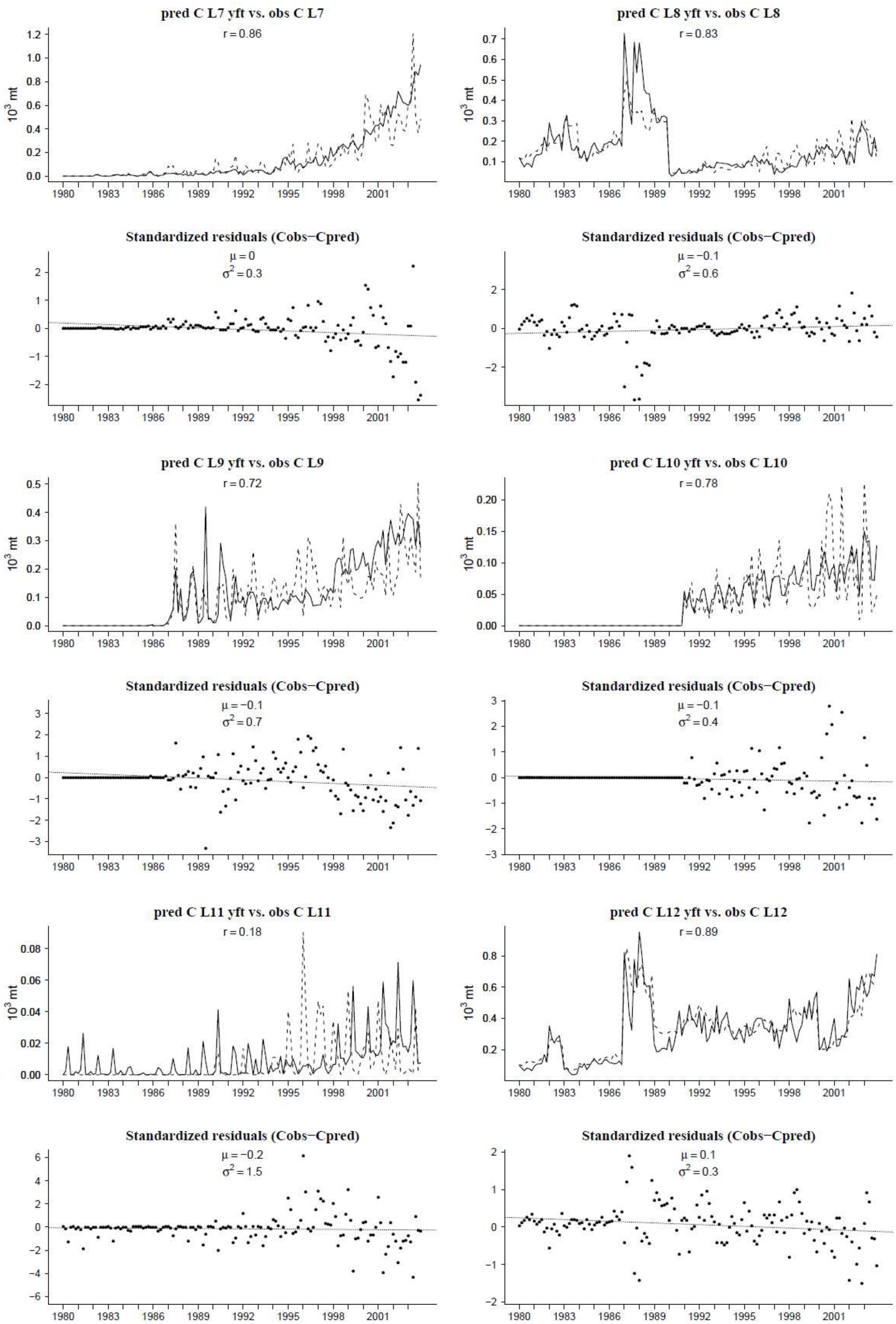
14. APPENDIX 3 – YELLOWFIN



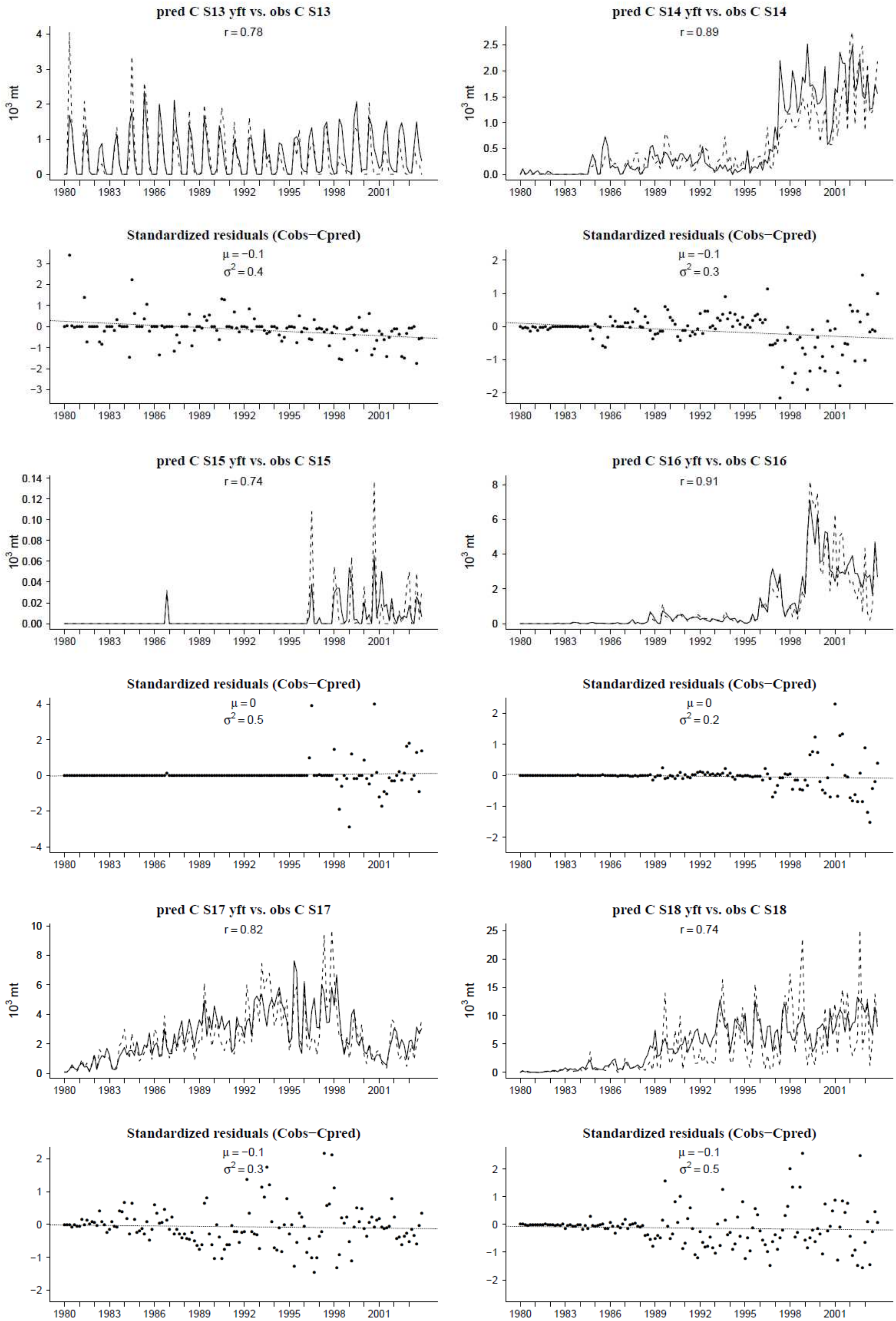
Time series of total observed and predicted catch (left) and CPUE (right)



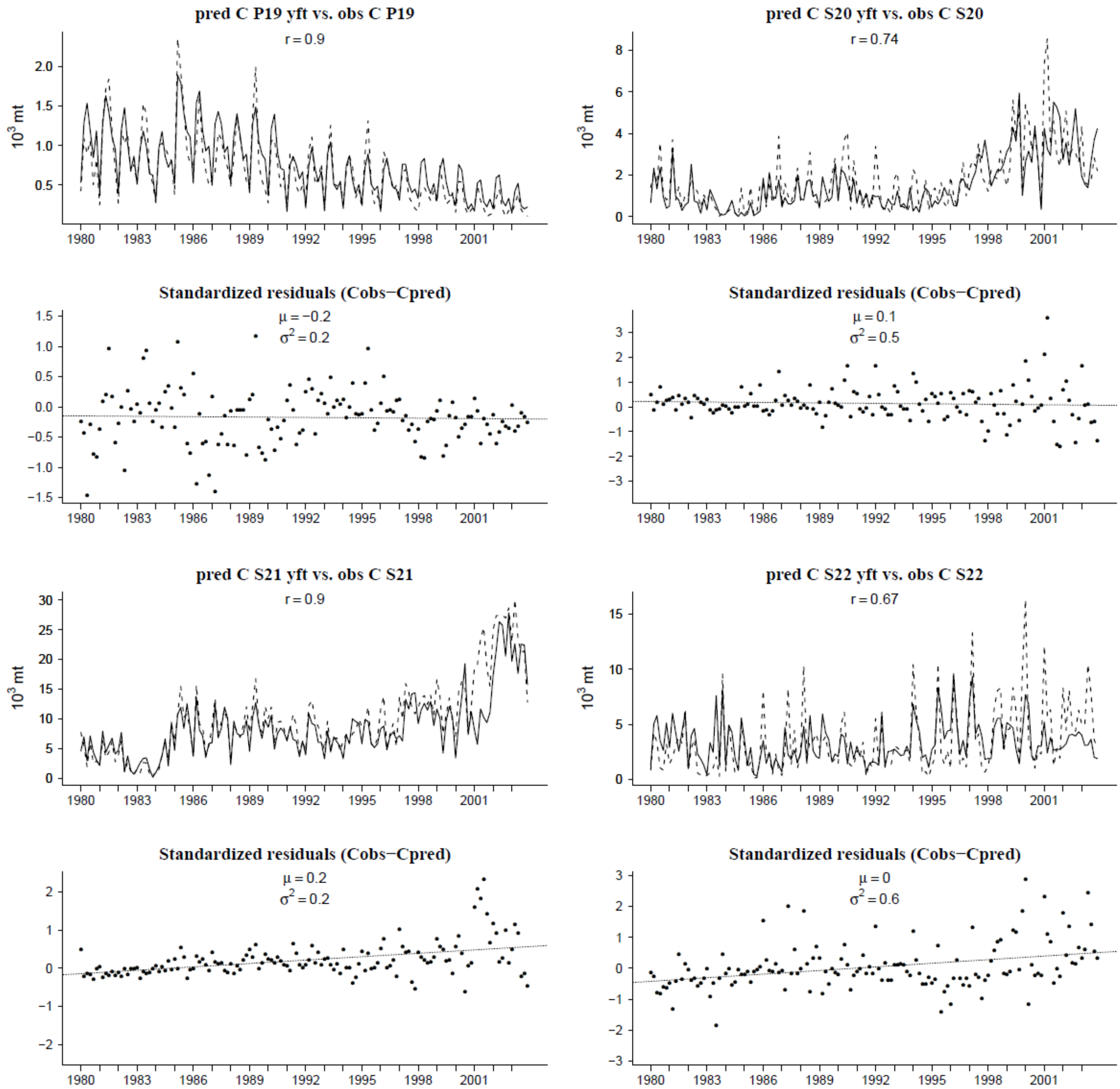
Time series of observed and predicted catch by fishery



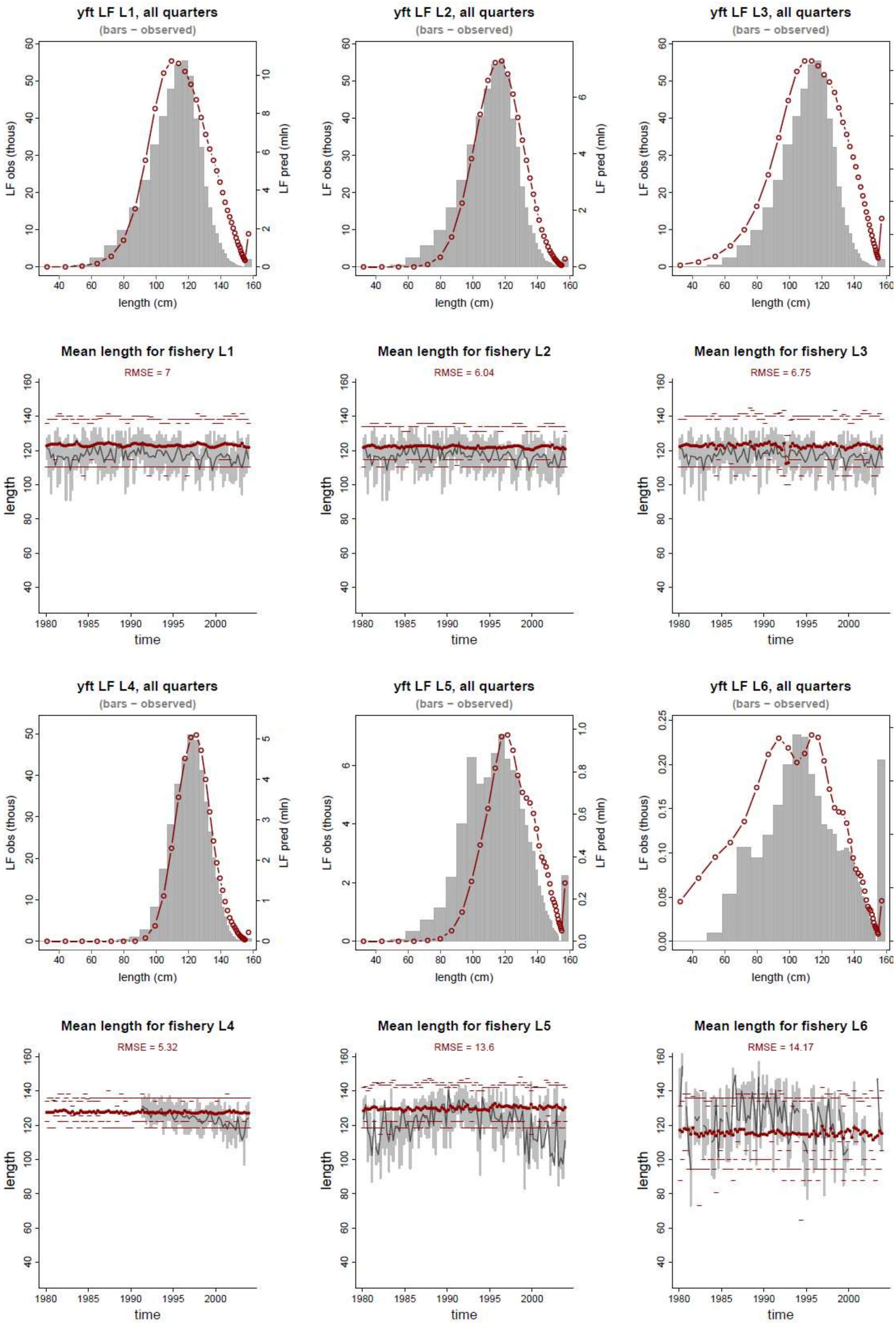
Time series of observed and predicted catch by fishery (cont.)



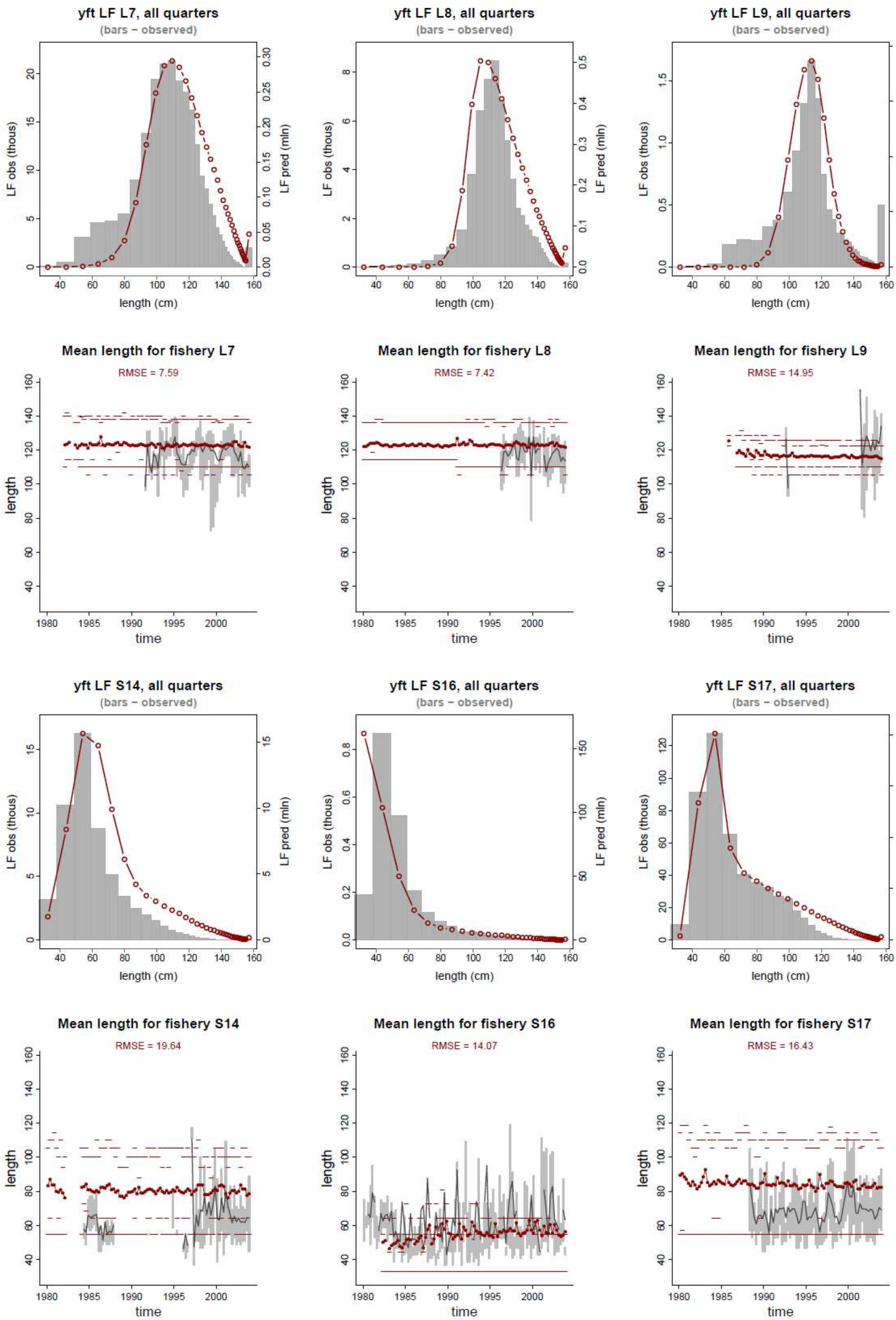
Time series of observed and predicted catch by fishery (cont.)



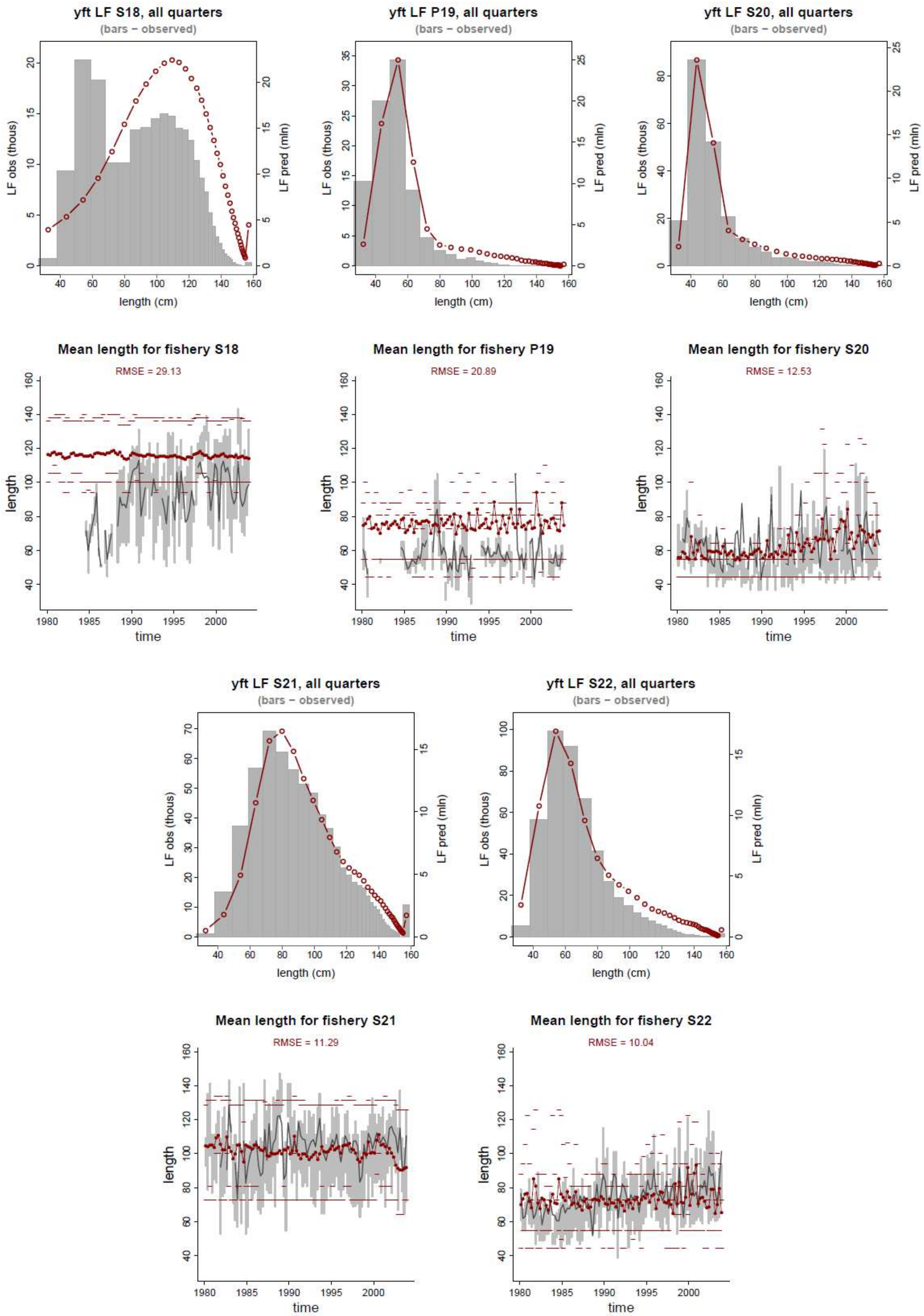
Time series of observed and predicted catch by fishery (cont.)



Observed (grey) and predicted (red) length frequencies distribution and mean length in catches



Observed (grey) and predicted (red) length frequencies distribution and mean length in catches (cont.)



Observed (grey) and predicted (red) length frequencies distribution and mean length in catches (cont.)