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Report of activities conducted under the EU DG-MARE project on the Hydrography and Jack Mackerel stock in the South Pacific

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1) Background

This study focuses on the Chilean Jack Mackerel (*Trachurus murphyi*) population stock distributed throughout the sub-tropical waters of the South Pacific Ocean, and managed under the framework of the South Pacific Regional Fisheries Management Organization. The present study is part of the objectives of a research project submitted by a consortium gathering IMARES, IRD and CLS to the open call for tenders No MARE/2011/16 Lot 1 released by the EU DG-MARE, and that included the development of a SEAPODYM model for jack mackerel to investigate its stock structure. SEAPODYM is a model developed for investigating spatial population dynamics of fish, under the influence of both fishing and environmental effects. In addition to fisheries and other fish relevant data (e.g. tagging data, acoustic biomass estimates, eggs and larvae density), the model utilizes environmental data in a manner that allows high resolution prediction. SEAPODYM was initially developed for tuna species and complements the WCPFC Scientific Committee’s MULTIFAN-CL models by providing additional information on how tuna distributions are structured in space and time. This report presents the first application of SEAPODYM to the South Pacific Jack Mackerel population and fisheries.

2) Material & Methods

a) South Pacific Jack Mackerel and Fisheries

The south Pacific jack mackerel (*Trachurus murphyi*; hereafter referred as SPJM) is a medium-sized pelagic fish distributed from the Chilean and Peruvian coasts to more than 2000 km off the central coast of Chile with possible continuous extension to the coast of New-Zealand. It is a species with relatively long life span (> 10 years), mature after 3 years with maximum size of ~ 70 cm FL.

The population structure as described in the literature would include a large nursery ground in the coastal zone off southern Peru and northern Chile (north of 30°S), a feeding ground in the central-south zone off Chile (30°–40° S), where the recruitment of 2–3 year-old individuals occurs and an oceanic spawning area off central Chile, extending up to 1800 km offshore during spring (Vasquez et al. 2013). This single stock structure is currently used within the SPRFMO assessment studies. However, there are studies proposing alternative assumption to the panmictic stock (on single homogenous stock in the entire area) and suggesting a more dynamic stock structure that changes under the influence of hydrographical conditions. Ignoring this stock structure and dynamics may impact the accuracy of stock assessments and effectiveness of management actions. Given the strong decrease in catch rates and estimated biomass of SPJM, the on-going debate on stock structure becomes an issue with important potential consequences on the management of this species.

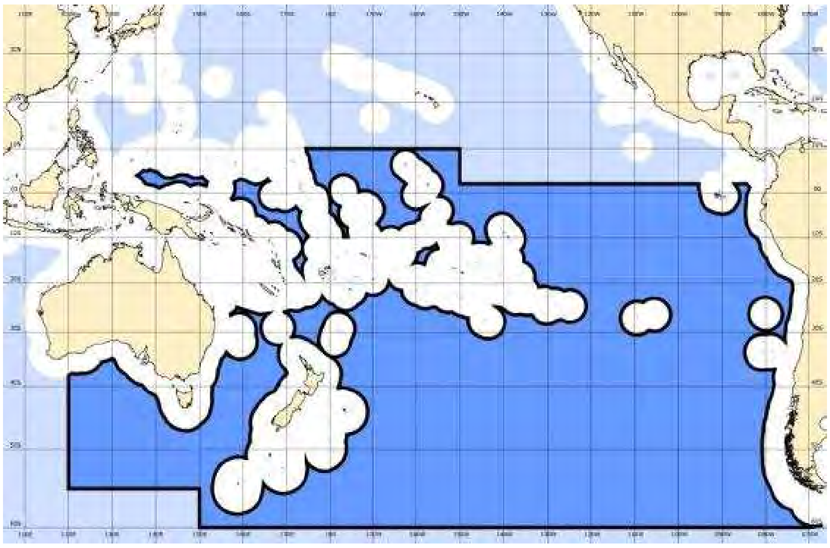


Figure 1: South Pacific Regional Fisheries Management Area. Dark blue represents international waters.

Industrial fishing of SPJM started in the 1970s mainly with fleets from Europe and South America. SPJM is primarily exploited during the austral winter (April to October). Purse-seine fisheries from Chile and trawl fisheries from Peru and the Russian Federation target adult jack mackerels in EEZ and international waters. All together these fisheries represent 90 % of the total catch declared to the SPRFMO between 1970 and 2013 (Fig. 2). Caribbean Countries (Belize, Vanuatu, Cook Islands), European Countries (the Netherlands, Faroe Islands, the Ukraine) and China contribute to the remaining catch, mostly by pelagic trawling. In addition, New-Zealand EEZ hosts a purse-seine and trawl fishing fleet since 1985 that represents less than 0.5 % of the total recorded catch.

From 1970 to 1980, the main fishing effort was applied with purse-seines in the Northern area of the Chilean EEZ (Fig. 2). Since 1980, a trawling fishery has developed in Peruvian and Ecuadorian waters and off the Chilean EEZ (Fig. 2). But from 1986 to 2007, the bulk (58%) of recorded catches has originated from the Chilean purse-seine fishery in Southern areas (Fig. 2). Total annual reported landings of SPJM range between 95 000 metric tones (mt) in 1972 and over 4.7 millions mt in 1995. Since 2000, landings have generally begun to decline and reached historically low levels in 2012, that is less than 500 000 mt for the whole South Pacific fishing areas.

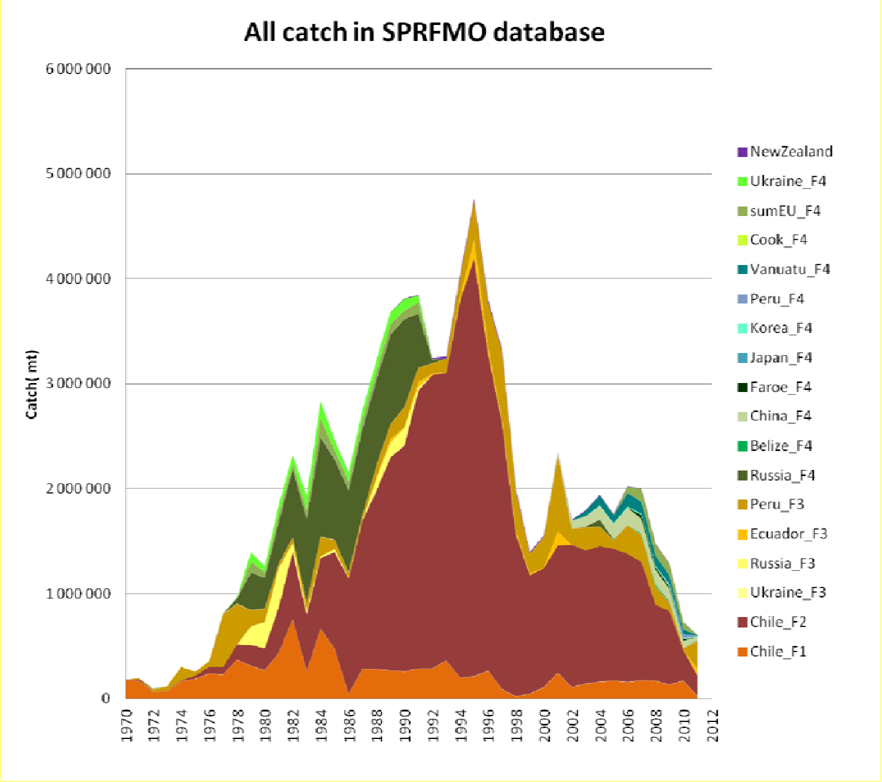


Figure 2: SPRFMO annual catch time series by country and by fleet. Four fishing areas, referred as fleets, are defined in SPRFMO for SPJM assessment. Fleet 1 (F1) includes all purse-seine fisheries in Chilean northern area (< 37°S) within its EEZ. Fleet 2 (F2) includes purse-seine fisheries in Chilean southern area (> 37°S) within EEZ and high seas. Fleet 3 (F3) includes far northern area fisheries (mainly trawlers in latitudes < 20°S), inside and outside the Peruvian EEZ and inside the Ecuadorian EEZ. Finally, fleet 4 (F4) includes the international high seas trawl fisheries off the Chilean EEZ.

b) SEAPODYM

SEAPODYM is a model developed for investigating spatial tuna population dynamics, under the influence of both fishing and environmental effects (Lehodey et al. 2008). 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 (MLE) approach is used to optimize the model parameters (Senina et al. 2008). Integration of conventional tagging data has been achieved recently. In addition, prior information (*a priori* average spawning biomass in the whole South Pacific) can also be used to constrain the likelihood function and help in stock estimation. This model has been described in detail in Lehodey et al. (2008; 2010a), Lehodey and Senina (2009) and Senina et al. (2008), and has been used for investigating tuna fishing management scenarios (Sibert el al., 2012) and climate change impacts on skipjack (Bell et al., 2013; Lehodey et al., 2013a) and bigeye tuna (Lehodey et al., 2010a; 2011; *in press*). Since the model relies on generic mechanisms shared by many populations of pelagic species, it can be easily adapted to the SPJM.

c) Environmental forcing

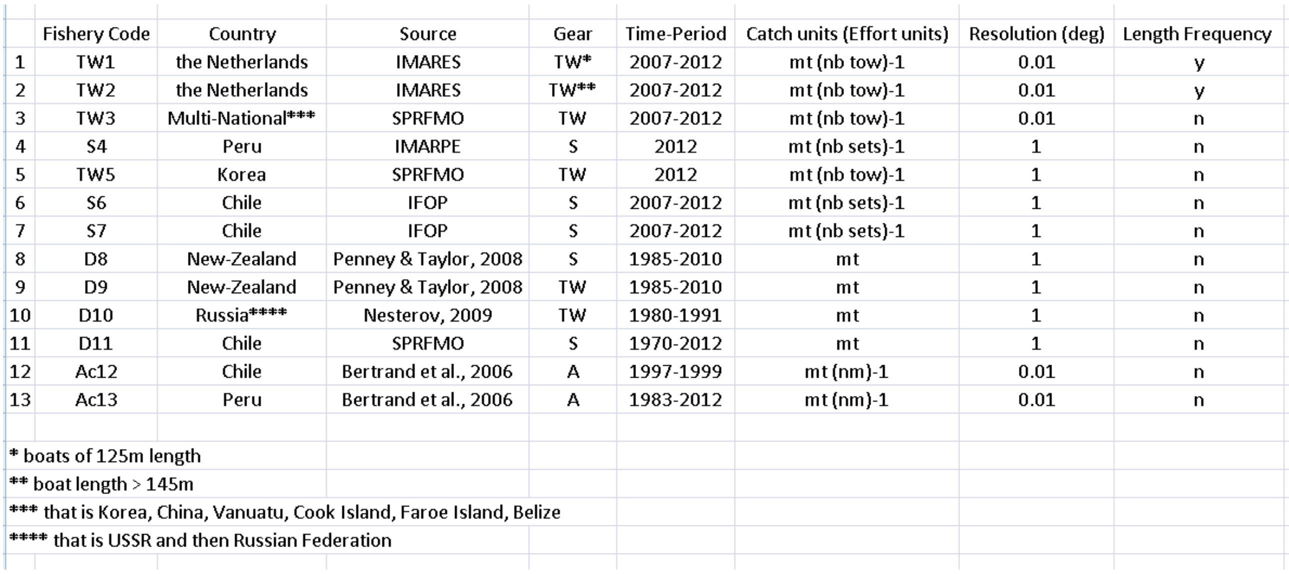
SEAPODYM uses spatially explicit estimates of ocean and biological properties such as temperature, current speed, oxygen, phytoplankton concentration and euphotic depth from physical-biogeochemical ocean models to constrain fish population dynamics. The outputs of SEAPODYM are therefore strongly dependent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

Several forcings were used in a preliminary round of simulations. However, this document presents the results of the final configuration achieved with a coupled physical-biogeochemical model. The physical ocean circulation model is NEMO (Nucleus for European Modelling of the Ocean; version 3.5) forced with a mix of “realistic” atmospheric fields (provided by an improved ERA-interim reanalysis). The biogeochemical model is PISCES (Pelagic Interaction Scheme for Carbon and Ecosystem Studies, Aumont and Bopp, 2006). The model grid (ORCA2) has a horizontal resolution decreasing from equator (0.5°) to high latitudes 2° in highest latitude. With this method, we produce simulations of the dynamic and biogeochemical state of the ocean which span over the historical (1979-2010) periods. The forcing variables are then processed and interpolated on a regular grid of 1 or 2 degrees to be used with SEAPODYM. An analysis of this environmental forcing can be found in Nicol et al (2014).

d) Fishing data

Conventional Catch/Effort data

Prior to the optimization experiments, spatially disaggregated fishing data were prepared with the objective of limiting the number of fisheries to a reasonable number while defining homogeneous fisheries as far as possible according to several criteria, i.e., fishing gear, fishing areas, size of the boats, CPUE (Table 1).



	Fishery Code	Country	Source	Gear	Time-Period	Catch units (Effort units)	Resolution (deg)	Length Frequency
1	TW1	the Netherlands	IMARES	TW*	2007-2012	mt (nb tow)-1	0.01	y
2	TW2	the Netherlands	IMARES	TW**	2007-2012	mt (nb tow)-1	0.01	y
3	TW3	Multi-National***	SPRFMO	TW	2007-2012	mt (nb tow)-1	0.01	n
4	S4	Peru	IMARPE	S	2012	mt (nb sets)-1	1	n
5	TW5	Korea	SPRFMO	TW	2012	mt (nb tow)-1	1	n
6	S6	Chile	IFOP	S	2007-2012	mt (nb sets)-1	1	n
7	S7	Chile	IFOP	S	2007-2012	mt (nb sets)-1	1	n
8	D8	New-Zealand	Penney & Taylor, 2008	S	1985-2010	mt	1	n
9	D9	New-Zealand	Penney & Taylor, 2008	TW	1985-2010	mt	1	n
10	D10	Russia****	Nesterov, 2009	TW	1980-1991	mt	1	n
11	D11	Chile	SPRFMO	S	1970-2012	mt	1	n
12	Ac12	Chile	Bertrand et al., 2006	A	1997-1999	mt (nm)-1	0.01	n
13	Ac13	Peru	Bertrand et al., 2006	A	1983-2012	mt (nm)-1	0.01	n

* boats of 125m length

** boat length > 145m

*** that is Korea, China, Vanuatu, Cook Island, Faroe Island, Belize

**** that is USSR and then Russian Federation

Table 1: SPJM fisheries and data availability in SEAPODYM. Gears are trawlers (TW), purse-seine (S) and acoustic (A). Length frequency data were only available for the two first fisheries, i.e. the Dutch trawling fleet operating in international waters.

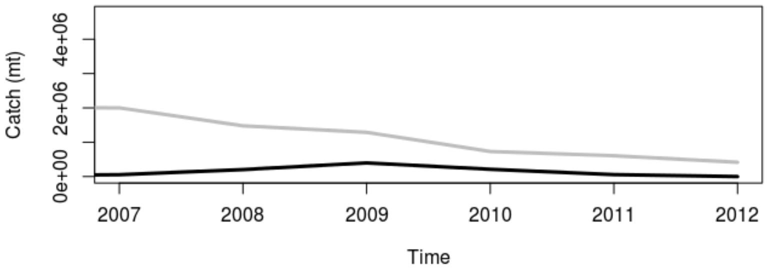
The first three fisheries (TW1; TW2; TW3) include vessels operating outside the 200 miles EEZ and using pelagic trawls with fishing effort expressed in number of tows. TW1 and TW2 are Dutch fisheries of small (125m length) and large (> 145m length) trawlers respectively. Catch and effort data are available daily and at high spatial resolution from 2007 to 2012. TW3 has also daily catch and effort data at high spatial resolution but combines several Countries (Belize, China, Korea, Vanuatu and Faroe Islands) operating from 2007 to 2012.

It is worth noting that fishing records were not available when less than 3 vessels were present in the data unit (e.g. a month and one cell of 1°x1°) as per the agreed data standards of SPRFMO. This rule obviously removes a substantial amount of fishing data (eg Fig. 3a) with the consequences of underestimating the fishing mortality and eliminating useful information for the optimization approach.

Fisheries S4 and TW5 are based on respectively Peruvian and Korean catch and effort data for year 2012 with daily temporal resolution and high spatial resolution (< 0.01°). Since the environmental forcing stop in Dec 2011, those two fisheries were not used in the optimization experiment but were prepared for future work with predicted physical forcing (see below perspectives section).

Fisheries S6 and S7 are based on Chilean 1°x1° gridded monthly catch and effort data. The original data was prepared by the Chilean fishing institute (IFOP) and covers the period 2007 to 2012, which corresponds to the readily available information (under the SPRFMO format/template). The fishing effort is recorded in number of purse-seine actions and Figure 3b shows that the geo-referenced catch data match the SPRFMO records.

a) Fisheries TW1, TW2 and TW3 vs. SPRFMO catch records



b) Fisheries S6 and S7 vs. SPRFMO catch records

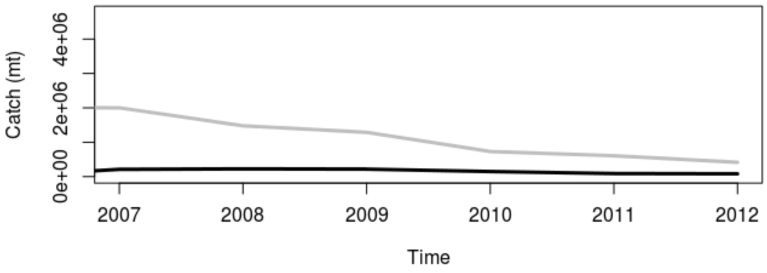


Figure 3: Difference between the sum of geo-referenced records available for SEAPODYM and the nominal catch recorded in SPRFMO for the same period for (a) the fisheries TW1, TW2 and TW3 and (b) the fisheries S6 and S7. Black and grey lines illustrate respectively SEAPODYM and SPRFMO data.

▪ Spatial extrapolation of total catch by fisheries

Unfortunately a very large part of the nominal catch is not recorded or available under a geo-referenced form. However, it is critical to account for this catch in the computation of fishing mortality. Therefore it was decided to produce “dummy” fisheries datasets to be used only in the fishing mortality computation and not in the MLE approach. Catches since the 1970s were extrapolated from published articles and reports. There is no effort associated to these catches since they are only used to be retrieved from the SPJM total stock in order to better estimate fishing mortality. The code of SEAPODYM was modified to take specifically into account the mortality caused by “dummy” fisheries for which there are estimations of annual catches but no associated effort.

Four “dummy” fisheries were defined:

- The New-Zealander Purse-Seine (D8)
- The New-Zealander Trawlers (D9)
- The Russian Trawlers (D10)
- The Chilean Purse-Seine (D11)

Monthly catch data (1985-2010) of the fisheries D8 and D9 were extrapolated from Penney & Taylor (2008) assuming a uniform distribution in each of the 3 management areas used by New-Zealand for this fishery. The Figure 4a shows the match between catches interpolated for SEAPODYM and the SPRFMO catch time series for New-Zealand.

Extrapolated monthly catch data (1980-1991) of the fishery D10 were based on published Russian catch data on a 1°x1° grid and with annual temporal resolution (Nesterov, 2007 and 2009) and according to the average seasonal distribution of geo-referenced SPJM fishing data (i.e., the seasonal catch history of fisheries TW1 and TW2). Figure 4b shows that the catches match the SPRFMO combined records for the Russian fleet.

The fourth dummy fishery (D11) extrapolates annual Chilean catch data (1970-2012) as recorded in SPRFMO according to the average seasonal distribution of SPJM fishing (same method as above). Considering that data was aggregated in the whole fishing area (see Figure 4 of IFOP 2013 report for Chilean fishing areas and Figure 1 of 10th report of Chilean

Jack Mackerel Workshop), we defined four decadal average fishing areas (1970-1979, 1980-1989, 1990-1999 and after 2000). We then spatially interpolated the catch data according to a uniform distribution in each of the four areas. Figure 4c shows the match between catches interpolated for the SEAPODYM application and the SPRFMO catch time series for Chilean fisheries.

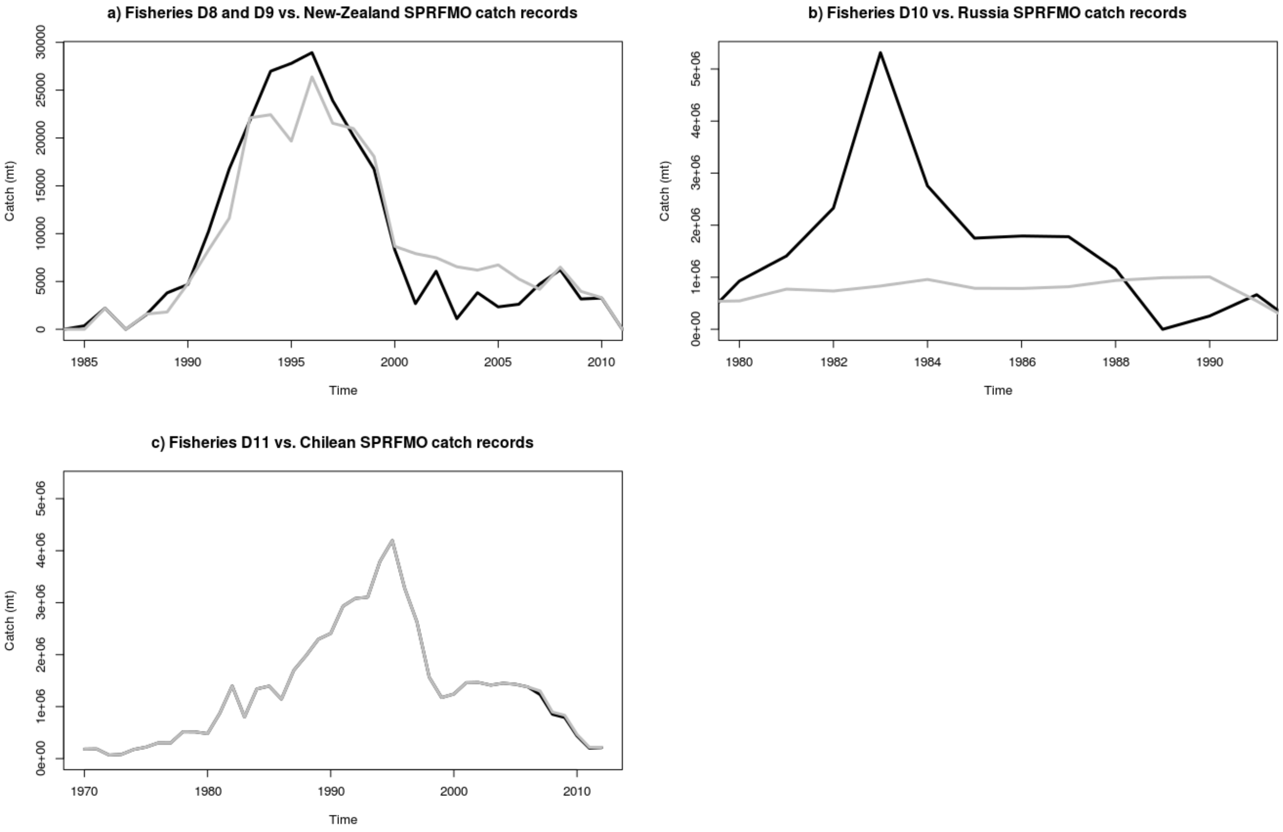


Figure 4: Difference between the sum of geo-referenced records available for SEAPODYM and the nominal catch recorded in SPRFMO for (a) the "dummy" fisheries D8 and D9, (b) for the "dummy" fishery D10 and (c) the "dummy" fishery D11. Black and grey lines illustrate respectively SEAPODYM and SPRFMO data.

- **Length Frequency data**

Length frequency data were available only for fisheries TW1 and TW2 (Dutch fleets). They were extracted with a monthly temporal resolution and spatial resolutions varying from 1° x 1° to 10° x 20° (Fig. 5). The resolution used to measure the fish was based on size-bins of 1cm, 2cm and 5cm (Fork Length). The number of samples is well distributed over the entire Dutch fishing ground (e.g. international waters) but is only representative of the last years of the fishing period.

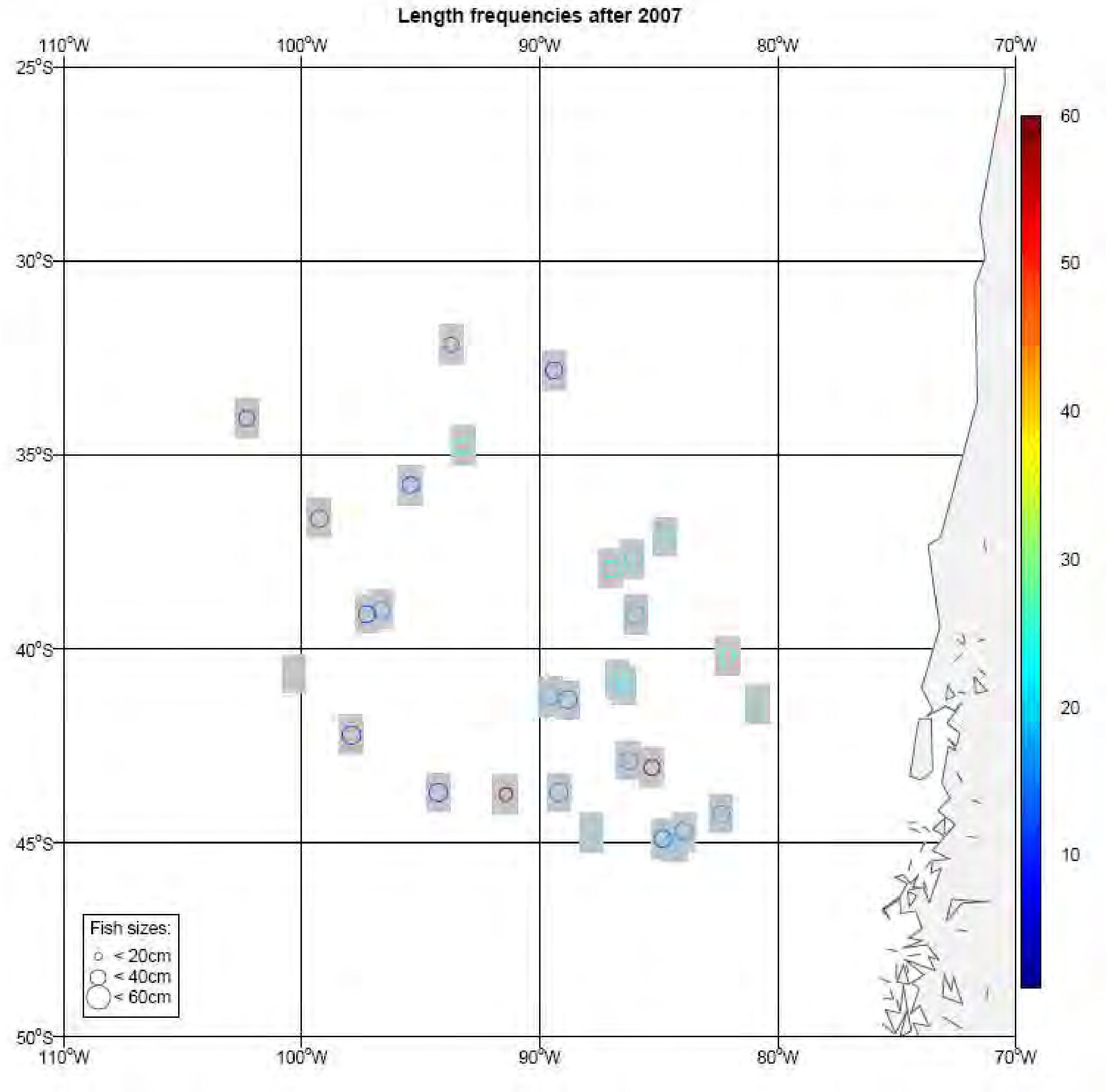


Figure 5: Length frequency data available in SEAPODYM. The data samples are aggregated at the spatial resolution of 1°x1° illus trated by rectangles with grey shading.. In the centre of each region, a circle gives the predicted mean size of fish (the larger the circle, the longer the fish) and the variance associated to this mean (colorbar, cm in FL).

▪ Acoustic survey

In addition to geo-referenced catch and effort data, we planned to use biomass estimates from acoustic data. They can be introduced in the MLE as additional fisheries with (sampling) effort and catch (the biomass estimate) assuming a catchability of 1 and no associated fishing mortality.

- Chilean Acoustic Survey (Ac12)
- Peruvian Acoustic Survey (Ac13)

For “fishery” Ac12, we used published Chilean acoustic data from 1997 to 1999 (Bertrand et al., 2006). And for “fishery” Ac13, we used published Peruvian acoustic data from 1983 to 2011 (Bertrand et al., 2004). To calculate jack mackerel potential biomass from nautical area scattering coefficient (Sa), we used the equation from Bertrand (1999):

$$B = (Sa * W) / (1852^2 * 4\pi * 10^{(TS/10)})$$

with B the acoustic biomass in g.m-2
with Sa in m^2.mn-2
with W the mean weight of jack mackerel (i.e. 275g)
with TS the target strength estimated to -39.5dB, according to Lillo et al., 1995.

We then estimated the associated captures and effort on a 1°x1° monthly grid. Captures were calculated for each pixel and each sampling month as:
$C = a * \Sigma B$
with C the capture in mt
with a the sampling surface in nm^2 (0.25 nm^2, resp. 1 nm^2, for Chilean, resp. Peruvian, acoustic devices)

Effort was finally calculated for each pixel and each sampling month as:
$E = n * a$
with E in nm^2
with n the acoustic sampling number

It is to be noted that the acoustic estimates of catch and effort were cross-multiplied to get potential SPJM biomass estimates in the survey areas (i.e. about 500 000km²). In this optimization experiment, the acoustic estimates (Fig. 6) were not used in the fishing mortality calculation but are intended to serve as a stock availability reference. Since the acoustic surveys were conducted in Chilean and Peruvian EEZ (i.e. in coastal waters), those two fisheries were not used in the optimization experiment conducted on a 2° grid but were prepared for future work with higher spatial resolution physical forcing (see below perspectives section).

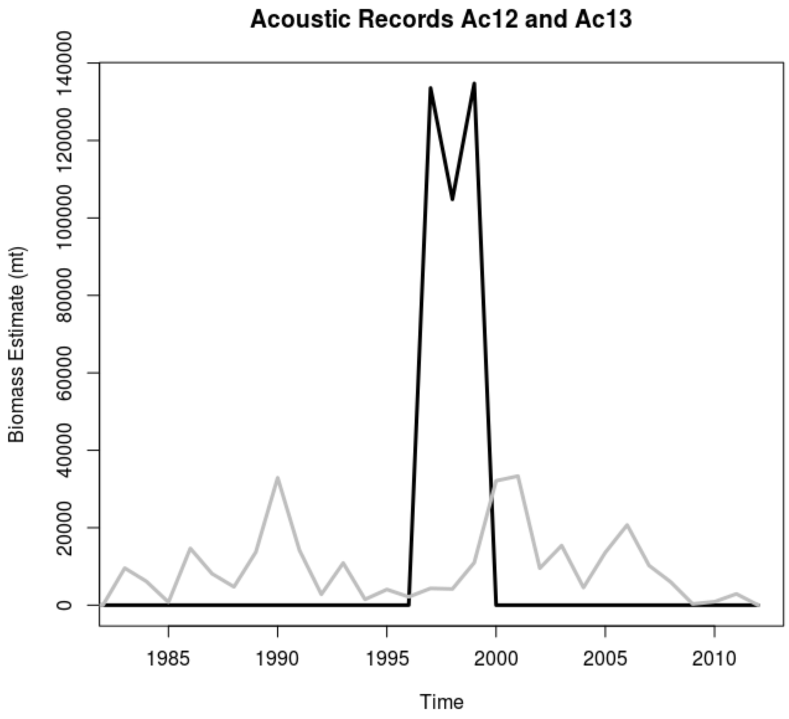


Figure 6: Biomass estimates from acoustic records from surveys in Chilean (black line) and Peruvian (grey line) waters.

- **<u>Final Catch, Effort and size-frequency dataset for SEAPODYM modeling</u>**

For all available data sources (Table 1, Fig. 7), a careful data screening led to the exclusion of a few obvious wrong data (e.g, with geographical coordinates on land). We extracted monthly SPJM catch and effort with geographical coordinates at high spatial resolution or no less that

1°x1° squares. In total for the experiment, five fisheries and four “dummy” fisheries were used for the period 1986-2011 (Table 1, Fig. 7). Globally, “dummy” fisheries allowed to compensate for the little number of spatialized catch/effort data, especially prior to 2007 (Table 2). The use of “dummy” fisheries avoided the underestimation of fishing mortality that was observed in previous optimization experiments. In addition, an average spawning biomass in the whole South Pacific (of 38.10^6 mt) was used to constrain the likelihood function and help in stock estimation.

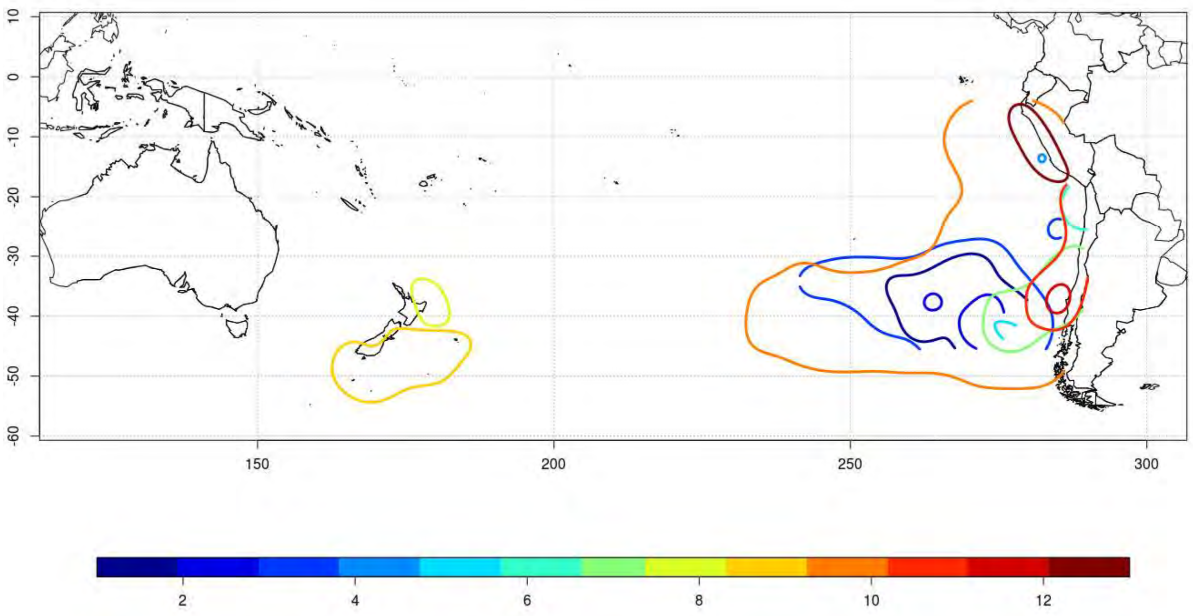
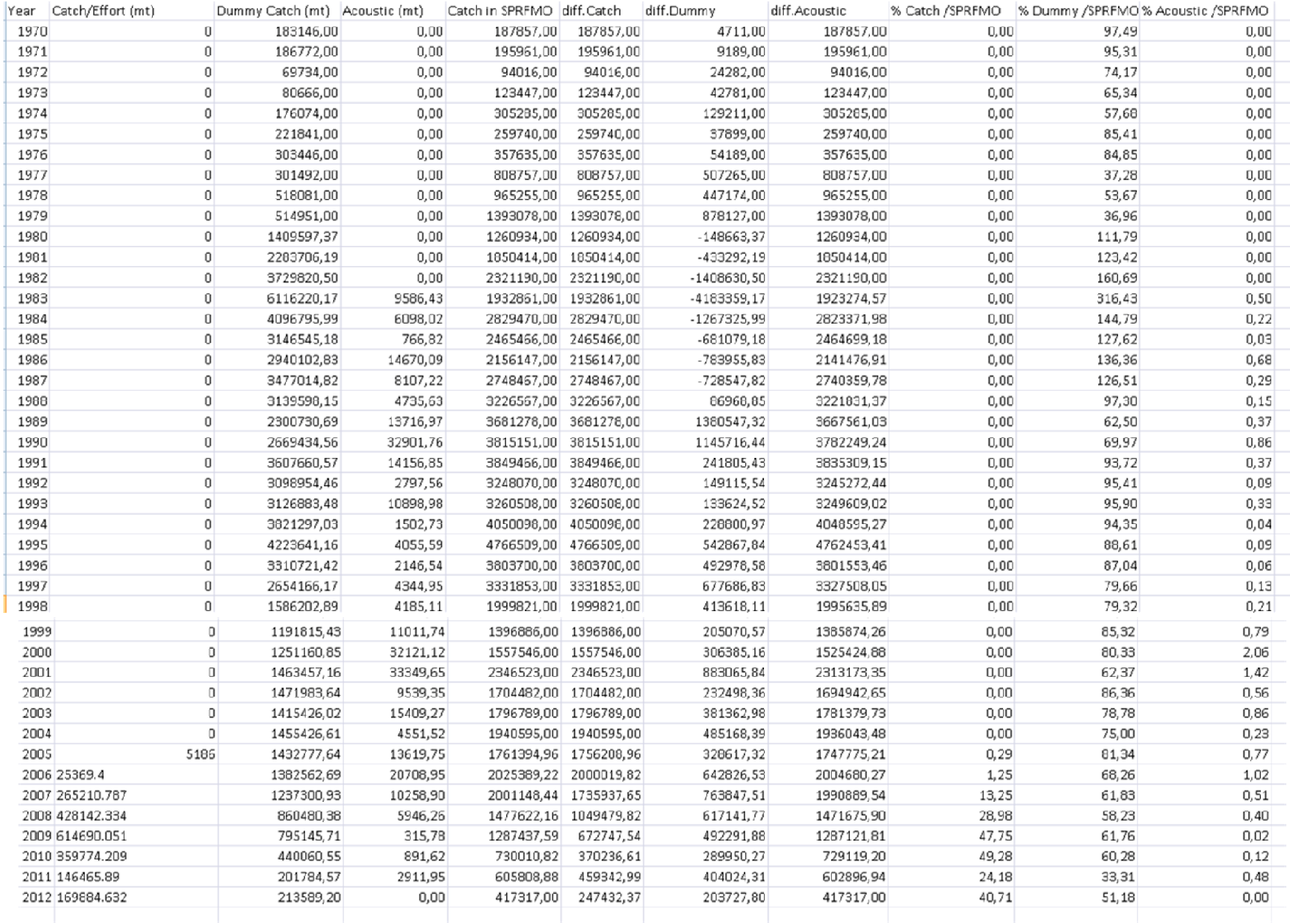


Figure 7: Spatial distributions of available data in SEAPODYM. The colour circles delineate the fishing areas of the 13 sources of data (acoustic, conventional and dummy fisheries).

Table 2: Total annual catch 1970–2012 (metric tones) used in SEAPODYM South Pacific Jack Mackerel simulations compared with total annual catch by all fisheries declared in SPRFMO database. The three types of data source (conventional catch/effort, dummy and

acoustic catch) are presented with associated differences in metric tones and corresponding percentages of coverage.



Year	Catch/Effort (mt)	Dummy Catch (mt)	Acoustic (mt)	Catch in SPRFMO	diff.Catch	diff.Dummy	diff.Acoustic	% Catch /SPRFMO	% Dummy /SPRFMO	% Acoustic /SPRFMO
1970	0	183146,00	0,00	187857,00	187857,00	4711,00	187857,00	0,00	97,49	0,00
1971	0	186772,00	0,00	195961,00	195961,00	9189,00	195961,00	0,00	95,31	0,00
1972	0	69734,00	0,00	94016,00	94016,00	24282,00	94016,00	0,00	74,17	0,00
1973	0	80666,00	0,00	123447,00	123447,00	42781,00	123447,00	0,00	65,34	0,00
1974	0	176074,00	0,00	305285,00	305285,00	129211,00	305285,00	0,00	57,68	0,00
1975	0	221841,00	0,00	259740,00	259740,00	37899,00	259740,00	0,00	85,41	0,00
1976	0	303446,00	0,00	357635,00	357635,00	54189,00	357635,00	0,00	84,85	0,00
1977	0	301492,00	0,00	808757,00	808757,00	507265,00	808757,00	0,00	37,28	0,00
1978	0	518081,00	0,00	965255,00	965255,00	447174,00	965255,00	0,00	53,67	0,00
1979	0	514951,00	0,00	1393078,00	1393078,00	878127,00	1393078,00	0,00	36,96	0,00
1980	0	1409597,37	0,00	1260934,00	1260934,00	-148663,37	1260934,00	0,00	111,79	0,00
1981	0	2283706,19	0,00	1050414,00	1050414,00	-433292,19	1050414,00	0,00	123,42	0,00
1982	0	3729820,50	0,00	2321190,00	2321190,00	-1408630,50	2321190,00	0,00	160,69	0,00
1983	0	6116220,17	9586,43	1932861,00	1932861,00	-4183359,17	1923274,57	0,00	316,43	0,50
1984	0	4096795,99	6098,02	2829470,00	2829470,00	-1267325,99	2823371,98	0,00	144,79	0,22
1985	0	3146545,18	766,82	2465466,00	2465466,00	-681079,18	2464699,18	0,00	127,62	0,03
1986	0	2940102,83	14670,09	2156147,00	2156147,00	-783955,83	2141476,91	0,00	136,36	0,68
1987	0	3477014,82	8107,22	2748467,00	2748467,00	-728547,82	2740359,78	0,00	126,51	0,29
1988	0	3139598,15	4735,63	3226567,00	3226567,00	86968,85	3221831,37	0,00	97,30	0,15
1989	0	2300730,69	13716,97	3681278,00	3681278,00	1380547,32	3667561,03	0,00	62,50	0,37
1990	0	2669434,56	32901,76	3815151,00	3815151,00	1145716,44	3782249,24	0,00	69,97	0,86
1991	0	3607660,57	14156,85	3849466,00	3849466,00	241805,43	3835309,15	0,00	93,72	0,37
1992	0	3098954,46	2797,56	3248070,00	3248070,00	149115,54	3245272,44	0,00	95,41	0,09
1993	0	3126883,48	10898,98	3260508,00	3260508,00	133624,52	3249609,02	0,00	95,90	0,33
1994	0	3821297,03	1502,73	4050098,00	4050098,00	228800,97	4048595,27	0,00	94,35	0,04
1995	0	4223641,16	4055,59	4766509,00	4766509,00	542867,84	4762453,41	0,00	88,61	0,09
1996	0	3310721,42	2146,54	3803700,00	3803700,00	492978,58	3801553,46	0,00	87,04	0,06
1997	0	2654166,17	4344,95	3331853,00	3331853,00	677686,83	3327508,05	0,00	79,66	0,13
1998	0	1586202,89	4185,11	1999821,00	1999821,00	413618,11	1995635,89	0,00	79,32	0,21
1999	0	1191815,43	11011,74	1396886,00	1396886,00	205070,57	1385874,26	0,00	85,32	0,79
2000	0	1251160,85	32121,12	1557546,00	1557546,00	306385,16	1525424,88	0,00	80,33	2,06
2001	0	1463457,16	33349,65	2346523,00	2346523,00	883065,84	2313173,35	0,00	62,37	1,42
2002	0	1471983,64	9539,35	1704482,00	1704482,00	232498,36	1694942,65	0,00	86,36	0,56
2003	0	1415426,02	15409,27	1796789,00	1796789,00	381362,98	1781379,73	0,00	78,78	0,86
2004	0	1455426,61	4551,52	1940595,00	1940595,00	485168,39	1936043,48	0,00	75,00	0,23
2005	5186	1432777,64	13619,75	1761394,96	1756208,96	328617,32	1747775,21	0,29	81,34	0,77
2006	25369.4	1382562,69	20708,95	2025389,22	2000019,82	642826,53	2004680,27	1,25	68,26	1,02
2007	265210.787	1237300,93	10258,90	2001148,44	1735937,65	763847,51	1990889,54	13,25	61,83	0,51
2008	428142.334	860480,38	5946,26	1477622,16	1049479,82	617141,77	1471675,90	28,98	58,23	0,40
2009	614690.051	795145,71	315,78	1287437,59	672747,54	492291,88	1287121,81	47,75	61,76	0,02
2010	359774.209	440060,55	891,62	730010,82	370236,61	289950,27	729119,20	49,28	60,28	0,12
2011	146465.89	201784,57	2911,95	605808,88	459342,99	404024,31	602896,94	24,18	33,31	0,48
2012	169884.632	213589,20	0,00	417317,00	247432,37	203727,80	417317,00	40,71	51,18	0,00

3) Results

a) South Pacific Jack Mackerel population structure

The population is structured with 3-month cohorts and a last “+ cohort” that accumulates older fish. The age at maturity occurs after cohort 12, i.e., at age 3 yr. Age-length and age-weight relationships are derived from the review by Cubillos et al., 1998.

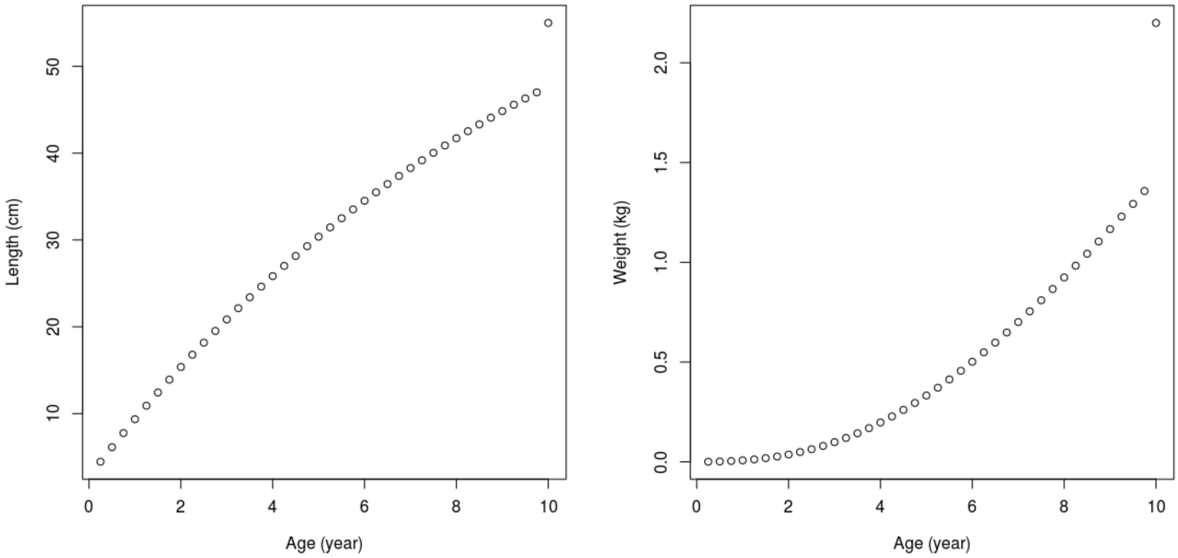


Figure 8: South Pacific Jack Mackerel size (FL in cm) and weight at age (yr) functions used in SEAPODYM simulation based on Cubillos et al., 1998.

b) Optimization experiments

This optimization for SPJM was conducted with the dataset presented in the previous section (conventional catch/effort data, size frequencies data and “dummy” fisheries). This optimization was conducted after the first optimization experiments conducted on NCEP and Glorys2 physical forcings (see preliminary reports). Preliminary estimates of the SPJM parameterization in SEAPODYM was achieved with the long historical hindcast provided by the coupled models NEMO-PISCES forced by the atmospheric reanalysis time series.

c) Fit to catch data

The model results were validated using the whole time series, i.e., 1979-2011. The details of fit for all fisheries separately are provided in Appendix 1 while a summary is provided below. The spatial fit to observed catch is very good in the main fishing grounds, in particular the “Jack Mackerel” belt but decreasing towards (i) the coastal areas where the model resolution (2°) is not precise enough and (ii) higher latitudes where catch become more occasional (Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.

Total catch is very well predicted (r = 0.99), showing a strong seasonality and decreased values since the early 2000s (Figure 10). The detail by fishery (Appendix 1) shows a difficulty to simulate the high variability observed in catch of purse-seine fishery S7 (offshore Chilean fishery). The fit is very high for all fisheries, the lowest (r = 0.87) being for TW2, an aggregation of several big trawlers in international waters that may vary in capturability and selectivity.

Despite the low number of available size frequency data, the overall fit to size frequencies samples are fairly good (Appendix 1). With the exception of large size fish in observed catch that are not predicted by the model.

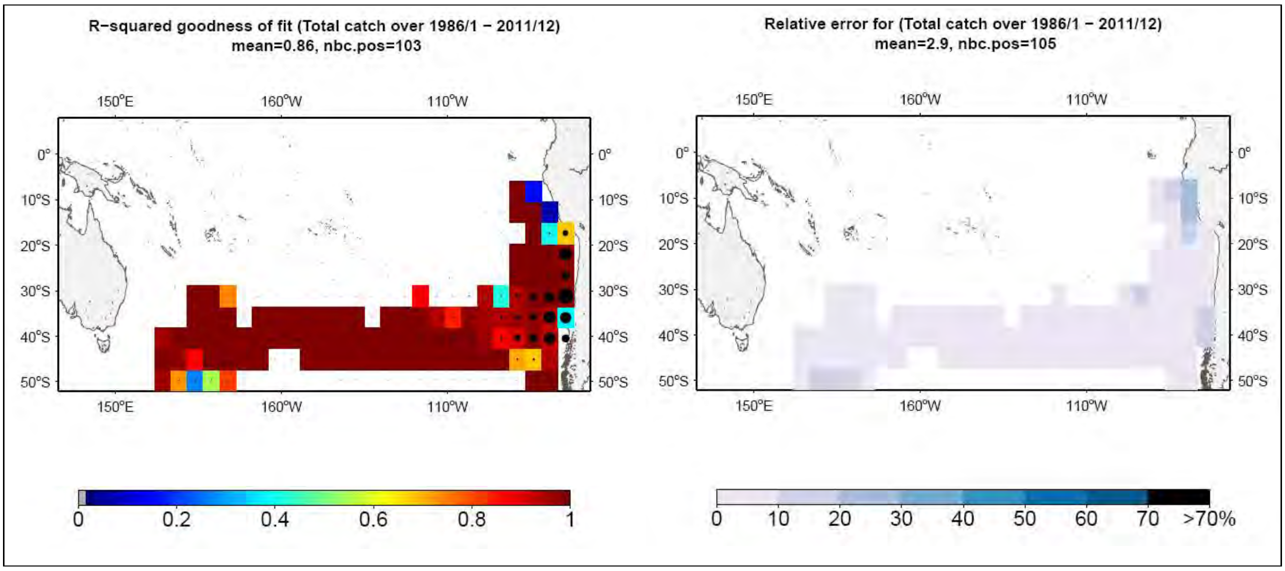


Figure Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.**: Comparison of fit to fishing data over the period 1986-2011 for Interim-Pisces-SPJM.** Left: R-squared goodness of fit representing the spatial fit over the period used for optimization (white squares indicate negative correlation between observations and predictions; Black circles are proportional to the level of catch. Right: relative error in predicted catch for all fisheries.

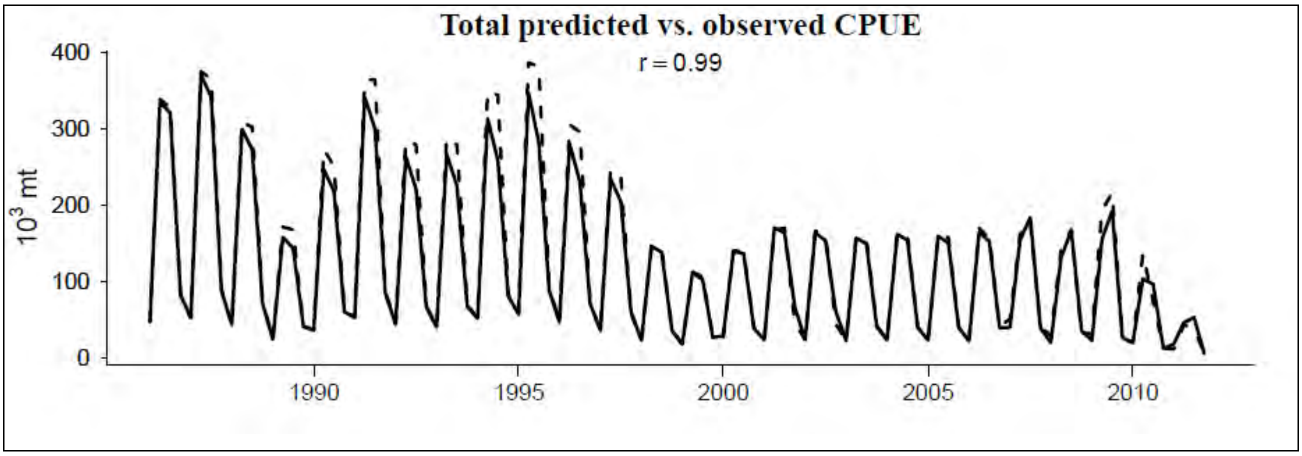


Figure 10: Fit between total observed (dotted line) and predicted (continuous line) SPJM catch.

d) Optimal Parameterization

The optimal spawning temperature was estimated (14.97℃) with a standard error reaching the upper boundary value (1.99℃). The value of the oxygen threshold parameter was estimated to 2.0 mL/L which is in accordance with the literature. The movement parameters were estimated with a diffusion parameter reaching its lower boundary value (0) but an advection coefficient about 0.95 BL/s. The mean natural mortality coefficients are estimated between 0.01 and 0.07 mo^{-1} (0.12-0.84 yr^{-1}) for cohorts older than 1 year (Figure 11).

Parameters estimated by the model			Unit	Interim-Pisces
T_s	Spawning	Optimum of the spawning temperature function	^{o}C	14.97
$\square_s$		Std. Err. of the spawning temperature function	^{o}C	1.99]
r		Maximal number of recruits per adult	Nb	137.5
T_a	Feeding habitat	Optimum of the adult temperature function at maximum age	^{o}C	[14
$\square_a$		Slope coefficient in sigmoid function describing tolerance to oxygen	^{o}C	1.13
$\hat{O}$		Oxygen threshold value at $\square_O$ =0.5	mL · L^{-1}	0.60
D_{max}	Movement	Diffusion parameter		[0*
V_{max}		Maximum sustainable speed	B.L. s^{-1}	0.95
e_p	Mortality	Slope in exponential decrease of predation mortality with age	-	0.248
M_s		Senescence mortality at age 0	mo^{-1}	[3.16*10^-6
e_s		Increase of senescence mortality with age	-	1.9
□		variability of mortality due to food requirement index	%	22.9

Table1: Estimates of habitats, movement and mortality function parameters for South Pacific jack mackerel based on Interim-PISCES forcing. The values marked with '[' or ']' were estimated at their minimal or maximal boundary value correspondingly

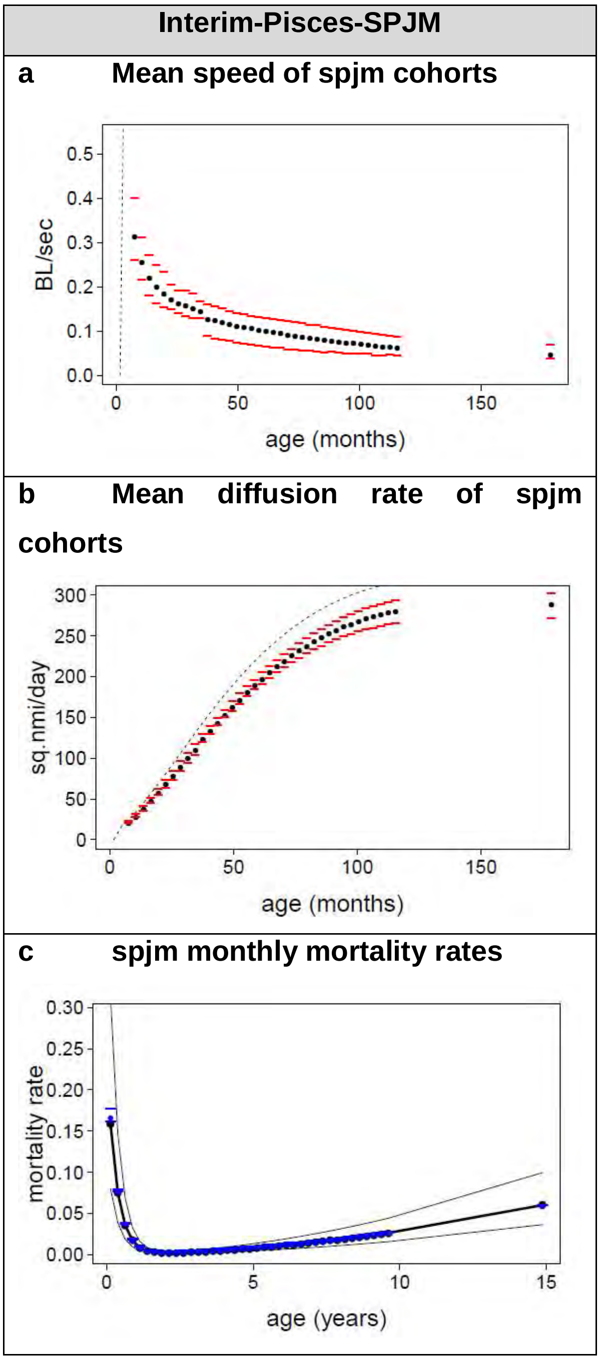


Figure 11: Optimal parameterization for South Pacific Jack Mackerel. a b: Maximum sustainable speed and diffusion rates by cohort (depending of age/size and habitat value / gradient) based on SEAPODYM parameterization (dotted lines) and predicted means weighted by the cohort density (black dots) with one standard error (red bars). **c**: 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.

e) Biomass estimates and population dynamics

This parameterization produces a biomass distribution with a core area surrounding the eastern and southern part of the South Pacific gyre and the cold currents moving north along the South American coasts (Humboldt current). A strong diffusion pattern is observed from these core areas while fish cohorts are getting older (Figure 12). It is to be noted that the current parameterization of SEAPODYM is based on 3-month cohorts and further development is planned in order to investigate in details the migration routes followed by juveniles.

The total biomass (adults and youngs) estimate for the South Pacific fluctuates between 39 and 47 million metric tones on the study period (1986-2011, see Figure 13). An abrupt decline to 39 Mt in the 1990's due to the large increase of catch by purse-seine Chilean fisheries (see Figure 1). The largest regional discrepancies between SEAPODYM and SPRFMO biomass estimates are from outside the main fishing regions, that is western areas of the South Pacific near New-Zealand and Australia.

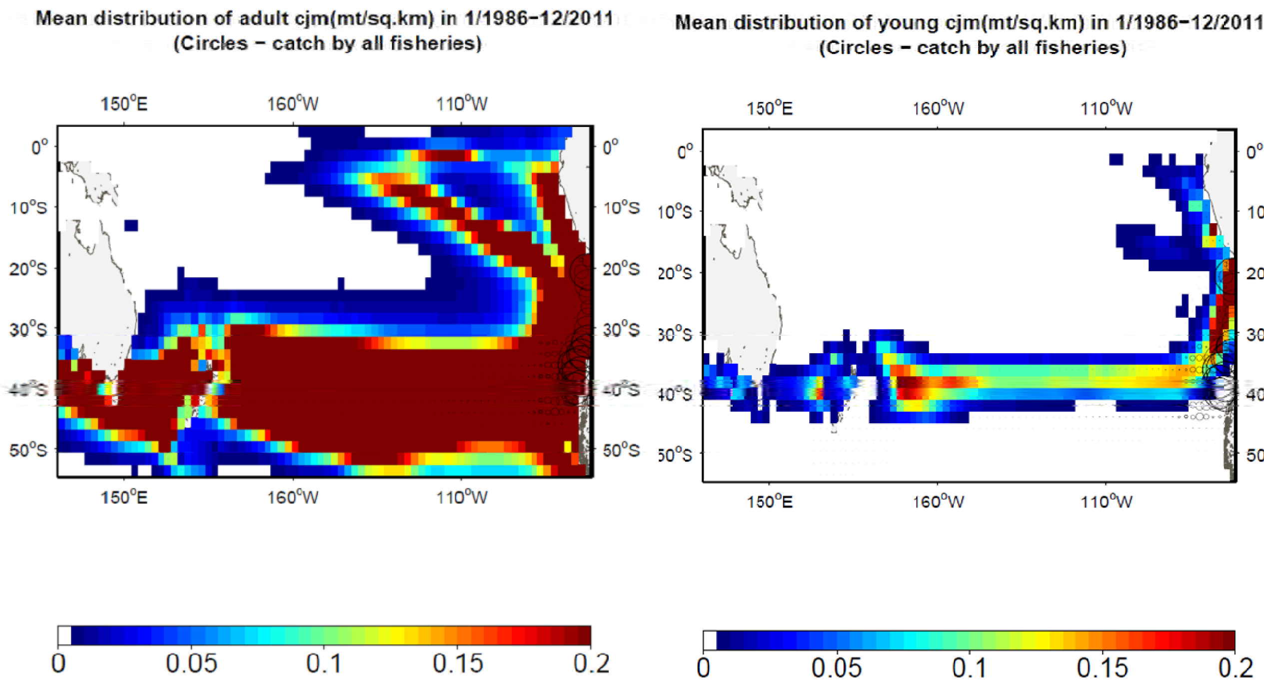


Figure 12: Average spatial distributions of SPJM young and adult

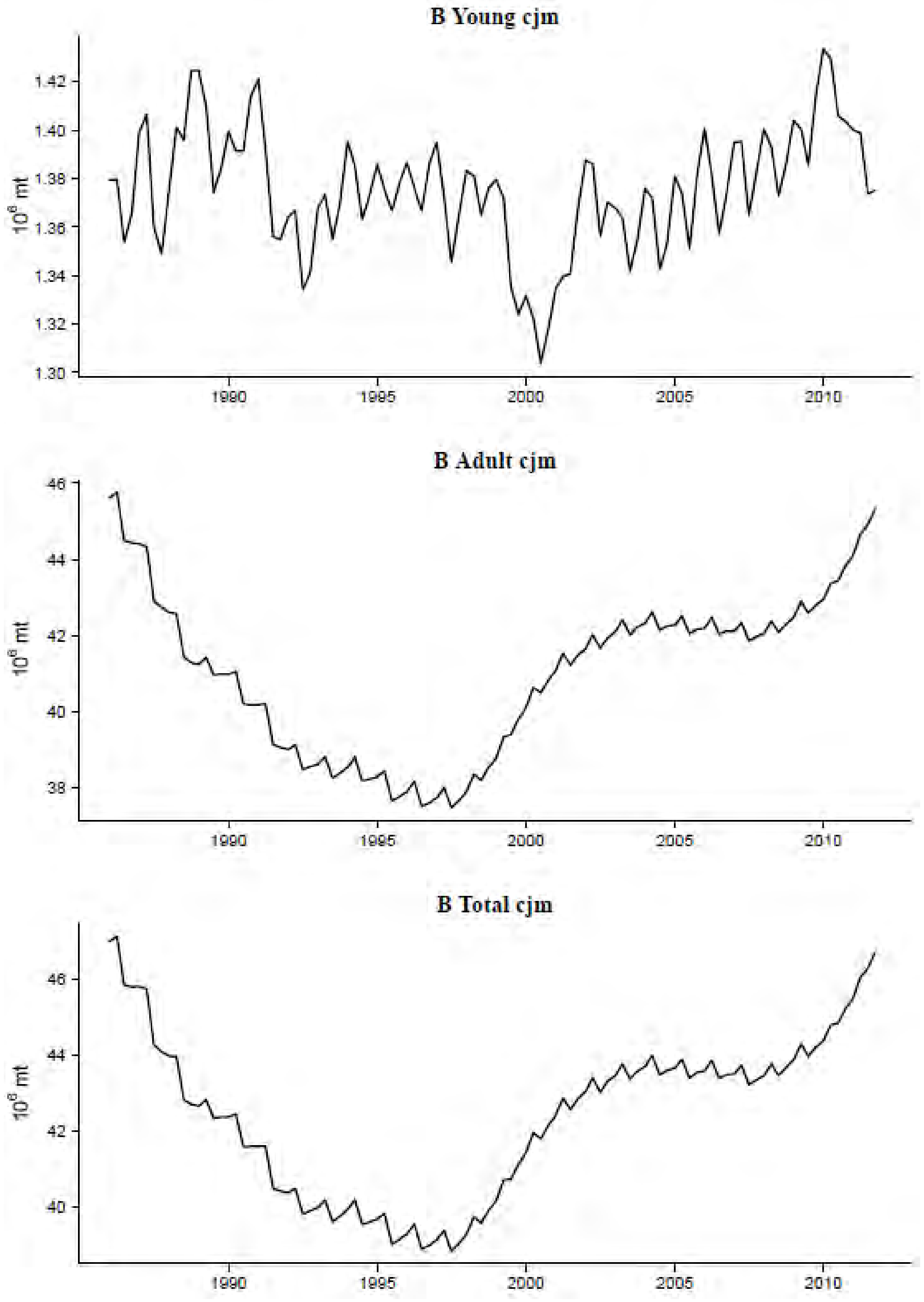


Figure13: Time series of (from top to bottom) South Pacific Jack Mackerel youngs, adults and total biomass estimated for the South Pacific Ocean with the new optimization experiment.

4) Discussion & Perspectives

a) Progress

Fitting SEAPODYM, incorporating catch, survey and environmental information allow to describe the relationships between jack mackerel and its environment, and hence make spatio-temporal maps of the species distribution. The spatial population dynamics is based on the definition of feeding and spawning habitats with first biological principles. They are estimated using all available detailed observations (catch, size, acoustic) and compared to the statistical approach above. Both approaches can in the end be used to predict the potential habitats and the potential meta-population structure. In SEAPODYM, the equations describing the underlying dynamics of the population and of its sensitivity to the environment are a priori defined, and their coefficients are estimated through model fitting (Maximum Likelihood Estimation approach). In the statistical habitat model, correlation analysis is used to identify which factors may be relevant, and what should be there effect.

Fishing data (catch, fishing effort and size frequencies of catch) of South Pacific jack mackerel by gear and region were collected from different sources: fisheries management organizations (SPRFMO, IFOP etc.), publications in peer-reviewed journals and stock assessment reports. These raw data were checked and processed to prepare two fishing datasets for SEAPODYM application: one with all available monthly spatialized catch/effort and acoustic/effort data and the other with additional annual catch data reinterpolated monthly but with no associated fishing effort (“dummy” catch data).

These data were used in a third optimization experiment conducted with a 2° grid resolution of the model (2°x month) over the south Pacific domain and over the period 1986-2011. The environmental forcing (2° x month) was obtained from a spatio-temporal reinterpolation of the available high resolution model configuration (1° x month) based on Satellite derived primary production (Behrenfeld & Falkowsky, 1997) and the ocean reanalysis Interim-Pisces (Nicol et al. 2014).

This third optimization experiment was conducted in parallel on the two sets of data. In this report, we only presented results obtained for the optimization experiment conducted on the dataset including “dummy” fisheries. A new version of SEAPODYM was developed to take specifically into account the mortality caused by fisheries for which we had estimations of annual catches but no associated effort. Both models were able to converge and provided an adequate fit to the fishing data both for catch and CPUE. The impact of additional “dummy” data, even without appropriate effort, was significant to improve the model spatiotemporal fit. Regarding SPJM spatial distribution, the current fit allows to reproduce the whole distribution area of South Pacific Jack Mackerel and will be used to investigate stock structure along the South American coasts and presumed migration routes between the Western and Eastern parts of the population.

b) Perspectives

Though the fit to catch data is good and the population dynamics is reasonable, the spatial resolution of the model (2°x2° grid) prevents the full use of coastal data (i.e. acoustics and catches in EEZ), hence a finer understanding of the impact of the Humboldt oceanographic system (upwelling systems, Oxygen Minimum Zone, El Nino Southern Oscillation etc.) on the SPJM population behavior. In future work, a finer estimation of SEAPODYM parameters, especially in coastal areas, will be obtained by the use of 1-month age cohorts and of a spatial resolution of 1°x1°. We will also use the acoustic records as a stock availability reference in the next optimization experiment. The population dynamics in terms of connectivity between presence areas and potential migration routes will then be investigated. Finally, the respective impacts of fishing and environmental variability (ENSO, Pacific Decadal Oscillation etc.) will be estimated by the use of the optimal parameterization (obtained on the data period 1986-2011) on the 2012-2030 predicted Interim-Pisces forcing.

References

Aumont, O., and L. Bopp, 2006. Globalizing results from ocean in situ iron fertilization studies, Global Biogeochem. Cycles , 20, GB2017, doi:10.1029/2005GB002591

Behrenfeld, M., and P., Falkowski, 1997. A consumer's guide to phytoplankton primary productivity models. Limnology and Oceanography, vol. 42, 7, 1476-1491.

Bell, J.D., Ganachaud, A., Gehrke, P.C., Griffiths, S.P., Hobday, A.J., Hoegh-Guldberg, O., Johnson, J.E., Le Borgne, R., Lehodey, P., Lough, J.M., Matear, R.J., Pickering, T.D., Pratchett, M.S., Sen Gupta, A., Senina, I., Waycott, M., 2013. Tropical Pacific fisheries and aquaculture will respond differently to climate change. Nature Climate Change 3, 591–599.

Bertrand, A. and F-X. Bard, 1999. The system {tuna - environment} in french polynesia : characterisation of the pelagic habitat, study of tuna distribution and catchability, by acoustic and halieutic methods. Thèse de Doctorat ENSAR.

Bertrand, A., M.A., Barbieri, J., Cordova, C., Hernandez, F., Gomez and F. Leiva, 2004. Diel vertical behaviour, predator–prey relationships, and occupation of space by jack mackerel (Trachurus murphyi) off Chile. ICES Journal of Marine Science, vol. 61, 7, pp. 1105-1112.

Bertrand, A., M.A., Barbieri, F., Gerlotto, F., Leiva and J. Cordova, 2006. Determinism and plasticity of fish schooling behaviour as exemplified by the South Pacific jack mackerel Trachurus murphyi. Marine Ecology Progress Series, vol. 311, pp. 145-156.

Cubillos, L., et al. (1998). Validacion de los metodos aplicados en la determinacion de edad y crecimiento y determinacion de la mortalidad del jurel en la zona centro sur. Informe Final Projecto FIP 95-10, 170p.

Lehodey, P., Senina, I., Murtugudde, R., 2008. A Spatial Ecosystem And Populations Dynamics Model (SEAPODYM) - Modelling of tuna and tuna-like populations. Progr. Oceanogr. 78, 304-318.

Lehodey, P., Senina, I., (2009). A user manual for SEAPODYM version 2.0: application with data assimilation. Fifth regular session of the Scientific Committee of the Western and Central Pacific Fisheries Commission, 10–21 August 2009, Port Vila, Vanuatu, WCPFC-SC5-2009/ EB-IP-13, 82 pp. http://www.wcpfc.int/meetings/2009/5th-regular-session-scientific-committee.

Lehodey, P., Senina, I., Sibert, J., Bopp, L., Calmettes, B., Hampton, J., Murtugudde, R., 2010a. Preliminary forecasts of population trends for Pacific bigeye tuna under the A2 IPCC scenario. Progr. Oceanogr. 86, 302–315.

Lehodey, P., Murtugudde, R., Senina, I., 2010b. Bridging the gap from ocean models to population dynamics of large marine predators: a model of mid-trophic functional groups. Progr. Oceanogr. 84, 69–84.

Lehodey, P., Hampton, J., Brill, R.W., Nicol, S., Senina, I., Calmettes, B., Pörtner, H.O., Bopp, L., Ilyina, T., Bell, J.D., Sibert, J., 2011. Vulnerability of oceanic fisheries in the tropical Pacific to climate change. *In* Bell J, Johnson JE, Hobday AJ (Ed.), Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Secretariat of the Pacific Community. Noumea New Caledonia: pp 447-506.

Lehodey, P., Senina, I., Calmettes, B, Hampton, J, Nicol, S., 2013a. Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. Climatic Change 119 (1), 95-109.

Lehodey, P., Senina, I., Titaud, O., Calmettes, B., Nicol, S., Hampton, J, Caillot, S., Williams, P., 2013b. Project 62: SEAPODYM applications in WCPO. 9th regular session of the Scientific Steering Committee, 6-14 August 2013, Pohnpei, Federated States of Micronesia. WCPFC□SC9□2012/EB□WP□03 Rev 1. http://www.wcpfc.int/meetings/2013/9th-regular-session-scientific-committee

Nesterov À.A., Chur V.N., Kolomeyko F.V., 2007, Russian fishery and researches in the Southern Pacific Ocean in 1978 −1991and 2002−2003. The jack mackerel fishery in the South Pacific Meeting, March 22, 2007, Talcahuano, Chile. Atlantic Research Institute of Marine Fisheries and Oceanography (AtlantNIRO), Kaliningrad, Russia

Nicol, S., Dessert, M., Gorgues, T., Aumont, O., Menkes, C., Lehodey P., Lengaigne M. (2014). Project 62: Progress report on climate simulations. Tenth regular session of the Scientific Committee of the Western Central Pacific Fisheries Commission, Majuro, Republic of the Marshall Islands, 6-14 August 2014. WCPFC-SC10-2014/EB-IP-02: 14 pp. http://www.wcpfc.int/node/18922

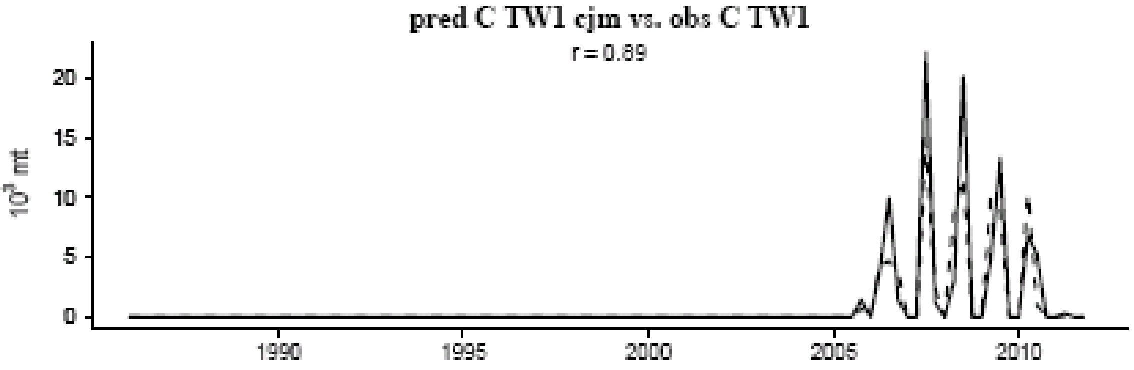
Penney, A. and P., Taylor, 2008. An Overview of the New-Zealand Jack Mackerel Fishery: Catch Composition, Catch Trends, Seasonality and Length-Frequency Composition. Information Paper submitted to the SPRFMO Jack Mackerel Workshop, Santiago, Chile, 30 June - 4 July 2008

Senina, I., Sibert, J., Lehodey, P., 2008. Parameter estimation for basin-scale ecosystem-linked population models of large pelagic predators: application to skipjack tuna. Progr. Oceanogr. 78, 319-335.

Sibert, J., Senina, I., Lehodey, P., Hampton, J., 2012. Shifting from marine reserves to maritime zoning for conservation of Pacific bigeye tuna (*Thunnus obesus*). P. Natl. Acad. Sci. USA 109(44), 18221-18225. doi: 10.1073/pnas.1209468109.

Vasquez, S., M. Correa-Ramirez, C. Parada and A., Sepulveda, 2013. The influence of oceanographic processes on jack mackerel (Trachurus murphyi) larval distribution and population structure in the southeastern Pacific Ocean. ICES Journal of Marine Sciences, doi: 10.1093/icesjms/fst065.

Appendix 1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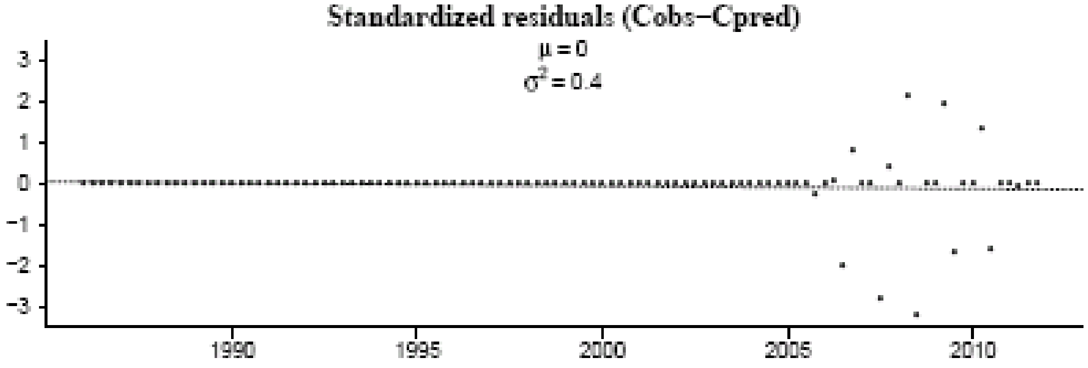
20
15
10
5
0
1990
1995
2000
2005
2010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2
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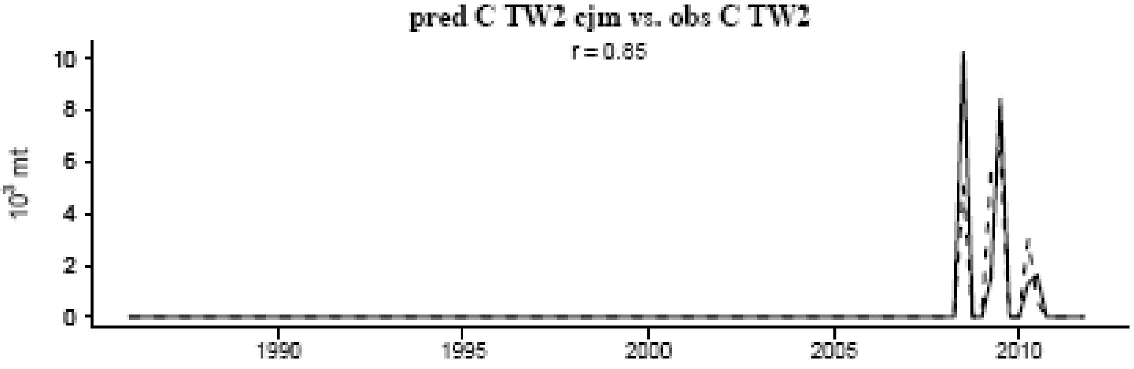
0
−1
−2
−3
1990
1995
2000
2005
2010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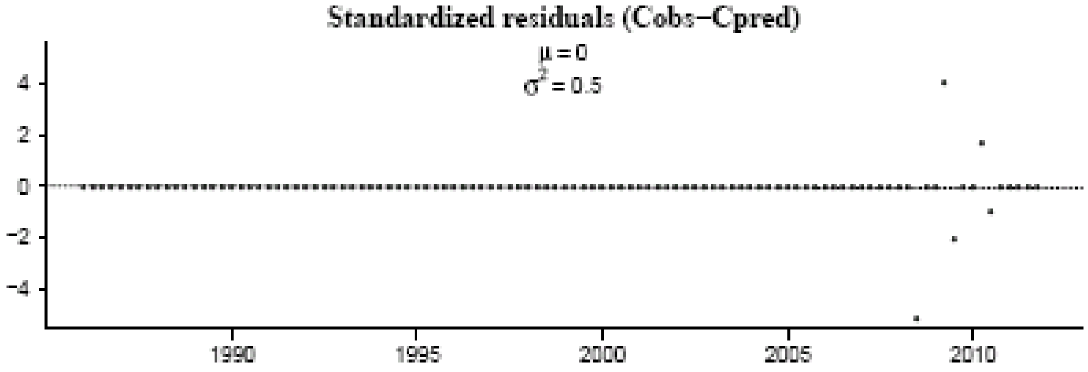
8
6
4
2
0
1990
1995
2000
2005
2010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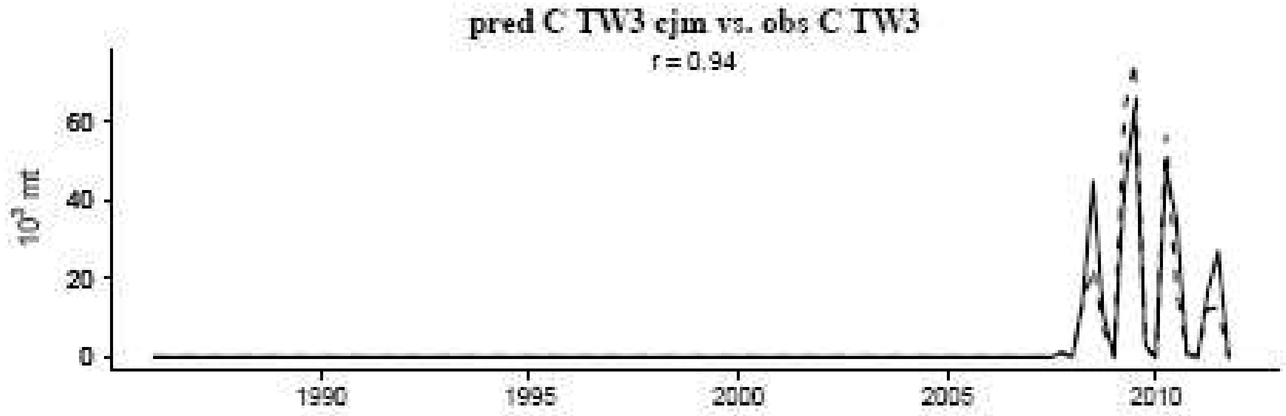
2
0
−2
−4
1990
1995
2000
2005
2010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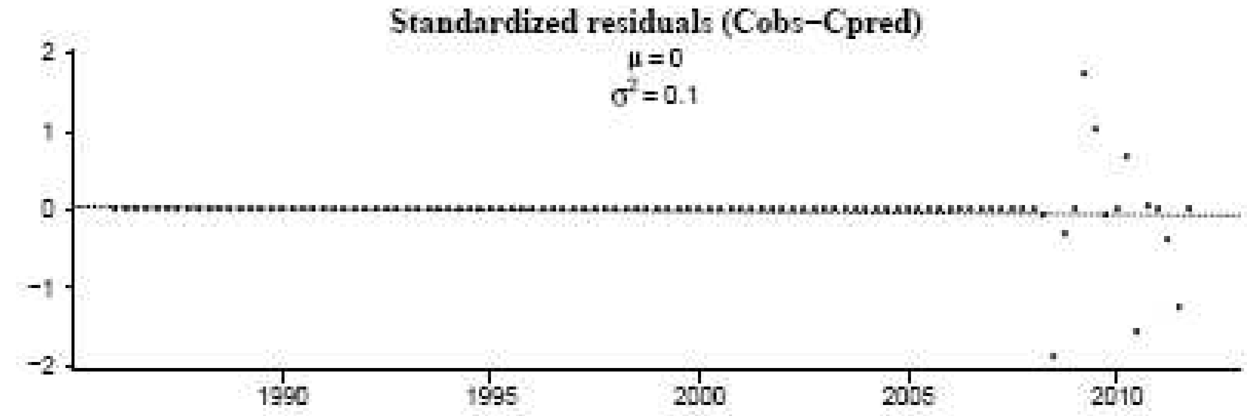
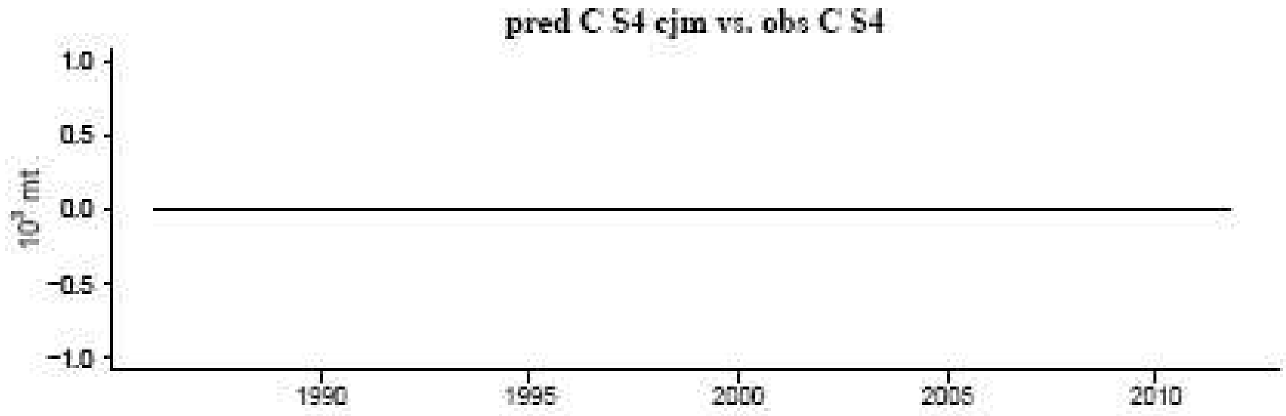

Standardized residuals (Cobs−Cpred)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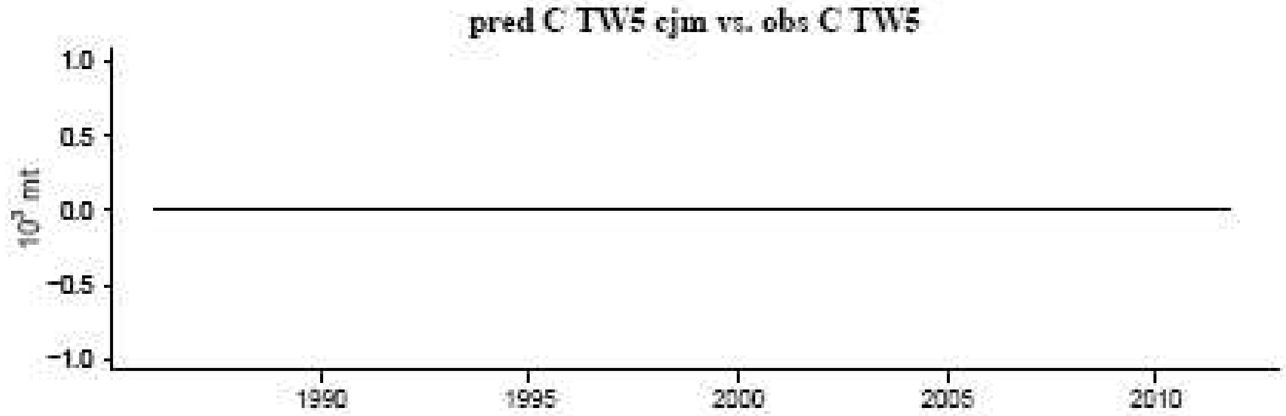
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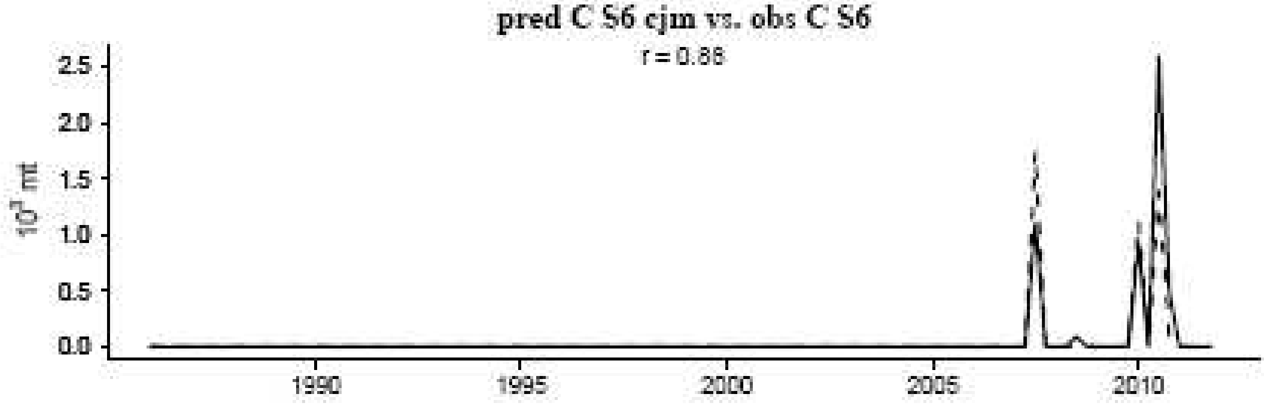
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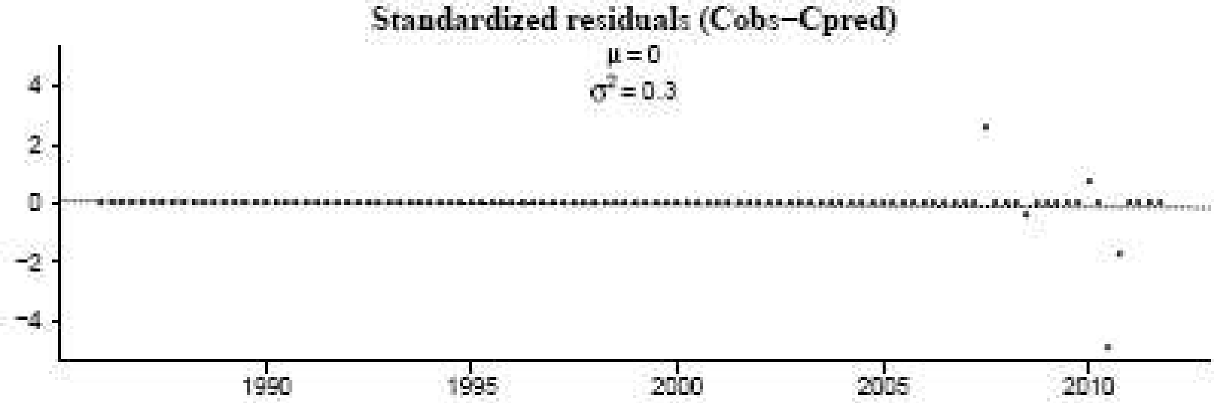
2.0
1.5
1.0
0.5
0.0
1990
1995
2000
2005
2010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2
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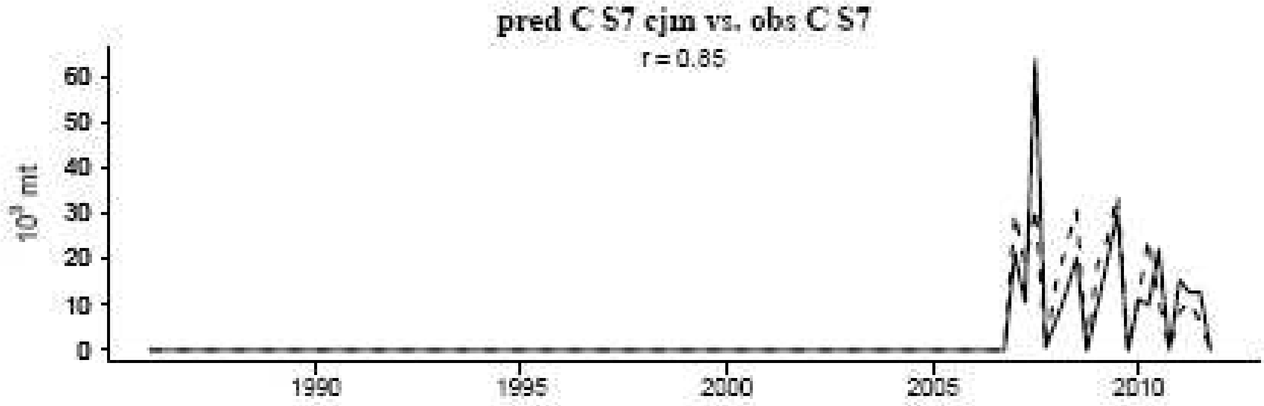
−2
−4
1990
1995
2000
2005
2010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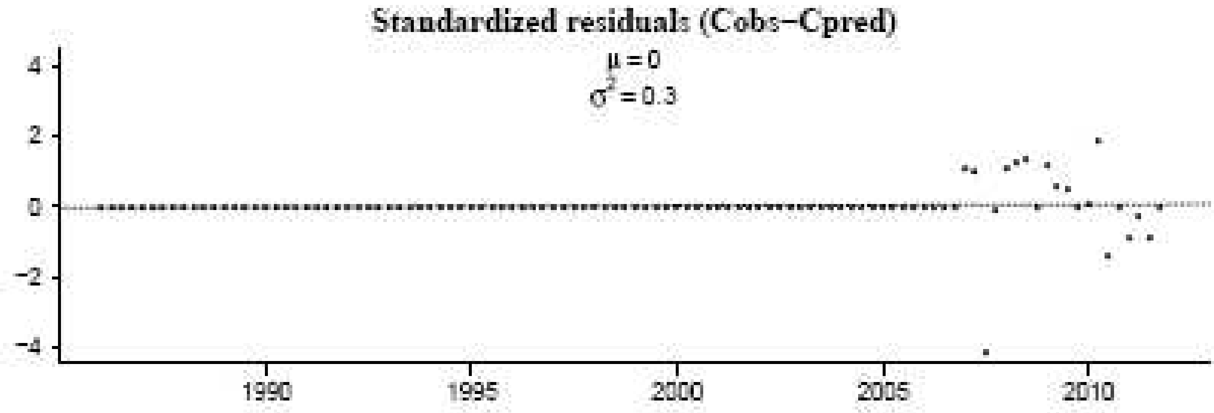
60
50
40
30
20
10
0
1990
1995
2000
2005
2010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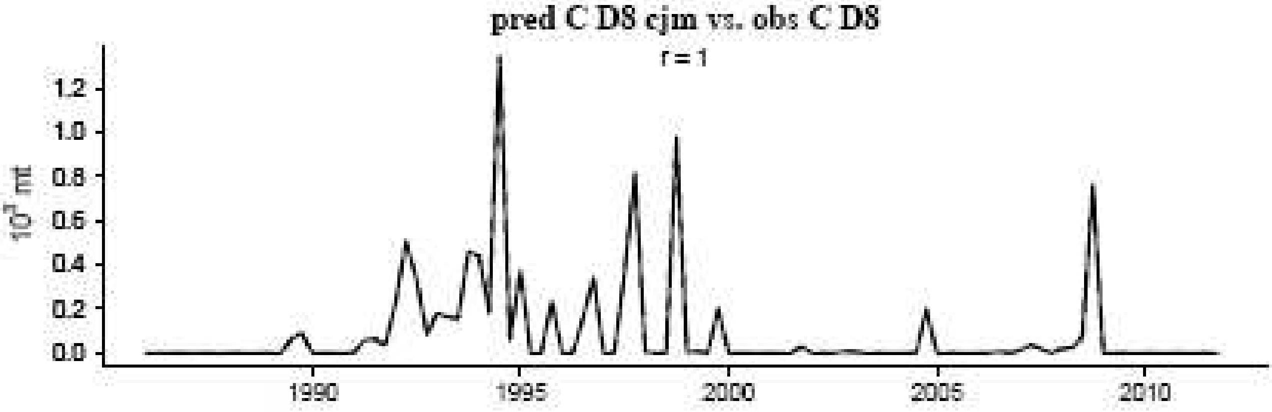
4
2
0
−2
−4
1990
1995
2000
2005
2010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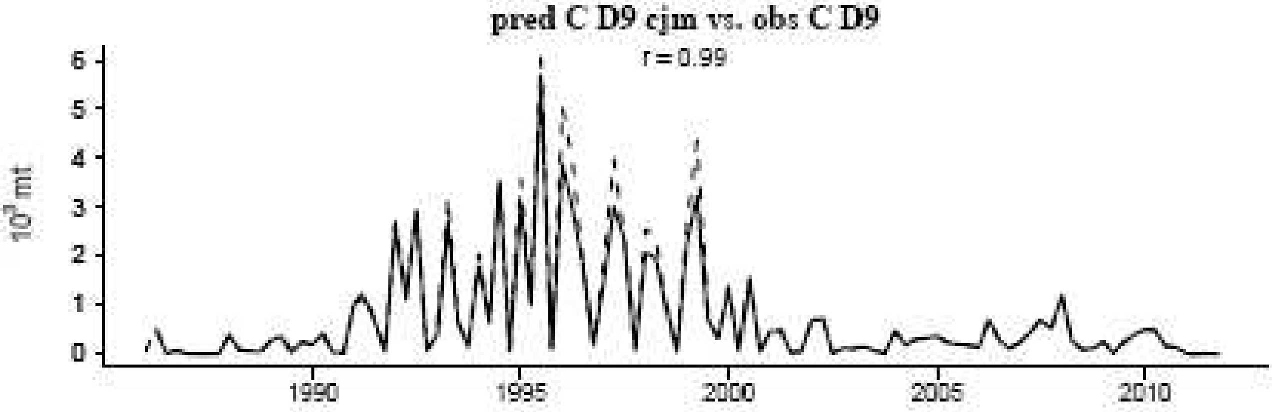
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1990
1995
2000
2005
2010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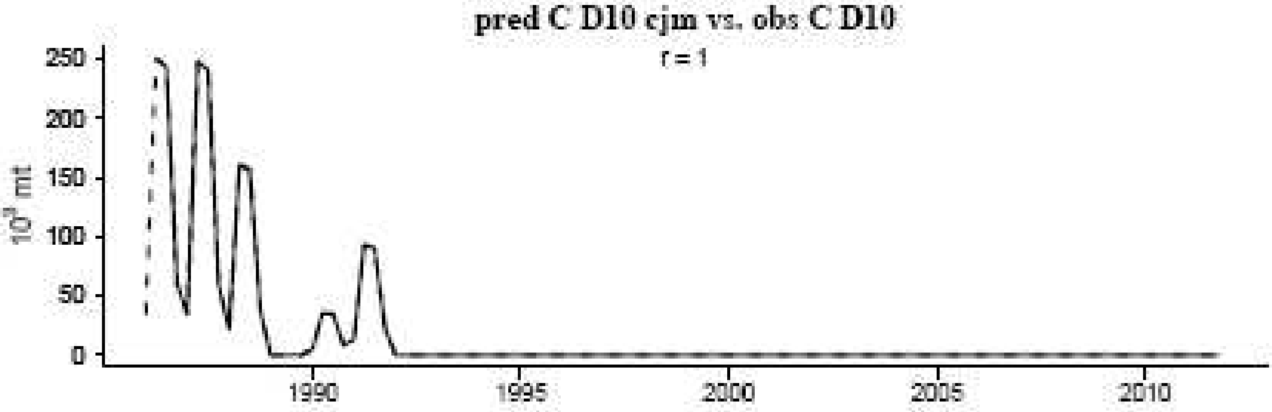
0
1
2
3
4
5
6
1990
1995
2000
2005
2010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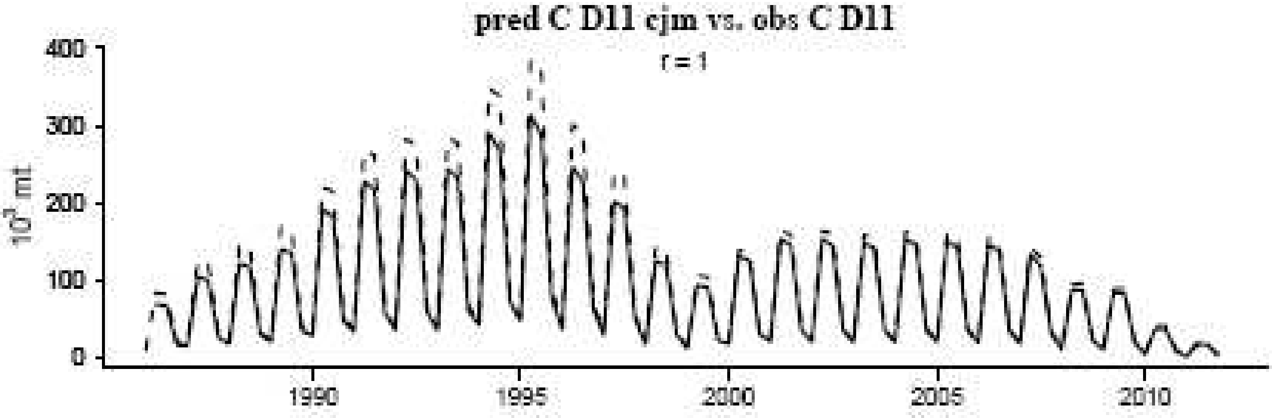
0
50
100
150
200
250
1990
1995
2000
2005
2010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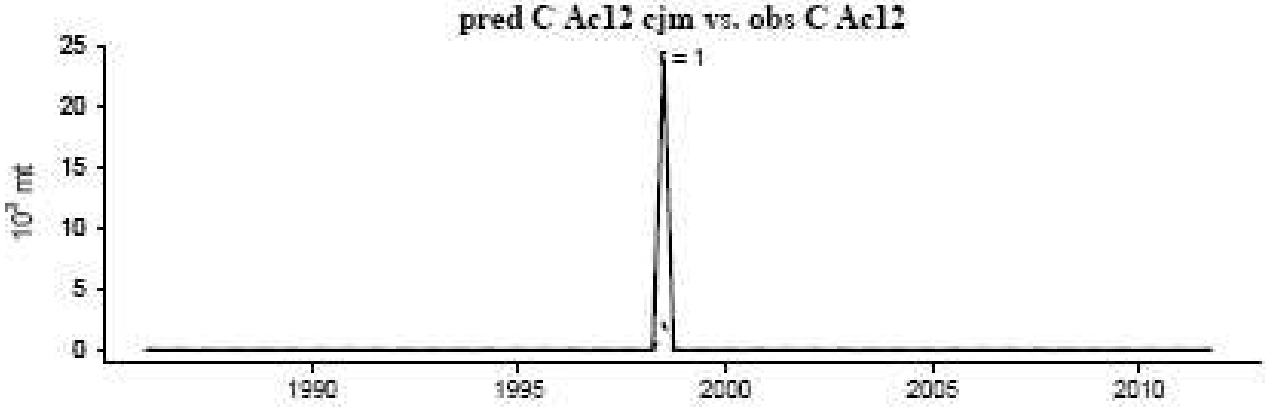
100
200
300
400
1990
1995
2000
2005
2010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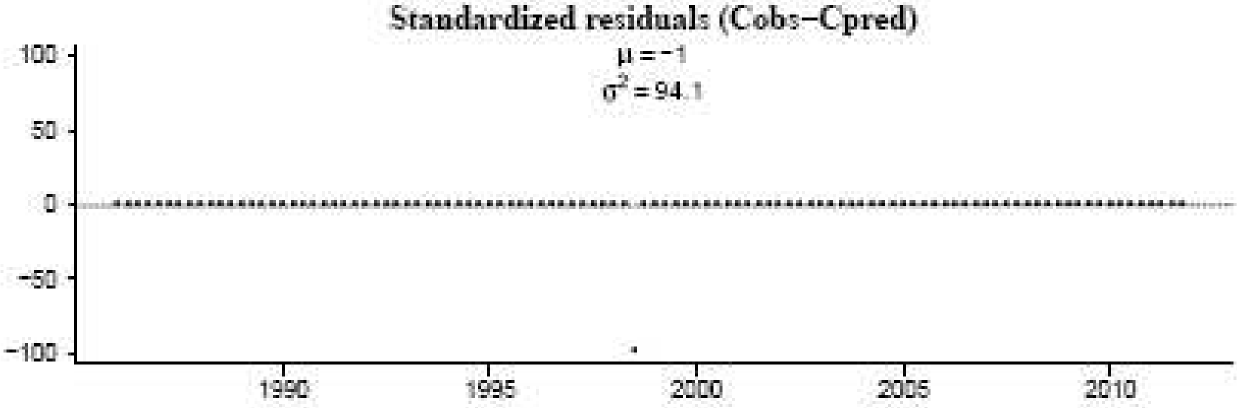
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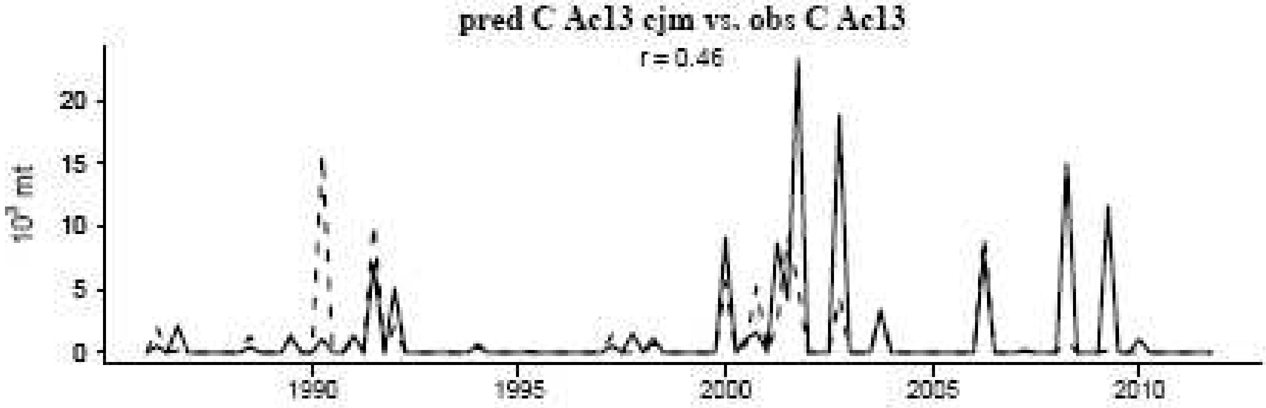
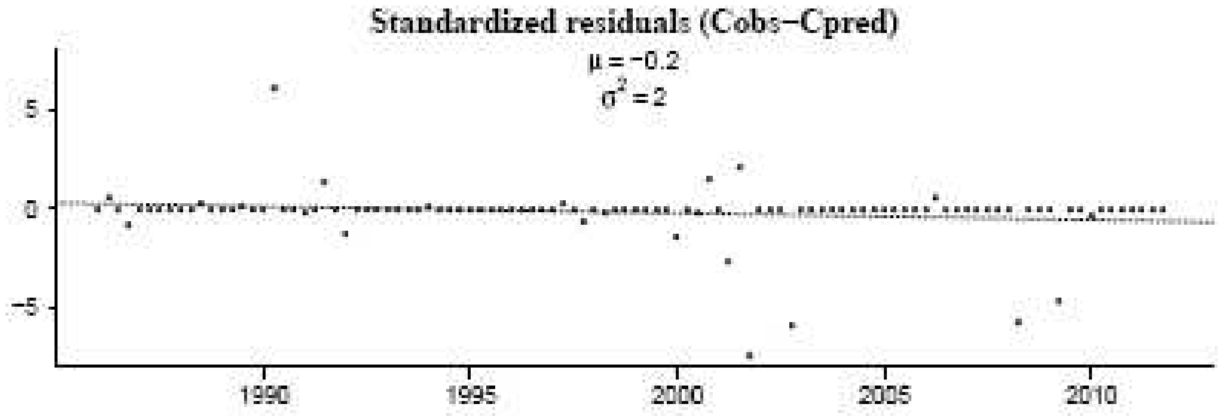
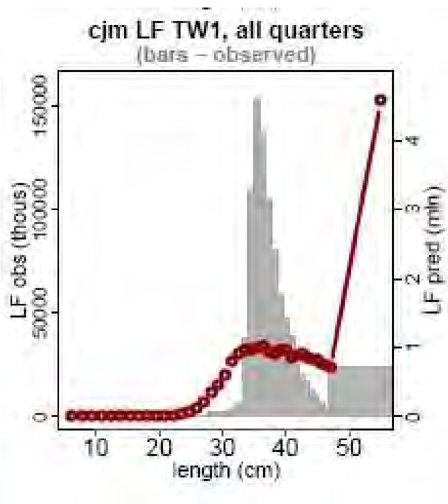
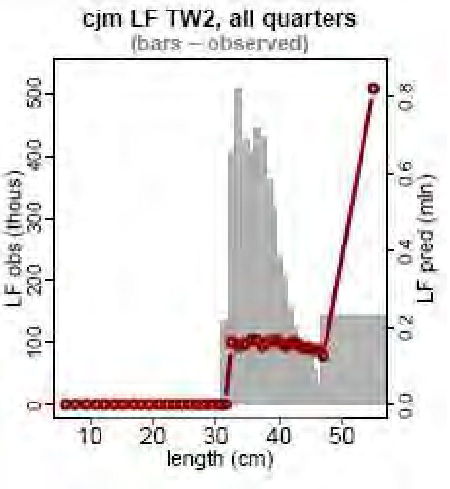

pred C Ac13 cjm vs. obs C Ac13


Standardized residuals (Cobs−Cpred)


cjm LF TW1, all quarters
(bars – observed)
LF obs (thous)
0
50000
100000
150000
LF pred (mln)
0
1
2
3
4
10
20
30
40
50
length (cm)


cjm LF TW2, all quarters
(bars – observed)
LF obs (thous)
0
100
200
300
400
500
LF pred (mln)
0.0
0.2
0.4
0.6
0.8
10
20
30
40
50
length (cm)