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Hydrography/biogeochemistry and Chilean Jack mackerel stock structure interactions

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Introduction

This work centres on the question of how hydrographical, environmental and biogeochemical conditions shape the Jack Mackerel habitat and determine its distribution, composition and population structure. Combining fisheries and survey data with hydrographical data allow characterising the environmental conditions in which Jack Mackerel is present in the South Pacific region. Using different modelling tools, predictions of the potential habitat for Jack Mackerel can be made. The spatial distribution of the potential habitat and its temporal variations will provide information on the likelihood of different hypotheses on stock structure.

The present study consists of two distinct activities:

1. Develop a statistical 3D habitat model for Jack Mackerel,
2. Develop a configuration of the SEAPODYM model for Jack Mackerel.

Statistical 3D habitat model for Jack Mackerel

1 Identification of key environmental factors determining CJM distribution

To develop a 3D conceptual model and build the statistical niche model, we selected three habitat variables (sea surface temperature, sea surface chlorophyll concentration as a proxy of primary production and dissolved oxygen concentration). Previous studies showed that these variables had a strong influence on CJM distributions (e.g., sea surface temperature (Bertrand et al., 2006), sea surface chlorophyll concentration (Bertrand et al., 2004) and dissolved oxygen (Bertrand et al., 2006)).

From the available data from different sources (satellite, scientific survey, fishing vessels capture and acoustic data), we estimated the favorable range of each parameter in both horizontal and vertical dimension. Note that size-frequency were not used so the work is realized mixing both adults and juveniles.

Oxygen concentration is a fundamental parameter in the South-Eastern Pacific, which is characterized by the presence of a shallow and intense oxygen minimum zone (up to 20 m below the surface along the Peruvian coastline). CJM is unable to live in waters with oxygen concentrations below 1 $ml.l^{-1}$ but 2 $ml.l^{-1}$ is accepted as a more representative limit. Moreover, it seems that besides a minimum Dissolved Oxygen (DO) concentration, the CJM requires a vertical range of oxygenated waters greater than 40 m (Bertrand et al. unpublished data).

Minimum temperature observed among all the datasets is 8.7°C. Considering eventual bias from satellite date, we can consider 9°C as the lowest tolerable temperature in accordance with (Bertrand et al., 2006). Minimum 9°C isotherm depth observed for Dutch catches position is 66 meters. Considering that this value is obtained from mean climatology field, we set the minimum depth of the 9°C isotherm at 60 meters depth.

The minimal sea surface chlorophyll concentration is 0.016 mg/m3. Considering eventual bias from satellite date, we based our estimation on the 2.5% quantile values, e.g. 0.06 mg.m^{-3}. (Polovina et al., 2008) showed that subtropical gyre are the ocean's most oligotrophic waters where surface chlorophyll not exceeding 0.07 mg.m^{-3}. Thus this concentration is considered as a good proxy of the minimum requested sea surface chlorophyll concentration.

Table 1. Estimated ranges of selected explanatory variables in both horizontal and vertical dimension

Dimension	Parameter	Estimated range
Horizontal	Sea surface temperature	[9-26]°C
	Chlorophyll-a concentration	>0.07mg.m-3
Vertical	Dissolved oxygen	>2 ml.l-1
	Depth of DO 2 ml.l-1	>40 meters
	Depth of isotherm 9°C	>60 meters
	Maximum depth	400 meters

CJM distributes over a wide oceanic area. We estimated that the tolerable temperature ranges from 9°C to 26°C. Between these limits we observed that in its southern distribution where waters are cold, CJM can be encountered in areas with lower productivity (< 0.1 mg.m^{-3}) than in its northern distribution boundary, where the water is warmer. This result is an illustration of physiological constraints. Indeed higher the temperature is, more food is needed (Kooijman, 2010). We therefore considered the interaction between these parameters (Figure 1).

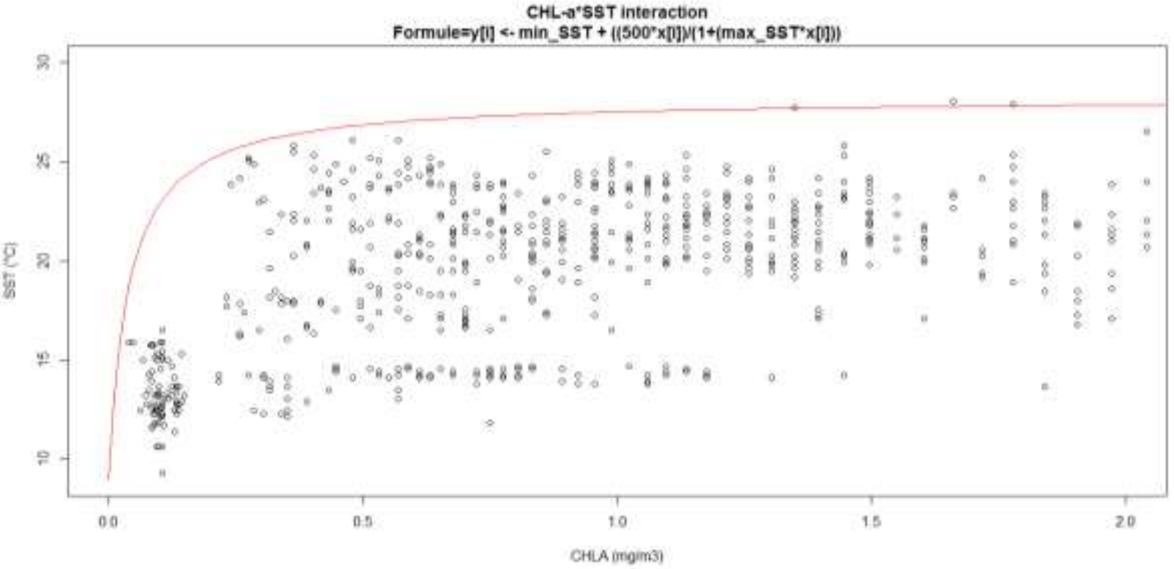


Figure 1. Model of CHL-a * SST interaction

2 Habitat boundaries and 3D conceptual model

From the significant hydrological conditions estimated previously, here we aim to develop a 3D conceptual model of CJM habitat. As previously shown, monthly variability of South Pacific environmental conditions is high. So, we propose to estimate the potential habitat limits and to develop a model by month (or season).

2.1 Horizontal dimension

For each month, a potential horizontal habitat was constructed using:

- the limit of the subtropical gyre (defined by CHL-a concentration ≤ 0.07 mg/m3),
- isoline SST 9°C as lower thermal limit,
- isoline SST 26°C as greater thermal limit,
- interaction between SST and CHLA.

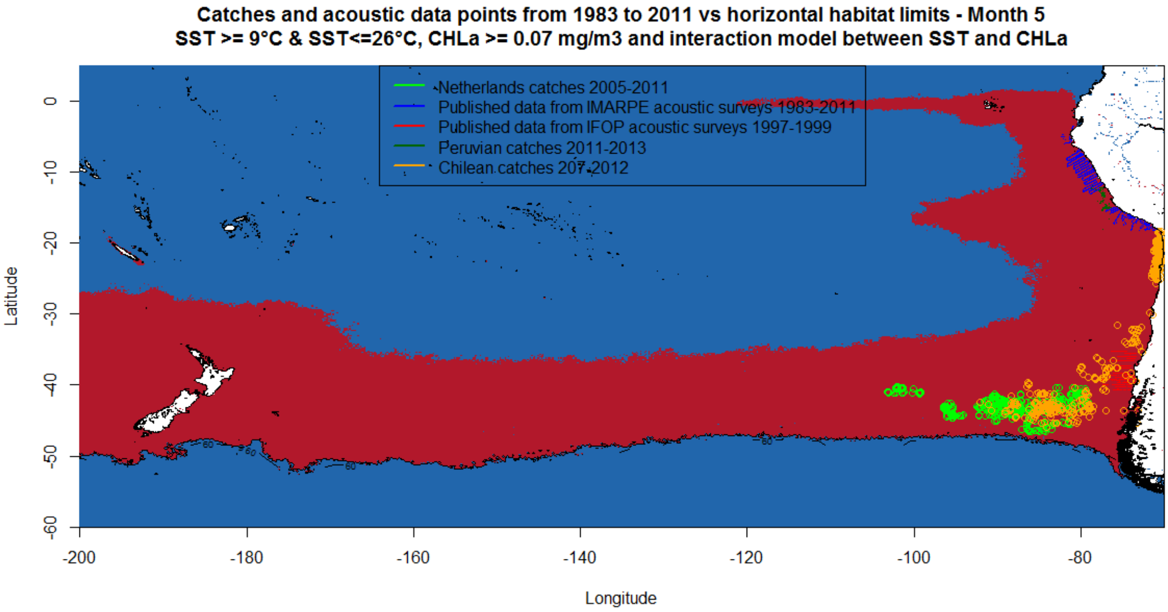


Figure 2. Suitable habitat limits map for month May. The red surface represents the suitable habitat for CJM while the blue surface represents the area with adverse conditions for CJM. Horizontal habitat is delimited by the lowest/highest thermal limits, the subtropical gyre and the interaction between SST and CHL-a

From Figure 2, we observe that the CJM southern latitude boundary is around 50°S, which correspond to the sub-Antarctic front. Analyzing this map, we see that some potential habitat zones (equatorial tongue, 15°S-20°S) are outside the known range of distribution of the CJM.

To understand why CJM do not distributes in the equatorial tongue, which was considered as favorable habitat in our model we explored the effect of other parameters: advection (organisms transport by ocean surface current), subsurface currents (Chaigneau et al., 2013). No significant effect was observed. We thus suppose that not tested abiotic (e.g. cumulative temperature) or biotic parameters (predation/competition e.g. interactions with tunas, giant squid, cetaceans) may be determinant.

Absences of catches in the Australian Fisheries Management Authority (AFMA) database confirm our assumption that the distribution of *Trachurus murphyi* does not extend to Australia except on very rare occasions. For practical purposes we consider New Zealand as the western boundary of the species.

2.2 *Vertical dimension*

After studying the horizontal habitat limits, we focused on dissolved oxygen concentration by the water column along the south-American coast (figure 3). The largest and most pronounced OMZ in the world plays an essential role in structuring the ecosystem (Bertrand et al., 2010, 2011). In the subsurface, the OMZ extends from the coast to several hundred kilometers wide, and tens to hundreds of meters deep.

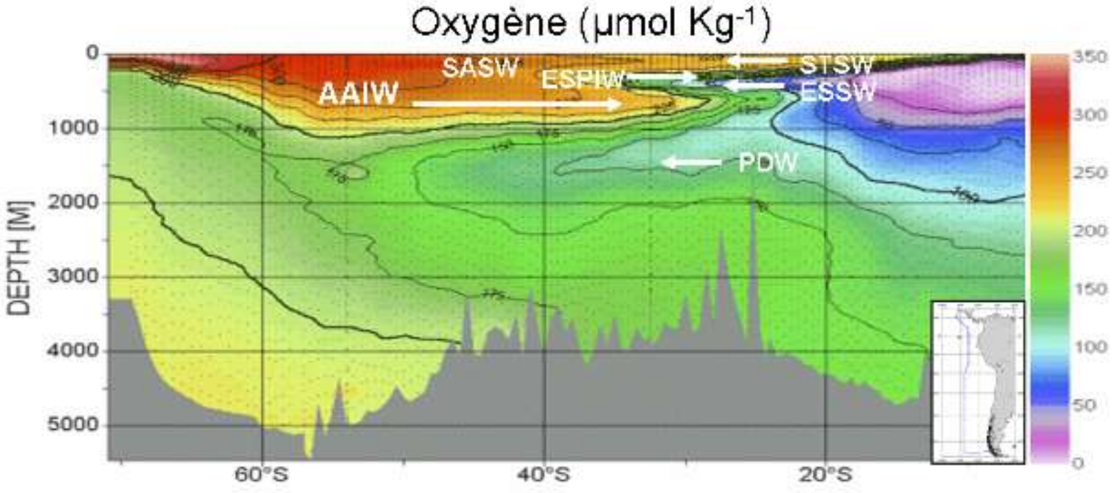


Figure 3. Dissolved-oxygen concentration (in µmol.kg^{-1}) distribution along the section WOCE-P19 off the south-American coastline. Main water masses: Subtropical Surface Water (STSW); SubAntarctic Surface Water (SASW); East-southern Pacific Intermediate Water (ESPIW); Equatorial SubSurface Water(ESSW); Antarctic Intermediate Water (AAIW); Pacific Deep Water (PDW).

Adding vertical parameters criteria, a conceptual model of the available habitat of the Jack Mackerel in 3D has been developed (figure 4).

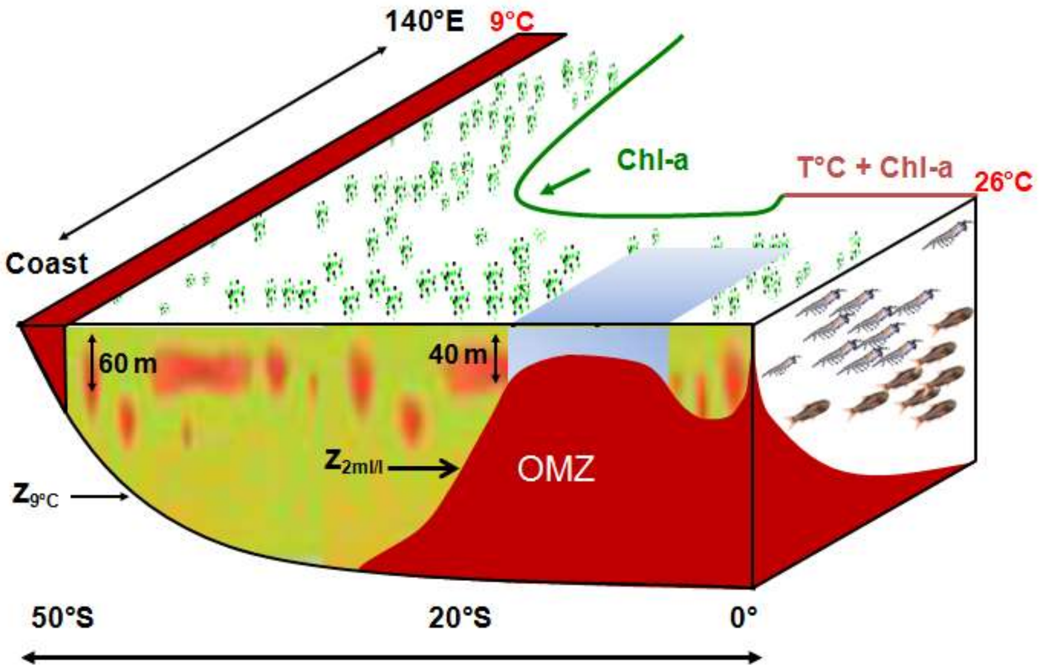


Figure 4. 3D conceptual model of the Jack Mackerel habitat in the South Pacific. The habitat is limited by the temperature, the productivity and the oxygen concentration. Red surfaces correspond to unfavorable habitat delimited in the south by the 9ºC SST isoline and a minimum depth of 60 m for the 9ºC isotherm ($Z_{9ºC}$) and in the north by the 26ºC SST isoline. Between these limits, the horizontal range of jack mackerel is limited by the oligotrophic waters of the subtropical gyre (green solid line) or a combination of temperature and productivity (light red solid line Vertically the distribution of jack mackerel is limited by $Z_{9ºC}$ or when the oxygen concentration reaches 2 ml/l ($Z_{2ml/l}$). If $Z_{2ml/l}$ is lower than 40 m then the habitat is unfavorable (light blue-grey area) Jack mackerel are represented by yellow to red small structures (fish abundance and density increasing from yellow to red). The green patches represent the primary productivity. The distribution of euphausiids and mesopelagic fish (important JM prey) is schematically represented on the right part of the habitat as a typical cross-shore section with euphausiids more abundant just after the shelf break and the mesopelagic further offshore.

3 Statistical niche modeling

3.1 Biological data

CJM occurrence data were obtained from:

- Published acoustic data from IMARPE surveys,
- Published acoustic data from IFOP surveys 1997-1999,
- Catches from Dutch fleet 2005-2011,
- Catches from Peruvian fleet 2011-2013,
- Catches from Chilean fleet 2007-2012.

Note that in catches dataset, absence data points can correspond either to a real absence (others species were caught) or to fishing sets with no catches at all; such specific information is not available in the data files.

3.2 Environmental data

Since the availability of biotic and abiotic data on the horizontal and vertical planes over the CJM range of distribution were scarce, satellite environmental data were used as explanatory variables to model its habitat. Sea surface temperature (SST in °C) and sea surface chlorophyll concentration (CHL-a in mg m^{-3}), were obtained from MODIS database (Figure 1). For modeling purpose, we built a 1 degree resolution monthly mean climatology using level-3 data at 18 km resolution. The most consistent satellite environmental data time series period ranges from 2003-2012.

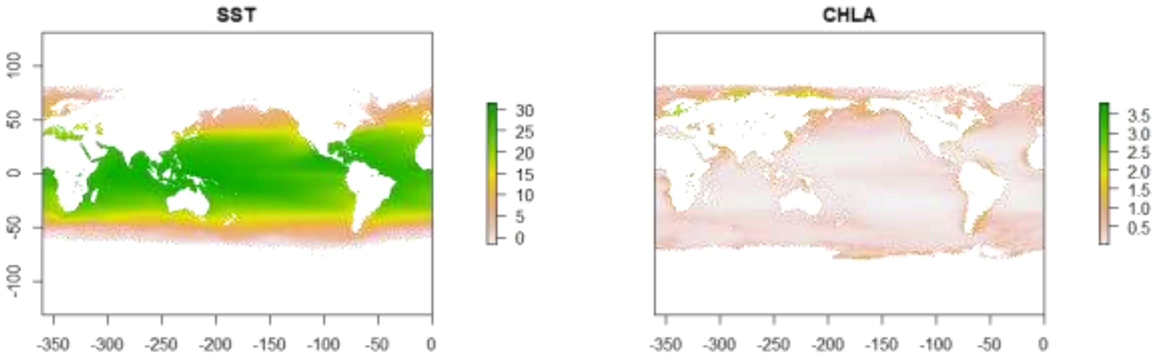


Figure 5. Maps of the habitat variables used to generate the predicted distribution maps: SST and CHL-a monthly mean climatology at 1 degree resolution.

3.3 Method

The methodology used for the statistical modeling is presented in Figure 6.

ENFA was used to create a habitat suitability map that depicts areas where species are unlikely to occur. To generate pseudo-absence data, geographic coordinates were weighted by ENFA predictions and the geographical location of presence-only records (Hengl et al., 2009).

Once the pseudo-absences were simulated, they could be combined with the occurrence locations to build a regression model to predict the probability distribution of occurrences. We used the jack mackerel occurrence (adult and juveniles) from all the available datasets combined with the environmental explanatory variables. Variable predictors of simulated pseudo-absences were extracted from world annual mean climatology. As response variable, we used the presence⁄absence of CJM.

For the regression analysis, assuming a binomial distribution in the response variable, we used a Generalized Additive Models (GAM, (Hastie and Tibshirani, 1990)) to describe the relationships between CJM distribution or catches and the environmental parameters.

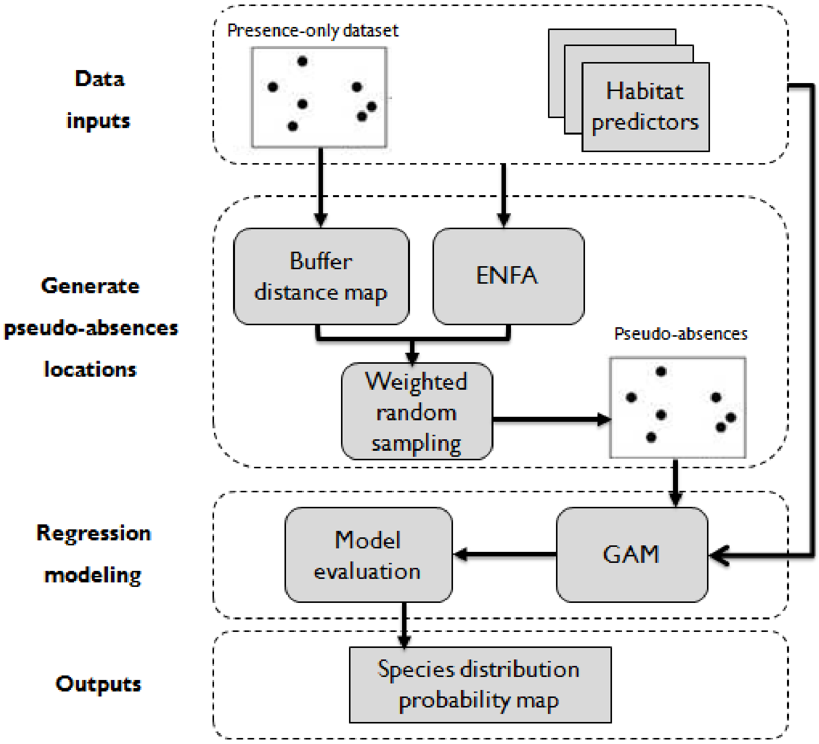


Figure 6. Computational framework and data processing steps

3.4 Results

3.4.1 Intra-annual variability of CJM potential habitat

Figure 7 presents results of the statistical niche modeling using simulated pseudo-absences and GAM algorithm. See Figure 8 for a focus on the Humboldt Current system.

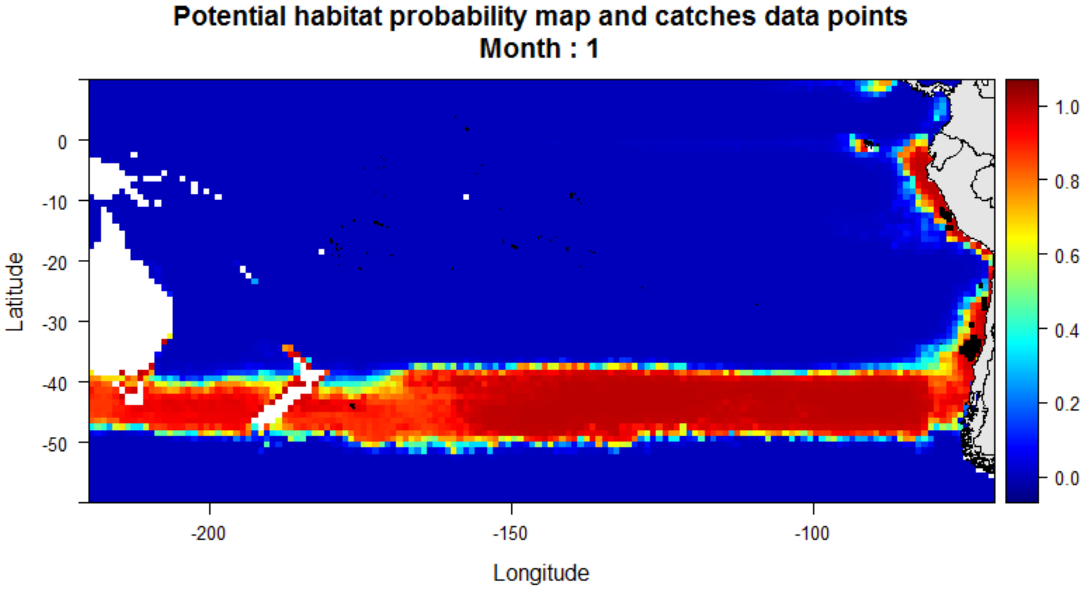


Figure 7. Example of potential habitat probability map using simulated pseudo-absences

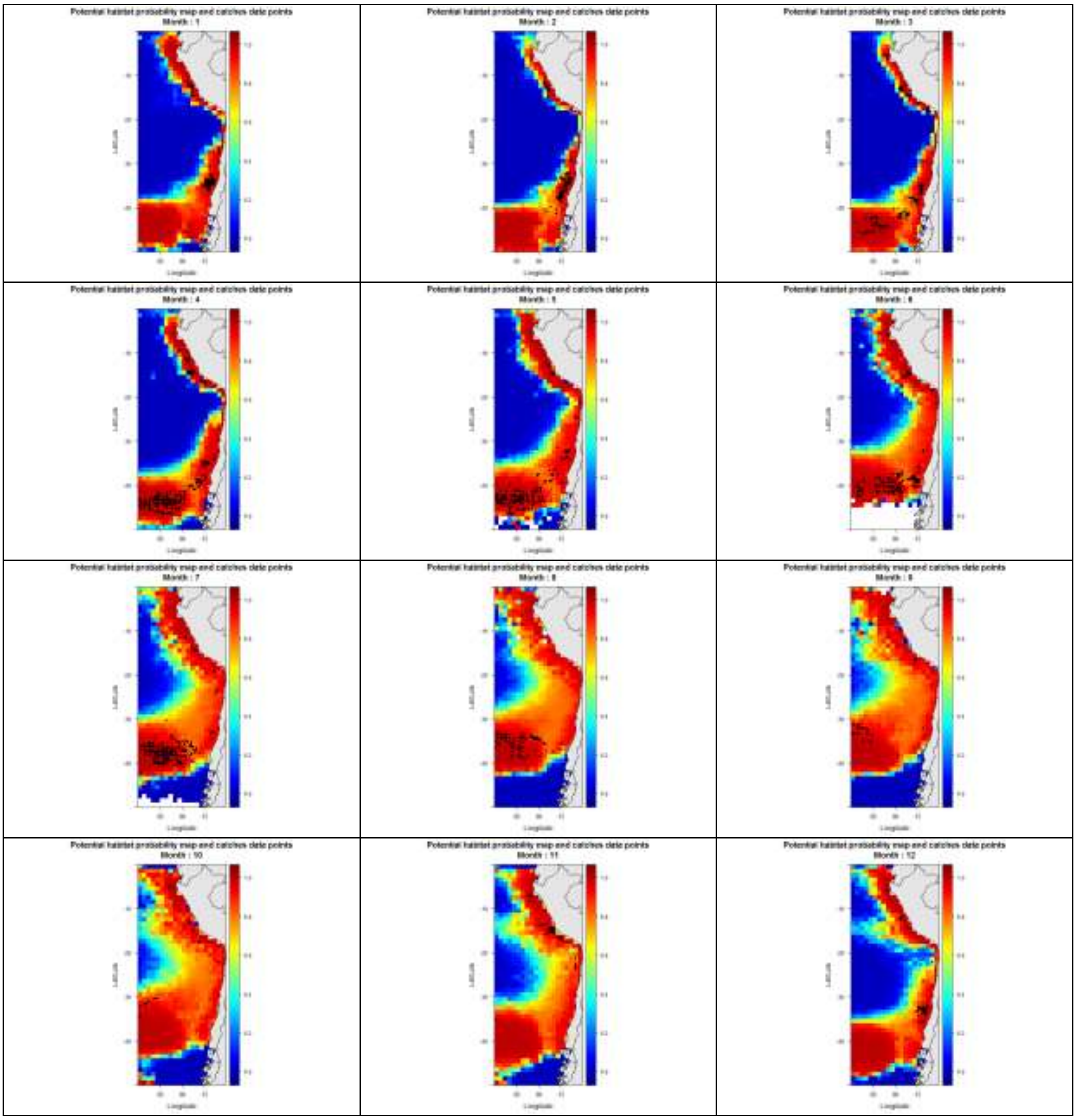
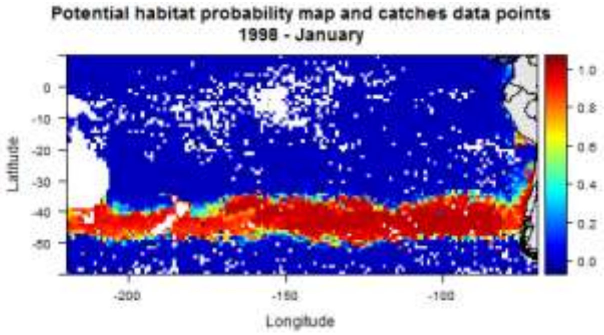
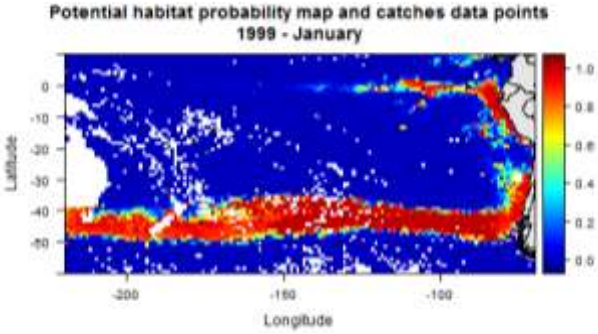
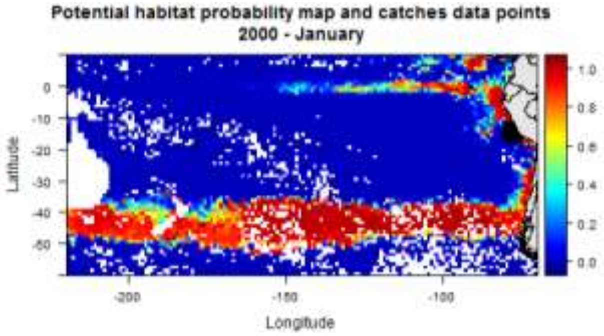


Figure 8. Monthly potential habitat probability map using simulated pseudo-absences. Focus on the Humboldt Current system

3.4.2 *Inter-annual variability of CJM potential habitat*


Potential habitat probability map and catches data points
1998 - January


Potential habitat probability map and catches data points
1999 - January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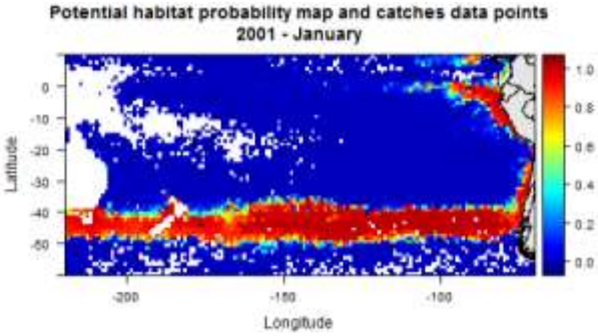
2000 - January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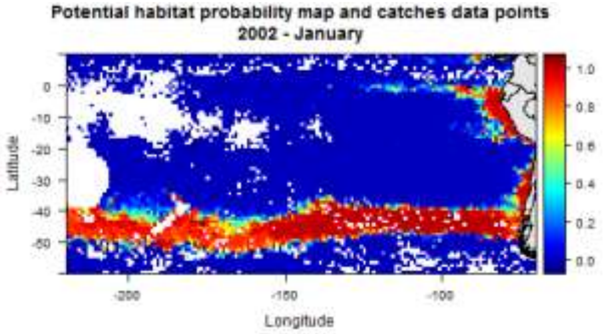
2001 - January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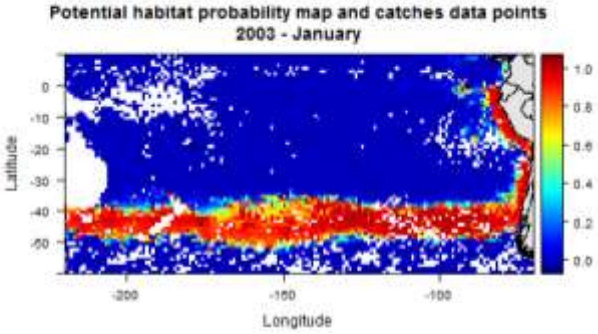
2002 - January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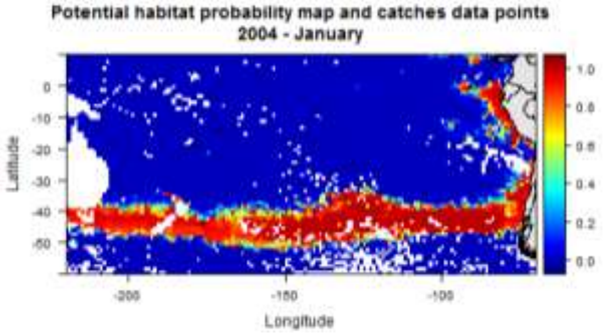
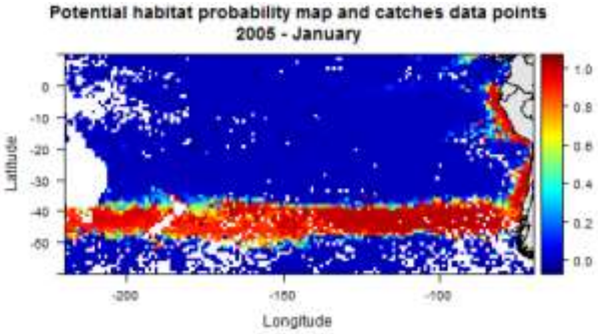
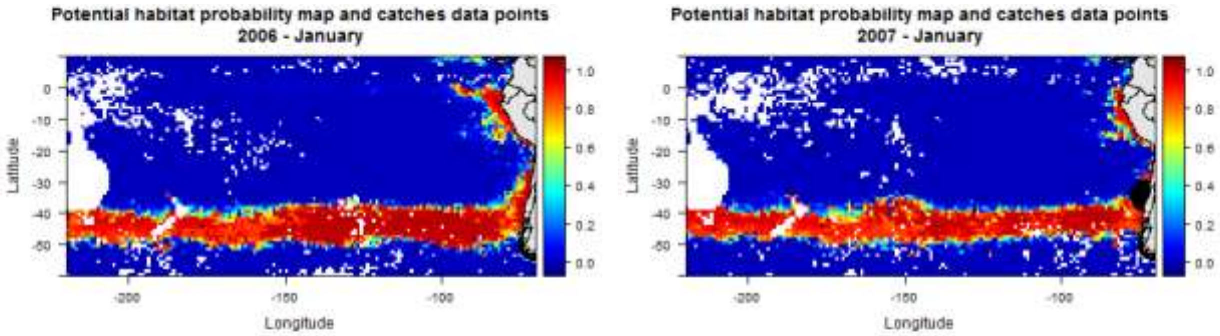
2003 - January


Potential habitat probability map and catches data points
2004 - January


Potential habitat probability map and catches data points
2005 - January


Potential habitat probability map and catches data points
2006 - January

Potential habitat probability map and catches data points
2007 - January

Figure 9. Predicted habitat probability map for month January from 1998 to 2007. Presence data are in black solid circle. White pixels corresponds to missing SST or CHL-a data.

3.5 *Discussion*

Overall, in spite of the low number of environmental parameters we used, results show that statistical model predictions seem accurate correct. Indeed, predicted maps of potential habitat nicely match the observed CJM data and knowledge from the literature. Additional biological datasets, such as historical spatial biological data in high seas and near New-Zealand, would obviously improve the regression model and spatial prediction.

To better capture CJM habitat dynamics in three-dimensions, we suggest to add new habitat predictors if available. As shown previously, oxygen plays a fundamental role in structuring the ecosystem in the south eastern Pacific. To include the vertical dimension, a monthly climatology of dissolved oxygen would be highly relevant.

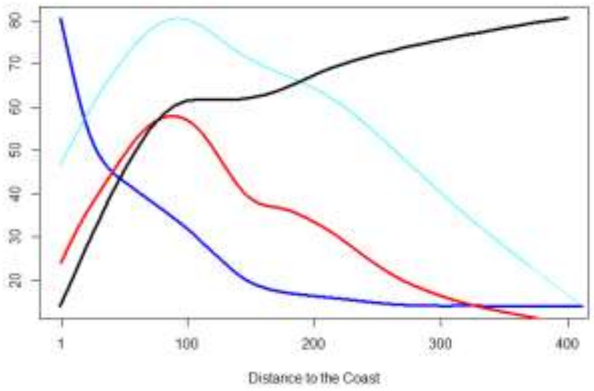


Figure X. Mean cross-shore profiles of Z2mL/L in m (black solid line), and the acoustic-estimated biomass of anchovy (blue solid line), sardine (red solid line) and jack mackerel (light blue solid line). Bertrand et al. unpublished.

(Bertrand et al., 2011) showed that when the oxycline is shallow, fish such as sardine are expulsed from the system. The upwelling of highly demineralized, sub-toxic water is evident close to the coast. However such feature cannot be resolved with climatology at 1º; for that purpose at least 1/3° climatology is required.

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