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Analysis of the spatio-temporal pattern of Southern blue whiting *Micromesistius australis australis* abundance in the bottom-trawl fisheries in the southwest Atlantic using GIS techniques

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ABSTRACT

Southern blue whiting (*Micromesistius australis australis*) inhabits the waters of the Southern Hemisphere, and in the south-west Atlantic Ocean. It is distributed over an area next to the Falkland/Malvinas Islands, where it is commonly the most abundant commercial finfish species. This fish migrates to the outer Falkland shelf and aggregates in dense schools to spawn in August-September in the south-western part of the islands. Feeding concentrations of Southern blue whiting are targeted by specialized surimi vessels until the following March. Southern blue whiting is also taken as an occasional bycatch by finfish trawlers. Fishery and biological information collected by scientific observers aboard commercial Spanish trawlers between 1988 and 2003 were analysed in relation to physical and environmental factors to establish the spatio-temporal pattern of the species. The data included 26 168 commercial hauls of which 4 797 positive (including effort, catches and discards, as well as biological and environmental information). CPUE (Catch Per Unit Effort, $kg \cdot hr^{-1}$) was used as abundance index. The analysis of the general spatio-temporal pattern of fish abundance, and the influence of environmental factors, such as SST, SBT and depth on fish abundance and distribution, was based on correlation, variograms, and time-series maps created using GIS. Mature individuals and more specifically spawning females were recorded mainly in the waters south and south-west of the Islands, between 100 and 200 m isobaths.

Keywords: Southern blue whiting, *Micromesistius australis australis*, SW Atlantic, GIS, spawning, environment, spatio-temporal pattern

INTRODUCTION

The Falkland Islands support a diverse fleet of finfish trawlers that operate throughout the year targeting predominantly Southern blue whiting, hoki, hakes, kingclip and red cod. The majority of the finfish trawling effort is concentrated in the west of FICZ (Falkland Islands Interim Conservation Zone) at water depths up to 400 m, but typically between 100-200 m. Southern blue whiting (*Micromesistius australis australis* Norman, 1937) is one of the largest finfish resources in the Southwest Atlantic. It is a schooling species that inhabits the waters of the Southern Hemisphere, and in the south-west Atlantic Ocean it is distributed over an area next to the Falkland/Malvinas Islands (Fig. 1). The taxonomic position of this genus was first introduced by Norman (1937). Blue whiting are benthopelagic/pelagic and live at depths of 100 to 600 m during winter and spring, live in shelf waters during summer and over the continental slope in winter (Cohen *et a*l., 1990). This species is divided into two subspecies, the Patagonian subspecies *M. australis australis* differing from the New Zealand subspecies, *M. australis pallidus*, on proportional lengths of the head, snout, upper jaw, eye diameter, and first dorsal fin base (Inada and Nakamura, 1975). *M. a. australis* forms large and dense spawning schools in the waters of south and east of the Falkland Islands during winter and early spring.

The stock assessment of Southern blue whiting performed by RRAG (Imperial College) in July 2003 suggested that the spawning stock biomass (SSB) stopped declining in 2002 at a level of ~ 325,000 mt (FIG Fisheries Department, 2004). The spawning season of *M. australis* in the south-west Atlantic Ocean extends from August to October, with a main peak during September.

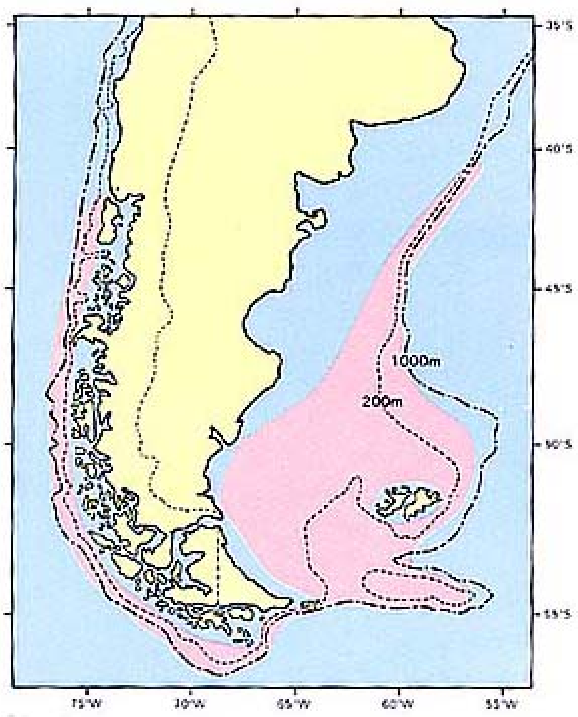


Figure 1. Distribution of *Micromesistius australis australis* in Patagonia. (Source: INIDEP)

Areas and fishing period

The area where fishing activity targeting to *Micromesistius australis australis* takes place is relatively limited. It extends from 45º S to 56º S, being the zone within 52º S, 55º S, 63º W and 64º W the most remarkable area where highest catches were collected by surimi fishing fleet from 1992. Southern blue whiting is also taken as an occasional bycatch by finfish trawlers.

The fleet targeting the Southern blue whiting around Falkland Islands basically occurs within two areas. The first is located to the northeast of the Islands and is visited throughout the whole year, the second one, is situated on the west, spreading towards the southwest during the second half of the year when the spawning of *M. a. australis* occur (FUCEMA- B.I.P. Base de Información Pesquera)

The Southern blue whiting is present throughout the year, but strong variations in its distribution and fishing yields were observed. Giakoni (1992) showed the lack of *M. australis australis* above latitude 52 ºS during December while Lillo and Paillamán (1996), Córdova and Céspedes (1997), Lillo and Céspedes (1998) and Lillo *et al*. (1999) described, from data gathered through fishing activity, seasonal variations in the distribution of this species with a northern limit located at latitude 47º S during winter and 52º S during summer.

Studies made in the past pointed out that the *M. australis australis* spawn in a discontinuous way, with an annual spawning (Sanchez *et al*. 1986) from August to September, extending occasionally until November in the Atlantic (Sanchez *et al*. 1986), whilst spawning in the Pacific takes place during mid July and September (Córdova and Céspedes, 1997; Lillo and Céspedes, 1998).

DATA AND METHODS

Data used into the GIS

Spatially referenced commercial fishery data, as well as bathymetric and SST data were examined using Geographic Information System (GIS) techniques in order to map and visualize information about the distribution and the abundance of commercial catches of *Micromesistius australis australis* in the Falkland Islands and in the High Seas from 1988 to 2003.

Fishery, bathymetric and SST data were integrated within the GIS (ArcGIS version 8.2). This process allows a visual analysis and also the extraction of more information about the parameters that are having an influence in the catches distribution.

1- Environmental data- SST

Sea surface temperature (SST) data collected by scientific observers on board commercial vessels were geo-referenced to a base map of the Southwest Atlantic and was used to analyse its relationship with *Micromesistius australis australis* abundance.

2- Bathymetry data

Bathymetry contours of the Patagonian shelf were extracted from GEBCO (General Bathymetric Chart of the Oceans) Digital Atlas. This bathymetry data were entered into the GIS. Bathymetric contours represented here are 0 m, 200 m, 500 m and 1000 m.

3- Fishery data- FIFD and Spanish data

Daily fishery data for the present study were collected by observers working for the IEO (Instituto Español de Oceanografía, Vigo, Spain) and FIGFD (Falkland Islands Government Fisheries Department, Stanley) on board commercial vessels for the 17-year period 1988-2003. All data were integrated into a MS Access database and used in analysis and modelling.

Fishery data were imported and integrated into the GIS as monthly time-series grids at spatial resolution of 0.5 degrees. CPUE (catches per unit effort, kg/hr) was used as an index of abundance in the fishery. This index reflects fish abundance and accounts for changes in fleet activity over the 17-year period. Maps were visually analysed in order to find relations between bathymetry, SST and fisheries data for the same month.

Geographical Information System methods

GIS maps

Southern blue whiting raster data sets were created with the GIS on a monthly basis. Each cell in the map, is a square that represents a specific portion of an area with a spatial resolution of 0.5º degree longitude and 0.5º degree latitude square. The size of the cell was selected in order to accomplish a detailed analysis of the temporal evolution of the features represented in the maps (CPUE , ratio of catches to the total catches and modal length).

Density surface maps

Southern blue whiting density surfaces were created in the GIS as monthly raster layers. Each cell in every layer gets a density value based on the number of features (hauls with CPUE > 0 kg/h) within a radius cell of 1.5 degrees. To create a density surface we have used the Kernel method that uses a mathematical function to give more importance to features closer to the centre of the cell. With this method, maps with patterns that are easier to interpret were obtained. The GIS defines a neighbourhood (based on the search radius specified, in this case 1.5 degrees) around each cell centre. It then totals the number of features that fall within that neighbourhood and divides that number by the area of the neighbourhood. That value is assigned to the cell. The GIS moves on to the next cell and repeats the same procedure, resulting in the creation of a smoothed surface. Mapping density shows where the highest concentration of Southern blue whiting is found on a monthly basis.

Besides the visual analysis of the maps, the rank correlation was carried out between *M. a. australis* abundance and other variables (month, latitude, longitude, average depth, SST, lunar cycle and sky pattern) in order to quantify the correlations between them.

Statistical analysis and modelling

Spearman´s rank correlations

The relationship between CPUE for Southern blue whiting and all the variables (SST, SBT, latitude, longitude, month, lunar cycle, etc) was investigated by calculating Spearman's rank correlation for three-month periods. The Spearman's rank correlation coefficient was used as a measure of linear relationship between paired sets of data (being CPUE one of them). This coefficient takes value between –1 and +1. A positive correlation is one were both variables increase together. A negative correlation is one in which the ranks of one variable increase as the ranks of the other variable decrease. A correlation close to zero means there is no linear relationship between the variables. The statistical calculation was carried out using the Statsoft version 5.1. Applying Spearman's rank correlations involves linearity between variables, and this assumption was not always true in this work. For this reason, Generalized Additive Models were applied to the data set.

Generalized additive models (GAMs)

Generalized Additive Models (GAMs) are able to deal with non-linear relationships between an independent variable and multiple predictors and are particularly appropriate to our study.

In order to model the variations of *M. a. australis* fishery abundance we have used GAMs. GAMs were first proposed by Hastie & Tibshirani (1990) and some of the first applications to fishery data were by Swartzman *et al*. (1992, 1994, 1995). A GAM is a non-parametric regression method with less strict assumptions of normality and linearity than linear regression. This method is an extension of the generalized linear models (GLMs; McCullagh & Nelder 1989). The principal strength of additive models is their ability to fit complex smooth functions (smooths) in the predictor rather than being constrained by the linearity implicit in GLMs. A GAM, the generalized version of an additive model, is expressed as:

$$g(E[y]) = \beta_0 + \sum_k S_k(x_k)$$

The right-hand side of the equation is the additive predictor. β_0 is an intercept term and S_k is a one-dimensional smoothing function for the k^{th} spatial covariate, x_k. The degree of smoothing is determined by the degrees of freedom (d.f.) associated with the smoothing function. The larger the degrees of freedom, the less the smoothing performed and more flexible the function obtained.

In order to model variation in *M. a. australis* abundance we fitted GAMs using the "gam" command in S-Plus and using cubic smoothing splines to smooth covariates. Spline smoothers are popular smoothers because they have a theoretical justification that can be used to determine the appropriate smoothness for the fit. Smoothing splines are locally cubic splines that minimize a penalized residual sum of squares, drawing a smoothed curve through the data points.

In our model, the expected value of Southern blue whiting abundance is expressed as a sum of smooth functions of the covariates (month, latitude, longitude, SST and average depth). All data were imported into S-Plus from excel files and configured as data objects. Data were screened to reveal characteristics of data sets and scatter plots were made for each pair of variables. The error distribution used was the Gaussian distribution, which is normally appropriate for describing spatial heterogeneity and abundance data (see Maravelias, 1997; Swatzman *et al*., 1994).

To measure the goodness of fit of the model, a pseudo-coefficient of residual determination, PCf, is estimated (Swartzman *et al*., 1992):

$$PCf = 1 - \frac{RD}{ND}$$

where RD is the residual deviance, i.e. the deviance of the full model, similar to the residual sum of squares in a linear model, and ND the null deviance, i.e. the deviance of the model with only the intercept term. PCf values obtained are listed in Table 1.

Table 1. Summary of GAM results for weighted and unweighted models

Unweighted model		
ND	**RD**	**PCf**
5,69736E+11 (4333 d.f)	5,31936E+11 (4313 d.f)	0,06634558
Weighted model		
ND	**RD**	**PCf**
2,12913E+11 (4333 d.f)	1,90369E+11 (4313 d.f)	0,105886287

Unweighted model		**Weighted model**	
Variable	Pr(F)	Variable	Pr(F)
Month	0	Month	0
Latitude	0	Latitude	0
Longitude	0	Longitude	0
AvgDepth	0	AvgDepth	0
SST	0	SST	0

In this work, the fishing effort variable was used as a weighting factor. The amount of fishing effort can be considered as an index of the quality of the sampling, and more effort probably implies more reliability in the data. Therefore, in the weighted model, less importance is assigned to data with low fishing effort and more importance to data with high fishing effort. An unweighted model was also fitted for comparison. Scatter plots and GAM plots are shown in figures 10 and 11 respectively.

Analysis of biological data

Data on length were collected by observers by measuring total length (TL) of at least 100 individuals in each sample when possible. A scale of four maturity stages was used in order to study the *M. a. australis* maturity stages distribution during the year.

Data on modal lengths in each haul were mapped using GIS.

Length weight relationships were calculated.

RESULTS AND DISCUSSION

Spatial distribution of catches of *M. a. australis*

The main fishing activity for the *M. a. australis* is distributed over the south west of the Falkland/Malvinas Islands, close to the 200 m isobath (Fig. 2). Highest CPUEs values are located in the spawning area (between latitudes 50º and 54º S). Southern blue whiting hauls were also recorded in 42º S and 46º S but CPUE values were not significant in comparison with the values found to the south west of the islands.

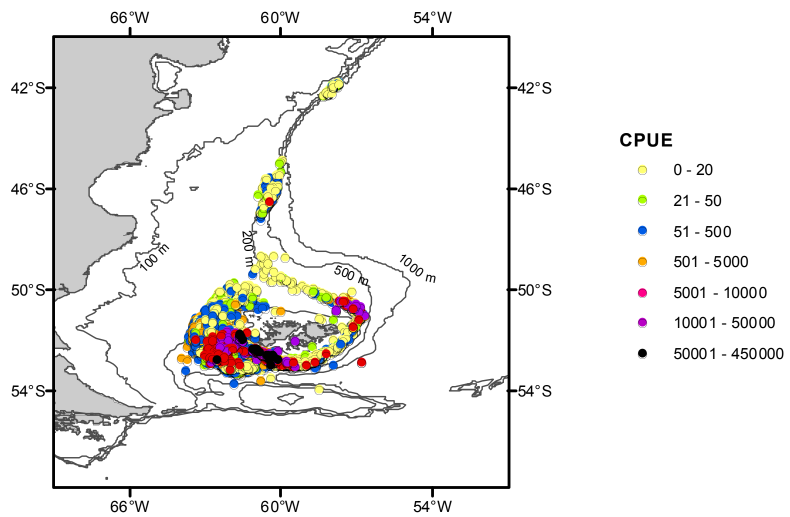


Figure 2. *M. a. australis* hauls and CPUE values

Figure 3 illustrates the monthly distribution of observed CPUE (kg/hr) from 1988 to 2003 for *M. a. australis.* Southern blue whiting were mainly encountered, as expected, in large aggregations to the south and southwest of the Falklands. It was found that CPUE monthly distribution was variable throughout the year and the highest concentration of positive hauls for this species was found for August to November period in the southwest of the Falkland/Malvinas Islands among parallels 51º 40' and 51º 50' S and meridians 61º 30' and 62º 00' W. CPUE values for this period were, for certain hauls, higher than 50,000 kg/h. On the other hand, June and July were characterized by low CPUE values (neither of them higher than 500 kg/h).

The display of the monthly averaged CPUE maps for *M. a. australis* (Fig. 4) shows that, for the first quarter, the maximum averaged values were reached in January and February in the southwest region of the Falkland Islands. During the second quarter the averaged values of CPUE in the southwest region show a decreasing pattern. August map shows two isolated points characterized by high values, they appear as the result of the proximity of several positive hauls with high CPUE values in a searching radius of 0.3 degrees. In general terms this is during the last quarter of the year (September to December) when the highest CPUE values were recorded. In September they were mainly located at the southwest coast of Falkland Islands. October and November the higher values were found in the east part of the islands. December was characterized by the concentration of high CPUE values around the southwest area and also in the northeast.

Regarding to the maps of the ratio of *M. a. australis* catches to the total catches (Fig. 5), it was especially significant in the southwest of Falkland Islands reaching proportions ranging between 80-100% during January and February. From March to July catches of Southern blue whiting were not significant in proportion with the catches of the rest of the species for the same haul. From August to December this proportion increases in areas located at the southwest of the Falkland Islands and keeps low values in other areas were positive hauls for this species were registered (42º S, 46º S and 49º S).

Density maps

Micromesistius australis australis was present in a significant number (4 797) of trawls in the area mainly located at the southwest of the Falklands Islands. Density surface maps (Fig. 6) show the presence of this species during the first and third four-month period. May, June and July were characterized by the low abundance of *M. a. australis* in the whole area. The highest densities values were found in the southwest of the Falkland Islands during September and October. This fact could be possibly related with the migration of the species from the south of Tierra del Fuego towards the spawning area located to the south of Malvinas. November and December density maps show also the presence of *Micromesistius australis australis* in the area located at the east of the Falklands.

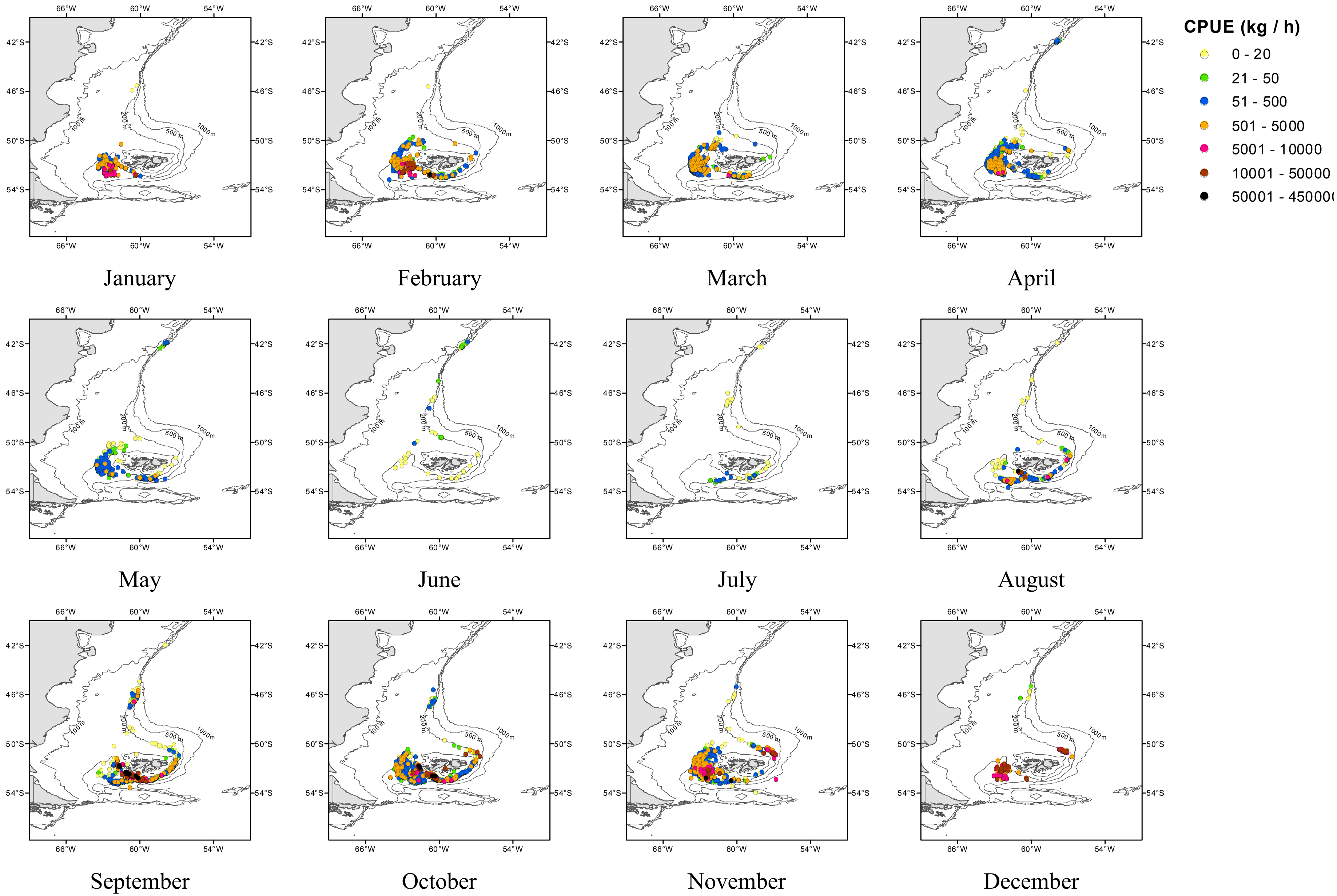


Figure 3. Location of hauls where *M. a. australis* was recorded and CPUE in different months over the period 1988-1999.

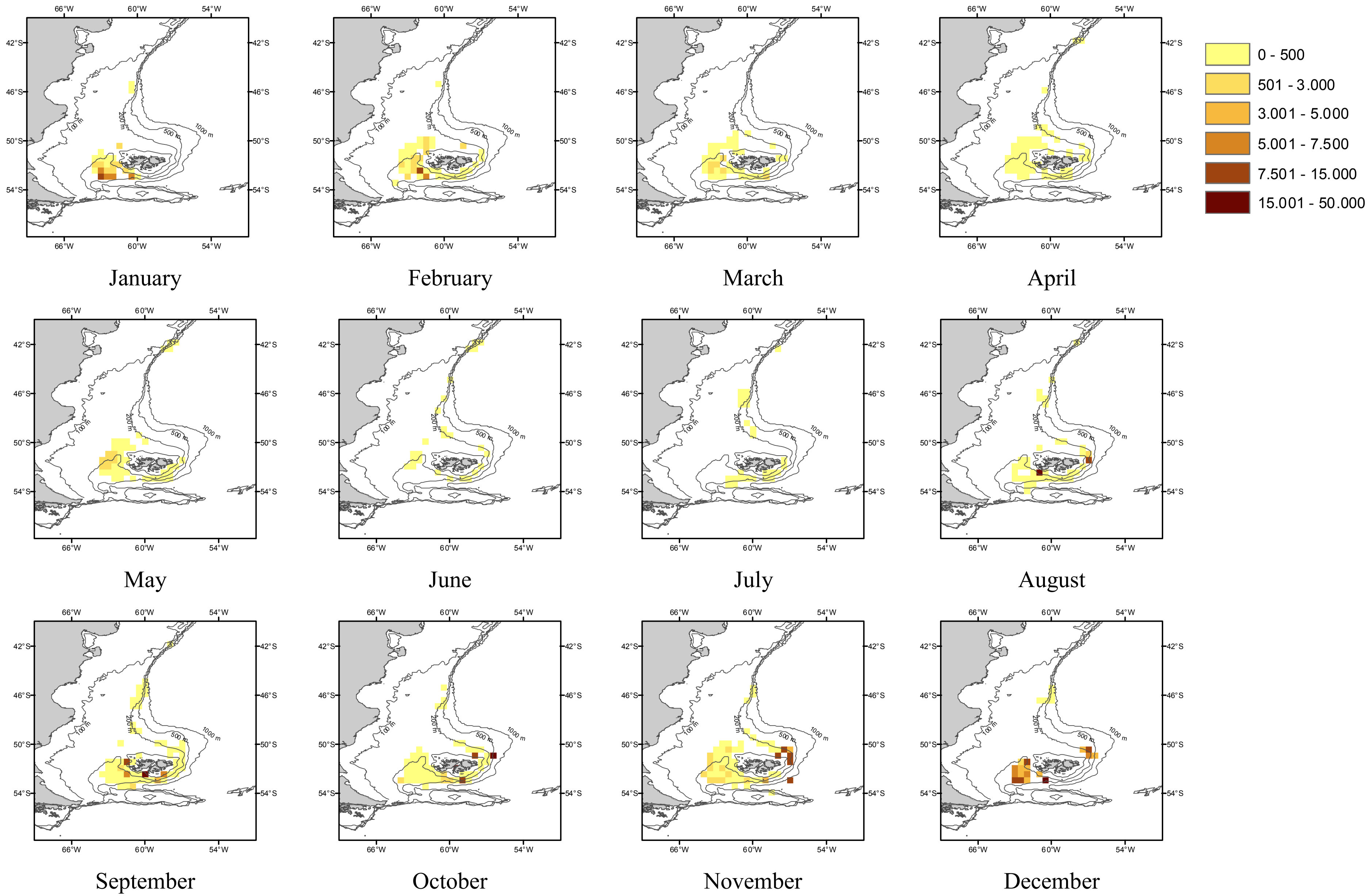


Figure 4. *M. a. australis* monthly averaged CPUE maps at 0.5 by 0.5 degree resolution

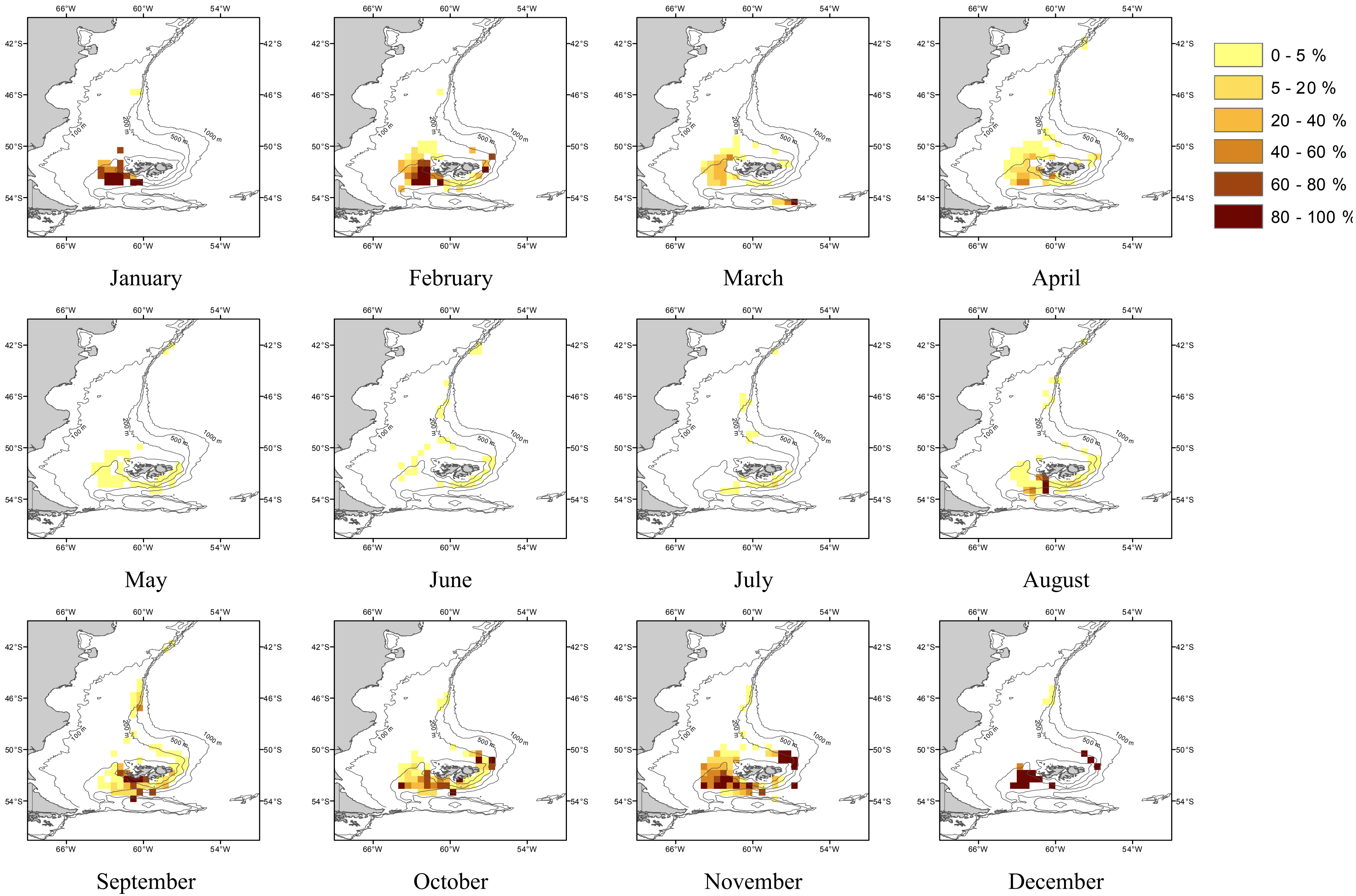


Figure 5. Monthly ratio of *M. a. australis* catches to the total catches of all species at 0.5 by 0.5 degree resolution

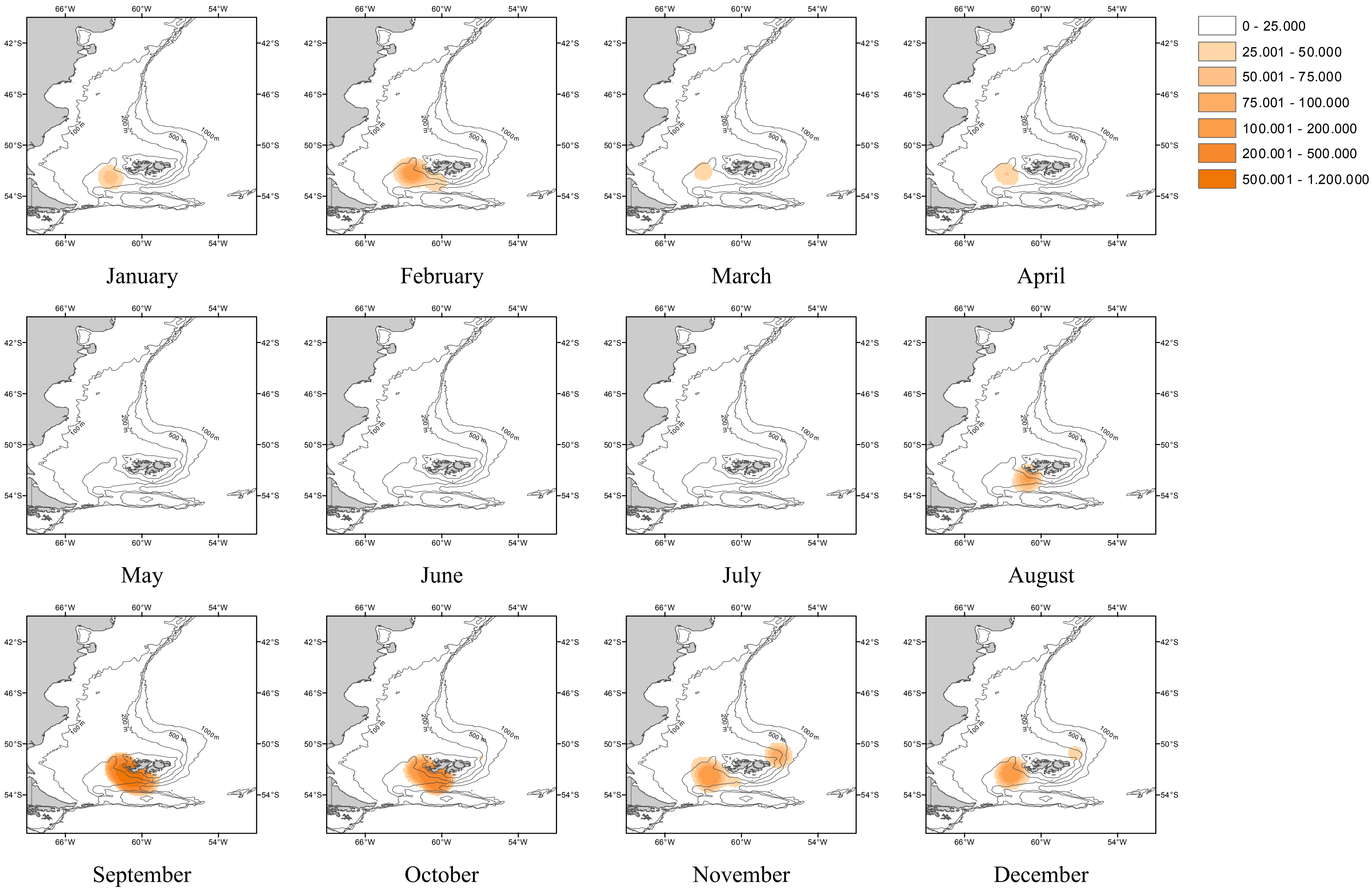


Figure 6. *M. a. australis* density maps (0.125 x 0.125 degrees resolution)

Biological data

Maturity

A scale of four maturity stages based on differences in the appearance and size of the gonads was used in order to study the *Micromesistius australis australis* maturity distribution during the year.

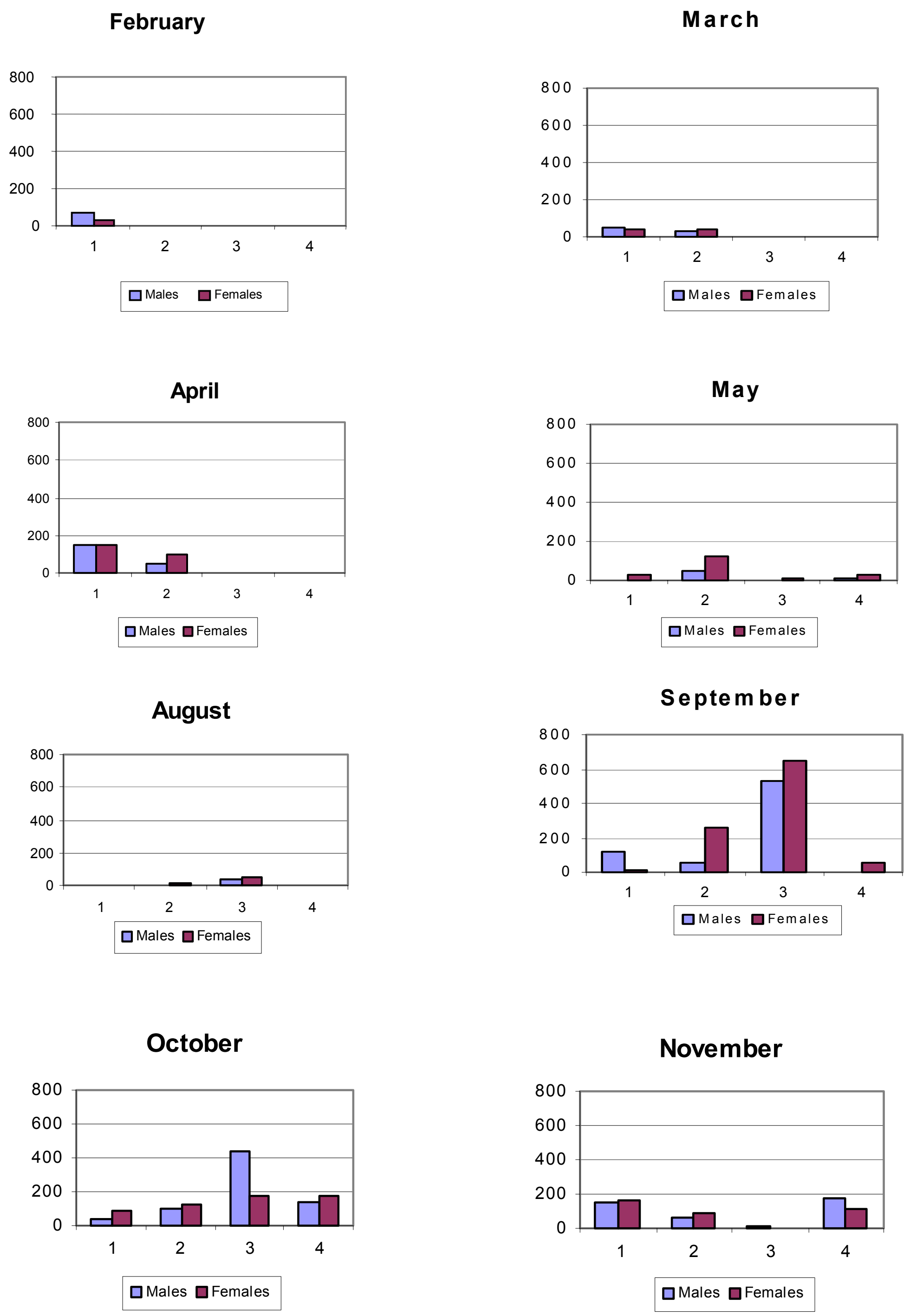


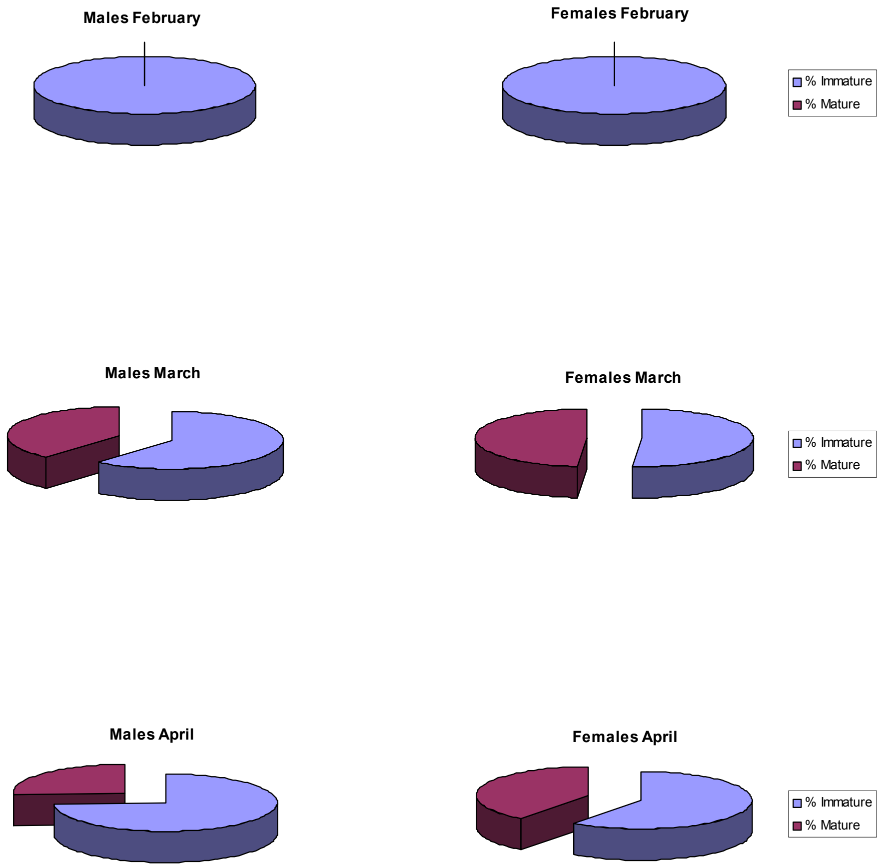
Figure 7. Monthly maturity status distribution

Graphs in figure 7 show the distribution of monthly maturity status for the Southern blue whiting where blue bars represent males and deep pink bars correspond to females.

During February no mature individuals (maturity stage ≤2) were found in the sampling. Small number of individuals with maturity stages 3 and 4 were found for the first time in the year during May as a result of the growing of the specimens.

From September to November, there is a clear increase in the amount of individuals and the proportion of mature specimens is quite significant for both sexes. Maturity stage 3 (spawning) was the predominant during September and October. In November the individuals are distributed within all the maturity stages (from 1 to 4), being the maturity stage 3 the less significant of all of them.

Maturity Pie Charts



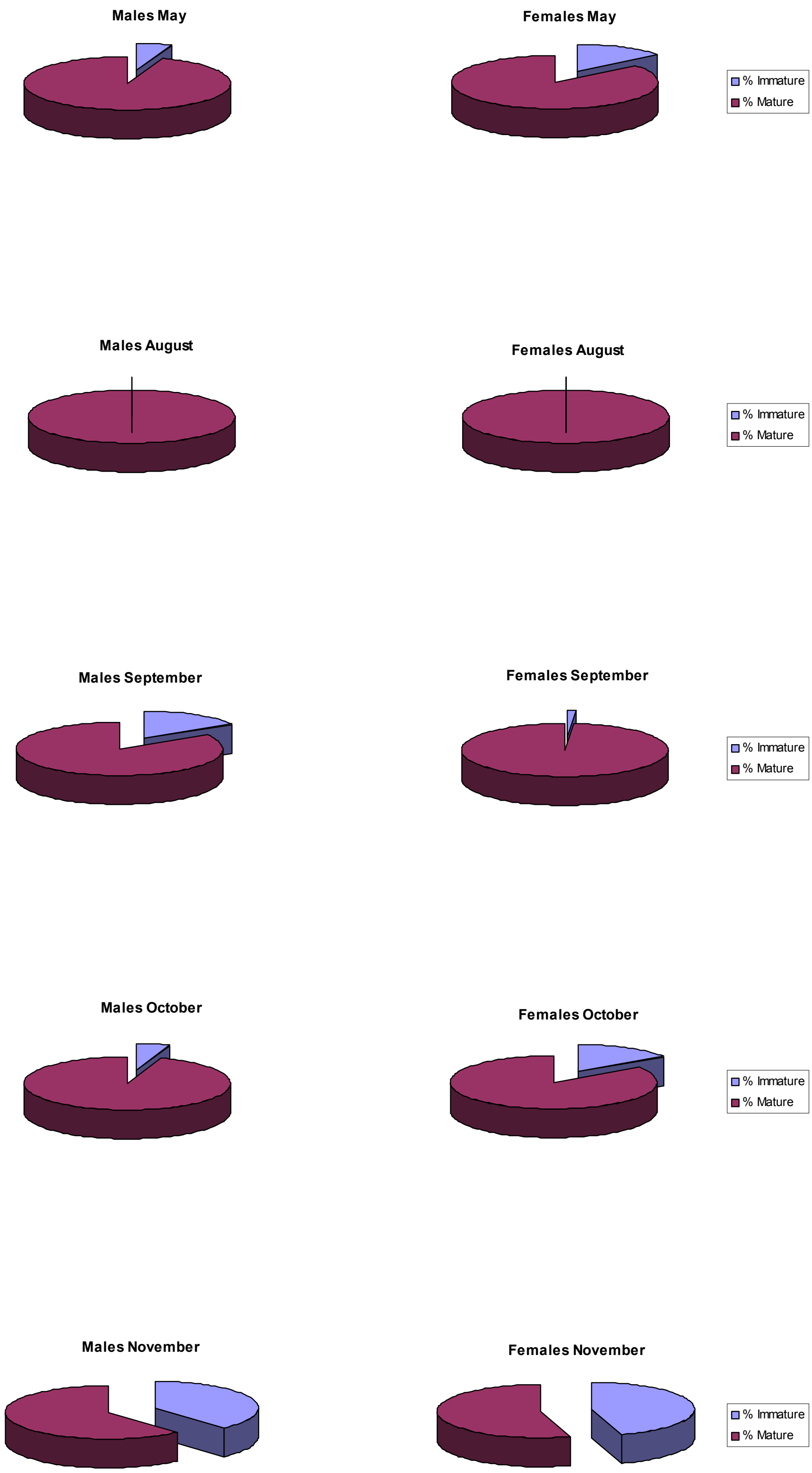


Figure 8. Percentage of mature individuals by sex and month

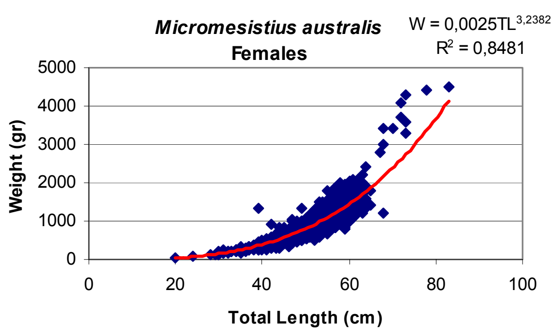
Percentage of mature individuals of *M. a. australis* by sex and month are presented in figure 8. February was characterized by the absence of mature males and females. All sampled individuals were mature.

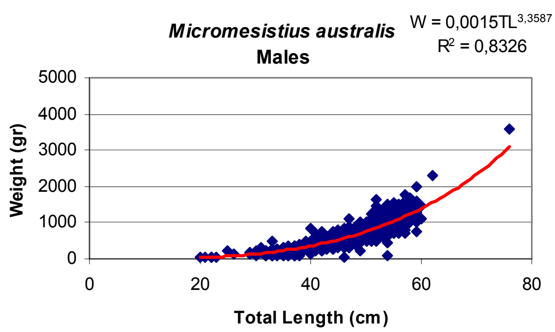
During March and May the proportion of mature males was lower than immature males. This situation changes from May to November where proportion of mature males was much higher than immature males individuals. In August no immature individuals (males and females) were found.

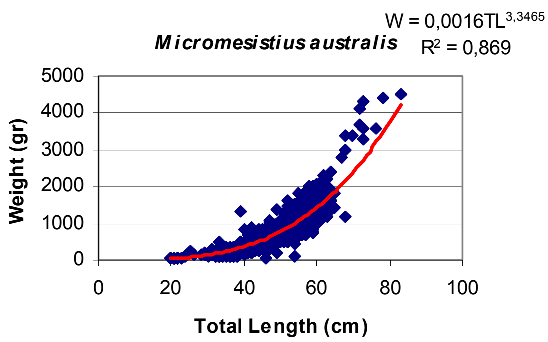
A similar pattern was found for females. Making a monthly description of the pie charts we observe that March and April were characterised by a significant amount of immature females. Proportion of mature females increases in May becoming100 % in August. From September to November the proportion of mature females was much higher than immature females and with a decreasing trend. Proportion of immature and mature females was quite similar during November.

Length-weight relationships

Maximum total length (TL) recorded for *M. a. australis* were 76 cm TL for males and 83 cm TL for females. The relationship between total length (TL) and body weight (W) is shown in figure 9.







	a	b	R^2
Males	0,0015	3,3587	0,8326
Females	0,0025	3,2382	0,8481
Total	0,0016	3,3485	0,869

Figure 9. Relationship between total length (TL) and body weight (W) for *M. a. australis*

Scatter plots

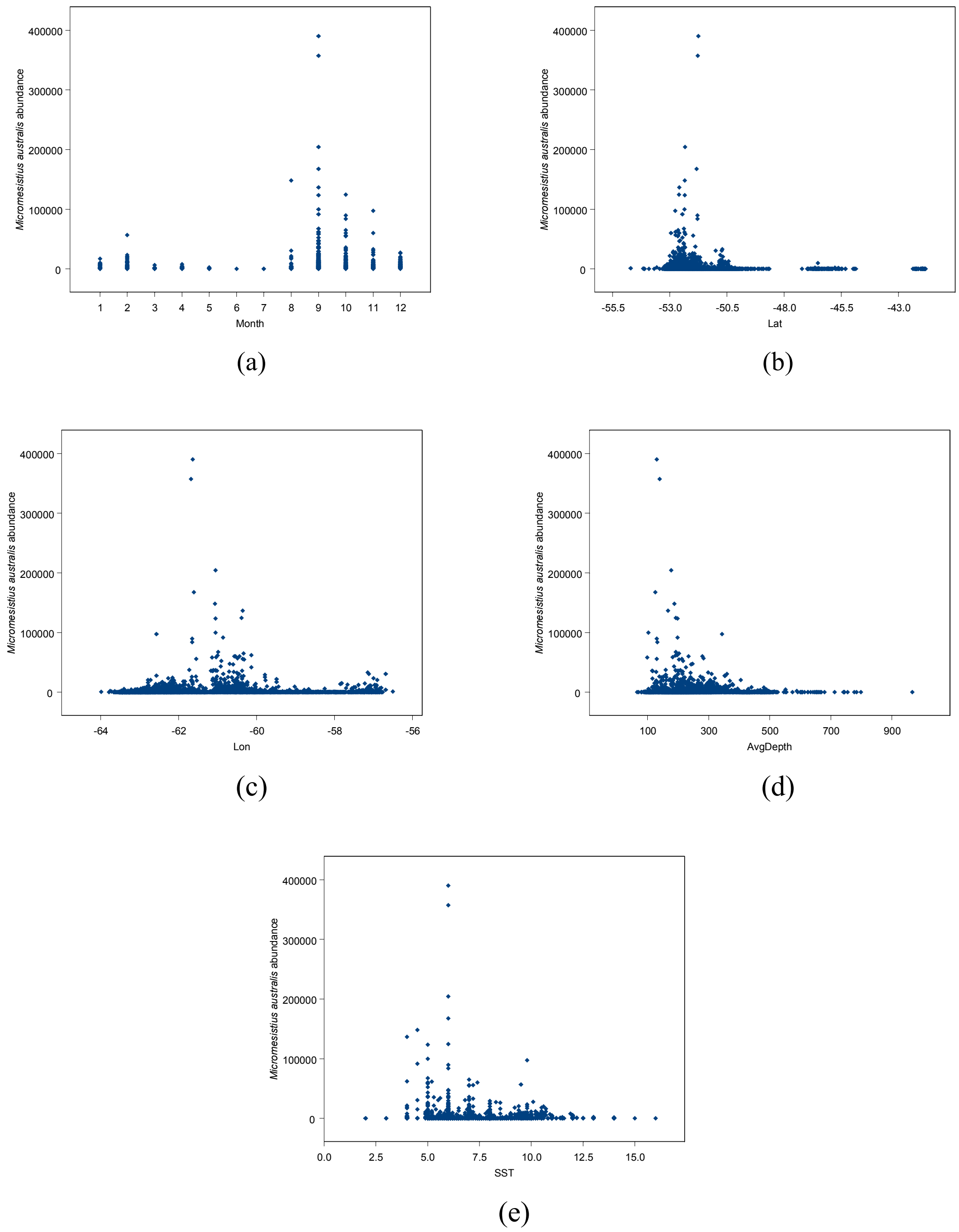


Figure 10. Scatter plots showing the relationship between *Micromesistius australis australis* abundance (CPUE as kg/h) and month (a), latitude (b), longitude (c), average depth (d) and SST (e)

The scatter plots represented in figure 10 suggest that:

1- Maximum and minimum CPUE values were found from August to December and from May to July respectively. Maximum CPUE values were recorded during September.

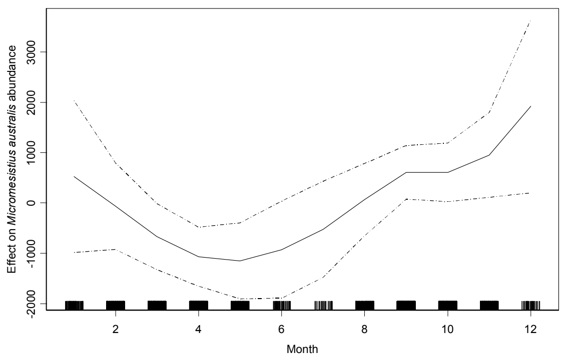
2- The relationships of CPUE with longitude and latitude are basically indicating the geographical area in which the fishery is located.

3- Large Southern blue whiting abundances occurred over a range of average depth from 100 to 250 m.

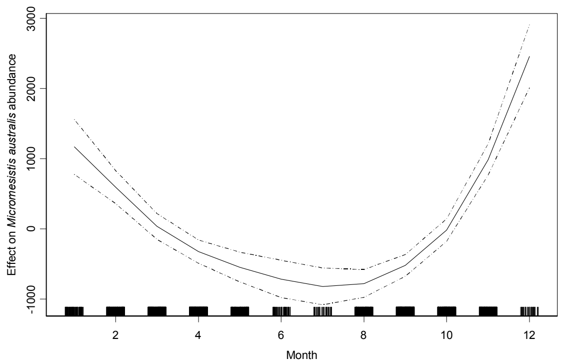
4- SST values between 3.75º and 6.25º C were associated with highest abundances. Relatively high CPUE values were found at SST around 9º C.

Generalized additive models (GAMs)

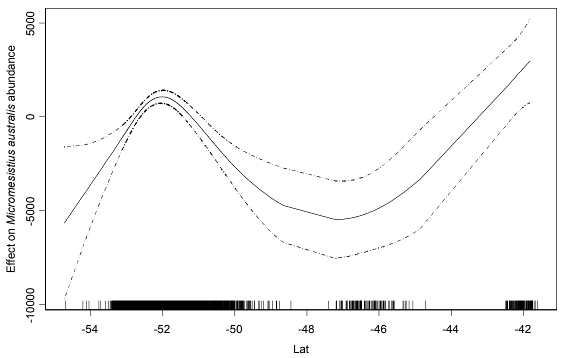
Unweighted model | *Weighted model*



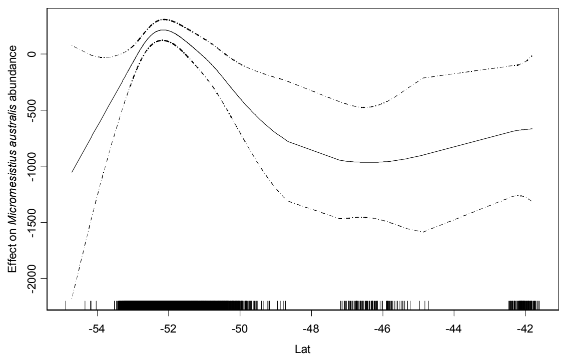
(a)



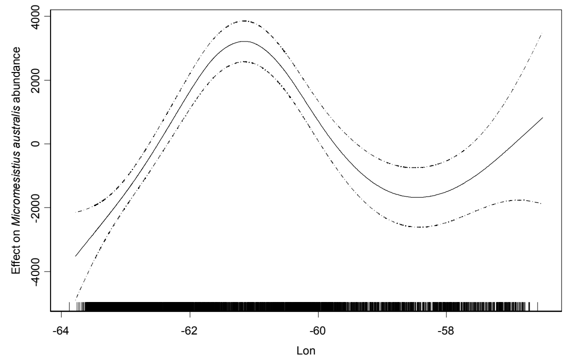
(b)



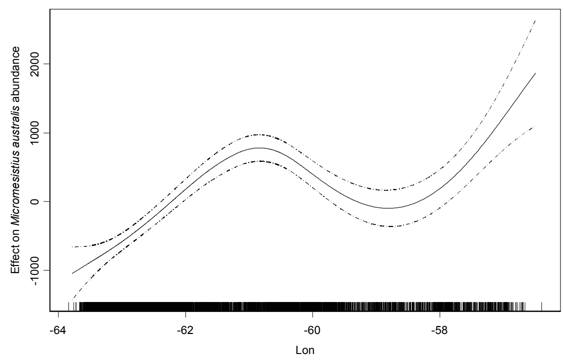
(c)



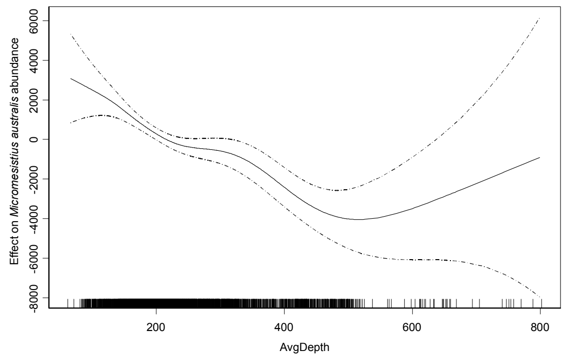
(d)



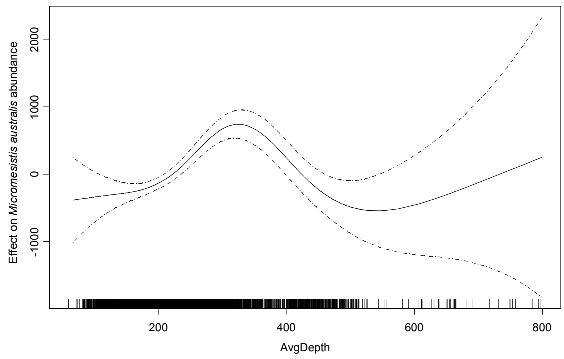
(e)



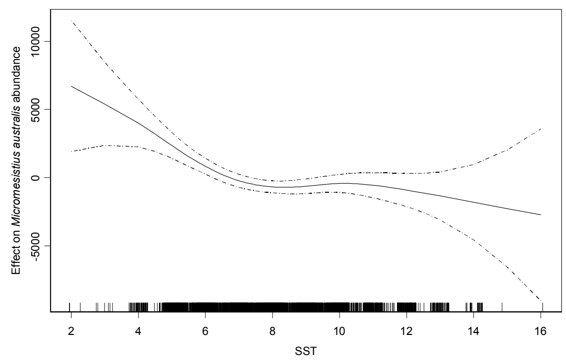
(f)



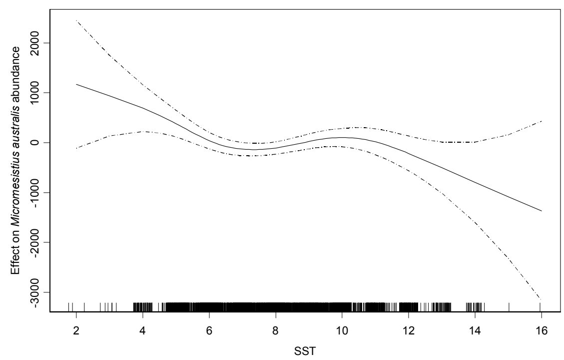
(g)



(h)



(i)



(j)

Figure 11. Results of GAM regression for unweighted and weighted model

M. a. australis abundance was represented as a function of month from January to December (Fig. 11 a & b); latitude (Fig. 11 c & d); longitude (Fig. 11 e & f); average depth (Fig. 11 g & h) and SST (Fig. 11 i & j). Dashed lines indicate plus and minus two pointwise standard error boundaries around the covariate main effects. Tick marks on the x-axis show locations of data points. The density of points for different covariate values is shown by the rug under the single covariate effect plots. Fewer points lead to larger standard error bands. The plots show the best fitting smoothers (and 90% confidence limits) for the effect of the covariates included in the model.

The effects that the explanatory variables have on *M. a. australis* abundance can be explained by examining the fitted contribution of each variable to total abundance plotted against the value of the variable.

As figures 11 (a) and (b) illustrates there is a clear seasonal effect in the abundances. This pattern is more notable in the weighted model. The maximum abundances are found during the first months of the year and then decreasing progressively toward July where the effect is clearly negative. From July the trend increases in a remarkable way towards the end of the year.

As it has been previously said, the relationships of *M. a. australis* abundance with longitude and latitude basically indicate the geographical area in which the fishery is located. Figures 11 (c) to (f) show a peak in abundances located within latitude 52º S and longitude 61º W.

Regarding to latitude, there are significant differences between the unweighted and weighted models. Both models depict a peak in abundances at 52º S and then a notable decreasing trend that reaches the lower level of abundances at 47º S (Fig. 11 (c)). From this latitude, the trend becomes positive again and abundances increase with latitude. In the weighted model the relationship between latitude and abundance consist of a peak in 52º S and of a negative effect from latitudes above 52º S.

The effect of longitude on abundance shows a maximum in 61º W and a minimum in 58.5º W (see Fig. 11 (e)). In the weighted model the maximum in abundances is shifted to 60.5º W (Fig. 11 (f)). Both models show an increasing trend in longitudes ranging between 64º W to 61º W (or 60.5º W in the weighted model) and a decreasing trend from longitudes between 61º W to 59º W.

Regarding the effect of depth (see Fig. 11 (g) and (h)), there are notable differences between unweighted and weighted model. In the weighted model, the relationship between average depth and CPUE consist of a negative effect on abundance at depths above 425 m.
There is also a peak in abundance located between 200 to 250 m. On the other hand in the unweighted model, relationships between abundance and depth follow a decreasing and negative pattern. This pattern was less clear in results than the obtained from the weighted model.

As figures 11 (i) and (j) show, there are significant differences between unweighted and weighted model. In the unweighted model there is an apparent relationship between high abundances and low temperatures (2 to 4º C). This relationship is derived from a few observations that lead to larger standard error bands. Moreover, there is a negative effect on abundances at temperatures above 13º C and a peak at 10º C. In the results from the weighted model, SST and *M. a. australis* abundance are related with high abundance restricted to a relatively narrow temperature range, from 8º to 11º C. As for the unweighted model, we found similar trends in those areas were the observations were low and therefore, error bands are significant.

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