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Analysis of the relationships between Patagonian squid (*Doryteuthis gahi*) abundance and environmental parameters in the SW Atlantic using GIS tools

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ABSTRACT

Doryteuthis (Loligo) gahi is the second most important cephalopod species in the SW Atlantic from a fisheries point of view. This species and hence, the fisheries profitability and sustainability, are subject to large inter-annual variability in recruitment strength, mainly due to interannual and seasonal variations of the Falkland/Malvinas Current. In this working document we analyse the environmental, geographical, temporal and physical factors affecting the distribution (abundance) of *D. gahi* in two areas where its abundance is highest, using geographic information systems tools. We found a slight positive correlation between CPUE and longitude, as well as between CPUE and depth in the northern area, but no correlations could be found between SST and the other explanatory variables. Regarding the southern area in summer-autumn, we found that CPUE increases with longitude as we go to the east, and with latitude. We also found positive correlations between SST and CPUE, as well as with depth. In winter spring our study revealed a slight relationship between CPUE and location, and with depth.

Keywords: cephalopods, *Doryteuthis gahi* fisheries, Southwest Atlantic, environmental parameters, GIS

INTRODUCTION

The Patagonian squid *Doryteuthis (*former *Loligo) gahi* is a near bottom distributed neritic species distributed in the South East Pacific Ocean from Peru (6ºS) to Tierra del Fuego (55ºS), and in the South West Atlantic Ocean from Tierra del Fuego to coastal (36ºS) and slope (38ºS) waters off Argentina (Castellanos and Cazzaniga, 1979; Roper et al., 1984; Cardoso et al., 1998). Spawning occurs in coastal and inner-shelf waters off the Argentine Patagonia, Falkland/Malvinas Islands and Chile (Hatfield and Rodhouse, 1994; Arkhipkin et al., 2000; Barón, 2001; Arkhipkin, 2013). After hatching, paralarvae and juveniles move from its spawning/nursery grounds located in shallow inshore waters around the south-eastern cost of the Falkland Islands to offshore feeding grounds on the shelf edge at depths of 200ï 300 m (Hatfield and Rodhouse, 1994; Arkhipkin et al., 2003), while mature individuals return to the coast to mate and spawn (Hatfield and Rodhouse, 1994; Arkhipkin et al., 2000; Arkhipkin and Middleton, 2002) (Figure 1). These ontogenetic migrations may be influenced by the Falkland/Malvinas Current, a branch of the Antarctic Circumpolar Current which moves northwards along the edge of the Patagonian Shelf (Peterson and Whitworth III, 1989; Arkhipkin at el., 2006).

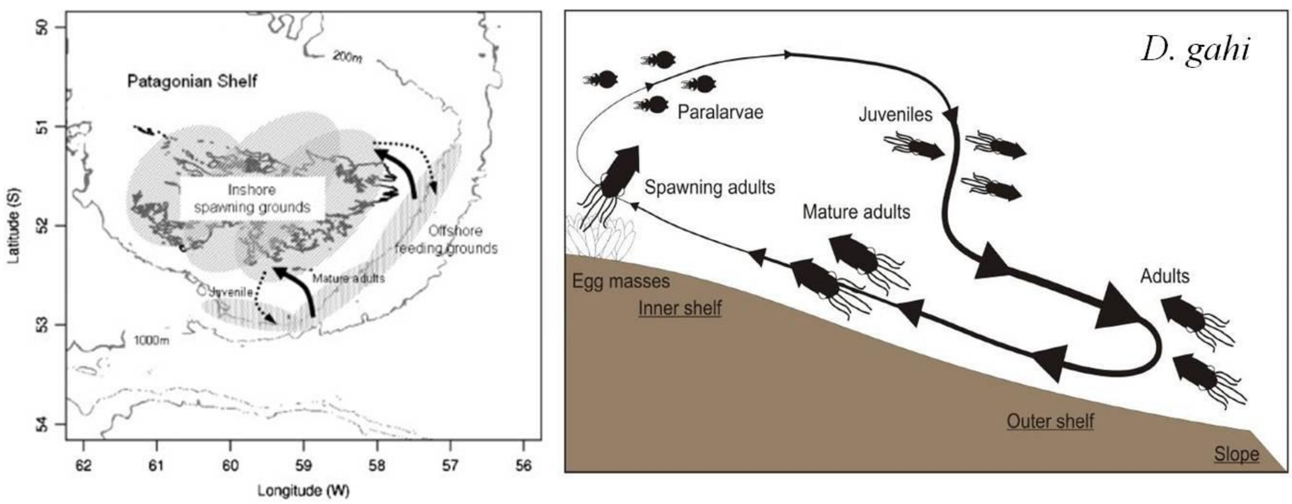

Figure 1.- Scheme of ontogenetic migration of *D. gahi*
(by courtesy of Dr. A. Arkhipkin, FIFD)

The Patagonian longfin squid is fished in the eastern and southern parts of the Falkland Shelf in the region called the ó*Loligo* boxô, this area being restricted to licenced *Loligo* vessels (Figure 2).

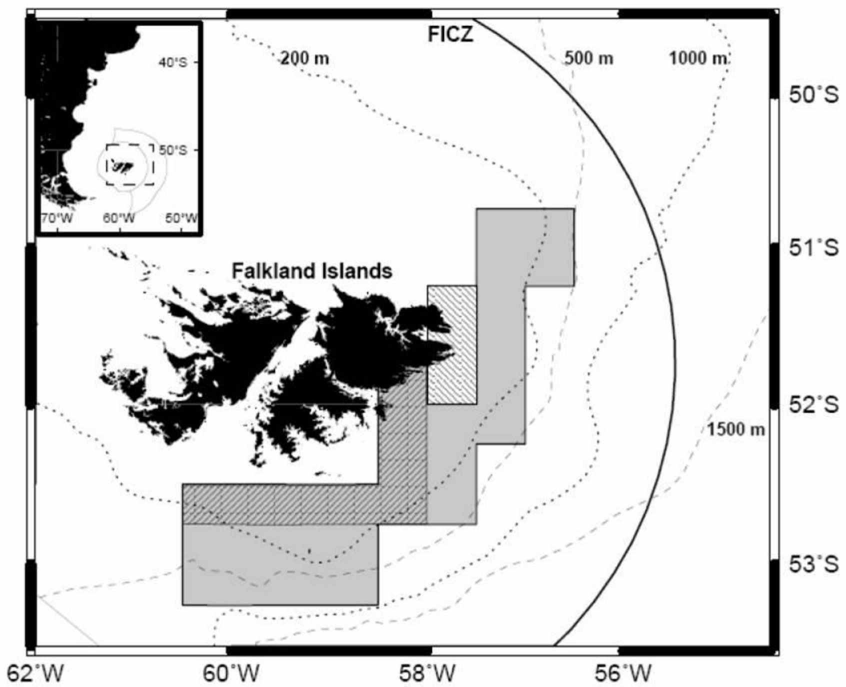

Figure 2.- *Loligo* box

Higher concentrations are found around the Falkland/Malvinas Islands, where it is the second major fishery resource after *Illex argentinus*.Two main cohorts of *D. gahi* are exploited; the autumn spawning cohort in February-April and spring-spawning cohort in May and August-October (Falkland Islands Government, 2005; 2011). Only in the Falkland/Malvinas waters, total annual catches of *D. gahi* ranged 23,700ï 64,500 t, over the period of 2000ï 2011 (Falkland Islands Government, 2011; Arkhipkin, 2013).

MATERIALS AND METHODS

Study Area

Two main geographical areas were defined for the study according to the location of commercial hauls reported by skippers of Spanish trawlers operating in the SWAO:

1. The high seas of the Patagonian Shelf roughly between 44º50ôS and 47º10ôS (the northern area)
2. The waters around the Falkland/Malvinas Islands (the southern area)

Data

Data analysis took into account the season of the year and included:

- Commercial fishery data on catches from logbooks filled in by skippers of Spanish bottom trawlers operating in the study areas (2010-2012). These data were provided to us by the Spanish General Secretariat for Fisheries
- Environmental and physical data: Sea Surface Temperature (SST), bathymetry, latitude, and longitude (2010-2012)

Seasonality

The analysis included time comparisons of CPUE by quarter, roughly coinciding with the seasons of the year in the southern hemisphere:

- First quarter: summer
- Second quarter: autumn
- Third quarter: winter
- Fourth quarter: spring

The environmental and physical data used in the analyses originated from the following sources:

Atlantic SST: large-scale monthly SST data between January 2010 and December 2012 was made available from the Physical Sciences Division, Earth System Research Laboratory, NOAA, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/). Previous research has shown SST data to be comparable with near-surface data derived from in situ expendable bathy-thermograph (XBT) profiles in the southern Patagonian shelf.

Bathymetry data: high resolution bathymetry data in high seas collected via several research cruises conducted by the Spanish R/V ñMiguel Oliverò between 2007 and

2010, and low resolution bathymetry data (GEBCO) around the Falkland/Malvinas Islands. The main objective of these cruises was the study of Vulnerable Marine Ecosystems (VMEs) on the high seas of the Patagonian shelf and possible interactions of bottom trawl activities in this area.

<u>Geographical data</u>: daily positions (latitude, longitude) recorded at noon by skippers were extracted from logbooks and integrated into a 5ô*10ô grid.

RESULTS

Logbooksô positions were located between 40ºS-53ºS and 42ºW-64ºW within the UTM20S and UTM21S zones, and were split in two geographical areas: the northern area, north of parallel 48ºS (contained by FAO Division 41.3.1) and the southern area, south of parallel 48ºS (contained by FAO Division 41.3.2), both divisions (Figure 3, left) within the FAO Major Fishing Area 41.

From the total 4514 hauls in the database, 2384 were found in the northern area (53%), and 2130 were found in the southern area. The northern area corresponds to high seas of the SW Atlantic Ocean (international waters in the external Patagonian shelf and slope) where no fishing regulatory measures are currently in force. The southern area matches with the Falkland/Malvinas waters which are divided in terms of fishery management in two separate zones: FICZ (Falkland Islands Conservation Zone) and FOCZ (Falkland Outer Conservation Zone) (Figure **3**, right).

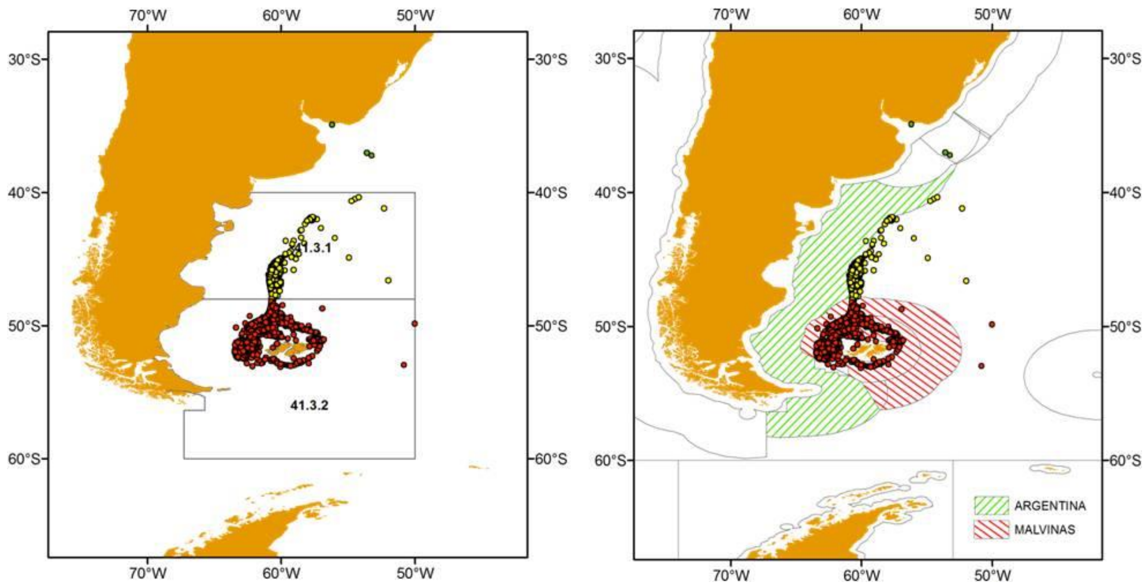

Figure 3.- Location of the hauls in relation with FAO Divisions 41.3.1 and 41.3.2 (left), and with the Argentine EEZ (green), the Falkland Conservation Zones (red) and with the high seas (colourless) (right). Hauls in yellow are located on the high seas, whereas hauls in red are within Falkland/Malvinas waters. It can be seen the presence of outliers located far east of the commercial fishing grounds, at impossible depths for trawling

In both areas respective polygons containing all the hauls selected for the study were delineated after debugging of outliers (hauls within Argentine waters, or at inadequate depths). Herewith, a 5ô*10ô grid was defined and superimposed over the two polygons (Figure 4).

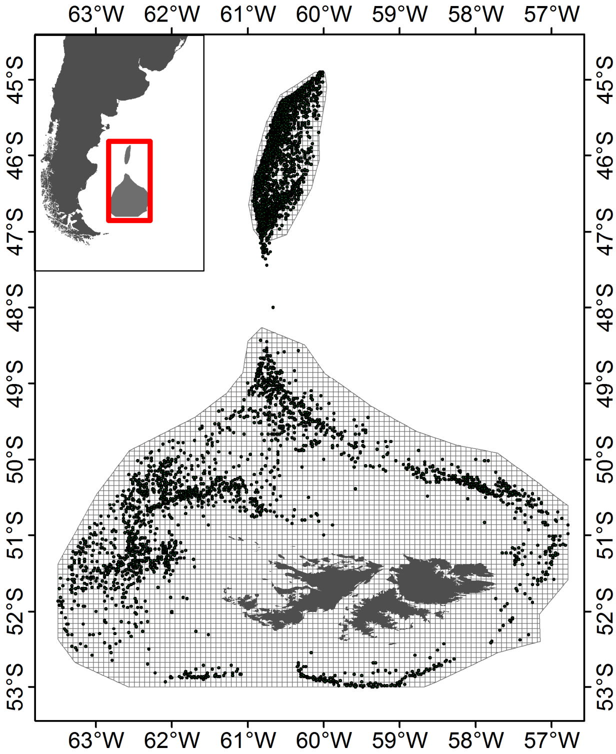

Figure 4.- Grid defined for the analysis (5ô*10ô)

The shape of the grid is based on a minimum boundaries algorithm that encompasses all locations in both the northern and southern areas/polygons. Each cell of the grid has an area of ~ 50 nm² and statistical analyses were performed based on the number of hauls per cell, thus allowing the addition of other parameter values (e.g. SST) to the corresponding cell.

3D model bathymetry

Location of the hauls in the study area: in the northern area hauls are located just within the outer shelf and upper slope of the Patagonian shelf (the high seas), beyond the 200 nm limit of the Argentine EEZ (Figure 5). Analysis was carried out using a high resolution bathymetry (as discussed above in the methodology).

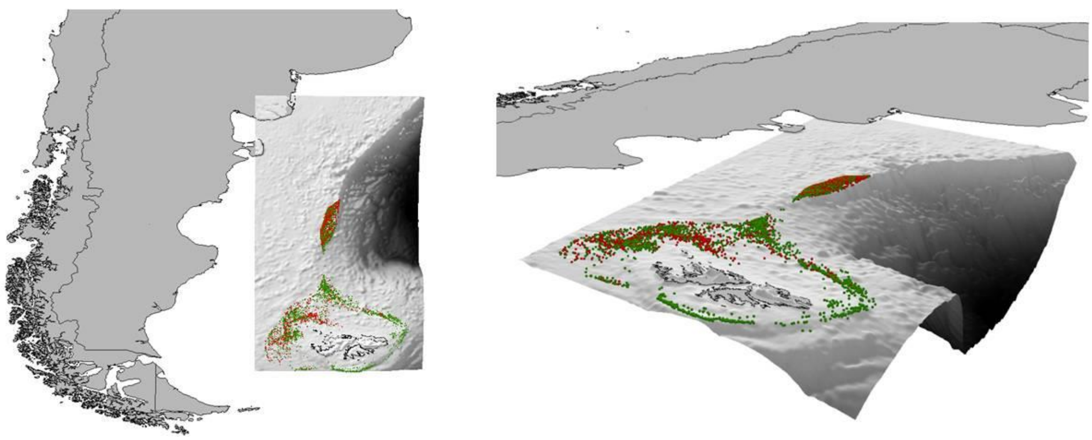

Figure 5.- 3D Bathymetry model

For the southern area, we used the low resolution bathymetry obtained from the GEBCO dataset. Opposite to the northern area, the hauls are spread all around the Falkland/Malvinas shelf where the maximum depth of the hauls is ~ 400 m.

A detailed view of the location of the hauls in northern area can be found in Figure 6. 100% of the positions fell above 400 m isobath. This result from the analysis is consistent with the findings of the study carried out by the IEO in 2007-2010 on board the R/V ñMiguel Oliverò. The Argentine EEZ is represented in green, whereas the northern part of the Falklands Outer Conservation Zone (FOCZ) is depicted in pink.

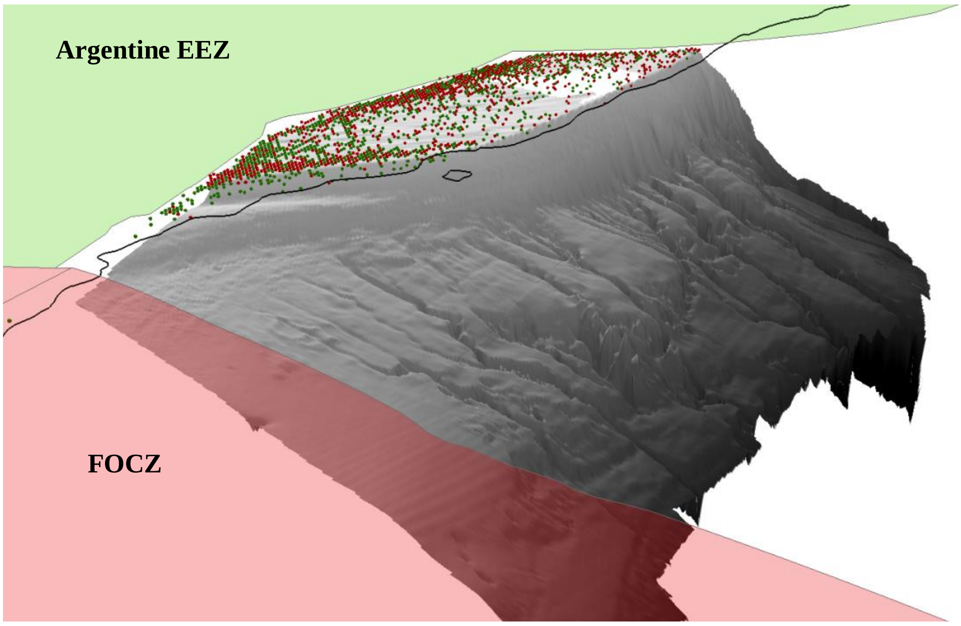

Figure **6**.- A detailed view of the hauls reported from northern area. The hauls to the north of this area fall within the shelf, however those that fall to the south (close to the FOCZ) are located in the slope of the Patagonian shelf

CPUE and SST Spatial Analysis

In this section we describe the relationship between the abundance of *Doryteuthis gahi* and the SST in northern and southern areas by season of the year. We used the CPUE from logbooks filled in by captains of Spanish fishing vessels between January 2010 and December 2012 as an index of abundance. To differentiate vessels targeting Patagonian squid from those targeting other species such as hake, or Argentine squid, we established a threshold of 500 kg/h.

North area

The values of mean CPUE and mean SST for each cell of the grid in summer and autumn in the northern area are shown in Figure 7, which illustrates that the presence of Patagonian squid in this area in summer-autumn -when the Falkland/Malvinas Current has lesser influence- is practically negligible, with only two cells in the southern most part of this region presenting significant abundances (CPUE between 500-1500 kg/h) at depths > 200 m.

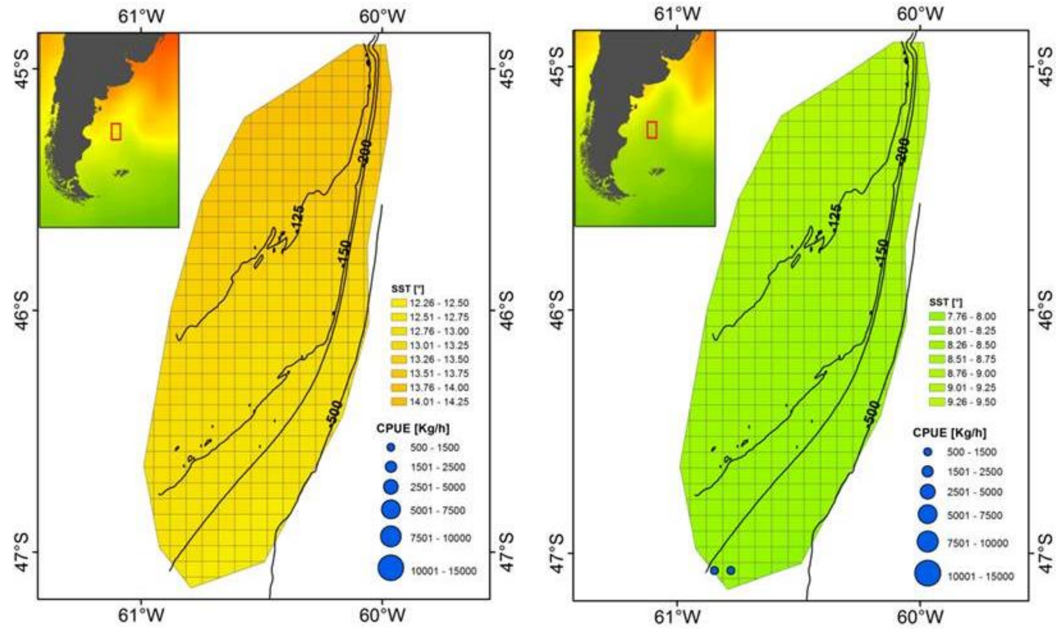

Figure 7.- Mean CPUE and mean SST in summer (left) and autumn (right)

However, maximum concentrations of the species were reported in winter, also in the south of the study area and at depths around 200 m. In spring, the abundance of *D. gahi* decreases in this area. It seems that Patagonian squid inhabit cold waters, probably migrating to the south when the presence of the Brazil Current is stronger.

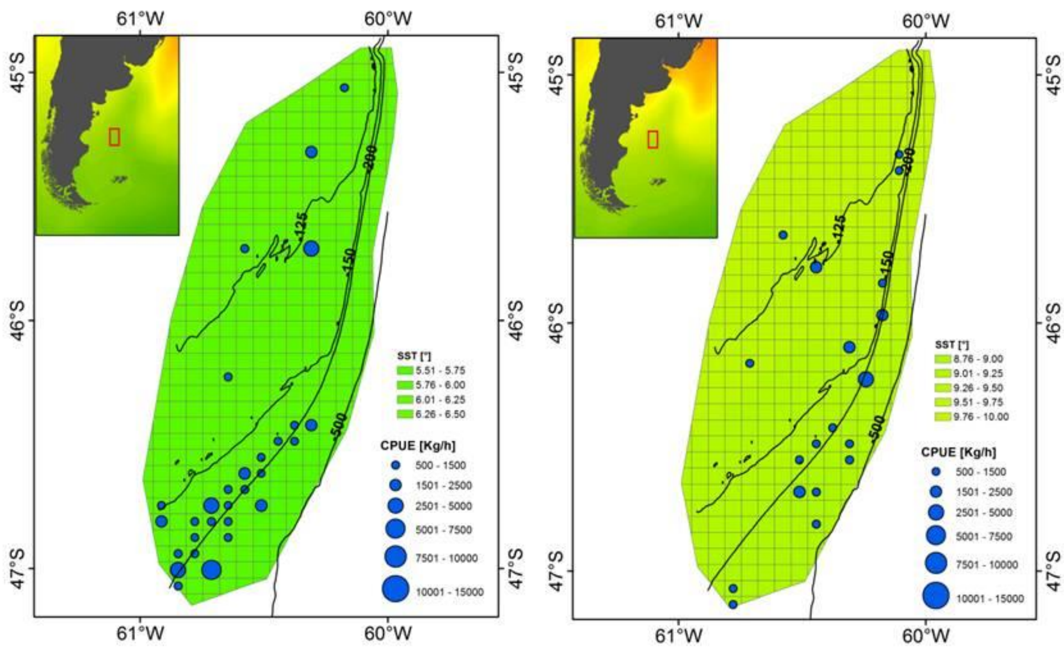

Figure 8.- Mean CPUE and mean SST in winter (left) and spring (right)

South area

Values of mean CPUE and mean SST for each cell of the grid in the southern area in summer and autumn are presented in Figure **9**.

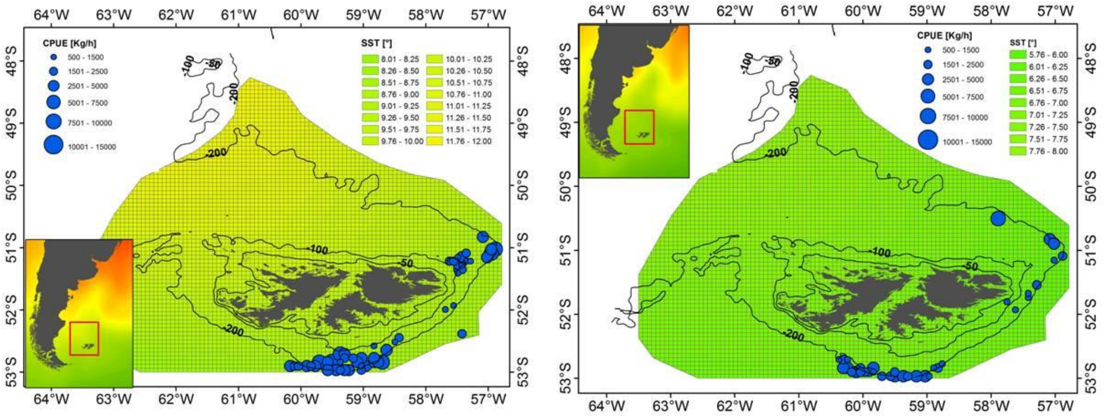

Figure 9.- Mean CPUE and mean SST in summer (left) and autumn (right)

Higher abundances are reported in summer, within the *Loligo* box, at depths around 200 m depth. It appears that squid were searching for colder waters to the south and escaping from warmer waters (Brazil Current) located to the north. In autumn, densities of Patagonian squid fall in relation to densities in summer, as cold waters spread into the region allowing a wider distribution of the species.

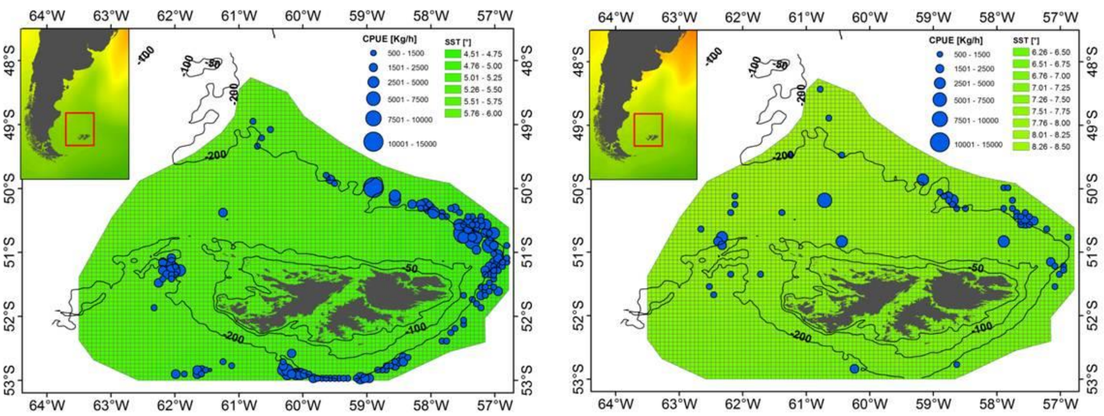

Figure 10.- Mean CPUE and mean SST in winter (left) and spring (right)

The wider spatial distribution of *D. gahi* is more apparent in winter, whereas its abundance decreases in spring as an effect of warmer waters entering into the area (Figure 10).

Data exploration

Box plots were created to compare Patagonian squid abundances (CPUE) against several oceanographic, geographical and physical parameters (SST, latitude, longitude and depth). To differentiate the vessels targeting *D. gahi* from the vessels fishing for other species, a threshold of 100 Kg/h was defined in both study areas (north and south areas).

The northern and the southern areas were analysed separately. Owing to the existence of two fishing seasons within Falkland/Malvinas waters, we categorised the data by seasons in this area: summer-autumn (first fishing season) was analysed separately from winter-spring (second fishing season).

North area

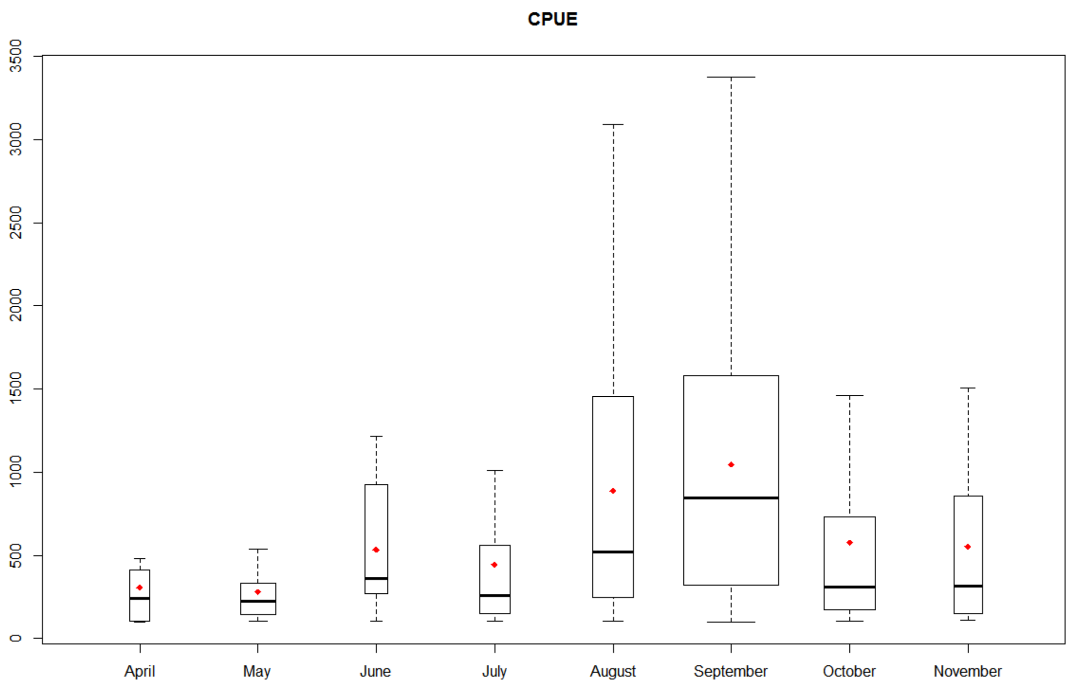

Figure 11.- Monthly CPUE values (kg/h)

Table 1.- CPUE statistical values

	Min	1st Quartile	Median	Mean	3rd Quartile	Max
April	100.6	109.2	241.2	305.9	387.5	945
May	102	147.2	223	278.7	330.6	886.1
June	106.1	268.3	358.1	534.4	884.1	1216
July	105.4	155.4	258.8	443.4	558.1	2084
August	103.3	250.3	521.5	886.9	1434	3089
September	101.2	320.6	847.4	1047	1576	4179
October	103.3	176.3	311.4	575	720.8	4548
November	109.6	150	316.7	552.9	854.2	1509

Figure 11 shows an erratic pattern of the CPUE throughout the analysed period. Mean CPUE shows an irregular trend during the first half of the year, followed by an increase in the mean and maximum CPUE values between July and September. At the end of the year, there is a marked decrease (maximum reported CPUE more than 4100 kg in September; Table 1).

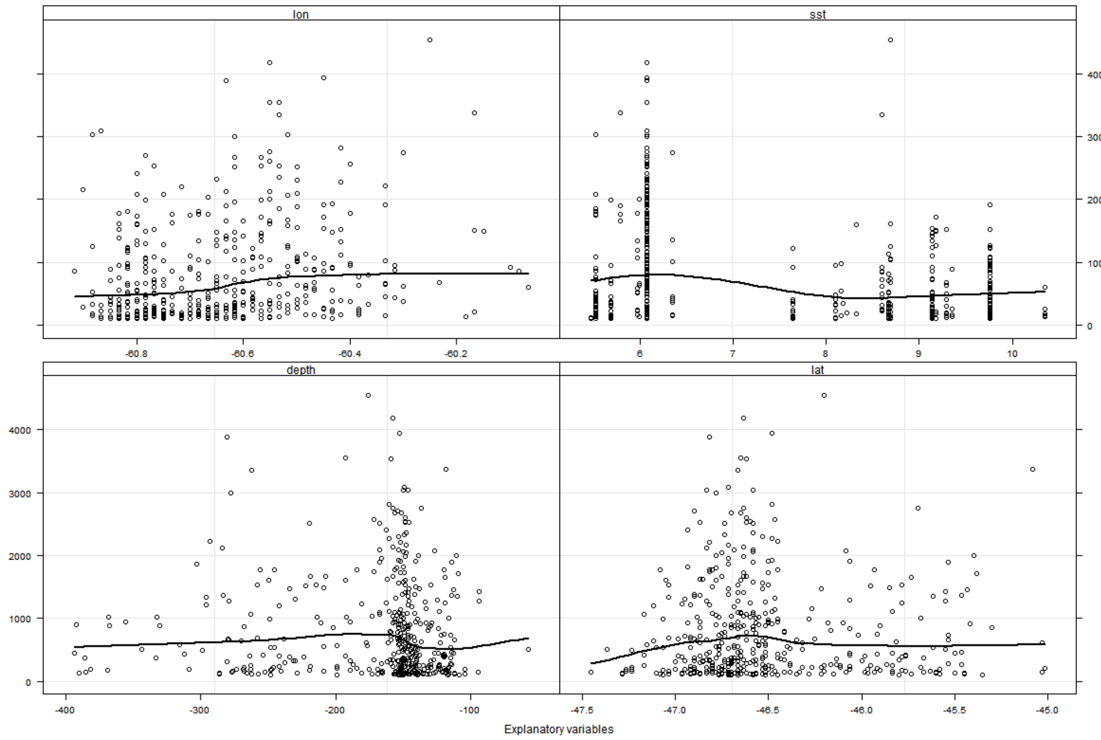

Figure 12.- Relationships between CPUE and explanatory variables

A slight positive correlation between CPUE and longitude, as well as between CPUE and depth can be seen in Figure 12, the majority of the catches being located in the vicinity of the 150 m isobath.

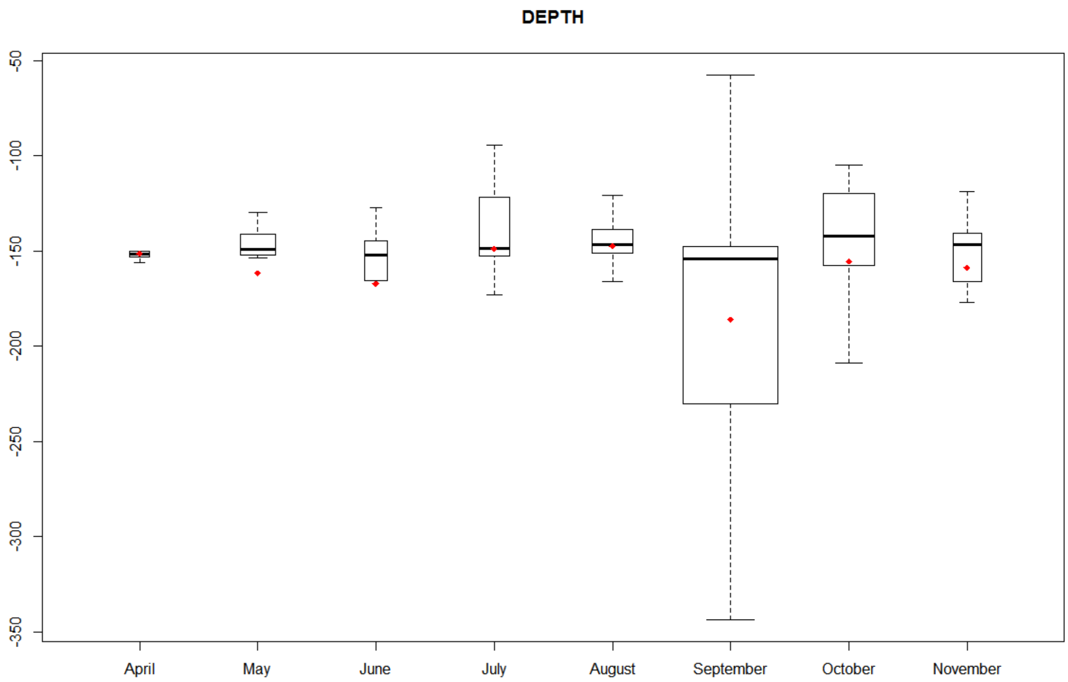

Figure 13.- Monthly depth values (m)

Table 2.- Depth statistical values

	Min	1st Quartile	Median	Mean	3rd Quartile	Max
April	-169.1	-153.1	-151.6	-151.4	-150.2	-138.2
May	-385	-152.1	-149.2	-161.7	-141.6	-129.9
June	-263.9	-163.1	-151.9	-167.1	-145.1	-127.2
July	-267.6	-152	-148.5	-148.7	-122.9	-94.51
August	-263.2	-150.8	-146.8	-147.5	-139.5	-110.4
September	-393.6	-229.7	-154.1	-186.1	-148	-57.68
October	-392.3	-157.6	-142.3	-155.5	-119.7	-104.6
November	-247.9	-166.2	-146.8	-158.7	-140.5	-94.18

Fishing depth remains almost constant during the whole period, with mean values close to the 150 m isobath. In September, when the maximum CPUE values were recorded, mean depth rises to almost 190 m. Maximum depth values are close to 400 m.

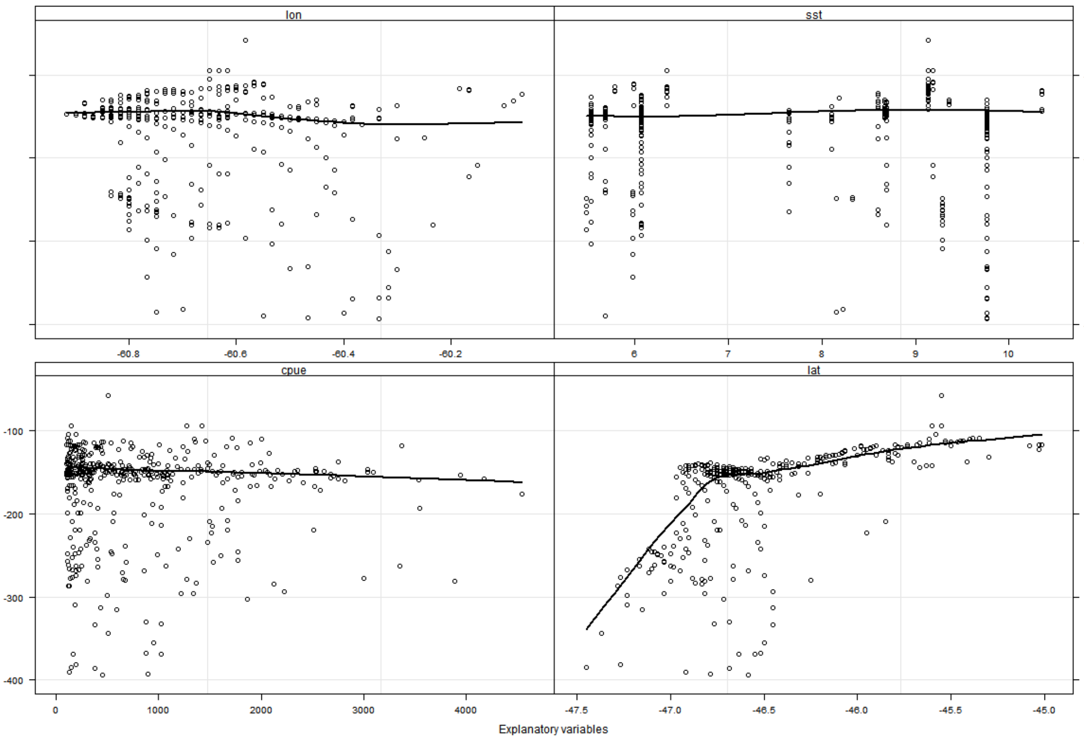

Figure 14.- Relationships between depth and explanatory variables

Figure 14 it shows that fishing depth is steady regarding longitude, but increases gradually with latitude until 46.80ºS, where a sharp increase is observed, until it reaches almost 400 m.

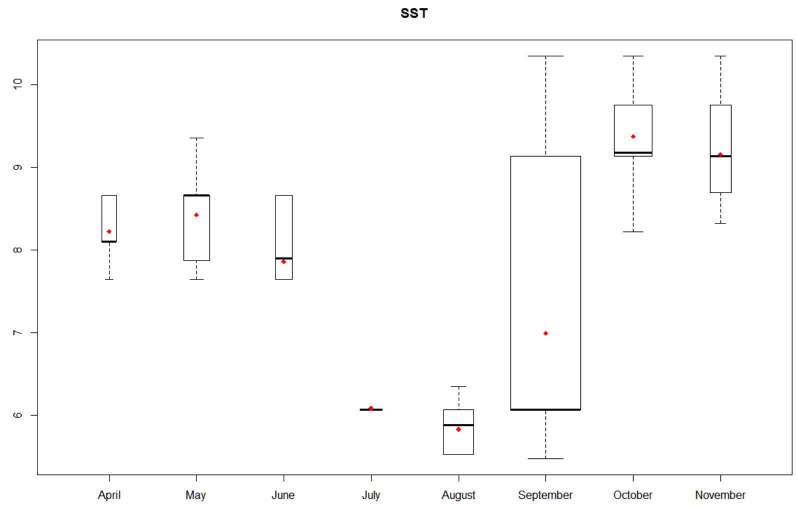

Figure 15.- Monthly SST values (ºC)

Table 3.- SST statistical values

	Min	1st Quartile	Median	Mean	3rd Quartile	Max
April	7.643	8.103	8.103	8.226	8.526	8.667
May	6.07	7.643	7.9	7.859	8.667	8.667
June	6.07	7.643	7.9	7.859	8.667	8.667
July	5.683	6.07	6.07	6.083	6.07	6.343
August	5.527	5.527	5.88	5.83	6.07	6.343
September	5.477	6.07	6.07	6.993	9.14	10.35
October	8.22	9.14	9.183	9.38	9.76	10.35
November	8.323	8.693	9.14	9.163	9.76	10.35

Mean SST (Table 3) is relatively high during the autumn months (April-June) with values between 8.2ºC and 7.9ºC. SST then decreases until 5.8ºC in winter (August), and finally recovering to reach 9.7ºC in spring (October).

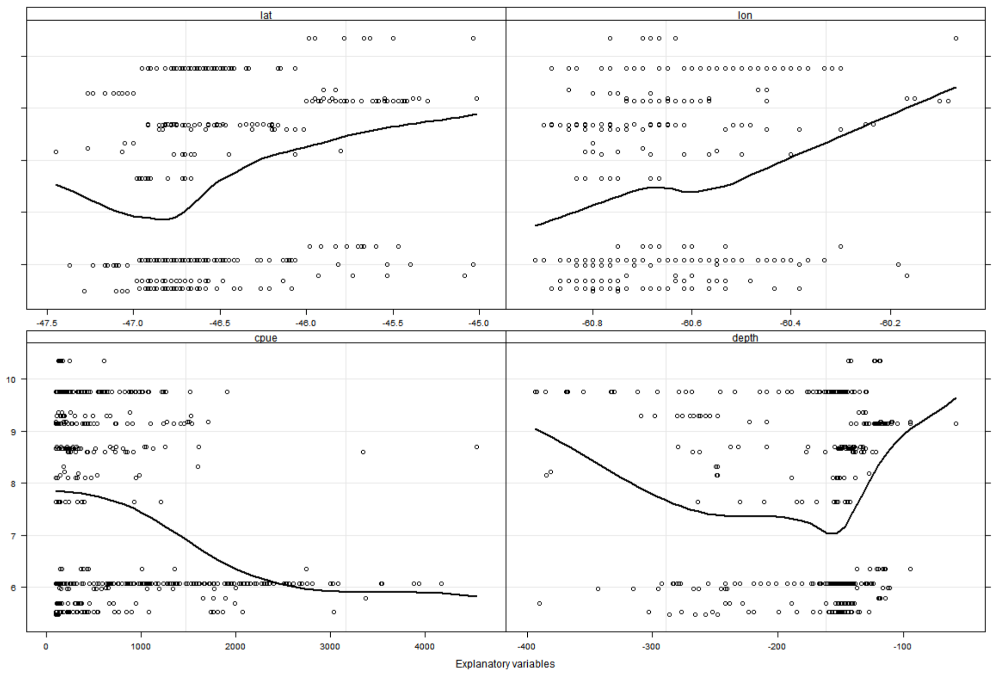

Figure 16.- Relationships between SST and explanatory variables

No SST correlations can be made concerning latitude, longitude and depth, probably owing to mix of several seasons. Nevertheless, there is a clear negative correlation between CPUE and SST (Figure 16). This can be explained by the water temperature preferred of *D. gahi*.

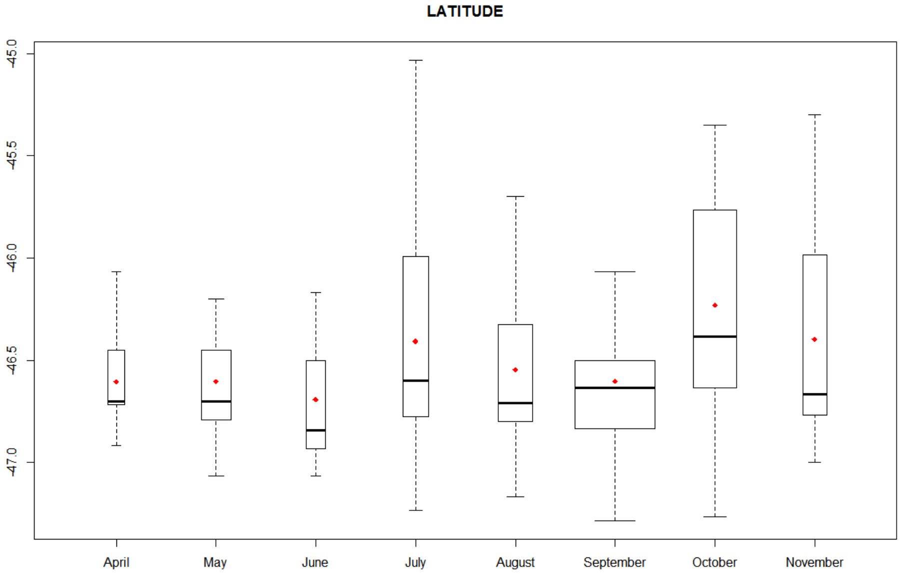

Figure 17.- Monthly latitude values

The fishing strategy of the Spanish fleet can be described from Figure 17 and Figure **18**. Figure 17 shows that the fleet operates preferentially in northern latitudes during winter-spring, and moving to southern most latitudes in autumn. Figure 18 shows the fleet fishing towards western (and shallower) waters throughout April-August, probably fishing for hake, since *Illex* has left these fishing grounds, and shift to eastern (and deeper) waters in September-October. No data were available for summer months.

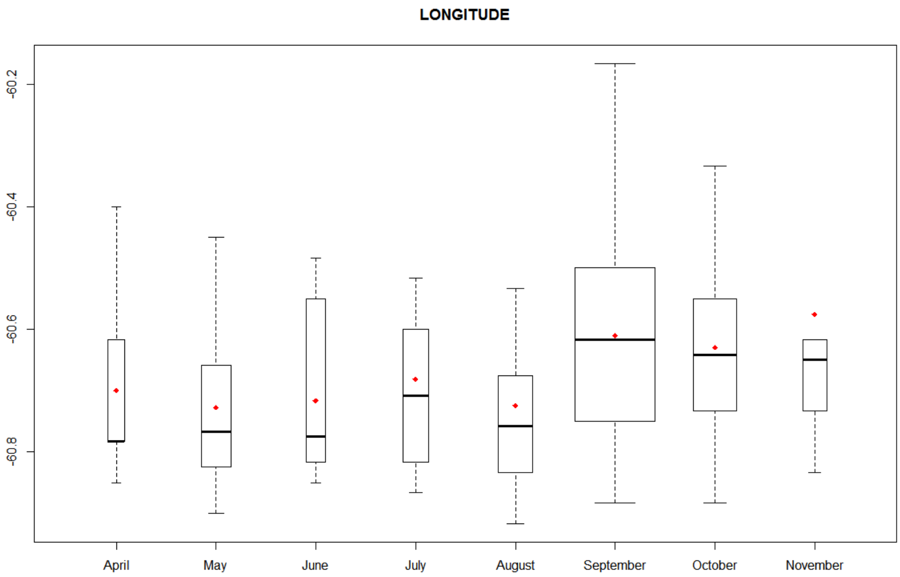

Figure 18.- Monthly longitude values

South area

We were able to obtain a larger data set for the southern area (hauls reporting significant Patagonian squid catches) , than for the high seas. This could be explained by a wider meridional distribution of this species within the *Loligo* box (see Figure 2).

Summer ï Autumn (first fishing season)

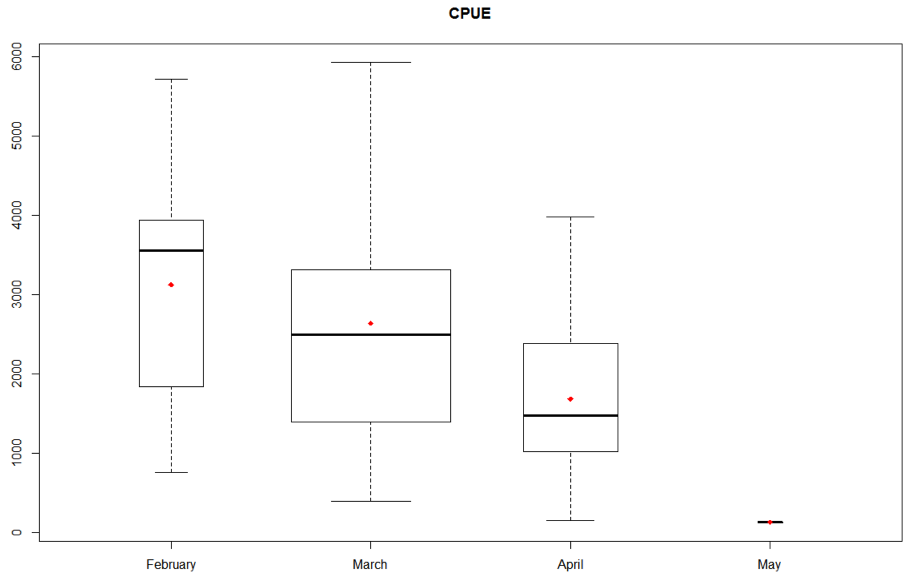

Figure 19.- Monthly CPUE values (kg/h)

Table 4.- CPUE statistical values

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
February	759.1	1840	3558	3125	3942	5720
March	158	1038	1476	1688	2365	3979
April	129.2	131.6	134	134	136.3	138.7
May	129.2	131.6	134	134	136.3	138.7

Figure 19 shows a marked drop in CPUEs during the first fishing season (February-May) within Falkland/Malvinas waters.

The analysis of the relationship between CPUE and the explanatory variables is shown in Figure 20. CPUE increases with longitude towards the east, and with latitude from 52.5ºS to 50.5ºS (the northern limit of the *Loligo* box), but falls between latitudes 53ºS and 52.5ºS. With regards to depth, CPUE rises between 100m-200m, but drops slightly from this last isobath onwards and a weak positive correlation is evident with SST.

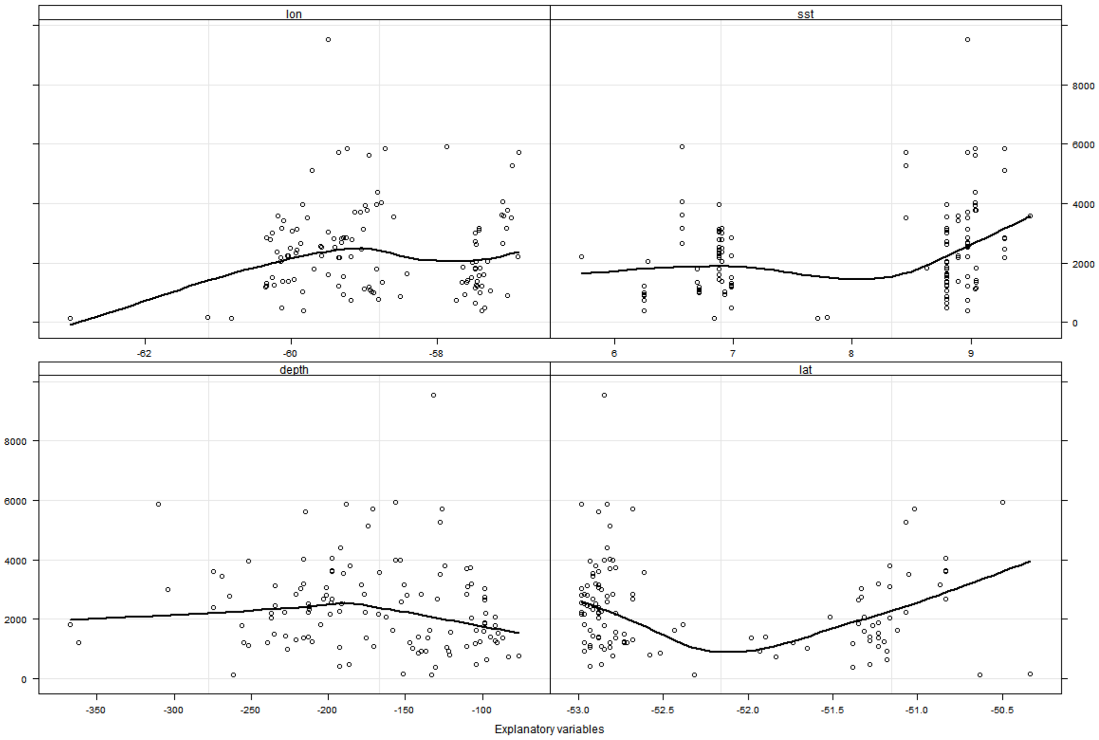

Figure 20.- Relationships between CPUE and explanatory variables

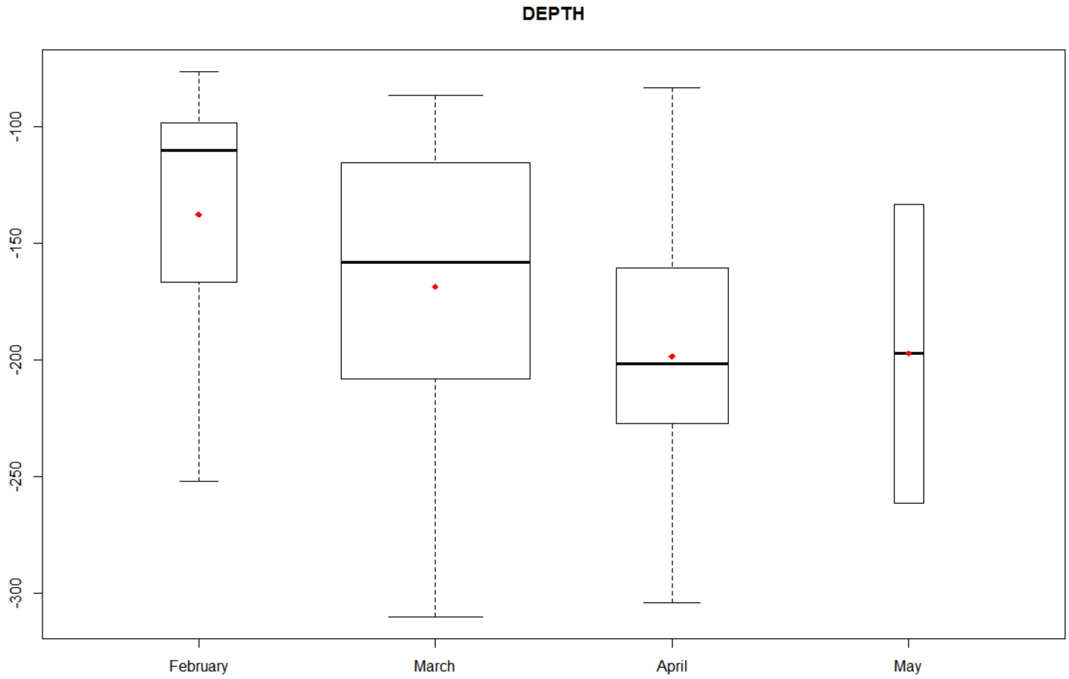

Figure 21.- Monthly depth values (m)

Table 5.- Depth statistical values

	Min	1st Quartile	Median	Mean	3rd Quartile	Max
February	-251.8	-166.7	-110	-137.6	-98.4	-76.43
March	-367.7	-205.4	-158.1	-168.5	-117.8	-86.6
April	-361.9	-226.8	-201.7	-198.4	-161.5	-83.4
May	-261.4	-229.3	-197.2	-197.2	-165.1	-133.1

D. gahi inhabit deeper waters during the fishing season, going from a mean depth of 138 m in February, to almost 200 m in April-May (Figure **21**; Table **5**). This may be explained by the feeding migration of this species to deeper feeding/maturing grounds (Arkhipkin, 2013).

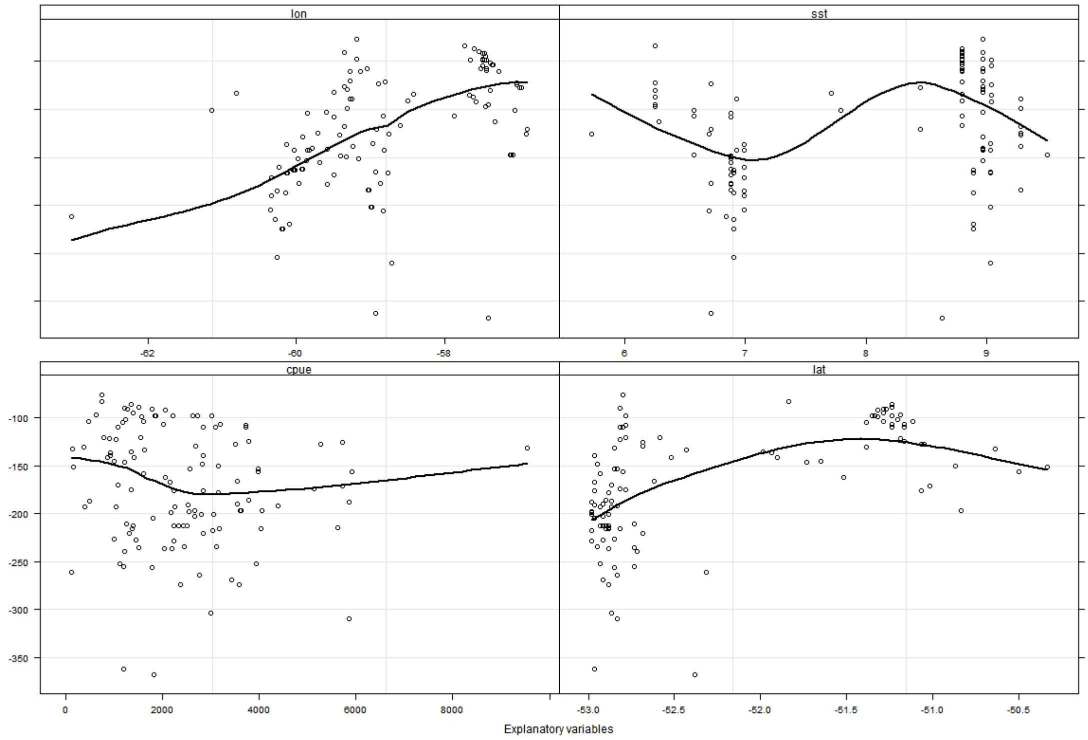

Figure 22.- Relationships between depth and explanatory variables

Figure 22 it shows that depth is lower in eastern ward locations, where reported CPUEs are higher.

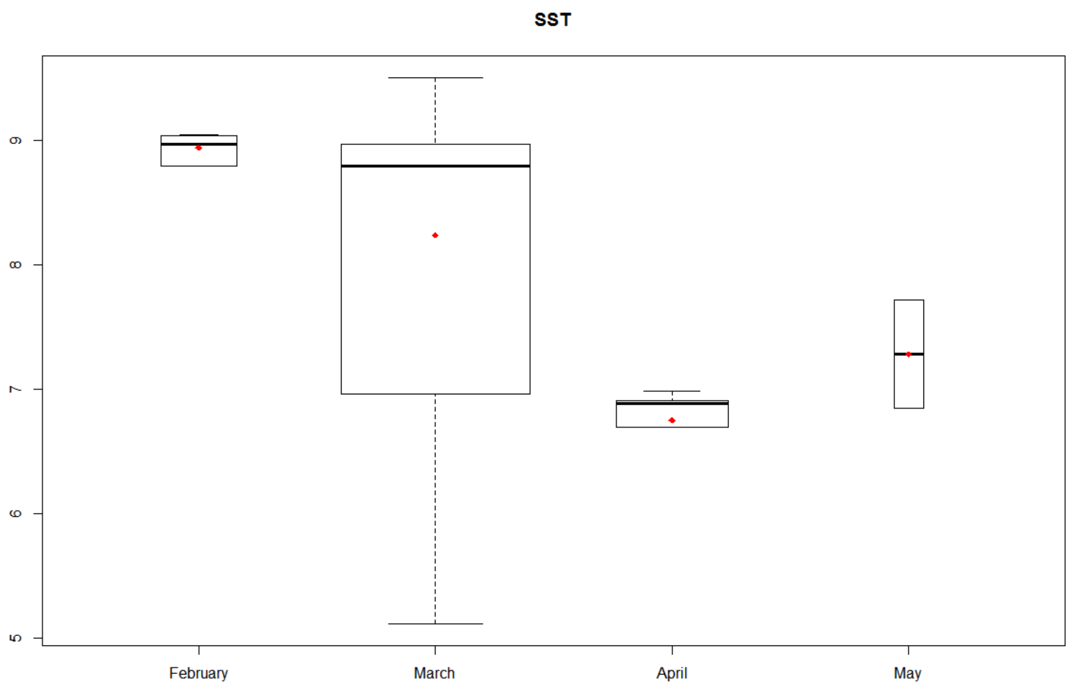

Figure 23.- Monthly SST values (ºC)

Table 6.- SST statistical values

	Min	1st Quartile	Median	Mean	3rd Quartile	Max
February	8.793	8.793	8.967	8.94	9.033	9.04
March	5.117	6.972	8.793	8.236	8.967	9.5
April	5.723	6.697	6.883	6.748	6.903	7.787
May	6.843	7.061	7.278	7.278	7.496	7.713

As to be expected, SST diminishes as autumn ends and winter approaches, passing from a mean SST of 8.9ºC in February to 6.7ºC in April. Intriguingly, SST rises in May to a mean value of 7.3ºC (Figure 23, Table 6).

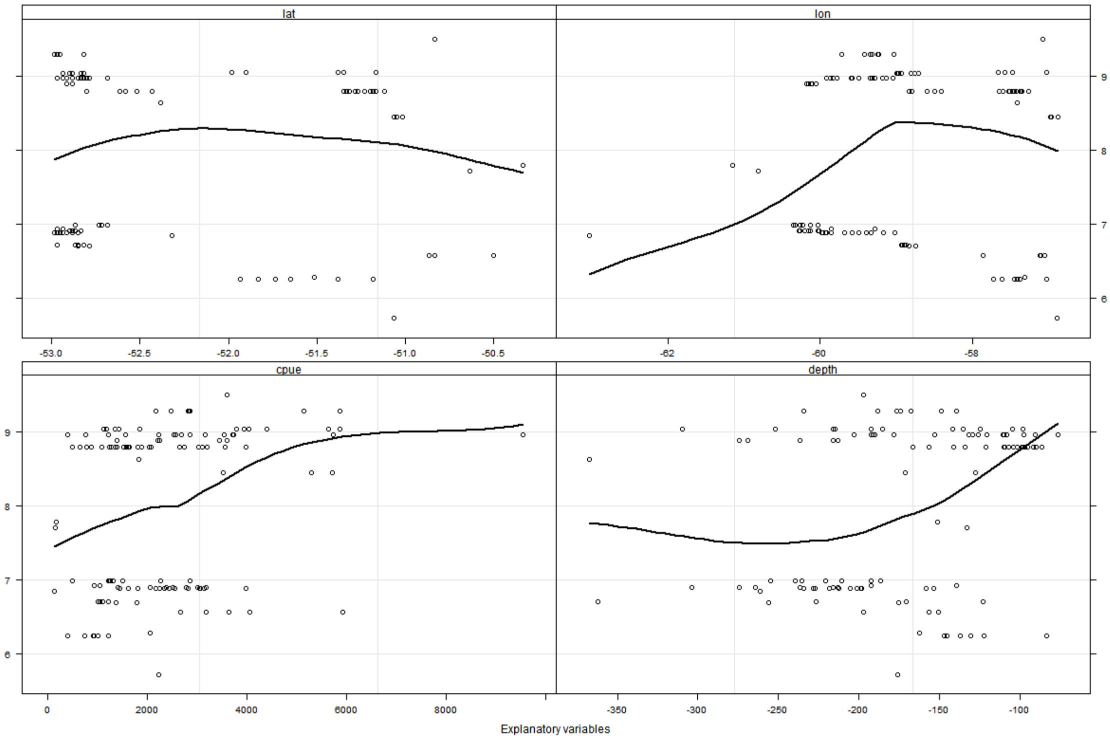

Figure 24.- Relationships between SST and explanatory variables

In Figure 24 we show that there is a weak, but positive correlation between SST and CPUE combined with depth.

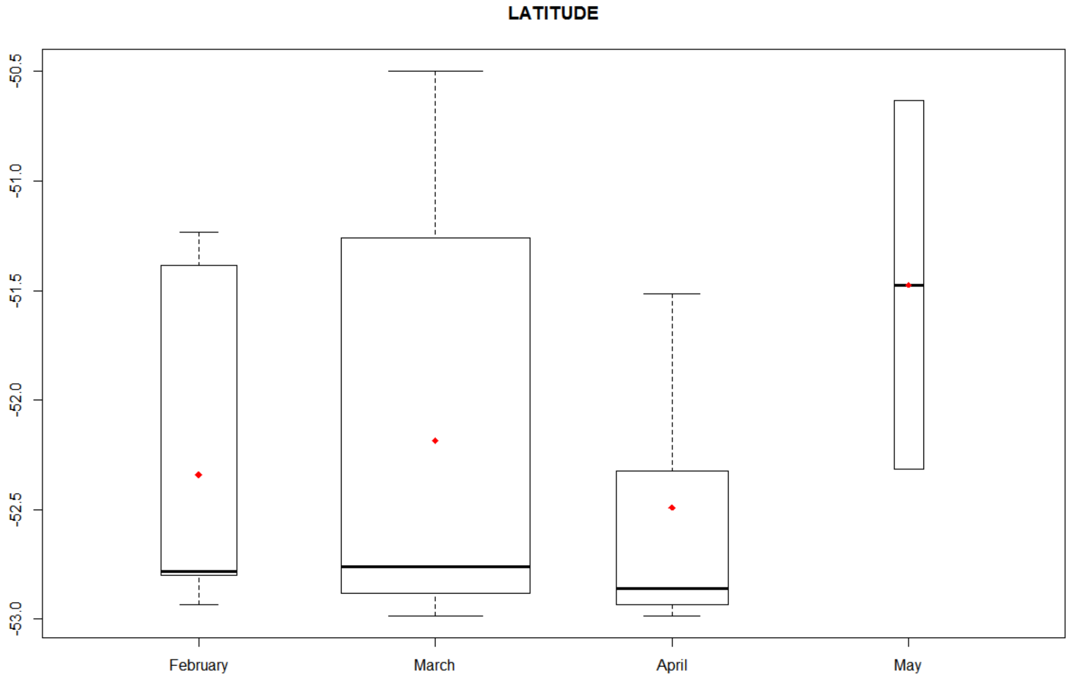

Figure 25.- Monthly latitude values

In comparison with the north area (the high seas), the mean latitude of the south area show very little variation during the seasons of the year operating mainly between 51.5ºS and 53ºS, despite only a few hauls being located around 50.5ºS in March (Figure 25).

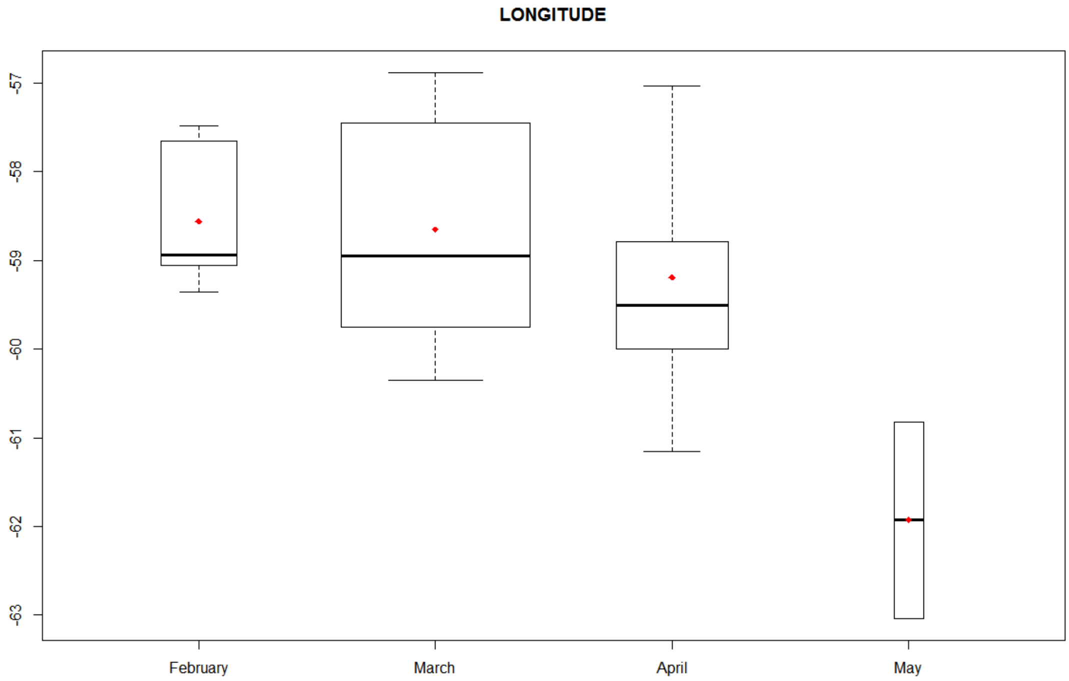

Figure 26.- Monthly longitude values

Figure 26, shows that the fleet moves to western and deeper waters in this area during this season.

Winter ï Spring (second fishing season)

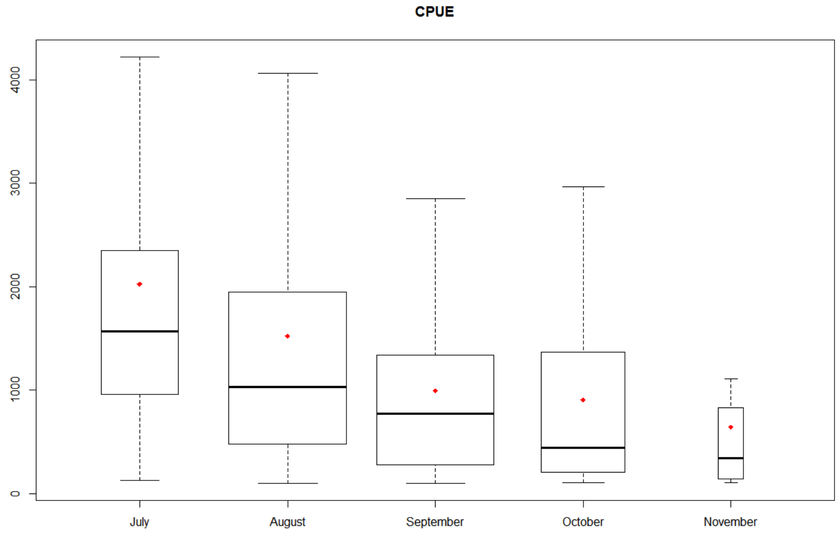

Figure 27.- Monthly CPUE values (kg/h)

Table 7.- CPUE statistical values

	Min	1st Quartile	Median	Mean	3rd Quartile	Max
July	124	971.1	1569	2023	2345	10300
August	100.1	275.2	774	993	1337	5098
September	100.1	275.2	774	993	1337	5098
October	106	208	440.1	904.7	1335	6432
November	107.7	143	339.6	640.2	687.3	2400

A steady decreasing trend is evident regarding mean and maximum CPUE values (Figure 27 and Table 7). Yields in the second season are higher than in the first one.

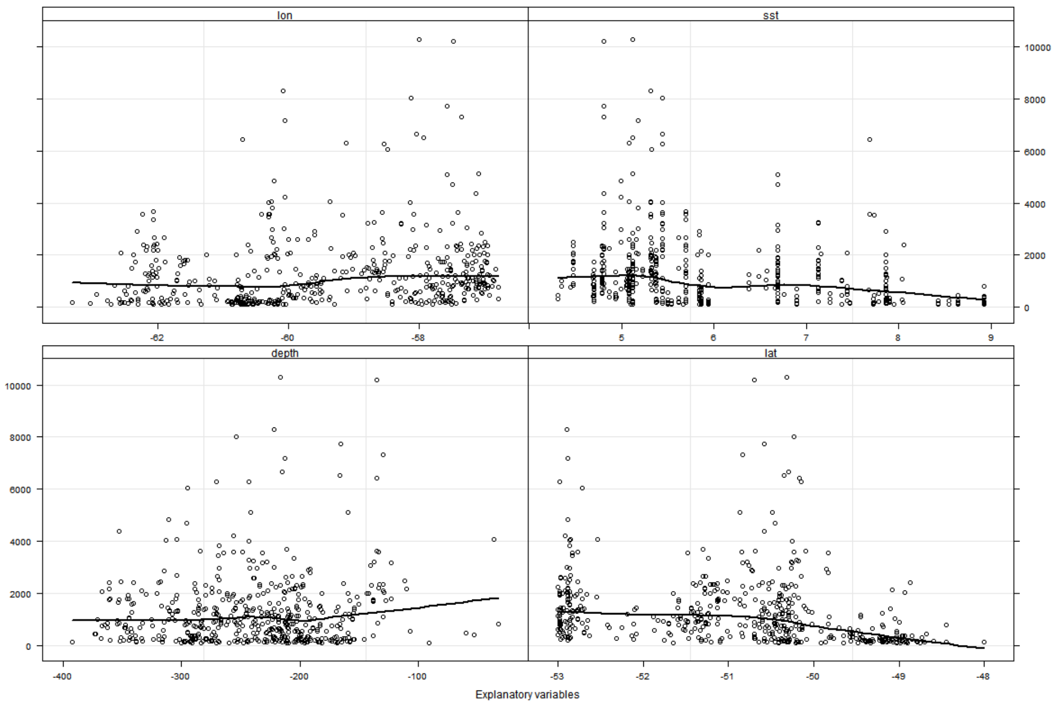

Figure 28.- Relationships between CPUE and explanatory variables

There is a slight relationship between CPUE and location, with the higher CPUEs found to the east and to the south and between 150 m and 250 m depth and at lower SST (Figure 28).

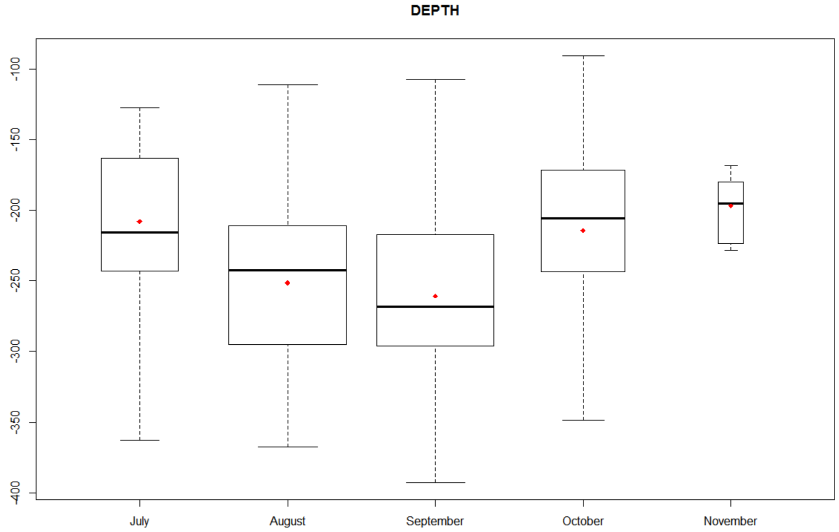

Figure 29.- Monthly depth values (m)

Table 8.- Depth statistical values

	Min	1st Quartile	Median	Mean	3rd Quartile	Max
July	-371.1	-243.3	-215.8	-208.2	-164	-32.73
August	-392.6	-296.3	-268.5	-260.8	-217.1	-107.5
September	-392.6	-296.3	-268.5	-260.8	-217.1	-107.5
October	-352	-243.3	-206	-214.3	-172.4	-90.88
November	-319.2	-221.4	-195.2	-197.1	-185.9	-59.68

Mean depth rises from July until September reaching 261 m depth. This then falls until November with a value of 197 m, similar to the value in July (Figure 29, Table **8**).

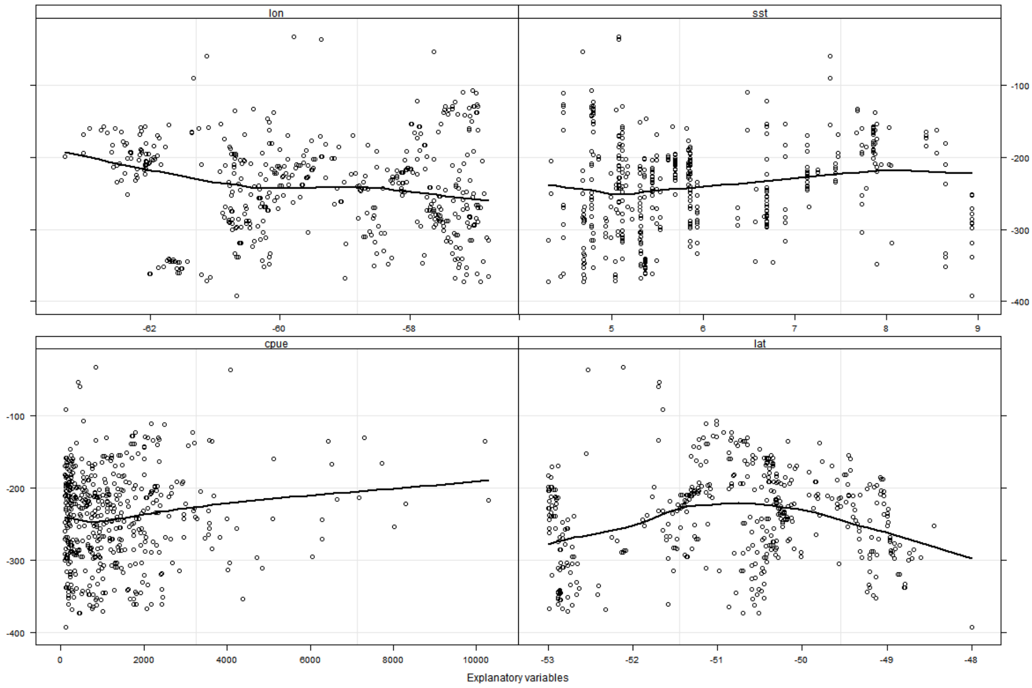

Figure 30.- Relationships between depth and explanatory variables

Hauls carried out at higher depths are situated to east of the islands at around 50.5ºS, whereas shallower hauls are located to the north at around 52ºS (Figure 30).

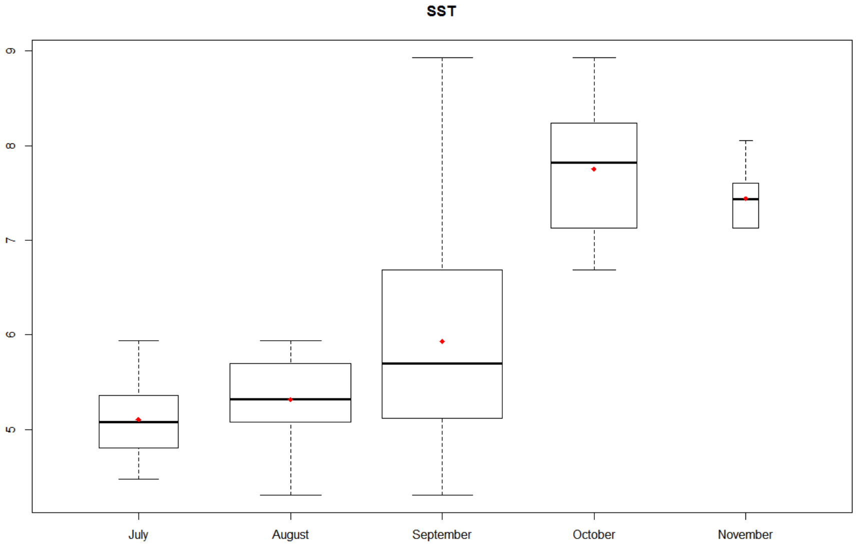

Figure 31.- Monthly SST values (ºC)

Table 9.- SST statistical values

	Min	1st Quartile	Median	Mean	3rd Quartile	Max
July	4.477	4.803	5.077	5.105	5.363	5.94
August	4.31	5.077	5.323	5.317	5.697	5.94
September	4.31	5.117	5.697	5.932	6.69	8.93
October	4.31	5.117	5.697	5.932	6.69	8.93
November	7.133	7.133	7.432	7.44	7.54	8.053

SST varies from 5ºC in July to 7.75ºC in October (Figure 31, Table 9).

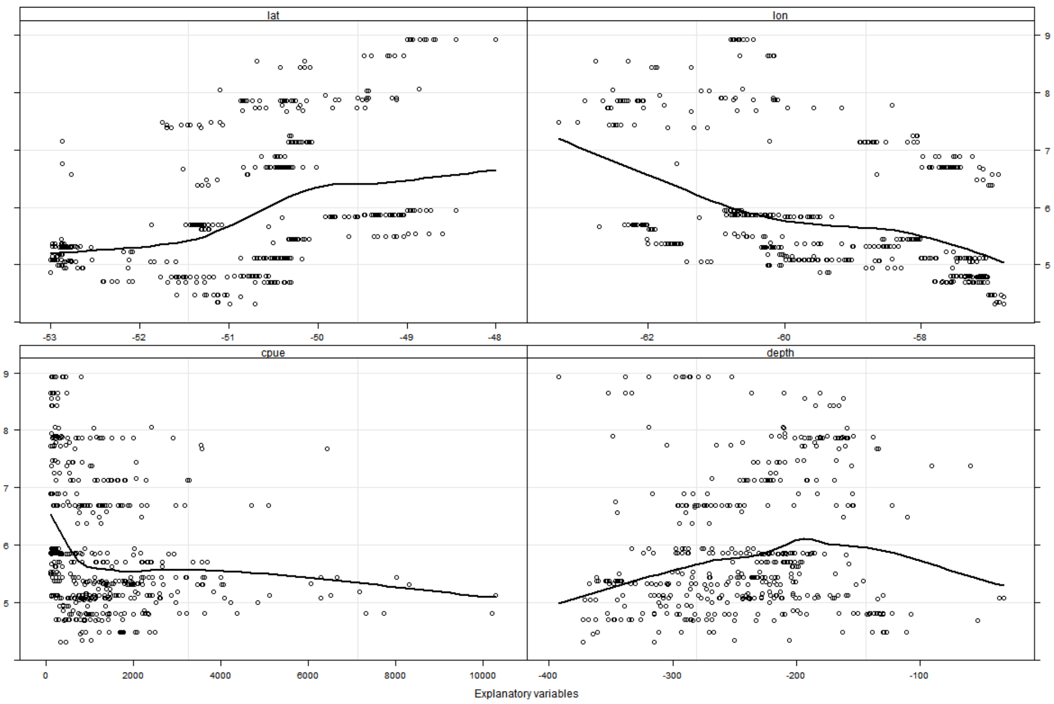

Figure 32.- Relationships between SST and explanatory variables

As expected, SST is higher to the north of the area and lower to the east. CPUE is significantly higher at lower SSTs (Figure 32).

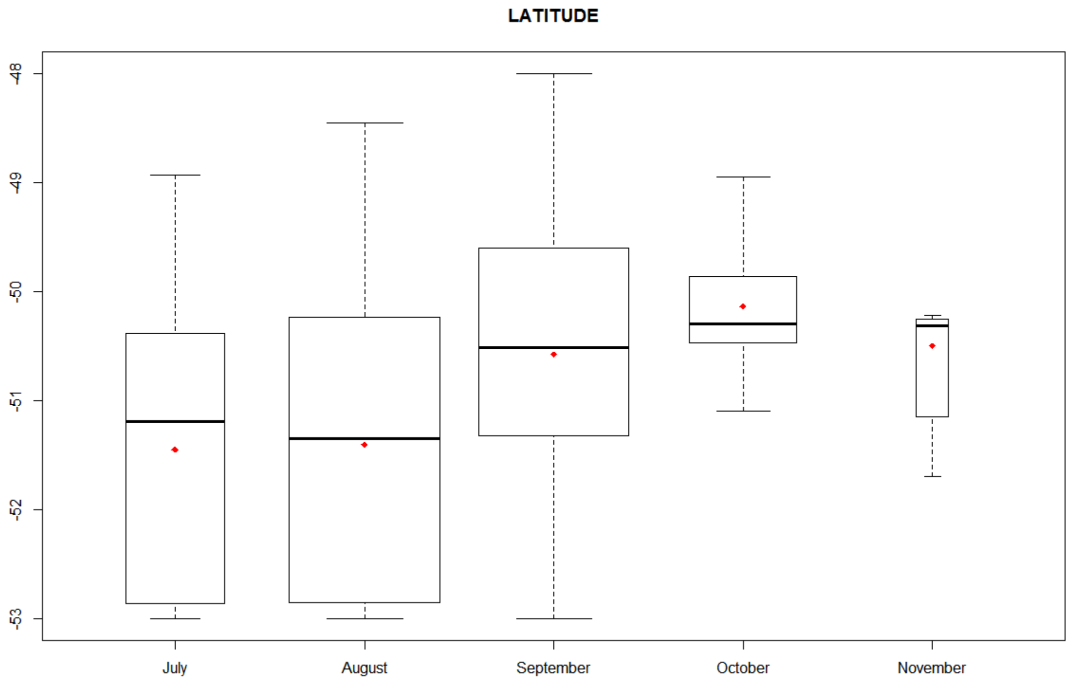

Figure 33.- Monthly latitude values

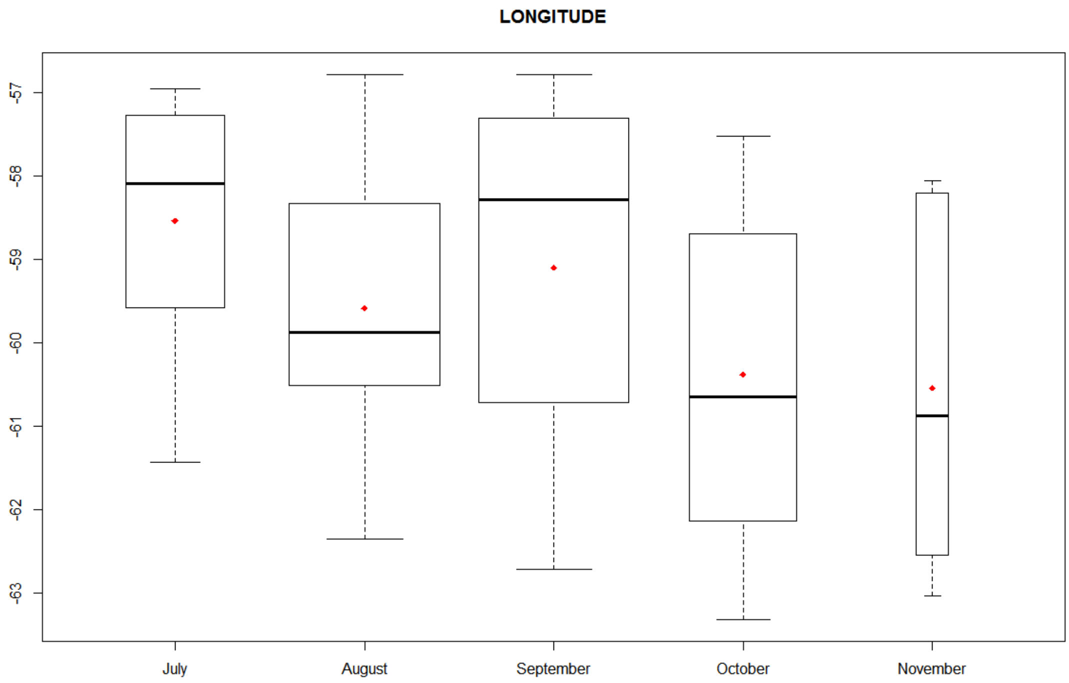

Figure 34.- Monthly longitude values

Figure 33 and Figure **34** shows the strategy of the fleet, moving to northern locations in winter and to the west in spring.

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