Analysis of the variability in the abundance of shortfin squid *Illex argentinus* in the southwest Atlantic fisheries during the period 1999-2004.

ABSTRACT

The Argentine shortfin squid *Illex argentinus* is the most important commercial squid species in the South West Atlantic and one of the target species for Spanish demersal trawlers operating on the High Seas of the Patagonian Shelf, i.e. on the edge of shelf and slope of 45-47° S and 41-42° S outside the Argentine EEZ. Catch data showed a very high level of biomass in 1999-2000 and the collapse of the fishery in 2003 and 2004. We examined whether these fluctuations can be attributed to environmental variation. Analysis of fishery catch data collected by scientific observers aboard commercial vessels was made to assess relationships between abundance variability of the slope-oceanic winter spawning group of *Illex argentinus* (CPUE) and environmental parameters. GIS and remote sensing data were used to study the influence of anomalies in sea-surface temperature (ASST) and oceanic circulation. Preliminary results show that relationship between sea surface temperature and abundance is non linear being the highest CPUE found at temperatures between 7 to 15° C. Sky, moon and sea state parameters explain a very low proportion of variation in the Illex abundance.

Keywords: abundance, squid, SW Atlantic, environment, ASST
1 INTRODUCTION

The Argentine shortfin squid (*Illex argentinus*) is a common neritic species occurring in waters off Brazil, Uruguay, Argentina, and the Falkland/Malvinas Islands in the southwest Atlantic (Nesis, 1987; Arkhipkin, 2000), where it is the most important cephalopod species in fisheries and plays a significant role in the ecosystem. Like many other cephalopod species it has an annual life cycle (Hatanaka, 1986) and is migratory (Caddy, 1983).

The life-cycle of *Illex argentinus* is associated with the subtropical confluence of the Brazil and Falkland (Malvinas) Currents during reproduction and the early life stages (Hatanaka, 1988; Brunetti and Ivanovic, 1992; Rodhouse *et al*., 1995; Haimovici *et al*., 1998) and with the Falkland (Malvinas) Current over the Southern Patagonian shelf during maturation, feeding and growth (Rodhouse *et al*., 1995).

Concentrations of shortfin squid are found 45-46° S in January or February and the animals subsequently migrate southward towards the Falkland Islands while growing rapidly. Peak concentrations are found around the Falkland Islands between March and May. Toward the end of this period, animals start migrating northward, ultimately to spawn and die in shelf and slope waters off northern Argentina, Uruguay and Brazil around July or August (Brunetti, 1988; Santos and Haimovici, 1997; Basson *et al*., 1996; Portela *et al*., 2002).

The marine environment off austral South America is rich in coastal fronts, having various forcing, and temporal and spatial scales. Spawning of the squid *I. argentinus* is associated with these fronts. The shelf-break front is a permanent feature that characterizes the border of the shelf. The inner boundary lies between the 90 and 100 m isobath. During the austral summer the front presents mild gradients in the density and thermal fields but is weak in the salinity field. During winter, salinity alone controls the density gradient. The gradients are strongest during autumn (Martos and Piccolo, 1988). The geographical location of the front may vary according to the dynamics of the Falkland (Malvinas) Current, for which cyclical variations - including semi-annual, annual and biannual periods - have been reported (Acha *et al*., 2004).

As aforementioned, *I. argentinus* is the most important cephalopod species for fisheries, being Spain the main European country targeting for it. The fishing grounds in the
Patagonian Shelf in which Spanish flag vessels are operating can be divided in two main fishing zones, one of them around the Falkland/Malvinas Islands in what are known as Falkland Interim and Outer Conservation Zones (FICZ and FOCZ respectively), and the second one in the “High Seas”.

The Instituto Español de Oceanografía (IEO) is running since 1988 a project for the study of the Spanish fisheries in the SW Atlantic. The activity of Spanish vessels in the High Seas is restricted to those portions of the continental shelf and slope which fall outside the Argentinean EEZ, i.e. a small patch around 42° S and a bigger area between parallels 43° 30’ and 48° S, namely “Area 42” and “Area 46” respectively. The fishing grounds around the Falkland Islands have been divided in three sub-areas: Malvinas North (MN), Malvinas West (MW) and Malvinas South (MS). Commercial fleets working in the area routinely carry fisheries observers, who record data on catches and associated conditions.

Squid are short-lived and their population dynamics are sensitive to environmental variation, making them suitable for the implementation of models that study the response of variables like abundance or maturity to environmental and geographical variations. Temporal and spatial changes in the relationship between squid abundance and climatic variables have been observed by several authors (Roberts and Sauer, 1994; Pierce, 1995; Pierce et al., 1998; Waluda and Pierce, 1998; Robin and Denis, 1999; Bellido et al., 2001). Pierce et al., (2001) investigated the relationship between cephalopod abundance and environmental factors in the Northeast Atlantic. By using GAMs and GIS they found that squid CPUE tended to be positively correlated with winter SST and negatively correlated with summer SST.

Catches time series have shown that 2003 and 2004 were unsuccessful years in the High Seas’s Illex fishery. During these years the Illex stock collapsed almost completely. The main reasons of this collapse seem likely to be due in part to unfavourable oceanography in the area and also that cephalopods are very responsive to environmental change due to their short life cycle.

*I. argentinus* seems to be strongly coupled with hydrographic patterns in the Southwest Atlantic and Sea Surface Temperature (SST) data is very useful to predict recruitment areas. The aim of this paper was to map the distribution of abundance (CPUE) of *I. argentinus* in
the High Seas and to examine the influence of SST in order to test the hypothesis that squid are associated with oceanographic processes.

2 MATERIAL AND METHODS

2.1 Data sources: Observers fishery data

The fishery data used in this analysis was taken from the scientific program “Observers on commercial vessels”. This program involves observers joining commercial vessels and recording numerous operational aspects of the trips such as characteristics of every haul, environmental and physical data, comprising fishing location, fishing depth, tow time, Sea Surface Temperature (SST), Sea Bottom Temperature (SBT), sea state, lunar cycle and sky state (cloud coverage).

The data used in this analysis included six years -1999 to 2004- of IEO (Instituto Español de Oceanografía, Vigo, Spain) and FIGFD (Falkland Islands Government Fisheries Department, Stanley, Falkland Islands) observers scientific program data. These six years were selected in order to gain an insight into the possible reasons of the Illex argentinus fishery collapse recorded during 2003 and 2004 years.

2.2 Geographic Information System (GIS)

Fishery and oceanographic data were incorporated into a GIS (ArcGIS version 9.0) allowing the overlay and display of the distribution of Illex argentinus catches for the 1999 to 2004 period. SST georeferenced data were also incorporated into the GIS to a base map of the Patagonian shelf. SST data were downloaded from the web site of the National Center for Atmospheric Researches (NCAR). SST data are global monthly data with 1º x 1º resolution, and are the output of a model, that uses marine surface observations, the NOAA Advanced Very High Resolution Radiometer (AVHRR) data and the presence of sea ice (Reynolds and Marsico 1993).
2.2 Statistical analysis and modelling

In addition to analyzing *Illex argentinus* distribution with GIS, we used Generalized Additive Models (GAMs) to visualize the response of *Illex* abundance to each variable included in the model separately.

GAMs are able to deal with non-linear relationships between an independent variable and multiple predictors and are particularly appropriate to our study. GAMs were first proposed by Hastie and Tibshirani (1990) and some of the first applications to fishery data were by Swartzman *et al.*, (1992 and 1995). A GAM is a non-parametric regression method with less strict assumptions than linear regression. GAM offer an attractive tool when parametric models do not seem to be flexible enough to capture the relationship of the covariates with the response variable.

This method is an extension of the generalized linear models (GLMs; McCullagh and Nelder, 1989). The principal strength of additive models is their ability to fit complex smooth functions (smoothers) to the predictors rather than being constrained by the parameterisation implicit in GLMs. A GAM, the generalized version of an additive model (relaxing the assumption that *y* has a Gaussian [normal] distribution), 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. $\beta_0$ is an intercept term and $S_k$ is a one-dimensional smoothing function for the $k^{th}$ explanatory variable, $x_k$. The degree of smoothing is determined by the degrees of freedom (df) associated with the smoothing function. The larger the degrees of freedom, the less the smoothing performed and more flexible the function obtained. The function $g$ is the so-called “link-function”, essentially a transformation applied to the expectation of the *y* values.

To model variation in *Illex argentinus* abundance GAMs were fitted using the “gam” command in Brodgar software (Highland Statistics Ltd). All data were imported into Brodgar from Microsoft Excel data files and initially screened to reveal characteristics of data sets and detect outliers. Quasi-Poisson distribution was assumed, accounting for the over-dispersed nature of the response variable (CPUE) data, and further GAMs were fitted. The link function used to model response
was log \([f(z) = \log(z)]\). A cubic smoothing spline method was chosen to smooth the variables, using 4 degrees of freedom by default.

Model was constructed following a forward stepwise procedure, evaluating alternative models in terms of the Akaike Information Criterion (AIC). The explanatory variables used in this model included: depth1, depth2, average fishing depth, SST, month, longitude and latitude. Year was included in the model in order to explore interannual trends in abundance of *Illex argentinus* during 1999-2004 period.

### 3 RESULTS

#### 3.1 Distribution of *Illex argentinus* abundance during 1999-2004 period

#### 3.1.1. GIS analysis

Satellite monitoring of SST allowed the analysis of hydrological conditions around the High Seas fishing area. From quarter mean SST maps (Fig 1a-1f) it was noticed that the intensity of the Falkland Current suffered variations during 1999-2004 period. It was found that, for the previous quarter of the fishing season of each year, the 10º C isotherm suffered variations in latitude.

In abundance terms, best years (i.e. 1999 and 2000) showed that 10º C isotherm arrived until latitude 41º S while during 2003 and 2004 (collapse years) cold water inflow (taking 10º C isotherm as a reference) occupied fishery region of the High Seas at latitude 39º S. This means that Falkland Current had higher intensity previously to collapse years than to successful years.
Figure 1a. Quarter mean SST maps and CPUE graph
Figure 1b. Quarter mean SST maps and CPUE graph
2000-4th Quarter

Year 2001

Figure 1c. Quarter mean SST maps and CPUE graph
Figure 1d. Quarter mean SST maps and CPUE graph
Figure 1e. Quarter mean SST maps and CPUE graph
Figure 1f. Quarter mean SST maps and CPUE graph
3.1.2 Generalised additive models (GAMs)

Scatter plots confirmed the non-linearity of the relationships between CPUE and environmental variables included in the model.

*Illex argentinus* abundance appears to be higher during 1999 and 2000 years, reaching the maximum value in March and between 100-200 meters depth. The highest squid abundances were associated with SST around 13º C (Fig. 2)
Figure 2. Scatterplots showing the relationships between *Illex argentinus* abundance (CPUE as kg h\(^{-1}\) per haul) and year, month, depth1, depth2, avgdepth, SST, latitude and longitude.

**Abundance (CPUE) model**

This model predicts the abundance of the species when present. The final model included effects of year, month, depth1, depth2, average fishing depth, SST, latitude and longitude (Fig. 3). Tables 1 and 2 show the numerical output for the final model.

The GAM output plots show the smoothers for the effects of all the variables included in the model. From the plots we concluded that:

- The Argentine shortfin squid *Illex argentinus* presented higher abundances during 1999-2000. After this year abundances suffered a marked decrease that led to the stock collapse in 2004.
• *I. argentinus* abundance presented a peak during March followed by a soft decrease in April and May when abundance shows a decreasing trend that reaches the minimum in June.

• Regarding latitude, maximum abundances were found around 48° S and in terms of longitude there is a minimum located around 61° W. Higher CPUE were found from 100 to 200 meters depth. *Illex argentinus* preferentially occurs in areas with SST between 13-14° C.
Figure 3. Partial plots showing smoothers, with 95% confidence limits, fitted to (partial) effects of the predictor variables retained in the final (optimal) model of Illex abundance (CPUE) in High Seas. Clockwise from top-left: Year, Month, Depth1, Depth2, AvgDepth, SST, Latitude, Longitude. Each variable in the model was fitted using four degrees of freedom.

Table 1. Goodness of fit measure for the GAM.

<table>
<thead>
<tr>
<th></th>
<th>R-sq (adj)</th>
<th>Dev.explained</th>
<th>AIC 1</th>
<th>AIC 2</th>
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<tr>
<td></td>
<td>0.487</td>
<td>67.9%</td>
<td>597505</td>
<td>507.92</td>
</tr>
</tbody>
</table>

The model was a Quasi-Poisson GAM with the form:

\[
\text{CPUE} \sim s(\text{Lat}) + s(\text{Lon}) + s(\text{Year}) + s(\text{Depth1}) + s(\text{Depth2}) + s(\text{Month}) + s(\text{SST})
\]

1) AIC according to formula: -2log(Likelihood) + 2*df *Overdispersion
2) AIC according to formula: (Deviance + 2*df *Overdispersion )/n

Table 2. Approximate significance of smooth terms used in the model.

<table>
<thead>
<tr>
<th></th>
<th>edf</th>
<th>chi.sq</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>s(Year)</td>
<td>4</td>
<td>58.459</td>
<td>&lt; 2.22e-16</td>
</tr>
<tr>
<td>s(Month)</td>
<td>4</td>
<td>240.82</td>
<td>&lt; 2.22e-16</td>
</tr>
<tr>
<td>s(Depth1)</td>
<td>3.838</td>
<td>7.7409</td>
<td>0.028100</td>
</tr>
<tr>
<td>s(Depth2)</td>
<td>3.809</td>
<td>9.8524</td>
<td>0.066125</td>
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<tr>
<td>s(AvgDepth)</td>
<td>3.353</td>
<td>9.3916</td>
<td>0.13208</td>
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<tr>
<td>s(Latitude)</td>
<td>4</td>
<td>51.328</td>
<td>2.2915e-12</td>
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<tr>
<td>s(Longitude)</td>
<td>4</td>
<td>55.477</td>
<td>2.2916e-12</td>
</tr>
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<td>s(SST)</td>
<td>4</td>
<td>54.065</td>
<td>3.4792e-10</td>
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</table>
4 DISCUSSION

One of its distinguishing characteristics is that during its life-cycle, *Illex* migrates from the spawning grounds off northern Argentina, Uruguay, and Brazil southwards to the Patagonian and Falkland Islands shelves (Arkhipkin, 2000). Concentrations of shortfin squid are found at 45-46º S in January or February. Peak concentrations are found around the Falkland Islands between March and May. Toward the end of this period *Illex argentinus* returns to the north where the animals spawn and die around July or August (Basson *et al*., 1996). The basic pattern of migration is described in Hatanaka (1988).

The analysis of SST images indicates that the area of study is dominated by warm Patagonian shelf waters and cooler waters from the Falkland (Malvinas) Current (Peterson and Stramma, 1991; Peterson, 1992). The boundary between both water masses can be seen clearly on all images.

Remote sensing methods have been used successfully to find associations between oceanic fish and certain temperature regimes (Laurs *et al*., 1984; Kumari *et al*., 1993). Even the thermal tolerance range of squid is less well known, GIS maps obtained in this study revealed that hydrological factors as variations in intensity of Falkland Current suggest a close relation between oceanographic conditions and distribution of catches of squid *I. argentinus* on the High Seas. The effect of the Falkland Current on fishing for *I. argentinus* according satellite monitoring of the SST was also studied by Vanyushin (2005). He studied the SST monthly anomalies for the Southwest Atlantic and concluded that deviations from the mean SST lead to different behaviours in squid migration. Relationships between physical oceanography, current systems and location of squid are also documented in Coelho, 1985; Hatanaka *et al*., 1985; Bakun and Csrke, 1998.

Our GAM analysis indicate that environmental conditions influence the squid abundance (CPUE). Final model explained a 67.9% of variation in the response variable. There is seasonal effect in the model that shows that minimum abundances were found during June.

The GAM model demonstrates that the relationship between SST and abundance is non linear being the highest CPUE found at temperatures between 13-14º C. Previous studies made by Waluda *et al*., (2001) have shown by analysis of remotely sensed SST that about
55% of variability in recruitment strength around the Falklands can be explained by variations in the optimum water temperature during the spawning season prior to recruitment.

Previous fishery studies have already used GAM techniques for spatial modelling of abundance of marine species. For example, Swartzman et al., (1992), Denis et al., (2002) and Wang et al., (2003) used GAM to analyze geographical variations of fish and squid distribution. Bellido et al., (2001) presented a preliminary application of GAM in order to model intra-annual (spatial and seasonal) trends in squid Loligo forbesi abundance as function of environmental, spatial and temporal variables in Scottish waters.

The representation of yearly maps of observer data allowed visualisation of the temporal variations of CPUE for Illex during 1999 to 2004 period. The combination of GIS with statistical analysis methods has become an important and powerful approach for spatio-temporal analysis, understanding, prediction, and visualization of fishery resources in relation to environmental variation in spatial and temporal dimensions.

Furthermore, the pronounced interannual variations seen in squid abundance indicates the need for further studies to identify the causes of this variation.

The discovery of relationships between environmental-geographical variability and squid abundance may form the basis of predicting abundance in these short-lived species, with applications in fisheries forecasting and management.

ACKNOWLEDGEMENTS
The authors wish to express their gratitude to scientific observers, crews, fishing companies and associations for their collaboration in data collection.

REFERENCES


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