GAM analysis of operational and environmental factors affecting swordfish (*Xiphias gladius*) catch and CPUE of the Reunion Island longline fishery, in the South Western Indian Ocean

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Abstract

This article deals with the Reunion Island based longline fishery, targeting mainly swordfish (*Xiphias gladius*) for almost 15 years, operating by night with very straight lines thus attaining quite shallow waters. During the PPR programme, jointly led by the Ifremer, IRD and University of La Reunion, a rigorous data collecting strategy has reached to a very good coverage of the fishery from 1998 to 2000. Operational parameters concerning the fishing gear configuration and fishermen habits had been collected for 3602 longline sets by the Ifremer, including their precise location (beginning and end of the longline setting). According to these positions, data extraction had been conducted from oceanographic satellite maps (available from the IRD S140 “Espace” team), dealing with depth, temperature, colour and vertical dynamics of the surface waters at the locations of the longline sets, supposed to witness the environmental context of the catch. After deleting redundant factors, several GAM models have been tested on these data, including operational (12 initial factors), environmental (20 initial factors) and both, in order to assess the respective influences of these parameters on swordfish catch and CPUE. Even with quite poor explanatory power of our best model (including every factor, with less than 50% of the initial total variance explained), it appears that the operational influence may be greater than environmental, in the way with introduced them in our analyses. As the most important, the main factors influencing swordfish vulnerability thus may be respectively the length of the buoys leaders sustaining longlines at the sea surface, number of hooks, duration of the retrieving of the line from water, mean distance between two successive hooks, duration of the drifting of the longline at night, time of the beginning of the longline setting and duration of the setting. Environmental parameters arrive after operational ones in the total inertia of this best model: horizontal gradients of Sea Surface Anomalies (SLA), Sea Surface Temperature, north-south component of the geostrophic currents derived from SLA, lunar phases and gradients of SST play a graduated role, while the horizontal gradient of the east-west component of the geostrophic currents and lunar days may play a stronger role while considering only environmental parameters on CPUE. Other models are discussed, with the results compared to studies on swordfish in other parts of the world oceans, that could bring some insights on swordfish biology and catchability in the south-western Indian ocean.

Résumé

Cette communication traite de la pêcherie palangrière réunionnaise de surface basée à La Réunion, qui cible principalement l'espadon (Xiphias gladius) depuis presque 15 ans, opérant de nuit avec des lignes de pêche très tendue en surface, atteignant ainsi des eaux très superficielles. Pendant le programme PPR (Programme Palangre Réunion), mené conjointement par l'Ifremer, l'IRD et l'Université de La Réunion, une stratégie rigoureuse de collecte de données a permis d'obtenir une couverture très étendue de la pêcherie de 1998 à 2000. Les facteurs opérationnels de pêche concernant l'engin et les pratiques des pêcheurs, notamment les positions de début et de fin de filage, ont été collectées auprès de 3602 filages par l'Ifremer. A partir de ces positions de pêche, des extractions de données ont été menées sur des cartes d'océanographie satellitale opérationnelle (disponibles grâce à l'Unité S140 « Espace » de l'IRD) : des valeurs de température de surface, couleur et profondeur de l'eau, dynamique verticale des masses d'eau ont ainsi pu être extraites aux positions de pêche, sensées représenter le contexte environnemental des captures. Après un tri des paramètres corrélés, des modèles GAM ont été testés sur ces données, incluant initialement 12 facteurs opérationnels et 20 facteurs environnementaux, associés et séparés, pour estimer les influences réciproques de chacun sur les captures et CPUE d'espadon. Même si notre meilleur modèle (modèle complet incluant tous les facteurs) n'explique qu'une faible part de la variance totale initiale de nos données (moins de 50%), il apparaît que les facteurs opérationnels dominent les facteurs environnementaux, du moins dans la manière dont nous les avons introduits dans le modèle. Les facteurs opérationnels les plus importants pour la vulnérabilité de l'espadon seraient donc respectivement la longueur moyenne des avançons de bouées supportant la ligne en surface, le nombre d'hameçons, la durée du virage de la ligne au matin, la distance moyenne entre deux hameçons, la durée de dérive de la ligne pendant la nuit, l'heure de début de filage et la durée de filage. Les facteurs environnementaux, qui arrivent tous après les facteurs opérationnels dans l'inertie du modèle complet, seraient les gradients horizontaux de l'anomalie de hauteur d'eau, la température de surface, la composante nord-sud des courants géostrophiques dérivés de la SLA, l'indice de luminosité lunaire et les gradients horizontaux de température de surface. Les gradients est-ouest des courants géostrophiques et les jours lunaires jouent un rôle important aussi dans le modèle restreint aux facteurs environnementaux sur les CPUE notamment. D'autres modèles sont aussi discutés, et leurs résultats comparés avec ceux obtenus sur l'espadon dans d'autres régions du monde, permettant d'apporter quelques compléments à la meilleure compréhension de la capturabilité et de la biologie de l'espadon dans le sud-ouest de l'océan Indien.

Introduction

As a quite recent statistical methodology to handle and analyse big data sets, characterised by numbers of factors and big sample size, Generalized Additive Models (GAM) have now been widely used in ecological and marine fisheries studies (Swartzman *et al.*, 1995; Adlerstein and Welleman, 2000; Maury *et al.*, 2001; Walsh and Kleiber, 2001; Denis *et al.*, 2002; Piet, 2002; Schoeman and Richardson, 2002; Daskalov *et al.*, 2003). Its is now commonly used as a robust method to assess the relationships between presence/absence, distribution, density or catches of plants and animals on one hand, and human and environmental factors affecting the latter processes on the other hand. As a generalisation of non-parametrical regression methods, they allow researchers to distinguish between factors affecting natural communities characteristics, and all the more to quantify between their relative influences. Today's computers are fast and powerful enough to analyses big data sets established from *in-situ* sampling collects, that often are established with *a priori* knowledge on relationships supposed to exist. Modern regression tools as GAM thus help to better orientate sampling strategies and predict strong ecological effects. In the fisheries sciences, GAM have been mainly used to assess relationships between oceanographic conditions prevailing during the catch of targeted species and the result of the fishing action (catch and CPUE). This has been particularly improved by the development of global oceanographic data collecting methods, such as satellite telemetry. In Reunion Island, a longline fishery has been developing in the south-western Indian Ocean waters for almost 15 years. A scientific program (the PPR programme) has been achieved from 1998 to 2000 in order to help fishermen better targeting swordfish (*Xiphias gladius*) and ensure sustainable exploitation of the fish (Poisson and Taquet, 2001). Comprehension of catchability parameters of the longline in the oceanic landscape is therefore of finest interest for both scientists and managers.

Material and methods

Ifremer fishing database

Fishing data have been collected from the Reunion longline fishery logbooks that Ifremer had distributed to local fishermen (Poisson, 2001). For each longline set (2915 records), catch (number of individuals of swordfish) and effort (number of hooks deployed) were available. Unfortunately, catch data were not precisely distributed along often quite long line sets (mean length is 56km; Figure 1). After a strong verification and selection of logbooks data (Poisson and Guyomard, 2001), twelve parameters have thus been chosen to represent the operational factors affecting each longline set and its fishing results (Tab 1).

IRD satellite maps

In order to characterise the oceanographic environment of each longline set, satellite data have been provided by the IRD. Three main parameters have been regularly collected and maps established: Sea Surface Temperature (SST) on a daily base with high spatial resolution, Sea Level Anomalies (SLA) and geostrophic currents (both zonal and meridian components)[1] on a 10-days base, and chlorophylle-a contents on an 8-days base. A detailed description of these parameters has been proposed by Desruisseaux *et al.* (2001b). Bathymetry has also been included in our study, thanks to the D. Sandwell altimetry map of the Indian Ocean (Smith and Sandwell, 1997)[2]. All the more, a spatial convolution filter (Sobel 3x3; Herron *et al.*,

[1] Computation of the geostrophic currents from SLA data have been led by CLS: http://www.cls.fr/html/oceano/general/applications/duacs_fr.html
[2] Data are available free on: **http://topex.ucsd.edu/cgi-bin/get_data.cgi**

1989) has been applied on each map, in order to characterise horizontal gradients of each parameter. A lunar index has been established too, in order to better render the luminosity of the moon instead of the classical quarter phases (Tab 2).

Data extraction

As longline sets have linear shapes covering quite wide areas compared to satellite maps spatial resolution, data extraction from maps have been achieved in two ways. First, the median position of each set has been arbitrarily chosen as the best position representing the whole environmental context of the catch, for every parameter. In order to introduce the effects of eventual discontinuity structures around longline sets, its has been chosen not to keep the median position alone, but to introduce geographic indexes. The first index chosen was the maximal value of the (up to) five extracted convolution gradient values from the median, beginning, ending, first and last-quarter positions of each longline shape. This index is assumed to better render the existence of possible surface fronts around longline sets. The second index was established as the absolute maximal difference between the five positions extractions values from raw parameters, in order to render the existence of fronts across the line.

Parameters selection

One of the main requirement for GAM statistics is to introduce independent variables as the response in the model (Chambers and Hastie, 1992). We thus have selected variables so that they are not correlated one to another and better represent operational and environmental effects. The Spearman rank correlation coefficient has first been selected as a quite robust correlation assessment tool, as it doesn't require variables to show strictly regular distributions.

GAM and indexes

As response variables, both catch and nominal CPUE (in number of individuals cached for 1000 hooks) has been selected for the main targeted specie, *i.e.* swordfish. Other important species but the total catch, mainly tunas, has not been kept as possible response variables, because of their non normal distribution.
The GAM generic formula is of the form:

Reponse Variable = s(Explanatory Variable 1) + s(Explanatory Variable 2) +...

S() is the smoothing non-parametrical function (cubic spline) we chose after Maury et al. (2001). The constraint on the Response Variable is to show a normal distribution, where the catch and CPUE data classically show a Poisson one. A log transformation has been applied to the data, then requiring every set to be added one catch (or every CPUE one per 1000 hooks) for the log transformation to remain positive (Figure 3). The gaussian distribution is not strictly observed, but, as other authors usually do (Denis *et al.*, 2002), we'll consider it is.

As every longline set is not completely informed for every variable (due to the absence of collect of certain parameters from some fishermen and subsisting holes in satellite maps), a complete model including every variable and two separated models (operational and environmental) have been tested.
For each model, three synthetic indexes have been calculated: (1) the *pseudo-R^2*, a "correlation coefficient like" index, which characterises the global level of explanation of the model

$$\text{pseudo } R^2 = 1-(\text{Residual Deviance}/\text{Null Deviance})$$

(2) the *p(F)* index given by the analysis of variance (F test of the `summary()`function in S+) for each model, which characterises its level of significance (threshold values of 0.05 and 0.01 have been considered as significant).

(3) the *inertia* of each parameter in the model, calculated thanks to the F test values given by the non parametric statistics of the S+ GAM function.

The graphical relationships between catch and CPUE on one hand, and operational and environmental factors on the other hand, are shown for the main proven effects.

A step GAM selection of the variables (based on the Akaike Information Criterion, AIC) has been applied to every model, in order to keep the best informative parameters.

Complementary survey

As the empirical knowledge of local fishermen may bring some relevant insights to scientific knowledge (Kaneko *et al.*, 2001), we decided to collect information to a group of fishermen, that were involved in the scientific programme or interested in the valorisation of satellite maps. For that purpose, a meeting with researchers and fishermen took place on March 14th 2001, at the CRPMEM[3] place. Even if no precise methodology had been set up to collect information, the quality of the discussions between professional and scientists allowed us to trust in the synthesis of this meeting.

Results

Variables selection

Tab 3 syntheses the results of the Spearman rank correlation analysis: only significant correlations (p<0.01) with the Rh0 coefficient at least equals to 0.5 are presented. The analysis allows to strictly confirm the strong relationships between the two "discontinuity " indexes: every index is correlated to the other, for each parameter. It has thus been chosen to keep the best informed parameter, *i.e.* with the highest number of records (Tab 1), or arbitrarily one of the two indexes (the maximum of the convolution gradient value). Other correlated parameters are swordfish catch with total catch and swordfish CPUE: in order to reduce the number of response variables, only swordfish catch and CPUE have been kept, but will have to be separated in the GAM analysis (Rh0=0.95). The total time of the fishing action `dtot` is correlated to both setting `dt1` and hauling time `dt3`, but not to drifting time `dt2`: it is so better to keep each of the different duration time indexes, so that the influences of each of it could be separated from the others. The beginning time of longline setting is strongly correlated to the sunset interval index, so the latter has been deleted from our analysis. Last of all, the mean distance between hooks (`interham`) is correlated to the total estimated length of the longline (`filage`): as an interesting index commonly used by fishermen, it is better to be kept than the total length, that has been derived from the `dt1` duration time (Poisson and Guyomard, 2001).

The complete GAM model can thus be expressed like the following, with 23 explanatory variables left:

```
log (SWO+1) = s(nbham) + s(longlead) + s(lstick) + s(interham) + s(dt1) +
s(dt2) + s(dt3) + s(hdebfil) + s(diffLune) + s(jourlun) + s(lune) +
s(profondeur) + s(chloro) +s(SST) + s(SLA) + s(U) + s(V) +
s(Mgr.profondeur) + s(Dchloro) + s(Mgr.SST) + s(Mgr.SLA) + s(Mgr.U) + s(DV)
```

[3] Comité Régional des Pêches Maritimes et Elevages Marins : Reunion Island representation of local professionnal fishermen ; elements of knowledge issued from this meeting will be referenced as CRPMEM, 2001 in the rest of this document

GAM synthetic indexes

All the more to the “complete” model, “simple” models have been tested, with each unique parameter introduced in the analysis. These results (so obtained from a lot more extensive data set, as seen on Tab 1) are expressed in Tab 4, in the “simple model pseudo R^2” and “simple model p(F)”.

The complete model explains almost 50% of the total initial variance in the model (pseudo $R^2 = 0.48$), where the six first significant parameters ($p(F) < 0.01$) represent 60% of the total cumulative inertia, with only operational parameters. It is noticeable that only 954 longline sets (for 2915 verified sets) are fully informed and thus used as individual records in this model. Mean length of the buoys leaders (`longlead`) and number of hooks (`nbham`) take almost a third of the total inertia by themselves (31.04%). The first environmental parameter (`Mgr.SLA`) only takes the 7st place ($p(F)<0.05$). Simple models are almost all significant ($p<0.01$, except for `DV`, `chloro` and `Dchloro`), but each only explains for a very tiny part of the initial variance (pseudo $R^2>0.1$ only for `nbham`, `dt3` and `dt1`).

We thus applied the `step.gam` function to our complete model, for AIC selection. Results are shown in Tab 5. The AIC selection keeps the first 13 variables of the complete model. Except for the lunar index and the SLA maximum gradient, the first 8 significant parameters ($p(F)<0.01$) are operational ones. They almost represent 80% of the total inertia, for a pseudo R^2 almost not weaker than for the complete model (0.45).

As the complete model has been established from only 954 longline sets, three other “restricted” models have been tested: one for the operational and two others for the environmental factors (catch and CPUE). The operational factors model can be expressed like the following:

```
log (SWO+1) = s(nbham) + s(longlead) + s(lstick) + s(interham) + s(dt1) +
s(dt2) + s(dt3) + s(hdebfil) + s(diffLune)
```

The environmental factors models can be expressed like this:

```
log (SWO+1) = s(jourlun) + s(lune) + s(profondeur) + s(chloro) +s(SST) +
s(SLA) + s(U) + s(V) + s(Mgr.profondeur) + s(Dchloro) + s(Mgr.SST) +
s(Mgr.SLA) + s(Mgr.U) + s(DV)

log ((SWO+1)*1000/nbham) = s(jourlun) + s(lune) + s(profondeur) + s(chloro)
+s(SST) + s(SLA) + s(U) + s(V) + s(Mgr.profondeur) + s(Dchloro) +
s(Mgr.SST) + s(Mgr.SLA) + s(Mgr.U) + s(DV)
```

Tab 6 synthesizes results of the different tested models (when the AIC criterion has been used, it is noted in the second column). In order to better compare the results of the different models, restricted models have first been applied to the initial dataset used with the “complete” model (954 longline sets). Then every longline set that could be totally informed by respectively every operational and environmental variables, has been added to the total dataset (numbers of longline sets used are presented in the third column of Tab 6). Significant factors are presented in accordance with their respective contribution to the cumulative deviance gain in each model.
The main significant factors of the « complete model » all stay significant in the “restrictive models” for operational factors: length of buoy leaders (`longlead`), number of hooks (`nbham`), duration of longline hauling (`dt3`), setting (`dt1`), and (but to a lesser extent) drifting (`dt2`), mean distance between two successive hooks (`interham`), number of light-sticks (`lstick`) and time of beginning of longline setting (`hdebfil`). The time duration between moon rising

and time of beginning of longline setting (`diffLune`) is a bit less significant than for the complete model concerning swordfish catch.

Concerning environmental variables, the most significant factors that we can find in almost every model are: meridian component (east-west) of the geostrophic current (`V`), maximum of sea-level anomalies convolution gradients (`Mgr.SLA`), maximum of zonal component (south-north) of the geostrophic currents convolution gradients (`Mgr.V`), bathymetry (`profondeur`) and sea-surface temperature (`SST`). Other factors are a little bit less significant: zonal component (east-west) of the geostrophic current (`U`), lunar day (`jourlun`), sea-level anomaly (`SLA`), maximum of SST convolution gradients (`Mgr.SST`), and zonal component (south-north) of the geostrophic currents (`V`).

Figure 5 syntheses the results of the different models for swordfish catch variability explanation. They show a constant degradation of the total amount of explanatory power of the analysis: it is mainly due to the fact that we chose not to keep the worst factors due to the AIC criterion (models n°s 2, 6 and 8) and to separate operational (models n°s 3 and 4) and environmental models (models n°s 5 to 9). The best model, regarding to the pseudo-R^2 value, is the complete model n°1, established with the maximum initial number of variables (23). The operational models show a still quite good value of pseudo-R^2 (0.41 for model n°3), compared to the loss in the number of explanatory variables (only 8 variables left). Operational factors tend to contribute to a larger extent to the variation of the total deviance in the model, thus explaining more in the variability of swordfish catch in the longline fishery.

GAM graphical relationships

One of the main interest in GAM is to graphically represent relationships between response and explanatory variables. The most significant and ecologically interesting relationships established from our different models are thus presented at Figure 6, Figure 7 and Figure 8 (dashed lines are 95% confidence intervals). When both the “complete” and “restrictive” models relationships are significant (and usually very alike in their shapes), we chose to show the latter one, established from a larger number of longline sets. When the relationships are really different, due to the added sets to the “restrictive models”, we chose to show and discuss them too.

Operational factors

The first significant operational factor is the mean length of buoys leaders (Tab 4, Tab 5, Tab 6). This factor had been measured as the mean length of each section buoys leaders (a section holds from 70 to more than 100 hooks). Reunion Island based fishermen usually alternate between long (>20 fathoms), short (5 to 7 fathoms) and medium (10 to 15 fathoms) segment buoys leaders, and this “mean length” is a quite imprecise factor established from a great number of sections (Figure 4). This mean length is however the only factor to integer the “vertical” dimension of the longline and has to be taken in account in our analysis as a “proxy” variable of the theoretical mean depth reached by hooks during drifting of the longline. Figure 6a shows that the effect of leaders length is clearly not linear. Swordfish catch are diminished when leaders are short but stabilise over 10-12 fathoms (almost 1.5 swordfish less per longline set). There seems not to have any strong effect on catch when mean leaders length is over 15 fathoms.

As the most used “nominal effort index” for longline fishing (and used by us as the CPUE effort index), the effect of the total number of hooks on swordfish catch is important to determine. Not surprisingly, its effect (Figure 6b) looks quite linear inside the boundaries of the most used numbers of hook, that is from 1000 to 1700 hooks (83% of the 2207 longline sets): the effect on catch is almost of 1.6 swordfish from 1000 to 1700 hooks used. This effect is nevertheless no more linear when more than 1700 hooks are used, with a threshold clearly appearing at this value. The setting time of the longline is partly correlated to the number of hooks (Spearman rank Rh0=0.42), but its effect on swordfish catch doesn't look the same (Figure 6c): no clear effect is observed on catch until a threshold is reached, above which catch seem to decrease. It seems that above 5 hours of setting, the number of hooks roughly reach the 1700 threshold observed on Figure 6b. This quite singular effect has to be compared with the one of the mean distance between two successive hooks (Figure 6d). The number of hooks and setting time duration indeed are linked by this factor (and the speed of the fishing boat during longline setting), that is currently discussed by fishermen as decisive for swordfish catch. The model n°3 clearly shows that it exists an optimum for the mean distance between hooks: it clearly appears that, even if shorter distances seem to have a minor effect on swordfish catch, hooks better fish when separated by 60m, and worst above. This effect is even stronger for model n°1 (Figure 6e), where closer hooks are definitely less efficient (with a minimum at 40m separated hooks).

One of the most significant factor in our analysis is the duration time of longline hauling (third position in models n°s 1, 2 and 3 and first in model n°4). It is quite correlated to the swordfish catch (Spearman rank Rh0=0.39), because greatly depends on the time spent on each animal to retrieve from the water. Nevertheless, the graphical representation (Figure 6f) clearly shows a bell-shaped link between swordfish catch and retrieving duration: the more the catch, the more the time to haul the line (quasi linearly), until a threshold is reached. After 10 hours of hauling, the fish tends to leave the hooks. The effect of drifting time duration is very significant too (fifth and sixth positions respectively, for models n°1 and 2), but the shape of the relationship is not very definite (Figure 6g): as for retrieving time, shorter drifting duration times (around 6 hours) seems to have a positive effect on swordfish catch, compared to longer duration (up to 10 hours).

Last of the operational factors, the time of beginning of longline setting is quite significant in every model. Most longlines are usually set at dusk, but some are set during night (after midnight) or in the morning, so the shape of the relationship with catch is somehow atypical (Figure 6h). Nevertheless, it appears that for most longlines (beginning time between 15h30[4] and 21h30, representing 99.5% of the 2207 sets in model n°4), the relationship is bell-shaped: from 15h30 to 18h00, catch increase (but with quite a large uncertainty, referring to the wider confidence interval before 18h00), and after 18h00 to 21h30, decrease. It seems that, the more the fishermen wait at the end of the afternoon (especially after sunset), the worst the catch for swordfish. The duration time between moon rising time and time of beginning of the longline setting appears not to be significant enough to be presented here.

The last significant factor only appears in model n°4 (7th position). The number of hooks between two successive light sticks seems to have a negative impact on swordfish catch (Figure 7a), that is to say, the more the fishermen use light sticks, the better the catch.

Environmental factors

As for operational factors, we only show graphical representations for both catch and CPUE when the shape of the relationship is different between the two indexes.

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[4] Time unit is in fraction of a day: 0.5 means midday (12h00), 0.75 means 18h00

The most significant environmental factor is, concerning swordfish catch, the meridian component (V) of geostrophic currents derived from SLA data, for both complete and restrictive models (models n^{os}5, 6, 7 and 8). This south-north surface currents component explains the third part of inertia for CPUE in the complete model (model n°5bis), the first part for the restrictive model (n°7bis) and the fourth part for the restricted model selected by AIC (n°8bis), but has no more effect in the final models (n°9 and 9bis). The graphical relationship clearly shows a very similar bell-shaped link with both catch and CPUE (CPUE shown on Figure 7c): null values are better for fishing results. It seems that low positive V values (i.e., light currents to the north) are a little bit more beneficial, but the trend becomes clearly negative for higher values.

The second significant factor in importance is the maximal value of the SLA convolution gradient value (Mgr.SLA). It appears at the second row for the complete model for catch and at the fourth row for CPUE, but second after AIC selection. For restricted models, it is only significant for swordfish catch. The graphical representation (Figure 7d) shows that light gradients (<20cm) have a small effect, but that higher gradients enhance fishing results. The stronger effect appears clearly at values from 20cm to 40cm of SLA gradients (almost 1.6 swordfish less per 1000 hooks). The effect is still positive above 40cm, but tends to decrease. The SLA absolute value is lightly significant (p(F)<0.05) in the complete model after AIC selection for catch (Tab 5) and in the restricted models n^{os}6bis, 8bis and 9bis for CPUE (Tab 6). The shape of the relation (Figure 7e) is not very marked: the effect of SLA is not very strong neither on CPUE nor on catch, but a minimum appears at null values of SLA, and a very light positive trend of the effect for positive values and negative for negative values (less than 1 swordfish more for 1000 hooks).

The maximal value of the zonal component of the geostrophic current convolution gradient value (Mgr.U) is the second significant factor in the restricted models for catch (7th and 8th position for the complete model, but 1st for model n°9). Concerning CPUE, it is highly significant for models n°6bis (4th position), n^{os}7bis, 8bis and 9bis (2nd). The shape of the relation (shown for CPUE on Figure **7**f) is not linear either, as for mainly every other factor: it expresses a positive effect on catch and CPUE from null values to gradients close to 50cm.s^{-1}. A threshold there appears, indicating a null effect on CPUE (still but less positive for catch) until the value of 100cm.s^{-1}. Quite few longline sets have very strong gradients in their surroundings (>100cm.s-1, less than 18% of the 1876 longline sets), and the effect is very variable (broader 95% confidence intervals).

The zonal component of geostrophic currents (U) is significant for models n°5 (p(F)<0.05) and n°6 (p(F)<0.01), only for catch. The shape of the relation (Figure **7**g) is very close to the one of the meridian component (Figure **7**c): weaker currents may be better for swordfish catch, but lightly positive values (up to 20 cm.s-1 in the western direction) seem to bring advantage for fishing.

Bathymetry is significant for every model concerning catch, excepting the last final one (model n°9). It stands at the first row for CPUE complete models (n^{os}5bis and 6bis) and at the third row for model n°8bis and the fourth row for model n°9bis. The shape of the relation is quite similar for both catch (Figure 7h) and CPUE (Figure 8a), with a “rocking movement” like relation. The restricted model n°7 clearly shows that catch decrease when the oceanic floor is shallower (from 5000 to 4000m deep), where the complete model n°5bis indicates that CPUE slightly decrease until depths around 4500m. The complete model then indicates that catch may rise when depths are below 3500m, but the variability of the relationship is quite high. The restricted model shows a similar but weaker effect on CPUE, between 4000m and 2700m, with a high variability too. Above 2700m, catch tend to decrease again, whereas CPUE still rise (with a high variability again).

Sea Surface Temperature is the last significant factor extracted from satellite maps. The absolute value (`SST`) appears in the first model (p(F)<0.05) and in the second one, selected by AIC (p(F)<0.01), as well as for model n°9 (2nd position, p(F)<0.01) for the catch. Concerning CPUE, the influence of absolute SST is significant (p(F)<0.01) for both the complete model (n°5bis) and the final model (n°9bis). Reunion Island based fishing boats usually fish in surface waters from 24°C to 29°C (94% of the 2915 initial longline sets): within this temperature range, catch seem to rise in 24-25°C waters and decrease above (Figure 8b). For CPUE, a clearly marked minimum is observed for temperatures between 27°C and 28°C (Figure 8c). The maximal value of the SST convolution gradient value (`Mgr.SST`) is slightly significant for models n^{os} 1,2, 5 and 6 for the catch and for models n^{os} 5bis and 6bis for CPUE. For both catch and CPUE (CPUE show on Figure 8b), the shape of the relation is positive from null to low gradients (3-4°C). Beyond that value, the very broad 95% confidence interval doesn't allow to clearly conclude that the effect is still positive or null.

The last of the significant factors is the lunar day, for restricted models n^{os}6 to 9 (p(F)<0.05, for catch) and even better for models n^{os} 8bis and 9bis (p(F)<0.01 for CPUE). The shape of the relationship is not surprisingly close to the lunar index graphical representation (Figure 7b): better catch and CPUE seem to occur around days 5 and 25, corresponding to periods 2 and 4 of our lunar index.

The effect of the meridian component of the geostrophic current gradient along the longline shape (DV) is never significant, neither for the catch nor CPUE.

One of the most striking results in our analysis is to notice that neither the chlorophyll content (`chloro`) nor the horizontal gradient (`Dchloro`) are significant in none of our models (Tab 4, Tab 5 and Tab 6), neither on catch nor CPUE of swordfish. The graphical relationships associated to these parameters nevertheless are interesting to observe, as their shape is quite reliable with previous studies on swordfish (Young *et al.*, 2000): Figure 8g suggests that for values less than 0.1 mg.m^{-3} the augmentation of the chlorophyll content is bad for the catch, whereas light chlorophyll gradients (less than 0.05mg.m^{-3}) along the longline (as seen on Figure 8h) may positively influence the catch.

The lunar index (explained on Tab 2) is not significant either, unless for the complete model n°2 selected by AIC, where it even arrives in 4th position. The graphical relationship (Figure 7b) shows that the fourth period is the best for swordfish catch, with the symmetric second period being quite positive too. It appears that both the new moon and full moon are the worst periods for swordfish catch.

Discussion

Our results clearly show that commonly collected operational factors have a larger influence on swordfish fishing results than environmental factors, at least in the way we introduced them in our analysis. Actually, in our complete model (model n°1), which holds the biggest part of the explanatory power in our data (almost 50%, Tab 4), significant factors (12 on a total of 23) are mainly operational ones (6 first factors, p(F)<0.01) than environmental (5 factors among the last ones, p(F)<0.05). The environmental influence may certainly be of greater importance than observed, but other indexes or even parameters should be proposed and introduced in the models, that may play an effective biggest role on the fishing efficiency.

Swordfish and the fishing gear

The GAM analysis gives new insight on different characteristics of the behaviour of the swordfish regarding to the configuration of the longline and its operational setting (what is commonly called the vulnerability of the fish).

Swordfish vulnerability and time of the day

Our results on time of beginning of longline setting confirm that swordfish preferentially bite at dusk time, in dim light conditions, when rising up to sub-surface waters (Carey, 1990). During the PPR programme, an experiment has been conducted on longline sets equipped with "hook-timers" and thermo-bathymetric recorders (Poisson and Reynaud, 2001; after Boggs, 1992): time of biting clearly indicated that the fish is active very soon after the longline setting, with 60% of the swordfish caught within the first 4 hours (17% during the very first hour). Bait freshness could be an explanation of this results, as appetence may decrease with time, but some rare longlines that had been set by local fishermen during daytime had shown worst fishing results that at night. This would bring us to the conclusion that swordfish definitely bites at dusk on longline hooks.

Swordfish vulnerability and soak time of the longline

Concerning the three factors relating to duration time of the fishing action (so called "soak time"), the threshold appearing at 10 hours after beginning of hauling shows that the fishing gear tends to saturate when staying too long in the water. Swordfish individuals, that mostly have bitten at dusk, may have stayed for a long time on the lines, and could be affected by different parameters that make them get off the hooks, even dead. It is actually common to observe fish that had been tight to the hooks with one fin or a flank, and are susceptible to escape from the lines due to currents or degradation of the flesh during the day (fishermen *personal communication*). The PPR "hook-timers" experiment tended to confirm this observation: the results had shown that 61% of the total number of equipped hooks had been set off, with only 7.4% of them to hold a fish. This PPR experiment showed that the number of swordfish caught by number of equipped hooks tended to increase from 19h00 to 21h00 too, then slowly decreasing until 1h00 AM to almost null values in the morning (Poisson and Reynaud, 2001). These results confirm the importance of the timing and soak time on pelagic longlines, just like Ward *et al.* (2004) proved it, with the swordfish being just a little bit less sensible to loss than in our study (losses tend to excess catches after 10 hours of longline retrieving, thus resembling the behaviour of skipjack in the results of Ward *et al.*, 2004). The GAM approach allows us to more precisely understand the way time interacts with catch, whereas other linear approaches don't and furthermore miss the principal information (loss of fish after a certain time, even if the relationship may be initially linear; Lokkeborg and Pina, 1997).

This quite poor efficiency of the gear had been detected by fishermen for a long time, after retrieving many hooks with no more baits on them (baits usually are very well attached to the hooks, and may be bitten by small fish and above all by squids). During the PPR experiment, it had been observed that hook-timers surrounding a caught fish had been set off a few minutes before the catch. This gives evidence that the swordfish usually hammers its preys by striking its head from left to right, very forcefully, then risking to get caught on the hooks or even on the lines. All the more, the risk of depredation is high in the south-western Indian ocean, due to species like pelagic sharks (mainly *Prionace glauca* and *Carcharinus* *longimanus*) and marine mammals (*Globicephaela macrorhyncus*, *Pseudorca crassidens*), that usually attack caught fish during the day (Poisson *et al.*, 2001). This combination of effects explains that the relationship between effective number of caught fish and duration times of the fishing action becomes negative after a certain time.

Swordfish vulnerability and hooks

The latter effects observed on soak time can be found again with the number of hooks, in the way that for large numbers of hooks (thus needing a longer time –up to 10 hours- to retrieve from water), the effect on catch and CPUE tends to diminish (Figure 6b). But one more interesting result about hooks is the effect of mean distance between two successive hooks: even if not highly significant, it comes out of our results that this inter-hooks distance could play a role in the catchability of the fish. When hooks are too close one another (around 40m), longlines seem to be less efficient than when they are at least separated by 60m. This could witness a quite complex effect of the behaviour of swordfish on longline catch, with the hypothesis of an "avoidance radius" existing for each individual toward its conspecifics, all the more as the effect of gear saturation. Reunion Island based fishermen have indeed observed that caught swordfish often have injuries caused by rostrums of other individuals (one was even caught with half a rostrum broken through its whole belly: it hasn't caused its dead before being caught, the wound apparently being very well healed!). Inter-conspecifics social relationships are not well known for swordfish, but it clearly seems that one individual may be very aggressive to another if too close, then leading to a sort of "defended territory" that may be reflected in the inter-hooks minimal distance for better catch. This "avoidance" and "attraction" (particularly during the reproduction period, where males and females have to meet very closely for the success of sexual gametes encounter, just like for a mating) behaviour could be led by a very complex social web (Olson and Polovina, 1999), due to possible long distance communication.

Swordfish and the environment

Some important information can be synthesised on swordfish after our results on vulnerability:

1. swordfish bite on hooks very soon after the setting of the line, occurring preferably before sunset;
2. longline setting positions (beginning and end) may thus better represent the positions of the original catch than hauling positions, after night drifting;
3. swordfish may be a bit more abundant than CPUE indexes tell, just because many of them may leave the hooks when the duration of the fishing action is too long;
4. swordfish are caught in quite shallow waters, and it's not illogical to envisage that the influence of the environment on the catch may be limited to this part of swordfish habitat;
5. satellite telemetry, allowing to comprehend the only surface dynamics of the open ocean, may thus be a quite relevant tool for comprehension of swordfish-environment relationships, in spite of the very strong diving abilities of the fish (Carey and Robison, 1981).

We thus can conclude on quite good correspondence between our results and the behaviour of the fish related to local oceanography.

Swordfish accessibility and the environment

Swordfish and the moon

The effect on moon light and moon phases on swordfish catch is subjected to very strong *a priori* assumptions from both fishermen and scientists, who regularly introduce "moon parameters" as environmental factors in their studies. Draganik and Cholyst (1986) first noticed that during full moon, swordfish feeding activity seemed to increase, particularly when and where thermocline is deep. For the authors, this was due to the fact that at full moon, the moon light can reach greater depths and thus allow swordfish to better hunt on its favourite preys at that depths. Bigelow *et al.* (1999) showed that the full moon, neither too much significant nor strong, has a positive effect on swordfish CPUE too. But they were the two only sources to conclude to such an effect, even if this idea that the swordfish may be more active during full moon and when the moon is high is very widespread among fishermen. Podesta *et al.* (1993) thus noticed that the temporal distribution of longline sets of north-American fishermen was in phase with the full moon period, reaching a peak during the two weeks around full moon. Same for Olson and Polovina (1999), who noticed that Hawaiian fishermen preferentially set their lines at the full moon period during some months of the year. However, neither Podesta *et al*. (1993) nor Olson and Polovina (1999) didn't notice any significant effect of the full moon on swordfish catch nor CPUE.

We observe the same kind of results in our study: local fishermen obviously prefer the full moon period (lunar index n°3) for their fishing trips (Figure 9). This contradicts the results of the GAM analysis: both the "ascending" and "descending" period seem to enhance the fishing results, on contrary to fishermen's *a priori*. Just like the same as our results, Gaertner *et al.* (2001) found that the influence of the moon on the CPUE was stronger during the ascending part of the moon cycle. This is quite coherent with results obtained by Young et al. (2000), who concluded that better swordfish catch occurred just before the full moon, while ascending. Gaertner *et al.* (2001) also found that the worst catch were observed at full moon, while the best occurred during the first and last quarter of the moon cycle, even if their results are subject to a high variability. The authors noticed that the influence of the moon could be more complex than due to the only influence of its light: they suggest that the tide currents, depending on the moon phases, could play a significant role in the observed results, especially when moonlight is dim (new moon period) and in waters close to coastal areas. The authors analysed the Reunion Island based fishery with a larger dataset than ours, including precise hours of catch for individual swordfish caught on the equipped longlines of the "hook-timers" experiment during the PPR programme: even if not very significant, their results concluded that catch better occur at low tide or when tide goes out, and when the moon rays weakly penetrate the surface waters. These results all show that fishermen mostly overestimate the effect of the moon and even misestimate the influence of the full moonlight on the swordfish catch.

The influence of the number of light-sticks used during longline setting is not very well marked in our results but could be closely associated with the lunar influence, due to night light. Bigelow *et al.* (1999) had shown that the use of light-sticks is of major importance for swordfish catch. But, as Poisson *et al.* (1998) had explained, local fishermen rapidly have all adopted the same techniques, thus diminishing the influence of this factor in our analysis. They usually use one light sticks every 3 hooks (82% of the 2207 longline sets in model n°4), which seems a good compromise between fishing efficiency and economic constraints (light sticks costs belong to the heaviest expenses of the longline economic budget).

Swordfish accessibility and the oceanography

The question of accessibility of the fish can be divided into the two dimensions of the fish habitat: vertical and geographical. Both have to be tackled in close relation with the biological oceanography of the fishing area, conditioning the existence and abundance of swordfish preys. It is indeed widely accepted that predators concentration is closely linked to their preys and that local oceanography in the tropical ocean is decisive as preceding the development of often fleeting forage animals abundance peaks.

Vertical dimension

Swordfish favourite preys are mainly cephalopods, that usually migrates from deep waters to sub-surface at night. Even if exploring these depths (down to 700m) during the day, swordfish generally hunts in surface waters a night, thus being accessible to the longlines. Nevertheless, some of our results deserves some attention in order to better understand the vertical dimension of the catch related to the behaviour of the fish.

The most significant effect in our analysis and the most related to the depth of the catch is the effect of buoys leaders, even if this parameter is one of the most imprecise of our study. The PPR experiments (Poisson et Reynaud, 2001) had brought us some pieces of information on the maximal depth reached by hooks during longline drifting : they could stay in the very upper layer of the ocean (20-30m) but could sink down to more than 190m deep. However, 63% of the equipped longlines were situated in a quite superficial layer, from 30m to 70m deep. For swordfish caught during these experiments, the authors could affirm that they were caught in depths from 20m to 83m. Reunion Island based longlines are very “tight” in the sub-surface layers of the open ocean, due to the absence on Reunion-based boats of the device that fishermen call a “shooter”, that literally “shoots” the line out of the boat during longline setting, allowing it to reach deeper waters. The length of the buoy leaders is thus almost the only way for the fishermen to reach deeper layers. It seems that the relative inefficiency of short leaders observed in our results has already been well understood by the local fishermen, that don’t use them too much any more (only 17% of the 2207 longline sets of model n°4 have leaders shorter than 10 fathoms) and generally use sinkers on hooks leaders to make them sink more quickly. For longer buoys leaders, the very weak difference observed on swordfish catch and CPUE tends to show that sub-surface shearing currents play an important role in making the longline rise up to the surface, thus not attaining very deep waters and homogenising the maximal fishing depths. Anyway, even if never very deep, Reunion-based longlines still catch swordfish: that would mean that fishing depths are quite adapted to the vertical habitat of the fish. That could be due to the fishing zone of the fleet, situated on the margin of the subtropical Indian Ocean gyre, an oceanographic region where the surface tropical mixed layer is generally not very thick (40m in summer, 100m in winter; Marsac, 1992). That would mean that fishermen usually exploit fish that live above or at the same depth as the thermocline, which is generally considered as the habitat for most pelagic fish, especially swordfish (Bertrand, 1999).

As a “proxy” variable of the thermocline depth variation, SLA is a key parameter. It is indeed closely related to the dynamics of the whole surface layer, not only the surface itself: when positive, SLA values indicate a “bump” at the surface of the ocean but a deepening of the thermocline (downwelling), whereas negative values indicate a “hollow” in the surface and a rising of the thermocline (upwelling; Bakun, 1996). This would then tend to bring away or on the contrary closer the hooks from the thermocline depth. In our results, the effect of the absolute value of SLA is a lot less significant than the gradients. However, our results suggest that negative values are beneficial for swordfish CPUE. Negative SLA values witness the existence of an upwelling, with the surface layer getting shallower and a hollow appearing at the surface of the ocean. The fact that gradients are more significant that absolute values indicate that the swordfish may be more actively hunting on border of these local open-ocean upwellings or at least may be more accessible to the longlines. A recent study analysing longline catch in the Indian Ocean at a more global scale (5°x5° monthly fishing data; Marsac *et al.*, *in press*) shows that SLA is particularly submitted to large scale transport of planetary internal waves (Rossby and circumpolar waves) and that interannual swordfish catch are closely associated with SLA falls and diminishing of the surface layer thickness.

Geographical dimension

After Garcia-Cortes and Mejuto (2003), swordfish fisheries areas can be divided into three main categories: “spawning”, “spawning-feeding” and “feeding”. The authors indeed observed that sex-ratios and size-distribution of swordfish are quite different whether they are fished in equatorial, subtropical or even temperate waters. Equatorial warm waters are favourable for all-year round spawning, with immature and males more numerous than females, which are quite always mature (“spawning”). In more sub-tropical areas, mature females and males are only found during a few months at the warm season but the oceanography is still intermediate concerning the availability of large quantities of forage preys (“spawning-feeding”). On the contrary, at higher latitudes, broad scale oceanographic systems induce development of large amounts of preys that large female hunt on (“feeding”). On the contrary, Ward and Elscot (2000), the authors proposed a classification of swordfish fisheries areas, without any consideration on swordfish reproduction biology, rather focusing on its exploitation on a feeding point of view. They separate swordfish fisheries areas into two categories, whether fisheries are associated with seabed features, such as continental slopes, banks and seamounts (“topographic fisheries”) or broadly distributed and associated with currents and fronts in the open ocean (“convergence fisheries”). In the light of our GAM analysis, we will try here to synthesize the characteristics of the Reunion Island based swordfish fisheries in regard to other fisheries in the world and the classification proposed by the previous authors.

A spawning area?

Our GAM analysis suggest that two different ranges of temperature are beneficial for fishing: 1) surface waters between 24 and 25°C and 2) waters above 28°C (especially for CPUE). The latter values correspond to the warming of waters around Reunion Island, mainly during the austral summer core months (January to March, Figure 11). Actually, results on the biology of swordfish obtained during the PPR programme (Poisson *et al.*, 2001a) suggest that this rising of the SST, associated with photoperiod increase, could produce the beginning of batch clutch of female swordfish spawning. Reproductive season in Reunion waters (during which most of the caught female are mature) has been determined as being spread over October to April, during austral summer (north-west monsoon). These results were consistent with those obtained by Young *et al.* (2000) in eastern Australia and Ward and Elscot (2000) in the northern Atlantic. Poisson *et al.* (2001) all the more analysed the evolution of the sex-ratio of a few individuals caught by the Reunion Island and Seychelles based fisheries during the PPR programme. The sex ratio around Reunion Island showed clearly marked seasonal variations: females were always more than males, but the proportion was less during the reproductive period. In the Reunion Island area, males were always less than in the equatorial area around the Seychelles. Even if every individual caught in the Reunion Island based fishery has not been sexually determined, the evolution of size frequency is very informative for that purpose: it has thus been often shown that, at an equivalent age, female swordfish are bigger than males (Palko *et al.* ,1981; Ward et Elscot, 2000). Hence, for big individuals sized during the PPR programme (Length Maxillaries Fork > 200cm), female largely dominate in Reunion Island waters (> 80%), all the more during the reproductive season, which is consistent with results obtained in the Atlantic subtropical area (De Martini, 1999). On the contrary, fish measured from the Seychelles equatorial fishery are significantly smaller than around Reunion Island (Poisson *et al.*, 2001a). These observations clearly conforms to the commonly accepted knowledge that swordfish size distribution is associated to the latitude: the smaller in equatorial areas, the bigger in higher latitudes (subtropical and tropical, even temperate areas).

An new question then rises and an hypothesis on the stock structure of swordfish in the Indian Ocean could then be proposed: could males and females be segregated in different zones of the western Indian Ocean basin, according to their respective sizes and adaptation to the oceanic habitats, and then only meeting during the reproductive season? This could explain the fact that at higher temperatures (>28°C), our GAM analysis suggest that swordfish CPUE are enhanced, due to the augmentation of young and/or males in the surrounding waters of Reunion Island. It is all the more very common to observe a male and female swordfish swimming literally “flank to flank” in surface waters during the reproductive season (CRPMEM, 2001), which is definitely a piece of evidence that a strong genesic constraint is exerted on these individuals, more usually very distant one to another (as seen with the paragraph dealing with mean distance between successive hooks).

A feeding area ?

Reunion Island oceanography is quite intermediate between different broad-scale systems, as defined by Longhurst (1998): it exhibits patterns from the wide subtropical gyre western boundary (east of around 53°E), with strong influences of the East Madagascar Current (EMC, along the Malagasy coast), itself largely influenced by the very seasonal monsoon system of the northern part of the Indian Ocean basin through the South Equatorial Current (SEC, from 10°S to 15°S, source of the EMC). On the southern part of the Reunion Island fishing area, the influence of the EMC is all the more important as the retroflexion of this current develops from the southern tip of Madagascar to the East, with meanders and vortices expanding North up to Reunion Island latitude, creating sometimes quite well marked surface thermal and water colour fronts. The Mascarene Plateau is all the more scattered with topographic features as islands themselves, but seamounts and other features too, that modify the local-scale oceanography, even if generally less shallow than in the Seychelles area. And at tropical latitudes, Reunion Island area is submitted to the transport of large planetary internal waves (Rossby and Kelvin waves), that modify SLA and the thermocline depth as seen previously.

The most significant effects observed in our analysis precisely comes from the SLA maps. First of all is the meridian north-south component of the geostrophic currents. What clearly appears in our results is that null values are beneficial for catch and CPUE: this is very coherent with fishermen knowledge, who observed that currents turning, witnessed by geostrophic currents null values, are very beneficial for fishing results (CRPMEM, 2001). This effect could be due too to the fact that, when surface currents are strong enough, longlines tend to sink down less quickly and less deep than when current is weak, with a detrimental effect on swordfish accessibility (as seen previously). This is all the more true concerning north-south oriented surface currents (zonal component), that may influence east-west oriented longline sets, which represent the majority of the sets in our dataset (Poisson et

Guyomard, 2001). All the more to geostrophic currents, SLA geographic gradients play a significant role in the variation of swordfish catch and CPUE. These gradients witness the existence of a slope in the sea surface in the surroundings of the longline and the fishing results are enhanced when this slope increases from 20cm to 40cm, respectively of 1.3 individuals in the catch and 1.5 individuals in the CPUE. This indicates that whether a "bump" or a "hollow" in the sea surface is a good spot to target swordfish, not only when the thermocline is shallower, as seen previously with SLA absolute values. Last of the SLA associated parameters, the gradient of the zonal component of the geostrophic currents indicates horizontal variations of the intensity of surface east-west currents. Our results suggest that areas where these currents vary quite rapidly (up to $50 cm.s^{-1}$) are favourable for the catch. Local fishermen do target these areas (CRPMEM, 2001), even if they usually are detrimental for the conformability of the fishing action (broken lines, drifting floats).

The fact that gradients are more significant that absolute values indicate that the swordfish may be more actively hunting on border of these local open-ocean upwellings or at least may be more accessible to the longlines. This can be understood as the concentration of the fish on areas where different water masses encounter or at the border of local upwellings or great surface currents. Olson and Polovina (1999) had clearly showed that horizontal gradients of SLA, often associated to meanders and vortex on the borders of great current systems in the North-Pacific subtropical frontal system of the Kuroshio current, north of Hawaii, have a positive influence on swordfish longline CPUE: when these oceanographic structures go down, as SLA maps clearly show, CPUE decline. Even if the oceanography around Reunion Island is quite different from this well-established frontal system, it is not impossible that the variations of the intensity of the East Madagascar Current and its south-Malagasy eastward retroflexion may influence swordfish catch of the Reunion Island based fishery. SLA maps are not yet a common tool employed by fishermen, who more easily access SST maps. And researchers have more often described the oceanography of the fishing areas thanks to SST maps too.

Sea surface temperature falling is indeed often associated with upwellings: SLA not only become negative as the thermocline rises up, but the very tighten isotherms reach the surface, bringing colder water to the upper layer. SLA negative values and cold SST are closely associated at meso scale, especially when observed on satellite maps (Marsac *et al.*, *in press*). Even if not too much correlated one another (Figure 10), these two parameters can be closely associated when analysing their effects on swordfish fishing results. We can observe that values of 24-25°C in SST mainly correspond to negative values around 10cm in SLA: this clearly corresponds to the values with positive effects on swordfish catch (as seen with SLA). Most of the bibliography nevertheless focuses on SST rather than SLA. Draganik and Cholyst (1986) also noticed that swordfish catch in the Mediterranean Sea were enhanced at respectively 18-20°C and 26-28°C, maybe proving quite identical effects as we observed ("feeding" and "spawning"). On the contrary, Podesta *et al.* (1993) didn't notice any effect of any range nor values of SST on better swordfish CPUE in the North-Atlantic American fishery. In Australia, Young *et al.* (2000) observed that, even if the best swordfish catch occurred in water surface temperatures from 26°C to 28°C, no significant effect of the SST was further obtained from their statistical models.

Other authors preferably discuss the effect of SST on swordfish fishing by means of the complete oceanographic description of the fishing area. SST is then very useful for the monitoring of great water masses movements by particularly witnessing the evolution of frontal systems. Bigelow *et al.* (1999) thus describe the North Pacific Transition Zone

(NPTZ), situated between the Sub Arctic Frontal Zone (SAFZ, between 40°N and 43°N) and the Sub Tropical Frontal Zone (STFZ, between 27°N and 33°N), in a more boreal area than the exactly symmetric of Reunion Island based fishing area (15°S-30°S). This area is highly exploited by Hawaii based fishing fleets, mainly targeting swordfish. Depending on the season, fishermen follow the surface temperature fields, with colder waters exploited in winter than in summer. Just like in our analysis, the authors observed that swordfish CPUE were higher whether in the seasonal minimum SST values of the STFZ (down to 17°C) or the seasonal maximal values of the SAFZ (25°C). They also noticed that CPUE were weaker when subtropical waters are warmer than 23°C in spring and better in colder waters (16°C-19°C): the divergence of surface currents observed in the STFZ induce upwellings that mark the surface waters with colder SST than the surroundings usual waters. The effect of the SST is nevertheless depending on the scale of the original data: Bigelow *et al.* (1999) observed a more significant effect of the SST on swordfish fishing results when both are considered at a quite larger scale (1 square degree/1 month) than the more precise one they used (18 square km/1 week). This effect could be found in our results too, that consider very small scale data (2 km / 1 day) and then influences the significance level of our analysis. And that would explain that Marsac *et al.* (*in press*) can observe more significant effects of SST on swordfish CPUE than we do.

Swordfish is known as being a very tolerant species toward water temperature conditions: its geographic distribution range is almost worldwide, covering every ocean from 50°N to 50°S, in temperate, tropical and equatorial waters (Palko *et al.*, 1981; Ward and Elscot, 2000). In the Indian Ocean, swordfish have been observed almost everywhere, from open ocean to coastal areas. It is thus not very surprising not to detect any strong effect of the SST on the fishing results of the Reunion Island based fishery, which is not too much spread in latitude, experimenting a quite narrow range of SST. Local fishermen don't consider that SST by itself is useful for determining better swordfish concentration areas (CRPMEM, 2001). Nevertheless, we observe that two different SST conditions may positively influence swordfish catch, whether because favourable for reproduction or preys concentration. As Seki (1999) noticed, swordfish is extremely ubiquitous –particularly large individuals- but "concentration areas" exist, that are a lot less widespread than its global geographic distribution range, depending on different reproductive and feeding strategies. SST thus should be considered associated with other oceanographic parameters and the life history of the fish better known before concluding to any direct effect.

The influence of well marked horizontal gradients on SST maps, so called thermal fronts, is the most studied topic tackled by fisheries researchers (Podesta *et al.*, 1993 ; Power and May, 1991; Fiedler and Benard, 1987 ; Polovina *et al.*, 1998). Most authors dealing with swordfish fisheries first notice that most swordfish fisheries have developed in ocean areas characterised by such well established frontal systems, on border of great currents systems or great water masses encounters. This is what Ward and Elscot (2000) called "convergence fisheries". This is the case of the North-American Atlantic fishery, studied by Podesta *et al.* (1989), where surface fronts, visible on SST maps, develop along the boarder of the Gulf Stream, depending on coastal winds, oceanic internal waves and Gulf Stream intensity, these fronts develops on the oceanic border of the Gulf Stream, with great warm core rings and vortex coming out of the main flow. Concentrations of swordfish preys, mainly squid (*Illex illecebrosus)*, are often observed in the surrounding areas. The system described by Young *et al.* (2000), the East Australian Current system, is very similar: coastal side upwellings, warm core rings and meanders separating from the main flow characterise this area, very close to the equatorially symmetrical Gulf Stream system. The existence of fronts in this area is closely associated with the intensity and dynamics of the East-Australian Current (EAC), originated from the South Equatorial Current, encountering the Australian coast at a latitude of 14°S to 18°S: this warm equatorial water then goes down to the South along the coast, penetrating water masses of sub Antarctic origin at the latitude of 30°S, then creating meanders and surface fronts known as the Tasmanian front to the East. This situation is very close to the situation of the Reunion Island based fishery, exploiting waters east of the East Madagascar Current, which flow originates from the South Equatorial Current when it encounters the Madagascar coast. This high importance of frontal systems on swordfish CPUE was pointed out too by Olson and Polovina (1999): they noticed that the succession of convergence and divergence of surface waters, observed on the borders of great currents (Gulf Stream in the northern Atlantic, Kuroshio in the northern Pacific), is a very good configuration for the concentration of swordfish preys, essentially squids like the red flying squid (*Ommastrephes bartrami*). These structures are then observable on SST maps and the authors even suggest that thermal clues could be used by swordfish in their environment to find these concentrations. Bigelow *et al.* (1999) pointed out too the importance of the large scale oceanographic system dynamics of the fishing area of the Hawaii based fishery, in the North Pacific Transition Zone, where meso-scale structures are intensely exploited by Japanese fisheries too, between the Kuroshio and the Oyashio currents.

SST gradients play a minor role in the results of our analysis but it nevertheless seems that light gradients (less than 3°C) are beneficial for both swordfish catch and CPUE (Figure 8d). The high variability of the relationship is probably due to the existence of incongruous structures and aberrant pixels still appearing on many SST maps (Desruisseaux *et al.*, 2001a). This overestimates circumvolution gradients values and then disrupts the effects for high gradients values in our analysis. Other authors had used the Sobel operator for determining horizontal gradients and even objective fronts: Podesta *et al.* (1989) redrew fronts from the Sobel operator derived SST maps by "subjectively" enhancing the most well marked structures (aligned pixels defining narrow structures, corresponding to the most intense gradients). The authors then tried to identify statistical relationships between frontal indexes and swordfish CPUE: they didn't notice any strong association with fronts, mainly because North-American fishermen do actively look for such thermal structures and then always set their longlines on these very contrasted areas (confirmed by Bigelow *et al.*, 1999). Paradoxically, they even found a negative association between swordfish CPUE and the distance of the longline to the nearest defined front, excepted for very high values of CPUE… Bigelow *et al.* (1999) tried to introduce more complex indexes for the description of frontal systems oceanography. They more particularly defined the "frontal energy" index as the magnitude of the vector composed by the intensity of the Sobel circumvolution gradient operator components, in the zonal and meridian directions. Bur as they noticed, the calculation of this index is not linear (Herron *et al.*, 1989) and then not possible to be interpreted as any spatial variation of the SST fields. They anyway concluded to a positive significant effect of this index on swordfish CPUE, nevertheless depending on the spatial scale chosen for the original data, just like the same as observed for absolute SST effects: the swordfish CPUE were better in quite cold waters where the frontal energy is the strongest. Like Podesta *et al.* (1989), Young *et al.* (2000) defined SST fronts from original maps and introduced frontal indexes in their statistical analysis, mainly relating to the distance of the catch to the nearest front. In the northern part of the fishing area they studied (at a latitude between 25°S and 30°S), they observed a very significant effect of the "distance to front" index on swordfish CPUE: this appears to enhance CPUE until an optimal distance of 10 nautical miles (~20km), then declining above. During the period of their study, Young *et al.* (2000) observed abnormal low swordfish CPUE in the southern part of their study area, at the usual southern extension of the East Australian Current (36°S). They indeed noticed that the EAC southern extension was exceptionally stronger and longer than usual at the beginning of year 1998: a large positive anomaly extending to the very southern tip of the eastern Australian coast was observed on SST anomalies maps. Due to this large homogeneous water masse, no thermal fronts could be found in this usually exploited area offshore the coastal city of Bermagui: fishing results where particularly good for yellowfin tuna (*Thunnus albacares*) in this "cul-de-sac" of tropical water, as observed by other authors in other areas (Laurs *et al.*, 1984; Fiedler et Bernard, 1987; Power and May, 1991), but bad for swordfish and bigeye tuna (*Thunnus obesus*) CPUE.

Olson and Polovina (1999) reported that Hawaiian fishermen actively look for the passage of these fronts and try to target swordfish by setting their longlines on the colder side of 5 to 6°C surface gradients, and make them drift along the front until they reach the warmer side. This has been practiced by Reunion Island based fishermen too (CRPMEM, 2001) but they also noticed that "big breaks" of several degrees Celsius don't systematically bring high catch. It mainly depends on oceanography of the fishing area: in the Seychelles zone, very homogeneous SST fields can be very favourable for the fishing whereas in subtropical waters (around 30°S), fishermen prefer to target surface gradients, vortex and "associated" fronts (both SST and chlorophyll).

Chlorophyll content of surface water masses is indeed supposed to be of high importance for pelagic food webs, being the (often fleeting) source of primary production in the upper layer of the open ocean. Chlorophyll content witnesses the existence of pelagic phytoplankton blooms (creating so called "green" waters), that can be absorbed by zooplacton and following components of pelagic food webs, including the preys of swordfish, either on surface or in deeper waters thanks to convergence currents and local downwelling (Olson *et al.*, 1994). The temporal effect of this "water masses maturation" could be of greater importance than the absolute values of chlorophyll content (and even geographic gradients) to pelagic fisheries (Stretta, 1990).

It is thus not so surprising that our results (that didn't involve any temporal effect) don't reflect any strong effect of chlorophyll to neither swordfish catch nor CPUE. Even if not significant, we can observe the shape of the relationship concerning the influence of the chlorophyll content and the horizontal gradient along the longline on the swordfish catch (Figure 7g and h). We observe that absolute chlorophyll contents from null to 0.1 $mg.m^{-3}$ has a negative effect on catch, then becoming null for values above (and too variable for values above 0.2 $mg.m^{-3}$). On the contrary, gradients values have a positive effects up to 0.05$mg.m^{-3}$ gradients. These results are partly contrary to the results obtained by Young *et al.* (2000) in the south-western Pacific, where low values of chlorophyll content are beneficial for swordfish catch. The authors used a fluometry recorder with *in situ* sampling during the catch of individual fish, and thus had a much more precise description of the very environment of the catch. Chlorophyll content was one of the most significant parameter influencing swordfish catch in their study. The authors observed that swordfish catch increase in water contents between 0 and 0,5 µg/l. However, for higher values, this effect become negative on swordfish catch, suggesting that the fish better hunts in clear waters than in "green" ones. This had been observed by Reunion Island based fishermen too (CRPMEM, 2001), that preferably set their longlines on the "clear" side of well marked chlorophyll surface fronts, that often are associated with SLA negative values –upwelling- and SST gradients too.

Many of the results obtained by different authors on SST gradients influence are quite disappointing and sometimes in contradiction to the hypothesis of association. Podesta *et al.* (1989) pointed out that the spatial imprecision of the original data (longline with imprecise limits *vs.* concentrated and narrow fronts) could have blurred the results of the analysis. But they more precisely introduced the idea of a temporal effect affecting the concentration of swordfish preys in the vicinity of such oceanographic structures: water masses have to "maturate" during a certain period before concentrating the effective preys. As Stretta (1990) noticed for tunas, the principal problem is to catch the right spatial and temporal scale for the understanding of swordfish concentration process. Bigelow *et al.* (1999) tried to quantify this temporal effect by introducing a temporal variation index for both the SST and frontal energy values (cf. former §). Their results indeed show that this "maturation time" is important for swordfish, as they observed that the frontal energy temporal variation index had a positive influence on swordfish CPUE: better CPUE were observed when the frontal energy decreased, that is to say when the fronts where dislocating. The authors noticed that about one week after the front being well established, the conditions are more favourable for swordfish, on the contrary to sharks, which CPUE were better when the front were building up.

Even if Reunion Island based fishermen very often set their lines close to seamounts and well-marked bathymetric structures like underwater canyons (CRPMEM, 2001), thus according to Carey and Robison (1981) observations on North American fishermen, the effect of bathymetry is not well marked in our results. It nevertheless appears that open-ocean areas, with the sea bottom being 4500 to 3500 m deep, are worst than shallower waters for swordfish. Bigelow *et al.* (1999) had introduced such an effect in their analysis but didn't find any strong effect either, observing that swordfish CPUE were better both in shallow and very deep waters…Olson and Polovina (1999) rather noticed that bathymetry may be of major importance for swordfish fisheries but that surface fronts – SST and density- associated to these underwater structures may overcome the indirect effect of bathymetry.

Conclusion

Our results clearly confirm that operational differences at the level of the fishermen action play an important role in the variability of the fishing results, particularly on swordfish. Our analysis also shows clearly less marked effects of environmental factors on swordfish catch and CPUE than other authors could have found (Bigelow *et al.*, 1999; Young *et al.*, 2000). The main question is then to know whether the indexes we chose for describing the surrounding environment of the catch were appropriate or not. As for other authors, we introduced the discontinuity by applying a Sobel convolution operator transformation on every parameter maps, but we didn't explicitly formalize "fronts objects" like Podesta *et al.* (1989) and Young *et al.* (2000), nor introduced a "frontal energy" index like Bigelow *et al.* (1999). Nevertheless, even if our results don't assume any strong links between the gradients and the swordfish catch, it seems that, as every other authors noticed, the imprecision of the location of the precise catch related to the length of the longline is detrimental to the results of the analysis: it is all the more true for the SST gradients, established from high-resolution maps, which paradoxically could be of too high quality for such an analysis. This could explain why the relationships with SLA are better than for SST, as this parameter was the less detailed we had. A more elaborated process allowing to handle "objective frontal objects", integrating the spatial multi-parameters patterns of the gradients (particularly with SST and SLA derivates) and a temporal "maturation" algorithm (mainly for chlorophyll) would be of main interest for determining better associations with fishing. A new expert system with a strong contribution of biology oceanographers and image analysis specialists should be developed in the closest future for that purpose.

Even if not too much explanatory, our “environmental” models allowed to point out the importance of mainly SLA and SST parameters and derived parameters: SLA information is associated to local oceanographic patterns that enhance swordfish preys concentrations (coupled with the effect of the depth of the longline), thus stimulating the fish feeding activity, whereas SST witnesses processes of concentration due to reproductive habits of the species. When SST increases at the beginning of the austral summer, with waters exceeding 24°C (known as the threshold isotherm for swordfish spawning; Ward *et al.*, 2000), reproductive behaviour of the fish tends to “concentrate” the individuals, which is favourable for the catch. On the contrary, well established frontal systems are rare in the vicinity of Reunion Island and situated more south (the South Madagascar upwelling at the latitude of Fort Dauphin and the East Madagascar Current retroflexion). It thus may diminish the importance of SLA and SLA derivates parameters in our analysis, as the “oceanographic landscape” of the main exploited area is a lot less submitted to SLA variations than this southern frontal system. As Reunion Island fishing area is a transition zone between equatorial waters, known as a “spawning area” for swordfish, and subtropical to temperate waters in the South, known as “feeding area” for swordfish, it exhibits patterns of both, as we can see in our results (Garcia-Cortes and Mejuto, 2003).

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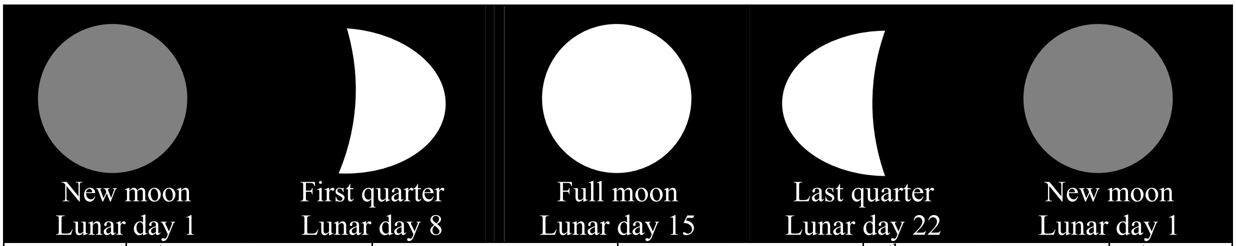
Tabs

Parameter	Description	Records	Mean value (range)
SWO	Number of swordfish individuals catch	3602	9.68 (0 ; 82)
TOT	Total catch	3602	22.89 (0 ; 136)
CPUE	Swordfish catch for 1000 hooks	3602	7.67 (0; 34.2)
nbham	Number of hooks	3602	1210 (300 ; 2610)
lstick	Number of hooks between two light sticks	3080	3.05 (2 ; 8)
longlead	Mean length of buoy leaders (in fathoms)	3449	13.6 (5 ; 30)
filage	Length of longline (in km)	2954	56.14 (14.05 ; 117.94)
interham	Mean distance between hooks (in m)	2954	48.51 (25.01 ; 96.73)
dt1	Duration of longline setting (in day)	3552	4.34 (1.67 ; 10)
dt2	Duration of longline drifting (in day)	3445	8.05 (1.41 ; 15.25)
dt3	Duration of longline hauling (in day)	3273	7.92 (1.42 ; 17.17)
dtot	Total duration of the fishing action (in day)	3124	20.37 (9 ; 32.43)
hdebfil	Beginning time of the setting (in day)	3595	0.74 (0 ; 0.99)
diffSoleil	Time interval between beginning time of the setting and sunset (in day)	3595	29.13 (-345 ; 515)
diffLune	Time interval between beginning time of the setting and rising time of the moon (in day)	3595	-303.66 (-1337 ; 504)
jourlun	Lunar day of the setting	3602	1 to 30
lune	Lunar index	3602	1 to 4
profondeur	Bathymetry at the median position of the longline (in m)	3547	-4023 (-5464 ; -1307)
chloro	Chlorophyll content at the median position of the longline (in $mg.m^{-3}$)	2439	0.095 (0.026 ; 0.414)
SST	Sea Surface Temperature at the median position of the longline (in °C)	2370	26.48 (20.25 ; 30.80)
SLA	Sea Level Anomaly at the median position of the longline (in cm)	3547	-3.52 (-32.43 ; 20.73)
U	Zonal component (east-west) of the geostrophic current at the median position of the longline (in $cm.s^{-1}$)	3547	3.35 (-50.91 ; 48.32)
V	Meridian component (east-west) of the geostrophic current at the median position of the longline (in $cm.s^{-1}$)	3547	0.93 (-69.87 ; 44.81)
Dprof.	Bathymetry gradient along the longline shape (in m)	3547	766.44 (2.73 ;4387.25)
Mgr.prof.	Maximal value of the bathymetry convolution gradient value (in m)	3547	1689.11 (80.32 ;6866.56)
Dchloro	Chlorophyll value gradient along the longline shape (in $mg.m^{-3}$)	2513	0.025 (0 ; 0.855)
Mgr.chloro	Maximal value of the chlorophyll value convolution gradient value (in $mg.m^{-3}$)	2142	0.108 (0.009 ; 2.518)
DSST	SST gradient along the longline shape (in °C)	2370	0.77 (0 ;6.16)
Mgr.SST	Maximal value of the SST convolution gradient value (in °C)	2388	2.56 (0 ;22.80)
DSLA	SLA gradient along the longline shape (in cm)	3547	3.17 (0.002 ; 29.20)
Mgr.SLA	Maximal value of the SLA convolution gradient value (in cm)	3547	24.31 (3.05 ;88.06)
DU	Zonal component of the geostrophic current gradient along the longline shape(in $cm.s^{-1}$)	3547	7.27 (0.057 ;63.26)
Mgr.U	Maximal value of the zonal component of the geostrophic current convolution gradient value (in $cm.s^{-1}$)	3547	58.9 (8.09 ;239.84)
DV	Meridian component of the geostrophic current gradient along the longline shape (in $cm.s^{-1}$)	3547	10.29 (0.049 ;79.87)
Mgr.V	Maximal value of the Meridian component of the geostrophic current convolution gradient value (in $cm.s^{-1}$)	3547	70.99 (13.50 ;246.28)

Tab 1 : Variables introduced in the GAM analysis



4th qu.	1st quarter	2nd quarter	3rd quarter	4th quarter	1st qu..

Index = 1 Lunar day 27…	Index = 2 Lunar day 5…	Index = 3 Lunar day 12…	Index = 4 Lunar day 20…	Index = 1 Lunar day 26…

Tab 2 : Lunar indexes established from lunar days and link with lunar quarters

	TOT	CPUE	dtot	Diff Soleil	Inter ham	Mgr. prof	Mgr. chloro	Mgr. SST	Mgr. SLA	Mgr. U	Mgr. V
SWO	1	1									
TOT		1									
hdeb fil				1							
dt1			1								
dt3			1								
filage					1						
Dprofondeur						1					
Dchloro							1				
DSST								1			
DSLA									1		
DU										1	
DV											1
Mgr.SLA											1

Tab 3 : Synthetic results of the Spearman rank correlation analysis

	p(f)	Simple models Pseudo R²	Simple models p(f)	Npar F	cumulative % inertia
longlead	**0,0000**	0,0103	0,0000	15,1389	18,90
nbham	**0,0000**	***0,0926***	**0,0000**	9,7289	31,04
dt3	**0,0002**	***0,1335***	**0,0000**	6,6989	39,40
interham	**0,0011**	0,0127	0,0000	5,3990	46,14
dt2	**0,0017**	0,0263	0,0000	5,0956	52,50
hdebfil	**0,0041**	0,0296	0,0000	4,4614	58,07
Mgr.SLA	***0,0130***	0,0554	0,0297	3,6116	62,58
dt1	***0,0173***	***0,1142***	**0,0026**	3,4029	66,83
SST	***0,0212***	0,0233	0,0000	3,2519	70,89
V	***0,0215***	0,0102	0,0000	3,2400	74,93
lune	***0,0434***	0,0045	0,0027	3,1535	78,87
Mgr.SST	***0,0481***	0,0158	0,0067	2,6448	82,17
SLA	0,1041	0,0191	0,0000	2,0591	84,74
U	0,1150	0,0247	0,0000	1,9824	87,22
profondeur	0,1564	0,0488	0,0000	1,7440	89,39
diffLune	0,2175	0,0071	0,0001	1,4835	91,25
Mgr.U	0,2633	0,0331	0,0091	1,3302	92,91
lstick	0,2867	0,0415	0,0000	1,2607	94,48
jourlun	0,3735	0,0064	0,0031	1,0413	95,78
DV	0,3815	0,0326	*0,3643*	1,0234	97,06
chloro	0,4330	0,0026	*0,6865*	0,9151	98,20
Dchloro	0,5066	0,0064	*0,0836*	0,7777	99,17
Mgr.profondeur	0,5738	0,0111	0,0003	0,6651	100

Pseudo R² = 0.4845355

Tab 4 : Synthetic results of the complete (model n°1) and simple models (bold: parameter with an F test probability less than 0.01; *bold italic*: parameter with an F test probability less than 0.05)

	Pf	NparF	% cumulated
longlead	**0,0000**	15,9310	21,18
nbham	**0,0000**	9,1132	33,30
dt3	**0,0000**	7,8317	43,71
lune	**0,0009**	7,1167	53,17
interham	**0,0006**	5,7886	60,86
dt2	**0,0011**	5,4176	68,07
hdebfil	**0,0029**	4,6907	74,30
Mgr.SLA	**0,0076**	4,0044	79,63
SST	***0,0114***	3,7080	84,56
dt1	***0,0167***	3,4270	89,11
SLA	***0,0200***	3,2955	93,49
Mgr.SST	***0,0294***	3,0119	97,50
lstick	0,1310	1,8820	100

Pseudo R²= 0.4562356

Tab 5 : Synthetic results of the complete model selected by AIC (model n°2)

Model n°	Kind of factors	Initial number of variables	Number of longline sets	Pseudo R^2	Significant factors (p(F)<0.01)	Significant factors (p(F)<0.05)	Cumulative inertia % (p(F)<0.05)
3	Op.	9	945	**0.410**	longlead, nbham, dt3, interham, dt2, dt1, hdebfil	diffLune	**97,71**
4	Op.	9	2207	**0.290**	dt3, longlead, dt1, interham, hdebfil, nbham, lstick	dt2, diffLune	**100**
5	Env.	14	945	**0.281**	V, Mgr.SLA, profondeur	SST, U, Mgr.SST, Mgr.U	**73,47**
5bis	Env.	14	945	**0.205**	profondeur, SST, V, Mgr.SLA	Mgr.SST, Mgr.U	**70,79**
6	Env. (AIC)	8	945	**0.263**	V, Mgr.SLA, profondeur, SST, U	jourlun, Mgr.SST, Mgr.U	**100**
6bis	Env. (AIC)	8	945	**0.191**	profondeur, Mgr.SLA, SST, Mgr.U	jourlun, V, Mgr.SST, SLA	**100**
7	Env.	14	1312	**0.212**	V, Mgr.U, profondeur, Mgr.SLA	jourlun	**53,93**
7bis	Env.	14	1312	**0.137**	V, Mgr.U, profondeur	jourlun	**47,18**
8	Env. (AIC)	8	1312	**0.194**	V, Mgr.U, profondeur	Mgr.SLA, jourlun	**76,86**
8bis	Env (AIC)	8	1312	**0.122**	jourlun, Mgr.U	profondeur, V, SLA, Mgr.SLA	**86,93**
9*	Env.	8	1876	**0.174**	Mgr.U, SST	jourlun	**53,63**
9bis*	Env.	8	1876	**0.102**	jourlun, Mgr.U, SST, profondeur	SLA, V	**91,86**

***: models n°S 9 and 9bis have been established from the factors selected by the AIC criterion, thus including a larger number of sets**

Tab 6 : Synthetic results of the different tested models

Figures

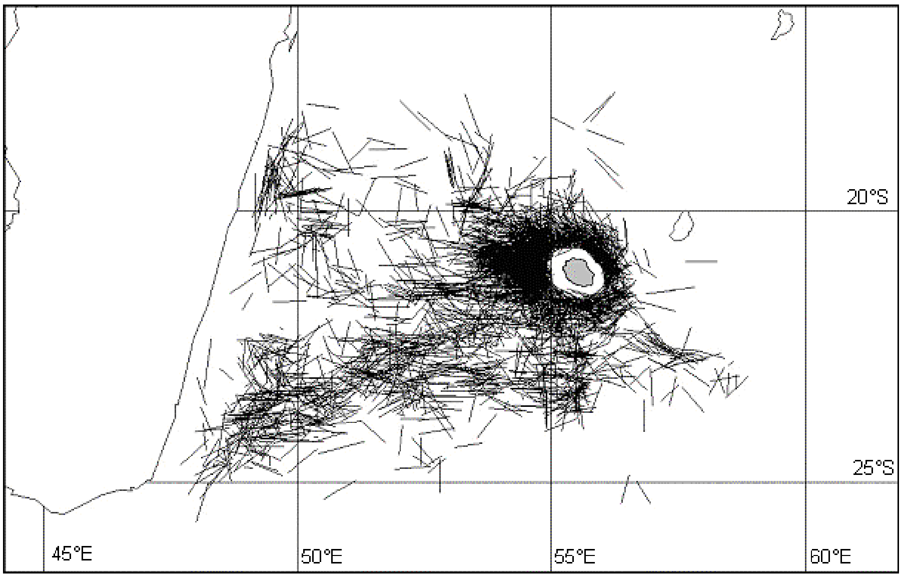


Figure 1 : Positions of the longline sets of the Ifremer database (2915 records)

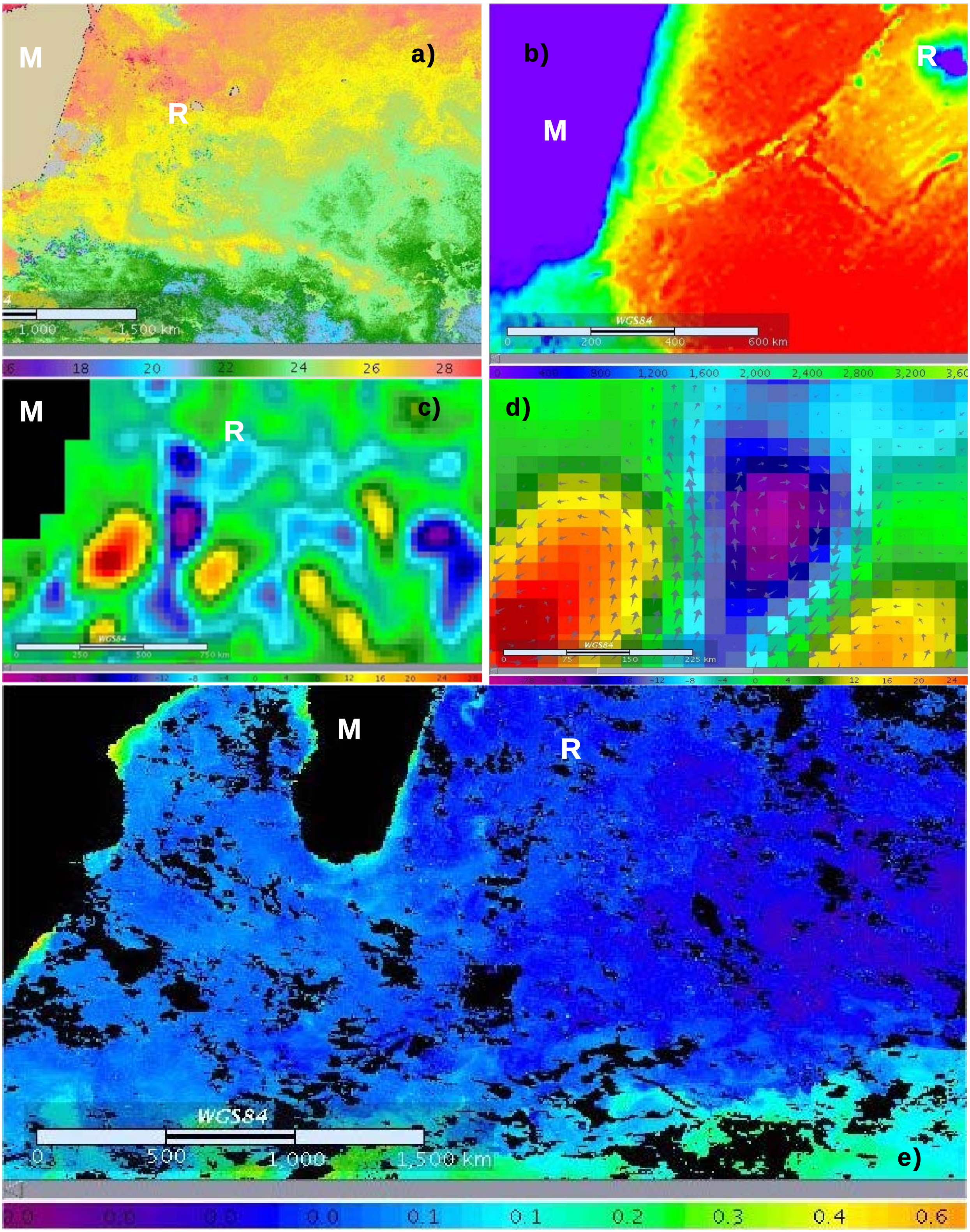


Figure 2 : Snapshots from the software SEASVIEW, developed by Desruisseaux *et al.* (2001a) in order to handle big datasets of satellite maps (a) SST map, b) bathymetry, c) SLA, d) SLA and geostrophic currents – arrows integer both the zonal and meridian components-, e) chlorophyll; M: Madagascar, R: Reunion Island)

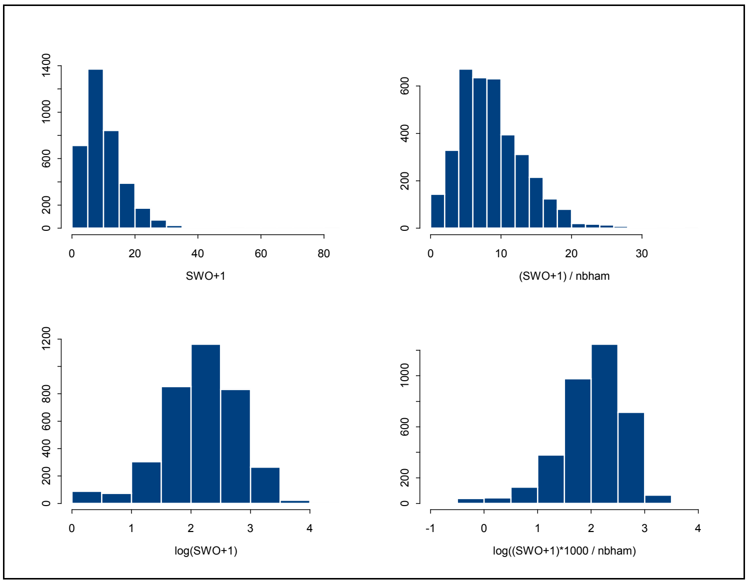


Figure 3 : Distribution of the catch and CPUE log transformed data

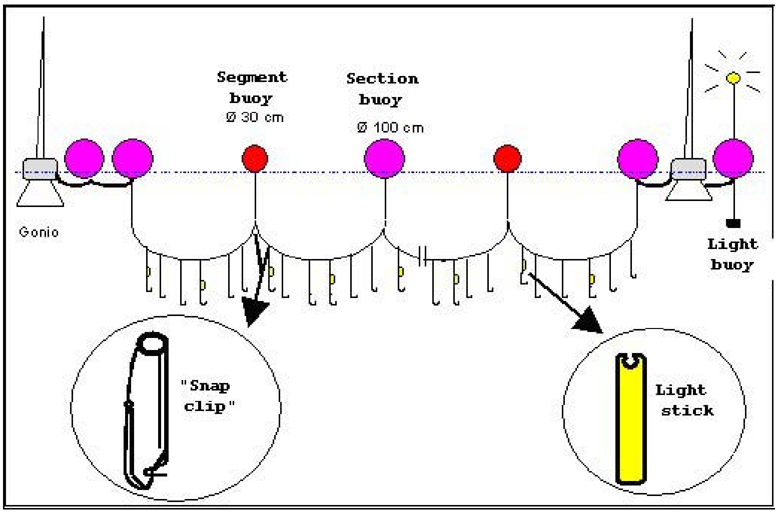


Figure 4 : The longline configuration, as usually set by Reunion Island based fishermen

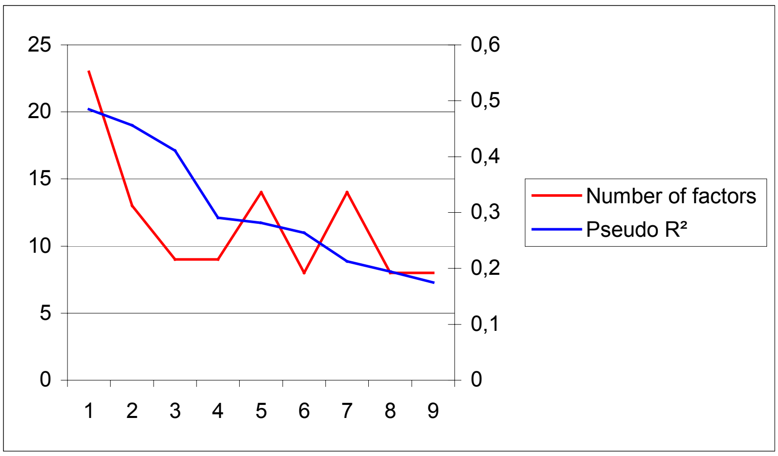


Figure 5 : Pseudo-R² values and number of factors of the different 9 models tested for swordfish catch

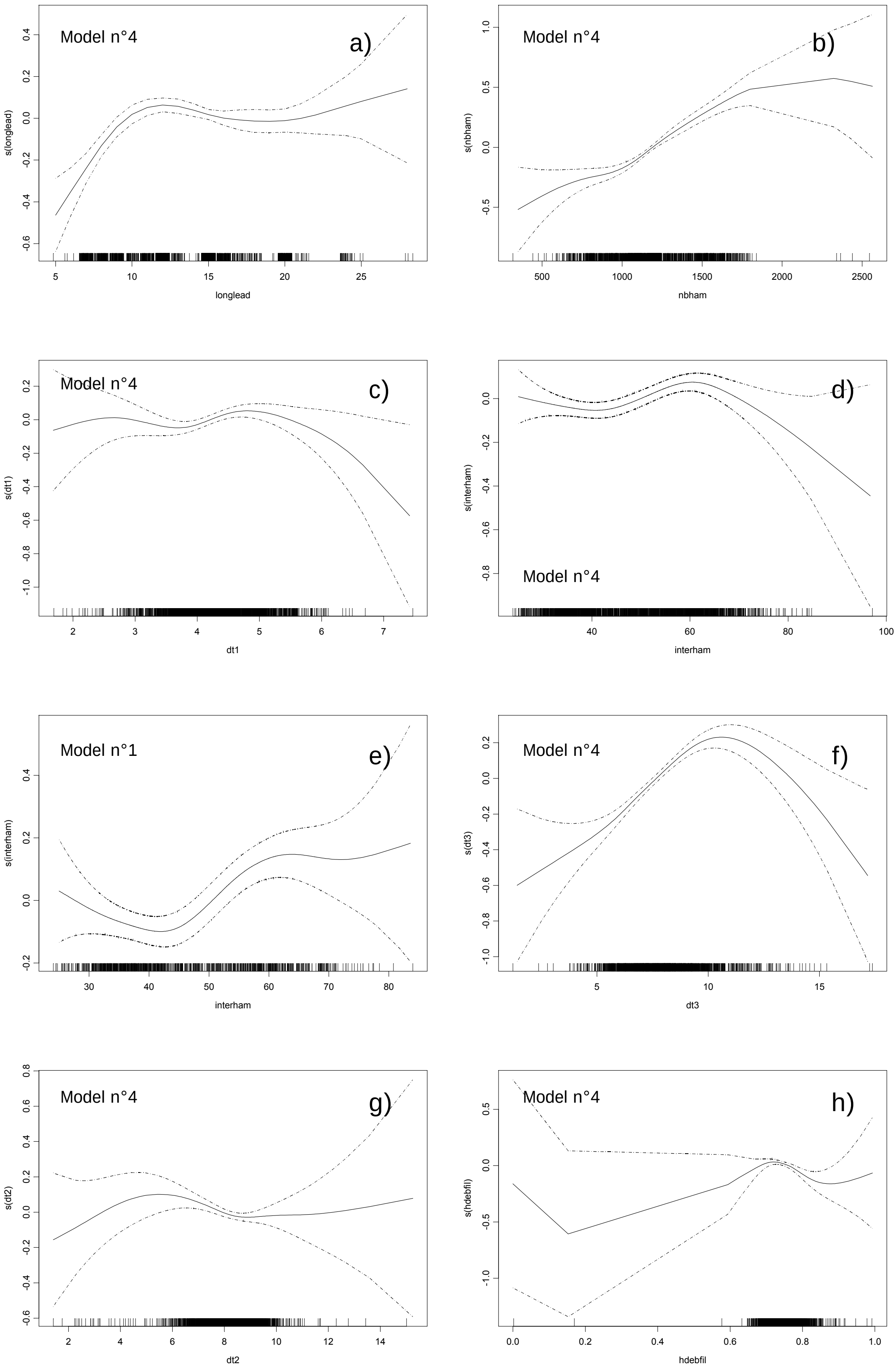


Figure 6 : Graphical representations of the relationships expressed by GAM analysis (a: longlead, b: nbham, c: dt1, d and e: interham , f: dt3, g:dt2, h: hdebfil)

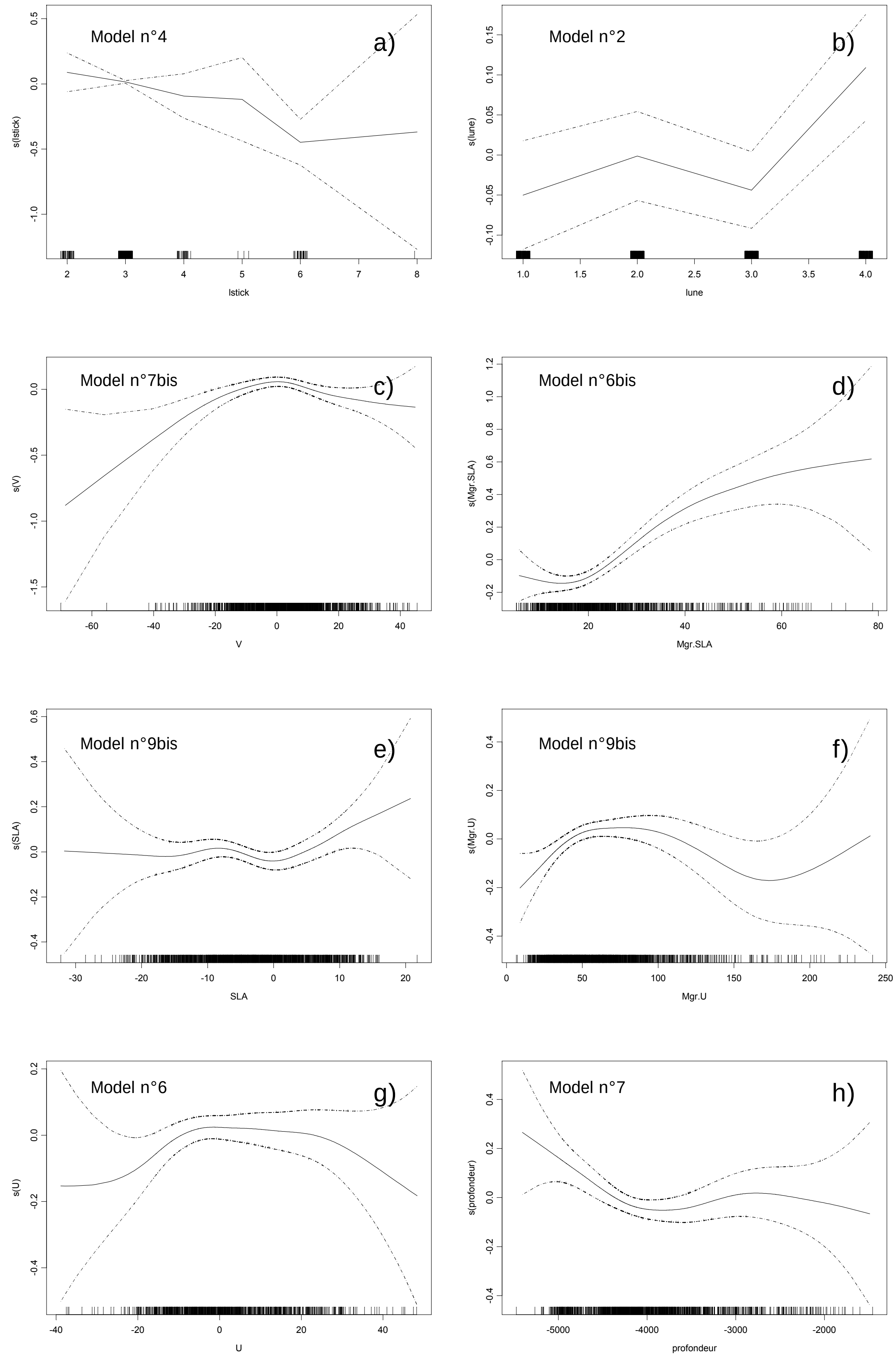


Figure 7 : : Graphical representations of the relationships expressed by GAM analysis (a: lstick, b: lune, c: V, d: Mgr.SLA, e: SLA, f: Mgr.U, e: U, h: profondeur)

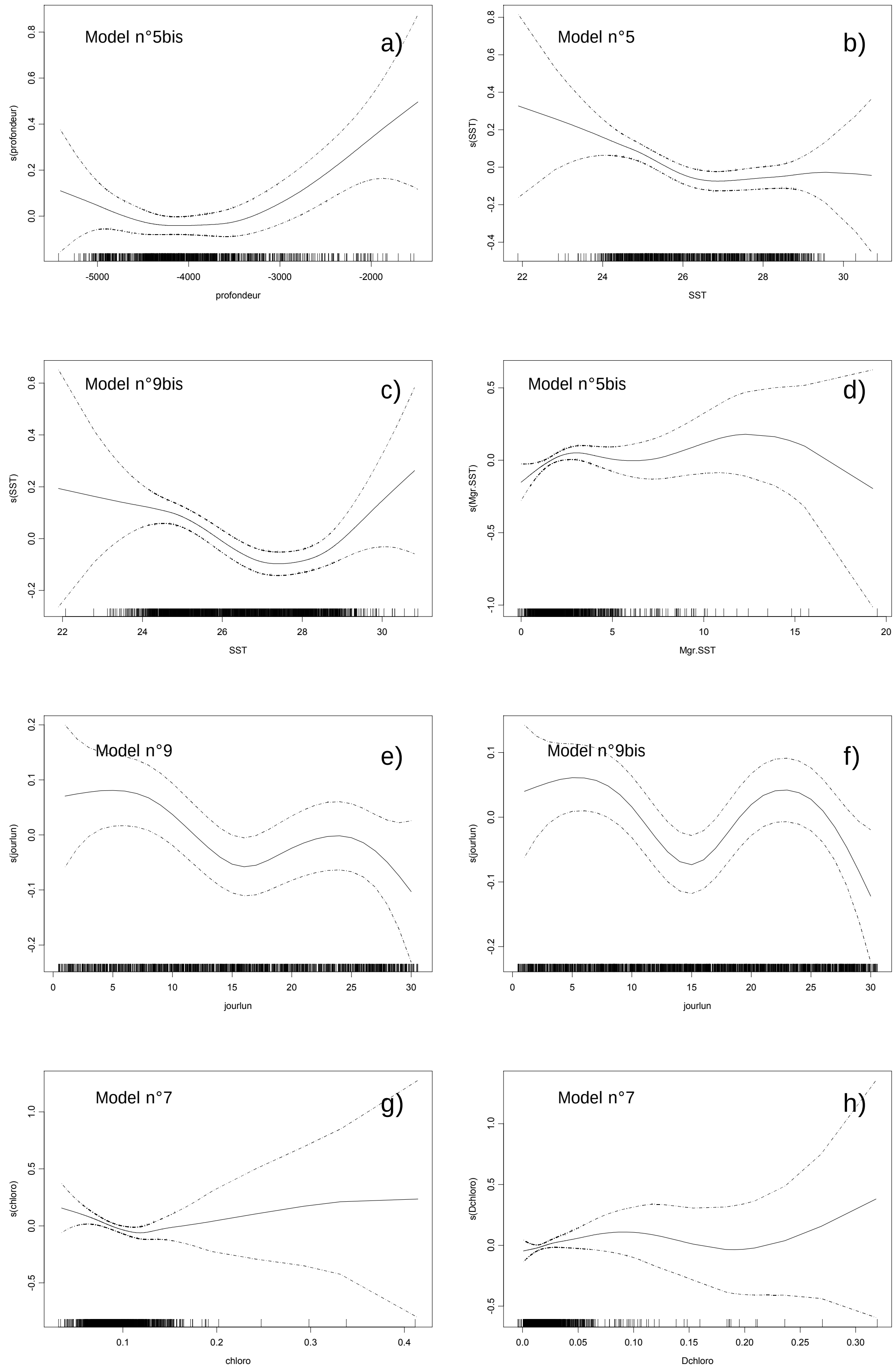


Figure 8 : Graphical representations of the relationships expressed by GAM analysis (a: profondeur; b and c: SST, d: Mgr.SST; e and f: jourlun; g: chloro; h: Dchloro)

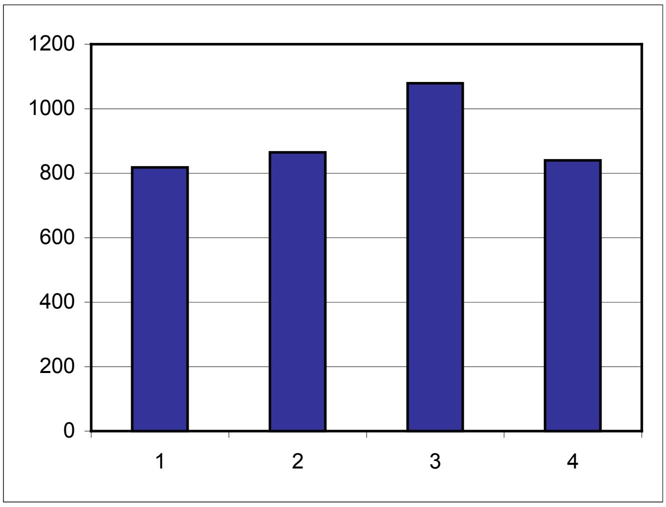


Figure 9 : Number of longline sets by period of lunar luminosity index (3602 sets from Ifremer database)

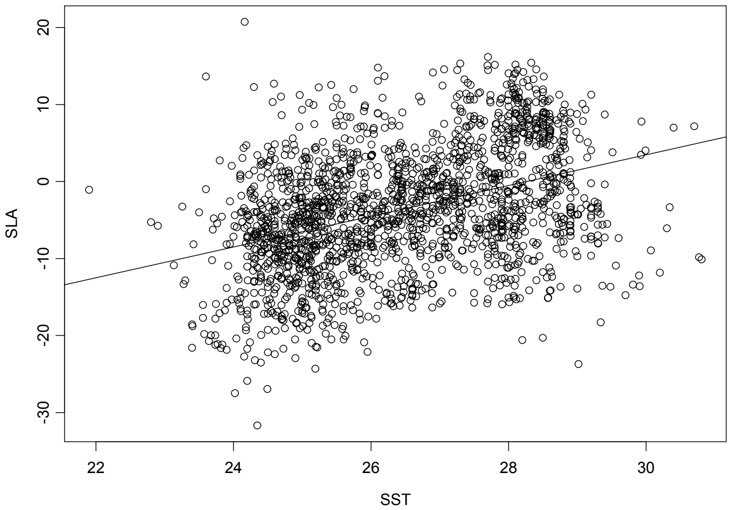


Figure 10 : Representation of the SST vs. SLA regression fit (Rh0=0.39, p<0.001)

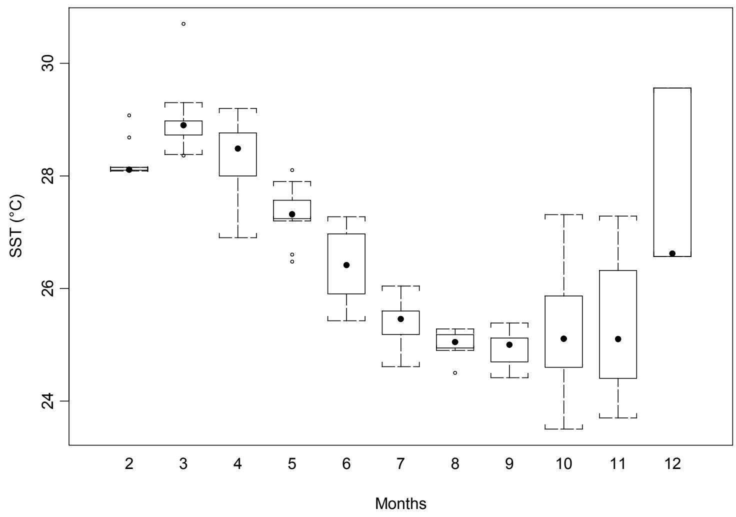


Figure **11 : Distribution of SST regarding to months**