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Squid stock fluctuations and water temperature: temporal analysis of English Channel Loliginidae

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Summary

1. Monthly series of abundance indexes for the English Channel squid stock, based on fishery statistics of the United Kingdom (1980–93) and France (1986–96), were compared with water temperature data. The two objectives of the study were to test empirical predictive models and to analyse the stock–environment relationship at various time scales; both correlation and time-series statistical techniques were applied. Sea surface temperature (SST) showed inter-annual fluctuations and month-to-month auto-correlation in addition to the annual cycle.

2. Trends in squid landings and temperature at the annual scale were found to be related, whatever the statistical method used (moving averages, cumulative functions or regression using averaged data).

3. Variable selection applied in a 'multi-month' model suggested that fishing season indexes could be predicted from temperatures observed in the previous winter. The link between mild winter conditions and cohort success in winter/spring spawning species suggested that early life survival (and/or growth) was involved. This empirical model is a first step in the development of environment-predicted recruitment indexes useful for management advice.

4. Seasonal decomposition was performed on both the squid resource data and SST data in search of short-term relationships. In spite of the flexibility of the loliginid life-cycle, no significant relationship was found between squid seasonally adjusted indexes and temperature anomalies in the previous months. This underlined the conclusion that temperature effect on cohort success was not constant throughout the year.

Key-words: cephalopod, correlation, environment, recruitment, time series.

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Introduction

The role of climate in the regulation of year-class strength is a question of major interest for scientists when estimating the effect of global climatic change on fisheries. Sea surface temperature (SST) is among the commonest parameters used to measure climatic change (Colebrook 1976; Colebrook & Taylor 1979). Water temperature can directly and indirectly affect marine poikilotherm populations. Cephalopod populations show highly variable growth rates and low inertia – due to their short life span – which suggests that temperature should markedly affect the size of such stocks (Caddy 1983). However, the relationship between temperature and cephalopod abundance is not well documented (Fogarty 1993).

The well studied Japanese squid *Todarodes pacificus* (Okutani 1983) shows abundance and migration patterns that depend on the fluxes of cold and warm currents around Japan (Murata 1989). In the North-west Atlantic squid *Illex illecebrosus*, egg development seems to be inhibited below a threshold of 12·5 °C (Coelho *et al.* 1994). In the European squid *Loligo forbesi*, Holme (1974) initially suggested a link between temperature and reproduction success. However, Pierce (1995) provided the first evidence of an empirical relationship between resource level and temperature. This analysis used data from the Northern North Sea – division 'IVa' of the International Council for the Exploration of the Sea (ICES) (Anonymous 1996) – and the best relationship was obtained with

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squid stocks around the North of Scotland (ICES division IVa and VIa).

The aim of the present paper is to examine empirical relationships between loliginid stock-size and temperature in the English Channel (ICES divisions VIId and VIIe).

The English Channel squid stock is a mixing of *Loligo forbesi* and *Loligo vulgaris* populations (Robin & Boucaud-Camou 1995). Both species have an annual life cycle (Holme 1974; Guerra & Rocha 1994) with different timing. In the English Channel stock, recruitment of *L. forbesi* begins in June whereas *L. vulgaris* enters the fishery in September/October and the fishing season ends in April/May (Pierce, Bailey & Robin 1996). Preliminary trials of stock assessments have been computed using depletion methods (Pierce, Bailey & Robin 1996). The results for the period 1989–93 showed that monthly Landings Per Unit of Effort (LPUE), and total landings of commercial fleets could be used as abundance indexes. There is currently no management for these species and conventional models used in the management of finfish stock, like surplus production models or cohort analysis, are hardly applicable (Pierce & Guerra 1994). These authors suggest, on the other hand, that environmental conditions should prove to be important predictors of stock size.

In the present study, squid landings and temperature (SST) data sets were analysed in order to answer the following questions.

- Is it possible to predict the strength of the annual cohort using temperature?
- Within a year, what months have temperatures that play the most important role in the determination of the cohort strength?
- Is there any relationship between temperature deviation from the annual cycle and abundance anomalies?

Materials and methods

This study makes use of existing, historical, data sets which have been analysed with two groups of statistical techniques: linear regression methods and time-series analysis.

DATA SETS USED

Fishery data

Stock-size indices for English Channel loliginids were derived from UK and French landings from commercial vessels fishing in the area (ICES divisions VIId and VIIe). United Kingdom data were obtained from national institutions, Scottish Office for Agriculture, Environment and Fisheries Department (SOAEFD) Aberdeen Marine Laboratory and the Ministry of Agriculture Fisheries and Food (MAFF) Lowestoft Fisheries Laboratory, with a monthly time-series for the period 1980–94. French data were obtained from the Centre Administratif des Affaires Maritimes (CAAM), on an annual basis for the period 1980–85 and monthly for the period 1986–1996.

Environmental data

Sea surface temperature data were obtained from the AVISO marine database managed by Météo-France. In this database, *in-situ* measurements and satellite images are combined in an interpolation model (Reynolds & Smith 1994) that computes daily SST on a grid of one-degree latitude by one-degree longitude. From the grid, the subset of 10 points falling in the English Channel was used to calculate monthly averages over the period 1979–93. In addition, a complementary time-series (monthly averages of daily SST measurements) was used that was collected at Flamanville between 1986 and 1996 (Drévès 1997). This data set is more local, although it comes from a central part of the English Channel where water currents are very strong. Mixing is sufficient here such that temperatures are homogenous throughout the water column at any time of the year (Pingree, Pennycuick & Battin 1975).

It is worth noting that, although Sea Surface Temperature is a very commonly recorded parameter, continuous time-series of *in-situ* measurements are rarely available. For example, in the ICES Oceanographic database there is a very good temporal coverage for the North Sea, but there are many gaps in English Channel data such that the database was useless for this study.

Fishery data were used cautiously as squid biomass indexes. As often as possible, analyses were repeated on all available data sets. In the following analyses, UK landings were always compared with Météo-France SST time-series (1980–93), whereas French landings were compared with the Flamanville temperature series (1986–96).

STATISTICAL ANALYSIS

Abundance indexes and temperature data sets collected on a monthly basis show a temporal structure. Dominant patterns reflect seasonal SST fluctuations and the squid annual life cycle. Time-series analysis and multivariate methods were therefore used to take into account the different components of both squid stock and temperature fluctuations.

Preliminary analysis of each data set

The first goal for the analysis of the fishery statistics was to check the quality of the time-series and the possibility of using the landings data as an index of biomass level. This was done with a series of graphs comparing the landings of different fleets (French and UK trawlers) and also landings, effort and Landings Per Unit of Effort (LPUE). Effort for UK trawlers is fishing time (hours) and for French trawlers, it is a combination of fishing time and vessels engine power. French trawlers Units of Effort are thus hours fishing for a standardized 100 kW boat.

Environmental changes between and within years cannot readily be ascertained with the original SST time-series (Fig. 1). Thus, the Météo-France series (1980–93) was analysed by tabulating the 14 years series (rows = years, columns = months) and undertaking a Principal Component Analysis to describe temperature variability and month to month correlation.

On both SST data sets (Météo-France and Flamanville) no significant linear trend was detected which indicated that time-series analysis could be applied.

General trends analysis

Relationships between inter-annual variations in cohort strength and in temperature were sought using three different techniques.

1. *Correlation between Moving Averages.* Each monthly time-series (biomass index and SST) was replaced by a series of 12-month moving averages centred on each original value (–5, +6).

2. *Correlation between Cumulative Functions.* Cumulative functions were first used in industrial quality control. They have been usefully adapted to the analysis of chronological data in oceanography (Dauvin *et al.* 1993; Ibañez *et al.* 1993; Fromentin & Ibañez 1994).

In both squid stock and SST time-series, the global mean of the series ($\bar{Y}g$) was used to build a cumulative function (C_t), where:

$$C_t = \sum_{i=1}^{t} Z_i \quad \text{with} \quad Z_i = Y_i - \bar{Y}_g. \qquad \text{eqn 1}$$

In these two methods, a correlation coefficient is computed between variables that are intrinsically autocorrelated. In that case, usual tests for a statistically significant correlation cannot be applied. A Monte-Carlo procedure was used instead. Simulated values based on a random subset of the series are computed 2000 times to estimate confidence limits for the correlation coefficient.

3. *Linear regression fitting of annual data.* Life cycles in English Channel loliginids indicate that annual cohorts are exploited during a fishing season ranging from June until April/May. Fishing season indices (total landings of a fleet or LPUE) were compared with annual average temperatures. Two coefficients, Pearson's correlation coefficient and Spearman's rank coefficient, were computed, the first one being more powerful and the second one being distribution free.

Seasonal aspects of temperature effect

Fishing season indices were also compared with temperatures observed in a calendar month. The aim was to determine at which season temperatures play a deterministic part in cohort strength. An empirical 'multi-month' linear regression model was developed. Temperature variables initially entered in the model were chosen, taking into account temperature structure as revealed by the Principal Component Analysis of temperatures described above. Regression analysis was then carried out with a variable selection based on two criteria (Mallow's Cp and R^2).

Short-term relationships

Squid stock indexes and SST both undergo seasonal fluctuations. Deviations from this pattern, that is the anomalies, were extracted using seasonal decomposition. Cross-correlations between anomalies were determined in order to express the predictable part of squid stock anomalies as the output of a transfer function model of temperature (Fogarty 1989). By analysing cross-correlations with lags of less than 12 months, short-term relationships were sought.

Seasonal decomposition requires series with homogeneous variance and without any long-term trend. It was performed on log-transformed and differentiated

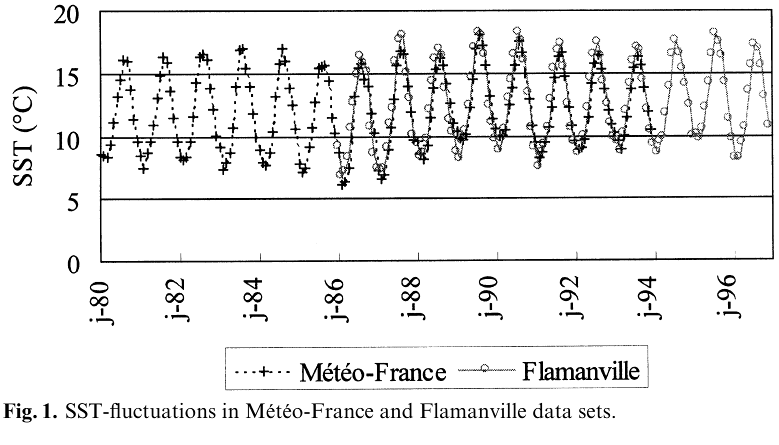

Fig. 1. SST-fluctuations in Météo-France and Flamanville data sets.

data Z_{ij} (where i denotes the year and j denotes the month).

The decomposed series were written as:

$$Z_{ij} = m_{ij}+s_j+d_{ij} \qquad \text{eqn 2}$$

(where m_{ij} is the centred moving average (−6, + 6), s_j is the mean seasonal index of each month, and d_{ij} is the irregular component) and seasonally adjusted data (*SAD*):

$$SAD_{ij} = m_{ij}+d_{ij} = Z_{ij}-s_i. \qquad \text{eqn 3}$$

Results

DATA SETS STRUCTURE

Squid biomass indexes

Annual landings from French and UK Fisheries (Fig. 2) show synchronous patterns during the overlapping period. UK landings represent a small proportion of English Channel production; however, squid is a by-catch resource for UK trawlers, and reductions observed in 1984–85 should correspond to a lower stock-size as in 1990. The French trawlers time-series (Fig. 3) shows that total landings and LPUE have very similar fluctuations in a context of constant fishing effort. Changes in total landings can thus be considered to describe changes in the population biomass.

SST data

Principal Component Analysis illustrates the main traits of monthly SST fluctuations (Fig. 4a). Components 1 and 2 explain more than 73% of the variability in the 12-month array (respectively, 57% and 16%). Monthly variables are well represented on the correlation circle, all positively related to Component 1, they split according to Component 2 where 'summer months' are positive and 'winter months' are negative. The projection of individual years in the plane of Components 1 and 2 underlines that Component 1 reflects 'between-year' changes and that Component 2 reflects seasonal structure 'within-years' (Fig. 4b). For example, 'cold years' 1980, 1981 and 1984 are negative on axis 1 and 'warm years' 1989 and 1990 are positive. The second axis separates 1982 and 1991 which have a similar temperature average, one with a 'cool' summer (1982) and the other one with a 'mild' winter (1991).

The positive correlation of all variables with the first component, which corresponds to 'between-years' fluctuations, suggests that a cold year has lower temperatures in all months. A second result of this

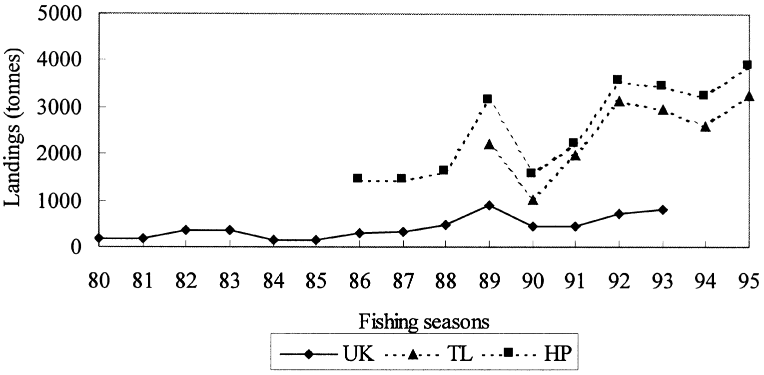

Fig. 2. English Channel squid landings per fishing season: Solid line = UK fleet; dotted line = French fleet (■ = harbour production, ▲ = trawlers' landings).

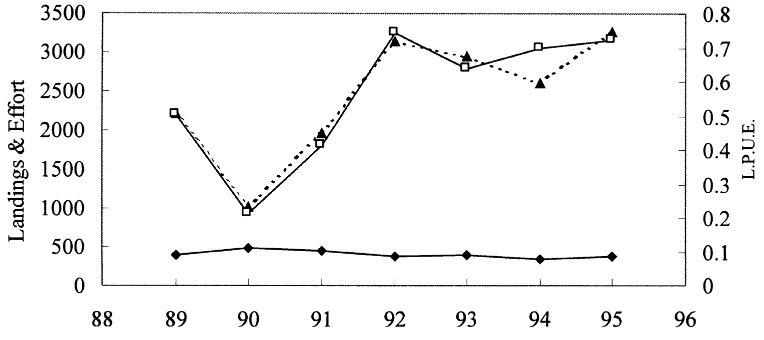

Fig. 3. English Channel season data of the French trawlers fishery: ▲ = total landings (tonnes); ◆ = fishing effort (standardized hours); □ = LPUE kg of squid per standardized fishing time.

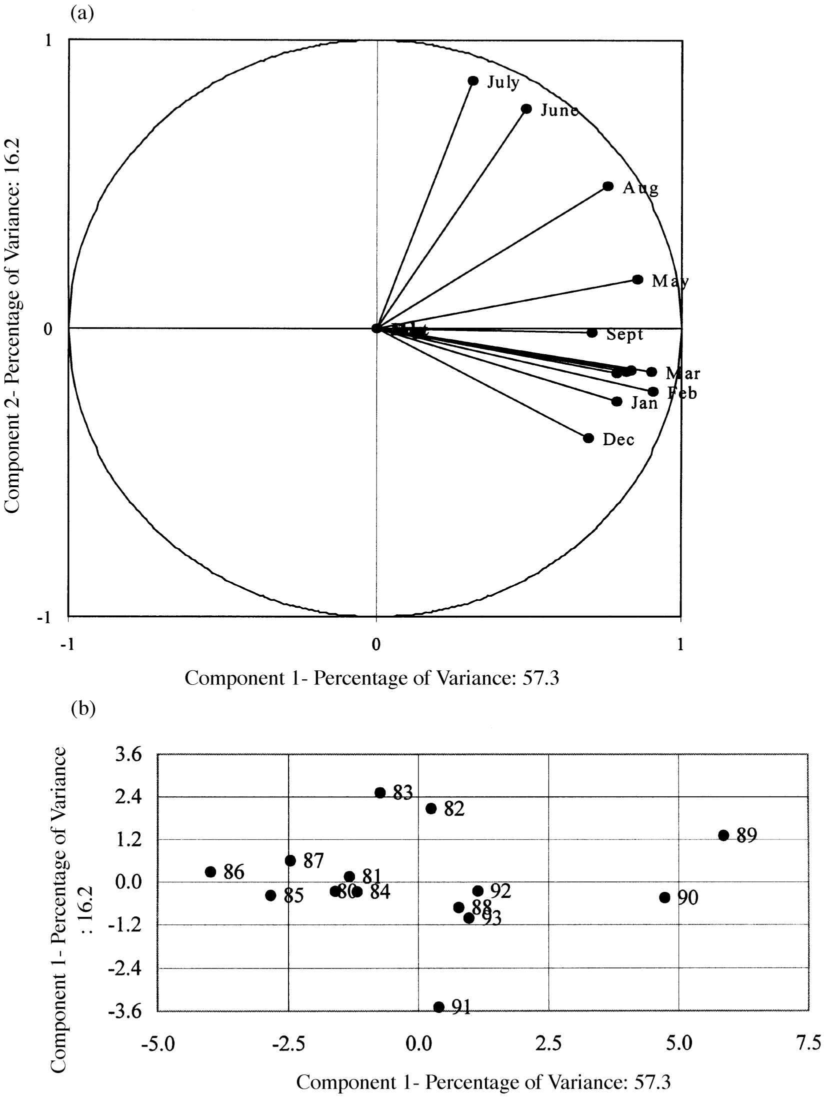

Fig. 4. Principal component analysis (projection in the plane of Components 1 and 2): (a) variable vectors in the Correlation Circle; (b) individuals (years) scatterplot in the Factorial Plan.

analysis is that close months have temperatures closely related (the weakest relations correspond to a change of seasons, e.g. in May/June).

Principal Component Analysis of the Flamanville data set shows a similar structure (with all variables positively correlated to Component 1 which explains 59% of the variability). Differences may be related to the time range (1986–96), which does not include cold years such as 1985.

GENERAL TRENDS

Landings and temperature moving averages show synchronous fluctuations in the periods 1980–82 and 1986–96 (Fig. 5). The correlation coefficient (*r*) between the series is 0·82. Estimated with the Monte Carlo procedure, 95% confidence limits (0·77–0·87) indicate a significant relationship. Some parts of the moving averages plots may suggest a lag in fluctuation in landings which peak later in 1982 and also in 1988. However, this does not apply to the whole series and correlation decreases when landings are shifted.

Cumulative Functions have been plotted for the two groups of available data (Figs 6 and 7). Annual cycles remain more clearly visible in the temperature Cumulative Functions as a simple result of smaller between-year variability than within-year variability for this variable. In both cases, Cumulative Functions of landings and temperature show related trends. Correlation is higher in the UK series (0·84 with confidence limits 0·80–0·88) than in the French (0·57 with confidence limits 0·46–0·67). It is worth noting that the greatest departure between landings and temperature functions is observed in the 1990–92 period, which covers a larger part of the French series (1986–96).

A linear model describing UK fishing season landings as a function of annual temperature confirms that general trends are related (Fig. 8). In spite of a significant correlation (Table 1), confidence contours indicate that such empirical models would be inap-

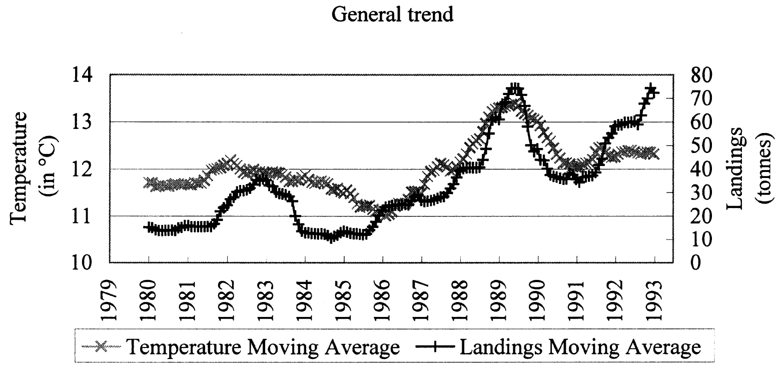

Fig. 5. Moving Average series from June 1980 to June 1993 (Météo-France SST and UK squid landings).

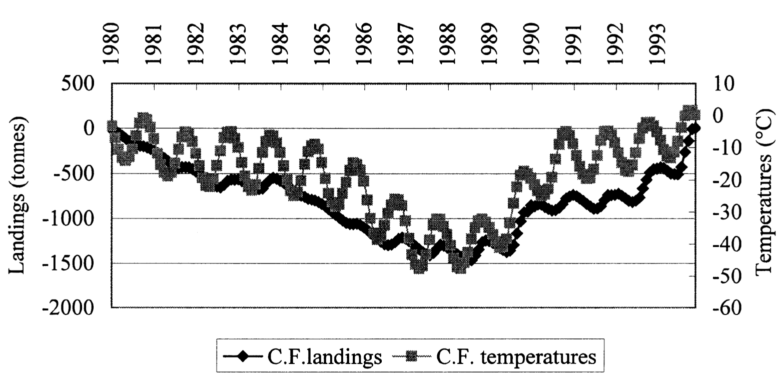

Fig. 6. Cumulative Functions of UK landings and Météo-France SST from January 1980 to December 1993.

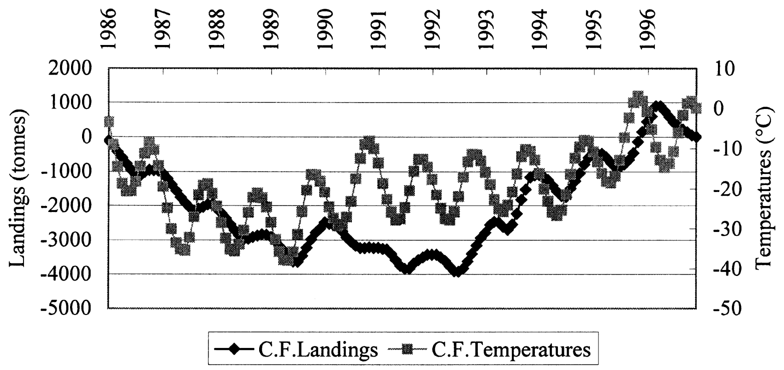

Fig. 7. Cumulative Functions of French harbours production and Flamanville SST from January 1986 to December 1996.

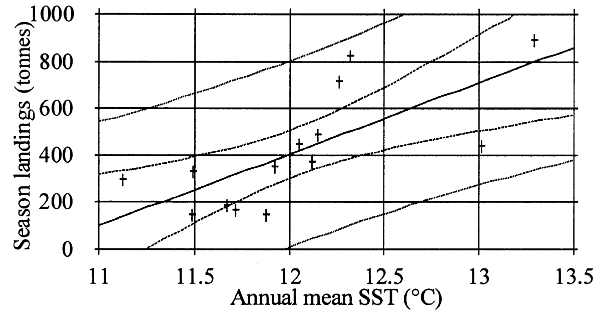

Fig. 8. Linear regression fitting of UK season landings vs. annual mean temperatures (Météo-France data) (dotted lines are prediction and mean response, 95% confidence limits).

Table 1. Correlation analyses of season squid landings vs. SST (Pearson's –r_P– and Spearman's –r_s– correlation coefficients)

	UK landings vs Météo-France SST	France HP vs Flamanville SST
Number of fishing seasons	14	10
r Pearson (r_P)	0·72	0·63
Probability: $P(r_p = 0)$	0·003	0·050
Spearman (r_S)	0·85	0·62
Probability: $P(r_s = 0)$	0·002	0·061

propriate for management purposes. The non-parametric Spearman's coefficient also gives a significant correlation, which suggests that the model is not an artefact due to outlying numerical values. On an annual scale, French landings are a shorter series (10 fishing seasons) and correlations with mean temperatures do not reach a significant level.

SEASONAL ASPECT OF TEMPERATURE EFFECT

A more detailed analysis shows that landings during a fishing season are mainly related to winter and spring temperatures (Table 2). UK landings show the closest relationship with January-SST, and French landings are significantly correlated with temperatures observed in February. On the other hand, landings peak in September in both fisheries, although there is no significant relationship between landings and temperatures observed in summer or autumn.

The analysis of temperature structure has already underlined correlations between close calendar months. Because of this, only one variable (February) was selected in the multi-month model of French landings. The best empirical model of UK landings (Fig. 9) was obtained with March SST and the first quartile of each year's temperatures (equivalent of the three coldest months average) ($r = 0{\cdot}78$ with a probability $P[r = 0] = 0{\cdot}006$).

COMPARISON OF TIME-SERIES ANOMALIES

Seasonally Adjusted Data have been computed for UK landings and MétéoFrance SST. These anomalies do not show any significant correlation at any lag (Fig. 10). In both series, tests for randomness indicate that the irregular component (d_{ij}) is a 'white noise' of random data. Just like *SAD*, the irregular component series do not show any correlation. The consequence of this lack of correlation is that no transfer function model could be fitted between variations at the short time scale.

From the statistical point of view, a non-significant correlation should not be considered as proof that the phenomena are totally independent. With the data sets used, it shows that possible effects of temperature anomalies on squid do not occur with a constant lag, in a constant direction, or with a constant intensity.

Discussion

Results from the correlation and time-series analyses show that squid cohort strength is related to water temperature, especially to winter temperature. This stock–environment relationship is suggested by two groups of data sets, which reduces the risk of spurious trends.

SST data sets that were used to describe English Channel temperature look very similar to the, incomplete, Roscoff Marine Station series (Dauvin & Joncourt 1991; Dauvin *et al.* 1989) with cold temperatures in 1986 opposed to a warming in 1989–90. Air-temperature data at coastal stations provide longer series but the pattern seems slightly different (Fromentin & Ibañez 1994). The 14-year long Météo-France data set does not seem to be long enough to exhibit a long-term cycle of climate change: 11 years according to Southward, Hawkins & Burrows (1995), 8–7 years in Glémarec, Lebris & Le Guellen (1986) and Fromentin & Ibañez (1994).

Data sets from the commercial fishery provide longer time series than finfish research cruise data where cephalopod catches are not consistently recorded. For instance, Channel Groundfish Surveys (CGS) carried out in October by IFREMER include squid catches since the 1993 cruise (Carpentier 1993). However, it is worth noting that average CPUE in the 1993–96 cruises follow the same trend as commercial fishery landings and emphasize that biomass and abundance are closely related (Robin, Denis & Carpentier 1998).

Table 2. Correlation analyses of season squid landings vs. calendar month temperatures (Pearson's –r_P– and Spearman's –r_s – correlation coefficients)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	95% limit
UK-data	r_P	0·71	0·67	0·59	NS	0·63	0·61	NS	NS	NS	NS	0·56	0·69	0·53
	r_S	0·75	0·71	0·69	0·66	0·67	0·58	NS	NS	NS	NS	0·62	0·66	0·53
France-HP data	r_P	NS	0·71	NS	NS	NS	NS	NS	NS	NS	NS	NS	0·65	0·63
	r_S	NS	0·73	NS	0·65	NS	NS	NS	NS	NS	NS	NS	0·75	0·64

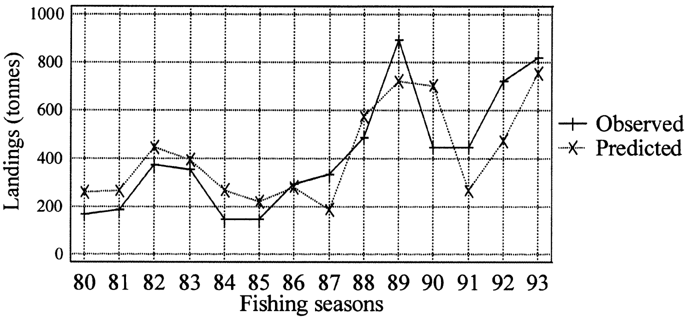

Fig. 9. Multiple linear model of UK season landings, Observed and Predicted values (selected SST variables are March temperatures and the First Quartile of temperatures within each year).

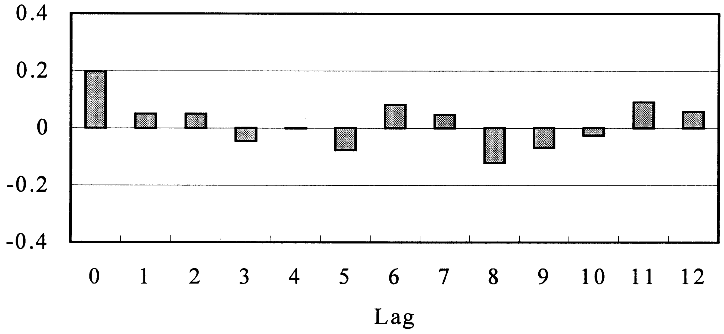

Fig. 10. Cross-correlations between Seasonally Adjusted Data of both UK landings and SST (with landings lags of 0–12 months).

Positive correlations between biomass indexes and SST do not, of course, prove that squid populations are directly controlled by temperature. However, this observed synchrony suggests hypotheses about the underlying phenomenon (Sinclair & Frank 1995).

At the annual scale, English Channel squid populations seem to be favoured by warm temperatures. A similar trend has already been observed in a number of finfish stocks (Southward, Hawkins & Burrows 1995). Cushing (1982) demonstrated that in periods of warming *Octopus vulgaris* could occur in the Western English Channel as a result of a shift in distribution range. It is worth noting that the northern limit of *Loligo vulgaris* is north of the English Channel. The low inertia of squid stocks is underlined by the rapid increase of landings in 1982 and 1989. Lower levels follow shortly after such peaks.

Each one of the three methods used to describe annual trends highlights one particular aspect of the correlation. Simple regression of annual averages shows that in spite of a significant correlation the quality of predictions based on such an empirical model would be rather poor. Cumulative functions are useful to show the consequence of small changes in the series which, when cumulated, are better-detected (Ibañez *et al.* 1993). For instance, the mismatch between temperature and biomass trends in the 1990–92 period is highlighted in both UK and French data sets. Moving Averages (MA) are not so much a tool for analysing annual trends as a preliminary step towards seasonal decomposition. With that aim, it is worth showing that landings and SST MA show a positive correlation when within-year anomalies (departures from the seasonal trend) do not.

Detailed correlation analysis using calendar month data shows that squid stock indexes depend on temperature in the previous winter. This is in agreement with other empirical models based on environmental variables originating from the North Sea (Pierce 1995). Variables selected in the UK multiple model include the first quartile of temperatures and not the annual minimum. The consequences of a sharp temperature decrease seem to be smaller than that of a long cold winter. Relationships between winter temperature and cohort strength of a winter/spring spawning stock (Holme 1974) (J.P. Robin & E. Boucaud-Camou, unpublished data) suggest that early life-stages of squid are sensitive to temperature or to temperature-related parameters, such as food availability, as demonstrated in the North Sea by Continuous Plankton Recorder surveys (CPR Survey Team 1992). However, population indices describing biomass fluctuations are not sufficient to understand which mechanism dominates between mortality changes and/or growth changes. This would require true abundance indexes (LPUE in numbers). In the case of French landings, this desirable information could be derived from the Fishery Statistics because squid landings are sorted by commercial categories of rather homogeneous size (Robin & Boucaud-Camou 1995).

The life cycle of both *Loligo forbesi* and *Loligo vulgaris* is often considered as highly flexible (Boyle, Pierce & Hastie 1995). Mature animals are observed during several months and the extended spawning season is a source of 'microcohorts' (Guerra *et al.* 1992) whose success depends on a variety of environmental conditions within each fishing season. The short-term analysis indicates that this scheme may not apply to English Channel populations or at least not with a straightforward response of squid stock to a single parameter. The lack of correlation between SST and squid-stock anomalies suggests that positive anomalies in temperatures are not necessarily followed by an increase in squid biomass, whatever the time in the year. The timing of life-cycles has to be taken into account and temperature is likely to have a variable effect according to the life-stage.

In conclusion, this first analysis of environmental variations in relation to the English Channel squid stock suggests that loliginid recruitment level can be predicted by temperature. This is a first step in the development of predictive tools that will be useful for management advice. Predictions of stock-level can be used to regulate fishing effort for biological and/or economical objectives. Long-standing series are necessary to fit a predictive model, which should be improved by updating the data sets and also by taking into account additional environmental predictors. Such models are still empirical but then also suggest hypotheses on key life stages that might affect cohort success.

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