

CLIMATIC DRIVING OF SPINY LOBSTER CATCHES IN NORTHEAST BRAZIL

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ABSTRACT

In the spiny lobster fishery in northeast Brazil, based in the two species *Panulirus argus* (Latreille) and *Panulirus laevis* (Latreille), the fishing effort has steadily increased more than twenty-fold between 1965 (with the equivalent of 2.5 million trap-days) and 1994 (65 million trap-days), according to official statistics. The annual production, after an almost steady increase from 3500 tonnes in 1965 to 9000 tonnes in 1974, since then has stabilized around an average of 8 000 tonnes, but presenting fluctuations of up to 3000 tonnes between consecutive years. This work therefore concentrates on analysis of the second moment structure of the statistical data base, which is dominant in the fishery. It is shown that analysis based on first moments, leading to a search for a Maximum Sustainable Yield (MSY), is useless due to the large variances and may be misleading when used for management purposes. Based on yearly catch and effort data, the Effort-Yield curve presents a constant long-term average Yield of 8 000 tonnes, being insensitive to changes in Effort between the levels of 15 and 60 million trap-days. Recruitment of juveniles of *P. argus* present oscillations of 5.5 years, while for *P. laevis* the basic periodicity is 6 years, with contributions from triennial components for both species. Lag correlation between % juveniles in the catch and total catch per species presents a positive maximum at zero lag for *P. argus*, suggesting that most juvenile recruits for this species are not able to grow into adult classes, and a negative maximum for *P. laevis* at zero lag, suggesting that maximum recruitment seems to occur when total catch for this species is at a minimum. The periodicities cited above, and another one at 11-12 years, are the dominant interannual ones in the sea surface temperature field (SST) of the Atlantic Ocean. The 5.5-6 year peak seems to also dominate the variability of thermocline depth (TD) adjacent to the fishing area. In a preliminary analysis we found periodic lag correlations between annual mean SST and catch per species, percentage of juveniles in the catch, and total catch. A deeper analysis of these correlations by a novel method (Singular Lag Correlation Analysis) was made, showing that 84% of the SST variance is correlated with 64% of the variance in catch of *P. argus*, this correlation being due to coupling with a basic signal component of 11-years and its harmonics 5.5 and 2.75 years, while for *P. laevis* the coupling is described by a basic signal component of 12 years and its harmonics 6 and 3 years. To get a better insight into the processes that might explain the observed coincidences in the basic periodicities, we develop a simple theory to determine the time-dependent changes in the flux of phyllosoma larvae into the continental shelf due to advective effects, as described by a reduced gravity model of equatorial ocean dynamics. This theory suggests that availability of phyllosoma larvae for settlement in a fixed coastal area should be expected to depend on the average current velocity divergence field, which can be monitored from fluctuations in TD or Mean Sea-Level (MSL). The unusually high stability of catch under changes in Effort suggests a balance between the larval flux out with a flux back to the fishing grounds, which requires the existence of large-scale closed current loops supporting the full larval cycle. We show that this requirement is met with the poorly known loop based on the upstream retroflexion of the North Brazil Current off Fortaleza into the eastward South Equatorial Undercurrent, and the return path through the central branch of the South Equatorial Current impinging the coast near Natal. During years of anomalous zonal wind stress intensification and advection of colder water by the South Equatorial Current System into the western equatorial Atlantic, with shoreward Ekman deepening of the thermocline, we should expect increases in the availability of late stage larvae of *P. argus* near the coast. On the other hand, settlement of *P. laevis* seems to be facilitated by a subsequent relaxation of the wind stress, which causes a shallowing of the thermocline and a decrease in the current-driven sediment resuspension in shallow areas. These results support the interpretation that cold events off NE-Brazil might be associated to maximum catches of *P. argus* 2.5 years later, and minimum catches 6-7 years later, while warm events might be associated with maximum catches of *P. laevis* 3 years later. Cold events are also correlated with a minimum in total catches 4-7 years later. These results point out that even with a lack of precise data on stock size, total fishing effort and good criteria to support the choice of a stock-recruitment relationship we can still understand half of the variance in the dynamical behaviour of this fishery by use of data obtained from ocean climate monitoring systems. Practical applications are recommendations for management and for the design of research projects on larval pelagic cycles.

1. INTRODUCTION

The importance of the effects of ocean climate change on variability of biomass yields from large marine ecosystems is now widely recognized, and international efforts are being conducted to identify the principal, secondary and tertiary driving forces causing major shifts in marine ecosystem structure that should impact future adaptive management strategies (Sherman, 1994).

In the case of the spiny lobster fisheries, evidences that climatic driving may be the primary forcing mechanism, as opposed to changes in fishing effort, have also been empirically found, mostly due to the intense research work related to the Western Australian lobster fishery based on *Panulirus cygnus*. Definite relationships between the level of puerulus settlement and subsequent abundance of recruits, and total catch four years, later served as a basis for the computation of catch predictions for the West Australian fishery (Phillips, 1986), the method being recognized and used by industry and government as a valuable management tool after 9 years of its operation up to 1986.

In a further development, the level of puerulus settlement was found to depend on ocean climatic variables, and this led to the interesting discovery that ultimately the levels of catch at a certain year might be more dependent on the state of the ocean environment recorded four years earlier than the level of fishing effort in previous years (Pearce and Phillips, 1988). Also in fisheries based in other genus of spiny lobsters, as in Tasmania (*Jasus edwardsii*), catches lagged by 7 years were shown in the study by Harris et al (1988) to be significantly correlated with sea temperature and with late spring outbursts of west winds, based on data between 1945-1985.

These recent findings of the impact of environmental factors in spiny lobster fisheries is just one of the important consequences of the general availability of good standardized geophysical data sets, especially for the world ocean. They have been recently reviewed by Phillips et al.(1994) on several different spiny lobster fisheries throughout the world,

demonstrating the general empirical finding that ocean climate is indeed a major factor controlling larval recruitment and catches, furnishing useful predictors for future catches.

Our interest in this important problem is the consequence of our recent involvement in the annual discussions on the Brazilian equatorial lobster fishery based on *Panulirus argus* and *Panulirus laeviscauda*, promoted by the Instituto Brasileiro do Meio Ambiente e dos Recursos Renováveis (IBAMA). These discussions were conducted within the Permanent Group for Lobster Studies (called GPE-Lagosta).

The discussions of this Group, in the meetings of 1990 and 1991, were largely based in the appraisal of Fonteles-Filho et al (1988). These authors showed in their fig.6 unexplained oscillations in lobster annual exports from the port of Fortaleza. They also show in their Fig.2 the interannual variability of the average total length of lobsters of each of the species, which reveal 6 year period oscillations. In their Fig.5 the "climatology" of exported tail weights between 1967-1987 is presented, exhibiting confidence intervals larger than the monthly averages themselves at the minimum confidence level of 68.3%. These are evidences that the second moment properties dominate the behaviour of the data base. In spite of such evidence, the authors suddenly abandon their interesting line of analysis, and proceed into the academic approach in the search for a short-term average behaviour of the fishery, by use of the Schaefer (1954) model. In this way they obtain "optimum" estimates of effort levels and catch (22.3 million trap-days and 8,730 tonnes whole lobster). These figures, calculated for the production through Fortaleza, have been used since then as the optimum figures for Brazil by Brazilian management (IBAMA), and the control of the effort to these levels having become the long-lasting ideal of IBAMA. This dangerous route seems even worse when we are reminded that we don't have a stock definition for Brazil, a prerequisite for these calculations to make any sense (Caddy, 1986).

This investigation was started from a feeling that management directions might have been in the wrong way, for a long time, due to a lack of a deeper analysis into the second

moment structure of the fisheries data, and to the insistence of IBAMA in using the parameters obtained from the naive academic exercise contained in Fonteles-Filho et al. (1988) for the design of policy. In fact, there are many objections as to the applicability of this model even from the standpoint of theories based on first moments (see Caddy, 1986, for a review on applicability of theories based on stock-recruitment relationships for crustacea).

To better illustrate these facts we first show in Fig. 1 the total Brazilian annual catch per species since 1965, together with the the total catch, the data being presented in Table 1. We see that the long term trends are very small, but large oscillations at annual time scales are of the same order as the averages. Fig.2 shows the geographic location of the fishing area, from where about 70-80% of the catch was exported through Fortaleza (Fonteles-Filho et al, 1988), up to around 1989. From this year on the industry started to use other ports, especially Recife, Rio de Janeiro and S.Paulo, to export the production (Silva and Cavalcante, 1994).

There have been several questions relating to management (and mismanagement!) of this fishery which are directly or indirectly related to the lack of understanding of the principal driving forces which change the catch from year to year. The most basic one, as stated above, has been caused by application of the assumption that there is an Effort corresponding to a Maximum Sustainable Yield, which has been attained in 1974, and the consequent belief that since then overfishing has been the major problem. This causes both fisheries statisticians and the fisheries authority (IBAMA) to give a great emphasis on recommendations to the maintenance of policies designed to curb Effort, even at the expense of losing the confidence of fishermen on the system, giving a reverse effect: Effort has been rising uncontrollably, and most of the fishermen (92% by our estimate based on the last official statistic) have been working illegally, neglecting the regulatory rules imposed by the management sector.

In order to try to put all these questions into the proper perspective, and offer some new results to serve as the basis of future discussions, we organized this paper in the following way:

(i) We describe in sections 2 and 3 yearly data on catch, recruitment of juveniles and effort for

the Brazilian fishery, as a motivation for the analysis.

(ii) We present in section 4 the foundations of a simple theory of climatic driving of puerulus settlement variability by deriving a relationship between changes in puerulus recruitment and changes in thermocline depth, which may be simply related to mean sea-level (MSL), and SST.

(iii) We review the data supporting the existence of a southwestern equatorial Atlantic current loop, which can explain a larval advective cycle which ensures conservation of larval fluxes. Evidence for an important role played by the poorly known retroflexion of the North Brazil Current off Fortaleza into the South Equatorial Undercurrent is discussed.

(iv) In section 6 we analyse the time series by a novel method of lag correlation analysis, the Singular Lag Correlation Analysis (Vianna and Peris,1995; Peris,1995), which we developed specifically to treat short noisy signals with periodicities in their autocorrelation. The method overcomes the problems of estimation mentioned by Jenkins and Watts (1968), and follows the same spirit of the recent Singular Spectrum Analysis of Vautard et al.(1992). It is a non-trivial extension of the well-known Canonical Correlation Analysis (Preisendorfer,1988). We discuss these lag correlations which lead to our main result, which shows that the Atlantic climatic oscillations (Warm/Cold Events) are the drivers of at least 50% of the variance of Brazilian spiny lobster catch fluctuations. This result is also shown to reinforce the conclusion that interannual upper ocean circulation changes might constitute the main driver of large fluctuations in spiny lobster catches not only in Brazil, but also elsewhere.

(v) A summary of conclusions is made in section 7, where the prediction of a climatically-driven crisis in catch between 1997-1999 (Vianna et al.,1994) is seen to be reinforced. The present state of the Brazilian fishery is commented upon, to exhibit how these new results, especially those that contradict present dogma, can be introduced with a minimum of pain and maximum benefit for the Brazilian and other spiny lobster fisheries.

2. DATA

Fisheries data

The fisheries yearly averages were presented in section 1. The data has been usually obtained from the Fisheries Statistics Department of IBAMA/Fortaleza, and from CEPENE-the Northeast Research Center of IBAMA based in the city of Tamandaré, State of Pernambuco. This data is available and is updated yearly through the annual reports of the GPE Meetings (e.g., IBAMA 1994). We also used some data from Fonteles-Filho et al., 1988.

Physical data

The original monthly gridded data on SST used here is part of the data bank known as the Servain data set, and its description can be found in Binet and Servain (1993) and references therein. It is based on data acquired regularly in a network of shipping lines by ships of opportunity, and is updated since 1964. From this set we formed a regional SST index which we called Zone1 SST. It is obtained by averaging the gridded data over all of the 2x2 degree squares adjacent to the coast between S.Luis and Recife, which corresponds to the adjacent continental shelf area from which most of the Fortaleza production comes.

3. THE EFFORT-YIELD CURVE AND THE 5-6 YEAR OSCILLATION

As a preliminary step in our analysis, we presented in Table 1 and Fig.1 the yearly data on catch for each species, total catch and the official estimated effort in equivalent trap-days, as recorded on the GPE-1991 Report (IBAMA, 1994). We plot the Effort-Yield curve by use of the yearly total catch and effort data from Table 1, completed with data from the interval 1990-1993. The Effort x Yield curve is shown in Fig. 3. It is clearly seen that instead of exhibiting one single maximum, the curve shows an average asymptotic behaviour towards a mean value of around 8 000 tonnes of whole lobsters, independent of fishing effort, with high amplitude

fluctuations not related to effort. This trend seems to be maintained in the effort interval of 15-60 million trap-days!

Hence, two basic and coupled questions to be posed to management, one scientific (treated in the present paper) and one political, are:

- how can one understand and possibly predict these oscillations ?
- who will be entitled to have a share of the yearly 8 000 tonnes of lobsters, and with what gear?

As to the question of the nature of the oscillations, let us take a look at Fig. 1, which illustrates the interspecific differences in catch. It is seen that only twice did maxima in catch occur simultaneously: in 1979 and 1991, which caused maxima in total catch.

Fig. 4 shows the frequency of occurrence of juveniles in the catch per species, from data recorded in Tables I and II of Fonteles-Filho et al., 1988. A maximum in 1986, coinciding with a minimum in total catch, hints on the importance of this periodical replenishment of the stock with new recruits: periods of low recruitment indices correspond to lower catches in subsequent years, until new recruitment maxima replenish the stock, increasing the catches in subsequent years.

During the interval of 1974-1987, the oscillations have a clear 5.5-6 year period. These authors also state that the interannual changes in average total length of both species exhibit a 6 year periodicity. Since a 5.5 year periodicity is found to be the dominant peak in the spectrum of the Tropical Atlantic SSTA field between at least 10N and 30S (Nicholson and Nyenzi, 1990; Vianna et al., 1995), we are induced to investigate if the Brazilian lobster catch interannual variability is basically climatically forced. This interpretation can be further reinforced if we observe the lower left panel of Fig.8 in Houghton (1991), showing maxima in thermocline depth in 1982 and 1987. In Fig.5 we show the yearly average SST-Zone1 interannual variations (see Table 3 for the values). We see clearly that warm or cold periods are long lasting (around 3 years in average).

To better see the lag relationships between SST, catch per species and % male

juveniles in the catch (% female juveniles follow the same proportions), we now show their lag correlations. In Fig.6 we show the lag correlations between SST and % juveniles in the catch, and in Fig.7 between SST and catch per species. The sharp periodicities complicate the interpretation, which will need the help of a physical-biological model to decide upon which might be the processes related to which lags. Next section is devoted to such an analysis, which seems to support the interpretation that a minimum in SST causes maxima in % juveniles of *P.argus* 3 years later, and *P.laevicauda* 3.5 years later. This is because the positive maxima at 1 year (*P.argus*) and 1.3 years (*P.laevicauda*) lags are too short times to allow for growth from puerulus to juvenile recruits. These juveniles seem to be able to grow to produce a maximum catch 3 years after the peak of a warm event (six years after the peak of a cold event, when they settled, *P.laevicauda*) and 2.2 years after a cold event (5.5 years after the cold event during which settlement took place). On the other hand, maximum total catch at a 4 year lag is the result of the out of phase response of each species to climate oscillations, which is dependent on the biology of each species. This decreases the correlation coefficient.

This can in part be seen in Fig.8, where the correlation between the % juveniles in the catch and the total catch per species is shown. The maximum amplitudes for *P.argus* are at zero lag (juveniles are caught without a chance to grow), and a small fraction 3 years later. On the other hand, *P.laevicauda* positive correlations only appear from 5 years on, with a broad maximum at 7 years lag. This curious result, in addition to the others seen above, seem to point out to the radically different biological response of *P.laevicauda* in relation to *P.argus*, especially its slower responses, which could possibly be the cause of its decreasing trend in the catches.

In all of these correlations the amplitudes look small, but it should be reminded that in analysis of interannual anomalies correlation amplitudes of 0.4 are really quite large. As an example, we calculated the correlation at zero lag between regional temperature and the Puerulus Index (non-transformed) of Pearce and Phillips (1988), from data in their Table 1. The

result was 0.52 for temperature and 0.57 for sea-level, which are quite high.

All of these results seem to indicate that minimum size limits for *P.argus* could probably be increased, to lower the excessive production of juveniles without a chance to participate in the breeding stock, while not bothering so much on curbing the fishing effort.

To make these relations more understandable, we introduce in the next sections a theory of climatic driving of variability in puerlus settlement, which will influence variability in total catch.

4.HYDRODYNAMICS OF CLIMATICALLY-DEPENDENT LARVAL RECRUITMENT

There are at least two ways in which ocean physics might influence the interannual variation in the level of settlement of lobster larvae in coastal habitats: by direct environmental stresses impacting natural mortality, including anomalous wind-driven turbulent resuspension of seafloor sediments in the shallow shelf (Vianna et al.,1991) where nursery areas are located, and by changing larval transport and favourable conditions for settlement through changes in the large-scale ocean circulation and winds. We next examine this latter issue.

4.1. Local Larval Recruitment

The presently proposed methods to tackle the problem of fisheries population dynamics, although having generated a massive literature (see Schnute,1985, and references therein), are all based on "spatially integrated" population dynamics variables.

Although a discussion on the possible alternatives to these theories is beyond the scope of the present paper, there is one formulation that is useful in our context: a local formulation, with the same spirit of classical hydrodynamics, which would be labelled by physicists a "field theory" for fish population dynamics. This type of approach has been used before in plankton ecosystem dynamics, at least since the work of Walsh (1975).

To this end, let us start the discussion by making the simple assumption that, throughout

a large area of the coastal ocean, adjacent to an area where fishing takes place, the number of ovigerous females is of the same order of magnitude at all months of the year. Moreover, let us assume that the average currents within the upper 200m layer of the ocean, in our case the strong western boundary current environment squeezed between the equator and the northeast Brazilian coast, offer a cyclic pathway whereby larvae are able to spend about one year offshore, before returning to the coast. In the next section we present a description of these possible pathways which are compatible with the known circulation of the western equatorial Atlantic, and the zoogeography of Palinurids in the tropical Atlantic (Vianna,1986).

We use then the simplifying assumption that within the fishing area F the larval number density is approximately constant in space, being $n(\mathbf{x},t) \approx n_0(t)$. Obviously, the space-time dependence of the process by which eggs and nauplii are dispersed should be described by a advective-diffusion equation, with the surface number density of ovigerous females as the source term, a subject which will be treated in another work.

The basic larval "continuity equation", which balances the flux of larvae entering a fixed-area by the action of the ocean current $\mathbf{v}(\mathbf{x},t)$ with the rates of growth of the larval number density, subject to a natural mortality coefficient μ , can be written as

$$n_t + \nabla \cdot n\mathbf{v} = -\mu n \quad (1)$$

where the t -subscript denotes the time derivative. We are also neglecting the density-dependent mortality coefficient (see Beverton and Holt,1957, p.48). The current velocity can be determined from the sea-level anomaly field by use of, e.g., the shallow water equations for the description of the ocean dynamics, which implies that velocities and positions are taken as horizontal variables

We can integrate (1) easily by linear perturbations: we assume that $n \approx n_0 + n_1$ and $\mathbf{v} \approx \mathbf{v}_1$. The zero and first order equations are, respectively,

$$\begin{aligned}
n_{0t} &= -\mu n_0 \\
n_{1t} + n_0 \nabla \cdot \mathbf{v}_1 &= -\mu n_1
\end{aligned}
\tag{2}$$

and, integrating between a initial time t_r and a time t , we get

$$n_0(t) = N_0 e^{-\mu(t-t_r)} \tag{3a}$$

$$n_1(\mathbf{x}, t) = n_1(t_r) e^{-\mu(t-t_r)} - N_0 e^{-\mu t} \int_{t_r}^t dt \nabla \cdot \mathbf{v}_1 \tag{3b}$$

This proves that the number of larvae per unit area will be affected by the local current divergence field.

4.2. The Shallow Water (SW) Model for Tropical Ocean Dynamics

The simplest possible model which captures the large-scale wind-driven circulation in the equatorial Atlantic is the SW (or reduced gravity) model with one active layer (Busalacchi and Picaut, 1983; Philander, 1990). Linear hydrostatic motion in this upper homogeneous layer is driven by a windstress τ that acts as a body force. The motion causes variation of the depth of the layer interface, which simulates the thermocline depth, and is described by the SW equations

$$\mathbf{v}_H + f \mathbf{z} \times \mathbf{v}_1 + g' \nabla \eta = \frac{1}{H} \boldsymbol{\tau} \quad (4a)$$

$$g' \eta_t + c^2 \nabla \cdot \mathbf{v}_1 = 0 \quad (4b)$$

with

$$g' = \frac{\rho_2 - \rho_1}{\rho_2} ; \quad c = (g'H)^{1/2} ; \quad h \approx (g'/g)\eta.$$

Here \mathbf{z} is the unit vector pointing vertically upwards, H is the depth of the upper layer, h the sea-level anomaly, g' the reduced gravity and η the thermocline depth anomaly. In this SW theory, the β -plane approximation ($f = \beta y$) is always used. The SST field T in the equatorial Atlantic is not easy to parametrize as a function of η (Houghton, 1991), although it could possibly be parametrized by use of the heat equation (Weingartner and Weisberg, 1991), where the advection of SST gradients is taken into account.

By using (4b) in (3b), we get

$$n_1(\mathbf{x}, t) = e^{-\mu(t-t_r)} n_1(\mathbf{x}, t_r) + \frac{N_0}{H} e^{-\mu t} [\eta(\mathbf{x}, t) - \eta(\mathbf{x}, t_r)] \quad (5)$$

This means that if we have a long term average of N_s larvae available for settlement, by neglecting the first (regional) term in (5), we may write

$$n = N_s (1 + \Delta \eta / H) \quad (6)$$

Equation (5), if integrated over the total fishing area, can furnish order-of-magnitude estimates of this effect on recruitment of juveniles. We can assume that all of the pueruli will become juvenile recruits a few years later. Then it demonstrates, very crudely, that if we have a 20% peak-to-peak change in TD at interannual scales as observed in the western equatorial Atlantic (see Houghton, 1991), we should expect changes of the same order in the percentage of juveniles in the catch a few years later. This is the correct order of magnitude of the observed fluctuations (Fig. 4), with the correct phases, as will be seen below.

Moreover, the number of larvae available for settlement around the position x at time t can be estimated by the measurement of sea-level, a fact discovered experimentally by Pearce and Phillips (1988). Climatic driving of changes in puerulus settlement rates might then happen as the result of variations in availability of late-stage larvae around the settling area due to ocean dynamics, which is directly related to sea-level variability and thermocline depth. In our case, since the SSTA and thermocline depth fields are correlated at interannual scales and have opposite phases, we may use the former as a tracer for the latter, and try to find lag-correlations between population variables and SSTA's (or annual SST's).

The above-described process, however, probably tells only part of the story, with the rest of it to be told by taking into account the full history of the planktonic drift of the animals through the varying current loop cycles. If we assume that it takes around 2-3 years for the puerulus to grow and recruit into legal-sized lobsters, we should expect to find, for a severely fished stock that depends on the new recruits, correlation maxima between present-day catch per species and SST anomalies a few years before. This is what we mean by "climatic driving of lobster catches", a process discovered empirically by the outstanding works leaded by Phillips (see Phillips et al., 1994, and references therein). At the same time, this effect permits us to predict an expected natural trend in the catches from easily measurable physical indicators. This might be a valuable new tool for management, an issue discussed in the last section.

5. NORTH BRAZIL CURRENT RETROFLECTION IN THE SOUTHWESTERN EQUATORIAL ATLANTIC AND A MODEL DRIFT CYCLE FOR PELAGIC LARVAL PHASES

Relatively few work has been published concerning the description of the upper 150m circulation of the southwestern equatorial Atlantic, especially around the upstream portion of the North Brazil Current, which dominates the fishing area offshore. However, the works of Molinari et al.(1981), Molinari (1982), the model results of Schott and Boning (1991) and the

monthly model assimilation and observation program results routinely reported by J.Servain in the French BOAT series are sufficient to give us a picture of this circulation in its equatorial portions, which is radically different from traditional views (Pollock,1990).

The model drift cycle for the larval phases (phyllosomata) of *P.argus* and *P.laevicauda* proposed here starts with entrainment of the newborn larvae into the North Brazil Current (NBC). While *P.argus* breeds at depths greater than 30m, *P.laevicauda* seldom occur beyond 25m. Therefore, entrainment of larvae into the Ekman downwelling transport of NBC water, which retroflects around 03S into the South Equatorial Undercurrent (SEUC) (Molinari, 1982), is more likely. This current occasionally surfaces, probably more so during Atlantic Warm Events. This is consistent with the relative absence of larvae at the surface, as determined by plankton tows in the area (P.A.Coelho, private comm.). The relatively thin SEUC does not reach either Atol das Rocas or Fernando de Noronha south of the Equator, or St.Peter/St.Paul's Rocks, where only *P.echinatus* was found in 1982 (Vianna,1986). On the other hand, quasi-permanent return paths are found, the easternmost portion being around 25W (Molinari et al., 1981; Molinari, 1982). A thin return path would be through the westward central branch of the South Equatorial Current reaching the coast just south of Natal, where a small area known by local fishermen as rich in tuna may indicate the presence of upwelling due to current divergence. A thermal signature of this current has been also detected in a EOF analysis of multiyear SST anomaly data based on the NOAA/AVHRR MCSST weekly product (18x18km grid) for the Atlantic (Vianna and Kampel,1995). The southern portion of this bifurcation would feed the South Equatorial Countercurrent (SECC), which extends to the east in a zonal band between 07S-and 09S. This model suggests two westward current bifurcations, at 6S and 10S (Fig.9).

We will concentrate on circulation at 50-90m depth guided by the above informations, and as described in the BOAT monthly reports (Fig.9c), to get an idea of the possible seasonal variability not detected by the former authors. The proposed current loop seems to have a seasonal cycle at the upper 100m, extending eastwards to 5E between February and May, with

intensification and eastward extension of the SEUC, and intensification of the westward return path in the SEC between June and December, joining the NBC. However, the semi-permanent circulation described by Molinari would be consistent with a natural interannual low-pass filter, which would induce interannual variabilities in catch as dominant in the total variance. In terms of seasonal variability, settlement levels would then have a peak during March-April, when the seasonal wind stress is at a minimum, facilitating the swimming phase of the metamorphosed pueruli (Phillips and McWilliam, 1986). Interannual variability and Rossby waves may, however, cause some meandering and loop closing at different longitudes, reducing the time spent by larvae in the drift cycle. This picture is also consistent with the records of occurrence of *P. argus* around Abidjan in the Gulf of Guinea (Marchal, 1968).

Therefore the cycle may be described in time in the following way:

- (a) After hatching at depths of 30-70m and drifting with the NBC, Ekman downwelling offshore circulation entrains the larvae off the NBC, between 06S and 02S, where part it retroflects at around 02S into the eastward SEUC.
- (b) The dominant presence of *P. echinatus* in Atol das Rocas and the islands of Fernando de Noronha in 1982 (Vianna, 1986), at around 04S, and the more frequent relative occurrence of *P. laevicauda* and *P. argus* observed during the past two years in the latter islands, seem to coincide with a period of more frequent Atlantic Warm Events, which may cause a NBC retroflection more to the south, and a probable spread of the SEUC to the south. However, it seems that the return path in the SEC could possibly be to the south of these islands, usually not crossing them. This picture is unchanged if we consider circulation at 200m depth (see fig. 7 of Schott and Boning, 1991) and is consistent with the fact that there seems to be a minimum population of these two species between 08S and 11S (Vianna, 1986), where the bifurcation of the SEC occurs (due to minimum onshore transport around the stagnation point). However, an appreciable stock to the south of this latitude is found.

These evidences seem then to imply that we should expect to find an almost constant

supply of larvae in the coast between 08S and 02S during all the year round, but subject to the

interannual variability of the south equatorial Atlantic circulation, which accounts to almost half of the total variance of the SST field in the western equatorial Atlantic (Kampel, 1993; Vianna and Kampel, 1995). Discussion of the difficult question of the gene flow in Palinurids occurring in the South Atlantic was only touched upon very recently by Pollock (1990) in relation to *P.echinatus*, but his proposed generalized circulation pattern is not realistic in its southwestern portion. This is a subject that deserves further discussion in future papers.

6. LAG CORRELATION ANALYSIS

The preliminary analysis presented in Section 3 was qualitative, in the sense that the variances associated with each mode of variability, and the variances due to white noise, were not estimated. There are various difficulties associated with spectral estimations for very short time series (order of 20 terms), which can be overcome with good confidence by use of autorregressive (Gangopadhyay et al., 1989) or by use of the more recent Singular Spectrum Analysis of Vautard et al. (1992). For the bivariate case we did not find any method published in the literature which could overcome the type of spurious results which can contaminate the estimates of cross-correlations, even with the use of a large number of data points (see Jenkins and Watts, 1968). In previous articles (Vianna et al., 1994; Vianna et al., 1993, both unpublished), analysis of monthly climatic and lobster tail exports from Fortaleza was presented, with extensive use of Maximum Entropy Spectral Analysis (MESA) and multiple regression analysis to adjust the data in multiple sinusoid expansion models, in a least-squares sense. Although the results obtained are consistent with those presented here, the non-uniqueness of the expansions is a drawback in this method. It depends on the subjective choice of the M-parameter (length of the prediction error filter) in the MESA estimates of the spectral peaks (Press et al., 1994). Calculations of lag correlations were made, but these had to be based in the

method expounded in Jenkins and Watts (1968). The correlation maxima were not very large, with the result that Brazilian fisheries specialists became skeptical as to the importance of these preliminary findings.

Following an entirely different line, we showed very recently that simple and elegant solutions to this problem may be constructed (Peris, 1995; Vianna and Peris, 1995) via the Singular Value Decomposition (SVD) of estimates of the Cross-Correlation Matrix. The method, explained succinctly in the Appendix, has the following advantages and features:

- (a) All input signals are standardized. The "driving" signal, when expanded in terms of the orthonormal column vectors composing the left unitary matrix of the SVD, furnishes an estimate of the noise "plateau", which can be filtered out in the same manner described by Marple (1987). On the other hand, the method is amenable to a Monte Carlo error analysis which may furnish estimates of the true signal at any required level of confidence. The "eigenvectors" exhibit the main oscillation patterns which compose the signal, and the % variance explained by the mode.
- (b) The "driven" signal is analogously expanded with the column vectors of the right unitary matrix of the SVD.
- (c) The right-hand basis vectors are lagged versions of the left-hand basis vectors, showing the relative lags for each of the modes.
- (d) By means of the reconstructed signals, we are able to extract the degree of correlation between the signals, and the percent variance in each signal likely to be involved.

Our objective here is to exhibit a demonstration that the correlations detected qualitatively in Section 3 are not spurious at all. The analysis is applied to examine if and how the catch time series for each of the species might be correlated to previous SST changes. Data is the same as those presented in the Tables above for annual catch and annual average SST's (SSTA's are obtained by subtracting SST's from the total regional average of 27.3 deg. C), but the period used was 73-93 (21 data points), corresponding to better quality data and to what may be called the steady state of this fishery.

For the singular correlation between SST and catches of *P.argus*, we start explaining the results with Fig.10, which shows the singular values in the upper panel, and the energy contained in each of the modes obtained in the expansion (SST in the middle panel, *P.argus* in the lower panel). The pairing of the singular values reflect the existence of periodicities in the data, a result similar to that of Vautard et al.(1992). The noise "plateau" is easily identified visually in all panels, furnishing a first guess on which modes represent a signal and which represent noise. Table 4 gives the "principal components"(PC's), each mode being represented by the product of the PC's by each basis functions of time (Fig.11), denoted by (ϕ). Notice that the high SSTA's around 74 and 85, and large catches centered in 80-81 and 92. The modes reflect oscillations at 11, 5.5 and 3-4 year periods. The original signals are compared with their model expansions with 10 modes in Fig.12a and 12b. The resultant lag correlation function (Fig.12c) shows a large negative maximum at 2-3 years of lag with a value of -0.44. Since we have shown that the catch is incident mostly in the juvenile strata, this result is suggestive of increases in catch 2-3 years after a cold event, which probably corresponded to increases in puerulus settlement coinciding with a deeper thermocline. By the same token, sharp decreases in catch should be expected 6-7 years after a cold event, as the recent one centered around 1992, corresponding to the highest lag correlation of almost 0.6. This would then imply expected low catches of *P.argus* around 1998-1999, having nothing to do with fishing effort.

Corresponding results for *P.laevicauda* are shown in Figs.13-15 and Table 5. The expansions are different from the ones obtained for *P.argus*, where for the latter the SST representation has a faster convergence. Fig.15c shows the lag correlation function. The most suggestive interpretation for the maximum of 0.59 at a 3 year lag seems to be a large correlation between a warm event, which would be simultaneous with increases in settlement, and increases in catch 3-4 years later. This species has a depth range of 5-25m, and personal observations by one of us, who worked as a fisherman for several years (M.L.V.), indicates that settlement occurs shoreward of coral and rocky reefs, well protected from wave-induced turbulence (see Vianna et al., 1991). Warm events seem to coincide with low catches, and we interpret the -0.41 correlation at zero lag as

an indication that at the time of a new maximum in puerulus recruitment the stock of *P. laeviscauda* is depleted, to be recovered only 3-3.5 years later.

Singular Correlation Analysis for the total catch is presented in Figs.16-18. The phase mixing between species renders the basis functions not so regular in terms of component periodicities. The Correlation Function indicates larger catches during cold events, and also lower catches 4-7 years after. The interpretation is not unique due to the oscillatory behaviour of the forcing climatic variables. We can also expect that between 4-7 years after the peak of a warm event, catches should be larger.

7. DISCUSSIONS AND CONCLUSIONS

The above results show unequivocally that one cannot statistically model the population dynamics of the northeast Brazilian spiny lobster fishery without including the second moment structure of the fisheries data, which seems to be strongly driven by climatic fluctuations. Moreover, these results, including the Effort x Yield curve (Fig.3) based on whole lobster weights, demonstrates that any analysis based on first moment modeling, especially the simple models based on hypothesis that the stock-recruitment relationship is known (e.g., of Schaeffer type), gives misleading directions for management. We mention also that the total stock is unknown and difficult to determine, and this fact renders the application of these models even more artificial. Their use did not show any predictive potential either: based on them, the catch recoveries always came out as a surprise.

The fact that significant correlations exist between catch per species and SST, the latter leading the former, unequivocally indicates that fisheries predictions can only be achieved if these correlations are taken into account. Of special significance is the different responses of each of the species to environmental forcing, the theoretical basis of which was only touched upon for the first time in the present paper. We should at this point mention that these findings are consistent with present-day knowledge of spiny lobster fisheries dynamics in general (Phillips et al.,1994), and the use of both a size-structured model and climatic correlations in the Hawaiian spiny lobster fishery demonstrated the predictive capabilities of a model which only uses the latter (Polovina and Mitchum,1992).

Since the main task of management is to guarantee the sustainable operation of the fishery, which means that its main scientific goal is to predict evolution, the above findings cannot be ignored. The lack of application in Brazil of the more recent size-structured models, which could be used in conjunction with the climatic correlations (Polovina and Mitchum, 1992) and having predictive capabilities, is at the root of the increasing socio-economic problems yet unsolved in this fishery. The present work was designed to stimulate new approaches to the management problem (especially a recommendation to drop MSY-based arguments), and to suggest some new lines of investigation and data collection which are important both to science and management.

The study of correlations between the SST field (used as a climatic index) and the catch gave the following results:

1. For *P. argus* (Fig.12c) a first negative maximum at lags of 2-3 years is related to recruitment of juveniles being large 2 years after cold events. A positive maximum at lags of 6-7 years could mean decreases in catch 6 years after cold events, or increases in catch 6-7 years after warm events. The scale of 7 years is consistent with the findings of Harris et al. (1988) in Tasmania for *Jasus edwardsii*.

2. For *P. laeviscauda* (Fig.15c) the positive maximum at 3-4 year lags may be interpreted, with the aid of Fig.6, as corresponding to maximum catches 3-4 years after warm events, when the new recruits are caught.

3. For the Total Catch (Fig.18c), a very broad maximum at 4-7 year lags indicates the effect of phase mixing between species, and interpretation is only possible by using the above results (1) and (2). Analysis of correlations with Total Catch is very dependent on the interval of time chosen for the analysis, but the result seems to be consistent with the predictions of Vianna et al.(1994), based on monthly data, which suggests decreases in catches 4 years after cold events.

4. An important finding is the proof of the dominance of a quasi-periodic behaviour of recruitment around periods of 11-12, 5-6 and 2-3 years, driven by ocean climate fluctuations at these same periods. The 5-6 year period has been reported first by Fonteles-Filho et al. (1988).

5. The existence of a retroflection of the North Brazil Current adjacent to the States of Ceará and Maranhão is felt as a necessary condition for the extreme resilience of this fishery against increases in fishing effort, since it offers a viable conservative route for the larval advective pelagic stages. Larvae would not be lost through a one-way path, but would be able to return after a multi-month drift cycle. However, such conjectures can only be established after measurements of larval content in these suggested current loops are made.

From the results of this study, the following suggestions may be offered to management:

(a) Investment into development of numerical ocean-atmosphere-fisheries prediction model along the lines suggested here, used to estimate the expected space-time dependent puerulus settlement rates.

(b) Investment into development of a Sea-Level Data Bank for the Brazilian coastline, a Puerulus Settlement Monitoring System based on a network of collectors, and a research project to determine the larval drift cycles experimentally by use of deep plankton tows. Towing strategies should take into account the current systems suggested here, especially the NBC retroflection into the SEUC and the Equatorial Undercurrent..

(c) Management should introduce more flexibility in regulations regarding fishing effort, by using a higher employment strategy to take out of clandestinity the absurd 90% of the fishermen active in this fishery. However, management should be more conservative in guaranteeing enforcement of minimum size limits, which should be increased.

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APPENDIX

We define below the Singular Lag Correlation Analysis (SLAG) between two discrete standardized signal column vectors $\mathbf{f} = [f_1, \dots, f_N]^T$ and $\mathbf{g} = [g_1, \dots, g_N]^T$, based on the Yule-Walker biased type of estimator for the lag cross-correlation functions (ccf)

$$C_k = \frac{1}{N} \sum_{n=1}^{N-k} f_n g_{n+k} ; D_k = \frac{1}{N} \sum_{n=1}^{N-k} f_{n+k} g_n ; k = 0, \dots, N-1 \quad (A1)$$

from which we form the correlation matrix

$$\mathbf{C} = \begin{bmatrix} C_0 & C_1 & \dots & C_{N-1} \\ D_1 & C_0 & \dots & C_{N-2} \\ \vdots & \vdots & \ddots & \vdots \\ D_{N-1} & D_{N-2} & \dots & C_0 \end{bmatrix} \quad (A2)$$

Singular Value Decomposition (SVD) for this matrix can be obtained by means of the unitary matrices $\mathbf{U} = [\mathbf{u}_1, \dots, \mathbf{u}_N]$ and $\mathbf{V} = [\mathbf{v}_1, \dots, \mathbf{v}_N]$, and a diagonal matrix

$\mathbf{\Lambda} = \text{diag}(\lambda_1, \dots, \lambda_N)$, such that $\mathbf{C} = \mathbf{U} \mathbf{\Lambda} \mathbf{V}^T$, where superscript T denotes the transpose as usual. After the decomposition is obtained (we used the *Mathematica* software), we use the column unit vectors of \mathbf{U} and \mathbf{V} as basis vectors to expand \mathbf{f} and \mathbf{g} respectively:

$$\mathbf{f} = \sum_{n=1}^L \alpha_n \mathbf{u}_n ; \mathbf{g} = \sum_{n=1}^L \beta_n \mathbf{v}_n \quad (A3)$$

where $L < N$ is chosen by examining the percent energy explained by each mode. This is done by reordering the mode sequence by decreasing energy, truncating the sum just above the noise plateau, where the energy of the $(L+1)$ mode is about the same as the energy of each of the other $N-L$ -modes. Separation of signal from noise by this method follows the analysis of Marple (1987).

The unit vectors represent the basic waveform components, and in our case they are sometimes sinusoidal, with \mathbf{u} 's and \mathbf{v} 's corresponding to the same λ being lagged versions of each other. Once the number of modes L is chosen, one may reconstruct the signal with the noise filtrated out, and then calculate again the ccf through (A1).

Exercises with random noise signal inputs revealed, as expected, very low amplitudes for lags different from zero, forming the "plateau", and flat first mode \mathbf{u} and \mathbf{v} . See the text examples, illustrating this simple method of correlation analysis.

FIGURE CAPTIONS

Fig.1. Brazilian Yearly Catch (per species and total, see Table 1) in whole lobster weights (1965-1990 from IBAMA, 1994, with data in 1991-1993 obtained from more recent unpublished GPE reports).

Fig.2. Main fishing grounds (which we label as Zone 1) over the continental shelf between the Equator and 9S. About 2650 boats fishing lobsters are based in this region. The fishery extends down to 22S, but only around 460 boats are estimated as operating in lobster fishing south of 9S. The shaded areas correspond to the 2x2 degree grid for the Servain data set used to calculate the average SST for the region (SST-Zone 1).

Fig.3. Plot of the Total Yearly Catch (tonnes of whole lobster weight equivalent) against estimated Effort in equivalent millions of trap-days. Data from Table 1. The striking asymptotic steady state average behaviour is qualitatively different from the parabolic-type curve of Maximum Sustainable Yield models. With the fluctuations shown to be due to climatic forcing, this plot indicates that fishing effort is not yet a critical problem in the usual sense.

Fig.4. Relative frequency of occurrence of juveniles in the total catch of males for each species, 1974-1987. The result for females is quite similar. Data from Table 2, adapted from Fonteles-Filho et al. (1988).

Fig.5. Time series of annual means for SST Anomalies for Zone 1($SSTA = SST - 27.3$). The total average SST is 27.3 deg.C. Based on monthly gridded data from the Servain data set, averaged spatially for Zone 1 as indicated in Fig.2, and recorded in Table 3.

Fig.6. Qualitative behaviour of the lag cross-correlation function (ccf) between SSTA from

Table 3 and % juveniles in catch from Table 2. The latter data has been "slided" against the whole of the SST data (expectation value used a constant number of terms). Periodicity in ccf complicates interpretation, but the negative maxima for *P.argus* (3 years) and *P.laevicauda* (3.5 years) suggests interpretation that juvenile recruitment maxima correspond to maximum settlement of pueruli during cold events 3 (3.5) years earlier for *P.argus* (*P.laevicauda*), the positive maxima corresponding to the fact that warm events follow cold events about 1-1.5 years later in the Equatorial Western Atlantic.

Fig.7 Qualitative behaviour of the lag correlation between SSTA and Catch per species. Negative maximum at a lag of 2 years is consistent with the interpretation that 2 years after the peak of a cold event catches attain a maximum (*P.argus*), while 3 years after it catches reach a minimum (*P.laevicauda*). The opposite case based on warm events would imply low catches 2 years after (*P.argus*), and high catches 3 years after (*P.laevicauda*).

Fig.8. Qualitative behaviour of the lag correlation between % of Juveniles in the Catch and Total Catch. The maximum at lag zero may be interpreted as an indication that the lobsters are caught immediately as recruits, having been depleted completely for the next season, when large catches correlate with minimum % Juveniles (*P.argus*). The negative maximum at zero lag indicates that highest catches correlate with minimum presence of juveniles, and minimum catches correlate with maximum recruitment (*P.laevicauda*).

Fig.9. Ocean circulation in the southwestern equatorial Atlantic at 90-140m depth interval. (a) numerical model results for seasonal (february) circulation at 133m depth by Schott and Boning (1991): notice retroflection of the North Brazil Current (NBC) starting at 40W, close to Fortaleza, the strong Equatorial Undercurrent and the almost total retroflection of the NBC attained at 45W. (b) Same, but for August: notice the almost total retroflection at 40W, and the strong South Equatorial Undercurrent south of the Equator. (c) ORSTOM model assimilation results for July 1990 (BOAT,1990), for circulation at 90m depth: results are representative of the same phenomena during other years, tying in with results from other authors. Notice the

return flow cell at 25W, and a weak bifurcation of the South Equatorial Current on the coast around 6S; 35W. (d) Synthesis: probable circulation cells supporting the replenishment of the spiny lobster stock in Zone 1-loss of larvae through the westward cross-equatorial flow of the NBC should be quite small according to this view.

Fig.10. Singular Lag Correlation (SLAC): singular values for the SVD of the SLAC matrix for SST leading total catches of *P.argus*. Singular values in increasing order of modes, which correspond to decreasing order of periods; the presence natural sinusoids is detected by the occurrence of pairs of modes with almost equal singular values (upper panel); squared PC expansion coefficients or energy per mode for SST, with mode number indicated (middle panel) and energy per mode for catch (lower panel). Notice the strong convergence in the energy expansions, and the low-level noise plateaus.

Fig.11. Most important basis functions for the SLAC between SST and catch of *P.argus*. (a) First mode is a 11-12 year period oscillation, and we interpret the low SST component of 1979 as leading the low catch component of 86-87 by 6-7 years, and also the high catch component of 1980; (b) second important mode (mode 4) is a 5.5 year oscillation, one of the interpretations being that negative SST's are leading positive catch by about 5 years; (c) third most important mode (mode 5) is a triennial oscillation, with the same ambiguities for the interpretations for the possible lags.

Fig.12. Reconstruction of the original signals from the first 10 modes with highest energies: (a) for SST; (b) for catch; (c) SLAC based on the first 10 modes, suggesting that increases in catch correlate with negative SSTA's 2-3 years earlier, which is consistent with Fig.7, and positive SSTA's 6-7 years earlier.

Fig.13. Singular Lag Correlation (SLAC): singular values for the SVD of the SLAC matrix for SST leading total catches of *P.laevicauda*. Singular values in decreasing order of modes, which correspond to decreasing order of periods, the presence of which are detected by the occurrence of pairs of modes with almost equal singular values (upper panel); squared PC expansion

coefficients or energy per mode for SST, with mode number indicated (middle panel) and energy per mode for catch (lower panel). Notice the strong convergence in the energy expansions, and the low-level noise plateaus.

Fig.14. Basis functions for SST and catch of *P.laevicauda*. Most important modes are modes 1 (a) and 2 (b), both with a 12 year period, and mode 4 (c), with a 5 year period. Phase lags have the same ambiguities in interpretation as shown in Fig. 11.

Fig.15. Signal reconstruction with the first 10 modes for SST (a) and catch of *P.laevicauda* (b); corresponding SLAC, which is consistent with Fig. 7.

Fig.16. SLAC analysis for Total Catch (analogous to Fig. 13).

Fig.17. Three most important basis functions, where the first one is the clear 12 year signal, while the other two are quite irregular: they are sensitive to the phase mixing between each of the species response, which is a good indication of the sensitivity of the method and the reality of the periodicities.

Fig.18. Signal reconstruction with 7 modes: (a) for SST; (b) for total catch; (c) SLAC, showing a positive maximum at 4-7 year lags, consistent with the interpretation that catches are higher 4-7 years after warm events, and lower 4-7 years after cold events, which makes sense when we notice that a typical warm (cold) event lasts about 3 years in the southwestern equatorial Atlantic.

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Table 1: Annual catch per species and total annual catch (whole lobster-tonnes), with corresponding estimates of effort in equivalent trap-days (in millions); from IBAMA(1994)

years	P.argus	P.laev	total	effort
65	2826	581	3507	3.15
66	2614	628	3242	4.04
67	2514	600	3114	4.45
68	4467	1069	5536	8.3
69	6310	1514	7824	13.86
70	6752	1627	8379	14.51
71	5783	1391	7174	14.69
72	6880	1655	8535	22.38
73	6369	1528	7897	27.27
74	7859	1372	9231	25.6
75	5606	1073	6679	24.1
76	3583	3368	6951	26.4
77	5268	3033	8301	28.76
78	6260	3639	9899	29.82
79	7826	3207	11033	36.99
80	6218	1805	8023	32.09
81	7331	1508	8839	36.53
82	7426	1358	8784	41.25
83	4057	952	5009	31.31
84	8189	714	8903	37.1
85	6029	1148	7177	32.62
86	3686	755	4441	37.01
87	4574	2356	6930	38.5
88	5499	1588	7087	39.37
89	5466	1624	7090	50.64
90	7277	1946	9223	51.24
91	8841	2218	11059	36.86
92	7302	1825	9127	53.86
93	6613	1309	7922	68.89

Table 2: percent juveniles in catch < 18cm-per species

	P.laev.(m)	P.argus(m)
74	28	19.6
75	24.8	25.2
76	6	11.5
77	5.6	5.4
78	14.4	6.6
79	24.6	20.2
80	34.4	14.2
81	27.5	15.3
82	19.9	13.2
83	14.4	5.8
84	8.8	1.3
85	23.5	19.6
86	32.7	3.8
87	21.3	5.8

Table 3: yearly Sea Surface Temperature Anomaly (SSTA) for Zone 1(=SST-27.3 deg.C)

year	ann.av.ssta
64	0.31225
65	-0.00775
66	0.16725
67	-0.10608
68	-0.07275
69	0.390583
70	0.15225
71	0.125583
72	-0.28608
73	0.598917
74	0.398917
75	0.108917
76	-0.27775
77	0.07725
78	-0.00108
79	-0.30275
80	-0.18275
81	-0.36942
82	-0.33775
83	0.07225
84	0.43225
85	0.215583
86	-0.23775
87	0.223917
88	0.28725
89	0.01225
90	-0.11442
91	-0.46942
92	-0.60442
93	-0.20442
94	0.085333

Table 4: Principal Components for SST Z1 (alpha) and P.argus (beta) in the Singular Lag Cross Correlation Analysis

n	alpha	beta
1	3.062311	2.561957
2	-0.41074	-0.49292
3	-0.43893	-0.29452
4	2.456946	2.22491
5	1.17759	1.303591
6	-0.73892	-1.30956
7	0.035263	-0.71548
8	-0.44391	0.514208
9	-0.14894	0.077357
10	-0.10103	0.212991
11	0.670299	1.267038
12	0.605673	1.013355
13	0.226357	-0.19229
14	-0.59032	0.277933
15	0.11014	0.787809
16	0.224925	-0.23849
17	0.183312	-0.07924
18	-0.02023	0.266438
19	-0.18079	-0.32598
20	-0.28425	-0.15282
21	0.796742	0.532486

Table 5: Principal Components for SST Z1 (alpha) and *Plaeuicauda* (beta) in the Singular Lag Cross Correlation Analysis

n	alpha	beta
1	2.708495	2.872388
2	-1.73569	-1.93918
3	0.515181	1.052656
4	-2.20359	-1.17587
5	0.108003	0.984327
6	0.051511	-0.53528
7	-0.07393	-0.25306
8	1.406224	1.089224
9	0.362353	0.086207
10	0.487559	-0.14008
11	-0.43293	-0.27267
12	0.110654	-0.59577
13	-0.1786	-0.54365
14	0.411521	0.579203
15	-0.87573	-1.08608
16	-0.20067	-0.20965
17	-0.10617	-0.38939
18	0.080888	0.261358
19	0.910777	0.649335
20	-0.30011	0.139678
21	-0.13582	-0.14267

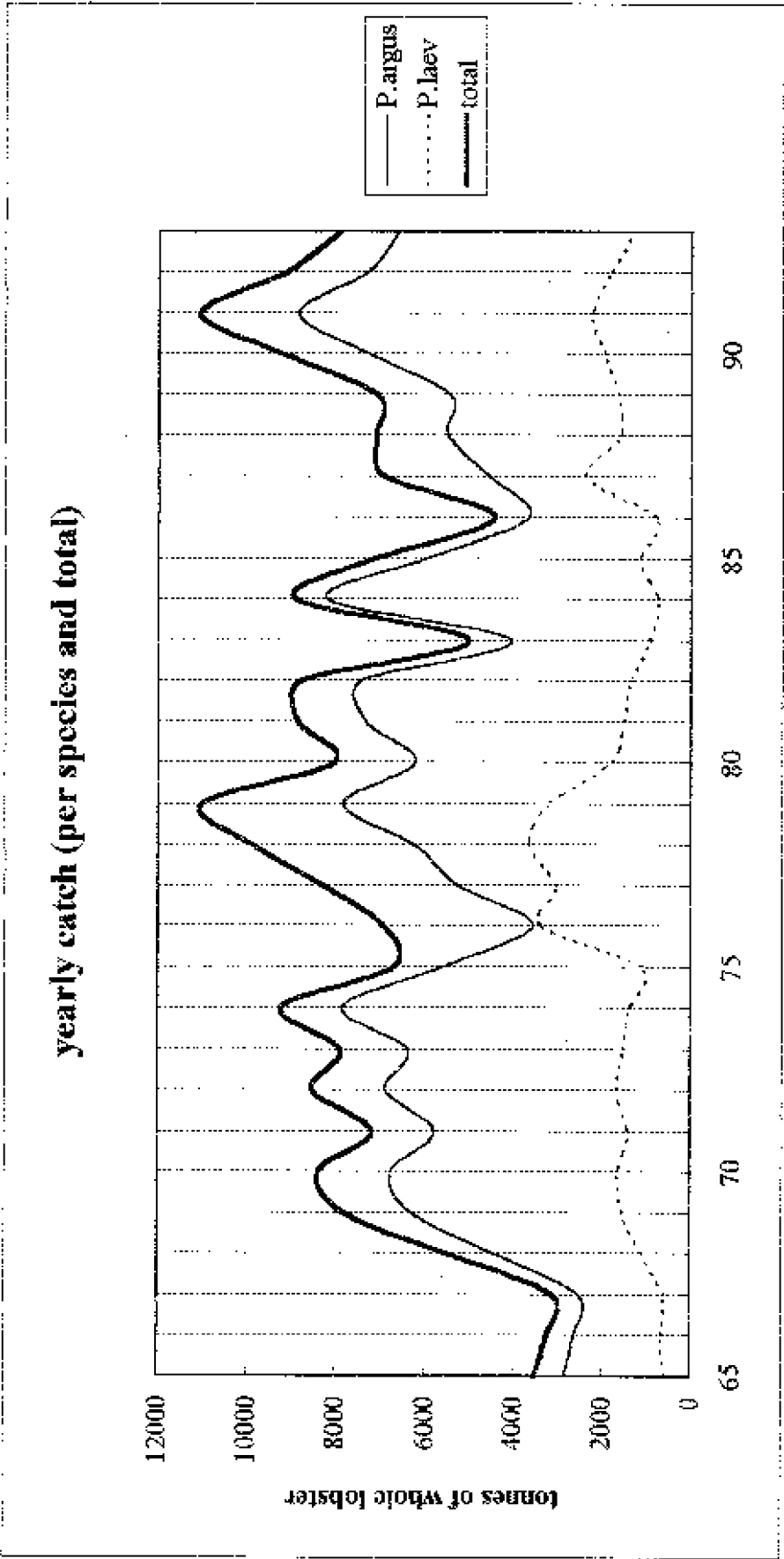


Fig.1

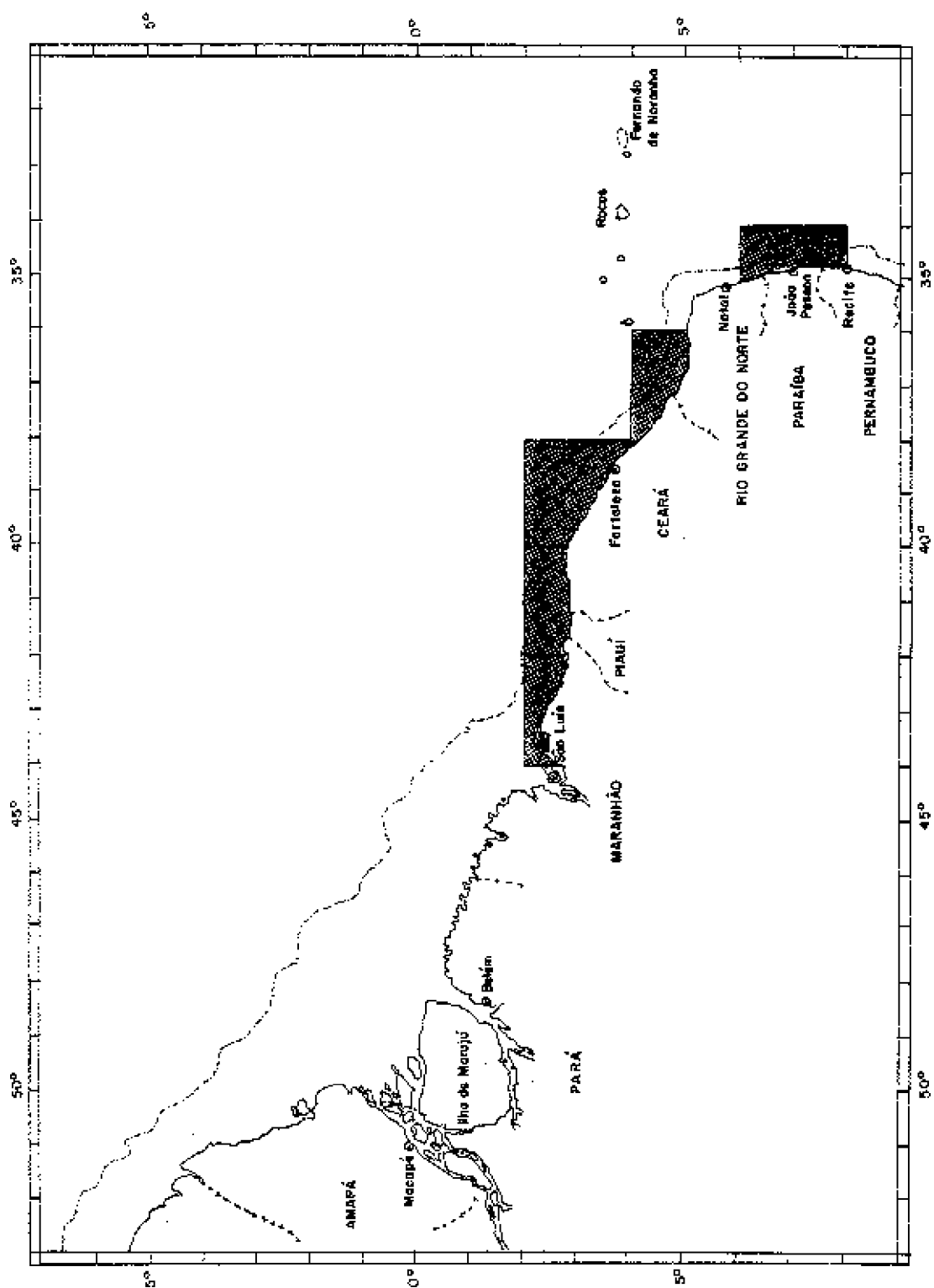


Fig.2

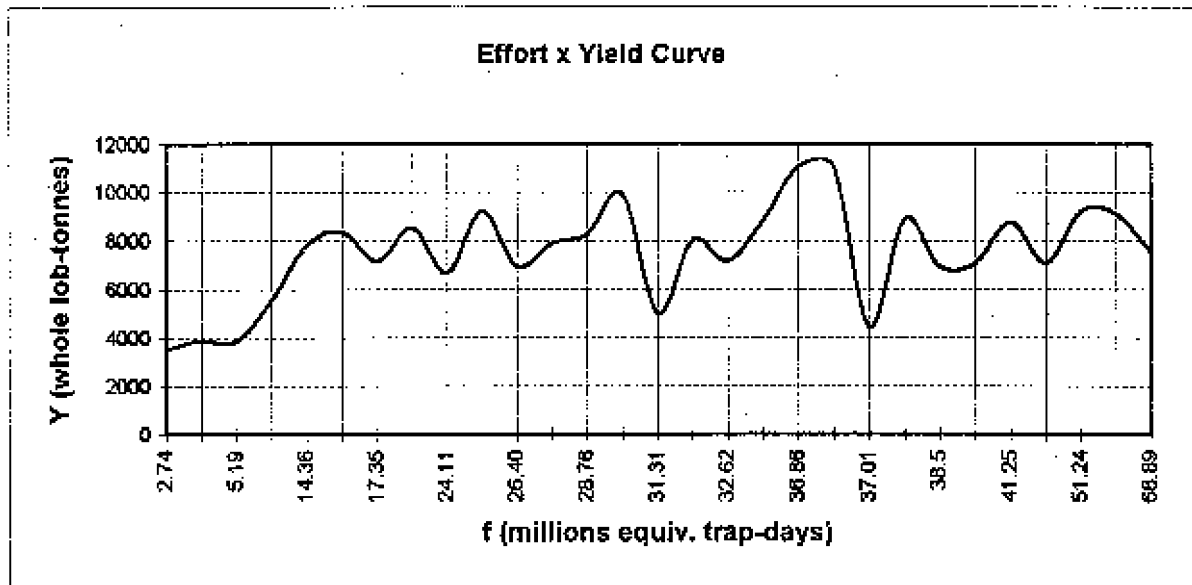


Fig.3

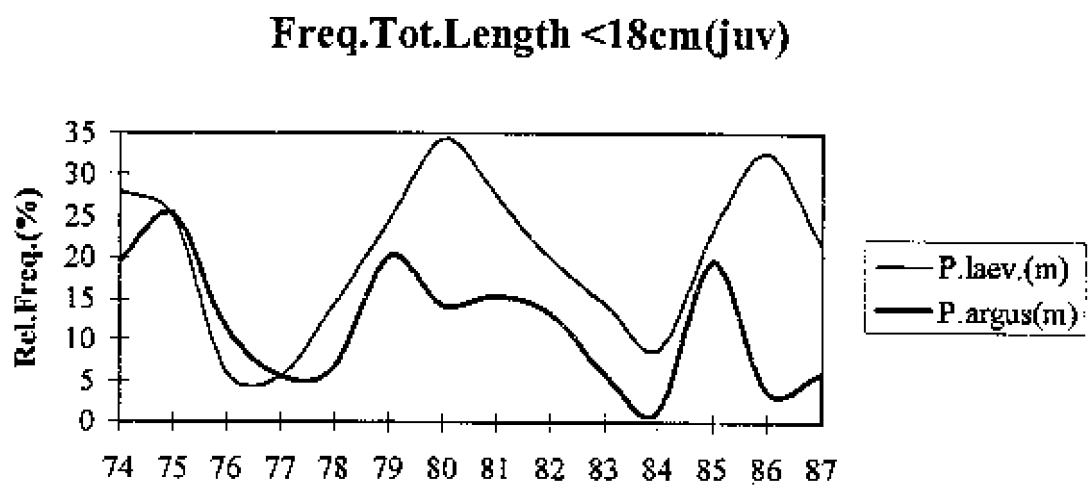


Fig. 4

Annual Mean SST Anomalies

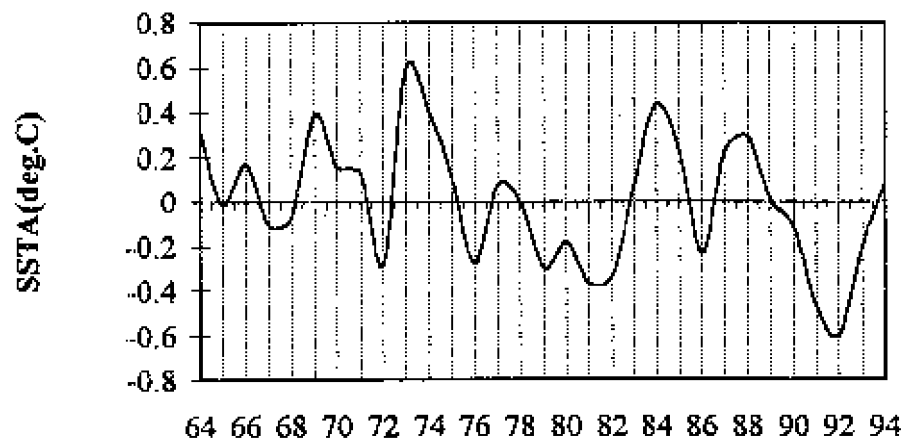


Fig. 5

lag corr ssta x % juv

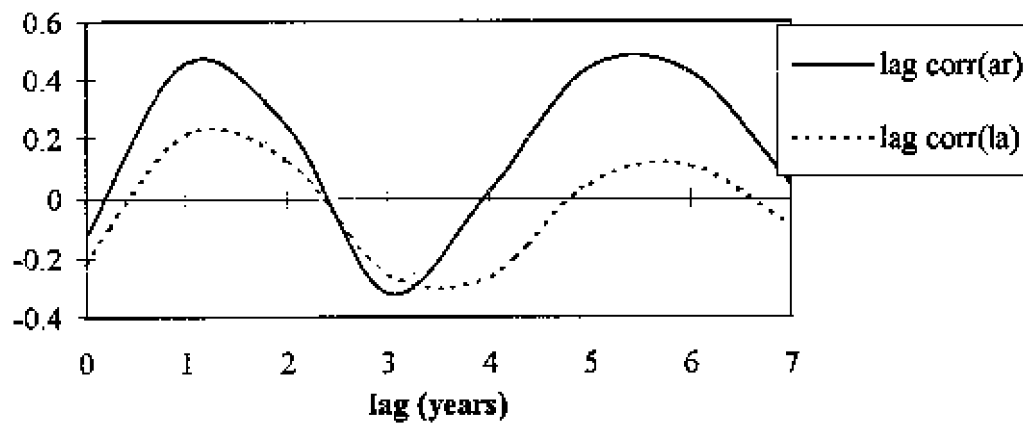


Fig. 6

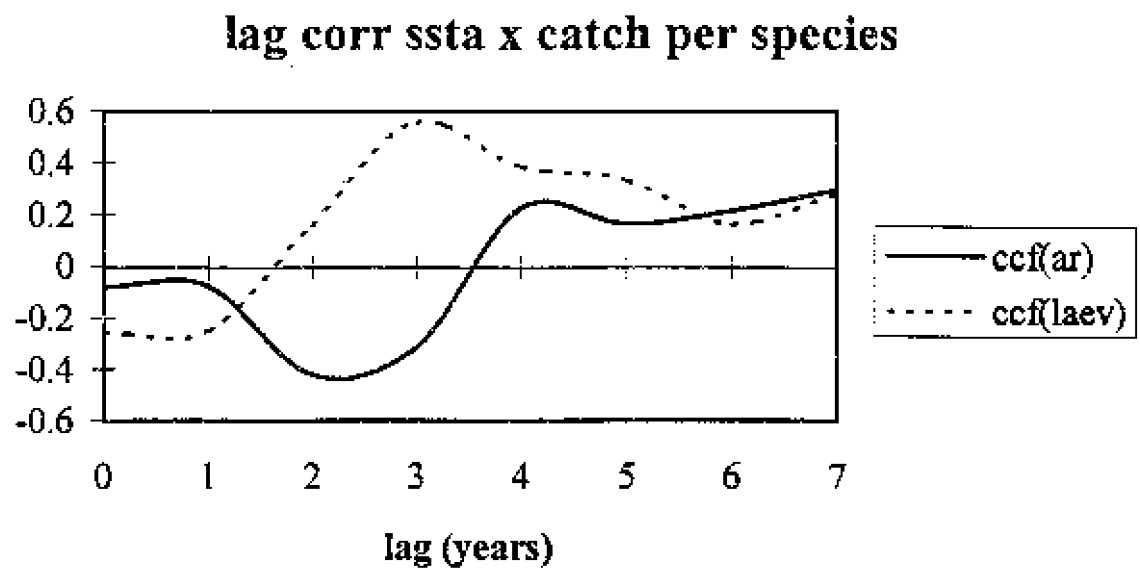


Fig. 7

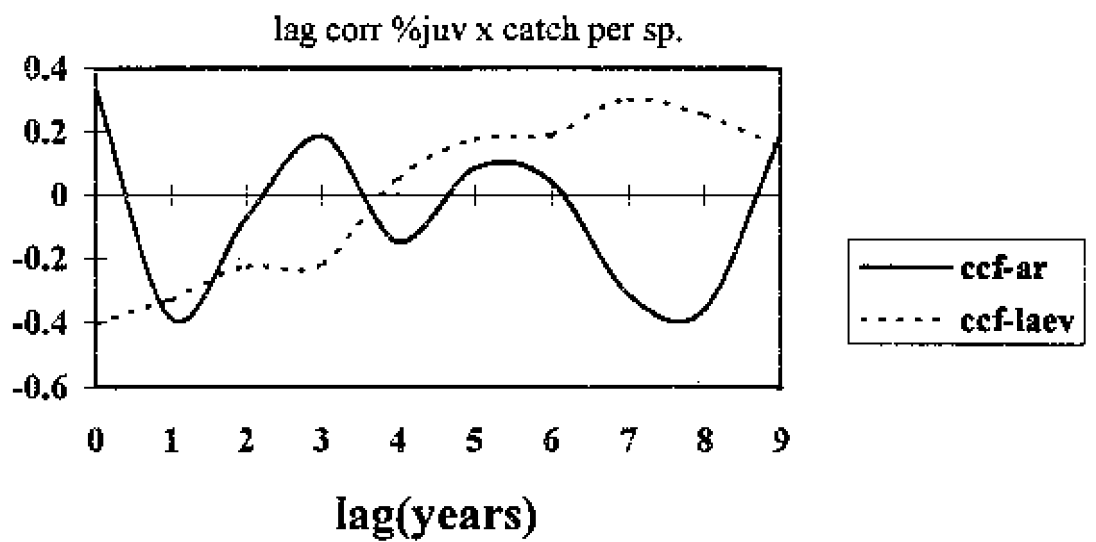


Fig.8

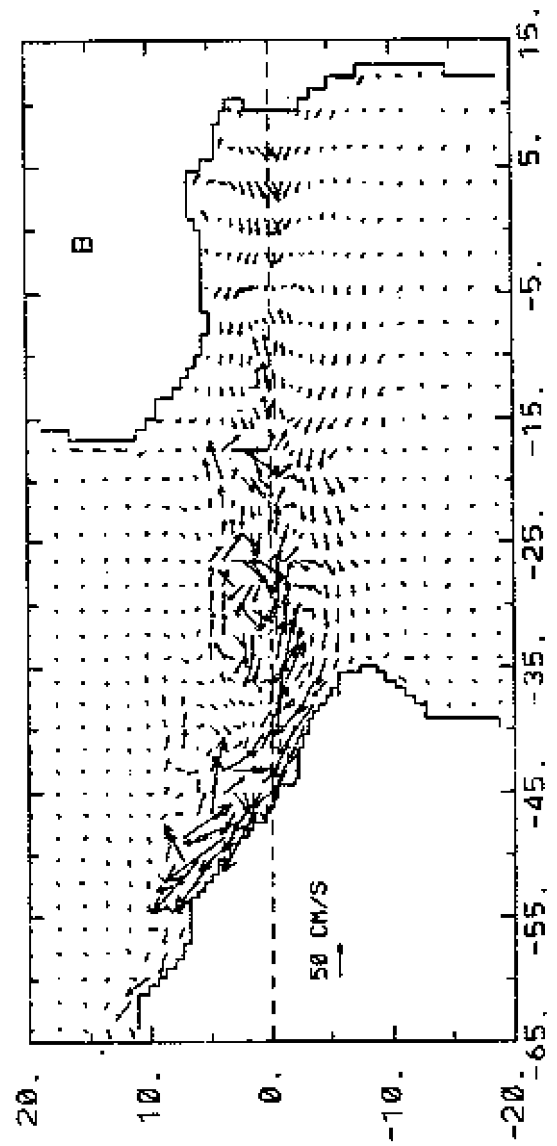
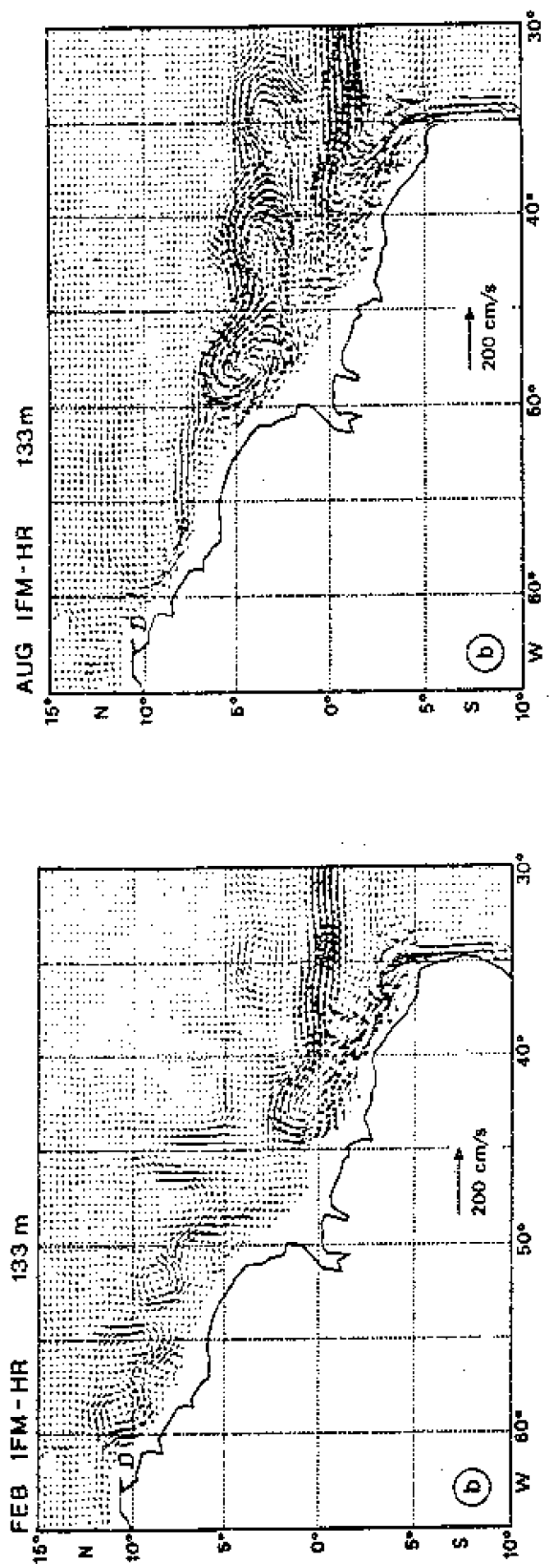


Fig. 9

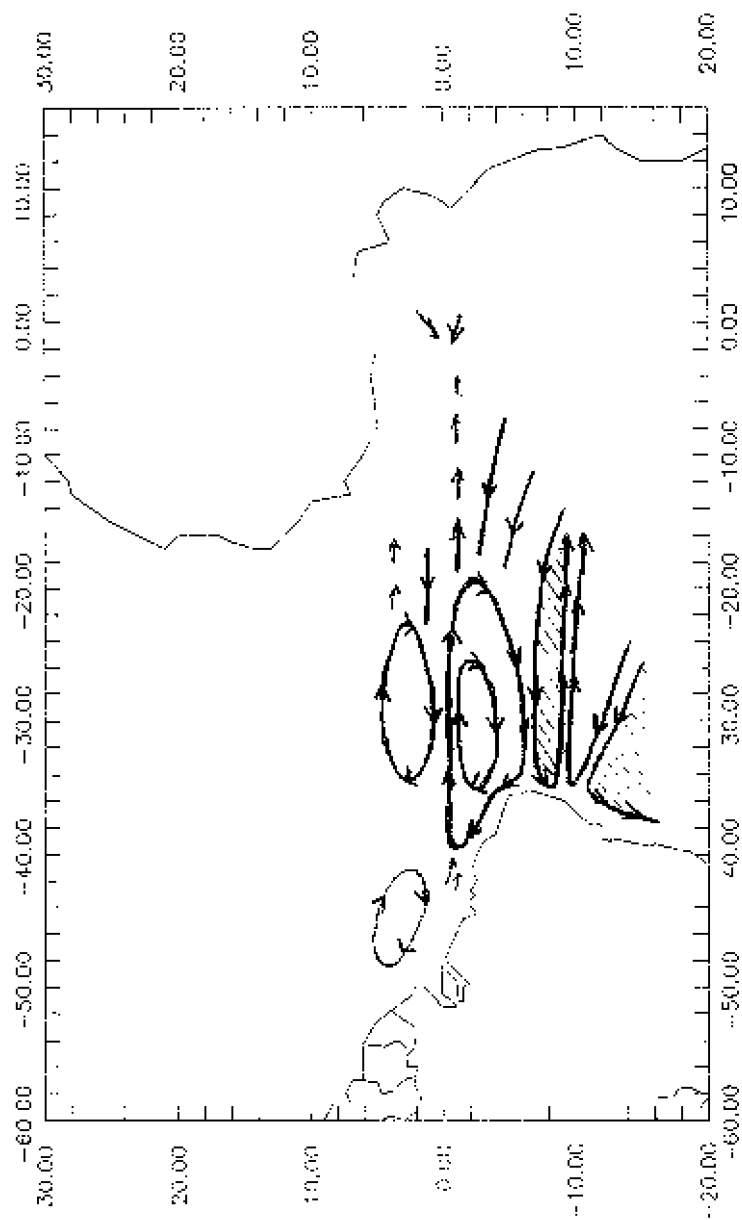


Fig 9 (d)

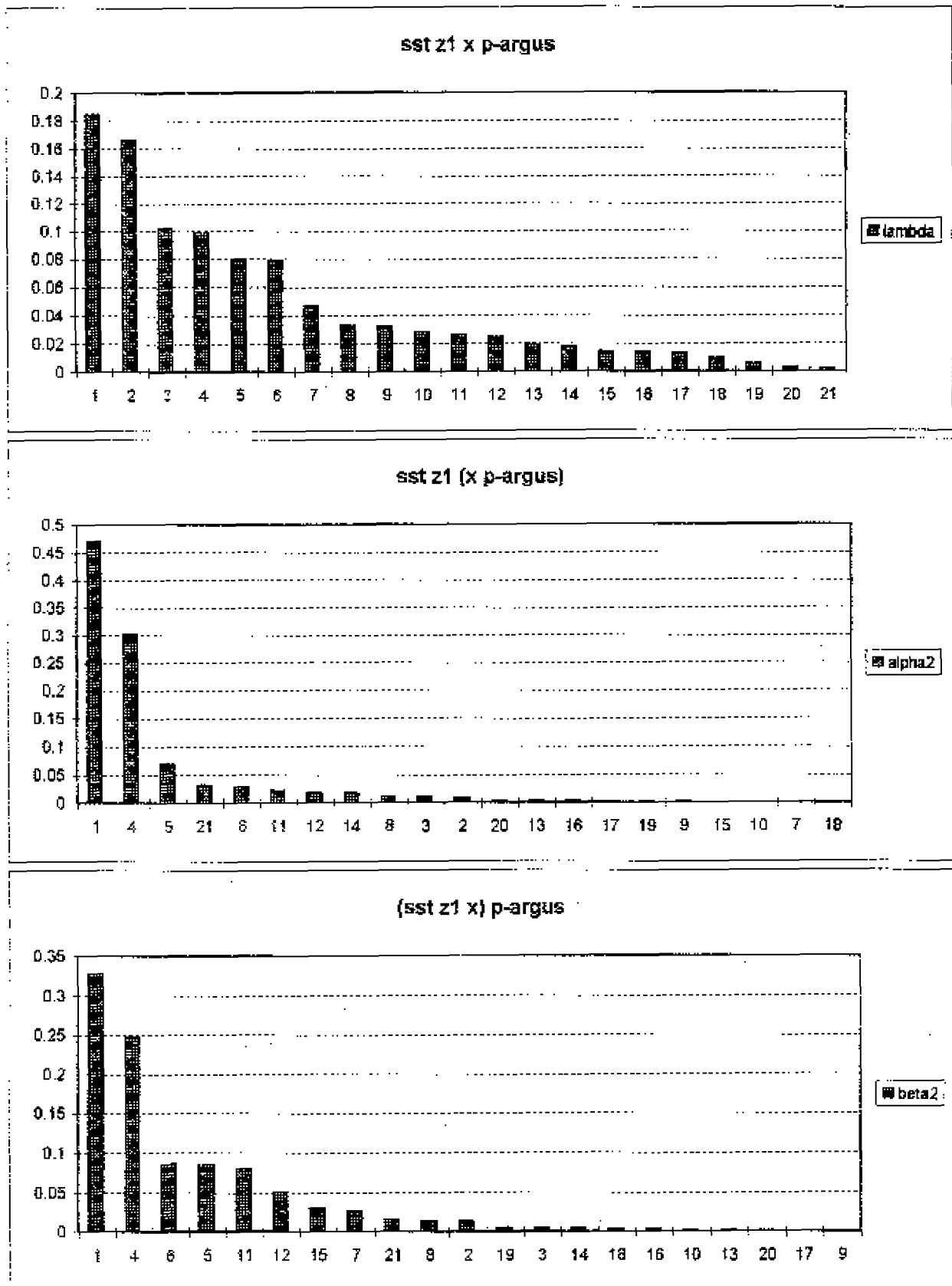
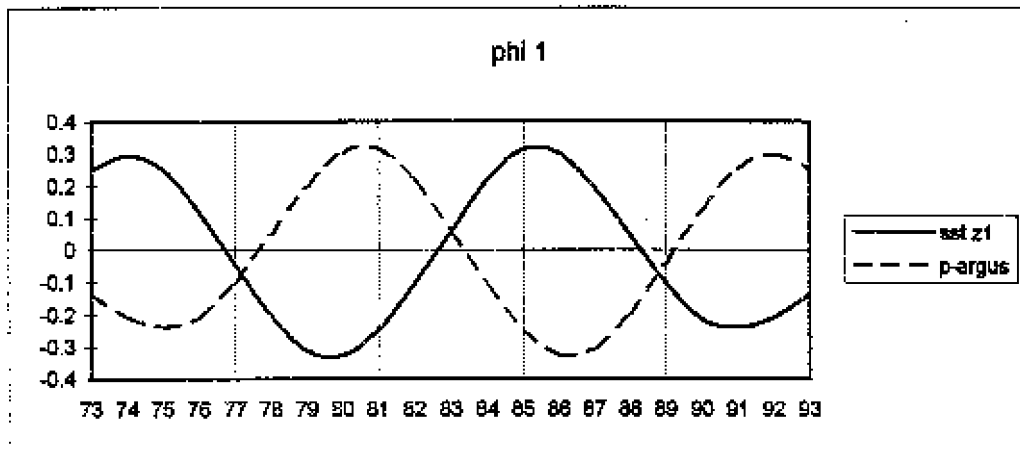
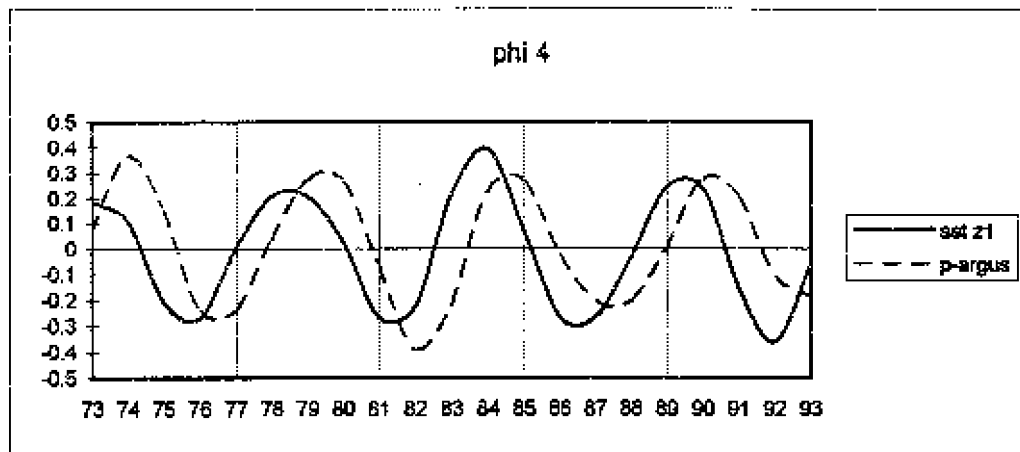


Fig.10

(a)



(b)



(c)

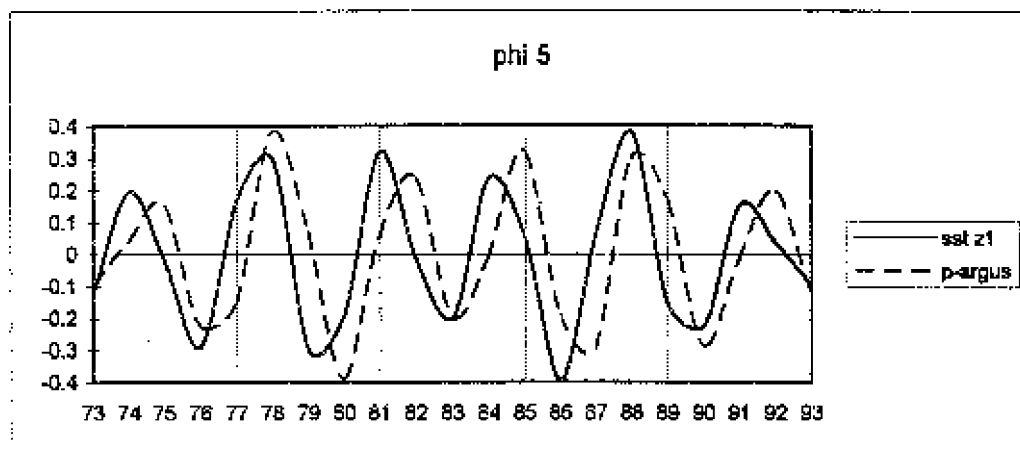
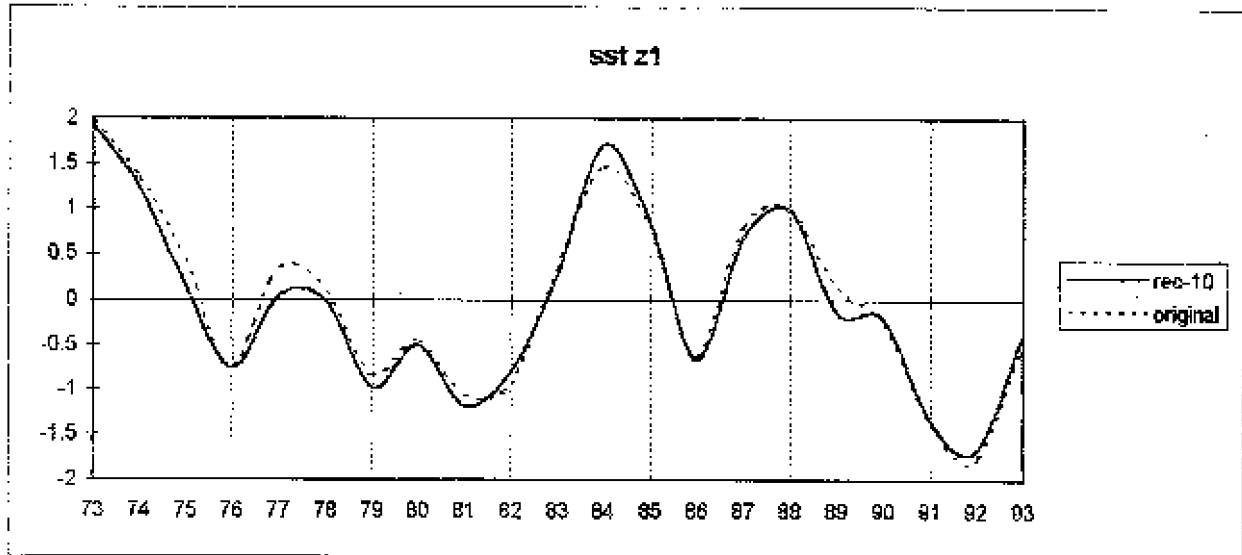


Fig.11

(a)



(b)

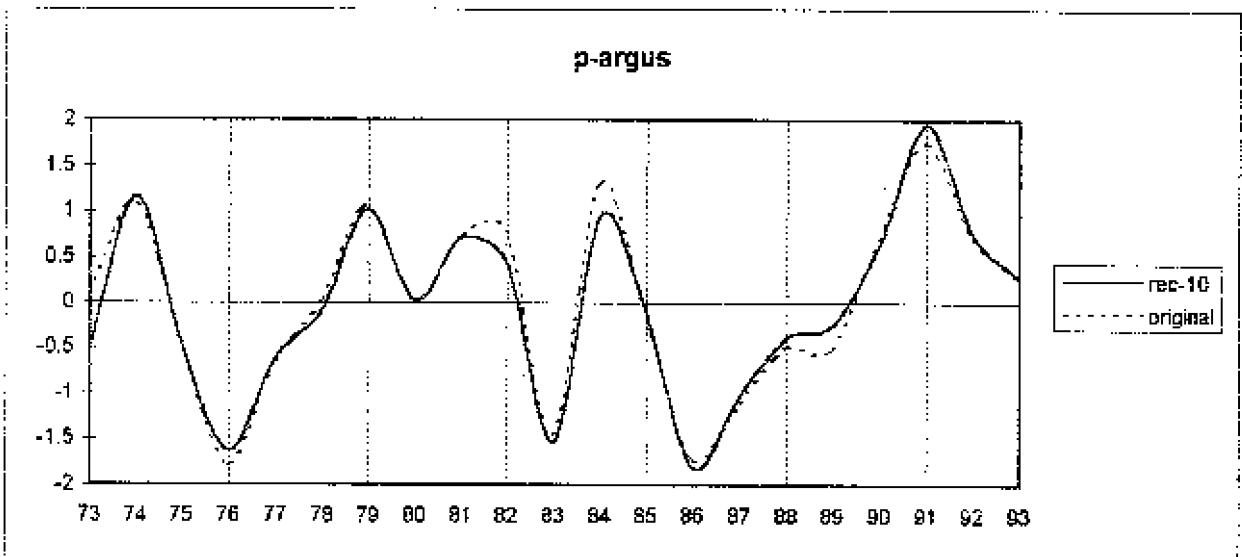


Fig. 12 (a) and (b)

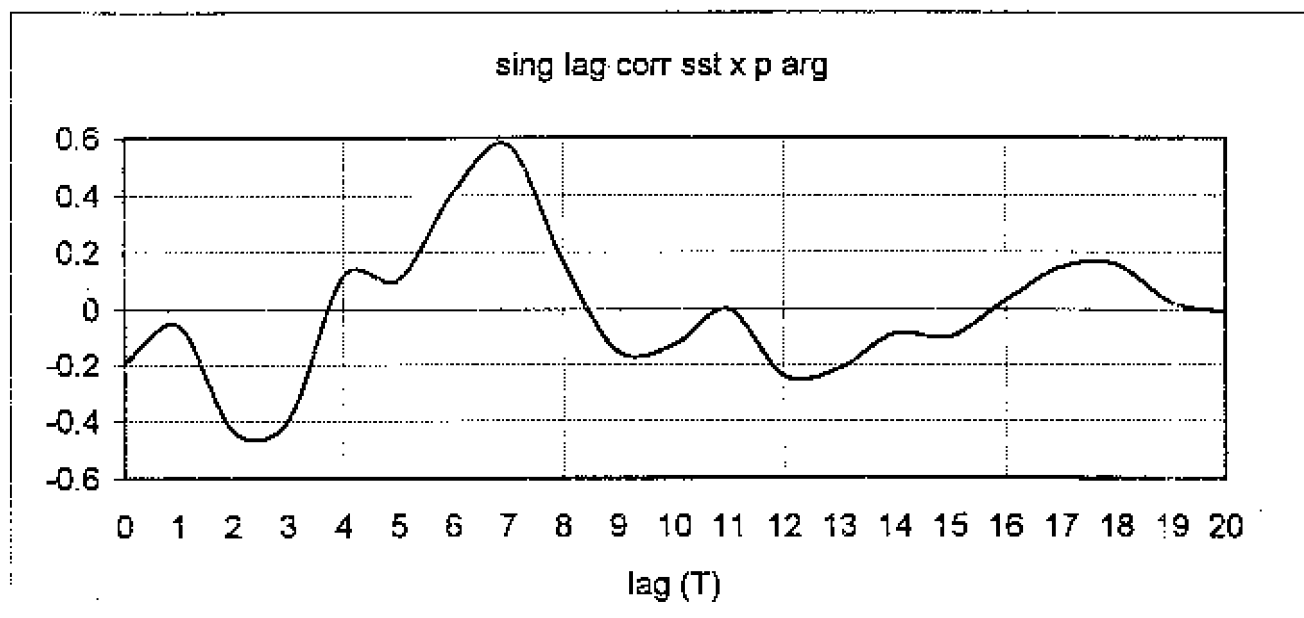


Fig.12 (c)

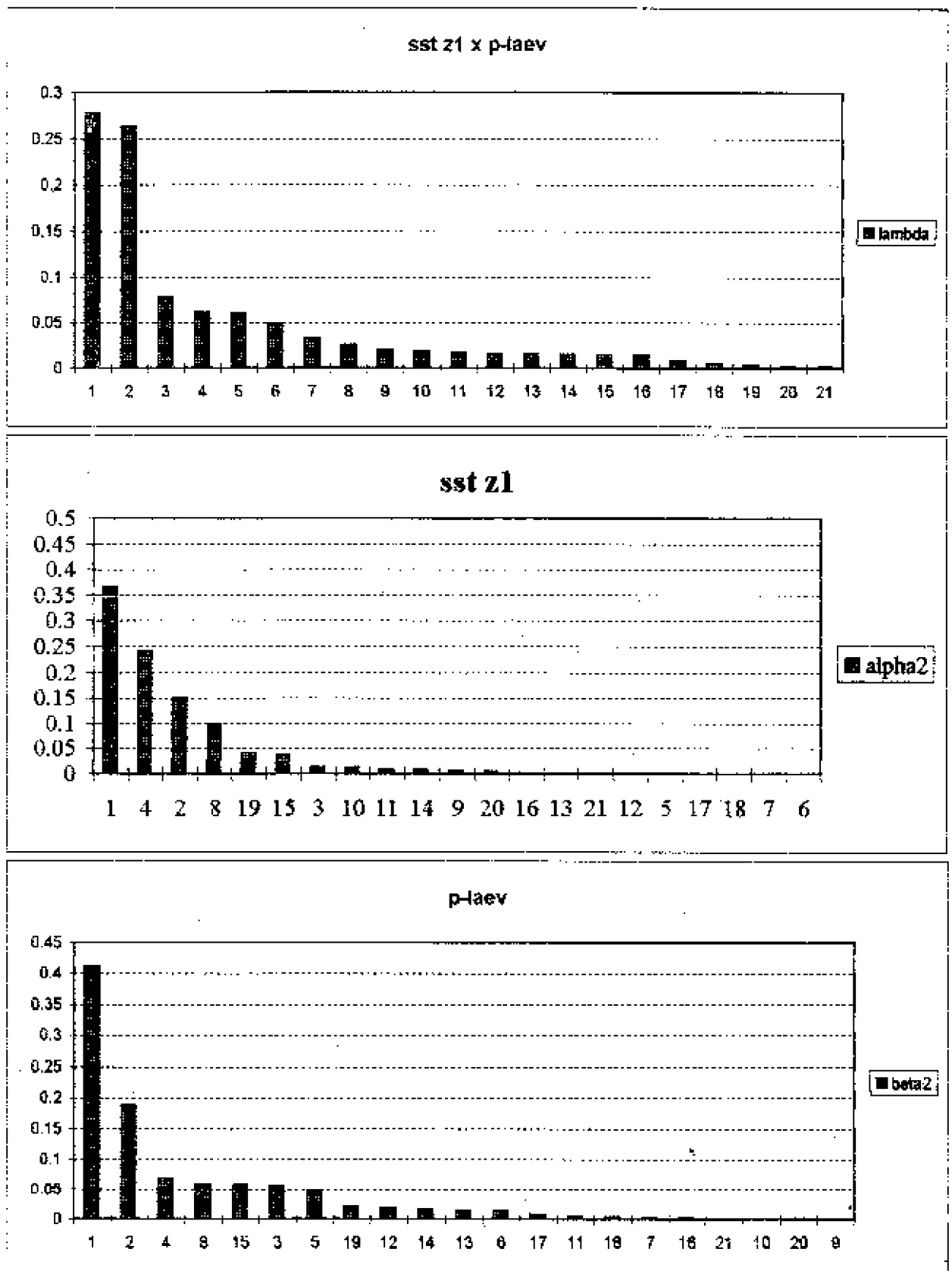
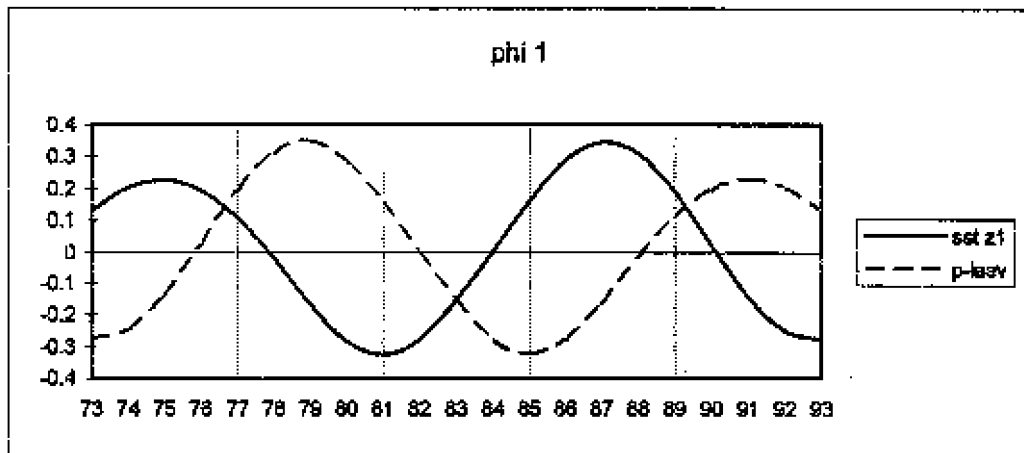
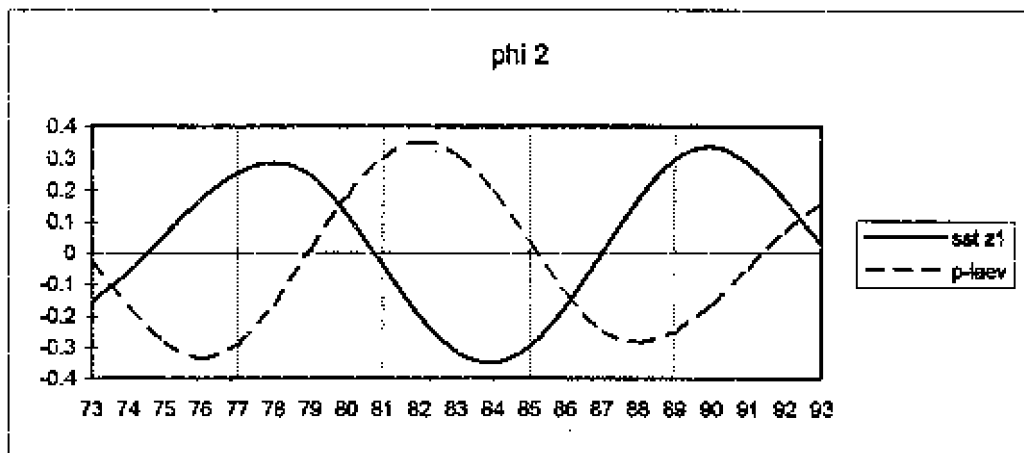


Fig. 13

(a)



(b)



(c)

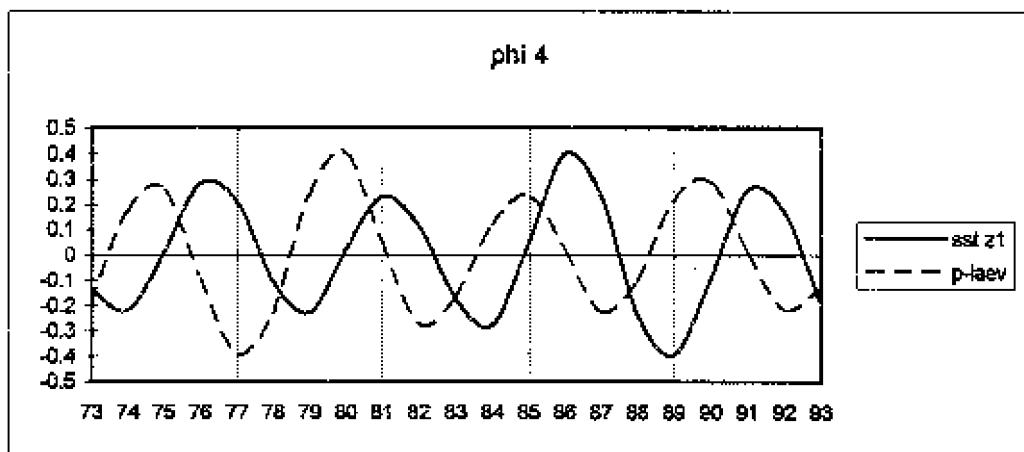
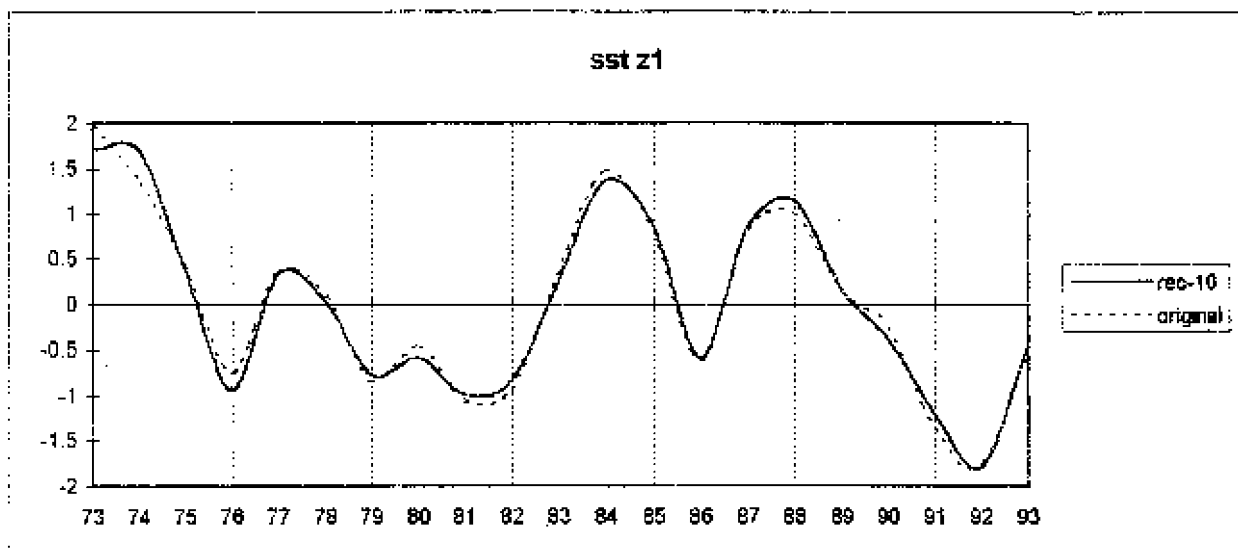


Fig.14

(a)



(b)

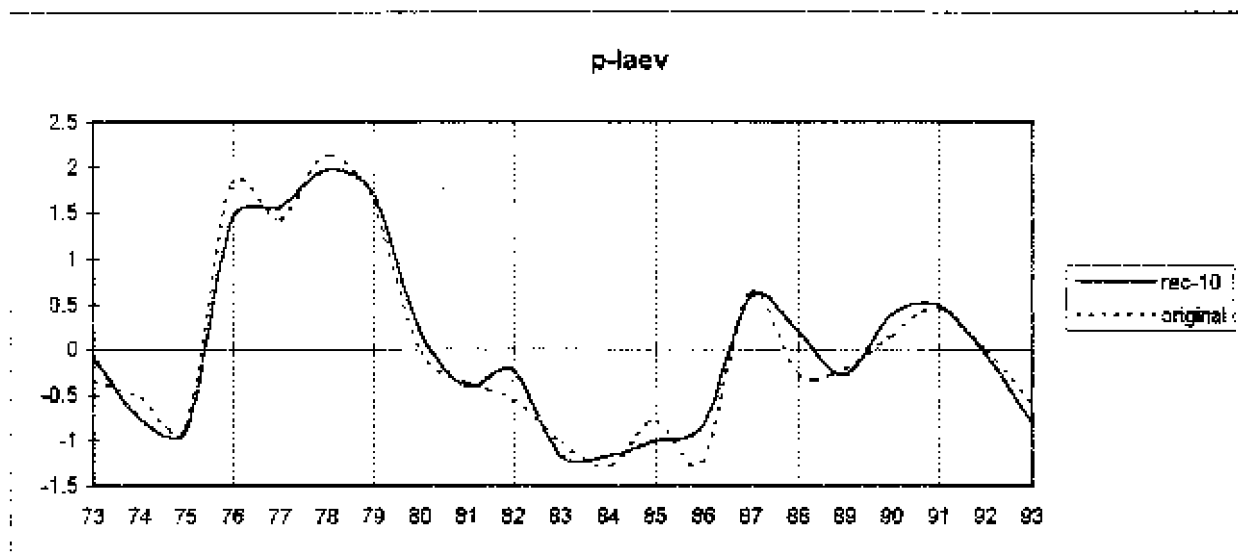


Fig.15

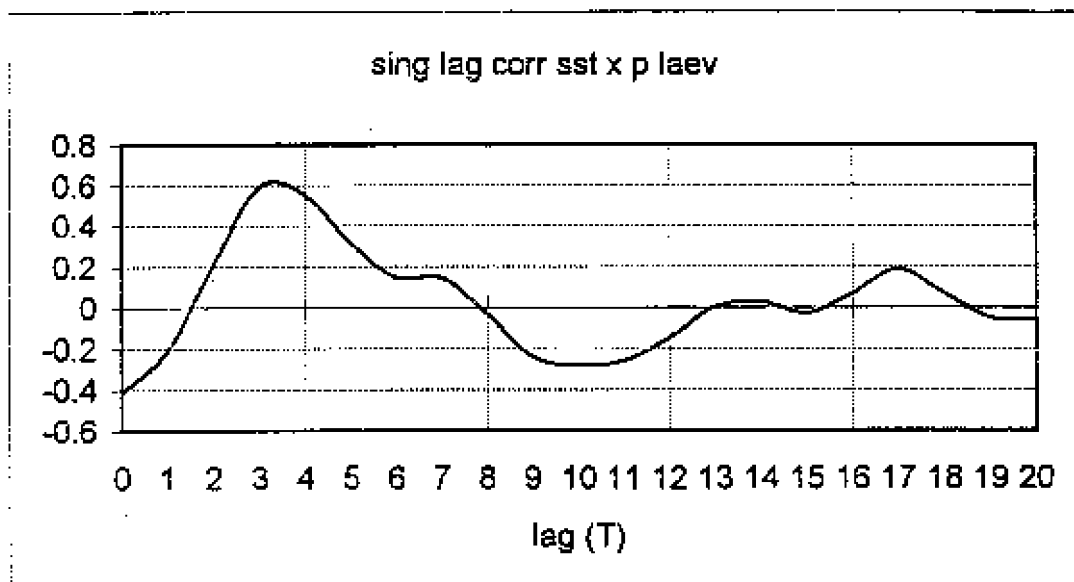


Fig.15 (c)

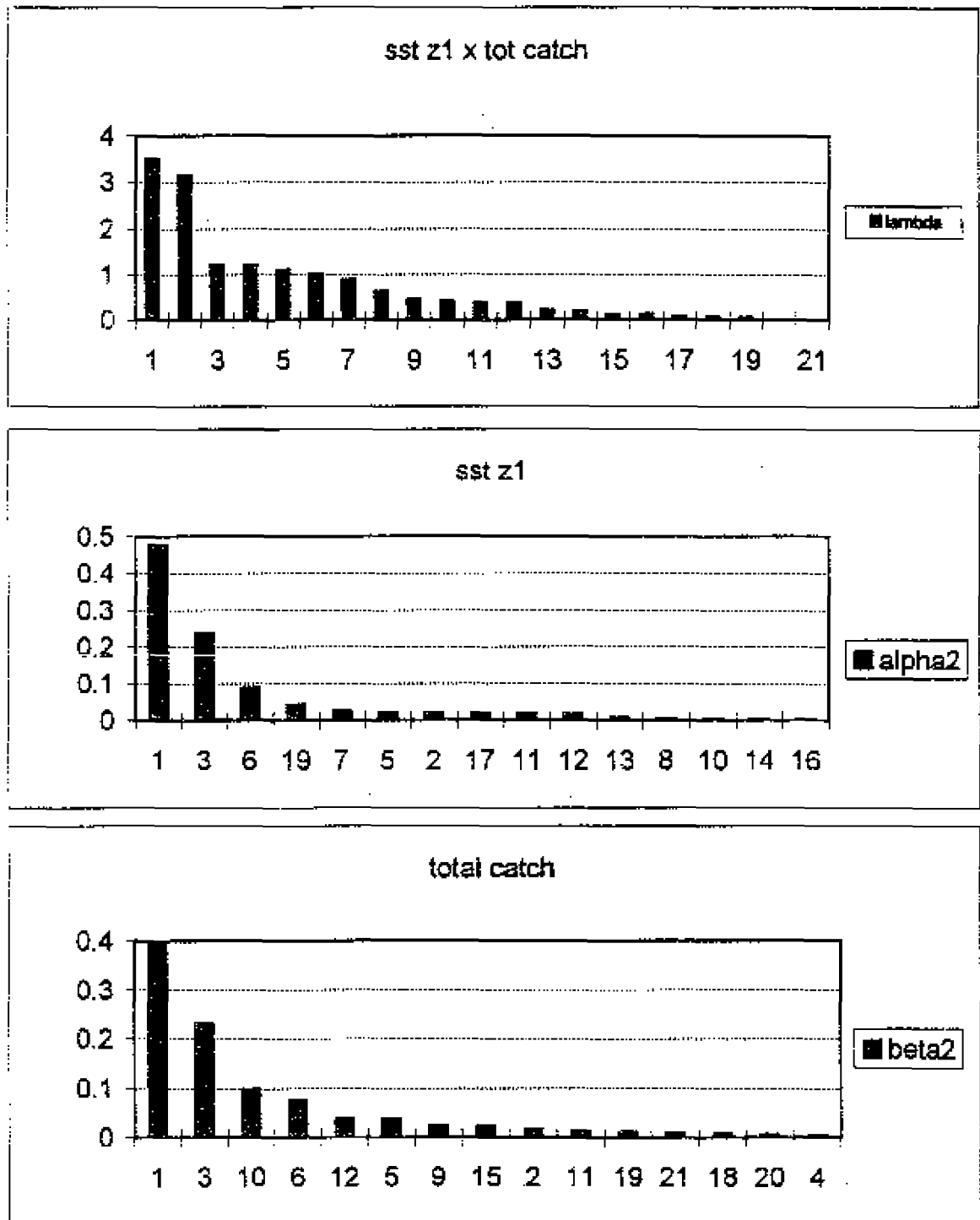


Fig.16

