Oceanographic changes during the 1997-1998 El Niño in the Indian Ocean and their impact on the purse seine fishery

Francis Marsac[1] Jean-Luc Le Blanc[2]

Abstract

The latest 1997-98 warming event, a consequence of one of the strongest ENSO in the century, has caused dramatic temperature and wind stress anomalies in the equatorial Indian Ocean. These anomalies are likely to be the strongest ever recorded in the Indian Ocean. This paper focuses on their impact on the purse seine fishery (European Union and NEI vessels). The geographic distribution of the purse seine catches has been drastically modified, especially at the beginning of 1998, at the peak phase of the El Niño phenomenon. The usual fishing grounds of the Western Indian ocean basin were deserted, and the fleets started a massive shift to the Eastern basin, as far as 100°E, a longitude never reached before by the EU fleet. This change may be explained by a significant decrease of catchability of the unassociated schools (that are usually exploited during the first quarter of the year in the West) to the purse seine gear. Tuna habitat was deepened by an anomalous deep thermocline, a consequence of the tilt of the slope of the ocean due to the ENSO. The piling up of warm water in the West turned to be the result of anomalous strong easterlies; at the same time, cool conditions prevailed in the East. It appears that the fishers reacted very quickly to the environmental anomaly. The changes of fishing strategy are not well assessed in the current CPUE indices that we use to relate to the environment. The tools to be promoted to undertake more reliable quantitative analysis are multispecific simulations models of distribution of tuna, forced by the environment, and incorporating simultaneously the behavioural response of the species and the fishing strategy changes. This type of models requests an underlying physical model that is used to force the movements of tunas and their catchability. The most powerful physical models, such as the coupled models, are complex to use. In a first step, simple shallow-water models can be used to estimate environmentally-related catchability indices on the large scale. In a further stage, the coupling with more complex bio-geochemical models should be attempted for process-oriented studies, such as the effect of environmental anomalies on recruitment and forage availability for tuna.

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[1] IRD (Institut de Recherche pour le Développement), HEA, BP 5045, 34032 Montpellier Cedex 1, France
e-mail : marsac@mpl.ird.fr

[2] School of Ocean and Earth Science, Southampton Oceanographic Centre, UK.
e-mail : tranthao@iprolink.fr - Internet : www.iprolink.fr/~tranthao/index.html

INTRODUCTION

The El Niño is one of the most well-monitored climatic phenomenon in the world. The devastating effects of the great warming that occurred in the Pacific in 1982-83 (droughts, floods, anomalous hurricanes) made climatic experts recognise the large scale consequences of this event, which was initially thought to be restricted to the Galapagos-Ecuador-Peru area. Actually, El Niño is a component of an ocean-wide oscillation in the atmosphere (SO). A lower than average atmospheric pressure gradient from East to West Pacific favors El Niño conditions, and higher than normal gradient leads to a La Niña event. These findings triggered the development of scientific programs aiming at surveying in real time the coupled ocean-atmosphere system: TOGA, WOCE programs, Equatorial TAO moorings are some examples of international cooperation to set up the observing systems, combining in situ measurements with satellite imagery.

The Pacific Ocean is the nest of the Niños: this is due to its width (18 000 km at the equator, against 6 000 km in the Indian Ocean and 5 000 km in the Atlantic) which enables a full development of the anomalies generated by the air-sea interactions. During strong Niños, the whole pelagic ecosystem can be affected: in depth, with significant changes affecting the mixed layer (due to a flattening of the slope of the ocean) and the distribution of the planktonic production, and in latitude with a poleward extension of the habitat of tropical predators. Local fisheries can face economic problems with the collapse of their marine resources (preyed upon by the new predators or affected by the recession of coastal upwellings), whilst high seas industrial fisheries have to seek for other fishing grounds.

Some studies are suggesting that the Indian Ocean is far from being a passive player of the Niños (Barnett, 1991; Mehl, 1993). There is a strong coupling between warm events in both oceans (Tourre and White, 1995) and the Indian monsoon might be on of the multiple triggers that can initiate an ENSO (El Niño-Southern Oscillation) cycle.

2- CLIMATIC RESPONSE OF THE INDIAN OCEAN TO AN EL NIÑO

The normal situation is a warm pool in the Western Pacific, generating strong convection and low atmospheric pressure at sea level (SLP). The convection (and associated precipitation) is located over Indonesia, where the Pacific and Indian ocean Walker Circulation cells are converging. This situation is forced by the easterlies in the Pacific, maintaining an increasing slope of the sea level from East to West. The Indian Ocean responds symmetrically to the Pacific: the ocean slope rises from West to East, the prevailing winds at the equator are westerlies, and the deeper mixed layer is located in the East (fig.1a). The subsiding branches of the Walker cells in the Eastern Pacific (EPAC) and over Eastern Africa inhibit precipitation at these locations.

With the advent of El Niño, the warm pools shifts eastwards, to the central Pacific, where the convection becomes active. This displacement affects the Walker cells pattern: there is an increased subsidence over Indonesia (associated with drought); in the Indian ocean, the wind convergence occurs over East Africa (associated with severe rainstorms). The low SLP which develop in the Western Indian Ocean (WIO) generates a reversal of the wind stress, with prevailing easterlies along the equator. This dramatic change leads to a flattening (in the case of a weak El Niño) or even a tilt (strong El Niño) of the ocean surface which is elevated to the West. (fig. 1b).

La Niña is the opposite phenomenon, where the westerlies in the Pacific and the easterlies in the Indian Ocean are strengthened. The temperature anomalies average +1.4°C in the EPAC when it is only +0.2°C in the Indian Ocean. During La Niña, the temperature anomalies are respectively –1.2°C and –0.22°C. As for El Niño, the respective anomalies recorded during the latest warm event (1997-98) were +2.2°C and +1.1°C, that is the most dramatic warming ever recorded in the Indian (Webster et al, submitted).

The Southern Oscillation Index (SOI) is one of the typical climatic indices used to assess the intensity of the ENSO events. It is obtained by subtracting the standardised SLP anomalies at two reference locations, Darwin (Australia) and Tahiti (French Polynesia). Lowest (highest) values denote the peak phase of El Niño (La Niña). The remote connection between the Pacific SOI and the Indian Ocean can be detected through the SLP anomalies recorded in Mahe, Seychelles (5°S, 55°E). The combined plot of SOI and standardised SLP anomalies in Mahe (fig. 2) exhibits significant positive anomalies of SLP in Seychelles during the growing phase of El Niño, prior to the negative peak value. In that sense, this local and easy-to-get index may be useful for predicting the advent of El Niño in the Indian Ocean.

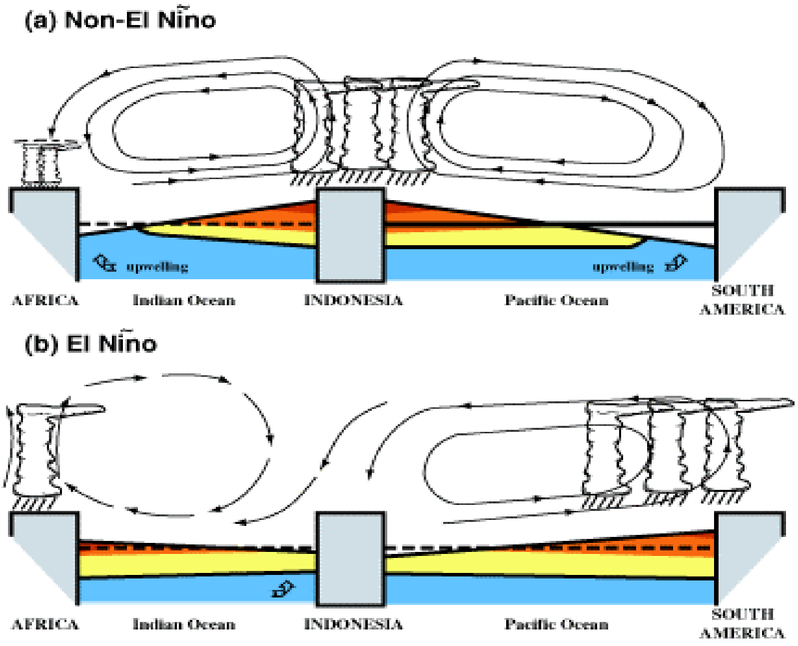


Fig. 1 - Diagram of the large scale differences between “normal” (a) and “El Niño” (b) periods. The elevated slope of the ocean is associated to surface warming and deep thermocline. (From Webster et al, submitted).

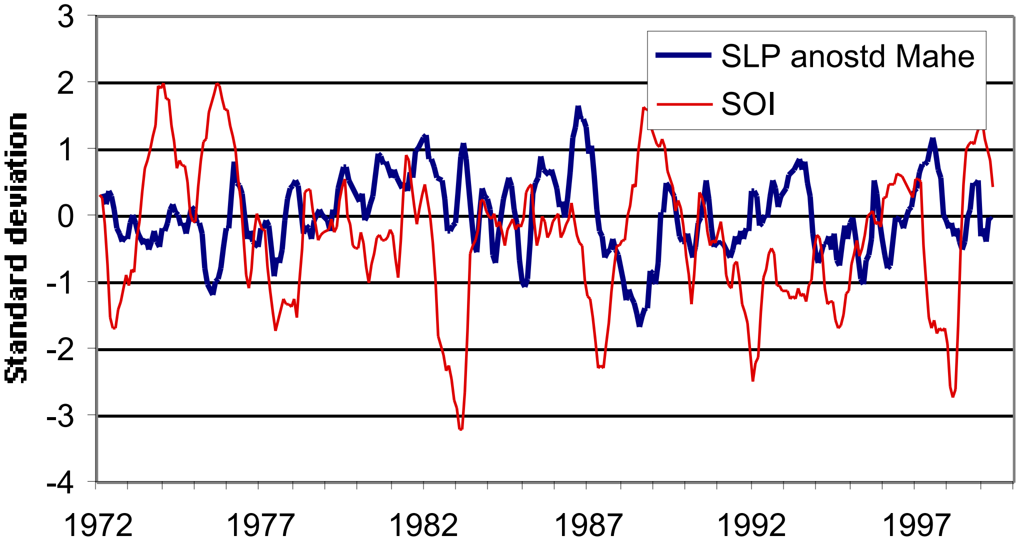


Fig. 2 - Time series of the Southern Oscillation Index (SOI) and the standardised atmospheric pressure anomaly at the sea surface in the Seychelles (Western Indian Ocean). Raw values were smoothed by a five- month running weighted average. The monthly SLP data for Seychelles were provided by the National Meteorological Services based at the Pointe Larue International Airport were data collection started in 1972.

THE 1997-98 EL NIÑO IN THE INDIAN OCEAN

The latest El Niño can be traced back using the SST and zonal wind anomaly fields (fig. 3). The warming across the whole ocean started in late spring 1997, with maximum SST anomalies recorded in the West. Actually, since the normal situation at this time of the year is a cooling due to intense mixing and Ekman transport caused by the summer monsoon, this positive anomaly must be seen as a lower than average cooling. Then, during the last quarter of 1997, an intense cooling occurred in the Eastern Indian Ocean, associated to strong surface easterly winds replacing the usually weak westerly flux. The peak SST anomalies in the West occurred while the cooling in the East was turning back to normal situation. The ocean slope was elevated to the West by 40 cm above the 0 level, when the intra-annual amplitude is usually about 40 cm. Provided the relative small size of the Indian compared to the Pacific, the height gradient generated in 1997 is about three times the normal values observed in the Pacific (Webster *et al*., op.cit.).

One of the salient features of the height anomaly (an ancillary variable for the changes in the mixed layer) is the appearance of a ridge located between 5°S and 10°S, mostly developed in the western basin in November 1997 (fig 4). This ridge, a converging system with a height anomaly of about 35 cm, was a dynamic structure moving westwards. This anomalous pattern was the consequence of the persistence of strong easterlies along the equator and anomalous westerlies along 20°S. Ekman mass transport (to the left by easterlies and westerlies in the southern hemisphere) caused the formation of the ridge between the two zonal wind anomalies.

IMPACTS ON THE PURSE SEINE FISHERY

Distribution of purse seine catches

The series of maps (fig. 5) showing the distribution of purse seine catches for 1991-98 dwells on the recent expansion to the East of the fishing activity, which was mainly limited to the western basin (west of 70°E) until 1992. The fishery expanded in two phases. From 1993 to 1996, the fishery stretched out towards 80°E, at the turn of the year (December to March) where unassociated schools are usually targeted. The second phase was a sudden expansion as far as 90°E to 100°E during the fourth quarter of 1997 and the first quarter of 1998. The latest data available (December 1998) only show a restricted but very productive area (unassociated schools) at 5°S and 85°E.

Figure 3a

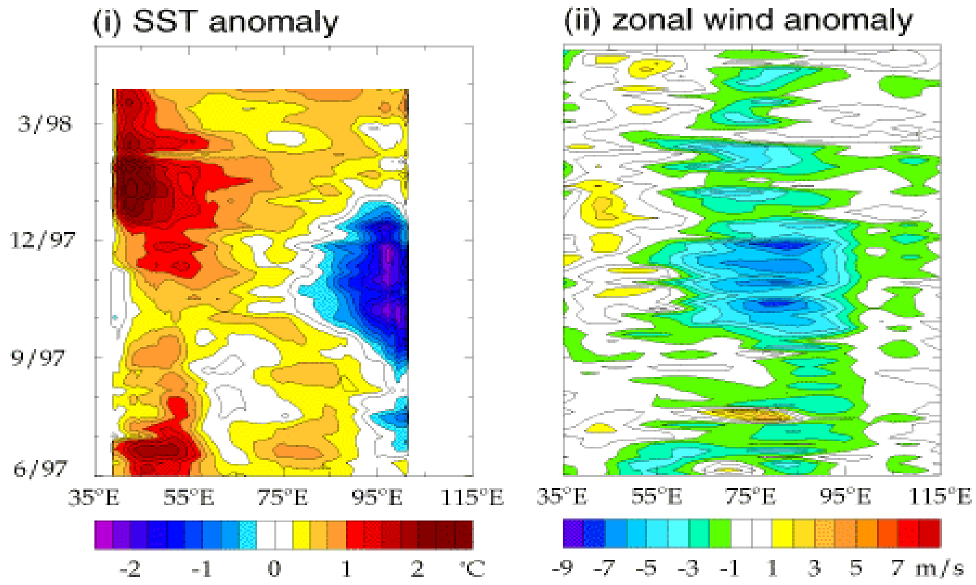
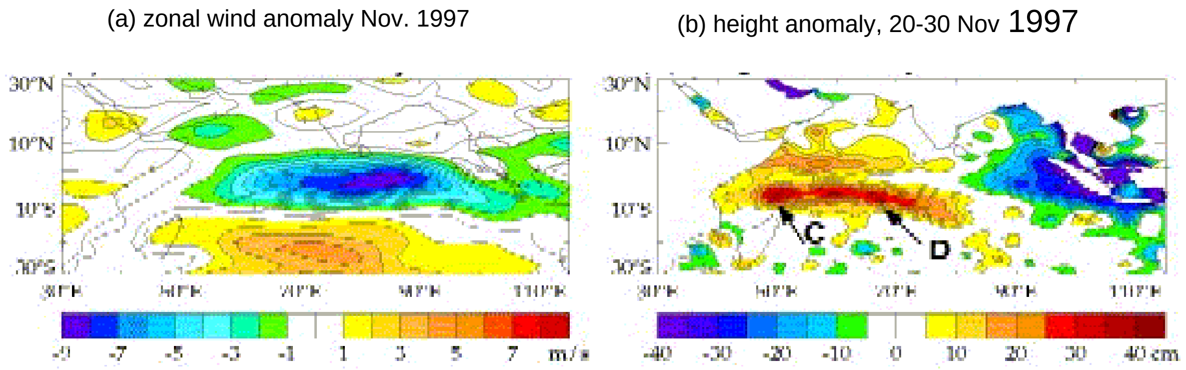


Fig. 3 - Time-longitude sections across the Indian Ocean of (i) the anomalous Reynold's SST7 and of (ii) the zonal wind anomaly at sea level. (From Webster et al, op.cit.). W denotes the warm pool and C the upwelling.



(a) zonal wind anomaly Nov. 1997

(b) height anomaly, 20-30 Nov 1997

Fig. 4 - Maps of anomalous (a) zonal wind (m s-1) and (b) surface height anomaly (cm) from TOPEX-POSEIDON, for November 1997. (From Webster et al, op. cit.). C and D denote the highest sectors of the converging ridge, and L the lowest sea level?

However, if we consider the distribution of school catches made during the first quarter 1998 (fig. 6), it appears (i) that the unassociated schools were virtually absent from the usual western fishing grounds, and (ii) that, even in the East, the catch were essentially made on logs apart a very limited area by 90°E. The anomalous non productive area stretching between 5°S and 10°S is located on the core of the converging ridge mentioned earlier. The dynamics of this feature is due to a downwelling Rossby waves propagating westwards. A thicker mixed layer enlarges the optimal habitat of tropical tunas, therefore less restricted to the surface layers. In such situations, the surface sightings are seldom seen by the purse seiners.

Trends of catches, effort and CPUE

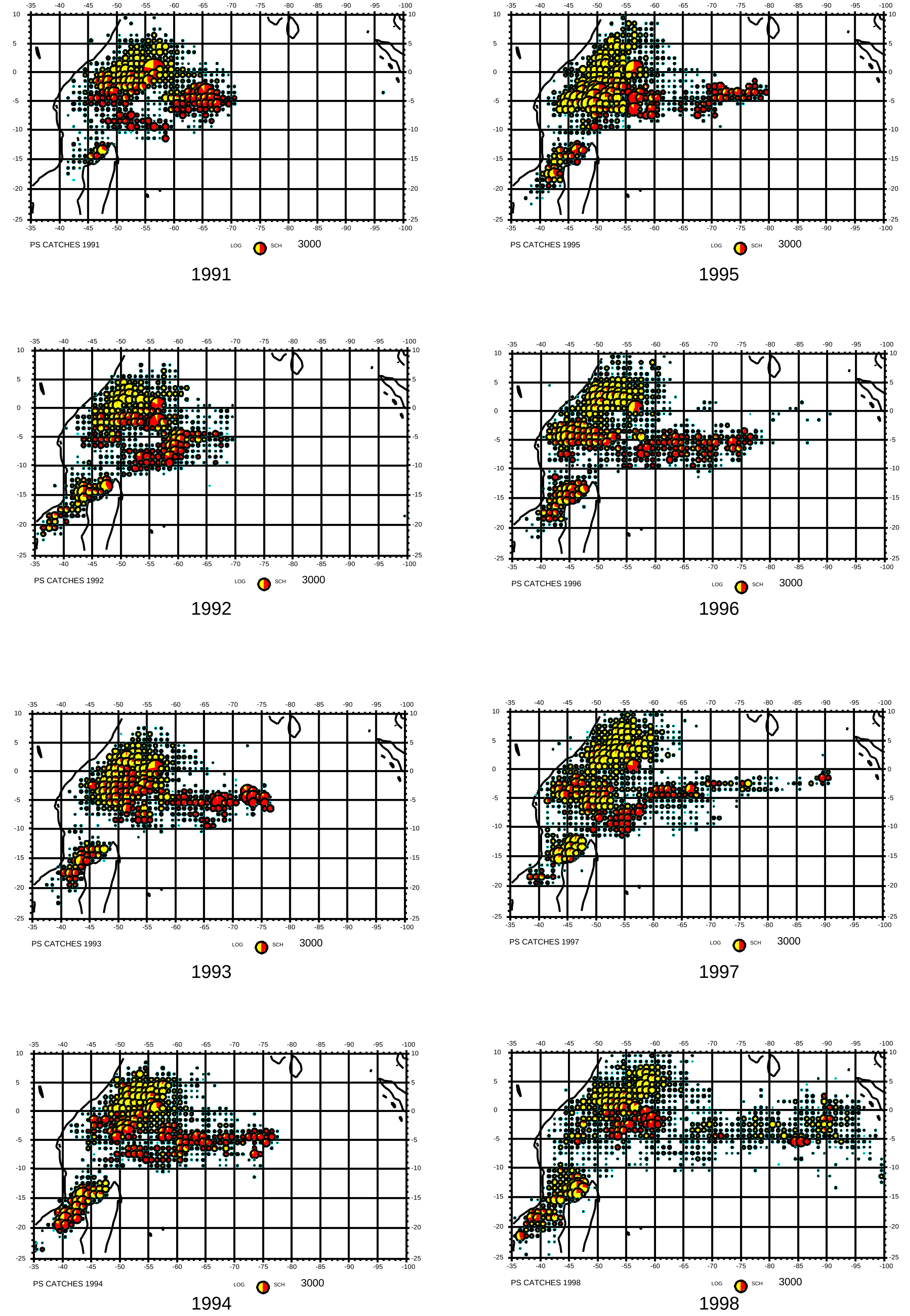
Catches, effort and CPUEs of both Western and Eastern basins are compared. First of all, an overall decrease of the number of school sets is noticeable in the West (about 25% from 1991 to 1998). During the same time, the number of sets made on logs (and FADs) increased by 100%. This denotes the drastic change in the fishing strategy of the fleets from the usual school-searching activity to the drifting-objects fishing mode. The recent expansion to the East was characterised by catches on unassociated schools during the first phase (in the Chagos sector), and mostly on logs in the far East, reached in 1998 (fig. 7).

Considering the area where unassociated schools are more abundant (0°-10°S), the catches on schools in the West exhibit a continuous decreasing trend, even greater (about 100%) than that of the number of sets. In the East, between 0° and 10°S, the level of school catches is much lesser but fluctuates without any trend. The continuous decreasing trend of the catches is driven by the similar trend of the yellowfin catches. Although the lowest level of catches was obtained in 1998, that is during the warming event, it can be also interpreted as the result of a regular depletion of the biomass (fig. 8).

CPUE indices were calculated in the same 0°-10°S equatorial belt for large yellowfin (> 10 kg) and for skipjack.

- *yellowfin* this species being the major contributor to school catches, the effort considered was the fishing day and only the school fishing mode was selected in the sole Western basin: CPUEs were first calculated in each 1°square-fortnight strata considering a minimum threshold of 2 days fished by stratum. Then, the CPUE index for the year was obtained by calculating the average first level-CPUE during the peak season, that is from January to March. Results are shown in figure 9a. The indices fluctuate about a regular decreasing trend, to reach 0 during 1998 (no catch during the first quarter in the west).

- *Skipjack* this species is strongly associated to the floating objects. Therefore, the relevant fishing effort was the number of successful set on logs (and FADs). CPUEs were calculated by 1°square-fortnight, without any threshold in the minimum number of sets by stratum. The CPUE index was the average of the CPUEs from March to October in the west, and from January to April in the East. Results are plotted in figure 9b. The indices are rather stable until 1996. From 1996 to 1998, the changes in both basins are very similar, with a lower CPUE index in 1997.



1991 1995

1992 1996

1993 1997

1994 1998

Fig. 5 - Distribution of purse seine catches (EU vessels including convenience flags) by fishing mode (light pie: logs; dark pie: unassociated schools) and year, for 1991-1998.

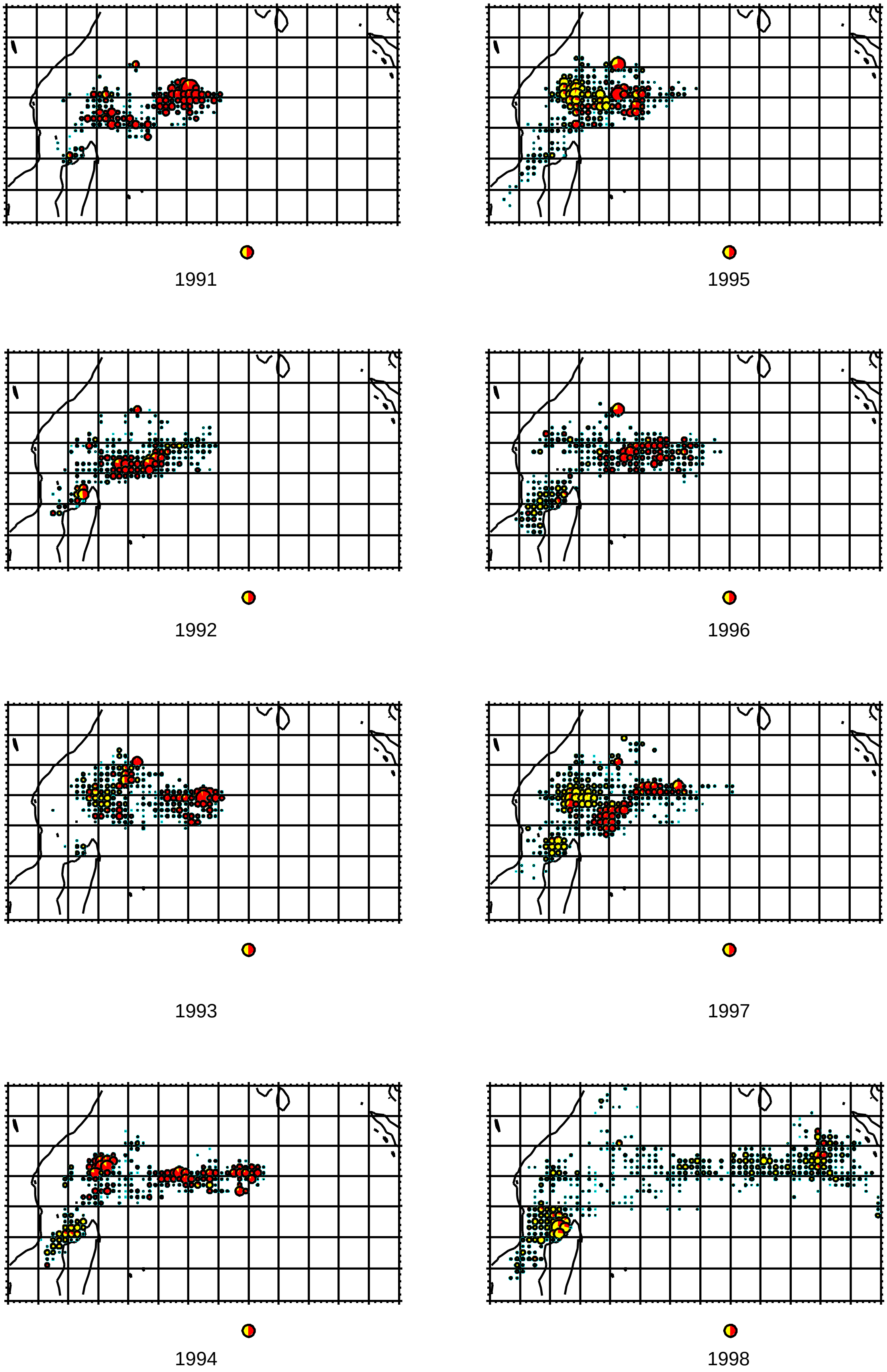

1991

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Fig. 6 - Distribution of purse seine catches (EU vessels including convenience flags) by fishing mode (light pie: logs; dark pie: unassociated schools) for the first quarter only, 1991-1998.

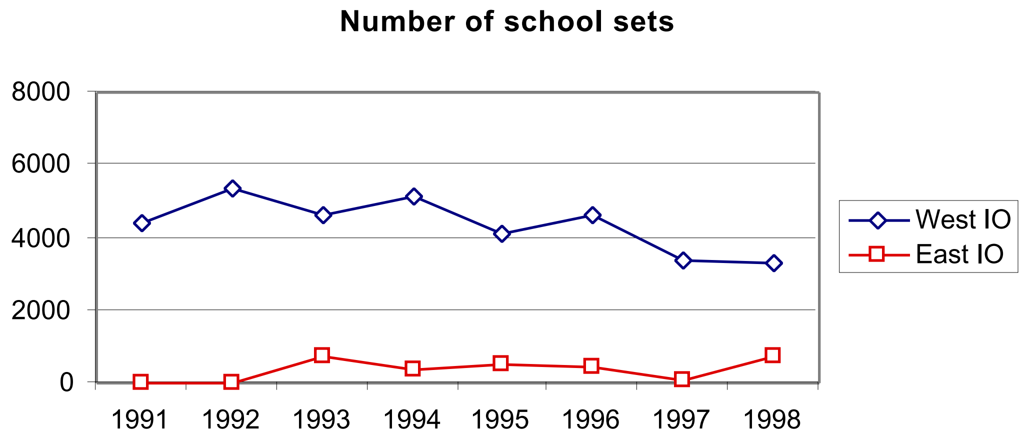

Fig. 7 - Comparative trends of the number of log and school sets in the Western (30°N-30°S / 30°E-70°E) and Eastern basin (30°N-30°S / 70°E-110°E), for 1991-1998.

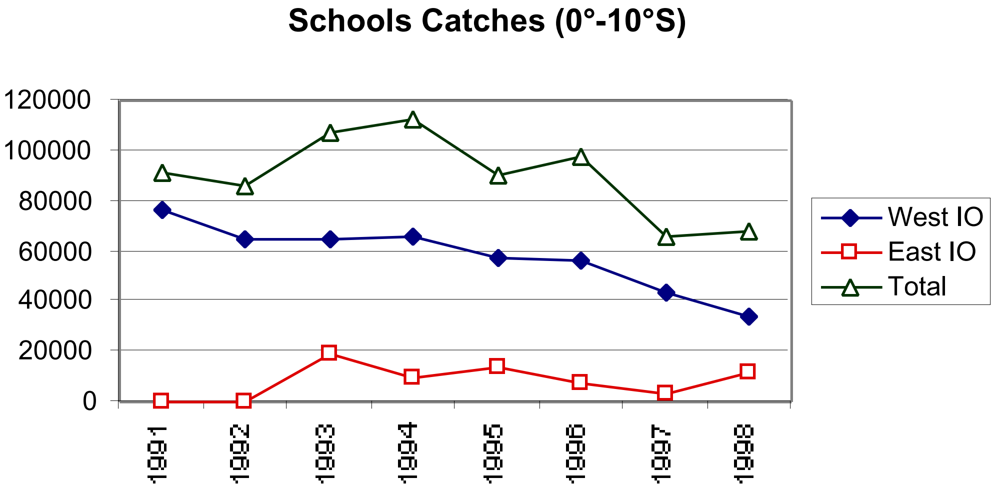

Fig. 8 - Comparative trends in the school catches in the equatorial area 0°-10°S, in both Western and Eastern basins of the Indian Ocean, and on the overall.

DISCUSSION

Significant oceanographic changes induced by the 1997-98 El Niño have been detected in the Indian Ocean, making this event one of the strongest ever recorded in this ocean during the century. The deepening of the thermocline in the West is one of the factors that could explain the collapse of the catches and CPUE indices on unassociated schools. On the other hand, the anomalous upwelling conditions which occurred in the East, providing biological enrichment and a shallower thermocline should have favoured the catchability of unassociated schools. Actually, this did happen: the number of schools sets exhibited a sudden rise from 100 in 1997 to 705 in 1998.

The behaviour of the fishers is a another key factor to be taken into account. The fishers can react very quickly to an environmental change: if they do not locate good fish sightings in an area, they will leave to searching for

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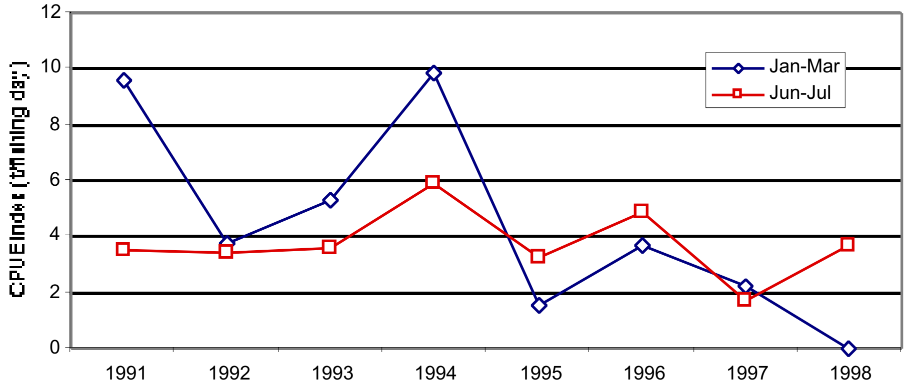

(b) Skipjack - Floating objects sets

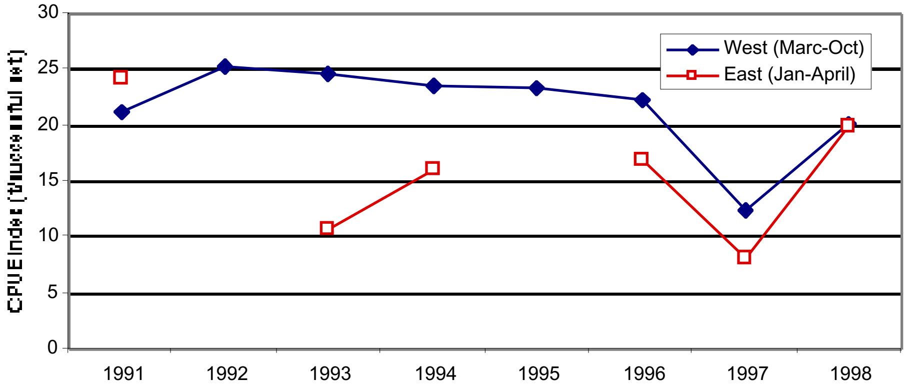

Fig. 9 - CPUE indices estimated in the equatorial belt (0°-10°S) for (a) yellowfin (in t/fishing day) caught on unassociated schools in the West, and (b) skipjack (in t/successful log set) in the West and in the East. Both basins are parted by the longitude 70°E.

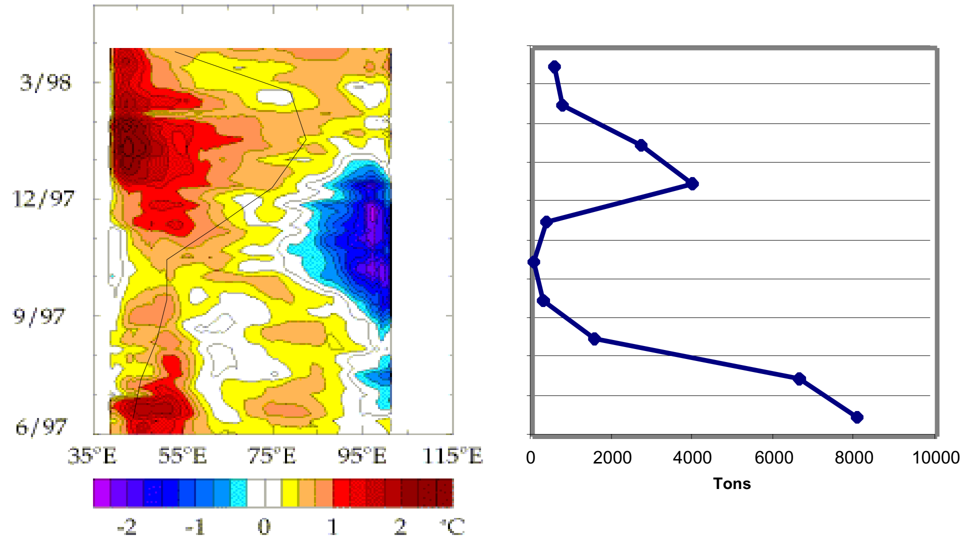

Fig. 10 - Plot of the gravity centre of the unassociated school catches (thick line), by month, superimposed to the SST anomaly (a) and plot of the corresponding catches (b) from June 1997 to March 1998.

other sectors: the use of FADs allow them to guarantee a minimum level of catches. The warming event in the West forced the fleet to expand eastwards, where the floating object fishing mode turned to be dominant. This phenomenon is be well depicted in the plot combining SST anomaly and the longitude variation of the gravity centre of the sets made on unassociated schools (fig. 10). The gravity centre is shifted eastwards, in the intermediate area between cold and warm waters, where the catch increase sharply in December 1997.

The major constraint in assessing the impact of environmental anomalies on the resources is that we deal with fishery-dependent indices. The CPUE index only reflects changes of availability to a given fishing gear, but is far from estimating the abundance. If the fishers decide to leave an area, there will not be a continuous sampling of this specific area and we loose information. This is a major difference with measurements carried out by oceanographic programs, where a single spot is sampled at regular time steps (e.g. the 70 buoys of the TAO program, moored on a permanent basis along the equator in the Pacific to track the Niño/Niña variability).

Then, what type of tools should be used ?

Facing such problems with the field fishery data, a better understanding of « how the fishery reacts ? » can be attempted by promoting the development of simulation models. Those models must integrate at the same time (i) the behavioural response of the fish (based on eco-physiological constraints and on the space-time distribution of the forage) and (ii) the strategy changes, like the concentration of the fleet in a given area, or the decision to shift to another fishing method or to cruise towards other fishing grounds. A spatial model explaining a significant part of the yellowfin tuna movements under environmental forcing has already been developed in The Atlantic (Maury, 1998). An application of this model at a multispecific level in the Indian Ocean is underway.

The resource model is forced by the environment, that has to be described at each time step by a physical model. Basically, there are two families of physical models, the shallow-water model and the General Circulation Models (CGM). They can be briefly compared according to physical and biological considerations

Physical considerations:

- Shallow-water models have the advantage of being easy to use. In addition, they can be ran on individual computers. One can easily change a parameter and compare results. Such simple models can provide results within short delays, but in turn, they neglect important components of the system. For instance they do not take into account temperature nor salinity and have a very simple vertical structure (2 or 3 layers). They are still very useful for studying upper-layer large scale dynamics, namely waves, convergence and divergence, upwelling and downwelling, etc.
- GCMs or coupled ocean-atmosphere models can provide a more accurate solution, but they are heavy to use and require powerful computers with big storage capacity. Because of their complexity, it is not always possible to use them as prognosis models but are often used for diagnosis studies, i.e. studies of past conditions used for validation and for understanding a particular climatic phenomenon.

Biological considerations:

- The advantages of using simple or complex models depend on the processes under study. If one wishes to study spawning conditions, food chain processes, or recruitment in detail, then GCMs are more useful. On the other hand, if one wishes to use modeling for prediction purposes and for catchability forecast, a simple shallow-water model might be sufficient if forced by proper winds. For instance, one could easily force the model with winds predicted with an atmospheric model.
- In conclusion, GCMs are more useful for theoretical studies and for understanding the coupling between physics and biological processes such as primary production, fish behavior, etc. while shallow-water models could be useful for studying fish stock migrations or catchability predictions.

Now, a comprehensive modelling of the processes leading to forage for predators like tunas requires the use of coupled bio-geochemical models linking the physical dynamics to the biological response. Inter-disciplinary collaboration between oceanographers and meteorologists has been extended to biologists enabling the development of several coupled bio-physical or bio-geochemical models used in fisheries studies. Lehodey *et al.* (1998) have developed such a model for predicting skipjack tuna forage distributions in the equatorial Pacific. The OPA GCM from LODYC (Laboratoire d'Océanographie Dynamique et de Climatologie), was used to predict the water dynamics. A high resolution of OPA (1/3°longitude x 1/3°latitude, 16 vertical levels in the upper 150 m; Blanke and Delecluse, 1993) was forced at the surface with the 5 day winds deduced from the ERS 1 scatterometer and with fresh-water and heat fluxes based on these winds, on Reynolds' SST (Reynolds and Smith, 1994), and on output fields of the atmospheric model Arpège-Climat (Dequé *et al.*, 1994). This forcing allowed a 3 year simulation from April 1992 to June 1995.

The OGCM was coupled to a bio-geochemical model to predict primary production (Stoens *et al.*, 1998) and hence, skipjack tuna forage. The simulated forage production combined with other environmental parameters, such as temperature and dissolved oxygen concentration should lead to a realistic habitat index useful for large-scale spatial models of tuna populations (Lehodey *et al.*, 1998).

The new tuna research program of IRD (Institut de recherche pour le développement), to be implemented in 2000 for a four-year period encompasses this field of research that will be applied to Indian Ocean tuna fisheries in relation to spatially based population dynamics models.

CONCLUSION

Process-oriented studies that were developed in the recent years triggered the development of coupled models able to assess the interactions between the physical dynamics of the ocean to biological responses (that can help predicting forage for apex predators). This does not imply that field observations must be neglected. The sampling survey programs of tuna fisheries must be maintained and improved, in order to guarantee the validation and calibration of the sophisticated models mentioned earlier. On the climate side, the definition of simple indicators (SLP anomalies, composite indices like those presented in the Climate Diagnostic Center bulletin of the NOAA, primary production estimates by SeaWifs, etc.) must be seen as a baseline for an efficient monitoring and prediction of the interannual variability of the ocean-atmosphere coupled system.

Note: the description of the 1997-98 warm event in the Indian Ocean was essentially found in a paper by Webster et al, submitted to Nature On July 1, 1998. Some of the original figures of this paper are inserted in the present document.

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