WHAT DO WE KNOW ABOUT EL NIÑO IN THE INDIAN OCEAN? A "TOOLBOX" FOR FISHERIES BIOLOGISTS

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ABSTRACT

This paper aims to guide fisheries biologists in the use of current knowledge of the El Niño-Southern Oscillation (ENSO) phenomenon in order to address its impact on fisheries in the Indian Ocean.

It is widely accepted that both the Indian and the Pacific Oceans are closely linked through the Indonesian Throughflow and the strong convective activity that occurs there. In order to tackle the ENSO phenomenon, it is therefore crucial to adopt a coupled Indian-Pacific Ocean approach.

ENSO mechanisms in the Pacific are well known, but the role of the Indian Ocean in these mechanisms is not as clear. Due to the fact that air-sea interactions in the Indian Ocean are a new area of research, our knowledge is still not sufficient to have an overall view of the Indian-Pacific/ocean-atmosphere system.

Nevertheless, climate monitoring is increasing in the Indian Ocean in order to enable its study. Hence parameters useful for taking the Indian-Pacific coupling into account are identified in this paper and their real-time monitoring, available on the internet or through National Meteorological Centres, is proposed for the purpose of fisheries biology studies.

To make full use of the available data and to facilitate the interpretation of observations, the unique features of the Indian Ocean's climatology and oceanography and the monsoon system are first described in relation to the ENSO phenomenon.

RÉSUMÉ

Ce rapport a pour dessein de guider le biologiste des pêches dans l'utilisation des connaissances actuelles sur le phénomène El Niño-Oscillation Australe (ENOA) afin d'en étudier l'impact sur les pêcheries de l'Océan Indien.

Il est largement accepté que l'océan Indien et l'océan Pacifique sont intimement liés à travers le passage indonésien (le « throughflow ») et de part la forte activité convective qui y a lieu. Pour comprendre le phénomène ENOA, il est donc nécessaire de considérer le système couplé Pacifico-Indien.

Les mécanismes d'ENOA sont bien connus dans le Pacifique, mais le rôle de l'océan Indien dans ces mécanismes n'est pas clair. Les interactions océan-atmosphère dans l'océan Indien étant de nouveaux axes de recherche, notre connaissance actuelle n'est pas encore suffisante pour permettre de dégager une vue synthétique du système couplé Pacifico-Indien/océan-atmosphère.

Cependant, la veille climatique s'intensifie dans l'océan Indien afin de permettre son étude. C'est pourquoi, les paramètres utiles à la prise en compte du système Pacifico-Indien sont identifiés dans ce rapport et leurs mesures en temps quasi-réel, accessibles sur l'Internet ou à travers les Centres Nationaux de Météorologie, sont présentés à des fins d'études des pêches.

Les caractéristiques uniques de l'océanographie et de la climatologie de l'océan Indien, ainsi que le régime de mousson, sont décrits dans un premier temps, en relation avec ENOA, afin de permettre un plein usage des données disponibles et d'en faciliter l'interprétation.

Introduction

There is a growing interest in the study of the role of the Indian Ocean in the El Niño/Southern Oscillation (ENSO) phenomenon. The Tropical Ocean Global Atmosphere (TOGA; 1985 -1995) program, through intense monitoring and modelling work, provided scientists with substantial results, enabling them to understand ENSO mechanisms in the tropical Pacific Ocean. We are now able to predict the advent of an El Niño episode several months in advance by analysing various parameters such as sea-surface temperature (SST), sea-level pressure (SLP), surface winds, heat budget, and precipitation. Numerical models enable climatologists and oceanographers to forecast the response of the coupled ocean-atmosphere system and to tell them when conditions seem to be adequate to cause an El Niño event. The latest El Niño event was successfully announced at least six months in advance, enabling many countries to prevent catastrophes.

However, uncertainties still remain. For instance, the 1982-83 El Niño was not predicted with the same success. By all published accounts, most scientists involved in El Niño research had failed for several months to recognize the potential for the development of the 1982-83 El Niño. This was because it differed in both timing and location from the set of post-World War II El Niños used to compile the characteristics of a 'typical' event (Glantz, 1996). In fact, some studies mention a so-called composite El Niño, describing a number of recursive mechanisms, but such studies lack the precise time sequence of those mechanisms, especially concerning the initial forcing during the onset of an El Niño, which tends to shift the convection centre from the Indonesian archipelago towards the central Pacific, one of the main precursor signs of an El Niño event. El Niño events may thus differ in their development, duration and amplitude.

What makes the low pressure over Indonesia move to the east? What produces the strong westerly wind bursts associated with that shift? Is the SST maximum in the warm pool advected towards the central Pacific through wind-induced currents or through geostrophic flow? To answer these questions, atmosphere and ocean scientists are now investigating the Indian Ocean climatology to find out

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whether this ocean may play a role in producing such patterns, through the monsoon system and its variability.

The aim of this paper is not to find an answer to these questions, but to present the recent progress made in finding answers and hence in understanding the Indian Ocean's climatology. Current knowledge may already be used for purposes other than only the prediction of the ENSO phenomenon, and our concern here is fisheries in the Indian Ocean.

A presentation of current knowledge will therefore be the subject of the next two sections: the first concerning the monsoon system, and the second the ENSO phenomenon. In the final section, available climatic "tools" and their use will be proposed for fisheries research.

Unique features of The Indian Ocean

Climatology

The Indian Ocean is unique in many ways, in its geography, its climate and its oceanography. Its geography is unique since it is the only ocean bounded in the northern hemisphere, (by the Asian continent Figure 1). This particularity is the cause of the monsoon-type climate (seasonally reversing winds) which give rise to oceanic features such as the Somali Current and the equatorial jets.

The monsoon climate dominates the northern Indian Ocean, and its effects are felt far into the subtropics of the southern hemisphere. Because of the wind reversals, annual mean distributions of atmospheric and oceanic parameters are of only limited use. However, a few facts should be noted:

- the Indian Ocean mean equatorial zonal wind blows to the east, while trade winds in other oceans blow to the west). This is in part due to the low pressure over the Indonesian region and the strong convection where low-level air converges;
- the Indonesian Throughflow is the only tropical connection between two oceans, with transport from the Pacific Ocean to the Indian Ocean;
- the pattern of surface heating in the Indian Ocean shows a maximum at the western side of the basin. Upwelling along the Arabian and east African coasts is associated with heat gain. Longshore winds along the west coast of Indonesia do not strongly favour upwelling at any time, except along the coast of Java in the Asian summer monsoon, and surface heating is therefore weak. This pattern is unique to the Indian Ocean (Tomczak and Godfrey, 1994).

The monsoon regime

A detailed description of the monsoon system can be found in many publications (Figure 2), so it will therefore be only briefly described here. Being the smallest of all oceans, the Indian Ocean does not have as large a number of subregions as the Pacific and Atlantic Oceans, but they are all distinct in their behaviour towards the strong monsoon regime (Figure 3). These major regions include:

- the Arabian Sea;
- the Bay of Bengal;
- the Mozambique Channel;
- the Indonesian Throughflow;
- the Equatorial Band; and
- the South-Equatorial region.

All these regions present two different oceanic circulations, in response to the monsoon winds.

- The central Arabian Sea experiences strong downwelling during the southwest monsoon (May-September), and strong upwelling on the western boundary. During the northeast monsoon (November-March) this pattern is reversed, but with less intensity. There is upwelling on the eastern boundary and downwelling in the centre and on the western boundary (Figure 4). This region is therefore important for heat-budget processes. Due to upwelling of cool subsurface water, there is an annual mean heat flux into the Arabian Sea. This flux is associated with abrupt cooling (decrease in heat content and SST). This cooling is unique since it occurs during the southwest monsoon in the boreal summer, at a time which would coincide with warming in other parts of the northern hemisphere (Wacongne and Pacanowski, 1996). Hence there must be a southern circulation cell that carries warm surface water out of this region. The determination of this circulation cell, which has not yet been achieved, is a major goal for Indian Ocean research and might explain variations in the monsoon regime. It is an important air-sea interaction process which might be useful in predicting anomalies in the Indian Ocean's ocean-atmosphere system.
- The Bay of Bengal is the second of the two basins of the northern Indian Ocean, separated by the Indian subcontinent. A unique feature of the Bay of Bengal is the coastal upwelling on its western boundary, similar to that along the Somali coast but not as strong. Like the Somali Current in the Arabian Sea, the East India Coastal Current (EICC) reverses direction twice a year. The circulation in the Bay of Bengal is characterised by anticyclonic flow during most months and strong cyclonic flow during winter. It is not yet fully understood whether the forcing of the circulation within the Bay of Bengal is local or remote or due to wind or equatorial waves. Its role in the ocean-atmosphere system of the monsoon regime is not well known, but SST and heat content within the Bay of Bengal are part of the Indian Ocean warm pool, where strong convection occurs. Variations of temperature in that region are therefore important for the study of the monsoon-ENSO system as a whole.
- A unique aspect of the Mozambique Channel and the Agulhas Current is that they run against the prevailing wind direction, especially in the southern part of the channel. The northern tip of the channel is characterized by a strong anticyclonic curl associated with strong convergence. Due to its geometry, the channel is crossed by very complex flows, with many eddies. These eddies are important for fisheries and their study might be useful. On a larger scale, what we know is that the southwestern Indian Ocean is the location for cyclone formation. It is also a sensitive area for air-sea interactions on interannual time scales (relevant to climate in South –Africa, for instance). Therefore, monitoring of cyclonic activity, SLP, latent heat and SST might be useful in this region in order to relate them with the ENSO phenomenon.

- The Indonesian throughflow is the subject of many recent studies. Its role in the global climate system seems much more important than was thought because of its complicated geography. The transport between the Pacific and the Indian Ocean is driven by the pressure difference between the two basins. This pressure gradient varies seasonally with the monsoon. The transport is thus weaker during the northeast monsoon and stronger during the southwest monsoon, due mainly to elevation of the sea surface on the eastern Indian Ocean boundary. It has been shown that opening or closing the throughflow in numerical models has an influence on the circulation within the Indian and Pacific Ocean and on the winds around the Indonesian convective region. Whether associated or not, it has been proven that the movement of this convective centre over this region is part of the onset of an El Niño. Anomalies of Throughflow transport are therefore crucial for climate prediction. The transport tends to be poor during El Niño events and high during La Niña events.
- The Equatorial Band is very complex in the Indian Ocean due to the important southern component of the wind stress crossing the equator. Furthermore, the wind stress reverses direction by 180° seasonally, inducing jets and waves along the equator, such as the Wirtky Jet during the inter-monsoon periods (April and October) and the Yanaï and Kelvin waves. During the northeast monsoon the North Equatorial Current (NEC) flows westward, as in the other oceans, with a Counter-Current to the South. During the southwest monsoon, the equatorial current becomes the South-West Monsoon Current, including the Counter-Current, and flows towards the East. This is unique to the Indian Ocean, and is the reason for the absence of the equatorial upwelling observed in the two other major oceans. The equator is interesting in the sense that it is a wave-guide. Waves propagating in the basin might play an important role in climate anomalies by triggering remote air-sea interactions. Their influence upon fisheries is not yet well established, but seems likely and may be important. Waves are very dynamic and the fish (especially migrating species) might be very sensitive to these rapid changes in ocean parameters. These oceanic signals might be compared to radio or television information, stimulating the behaviour of the fish.
- The South-Equatorial Current (SEC) is found around 12°S and flows westward. It can be observed through Ekman pumping calculated from wind-stress measurements. This current generates a zonal divergence due to the Coriolis force and the Equatorial Counter-Current flowing East just to the North. This divergence is clearly defined during the northeast monsoon, when trade winds are meeting northern monsoon winds at the Inter-Tropical Convergence Zone (ITCZ), approximately situated at 10°S. During the southwest monsoon, the ITCZ is found much further North, and the divergence is not so strong. Observation of this divergence may help in determining the location and variability of the ITCZ. The ITCZ and rainfall over India are parameters which define the strength of the summer monsoon. They are the "signatures" of the biennial oscillation between strong-cold/weak-warm Asian monsoons. This oscillation is assumed to be a pacemaker for ENSO events (Figure 7b); an El Niño would be an extreme warm event (Meehl, 1987). The biennial oscillation might have an important influence on fisheries. A strong-cold summer monsoon (heavy rainfall, strong winds and cold SSTs) might be favourable to catchability, while a weak-warm summer monsoon might be more favourable to spawning and larval survival. It is worth noting that a warm summer monsoon is preceded by a cold winter monsoon, and *vice versa* (*i.e.* while the monsoon is strong or weak every second year, temperature varies twice a year). Divergence is also important on a local scale because it is associated with a thinning of the mixed layer where the fish schools are confined. This is even more true for the region between 5°-10°S, where substantial catches are made.

The El Niño phenomenon

El Niño in the Pacific

The El Niño mechanisms in the Pacific are also well described in many publications (Philander, 1990; Rasmusson & Carpenter, 1982; Webster & Yang, 1992). Some specific mechanisms are, however, relevant to the understanding the role of the Indian Ocean, its action and reaction.

"Understanding the evolution of an ENSO event begins with an understanding of the evolution of the SST field. Many factors can influence the sea surface temperature. [...] there is a general agreement on one point: westerly wind bursts in the western Pacific Ocean, i.e. reversal of the general trade wind pattern, seem to be a necessary ingredient of the initialisation process for an ENSO event." (Tomczak and Godfrey, 1994). During an ENSO event, the apex formed by the ITCZ and the South Pacific Convergence Zone (SPCZ) moves to the date line, creating a small Walker circulation cell on its West, with a descending branch over Indonesia and Australia. This descending branch is associated with high SLPs and divergent winds. Winds are thus reversed in both oceans.

ENSO in the Indian Ocean

The role of the Indian Ocean in producing these eastward shifts of SSTs and convection maxima is not known. They might be due to anomalies in the monsoon regime, propagating East and disturbing the atmosphere in the Pacific (Yasunari, 1990). Variations in the throughflow transport might also be a cause of SST advection towards the central Pacific. Finally, SST might also be influenced by heat budgets in the warm pool.

Whatever the mechanism, due to the wind reversal in both oceans, the Indian Ocean experiences strong easterly winds, with high SSTs. During El Niño events conditions in the Indian Ocean are those of an exaggerated southwest monsoon.

- The northern Indian Ocean - the Arabian Sea and the Bay of Bengal - does not seem to be strongly affected by interannual variations such as ENSO events (Figure 5, Le Blanc, 1996). The annual cycle is much stronger there due to the continent. One might expect that the southwest monsoon oceanic conditions would be enhanced during El Niño years and that the northeast monsoon might be much weaker, but this does not take into account the atmospheric conditions which might enhance or inhibit the oceanic response. Furthermore, seasonal prediction schemes for predicting the strength of the Indian monsoon have shown that the influence of the Indian monsoon on ENSO events might be greater than the influence of ENSO events on the monsoon. This is due to a southeastward propagation of atmospheric parameters from the Indian sub-continent towards Indonesia and Australia. ENSO events seem to influence the monsoon indirectly through teleconnections with higher latitudes.

- The equatorial band and the south-tropical Indian Ocean are much more directly influenced by ENSO events in the Pacific (Figure 6, Le Blanc, 1996). The wind reversal is associated with a change in thermocline depth. During normal conditions, the trade winds in the Pacific Ocean pile water on the western boundary, with a deepening of the thermocline from East to West. On an annual mean, the situation is symmetrical in the Indian Ocean, where the thermocline is deeper in the eastern than in the western boundary. During an ENSO event, the reversal of the trade winds in the Pacific Ocean reduces the thermocline depth in the western part of the ocean and deepens it in the eastern part (Figure 7a, Webster *et al.*, 1998). In the Indian Ocean, easterly winds provide favourable conditions for upwelling along the coasts of Java and push water towards the African coast, thus increasing the mixed-layer depth there with a deepening of the thermocline (Figure 8). The conditions are therefore similar to those in the Pacific Ocean during normal conditions. The Indian Ocean can therefore be considered as a mirror image of the Pacific Ocean, the mirror being the Indonesian convection cell. The image is however distorted by the strong monsoon regime and the specific Indian Ocean geographic configuration previously discussed.
- Further South, the SEC is stronger than usual, associated with a stronger divergence around 10°-15°S. A stronger SEC means stronger westward flow towards the coast of Africa. The circulation within the Mozambique Channel might be influenced by this, as might the East African Coastal Current, joining the SEC to the Somali Current. These features have not yet been studied on interannual time-scales, and results are therefore not available.

Available data: a "toolbox" for fisheries biologists

Oceanic and atmospheric parameters for climate and fisheries relationships studies

These parameters are well known to fisheries biologists interested in the impact of climate on fish behaviour. They are:

- sea surface temperature (SST);
- sea level pressure (SLP);
- wind;
- thermocline depth (or the depth of the 20°C isotherm); and
- vertical currents (Ekman pumping or upwelling).

Some others are less used:

- heat budget (incoming-outgoing heat);
- outgoing longwave radiation (OLR);
- fresh water budget (evaporation-precipitation); and
- salinity.

Two type of studies might be defined:

1. Theoretical studies analysing the relationships between the behaviour of the fish and their environment. Such studies are crucial to understanding what stimulates the fish, their reproduction cycle and food behaviour. The goal is to have a clear understanding of how the fish fulfil these two essential functions, considering their environment. These questions can be tackled with historical data sets and complex numerical models;
2. More applied studies taking in account the catchability of the fish. These studies are mainly based on the mixed layer depth and/or SST. The shallower the mixed layer, the more vulnerable the fish to surface fishing gears. The use of climate indices such as the SLP index or wind stress observation, together with simple shallow-water models and near real-time satellite observations, are best for that purpose.

Both types of research are complementary, since interpreting real-time observations in order to best predict future fishing conditions requires an understanding of fish behaviour. Conversely, in order to validate fish-behaviour theories and take into account the influence of fishing activity when interpreting historical data, catchability studies are needed. Both types of studies, when carried out together, can help to distinguish between environmental effects and fishing effects on fish behaviour and fish stocks.

Availability of data and observation

The availability of data and observations are presented in the Appendices, with notes on their application and interpretation.

References

Barnett T.P., 1983 : Interaction of the Monsoon and Pacific Trade Wind System at Interannual Time Scales. Part I : The Equatorial Zone. *Monthly Weath. Rev.* Vol. Ill; 756-773.

Barnett T.P., 1984 : Interaction of the Monsoon and Pacific Trade Wind System at Interannual Time Scales. Part II : The Tropical Zone. *Monthly Weath. Rev.* Vol. 112; 2380-2387.

Barnett T.P., 1984 : Interaction of the Monsoon and Pacific Trade Wind System at Interannual Time Scales. Part III : A partial anatomy of the Southern Oscillation. *Monthly Weath. Rev.* Vol. 112; 2388-2400.

Barnett T.P., 1985 : Variations in Near-Global Sea Level Pressure. *Journ. Of the Atmos. Sc.* Vol.42 : 478-501.

Das P.K., 1986: Monsoons. *WMO* -No., 613.

Le Blanc J-L. 1996 : Variability in the Indian Ocean with emphasis on ENSO-associated variations since 1970. *Thesis Proposal: The Role of the Indian Ocean in the Global Climate System.* Unpublished.

Le Blanc J-L, 1997 : Climate Information and Prediction Services (CLIPS) for Fisheries. *WCASP-39.WMO/TD-No.* 788.

Glantz M.H.,1996 : Currents of Change : El Niño's impact on climate and society. *Cambridge Univ. Press.* pp194.

Marsac F. and J-L Le Blanc, 1998 : Interannual and ENSO associated variability of the coupled ocean/atmosphere system with possible impacts on the Yellowfin tuna fisheries of the Indian and Atlantic Oceans. *Symposium ICCAT; Ponta Delgada Açores.*

Meehl G.A., 1987; The annual cycle and interannual variability in the Tropical Pacific and Indian Ocean regions. *Monthly Weath. Rev.* Vol.l 15 : 27-50.

Monsoon Dynamics. Sir James Lighthill and R.P. Pearce (Eds.) *Camb. Univ. Press.* 1981.

Philander S.G., 1990 : El Nino, La Nina, and the Southern Oscillation. *Academic Press*, San Diego.

Rao T.S.S. and C. Griffiths, 1998 : Understanding the Indian Ocean. Perspectives *in* Oceanography. IOC *Forum.* UNESCO Publishing.

Rasmusson E.M. and T.H. Carpenter, 1982 ; Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Monthly Weath. Rev.* Vol. 110 ; 354-384.

Tomczak M. and J.3. Godfrey, 1994 : Regional Oceanography: an introduction. *Pergamon Press.*

Wacongne S. and R. Pacanowski, 1996 : Seasonal heat transport in a primitive equations model of the tropical Indian Ocean. *J. Phys. Oceanog.* Vol. 26. No. 12, p.2666-2699.

Webster P.J. and S. Yang, 1992 : Monsoon and ENSO : Selectively interactive systems. Q. J. *R. Meteorol. Soc.* Vol. 118. p. 877-926.

Webster P.J. and T.N. Palmer, 1997 : The past and future of El Niño, *Nature.* December 12; 390, 562-564.

Webster P.J., J. P. Loschnigg, A.M. Moore and R.R. Leben, 1998: The great Indian Ocean warming of 1997-1998 : Evidence of Coupled Oceanic-Atmospheric instabilities. *Sub. Nature.*

Yasunari T., 1990 ; Impact of Indian Ocean on the Coupled Atmosphere/Ocean system in the Tropical Pacific. *Meteo. Atmos. Phys.* Vol. 44 ; 29-41.

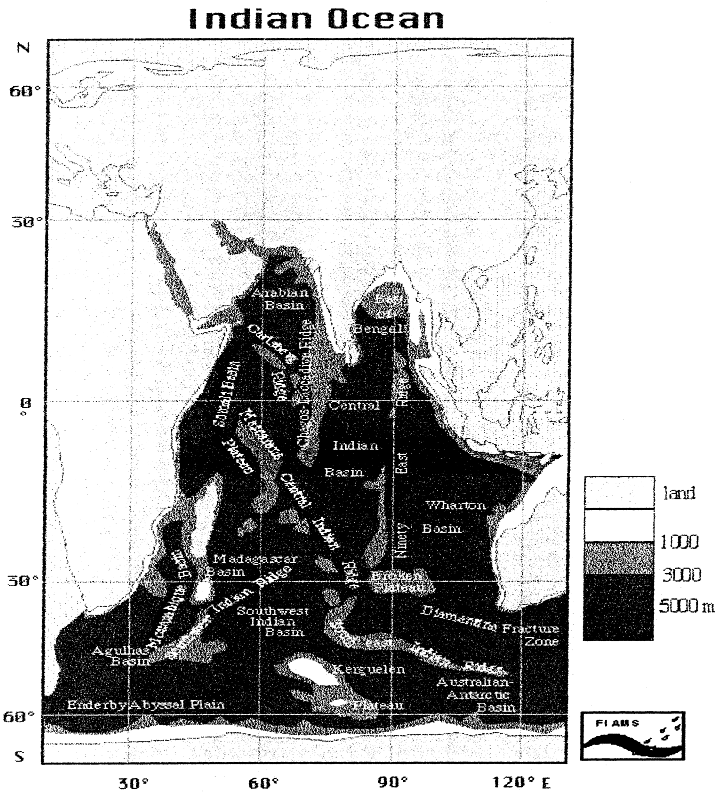


Figure 1: The Indian Ocean topography (from Tomczac & Godfrey, 1994)

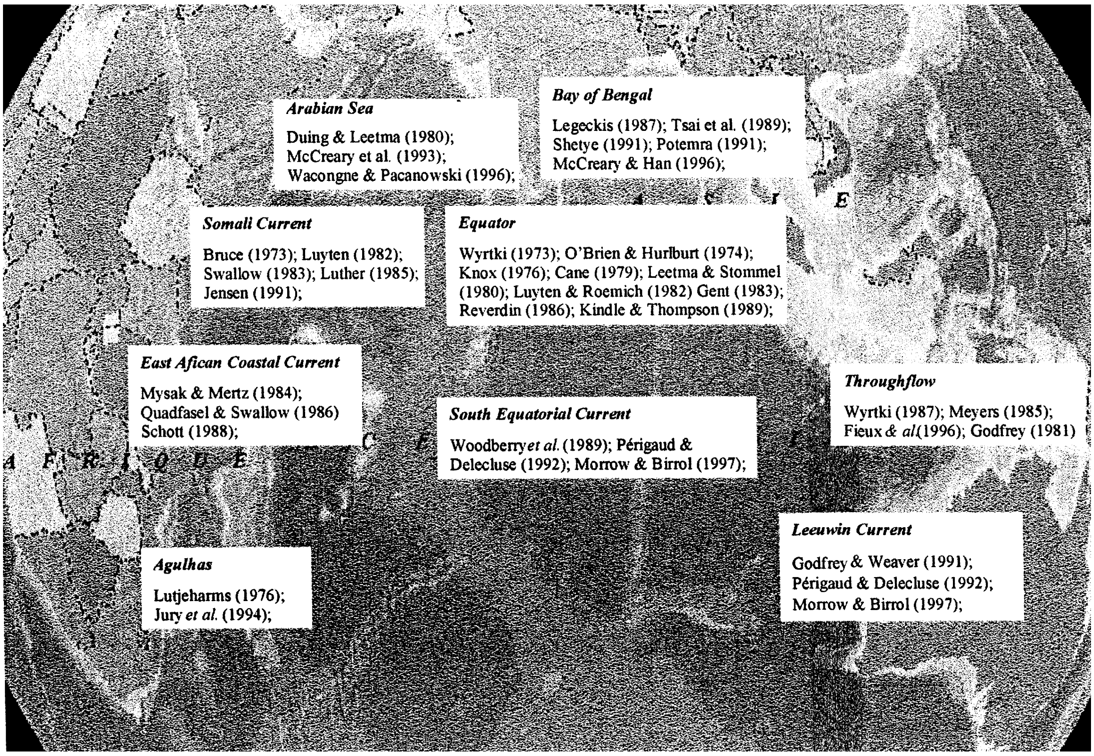


Figure 2: References – for details please visit the web site http://www.iprolink.fr/~tranthao/indianocean.htm

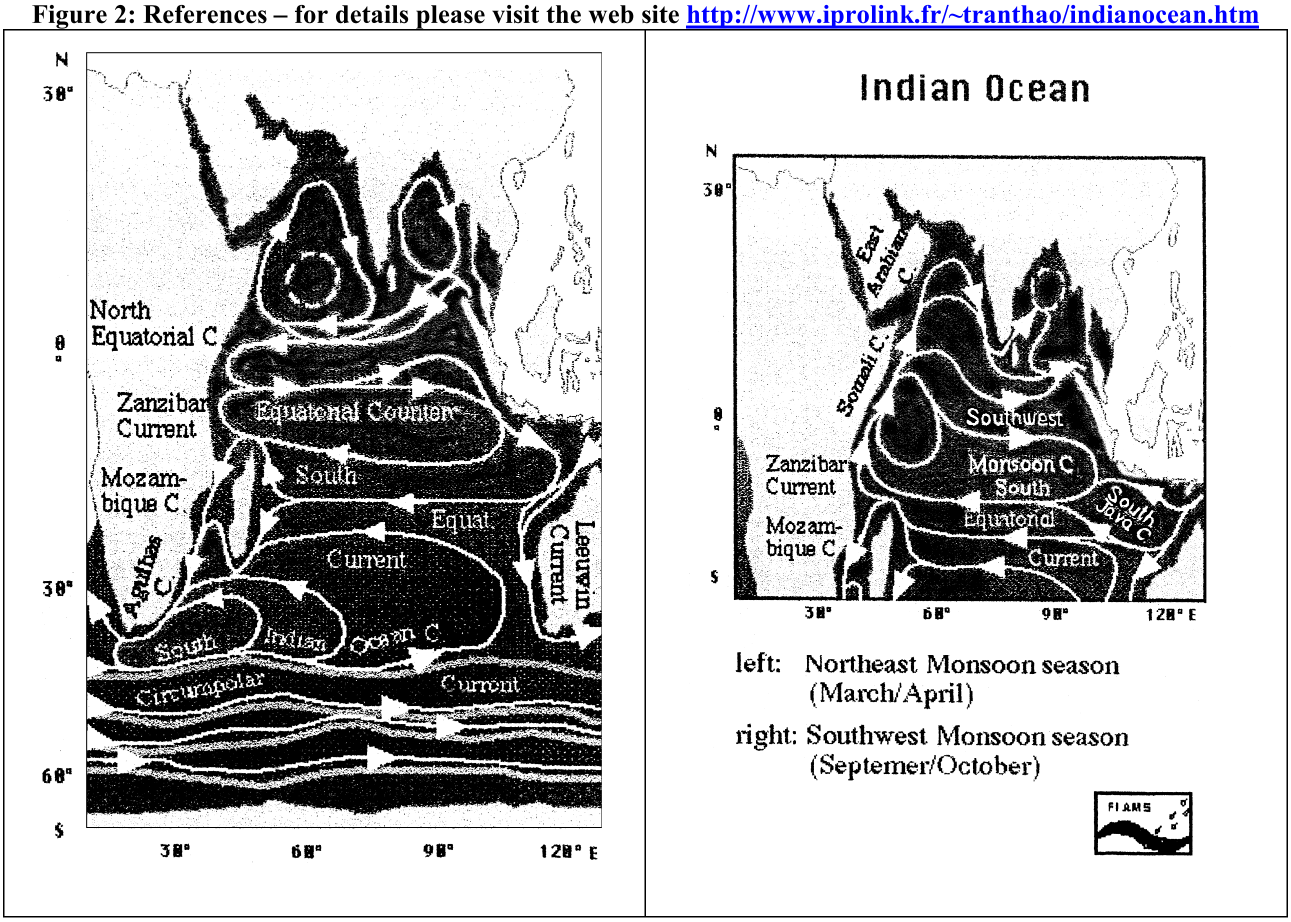


Figure 3: Oceanic circulation of the Indian Ocean during the northeast and southwest monsoons.

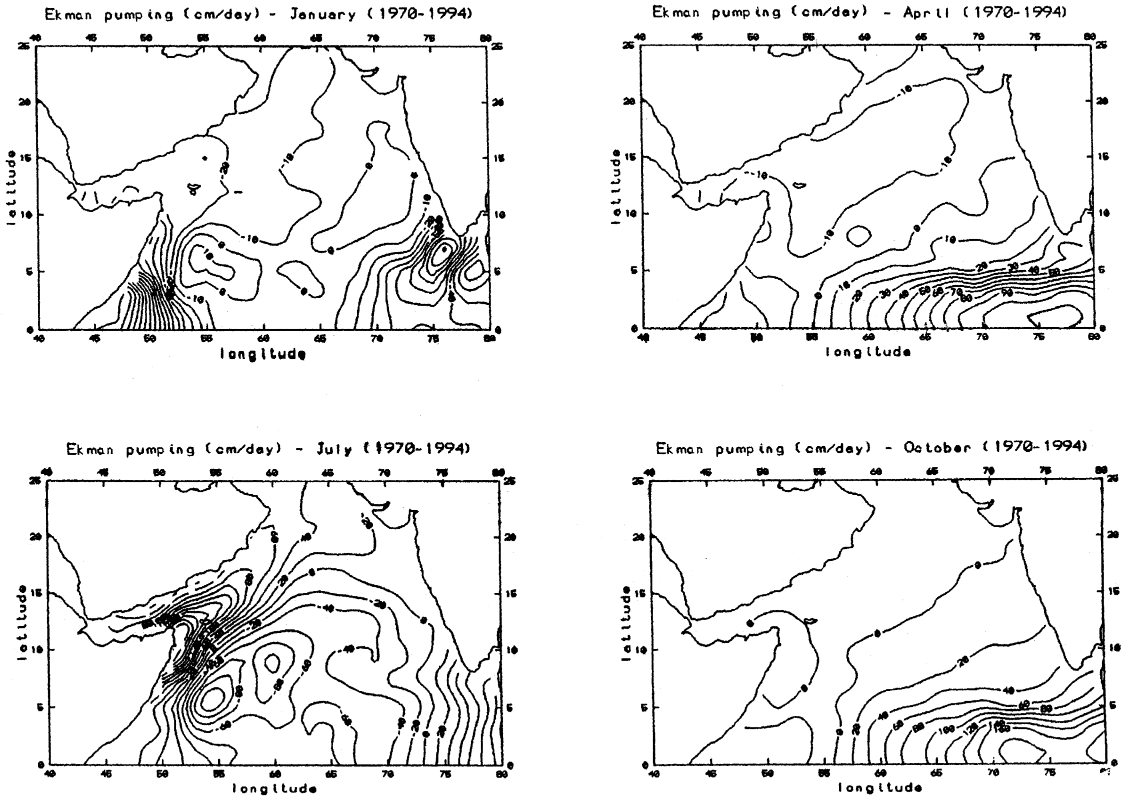


Figure 4: Upwelling in the Arabian Sea – Climatological mean (positive values are upwelling, negative are downwelling) (From Le Blanc, 1996)

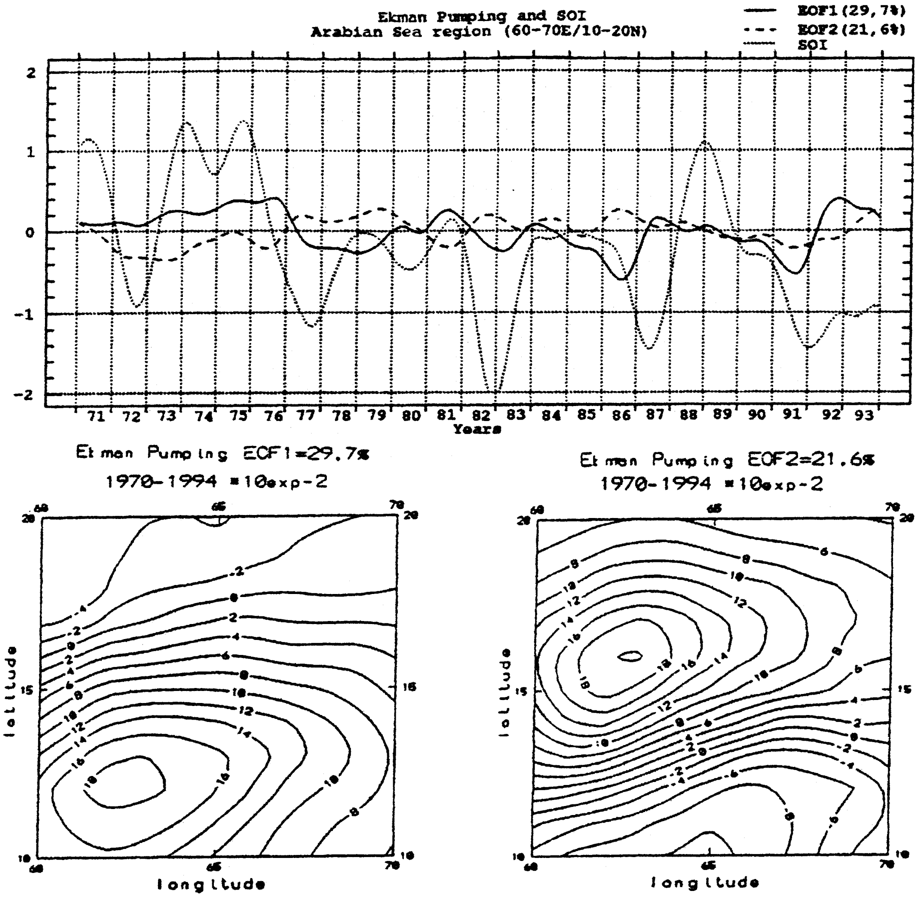


Figure 5: Interannual variations (from Le Blanc, 1996)

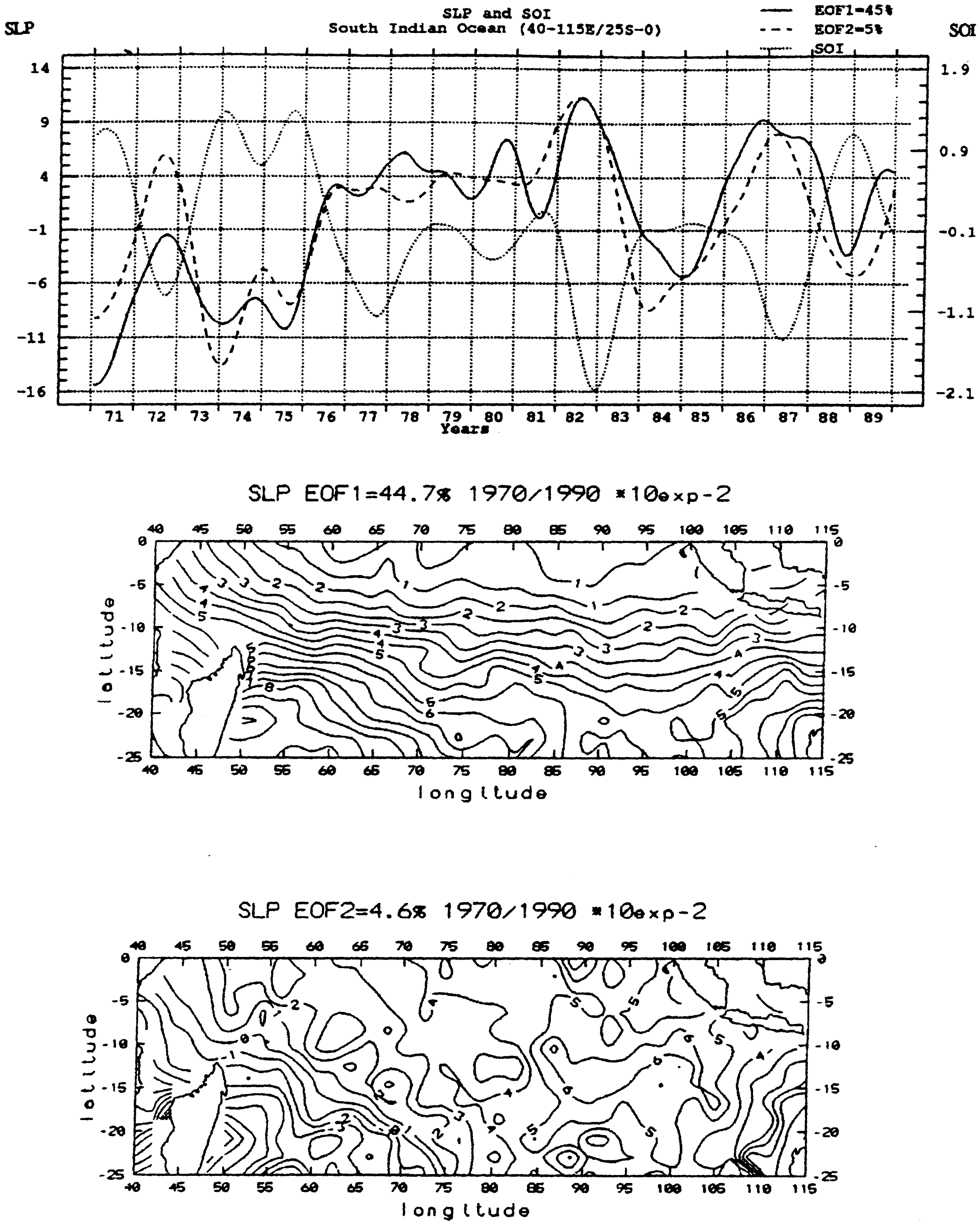


Figure 6: Sea level pressure (COADS) (from Le Blanc, 1996)

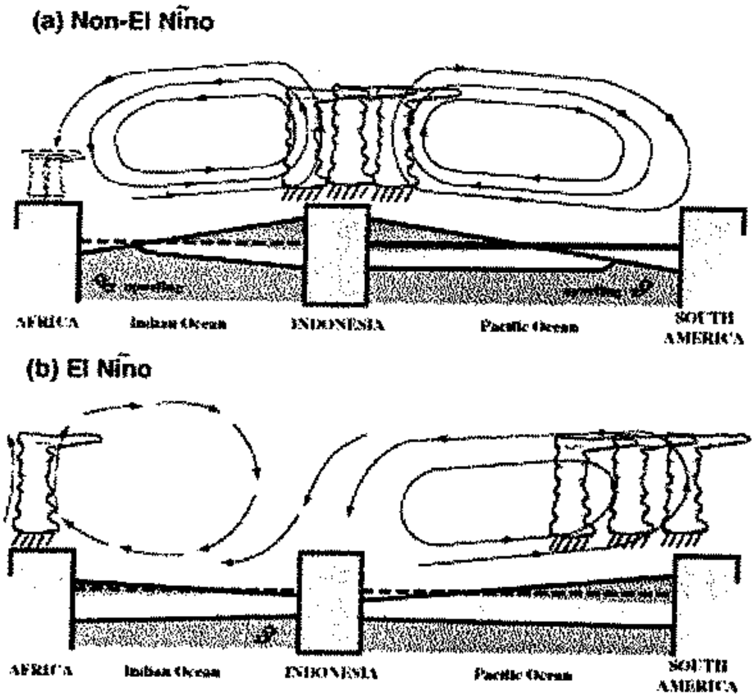
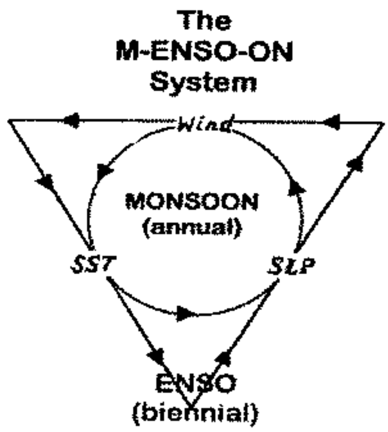


Figure 7a. Schematic Diagram of the large scale differences along the equator between(a) normal periods and (b) El Niño periods.

Figure 7b. Conceptual view of the Monsoon/ENSO coupling



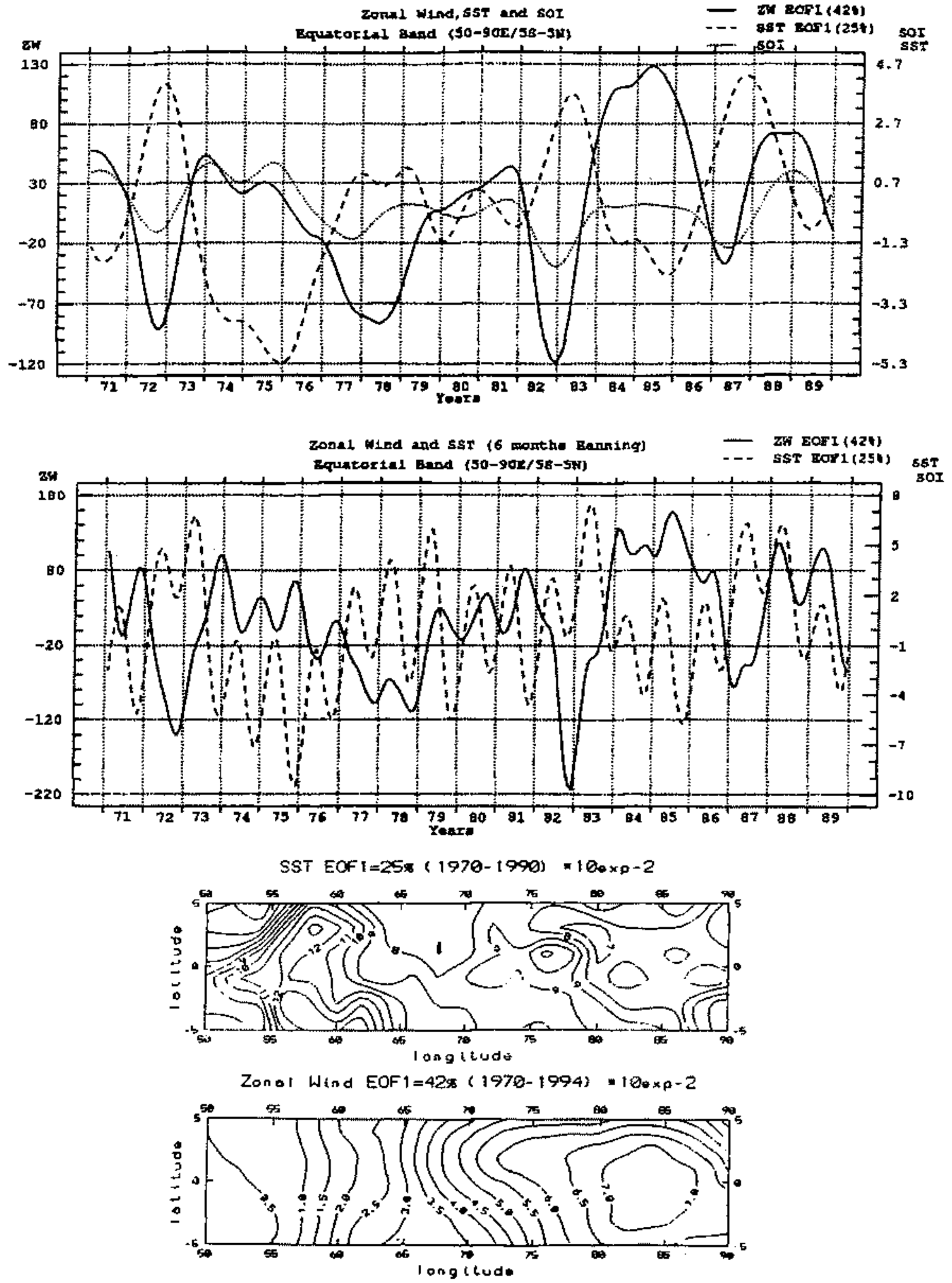


Figure 8: Zonal wind and SST anomalies – Interannual variations (positive wind anomaly means easterly winds and conversely (from Le Blanc, 1996)

APPENDIX A.
NEAR REAL TIME OBSERVATIONS AND DATA

1. ***Remote Sensing*** enables to have a daily view of the oceans. Some parameters such as SST are affected by the presence of clouds, but some others such as the sea-level are not because their measurement requires other techniques. The reliability of those measurements are therefore to be taken into account, especially on the way data has been interpolated.

However, comparison of measurements are now possible and it is now possible to estimate the reliability of an observation.

This appendix presents the website of the American Navy [http://www7300.nrissc.navy.mil/altimetry/] which proposes satellite observations of the Indian Ocean and the Arabian Sea. Measurements are achieved through different techniques for comparison, and anomalies to the mean are calculated.

Anomalies are interesting since they show local mechanisms such as convergence, divergence associated downwelling or upwelling respectively. Heat transfer might be detected and long waves too. As mentioned before, these dynamic mechanisms might be essential in understanding and predicting the fish behaviour, especially tuna which is very sensitive to variations of temperature or currents.

Furthermore, such anomalies can be associated with interannual variations. This has been explained previously and it is the climatologists job to find out which anomalies might be precursors to interannual variations such as ENSO.

2. The ***Climate Diagnostic Center (CDC)*** [http://www.cdc.naoo.gov/cdc/data/nmc/marine.html] also proposes near real-time marine data. Parameters measured are various and include SST, SLP, wind (u & v components), air temperature, and cloudiness. They have also estimated derived variables such as latent heat flux and the wind stress which enables air-sea interaction studies.

The user can select a variable and has the choice to visualize it on a plot. Measurements being scarce out of the ship tracks, it is necessary to select a long enough period in order to have sufficient data to enable the interpolation.

This tool is therefore interesting for seasonal (or longer) studies. Thus, variables can for instance be observed for a specific monsoon. The data are also available through FTP.

3. ***Wind stress*** is a crucial parameter for the study of fish-environment relationships. The fish often lives in the upper mixed layer of the ocean. This mixed layer is directly under the influence of wind stress. The wind stress induces currents, horizontal and vertical (upwelling or downwelling); creates turbulence and thus, the mixing of the upper-layer. Upwelling is important for bringing nutrients from the subsurface layers to the upper-layer, and turbulence is not favourable to larval survival.

Wind stress is also used as a forcing for numerical models, thus enabling the study of the ocean response to the applied winds (especially the wave response). Furthermore, coupled ocean-atmosphere models might have predictive skills enabling to detect strong interannual variations.

As for SST or any other parameter, there are two measurements techniques:

- Remote sensing;
- In-situ measurements through ships of opportunity.

The Center for Ocean-Atmosphere Prediction Studies (COAPS) [http://www.coaps.tsy.edu/WOCE/SAC/indianwinds.html], offers pseudostress analyses from merchant ships, buoys, and other marine observing stations. Anomalies are also proposed and data are available through images and FTP.

This data set is used for forcing Luther's Indian Ocean model (see figure A.3). Such simple models (Shallow-Water models) may be useful in providing the quick response of the ocean to real-time winds, showing divergence and convergence zones as well as oceanic waves. Monthly oceanographic forecasts are thus possible and catchability as well as larval survival conditions can be analysed on a real-time basis (i.e. as soon as the wind data is available). Models can also be forced with wind anomalies in order to observe the anomalous response of the ocean (supposed to be at rest when in climatic equilibrium). For more details, please visit the authors website referenced page 1.

Satellite ERS-2 is also measuring wind and the American Navy site (see above), shows images of real-time observation. But such data are not yet available in a suitable format for application.

APPENDIX B.
FORECASTS

1. The ***Fleet Numerical Meteorology and Oceanography Centre (FNMOC)*** treats satellite observations on a global scale and uses them together with numerical models to forecast the evolution of the observed parameter. Forecast of wave height are presented.

2. The ***South African Weather Bureau*** [http://www.sawb.gov.za/www/rt/s1indsst.htm] uses an Indian Ocean Canonical Correlation Analysis (CCA) model to forecast SST anomalies several months ahead.

The usefulness of such products is still to be determined. They are included here for information.

APPENDIX C.
HISTORICAL DATA SETS

Historical data sets can be found through several Climate Centres, especially American ones such as NOAA or NCDC. The data is usually compressed in CD-Roms.

Four major products may be mentioned:

- The Comprehensive Ocean-Atmosphere Data Set (COADS);
- The pseudo wind stress data set of the Florida State University (FSU);
- The World Ocean Atlas;
- The Tropical Ocean Global Atmosphere (TOGA) and WOCE data sets.

Regarding the first data set, the latest release covers the period 1950-1995. The extraction tool is designed for Mac computers only. For the previous release (1854-1990), software for PC Windows 95 has been written by ORSTOM[12] to extract the data.

The pseudo wind stress data set is the model output, by 1°x l° and month, computed by the Florida State University and available on the Web (see Appendix A).

The World Ocean Atlas includes oceanographic stations (discrete observations) at observed and standard levels, and climatology fields for temperature, salinity, dissolved oxygen and nutrients.

The TOGA data set is a compilation, since 1985, of vertical temperature profiles (mostly XBTs and CTDs). The WOCE data set include temperature profiles and multiparameter stations, but it is not yet available as a whole. Data must be gathered from the participating institutions or on the Web.

The pseudo wind stress data set, the observed levels of the stations extracted from the World Ocean Atlas, and the Indian part of the TOGA data set have been compiled in the GAO system, which includes an indexed database and processing tools in a Windows 95 interface. This product was developed by ORSTOM1 and will be available on CD-ROM in 1999. More information is available in the paper dedicated to GAO in this volume.

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