

Marine environmental conditions in the SW Indian Ocean and sympathetic trends of coastal fish catch

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Abstract—This study considers marine environmental factors driving fluctuations in coastal fish catch in the SW Indian Ocean using FAO data. A consistent oscillation of catch is found for Mauritius, Madagascar, Reunion and the Comoros, and is shown to be related to a widespread change in marine environmental conditions that prevails during the preceding year that include the following:

- An upper ridge of high pressure is present to the south of Madagascar where SSTs are above normal;
- Southerly winds are stronger to the east of Madagascar; westerly winds are strengthened in the monsoon zone around 5- 10 S;
- Dry weather prevails in a NW-SE band across Madagascar and the adjacent island nations; and,
- Sea surface temperatures (SST) off Angola increase well in advance.

Further work is needed to compare marine environmental signals that could emerge from locally sourced fish catch data and those reported here with the FAO time series.

INTRODUCTION

Marine fish populations show evidence of fluctuations in abundance related to climatic conditions and physiological requirements (Lluch-Belda *et al.* 1989, 1993; Regier and Meisner 1990; Glanz 1990; Kawasaki 1992a, b; Schlesinger and Ramankutty 1994; Kawasaki 1994; Polovina *et al.* 1994; Jonsson 1994; Garrod and Schumacher 1994; Brodeur and Ware 1995). With this background, the Food and Agricultural Organization (FAO) initiated research to analyze the world fishery and stimulate the development of forecasting (FAO 1994, 1996, 1997a, b). Beamish *et al.* (1999) found that a significant portion of catch fluctuations depend on environmental conditions rather than on fishing

effort. Klyashtorin and Sidorenkov (1996) and Klyashtorin (1998) found an alternation of roughly 30-year epochs in climatic indices and fish catch. Freon *et al.* (2003) give a critical review of these studies and have found that regime shifts occur in the response of regional fisheries to global climate fluctuations.

Reliable information on the marine environment has been gathered since the 1940s, as evidenced by numerous data sets available over the worlds' oceans. Initially sea and air temperature, air pressure and winds were monitored. Since 1980, with satellite coverage, estimates of the ocean's currents, heat exchange and sub-surface conditions are now able to be model-interpolated into global fields. The global average surface air temperature anomaly is a useful

index of climatic trends. Another is an atmospheric circulation index that distinguishes periods of relative dominance of either zonal or meridional winds in the mid-latitudes (Girs 1974). The formulation of similar indices for the SW Indian Ocean is hampered by a shorter period of dependable observations (e.g. 1960 onward). It has been found that 'zonal' epochs correspond to periods of global warming and 'meridional' epochs to global cooling (Lamb 1972; Lambeck 1980, LeRoux 1998).

The atmosphere is the most variable component of the global geophysical system (Salstein *et al.* 1993). A number of publications suggest that inter-annual variations in angular momentum imparted by zonal winds are important (Langley *et al.* 1981; Rosen and Salstein 1983; Robertson 1991) as indicated by the length of day (Stephenson and Morrison 1995) and related to the El Niño Southern Oscillation (ENSO) phenomenon (Salstein and Rosen 1986; Dickey *et al.* 1992a,b). The ENSO signal is expressed in the tropical south Indian Ocean as an east-west oscillation in the thermocline and the zonal overturning Walker circulation (Jury and Huang, 2004) and would thus be expected to play some role in determining the function of the marine ecosystem, as outlined in Marsac and LeBlanc (1997) and LeBlanc (1997).

Following from this discussion - a key question is: to what extent are coastal fisheries in the SW Indian Ocean affected by the surrounding environmental conditions. The total world marine catch amounts to 73 M T / year, made up of 550 species (FAO, 1997a). Catches of certain species are related with the zonal atmospheric circulation driven by ENSO phase, whilst catches of other species are more sensitive to the meridional circulation (Girs 1974). Although most (pelagic) fish catch is from the cold upwelling regions of the world, there is reason to believe that the SW Indian Ocean coastal fisheries (largely demersal) may respond in an organized way to climatic forcing. For example, fish catch along the coast of Tanzania responds to decadal variations in temperature of the west Indian Ocean which consequently influence rainfall and salinity (Jury *et al.*, 2005).

Catch alone is acknowledged to be a crude measure of abundance, but changes in catch of

dominant species appears to reflect real changes in population size (Lluch-Belda *et al.* 1989). Catch records are seldom of sinusoidal shape due to catch-dynamics, life history patterns and lags between fishing effort and natural productivity (Sharp *et al.* 1983). Important questions to be answered in assessing climatic dependence include: Which elements are of greatest significance (e.g. sea temperature, wind, rainfall, nutrients)?; and does the ocean or atmosphere lead? To establish the relationship between fish catch and marine conditions it is necessary to average the data over a time period that takes into account the generally slow variations of the ocean (Monin 2000) and the lifespan over which fish absorb and react to the environmental conditions (~3-4 years).

METHODS

Here a 'targeted' approach is taken considering four independent data sets of coastal fish catch from Mauritius, Madagascar, Reunion and the Comoros. A brief analysis of the dominant species indicates that they tend to oscillate together (correlations are significant). A potential deficiency of the data is that an unknown portion of the catch may be unreported. Hence to minimize noise and maximize the resource signal, 'catch' here refers to the combined weight of all fish species caught in territorial waters. Reliable fisheries records span a time of three to four decades, such that year-to-year fluctuations may be characterized and related to the regional marine environment. In this regard, sea surface temperatures, and climatic fields that influence the properties of sea water (e.g. rainfall, winds, etc) are analysed. As a step toward forecasting, environmental conditions are averaged for the calendar year preceding high and low fish catch years, using compositing techniques as described below.

Four independent time series are used to assess environmental impacts on coastal fish catch in the SW Indian Ocean. Annual fish catch totals for the period 1960-1998 were extracted from the FAO fish database. These records are divided by the total national population to estimate catch per capita, and then linearly detrended. Consideration of data for all countries of the SW Indian Ocean indicates that the Madagascar fisheries is largest, followed

by Tanzania and Mozambique; averaging 39 000, 36 000 and 21 000 mT, respectively. In comparison, the coastal fish catch (including EEZ catches, but excluding those offshore) reported for Mauritius, Reunion and the Comoros is rather small, eg. 9000 declining to 4000 mT. Because absolute catch varies widely, inter-comparisons are made using departures from each nation's mean. The detrended coastal fish catch for Mauritius and Madagascar is shown in figure 1. The time series for Comoros and Reunion show similar trends. They are significantly correlated ($r = +.47$, $p < .02$) and suggest a shared response to the surrounding environmental conditions, despite differences in geography. From an average of the four time series, the sensitivity of marine productivity (represented by fish catch) to the physical environment is assessed.

Marine environmental conditions are represented using the National Center for Environmental Prediction (NCEP) model-assimilated ocean and atmosphere data set. It is based on all available surface ship and coastal data, optimally interpolated using numerical weather prediction equations as constrained by environmental fields derived from satellite remote sensing. Statistical analysis is carried out based on an assessment of high and low catch years. Marine environmental fields (eg. SST, wind, rainfall, etc) over the domain 50 S - 20 N, 30 - 90 E are mapped, contrasting the years preceding high and low catch to determine resource sensitivities. The years preceding high (low) catch are slightly different for each island nation (as shown in table 1). By averaging together all four standardized departure time series with equal weighting, the high (low) years that emerge include: 1973, 1987, 1988, 1991, 1992; (1977, 1978, 1979, 1980, 1997). To highlight

differences, the low catch maps are subtracted from the high catch maps. The results are then considered in light of the above scientific questions.

RESULTS

Fish catch variability

The linearly detrended time series of catch for Mauritius and Madagascar (figure 1) exhibits roughly decadal oscillations, with high catch in the period 1965-1975 and 1985-1995 and low catch in alternate decades, within the forty year record. The Tanzanian fish catch also exhibits decadal oscillations that relate to fluctuations of tropical cyclone occurrences in the SW Indian Ocean (Jury *et al.*, 2005). Autocorrelation of the time series is significant for year+1 in all records as a result of the decadal oscillation. Hence a 'good' year is followed by another, and the statistical degrees of freedom are 'deflated' before significance tests are applied. Mechanisms for the decadal oscillation of SW Indian Ocean climate have been put forward in Chang-Seng (2005) in relation to tropical cyclone occurrence. These involve the low frequency part of the ENSO signal and its impact on the sub-tropical jet stream. Similar patterns are revealed in the composite analysis below, based on a time series constructed by averaging the various detrended catch records.

Composite environmental maps

Environmental fields for 60 high catch months versus 60 low catch months (H-L) are considered out of a total of 456 months. Composite maps for

Table 1: Years before high and low catch in the SW Indian Ocean, based on detrended FAO catch data for all species

Comoros		Reunion		Mauritius		Madagascar	
High	Low	High	Low	High	Low	High	Low
88	60	73	64	86	78	65	68
89	62	80	68	87	79	66	77
90	63	93	76	88	80	67	78
91	64	94	85	90	89	73	79
93	65	95	86	91	95	87	80
94	66	96	88	92	97	88	81

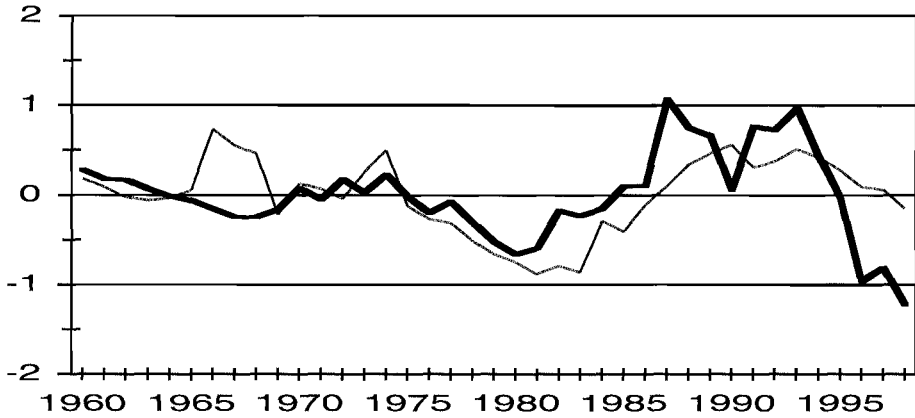


Fig. 1. Linearly de-trended Mauritius (lighter line) and Madagascar fish catch per capita from FAO data; expressed as standardized departures from the mean, y-axis)

surface winds, upper level atmospheric pressure, SST, rainfall and other climatic elements help indicate which processes are most important with respect to fish catch in the SW Indian Ocean. If the high and low catch years are treated independently, the inverse patterns that emerge indicate that marine environmental signals for high and low catch years are opposed.

The surface wind pattern prior to a year of high catch (figure 2) reveals increased southerly flow to the east of Madagascar, and increased westerly flow in the monsoon zone 5- 10 S between 50- 80 E. Southerly flow induces sinking (Jury and Mwfulirwa 2002) and brings drier mid-latitude

air over the region that limits the development of tropical cyclones and associated rainfall (Jury *et al.*, 1999). A positive feedback occurs, whereby the drier air and reduced cloud cover leads to increased solar radiation and surface warming. This in turn increases the geopotential thickness and supports an upper level high pressure ridge, as illustrated in figure 3 for the H - L years from the average catch series. The ridge is most prominent south of 30 S, in the longitudes 40- 50E. It remains quasi-stationary through the preceding year and thus anticipates catch fluctuations in the SW Indian Ocean.

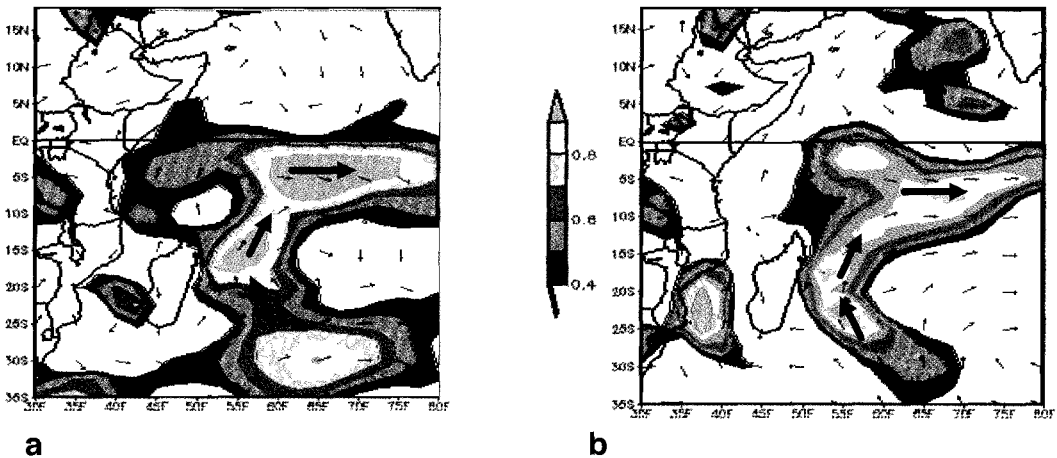


Fig. 2. High minus Low (H-L) composite surface wind maps for the preceding year for Mauritius (a) and Madagascar (b) fish catches illustrating southwesterly flow (colour bar in m/s)

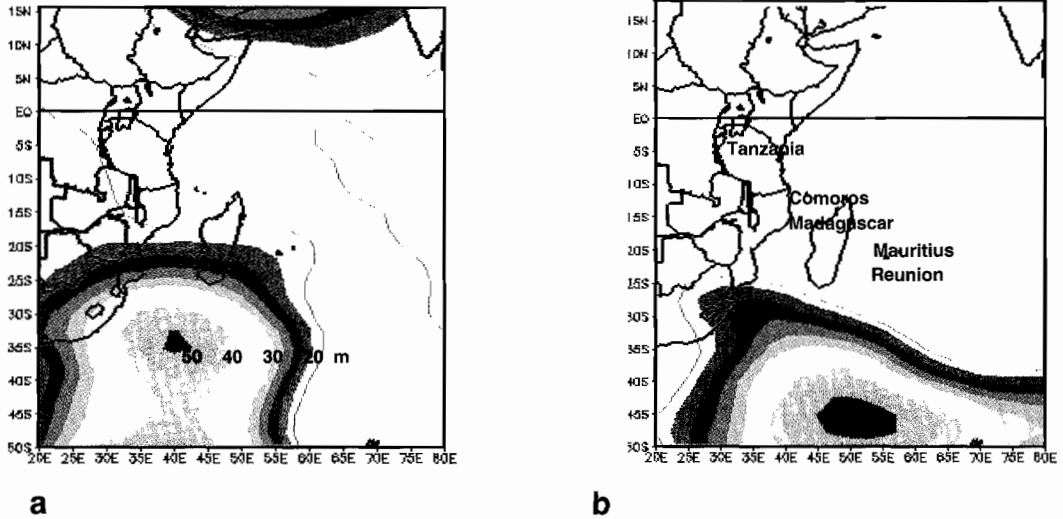


Fig. 3. H - L composite upper geopotential height pattern (upper pressure) for the 1st (a) and 2nd half of the year preceding high minus low fish catches, (b), illustrating a stationary ridge to the south. Place names are given in the right panel

The foregoing analysis of upper atmospheric conditions requires an evaluation of surface impacts. The composite rainfall map yields a significant pattern (figure 4a), revealing a NW-SE tilted 'wave train' of alternating wet- dry- wet conditions. The dry zone overlies northern Madagascar and the island nations of Comoros, Mauritius and Reunion. Wet zones prevail either

side: over southern Africa and in the central Indian Ocean. The NW-SE dry zone would be consistent with a reduction in tropical cyclones (Chang-Seng 2005). Two oceanic processes could play a role to enhance catch: 1. increased salinity would affect water density and vertical entrainment, and 2. a less disturbed sea state would contribute to greater efficiency. These aspects are briefly considered in section 4.1 below.

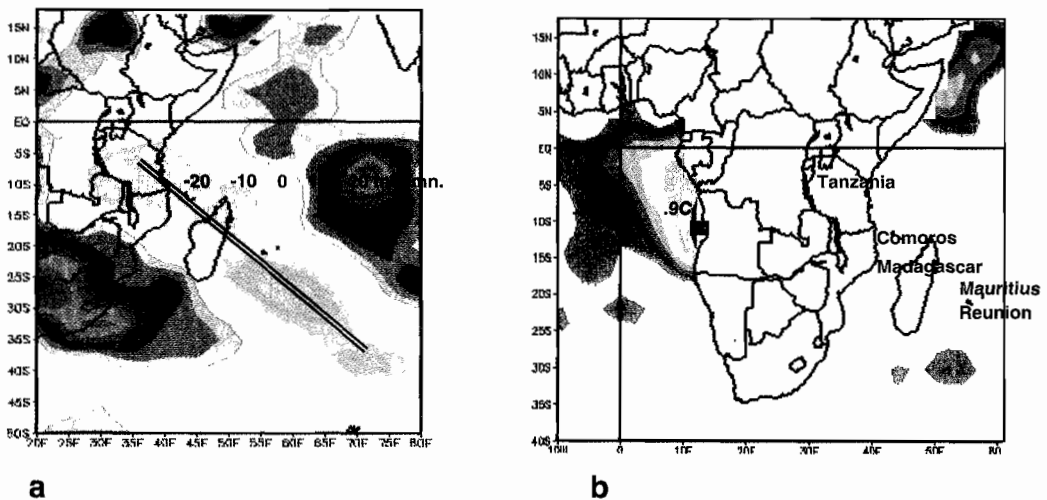


Fig. 4. H-L composite rainfall differences (a) and SST for the preceding year, illustrating dry weather extending across the SW Indian Ocean and above normal SST off Angola (b). Colour shading indicates rainfall (a) and sea temperature differences according to labelling

The occurrence of atmospheric conditions favouring more abundant marine resources may be predicted through the use of SST, gaining the benefit of the ocean's thermal inertia as a stable indicator. Past studies have suggested that SSTs over a wider domain are useful in predicting Africa's climatic anomalies. A number of factors govern ocean temperatures, including local wind-related surface fluxes, the radiation budget, vertical entrainment, horizontal advection by currents and Rossby wave undulations of the thermocline (Jury *et al* 2002). In figure 4b composite SSTs are mapped for the preceding year. Significantly above normal SSTs are found off the coast of Angola, a pattern similar to that found by Kanemba (2005) with respect to increased rainfall and malaria in Mozambique. The area of largest SST signal is located at the base of the tropical east Atlantic cold tongue that is known to be responsive to Pacific ENSO signals (Xie and Carton, 2004). SSTs are also above normal in the Somali region, hence the tropical upwelling regions either side of Africa experience a relaxation. However across the SW Indian Ocean, there is little difference in SSTs before high and low catch years.

DISCUSSION

At the outset of this research, a close correspondence in coastal fish catch time series for four island nations in the SW Indian Ocean was

not anticipated. The findings of the catch-environment relationship analysis yielded some points of interest. Increased catch for Mauritius, Madagascar, Reunion and Comoros is preceded by dry weather and southerly surface winds, supported by a quasi-stationary upper level high pressure to the south, beneath which are warm SSTs. Tropical rainfall is a key element that connects the marine resources of four island nations. A NW-SE axis of below normal rainfall extends from Tanzania and the Comoros, across Madagascar to Mauritius and Reunion prior to years with high fish catch. Convective rainfall from NCEP reanalysis (figure 5) exhibits alternating decades of high and low rainfall that is related to the oscillations of the Pacific and Atlantic (Yeshanew 2003). Stormy seas and high winds in the mid-1970s and 1990s (seen in NCEP area-averaged data) are followed by declining fish catch (refer figure 1), whereas reduced convective rainfall in the mid-1960s and 1980s (fig. 5) is followed by increasing catch.

Ocean response

To determine air-sea interactions, ocean data from the Univ. Maryland assimilation system, available on the IRI Climate Library website, were analysed. These monthly data are derived from observations interpolated with a numerical ocean model, and adequately represent low frequency variability. This analysis confirms that areas to the northwest

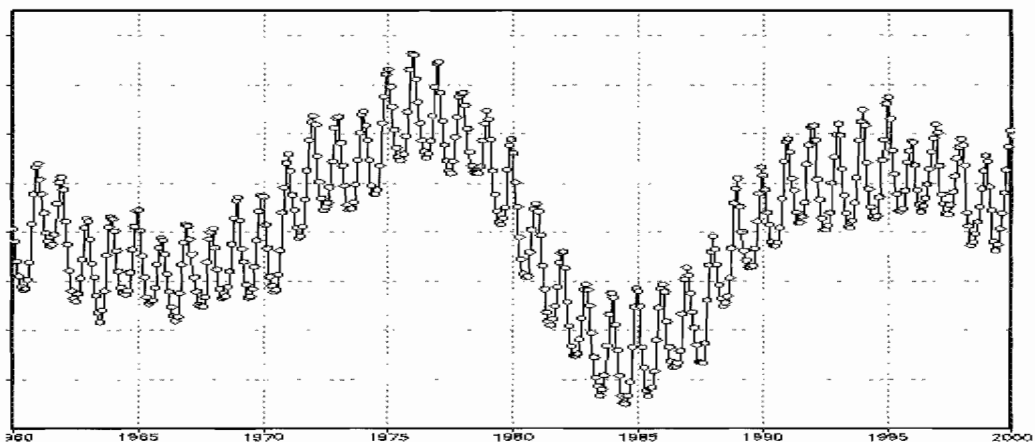


Fig. 5. NCEP reanalysis model convective rainfall averaged over the area 10-25 S, 40-60 E (Madagascar), smoothed with a multi-year running mean. Alternating decades of high and low rainfall are exhibited

and east of Madagascar exhibit similar sub-surface ocean signals in terms of decadal trends and annual cycle. In the sequence of years with low catch (late 1970s), salinity is lower (< 34.8 psu) and noisier (suggesting rainfall), whereas in years before and during high catches, salinity remains above 34.9 psu and variations are diminished. This supports the suggestion that higher catch in waters around Madagascar is preceded by periods of higher salinity associated with lower rainfall and reduced river run-off. It is speculated that increased water density would promote the entrainment of nutrients and higher productivity, a concept requiring further research.

The means by which reduced storminess is preceded by increased SST off Angola is discussed in Chang-Seng (2005), and relates to decadal trends in climate that influence the Atlantic zonal overturning (Walker) circulation. When upper easterlies and lower westerlies occur over the tropical Atlantic (with the onset of a Pacific La Niña), SST off Angola increase above normal and correspond with a downstream oscillation in the subtropical jet stream over the SW Indian Ocean. The meandering of this westerly current in the upper atmosphere contributes to alternating areas of wet and dry weather that appears to be sufficiently long-lived (years) to influence the ocean nutrients, availability of forage and 'catchability' of the fish around Madagascar, Comoros, Mauritius and Reunion.

The better management of fish stocks requires knowledge of the preferred environmental conditions of the most important commercial species and an indication of the carrying capacity for exploitation. Although the environmental patterns revealed here could offer a degree of forewarning, further work is needed to check whether the environmental signals brought out by the international data employed here are replicated in respect of locally sourced fish catch data. Once this is done, predictive modeling of catch could form a useful input to fisheries management.

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