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Outline of climate and oceanographic conditions in the Indian Ocean: an update to August 2013

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Abstract

In this paper, we provide an update on the trends of climate and oceanographic conditions in the Indian Ocean and in sub-regions (Somali basin, East and West Equatorial areas, Mozambique Channel and Maldives). The ENSO cycle has been largely fluctuating between ENSO-neutral and Niña conditions during the past 4 years. Positive sea surface temperature (SST) anomalies have prevailed since the early 2000 over the West Indian Ocean (WIO). Substantial deepening of the thermocline occurs in the WIO in relation with intense El Niño events, but the opposite response (shoaling) during La Niña events is not clear on the long term. Since 2008, SOI has shown predominantly positive values (Niña) and thermocline has shoaled without major disruption along this trend until April 2011. Chlorophyll (SSC) has shown a declining trend over 2006-2010, followed by a slight increase from October 2010 to May 2011 in association with a Niña event, then continued to decline until March 2013. Then, the trend reversed and positive anomalies developed from May 2013 onwards. Highly positive SSC anomalies were found in July-September 2013 in the Somali basin (40% above normal), suggesting an intensification of the Somali upwelling. In other areas, SSC was about the average in 2013 (Mozambique Channel, Maldives) or still slightly negative (10 % below normal) in the West equatorial (December 2012 to February 2013) and East equatorial areas. The overall chlorophyll-depleted conditions for 2006-2012 (except 2011) in the WIO, when the thermocline was shoaling, is unclear as we might have expected a positive chlorophyll response to an increased supply of nutrients in the photic layer associated with shallow thermocline. The skipjack purse seine CPUEs on associated sets, in the Somali basin during July-September, are distributed in chlorophyll-enriched areas resulting from the upwelling. In 2010-2012, the position of the 0.4 mg.m-3 isoline of chlorophyll concentration delineated the eastward boundary of the skipjack CPUEs.

Introduction

A detailed analysis of the climate and oceanographic conditions over the period 2002-2012 was presented at WPTT-14 in 2012 (Marsac, 2012). The series analysed at WPTT-A4 ended in August 2012. In this paper we use the same variables (atmospheric indices, sea surface temperature, depth of thermocline and sea surface chlorophyll concentration) as in 2012. The data series are updated to August 2013 and further discussed. An analysis of the environmental influences on skipjack CPUEs of the purse seine fleet in the Somali region is also presented.

Data used

Atmospheric indices

The Southern Oscillation Index (SOI) is documented in many websites. A comprehensive analysis of trends of a number of climate and oceanic variables, and climate updates at a global scale are found in the Climate Diagnostics Bulletin of the CPC/NOAA at the following URL :http://www.cpc.noaa.gov/products/analysis_monitoring/bulletin/).

The Indian Oscillation Index (IOI) was introduced by Marsac and Le Blanc (1998). Similarly to the SOI, this index is the difference of standardized anomalies of the sea level pressure in two distant sites characterized by a dipole-like pattern, namely Darwin and Mahé (Seychelles) for the IOI. The series is updated monthly and the whole series, starting in 1951, is available with the author.

SST and Z20

The long-term trend of the sea surface temperature (SST) is investigated with the Extended Reconstructed SST of the NOAA/NCDC which includes *in situ* data collected by ships and buoys. We now use the most recent version of the dataset (ERSST.v3b). With a spatial resolution of 2 degrees of latitude/longitude, ERSST is suitable for long-term global and basin wide studies; local and short-term variations have been smoothed in ERSST (Smith et al, 2008). The monthly anomalies were calculated from a climatology established by the author over the period 1971-2000.

The study of the variability patterns and the regional environmental assessments was carried out with the outputs of the NOAA/NCEP Global Ocean Data Assimilation System (GODAS), which provide fields of temperature, salinity, vertical velocity and current for 40 depth levels (5 to 4500 m), along a 1° longitude/0.33° latitude grid globally. The model outputs are produced monthly from January 1980 to the present. Here, we use the depth of the 20°C isotherm (Z20) as a proxy for the thermocline. Z20 is obtained by interpolation between consecutive depth levels. The monthly anomalies were calculated from a climatology established for each variable by the author over the period 1980-2005.

The Dipole Mode Index (DMI), that quantifies the Indian Ocean Dipole (Saji et al, 1999), is obtained by subtracting the SST anomalies between the West and East Indian Ocean. The west box is 50°-70°E/10°N-10°S and the east box is 90°E-110°E/0°-10°S The ERSST dataset was used compute the DMI.

SSC

The chlorophyll product of the SeaWifs (1997-2002) and Modis (2002 to present) sensors were used to study the trends in sea surface chlorophyll (SSC). The original dataset is the Level-3 monthly composite at a 9-km resolution. In order to combine the analyses with SST and MLD, we generated a monthly Chlorophyll dataset at the same grid as the NCEP-GODAS model output (1°Lon/0.33° Lat) from the original 9-km dataset. The monthly anomalies were calculated from a climatology established by the author over the period 2003-2008. The transition between SeaWifs and Modis series was done by averaging values of both sensors over a common period of 6 months (July to December 2012).

Skipjack catch per unit effort

The French and Mayotte purse seine catch per set data for 1991-2012 were used to compute CPUEs. The CPUE is expressed as tons of skipjack per positive set on associated school (floatsam or FAD). Catch and number of positive sets are pooled by 1° lat-lon/month strata, and then all strata having less than 3 sets on associated schools are discarded. CPUE is firstly calculated by strata then averaged for each month in the study area which is 10°N-5°S / 45°E-60°E.

Results and discussion

1- Atmospheric indices

The atmospheric indices used are the Southern Oscillation Index (SOI) and the Indian Oscillation Index (IOI) (Marsac & Le Blanc 1998). The series for 1972-2013 are shown in Fig 1 (a-b). A mature Niña event developed early 2008, then weakened in the middle of the year, then strengthened again in December 2008. A transition to ENSO-neutral conditions occurred in April 2009 until a transition to moderate El Niño conditions in Dec 2009/January 2010. Then a transition to strong La Niña conditions started in July-August 2010, peaked in January 2011 then decayed. Another transition to ENSO-neutral conditions occurred during May 2011, and a new Niña event started to develop in

September 2011. This event decreased in March 2012 and ENSO-neutral conditions have prevailed since then (Fig. 1a)

Until 2005, the IOI negative conditions (reflecting warm events) happened in synchrony with the negative SOI. Since 2006, IOI has been predominantly negative, with low IOI occurring during Niña events (like in 2008). The strong Niña which developed early 2001 had only a slight positive counterpart on the IOI (Fig. 1b). The mechanisms of such a transition from synchronized to non-synchronized situation remains unclear.

We used cumulated anomalies to describe the trend of IOI and SOI (Fig. 2a). These cumulated anomalies were then normalized. The trends of IOI and SOI were well in-phase until July 2006, when they started to diverge significantly. SOI increased dramatically, whereas IOI continued to decrease to negative values. Such a decrease of the IOI started in 2000.

The ENSO cycle has been largely fluctuating between ENSO-neutral and Niña conditions during the past 4 years. There are predominant positive SST anomalies since the early 2000. It is not clear whether the higher rate of increase of the SST in the recent years (post-2005) may explain the sustained trend towards negative IOIs (reflecting warm events). The IOI is supposed to account for a dipole situation in the atmospheric pressure between Darwin and Seychelles, across the Indian Ocean. Indeed, until 2005, sea level pressure anomalies (SLPa) were fluctuating about the mean in the two sites. Since 2006, we have observed a decrease of the SLPa in both sites, and the decline was sharper in Seychelles compared to Darwin. This situation has driven down the IOI to sustained negative values. The question that arises is whether there is a direct link between higher SST over the Indian Ocean and lower SLP. This needs further investigation.

2- Trends in SST, Z20 and chlorophyll concentration in the West Indian Ocean

The cumulated SST anomalies show a steady increase since the early 2000s (Fig. 2b). The rate of increase is greater during the most recent years compared to that of 2000-2005 (respectively 4.8 and 3°C of cumulated anomalies).

The Dipole Mode Index (DMI) fluctuations are not explicitly consistent with SOI (Fig. 1c). Positive DMIs have prevailed since 2007 whereas La Niña events were mostly dominant. There is little more consistency with IOI especially since 2006 where positive DMIs correspond with negative IOI, both denoting warmer conditions.

The thermocline (Z20) followed major 4 trends since 1980: 1) a shoaling trend until July 1991; 2) a deepening trend that peaked during the 1997-1998 El Niño with sustained positive anomalies until December 2000; 3) a shoaling trend that ended in April 2011; 4) a well-established deepening trend up to present (Fig. 2c).

The sea surface chlorophyll concentration (SSC) showed an upward trend in the early 2000, peaking in April 2006, followed by a constant decline until September 2010. Then, a slight reversal of this trend occurred until May 2011, in relation with a Niña event. A decline with a similar rate as the previous one was again observed until January 2013. A slight rising trend occurred afterwards (Fig. 2c).

Substantial deepening of the thermocline occurs in the WIO in relation with intense El Niño events, but the opposite response (shoaling) during La Niña events is not clear on the long term. Indeed, the thermocline has shoaled without major disruption along this trend until April 2011, when SOI exhibited positive values. However, a shoaling trend started in January 2001 when a quasi ENSO-neutral episode was established. The overall chlorophyll-depleted conditions for 2006-2012 (except during the transient 2010/2011 Niña event) in the WIO, when the thermocline was shoaling, is unclear as we might have expected a positive chlorophyll response to an increased supply of nutrients in the photic layer associated with shallow thermocline. This also needs further investigation.

3- Regional analyses

The Indian Ocean has been partitioned into 5 main areas: Somali basin (SOM), Maldives (MAL), west equatorial area (WEQ), east tropical area (ETR) and Mozambique Channel (MOZ) (Fig. 3). We computed the annual average of the SSC in each of these areas. Note that 2002 and 2013 are incomplete (2002 starts in July and 2012 ends in August), and therefore might not be strictly comparable to the other years. Three groups appear in terms of chlorophyll content: SOM and MOZ are the most productive areas (SSC : 0.30 to 0.50 mg/m3), then MAL and WEQ (SSC : 0.12 to 0.20 mg/m3), and lastly ETR being the less productive area (SSC around : 0.10 mg/m3) (Fig. 4). SOM exhibited a rapid decline from 2002 to 2007 then levelled off about 0.3 mg/m3. In 2010, CHL concentration increased of ca 25% compared to 2009 then decreased again until 2012. THE CHL trend reversed sharply in 2013. MOZ and WEQ had a more moderate decline in CHL content from 2003 to 2011 and 2012 respectively, and then the trend reversed in 2011 and 2012 respectively. CHL content in MALD decreased from 2005 to 2012, and then increased in 2013, whereas no trend was detected in ETR.

We examined the trends of SST, Z20 and SSC in the different regions. Regions are presented according to the three groups exhibiting similar productivity patterns, as shown in the previous paragraph. A detailed analysis of each region for 2002-2012 was presented during WPTT-14 (Marsac, 2012). Therefore, we only focus on the most recent years, after completing 2012 (the previous analysis stopped in August 2012) and including data for January-August 2013.

3.1 The Somali basin (Fig. 5)

The last 2 years of the series point out a return to colder than average conditions, after a period of warmer conditions from 2007-2011 (with the exception for 2008). The colder SST anomalies would reflect an intensification of the Somali upwelling. The rate of change in SSC mirrors the SST trend, with depleted CHL associated to warmer conditions. Chlorophyll content dramatically increases in 2013, likely a consequence of the upwelling intensification. It does not appear any clear ENSO/IOD effect on the two variables studied.

3.2 The Mozambique Channel (Fig. 6)

To make years comparable, we computed anomalies over the period January to August. The large positive SST anomalies observed in 2009-2011 weakened sharply in 2012-2013. Z20 anomalies have remained moderate since 2010 and a return to average conditions was initiated in 2013. No clear trend is expressed in the SSC series. Conditions are back to normal in 2013.

The Mozambique Channel is characterized by a strong mesoscale activity, with anticyclonic and cyclonic eddies formed in the north of the Channel and propagating to the south (Biastoch and Krauss, 1999; de Ruijter et al, 2002). Such eddies and rings, of ca 100-200 km radius, affect the thermocline depth and the spatial distribution of SSC through upwelling in the core of cyclones, concentration process at the edge of eddies, eddy-eddy interactions, and shelf-eddy interactions along the Mozambique and Madagascan coasts (Quartly and Srokosz, 2004; Tew-Kai and Marsac, 2009). It should be noted that the resolution of the GODAS model is too coarse to account for that kind of variability.

3.3 The West equatorial Indian Ocean (Fig. 7)

The analysis is focused on the core of the north-east monsoon, December to February, when free schools are harvested by the purse seiners. This area is also a major spawning ground for yellowfin tuna at that season. The value assigned to the year *y* is an average of December_{y-1} to February_{y}. The SST shows a clear increase from 2011 (cold anomalies associated to La Niña) to 2013 where the cumulated anomaly is above 0.5°C. After several years of shallow thermocline (2008-2011) when the thermocline remained at a depth of 70 to 80 m (15 metres above normal), the conditions were back to normal in 2012 and up to present. The Z20 fluctuations are well correlated to the ENSO cycle, with shallow thermocline associated to positive (Niña-like) SOI. Very low CHL content was observed in

2012 (20% below normal) which is opposite to the high CHL anomalies observed in 2004 (20% above normal). The SSC from December 2012 to February 2013 is 10% below normal.

3.4 Maldives (Fig. 8)

The statistics are calculated for the period January-August to allow between-year comparisons on the whole series. Warmer conditions have mostly prevailed since 2002. These anomalies peaked in 2010, with a cumulated anomaly of 3.4°C. The conditions were back to normal in 2013. The magnitude of changes in Z20 depth does not exceed 10 meters in Maldives. The most recent deepening was in 2012, and conditions were back to normal in2013. There is no clear relationship between SSC and SST or Z20. There was a highly CHL-depleted condition in 2012 (20% below normal) and the situation returned to the mean in 2013.

3.5 The East tropical Indian Ocean (Fig. 9)

The statistics are calculated over a 12-month period ranging from July (of the previous year) to June (of the current year). The rationale is that inter-annual anomalies, mostly related to ENSO/IOD variability, start to build up during the second semester, reach a peak at the turn of the year, then decrease during the subsequent first semester. Hence, the anomalies can be better appraised during a 12-month period covering to consecutive half-years than during a standard year. We do not present the Z20 anomalies as the area contains patterns of opposite variability, as shown by the spatial EOF1 (Fig. 6 in Marsac, 2012). The averaged-MLD over the area was therefore very close to 0 (range from -5.6 to +4.5 m). The warm anomalies which started in 2009 were interrupted in 2011 by La Niña, after which warm anomalies appeared again and increased over 2012 and 2013. The SSC variability is consistent with the SST variability, with warmer (colder) events corresponding to lower (higher) productivity. The highest positive CHL anomaly was recorded in 2011 (26% increase from the 2002-2012 baseline). It corresponded to a long and anomalously productive event already reported by Marsac (2011) and well shown in the spatial EOF1 (see Fig. 8, Marsac, 2012).

4- Environmental influences on skipjack purse seine CPUEs.

This analysis is restricted to skipjack CPUEs calculated in the Somali basin from July to October where purse seiners operate almost entirely on floating objects. There, catches are dominated by skipjack. We studied the influence of the current in the delineation of the fishing area from 2010 to 2012. The average pattern is a flow oriented northwards along the Somali coast that redirects offshore between 5°N and 10°N. Retention areas can be generated in the gyring flow which is generated offshore (Swallow and Fieux, 1982), promoting the accumulation of drifting logs and FADs (Fig. 10a and b). The offshore domain is enriched by the upwelling, as denoted by the chlorophyll content (Fig. 10c). The purse seine catches are distributed in waters with CHL content greater than 0.4 $mg.m^{-3}$. The offshore expansion or contraction of the CHL-enriched waters would potentially affect the spatial distribution of the catches. This would deserve further investigation.

The fluctuations of skipjack CPUEs and SSC exhibit some kind of synchrony, with higher CPUEs associated to enhanced CHL content (Fig. 11). The highest CPUEs (>30 t/set) were recorded when the CHL content was ranging from 20% to 40% above the mean. However, some discrepancies exist in 1999, 2008 and 2009 when the CPUE increased without any concomitant CHL enhancement (CHL content was 10% and 20% below the mean respectively for 1999 and 2008-2009). CHL is the source of the energy propagating through the trophic pathways and can be seen as a proxy of prey enrichment. This would apply particularly well in a region where the surface circulation tends to create retention areas, in which intermediate trophic levels could be retained. Tunas, whose feeding strategy is highly opportunistic (Roger, 1994, Potier et al, 2004) can forage on a broad range of sizes and take advantage of the biological enrichment in those retention areas. The increasing CHL content observed in 2013 should potentially promote good foraging conditions for tunas and consequently, higher CPUEs on associated schools during the 2013 fishing season.

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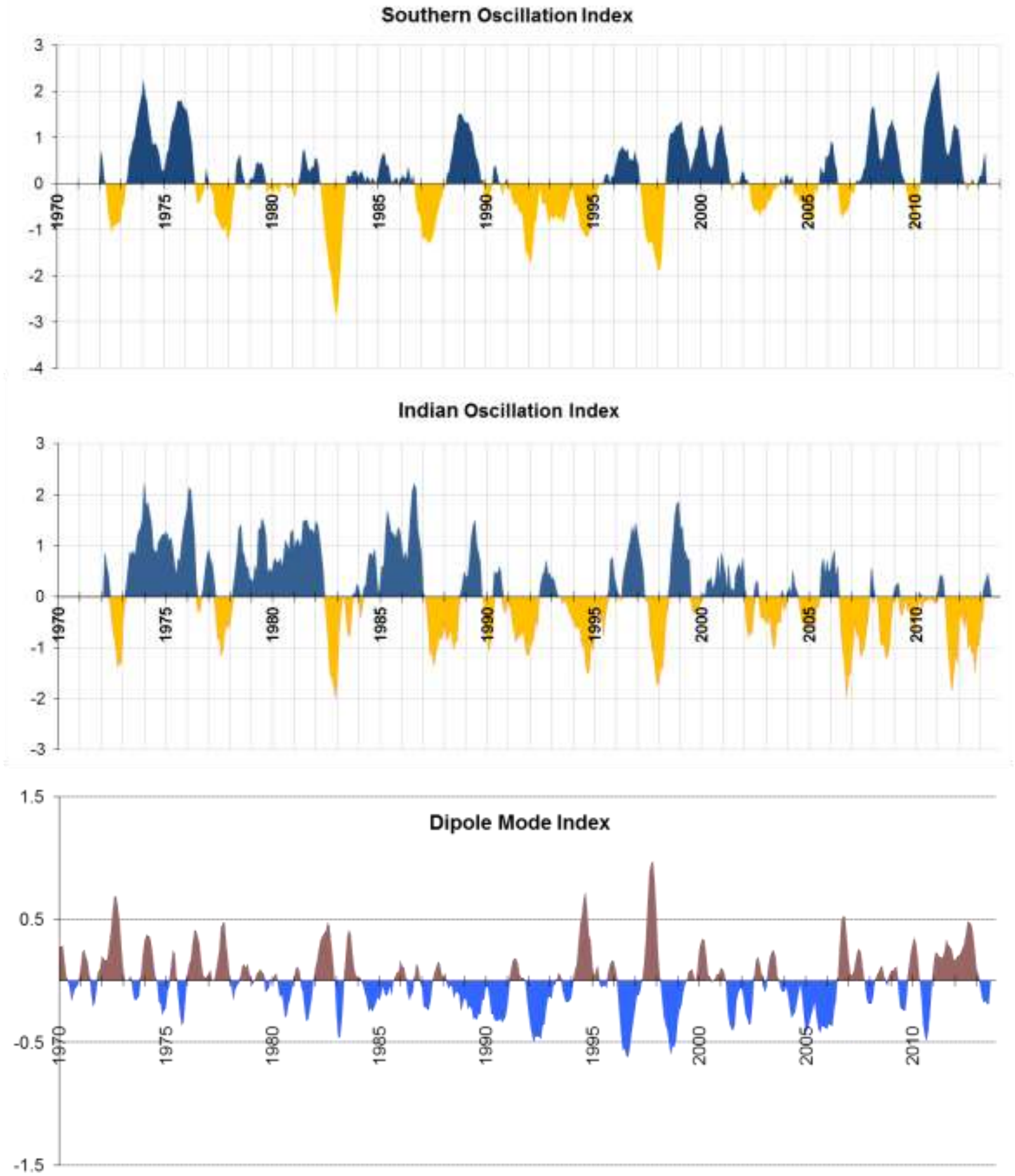


Fig. 1 - Southern Oscillation Index (a- top), Indian Oscillation Index (b-middle) and dipole mode index (c-bottom) over the period January 1972 – August 2013. The values plotted here are a 5-month moving average of monthly SOI/IOI/DMI. Warm (cold) events are represented by negative (positive) SOI and IOI, and positive (negative) DMI.

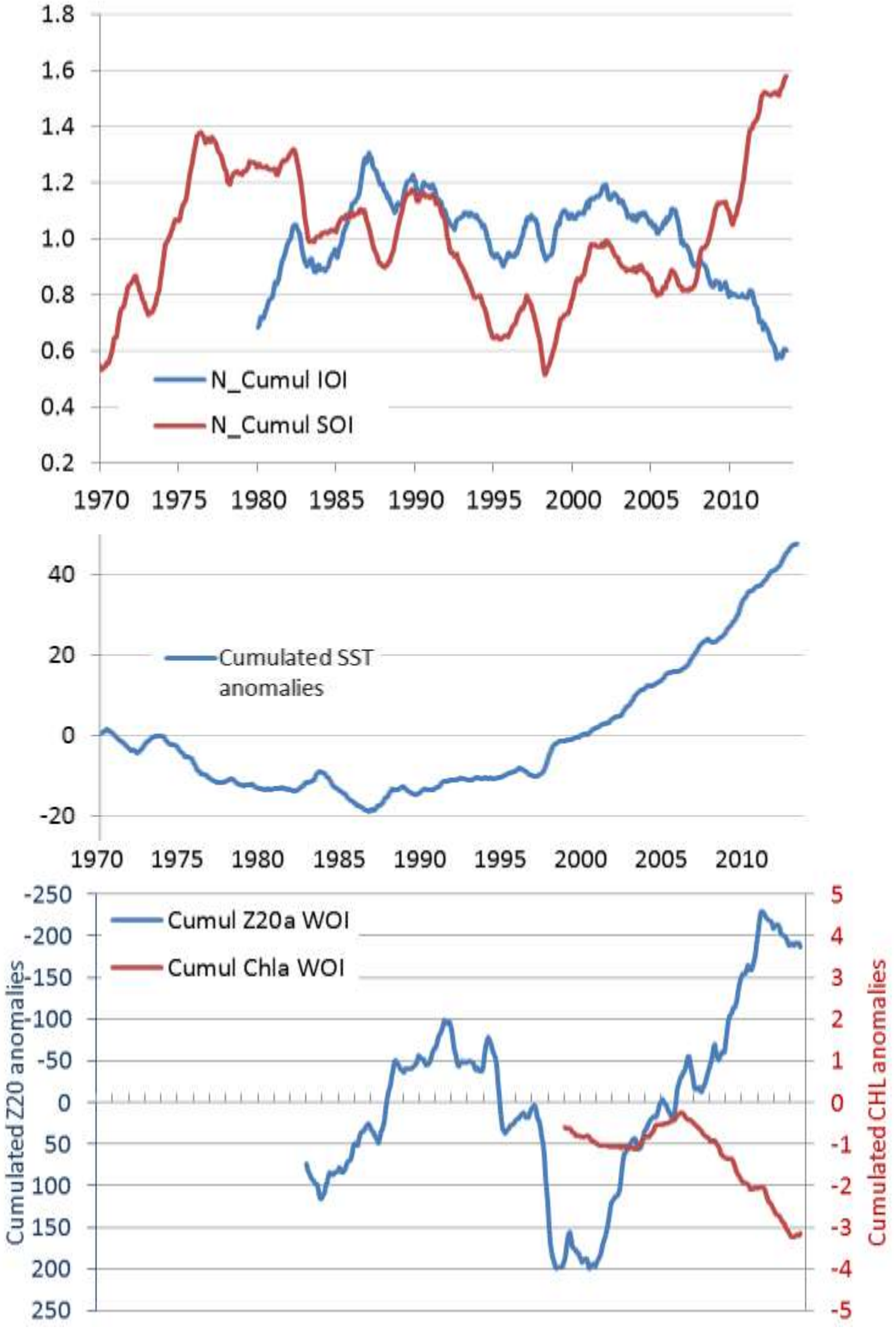


Fig. 2 – Normalized cumulated anomalies of SOI and IOI (a-upper panel), cumulated anomalies of the sea surface temperature (b-middle panel), cumulated anomalies of the depth of the thermocline and of the sea surface chlorophyll (c-bottom panel) in the West Indian Ocean (50° E-70 ° E / 10° N-10 ° S). Negative (positive) Z20 anomalies denote a shoaling (deepening) of the thermocline.

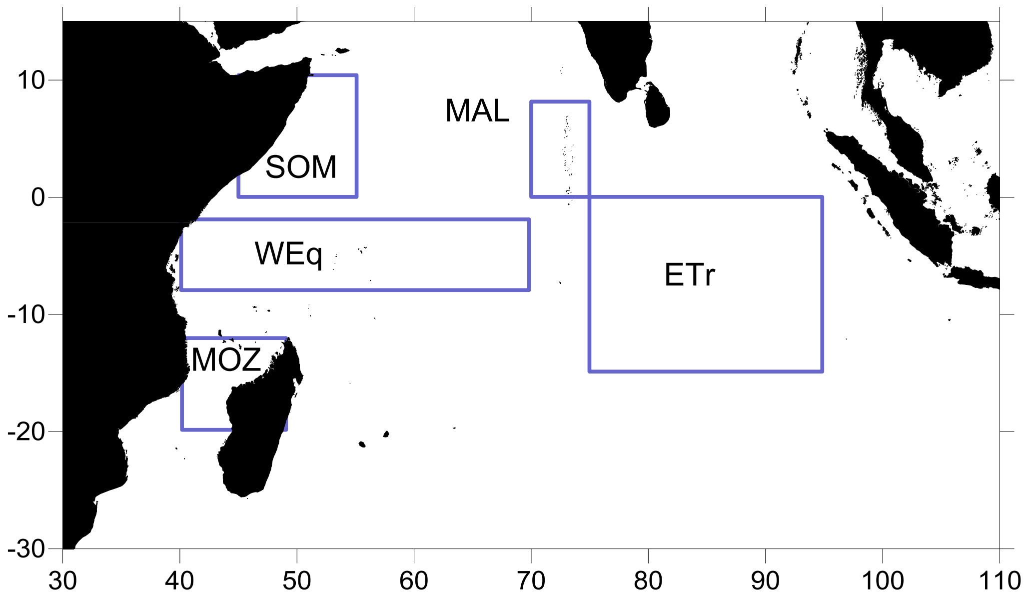


Fig.3 – Areas used for regional analyses

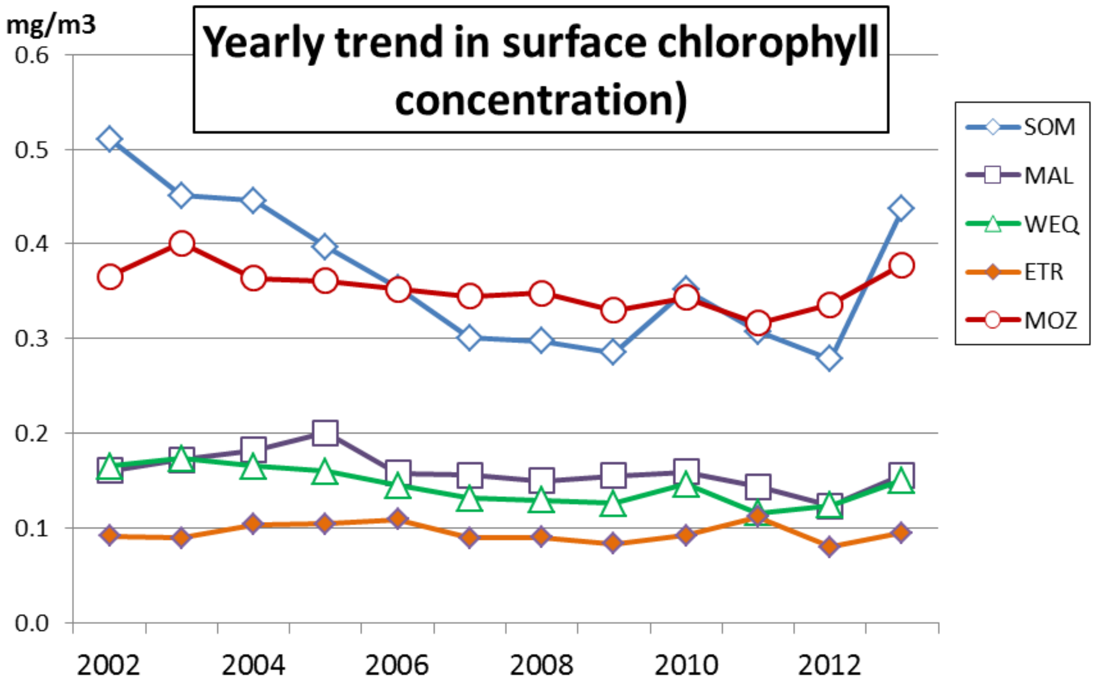


Fig. 4– Yearly trends of Sea Surface Chlorophyll by area, 2002-2013. Note that both 2002 and 2013 are incomplete (2002 starts in July and 2013 ends in August).

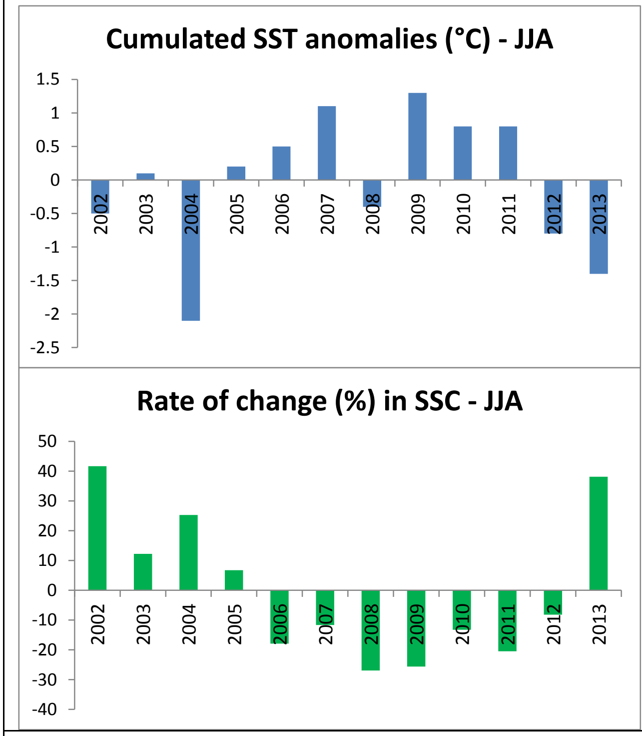


Fig. 5 – SST and SSC trends during the south-west monsoon, average June to August, in the Somali basin. SST anomalies are cumulated over the season, SSC is expressed as rate of change about the 2002-2013 average, June to August.

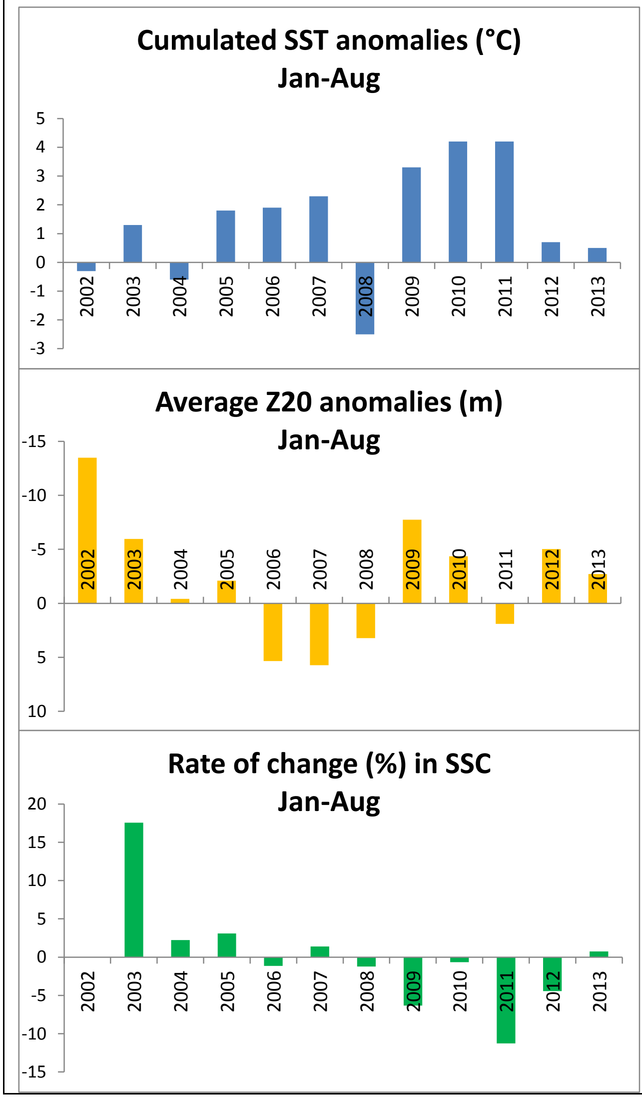
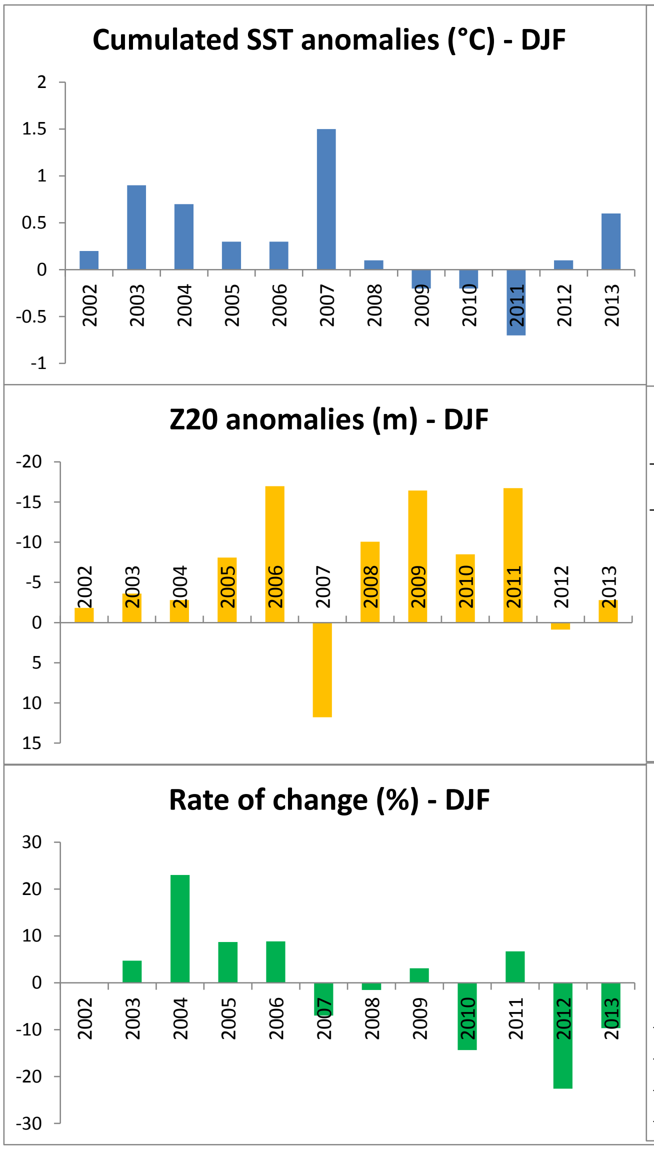


Fig. 6 – SST, MLD and SSC trends in the Mozambique Channel. Statistics are calculated for the period January to August. SST anomalies are cumulated over the period, MLD anomalies are the average over the period and SSC is expressed as rate of change about the 2002-2013 for the study period. Negative (positive) MLD anomalies denote shoaling (deepening) of the thermocline.



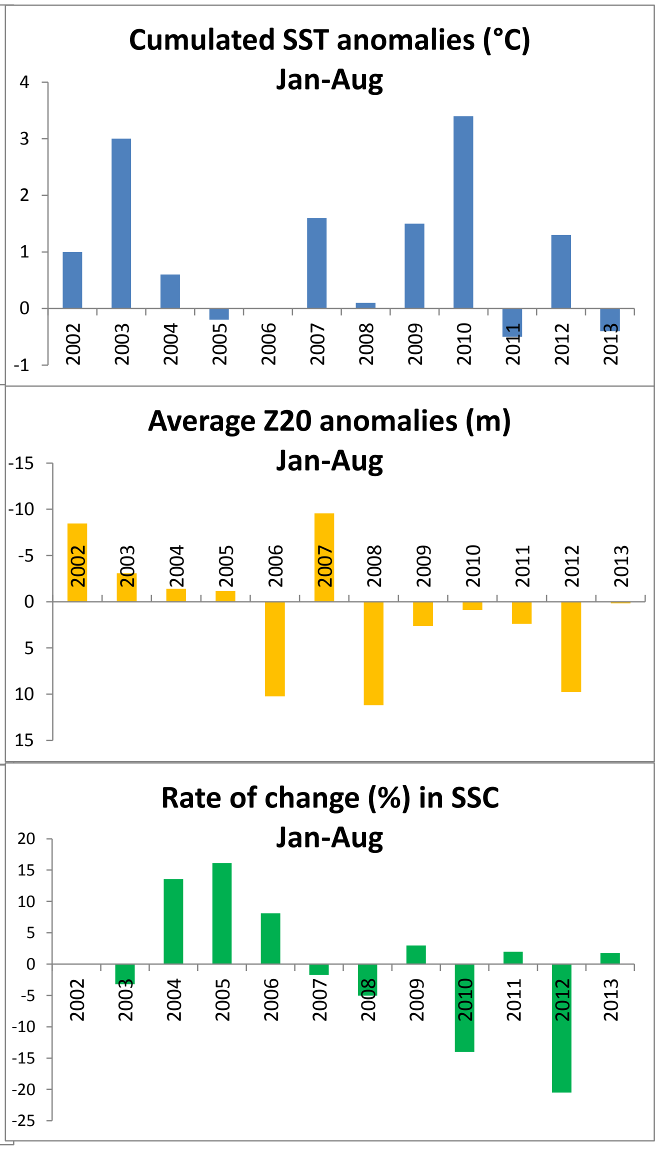


Fig. 7 – SST, MLD and SSC trends in the West Equatorial area, during the core of the north-east monsoon (December to February). SST anomalies are cumulated over the season, MLD anomalies are the mean over the season and SSC is expressed as rate of change about the 2002-2013 average for the season. Negative (positive) MLD anomalies denote shoaling (deepening) of the thermocline.

Fig. 8 – SST, MLD and SSC trends in the Maldives. Statistics are calculated for the period January to August. SST anomalies are cumulated over the period, MLD anomalies are the average over the period and SSC is expressed as rate of change about the 2002-2013 for the study period. Negative (positive) MLD anomalies denote shoaling (deepening) of the thermocline.

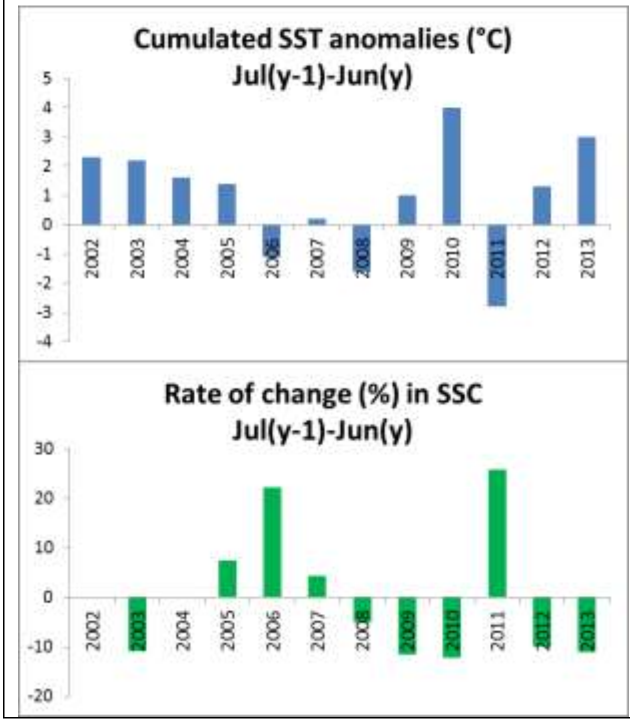


Fig. 9 – SST and SSC trends in the Eastern Tropical Indian Ocean, 12-month average from July (of the previous year) to June (of the current year). SST anomalies are cumulated over the 12-month period and SSC is expressed as rate of change about the 2002-2013 for the same period.

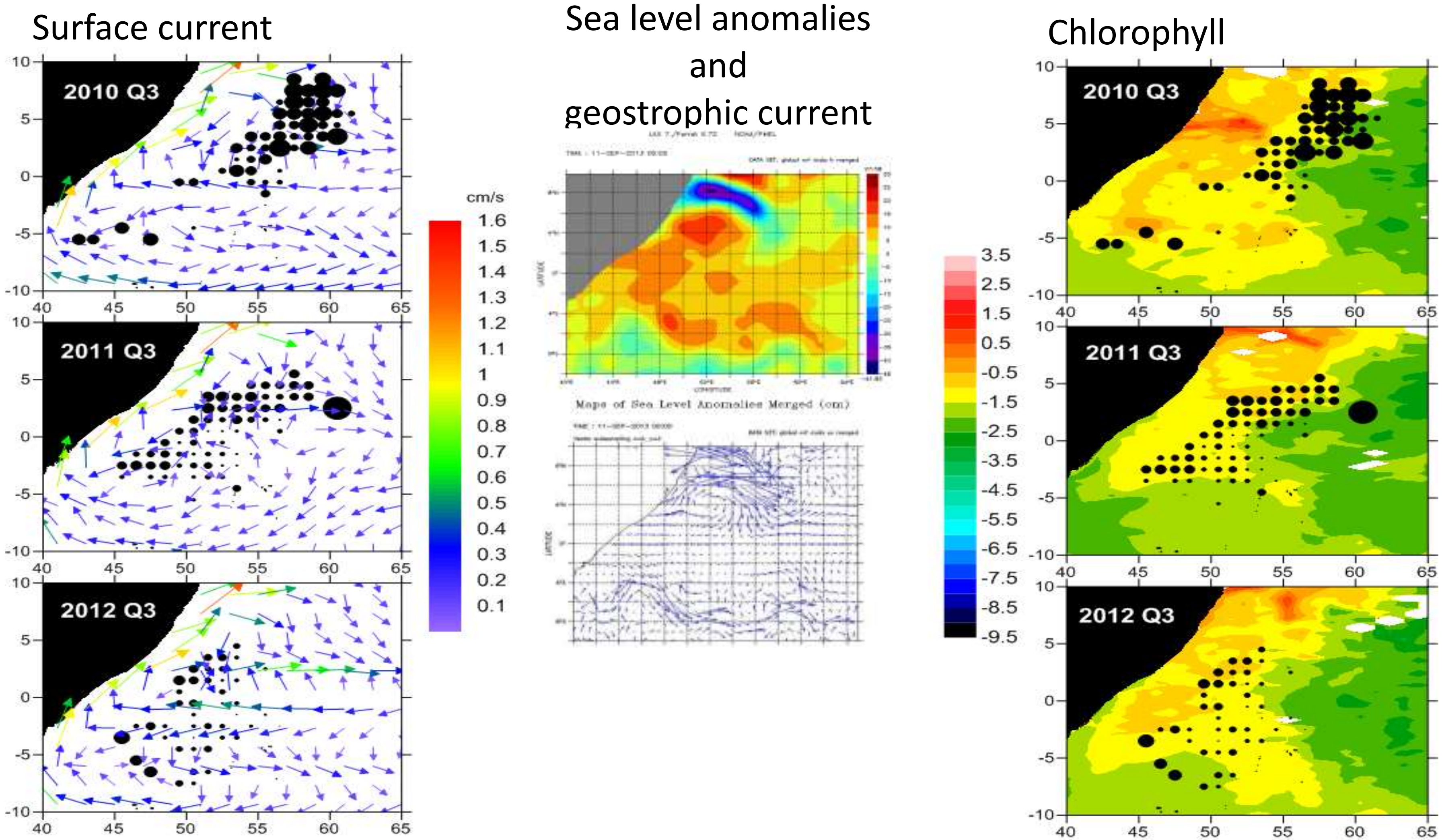
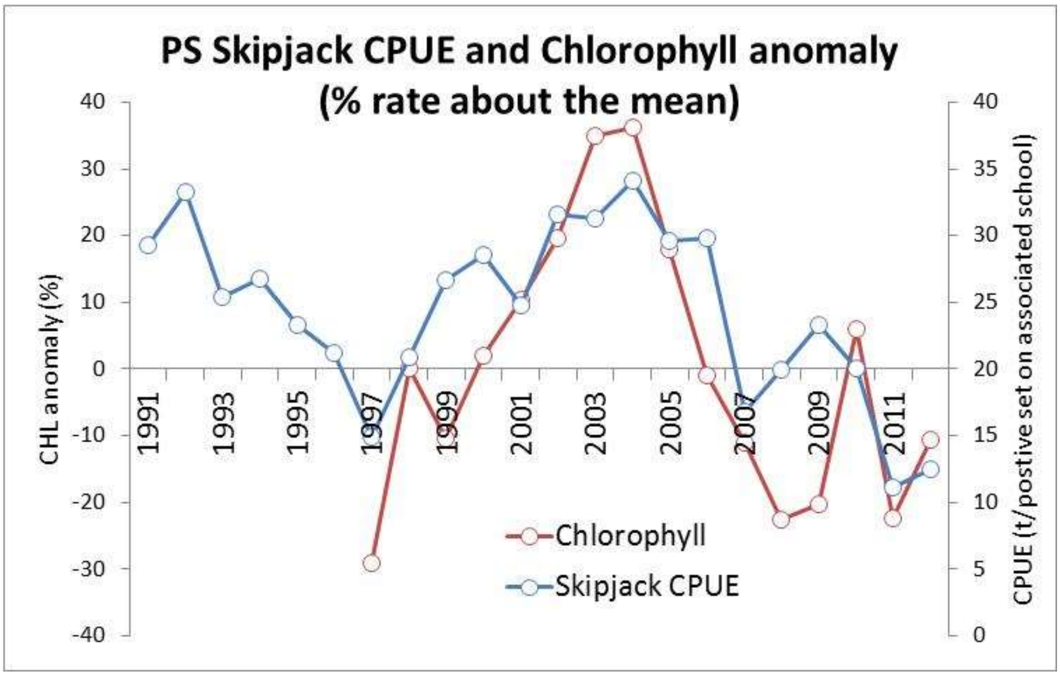


Fig. 10 – Spatial distribution of purse seine CPUEs on associated schools in the Somali Basin during the third quarter of 2010, 2011 and 2012. Left (a): CPUE with surface current vectors overlaid. Middle (b): a typical situation of sea level anomaly and geostrophic current during the southwest monsoon (11 Sept 2013) showing a large retention areas at 4°N and 8°N created by a gyring circulation. Right (c): CPUE with chlorophyll concentration. The chlorophyll color scale is in log. The limit between yellow and green denote the 0.4 mg/m^{-3} isoline.



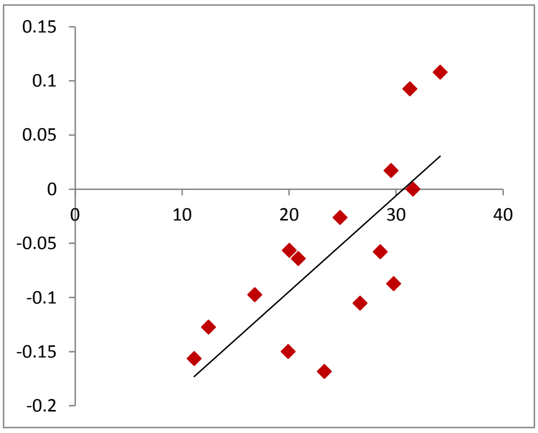


Fig. 11 – Skipjack purse seine CPUE (in tons/positive set) in the Somali Basin (10°N-5°S / 45°E-60°) from June to October, and sea surface chlorophyll anomaly (expressed as a rate of change, in %, compared to the 2002-2013 average for the area). The lower panel is the relationship between the two series (Chlorophyll anomaly, in mg.m^{-3}, is on the y axis and the CPUE on the x axis)