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West Indian Ocean variability and East African fish catch

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ABSTRACT

We describe marine climate variability off the east coast of Africa in the context of fish catch statistics for Tanzania and Kenya. The time series exhibits quasi-decadal cycles over the period 1964–2007. Fish catch is up when sea surface temperature (SST) and atmospheric humidity are below normal in the tropical West Indian Ocean. This pattern relates to an ocean Rossby wave in one phase of its east–west oscillation. Coastal-scale analyses indicate that northward currents and uplift on the shelf edge enhance productivity of East African shelf waters. Some of the changes are regulated by the south equatorial current that swings northward from Madagascar. The weather is drier and a salty layer develops in high catch years. While the large-scale West Indian Ocean has some impact on East African fish catch, coastal dynamics play a more significant role. Climatic changes are reviewed using 200 years of past and projected data. The observed warming trend continues to increase such that predicted SST may reach 30 °C by 2100 while SW monsoon winds gradually increase, according to a coupled general circulation model simulation with a gradual doubling of CO_2.

1. Introduction

Close to one-third of the world's population lives in countries next to the Indian Ocean, yet this region produces only 10% of global fish catch (Okemwa and Sted, 1995). Western Indian Ocean countries are in a developing state with annual economic production of ~$ 3 billion. The coastal zone is an important source of renewable food production and tourism activities. Increasingly coastal habitats are being degraded and natural resources over-exploited, causing conflict over resource use around coastal cities such as Dar es Salaam and Mombasa (Ohman et al., 2002). Marine resource utilization cuts across a diverse range of people and significantly affects socio-economic development in the region (Van der Elst et al., 2005). It creates challenges in the application of technology, design of sustainable scientific research, and the development of management strategies.

Estimating changes in production, abundance, and catch rate are key issues for reliable fish stock assessment. Marine environmental conditions are known to play a role in biological renewal and fluctuate on many time and space scales. In order to improve the management of marine and coastal resources for East Africa, we investigate the regional ocean climate and coastal circulation and examine relationships with commercial fish catch (Laevastu, 1993) using ocean reanalysis products to describe water properties and circulation off the East African coast (Fig. 1).

1.1. Marine-climate patterns

The Indian monsoon regulates the climate by instilling an annual cycle that affects the marine ecology. The coast of Tanzania and Kenya, our focus here, is largely concave and the shelf is relatively narrow. Around Madagascar southeasterly winds prevail throughout the year, while East African coastal winds alternate according to the monsoon, being from the north at 3 m s^{-1} from December to February and from the south in excess of 5 m s^{-1} between April and October. The coast channels the wind, producing acceleration around Cape Delgado at 11°S. The axis of strongest wind extends from the tip of Madagascar toward the Kenyan coast, overlying the incoming south equatorial current (SEC). An axis of 'blue' low-chlorophyll water marks the SEC (Fig. 1a). Primary production increases northward along the Kenya coast, where an upwelling circulation occurs in the June–September monsoon season. Coastal waters are affected by river discharges that increase nutrients and turbidity. A stable thermocline associated with light wind can lead to greater nitrogen fixation and increased productivity (Bryceson, 1982).

Whilst the coastal winds are important, remote influences can modulate marine resources through changes induced by water mass advection and vertical motion. A see-saw of the thermocline is known to occur in the Indian Ocean (Saji et al., 1999) in response to

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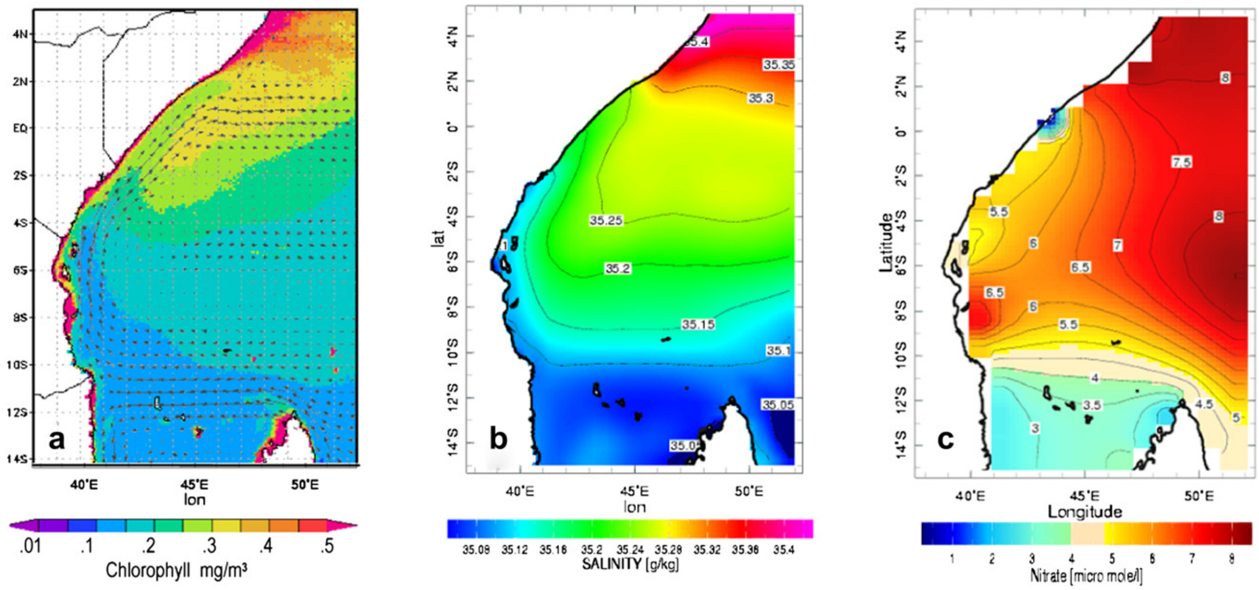

Fig. 1. (a) The mean annual SeaWifs chlorophyll concentration and 0–200 m current vectors (largest = 0.4 m/s), (b) SODA2.4 mean annual 0–200 m salinity, and (c) mean annual nitrate concentration from model assimilated observations.

large-scale coupled ocean–atmosphere Rossby waves that take 3–5 years to travel from Australia to Madagascar (White et al., 2004; Jury and Huang, 2004; Menard et al., 2007). Changes in zonal winds over the East Indian Ocean initiate this process and drive SST variability over the West Indian Ocean about a year later (Jury et al., 2002). This see-saw is partially modulated by the global El Nino Southern Oscillation (ENSO) and contributes to direct changes in water temperatures and sea levels, indirect changes in salinity due to shifts in rainfall and evaporation, and corresponding east–west shifts of the mid-ocean tuna catch (Marsac and Le Blanc, 1999a,b; White et al., 2004; Lu et al., 2008). Catch is significantly higher during times when the thermocline shoals, the mixed layer is shallow, and nutrients are brought into the euphotic zone (Marsac, 2001). Sequences of tuna catch and sub-surface temperature exhibit slow westward propagation in conjunction with the ocean Rossby wave (White et al., 2004). Yet associations are known to be irregular in time, and dependent on species and catch method. The zonally propagating ocean Rossby wave affects the entire basin, but its amplitude is damped near the coast where meridional currents are strong. There is also a slower decadal component to this oscillation that has received some attention in the context of tropical cyclone variability east of Madagascar (Chang-Seng, 2004).

2. Data and methods

2.1. Marine-climate data

Our ability to analyze regional climates has benefited from a long history of routine observations associated with national weather services and measurements from oceanographic and commercial ships (Fig. 2a). These have been centrally archived to enable the production of interpolated fields at monthly time scales. Recent advances in our understanding of the ocean have taken place through modeling and satellite data. Prior to 1980, only ship's data were routinely available to describe ocean conditions, with coverage adequate for climatological mean descriptions. Since then, satellites have provided wider coverage based on thermal infrared imagery, altimetric height, scatterometer winds, and ocean colour (Andrefouet and Riegl, 2004).

Advances in numerical ocean modeling have been made that combine *in-situ* observations and satellite fields in a monthly assimilation. The ocean reanalysis fields considered here derive from the GFDL modular ocean model. The ocean dynamics are driven by coupling with the atmosphere that makes use of surface wind stress and fluxes from ECMWF reanalysis at a grid resolution of $\sim 2°$.

Ocean temperature observations are assimilated from *in situ* sea surface temperature (SST) measurements of the ship-based COADS archive, temperature profile measurements and, since 1981, with satellite-estimated SST fields (Reynolds and Smith, 1994). *In situ* SST measurements exceed 90,000 per year in the Indian Ocean while the density of temperature profiles off East Africa (Fig. 2a) has been adequate since 1962. The subsurface data is concentrated near the coasts, along key lines from Durban, Madagascar and Mauritius to Mombasa. The simple ocean data assimilation (SODA) version 2.4 analysis of ocean currents, employed here, makes use of steric adjustments between upper ocean heat content and sea surface height anomalies from the Topex/Poseidon satellite altimeter. We consider temperature, salinity, currents and vertical motion fields as maps and depth sections with respect to fish catch, and study the seasonal cycle and natural variability using a mathematical cluster analysis technique known as singular value decomposition (SVD). The SVD analysis is an eigenvector decomposition of the covariance matrix within a single input field with variability reduced to modes that each has unique character. For each mode there is a spatial pattern of loadings and scores that describe its temporal fluctuations. The goal here is to characterize the leading patterns of regional to coastal scale inter-annual variability, to determine whether the findings specific to fish catch are also naturally occurring.

For the atmospheric data, we make use of the NCEP reanalysis (Kalnay et al., 1996) available via the IRI climate library website. From this source we analyze those patterns that are repetitious, through composite averaging, making use of SST, precipitable water (humidity) and surface winds. The reanalysis fields are considered for the West Indian Ocean and East African shelf region, to understand relationships between long-lived anomalies in regional ocean conditions and fisheries abundance in the coastal zone.

2.2. Fish catch analysis

The catch of marine fish along the coast of East Africa has been compiled by FAO since the 1950s and stored in various databases.