Deep-Sea Research II 100 (2014) 174–183

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Physical influence on biological production along the western shelf of Madagascar

T. Pripp [a], T. Gammelsrød [a,*], J.O. Krakstad [b]

[a] Geophysical Institute, University of Bergen, Bergen, Norway
[b] Institute of Marine Research, Bergen, Norway

ARTICLE INFO

Available online 6 November 2013

Keywords:
Madagascar
Upwelling
River runoff
Acoustic abundance
Trawling
Whale observation
Mozambique Channel

ABSTRACT

In September 2009, the R.V. *Dr. Fridtjof Nansen* surveyed the western coast of Madagascar. Environmental parameters of temperature, salinity, fluorescence and oxygen were profiled with a CTD probe and continuously underway at 5 m utilising a thermosalinograph equipped with a fluorescence sensor. A ship mounted Acoustic Doppler Current Profiler (ADCP) provided current profiles down to 250 m, while estimates of biomass were obtained from acoustics and trawling was used for species identification. In addition, visual whale observations were conducted. The survey revealed three areas that were identified as upwelling regions, namely the Southern Coast (26°S), offshore from Cap St. André (16°S) and near Nosy Be Island (13°S). In these upwelling regions, acoustic estimates, trawling and whale observations indicated high biological productivity. The total acoustic estimate for the whole western coast was as low as 62 000 t, typical for tropical waters. In addition to the upwelling areas, high biological productivity was also found outside river mouths. Ship born wind measurements, as well as re-analysed wind fields, indicated that the southern coast upwelling cell was wind-driven and had a larger extent than reported earlier. The wind conditions were not favourable for upwelling in the two northernmost upwelling cells. Here the ADCP showed high bottom velocities ($>1\ \mathrm{m\ s^{-1}}$) oriented northeast. These currents were probably forced by the migrating eddies in the area as indicated by the remotely sensed Sea Level Anomaly (SLA). Such currents induce bottom friction layer transport oriented towards the coast, thus driving upwelling, although not necessarily penetrating all the way to the surface layer as was the case near Cap St. André.

1. Introduction

The physical properties of the ocean have a crucial effect on living organisms, especially at the lower trophic levels. Features such as eddies, river runoff, upwelling and tidal fronts play a major role in regional ecosystems (Mann and Lazier, 2006) and therefore higher biological production is expected on the shelf than further offshore. These features have been studied by Ho et al. (2004), Lutjeharms (2006) and Aldegheri (1972) along the south and west coasts of Madagascar. In tropical regions, phytoplankton is less influenced by seasonal variations compared to temperate regions, and local blooms and plankton patches usually occur independently of the seasons (Mann and Lazier, 2006). Tew-Kai and Marsac (2009) used SeaWiFS data to indicate that the highest chlorophyll concentrations along the west coast of Madagascar were found during the austral winter, while highest concentrations were observed near the shelf compared with the less productive water in the middle of the Mozambique Channel.

Coastal upwelling has been detected on the southern shelf and contributes to increased primary production. Raj et al. (2010) indicated that the upwelling cell on the south-eastern shelf was likely to develop from the effects of the westward flowing East Madagascar Current (EMC) and the zonal wind component. Tew-Kai and Marsac (2009) suggested that primary production on the southern shelf of Madagascar was driven by two main processes during the austral winter, namely wind induced turbulence and upwelling. River runoff also contributes to nutrient enrichment, but the present cruise was conducted during the dry season with a low runoff (Aldegheri, 1972). Eddies are also known to occur regularly along the western coast of Madagascar and the effect on local ecosystems is quite variable (Heileman et al., 2009). Lutjeharms (2006) argued that eddies could draw nutrient-rich water into the Mozambique Channel and hence reduce the biological production along the coast.

There is little information about the fishery along the continental shelf of Madagascar, but fish catches increased during the 1980s due to an expansion of the fishing fleet. During the last two

* Corresponding author.
E-mail address: Tor.Gammelsrod@gfi.uib.no (T. Gammelsrød).

0967-0645/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.dsr2.2013.10.025

decades, fish catches have shown little variation and reported catches total about 100 000 t per year (Le Manach et al., 2011). Some pelagic surveys were conducted from 1968–1974 on the western shelf of Madagascar and the general impression was that fish stocks on the shelf were nearly depleted (Ralison, 1988). A promising area was observed at the north-western tip of Madagascar, however, but no biomass estimates were conducted as the availability of acoustic equipment was rather limited. During 1980–1982, the RV *Jurong* also conducted acoustic surveys along the western shelf, and calculated the total biomass to be 135 000 t, probably an overestimate due to unsuitable models. In general, low pelagic estimates were observed along the shelf, although high concentrations were observed on the northwestern coast of Madagascar. The same area was surveyed by the RV "Bonito" using demersal trawls and the biomass estimates showed little seasonal variability, with an average around 5000 t (Ralison, 1988).

During August–October 2009, the R.V. *Dr. Fridtjof Nansen* undertook a 6 week survey along the west coast of Madagascar to study pelagic ecosystems and in addition, demersal trawls were conducted for species identification. Madagascar constitutes the eastern boundary of the Mozambican Channel (Fig. 1) and the aim of the survey was to establish the physical, chemical and biological characteristics of the western shelf of Madagascar. The shelf is 90 km at its widest at approximately 16°S, i.e. west of Cap St. André. In contrast, the shelf is only a few hundred metres wide near the Onilahy river (~24°S). Large sections of the shelf are covered by coral reefs and the inner shelf is a continuous reef, hindering vessel navigation and trawling.

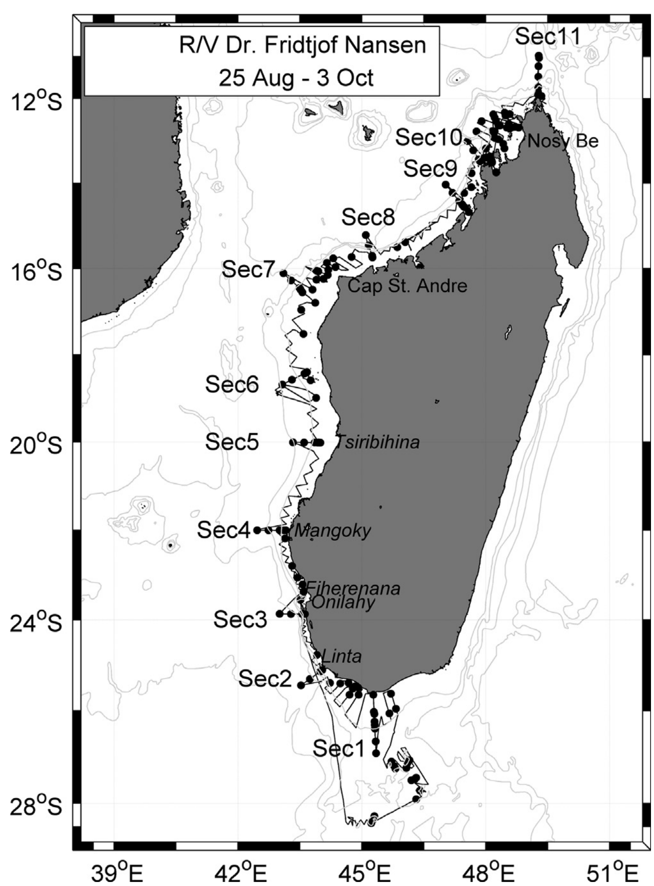

Fig. 1. Map of the study area during the austral spring 2009. Black dots are CTD stations and the black line indicates the cruise track. Positions for each of the 11 transect sections, Cap St. André, Nosy Be Island and rivers discussed in the text are indicated. Bathymetry is a 1000 m depth interval.

2. Data and methods

2.1. Hydrography

Vertical profiles of temperature, salinity, oxygen and chlorophyll *a* by fluorescence were obtained with a Seabird 911+ CTD, equipped with an AquaTracka MK III fluorometer, SBE 3+ temperature sensor, SBE 4C conductivity sensor and a SBE 43 oxygen sensor. Inshore profiles reached a few metres above the bottom, while offshore profiles were restricted to 3000 m. A total of 182 CTD stations and eleven CTD sections were conducted (Fig. 1). A few stations between 12°S and 20°S showed unrealistic salinity values ($S>42$) and were discarded. The CTD sections were taken in combination with trawling operations, lasting 8–21 h, and were considered synoptic as the tides were low in the area. Underway temperature, salinity and chlorophyll *a* at 5 m were recorded continuously along the cruise track by a SBE 21 Seacat thermosalinograph.

2.2. Acoustic Doppler Current Profiler (ADCP)

Current profiles were recorded continuously along the cruise track by an onboard Ocean Surveyor 150 kHz ADCP. The ADCP had a maximum depth range of 200–400 m and transmission of transducer pulses was synchronized with the echo sounder, with data averaged over 3 min. All data related to ship speed of <7 knots, and when direction changed more than 100° over 3 min, were removed since this indicated trawling operations. Data with <98% accuracy and values >200 cm s^{-1} were also discarded.

2.3. Net Primary Production (NPP)

Since plankton samples were not processed, average NPP data for September 2009 was downloaded from the NASA ocean colour website (http://oceancolor.gsfc.nasa.gov/). The data is derived from 1 km MODIS data and processed by the VGPM model of Behrenfeld and Falkowski (1997). The euphotic zone depth for the model was estimated from the surface chlorophyll concentrations according to Morel and Berthon (1989).

2.4. Sea Level Anomalies (SLA)

Daily SLA (delayed time), with a spatial resolution of 0.33°, was downloaded from the AVISO website (http://www.aviso.oceanobs.com/). SLA products are produced by the Ssalto/Duacs multimission project and utilises updated datasets from Jason-1 and 2, T/P, Envisat, GFO, ERS-1 and -2 and Geosat.

2.5. Wind

Wind direction and velocity was logged on board every minute on a WIMDA meteorological station and the data averaged over 10 min. Sea surface temperature, air temperature, relative humidity and air pressure were also logged by the WIMDA. In addition, modelled wind data for September 2009 was downloaded from the NASA website (http://gmao.gsfc.nasa.gov/research/merra/). The data was modelled with the Modern Era Retrospective-analysis for the Research and Applications (MERRA) model (Rienecker et al., 2011) every hour at a height of 10 m for the area encompassed by 9–28°S and 41–53°E, with a spatial resolution of 50 × 50 km^2. For comparison, Quickscat (microwave scatterometer SeaWinds) data was also downloaded and found to be quite similar to the MERRA wind field. The Quikscat wind field is included in the MERRA analysis (Rienecker et al., 2011).