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Interaction of dipole eddies with the western continental slope of the Mozambique Channel

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ABSTRACT

Sea Level Anomaly (SLA) data were used to track a southward propagating eddy dipole along the western slope of the Mozambique Channel over some 6 months. In April 2005, this dipole (with the cyclone to the south) was close to the continental slope off southern Mozambique. The contact zone between the contra-rotating vortices and the slope was surveyed by ship using onboard (S-)ADCP and CTD lines. The data showed strong ($>1.4\ \mathrm{m\ s^{-1}}$) southward (geostrophic) currents over the slope adjacent to the anticyclone with horizontal divergence over the shelf edge. Significant slope upwelling between the dipole and the shelf was evident, concomitant with enhanced nutrient and chlorophyll levels enriching shelf near-surface waters. Satellite observations depicted a 300 km long surface chlorophyll filament extending offshore in the frontal zone between the contra-rotating vortices. A satellite-tracked drifter deployed at the coastal base of this filament confirmed the offshore advection of chlorophyll-enriched shelf water, which ultimately wrapped around the cyclone and filling its centre. The slope upwelling was also clearly evident in hourly temperature data collected by a recorder deployed on a nearby reef (Zambia Reef) in a depth of 18 m. According to the SLA data, the dipole took several weeks to pass Zambia Reef causing prolonged bouts of upwelling that finally ceased when it left the continental slope and moved southwards into the open ocean. Further analysis showed that lone anticyclones and cyclones against the Mozambique continental shelf also induce slope upwelling as a result of horizontal divergence created by the radial circulation of the vortex. In the case of cyclones, the divergence occurs north of the contact zone. Overall, this case study confirms that eddies moving southwards along the western side of the Mozambique Channel are the main mechanism for pumping nutrients into the otherwise oligotrophic surface waters, and moreover, provide a vigorous mechanism for shelf–open ocean exchange.

1. Introduction

1.1. Origin and behaviour of Mozambique Channel eddies

The Mozambique Channel is dominated by a field of anticyclonic and cyclonic mesoscale eddies (Schouten et al., 2003). Tracks in satellite altimetry (Fig. 1, insert) and models show the anticyclones to migrate southward through the narrow Mozambique Channel entrance and then typically along the western slope with speeds ranging from 4.5 to 10 $\mathrm{km\ day^{-1}}$ depending on latitude (Biastoch and Krauss, 1999; Schouten et al., 2003; De Ruijter et al., 2005; Lutjeharms, 2006; Halo et al., 2013). This spatially biased behaviour has been emphasised using maps of sea surface height (SSH) variability as well as SVP (Surface Velocity Programme) surface drifters (Hancke et al., 2013). Model outputs such as time-averaged sea level skewness (Backeberg et al., 2009) and satellite-derived vorticity (Ridderinkhof et al., 2013) further illustrate this distinct "anticyclone corridor" that leads to the source of the Agulhas Current (Fig. 1). Schouten et al. (2003) and Ridderinkhof and de Ruijter (2003) estimate about four anticyclones are generated per year. However, the dominant frequency of variability in SLA data is found to decrease poleward in the Channel with a peak period of 55 days in the north and 90 days in the south. This infers a reduction from 7 to 4 anticyclones with dissipation and merging, both of which are commonly observed in the altimetry field (Schouten, 2003; Lutjeharms, 2006). On average, anticyclone energy expressed by SSH is found to increase between 12° and 24°S (i.e., 15–42 cm in SLA; Schouten et al., 2003). This is in agreement with the expected increase in eddy intensity due to the latitudinal displacement and the planetary vorticity gradient (Schouten, 2003). Palastanga et al. (2006) showed that

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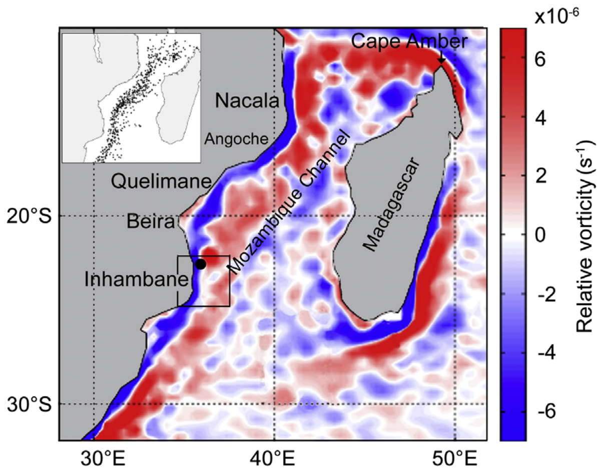

Fig. 1. Mean relative vorticity (s^{-1}, red = positive) in the Mozambique Channel from satellite altimetry (after Ridderinkhof et al., 2013). The black square indicates the location of the ship survey that investigated an eddy dipole in 2005. The black dot is the position of the underwater temperature recorder (UTR) for monitoring slope upwelling. Insert shows trajectories of 25 satellite-tracked anticyclonic eddies propagating along the western side of the Mozambique Channel (after Schouten et al., 2003).

a connexion exists between mesoscale eddy activity around Madagascar and Indian Ocean dipole (IOD) events.

The exact mechanism(s) of anticyclone generation in the Mozambique Channel has been a topic of considerable interest. Suggested mechanisms have included barotropic instabilities of the South Equatorial Current (SEC) north of Madagascar (Quadfasel and Swallow, 1986; Schott et al., 1988; Biastoch and Krauss, 1999; Fig. 1), incoming Rossby waves travelling westward across the Indian Ocean around 12°S at a frequency of about four per year (Schouten et al., 2002), and eddy shedding as a result of strong currents flowing through the Channel narrows at 17°S (Ridderinkhof and de Ruijter, 2003). Additionally, LaCasce and Isachsen (2007) demonstrated discontinuity in the Sverdrup stream function at the northern tip of Madagascar and the occurrence of a westward jet which is barotropically unstable leading to vortices. Harlander et al. (2009) observed a southward current along Madagascar as a precursor to the formation of an anticyclone in the Channel narrows which then propagated westward and was related to a Rossby normal mode in the Channel. Recently, Backeberg and Reason (2010) using current and vorticity fields from a model (HYCOM) and altimetry, showed anticyclones form in the Channel narrows some 20 weeks following a westward transport pulse in the SEC. At 13 weeks a positive vorticity anomaly initiated at the northern tip of Madagascar reached the Mozambique coast where it intensifed the poleward slope current. They argue that the conservation of potential vorticity generates additional anticyclonic flow curvature which further serves to intensify the positive vorticity anomaly leading to the formation of an anticyclonic eddy. A poleward moving eddy will then experience an increasingly negative f (Coriolis parameter) and thus, to conserve potential vorticity, its relative vorticity (ζ) must become increasingly positive (anticyclonic). The magnitude of f and ζ increases by about 40% between 14°S and 16°S. Interestingly, based on the model and altimetry data, Halo et al. (2013) also identified the westernside of Madagascar as a generation site for anticyclonic activity.

The origin, and in fact existence of cyclonic eddies (negative anomalies) in the Mozambique Channel, has also been contentious, especially on the western side. While early observations carried out during the ACSEX programme in 2000 confirmed the presence of anticyclonic eddies here, vessel-mounted (S-)ADCP current measurements and XBT lines in the vicinity of negative SSH anomalies during the cruise showed little sign of cyclonic dynamic features (De Ruijter et al., 2000, 2002; Schouten et al., 2003). This led to the view that negative SSH anomalies were perhaps a consequence of the dominant anticyclones on the western flank of the Mozambique Channel leaving a signal in the mean SSH data field and hence the fabrication of negative anomalies in their absence. Their existence however, has now been shown to be certain as not only do cyclones occur in models in this region (e.g. Biastoch and Krauss, 1999; Backeberg et al., 2009; Halo et al., 2013), but have also been observed in situ using S-ADCP by Ternon et al. (2013) and Roberts et al. (2008), both in the "anticyclone corridor" between positive anomalies and elsewhere in the Channel. Unlike anticyclones, Halo et al. (2013), using both model and altimetry data, showed that cyclones in the channel have little spatial preference and therefore occur everywhere.

Schouten et al. (2003) and De Ruijter et al. (2004) suggested that cyclones in the Mozambique Channel originate from the southwestern edge of Madagascar and not within the Channel. Observations of the SLA field, however, show some to also form in the northwestern bight of Madagascar at ~15°S, sometimes when a positive anomaly is generated to the north. This is supported in the 6 year average of vorticity data shown in Fig. 1 (i.e., area of negative ζ). As seen in Fig. 2, the northern cyclones can be comparable in size and energy to anticyclones, move southward through the Channel narrows and intensify in a similar manner as positive anomalies between 16°S and 18°S. They are often seen to move down the western flank of the Channel forming dipoles and tripoles with anticyclones (e.g. Fig. 2e). From model data, Halo et al. (2013) showed cyclones to be more frequent than anticyclones, to also form in the central Channel (possibly a consequence of ringlet formation at the periphery of the more energetic anticyclones; Wang, 1992; Nof, 1993), and tend to be smaller with shorter life spans and lower amplitudes. Certainly observations using SLA imagery show cyclones to be more fickle than their counterparts, seldom lasting complete propagation through the Channel. Models on the other hand show dipoles to be much more robust (Biastoch and Krauss, 1999; Halo et al., 2013).

1.2. Satellite observations of eddy interactions with the western slope

Quartly and Srokosz (2004) were the first to examine eddy activity in the Mozambique Channel using satellite-derived ocean colour. Confined to the southern part, they noted a number of large circular features (anticyclonic eddies) on the western side about 200 km in diameter, with low chlorophyll concentrations (CC) in their centres. These intermittently propagated poleward along the western edge of the Channel with long (~500 km) filaments of surface chlorophyll extending offshore between eddies. Later Tew-Kai and Marsac (2009) investigated the coupling between sea surface CC and the physical environment using statistical models. From satellite SST, altimetry and chlorophyll they found surface CC variance in the northern and southern regions of the Channel to be strongly driven by seasonality, with highest levels in winter (August–September), but less so in the central region between 16°S and 24°S. Here they observed an east – west gradient in chlorophyll increasing from Madagascar to Mozambique, suggesting drivers other than the seasonal cycle being involved in the spatial distribution of CC. Apart from noting higher levels of CC in the shelf regions (> 1 mg m^{-3}) in contrast to the less productive open Channel (average = 0.15 mg m^{-3}), they too remarked on the CC field on the western side being well marked in spatial features, with low CC in anticyclones and high CC in cyclones. They suggested that the observed chlorophyll filaments emanating from