Dynamics of Atmospheres and Oceans 72 (2015) 12–20

Contents lists available at ScienceDirect

Dynamics of Atmospheres and Oceans

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

First observational evidence of a North Madagascar Undercurrent

Leandro Ponsoni[a,*], Borja Aguiar-González[a], Janine J. Nauw[a], Herman Ridderinkhof[a], Leo R.M. Maas[a,b]

[a] NIOZ Royal Netherlands Institute for Sea Research, P.O. Box 59, 1790 AB Den Burg, Texel, The Netherlands
[b] Institute for Marine and Atmospheric Research, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands

ARTICLE INFO

Article history:
Received 25 September 2014
Received in revised form 14 July 2015
Accepted 7 August 2015
Available online 8 August 2015

Keywords:
North Madagascar Undercurrent
North Madagascar Current
Indian Ocean
Coastal downwelling
South Indian Central Water

ABSTRACT

In situ observations reveal a southeastward-directed North Madagascar Undercurrent (NMUC) below and opposite to the equatorward-directed North Madagascar Current (NMC) off Cape Amber, at the northern tip of Madagascar. Results show an undercurrent hugging the continental slope with its core at 460 m depth and velocities over 0.7 m s^{-1}. Its volume transport is estimated to be 3.1–3.8 Sv, depending on the velocity extrapolation methods used to fill in the data gaps near the slope (no-slip and full-slip, respectively). The thermohaline characteristics show a saltier and warmer NMUC, compared to the surrounding offshore waters, transporting mainly South Indian Central Water. Also, strong horizontal gradients of density are found in the NMUC domain. An inshore cell of coastal downwelling due to Ekman Transport toward the coast is identified, which can explain, at least in part, the strong baroclinic pressure gradients as well as the NMUC development and possible persistence.

1. Introduction

The South-West Indian Ocean (SWIO) presents one of the most intriguing western boundary regions of all subtropical gyres. Unlike other regions, in the SWIO the Madagascar island imposes a physical barrier to the westward flowing South Equatorial Current (SEC), which reaches the Madagascar coast between 17° S and 20° S (Fig. 1a). At this location, the SEC bifurcates into two branches: the southward branch feeds into the East Madagascar Current (EMC), which farther south will feed the Agulhas Current (AC); on the other hand, the northward branch feeds into the North Madagascar Current (NMC; Swallow et al., 1988; Chapman et al., 2003; Siedler et al., 2006), which turns around Cape Amber, at the northern tip of Madagascar, and continues westward toward the east coast of Africa (Swallow et al., 1988).

Besides the surface patterns of the boundary currents, an undercurrent flowing opposite and beneath the surface current appears to be a recurring feature near eastern and western ocean boundaries. At western boundaries, such a feature has been universally observed: the Luzon Undercurrent in the North Pacific (Hu et al., 2013), the East Australian Undercurrent in the South Pacific (Godfrey et al., 1980; Schiller et al., 2008), and the Intermediate Western Boundary Current in the South Atlantic (Evans and Signorini, 1985; da Silveira et al., 2004) are some examples.

* Corresponding author. Tel.: +31 0222 369 310.
E-mail addresses: lponsoni@nioz.nl (L. Ponsoni), Borja.Aguiar.Gonzalez@nioz.nl (B. Aguiar-González), Janine.Nauw@nioz.nl (J.J. Nauw), Hermanridderinkhofherman@gmail.com (H. Ridderinkhof), Leo.Maas@nioz.nl (L.R.M. Maas).

http://dx.doi.org/10.1016/j.dynatmoce.2015.08.002

In turn, three undercurrents have already been reported to occur in the SWIO: the Agulhas Undercurrent (AUC; Beal and Bryden (1997)), the Mozambique Undercurrent (MU; de Ruijter et al., 2002; van Aken et al., 2004) and the East Madagascar Undercurrent (EMUC; Nauw et al., 2008; Ponsoni et al., 2015), all flowing equatorwards (Fig. 1b).

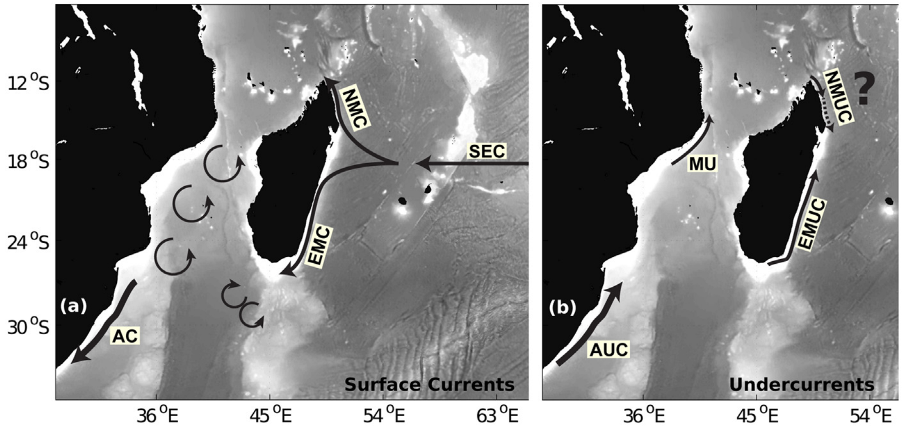

Fig. 1. Sketch of the surface currents (a) and undercurrents (b) in the SWIO: South Equatorial Current (SEC), East Madagascar Current (EMC), North Madagascar Current (NMC), Agulhas Current (AC), Agulhas Undercurrent (AUC), East Madagascar Undercurrent (EMUC), Mozambique Undercurrent (MU) and North Madagascar Undercurrent (NMUC).

To the knowledge of the authors, this work presents the first observational evidence of a North Madagascar Undercurrent (NMUC) flowing below and opposite to the NMC. First estimates about its spatial extent, core velocity, volume transport and thermohaline properties are addressed. The importance of the wind stress and Ekman Transport in the region are also investigated.

2. The ACSEX3 data set

The results of this study are based on thermohaline and velocity observations carried out on 30 March 2001, as part of the "Dutch-South African Agulhas Current Sources Experiment" (ACSEX). The ACSEX program (de Ruijter et al., 2002) was accomplished by three oceanographic surveys around Madagascar on board the RV Pelagia. More precisely, in this paper we use Conductivity–Temperature–Depth (CTD) and Lowered Acoustic Doppler Current Profiles (L-ADCP) from the six innermost stations (Sta18–Sta13) at Transect E1, located northeast of Cape Amber (ACSEX3 survey, Fig. 2). The deepest observation of each vertical profile (200, 580, 1060, 1040, 2520 and 3020 m, from Sta18–Sta13, respectively) is placed near the bottom, on average 17 m above the seafloor.

The CTD frame was equipped with two synchronized self-contained 300-kHz ADCPs. Vertical profiles of horizontal velocities were achieved either with an inverse solution method (Visbeck, 2002), if near-bottom data were available (stations shallower than 2400 m), or shear-based method (Fischer and Visbeck, 1993) for stations deeper than 2400 m. For a complete view of the ACSEX data processing the reader is referred to Nauw et al. (2008).

In addition, monthly fields (from July 1999 to November 2009) and an average field from 25 to 31 March 2001 of wind stress data from the SeaWinds scatterometer, coupled to the NASA's Quick Scatterometer (QuikSCAT) satellite, are analyzed in order to support our interpretations. We use the Version-4 (V4) data products produced by Remote Sensing System and available at www.remss.com (Ricciardulli and Wentz, 2011). The scatterometer spatial resolution is about 25 km. A full description of the SeaWinds is presented by Freilich et al. (1994).

3. Velocities and volume transport

The two measured components of current velocity were rotated into along-stream (x) and cross-stream (y) directions. The x component represents the main direction of the NMUC, since its flow is markedly perpendicular to Transect E1 (see arrows in Fig. 2). Horizontal extrapolations were performed to fill in the empty data regions created due to the depth difference between two neighboring stations. This is a typical problem, especially pressing in regions near a steep continental slope. For the sake of completeness, we apply two boundary conditions in order to compute the volume transport: no-slip and full-slip (Beal and Bryden, 1997; Nauw et al., 2008). The first condition assumes that velocity decreases linearly to zero at the continental slope, while in the second condition the velocity at the continental slope is assumed equal to the nearest measurement at the same depth.

Fig. 3a presents the vertical structure of the along-stream velocity. Negative values (dashed isotachs) represent the NMC flowing northwestward, while positive values on the upper part of the continental slope (solid isotachs, shaded) are related to the southeastward NMUC. The vertical reversal of the flow takes place at Sta17 and Sta16 at a depth of 250 and 320 m, respectively, where the strongly sheared profiles suggest an important baroclinic contribution to the total geostrophic flow.