Continental Shelf Research 114 (2016) 72–84

Contents lists available at ScienceDirect

Continental Shelf Research

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

Research papers

The formation of a cold-core eddy in the East Australian Current

H.S. Macdonald [a,*,1], M. Roughan [a], M.E. Baird [b], J. Wilkin [c]

[a] Coastal and Regional Oceanography Lab, School of Mathematics and Statistics, University of New South Wales, Sydney, Australia
[b] Plant Functional Biology and Climate Change Cluster, University of Technology Sydney, Sydney, Australia
[c] Rutgers, The State University of New Jersey, USA

ARTICLE INFO

Article history:
Received 1 August 2014
Received in revised form
1 January 2016
Accepted 6 January 2016
Available online 16 January 2016

Keywords:
Cyclonic eddy
Energy transformation
Regional Ocean Modelling System

ABSTRACT

Cold-core eddies (CCEs) frequently form in western boundary currents and can affect continental shelf processes. It is not always clear, however, if baroclinic or barotropic instabilities contribute more to their formation. The Regional Ocean Modelling System (ROMS) is used to investigate the ocean state during the formation of a CCE in the East Australian Current (EAC) during October 2009. The observed eddy initially appeared as a small billow (approx. 50 km in length) that perturbed the landward edge of the EAC. The billow grew into a mesoscale CCE (approx. 100 km in diameter), diverting the EAC around it. A ROMS simulation with a realistic wind field reproduced a similar eddy. This eddy formed from negative vorticity waters found on the continental shelf south of the EAC separation point. A sensitivity analysis is performed whereby the impact of 3 different wind forcing scenarios, upwelling, downwelling, and no winds, are investigated. A CCE formed in all wind scenarios despite the wind induced changes in hydrographic conditions in the continental shelf and slope waters. As such, the source of energy for eddy formation did not come from the interactions of wind with the continental shelf waters. Analysis of strain and energy transformation confirms this by showing that the prevailing source of CCE energy was kinetic energy of the offshore EAC. These results clearly link the formation of the CCE to the swift flowing EAC and barotropic instabilities.

1. Introduction

1.1. Cold-core eddies

Mesoscale cold-core eddies (CCEs) can form from instabilities in the flow in the vicinity of major western boundary currents (e.g. the Kuroshio, Kasai et al., 2002; Kimura et al., 1997; the Gulf Stream, Lee et al., 1991; and the Agulhas Current, Lutjeharms et al., 2003). These CCEs within western boundary current (WBC) systems have sizes ranging from submesoscale (diameter ~10 km) to mesoscale (diameter greater than 100 km) and last for timescales of days to months.

One type of CCE that forms in and around WBCs are frontal (Lee et al., 1991; Kimura et al., 1997) or shear-edge (Lutjeharms et al., 2003) eddies. They form on the inshore edge of the WBC on the front between the warmer WBC and the typically cooler coastal waters (e.g. Everett et al., 2011). Frontal eddies occur approximately weekly and may last for periods of up to months (Lee et al., 1991; Kimura et al., 1997) which is sufficient to support the early life history of many fish. Their formation is attributed to baroclinic instabilities (Ikeda et al., 1989; Lutjeharms et al., 2003; Jia et al., 2011) or a combination of baroclinic and barotropic instabilities (Lutjeharms et al., 2003; Oke and Griffin, 2010) which, in the case of submesoscale eddies, can be enhanced by local wind forcing (Mantovanelli et al., 2016).

Until recently, frontal eddies have been difficult to observe and measure. These CCEs are hard to capture in satellite altimetry and are therefore underrepresented in automated eddy census methods such as that of Chelton et al. (2011). Additionally, their short life spans mean that they are often missed by autonomous observation systems such as Argo or surface drifters and can be difficult to target with gliders or research cruises.

There are also issues that need to be overcome to resolve these eddies in numerical modelling studies. Their small scale (10–100 km) necessitates a high resolution model. However, it is also important to resolve the dominant larger scale features (such as the WBC) which are required to form the barotropic or baroclinic instabilities that contribute to eddy formation. Thus a high spatial resolution (<5 km) model over a large area or a nested grid is required to capture the formation of these eddies. It is no surprise then, that these frontal CCEs are understudied.

---

[*] Corresponding author.
E-mail address: helen.macdonald@niwa.co.nz (H.S. Macdonald).

[1] Now at National Institute of Water and Atmospheric Research, P.O. Box 14-901, Kilbirnie, Wellington, New Zealand.

http://dx.doi.org/10.1016/j.csr.2016.01.002
0278-4343/

1.2. Cold-core eddies in the East Australian Current

Physical and biological processes on the continental shelf off southeast Australia are dominated by the presence of the East Australian Current (EAC), a poleward flowing WBC (Godfrey et al., 1980b). The EAC forms between 15°S and 25°S, and extends along the East Australian coast, intensifying as the shelf narrows (Ridgway and Dunn, 2003). The EAC can extend to depths of 2000 m and has been observed to travel at speeds greater than 1 m s^{-1} (Godfrey et al., 1980a; Nilsson and Cresswell, 1980). Long term moored observations show depth averaged velocities at the shelf break can reach more than 1.3 m s^{-1} poleward (Schaeffer et al., 2013). The EAC bifurcates between 30°S and 31.5°S with part of the flow separating from the coast, traveling east (Cetina-Heredia et al., 2014). Downstream of the separation point large mesoscale warm (Macdonald et al., 2013) and cold (Suthers et al., 2011) – core eddies are formed. The eddy variability associated with this bifurcation can be larger than the current itself so that the EAC is not always distinguishable as a coherent current (Godfrey et al., 1980b).

CCEs and their formation have been well studied in other western boundary current systems such as the Kuroshio (Kasai et al., 2002; Kimura et al., 1997), the Gulf Stream (Lee et al., 1991) and the Agulhas Current (Lutjeharms et al., 2003). The EAC, however, is different to other western boundary currents. Unique features such as the narrow continental shelf, the bifurcation of the current and extremely large variability in transport and eddy shedding mean that there are different dynamics in the EAC system (Boland and Hamon, 1970). So, while CCE formation has been studied in other WBC systems, it is important to understand the different processes occurring in this unique region.

Previous modelling studies in the EAC have not focused on small (less than 100 km) CCEs. Instead, they have focused on large scale features such as the EAC separation and the shedding of large eddies (diameter greater than 200 km) (Marchesiello and Middleton, 2000; Tilburg et al., 2001; Wilkin and Zhang, 2007), long timescales (greater than 30 days) (Wilkin and Zhang, 2007; Roughan et al., 2011), or biogeochemical processes (Baird et al., 2006a,b; Macdonald et al., 2009).

CCEs, despite being smaller and short lived, tend to form on the inshore side of the EAC and can affect cross shelf transport and coastal species (Suthers et al., 2011; Everett et al., 2011; Henschke et al., 2011). These eddies can entrain continental shelf waters and provide a nursery ground for juvenile species (Everett et al., 2015). These smaller scale eddies (~100 km) occurring on short timescales (days to weeks) have not been adequately resolved in space or time in previous modelling studies and, as such, it is important to study them in this region.

One of the few modelling studies of CCEs in the EAC region (Oke and Griffin, 2010) found that a relatively large CCE eddy formed in early 2007 via a combination of baroclinic and barotropic instabilities. Oke and Griffin (2010) proposed that the eddy formation was connected to the strong upwelling events that occurred at the same time. A direct link could not be found as the eddy formation in the model was, in part, due to a data assimilation process rather than a free evolution of the model.

In this study we will investigate a CCE found in the EAC separation region in October 2009. The aims of this study are to assess how well a model can reproduce a frontal CCE in the EAC and then to understand the forcing mechanisms driving eddy formation. In particular, we investigate the impact of the wind field induced changes in continental shelf density on the eddy formation.

We investigate the temporal evolution of the eddy formation and growth as well as the vorticity balance through time (Sections 3.2–3.4). To investigate the sensitivity of eddy formation to wind forcing, different scenarios are undertaken with upwelling wind forcing, downwelling wind forcing, and with no wind forcing during the first two weeks of the simulation (Section 3.5). The strain created by the EAC (Section 4.1) and the transfer of kinetic and potential energy between the mean field and the eddy field (Section 4.2) is then discussed and a further simulation investigates the effect of removing density gradients on the eddy formation.

2. Methods

2.1. Model description

The ocean state is simulated using the Regional Ocean Modelling System (ROMS) during the formation of a CCE in October 2009. ROMS is well adapted for simulations of the coastal ocean as it allows for a terrain-following grid while reducing the pressure gradient truncation errors associated with this terrain following scheme (Shchepetkin and McWilliams, 2003, 2005). More details on ROMS can be found in Shchepetkin and McWilliams (2003, 2005).

ROMS uses a split-explicit scheme for computing timesteps. In this configuration a time step of 1 s is used for computing the (2-dimensional; barotropic) depth integrated continuity and momentum equations. A larger timestep of 60 s is used for the 3-dimensional (baroclinic) momentum and tracer equations. The Mellor and Yamada (1982) 2.5 turbulent closure scheme is used in parameterising vertical mixing.

2.1.1. The model grid

The model grid is modified from Macdonald et al. (2013). The grid spacing has been increased to approximately 1.75 km by 1.4 km and no limit has been set on the maximum depth. The resultant grid has 650 grid squares in the zonal direction and 461 grid squares in the meridional direction. The grid covers a region between 29.9°S to 37.33°S and 149.1°E to 159.2°E (Fig. 1A). This new grid uses the same high resolution (2 × 2 min) bathymetry from the Naval Research Lab (DBDB2 V3) as Macdonald et al. (2013). To reduce the pressure gradient error associated with terrain following models (Mellor et al., 1994), the bathymetry has been smoothed using a smooth positive method (Sikiric et al., 2009). This smooth positive method finds regions where steep bathymetry will create a pressure gradient error and flattens the gradient, making the water depths shallower. The smoothing for this region is minimal with shallow depths changing by only small amounts (Fig. 1B).

There are 50 sigma layers in the vertical with the stretching scheme implemented so that there is greater resolution in the top of the water column (Fig. 1B). This scheme creates a vertical resolution that varies with water depth. In the deeper parts of the grid (which yield less resolution using this scheme) there is approximately 500 m resolution at 4500 m depth, 50 m resolution at 500 m depth, 10 m resolution at 100 m depth, 7 m resolution at 50 m depth and 6 m resolution at 10 m depth.

2.1.2. Initial conditions

Temperature, salinity, sea-level height and geostropic currents used for model initialisation and the time-varying boundary forcing are sourced from a CSIRO product, SynTS (Ridgway et al., 2008). SynTS is a daily, 3D temperature and salinity estimate created from altimetry and satellite sea-surface temperature which has been calibrated by vertical profiles. For areas of the model below 2000 m the initial temperature and salinity conditions come from CSIRO's CARS climatology (2006 version) (Ridgway et al., 2002) and velocity is set to zero. The model is initialised on 18 September 2009 and model day 1 is after 5 days to allow the