Deep-Sea Research II 58 (2011) 574–591

Contents lists available at ScienceDirect

Deep-Sea Research II

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

The cold-core eddy and strong upwelling off the coast of New South Wales in early 2007

Peter R. Oke*, David A. Griffin

Centre for Australian Weather and Climate Research: a partnership between CSIRO and the Bureau of Meteorology; and Wealth from Oceans National Research Flagship, Australia

ARTICLE INFO

Article history:
Received 15 June 2010
Accepted 15 June 2010
Available online 1 July 2010

Keywords:
East Australian Current
Ocean Reanalysis
Upwelling
Eddy

ABSTRACT

During the Austral summer of 2006–07 a series of extreme oceanic events occurred in the Tasman Sea. Following a series of strong wind-driven upwelling events, an intense cold-core eddy developed off Sydney, Australia. A data-assimilating, eddy-resolving ocean model is used to create a three-dimensional time-varying reanalysis of these events. The reanalysis indicates that the cold anomalies associated with the upwellings were in excess of $-5\,^{\circ}$C near the coast, where sea level decreased by as much as 0.2 m. The reanalysed three-dimensional structure of the cold-core eddy shows the eddy "leaning" to the west–north–west, in towards the continental shelf. The diameter of the eddy is about 100 km and the sea-level anomaly at the eddy centre peaks at around -1 m, with an associated sub-surface temperature anomaly in excess of $-8\,^{\circ}$C at 200 m depth, corresponding to an upward isotherm excursion of 600 m. The circulation around the cyclonic eddy is ageostrophic, with upwelling in the southern sector of the eddy (where flow is onshore and climbing the continental slope) and downwelling in the northern sector (where flow is descending off the slope). Three-dimensional trajectories of water parcels around the eddy involve 50-100-m vertical excursions. Based on the reanalysed circulation and composite satellite images of Chlorophyll-a, we hypothesise that the circulation around the eddy led to significant nutrient enrichment in the euphotic zone around the perimeter of the eddy.

1. Introduction

During the Austral summer of 2006-07 two remarkable oceanic events occurred in the Tasman Sea. Firstly, there was a series of strong, sustained, upwelling-favourable wind events that resulted in unseasonably cold coastal waters along much of the New South Wales coast. Secondly, a very intense cold-core eddy developed at 33.5°S at the foot of the continental rise just off Sydney (34°S), with sea-level anomalies (SLAs) of almost 1 m below mean sea level at its core and cold temperature (T) anomalies exceeding $-8\,^{\circ}$C at 200 m depth. The intensity of these events was so great that explanations were demanded by Australian news sources. Coincident with these events, satellite observations show very high levels of Chlorophyll-a (Chl-a) along the coast; and above-average levels of Chl-a offshore. Based on results from a data assimilating, eddy-resolving ocean general circulation model, we describe the three-dimensional circulation associated with these events; and propose a mechanism for the nutrient enrichment of surface waters around the cyclonic eddy.

The salient oceanographic feature of the waters off the New South Wales coast is the East Australian Current (EAC) and the associated mesoscale eddy field (Fig. 1). These waters are generally low in nutrients, a characteristic of their source waters in the Coral Sea, and the wind stress is also predominantly downwelling favourable (southerly), so any sub-surface nutrients are rarely upwelled to the euphotic zone. Despite this, nutrient enrichment and algal blooms do occur in response to occasional upwelling-favourable wind events, encroachment of the EAC, or its eddies, onto the continental shelf, or the separation of EAC from the shelf (Blackburn and Cresswell, 1993; Tranter et al., 1986; Hallegraeff and Jeffrey, 1993; Cresswell, 1994; Gibbs et al., 1997; Oke and Middleton, 2000; Ajani et al., 2001; Roughan and Middleton, 2002; Ridgway and Dunn, 2003; Baird et al., 2007; MacDonald et al., 2009). As a result of the episodic nature of these events concentrations of Chl-a are typically low in the Tasman Sea.

The purpose of this paper is to provide a synoptic description of the ocean circulation off the New South Wales coast between December 2006 and April 2007, when the above-mentioned upwellings and eddy formation occurred, in order to better understand the factors that may have contributed to these extreme events. To these ends, we present an analysis of the mesoscale ocean circulation for this period using results from the

* Corresponding author. Tel.: +61 3623 25387.
E-mail address: peter.oke@csiro.au (P.R. Oke).

0967-0645/$ - see front matter
doi:10.1016/j.dsr2.2010.06.006

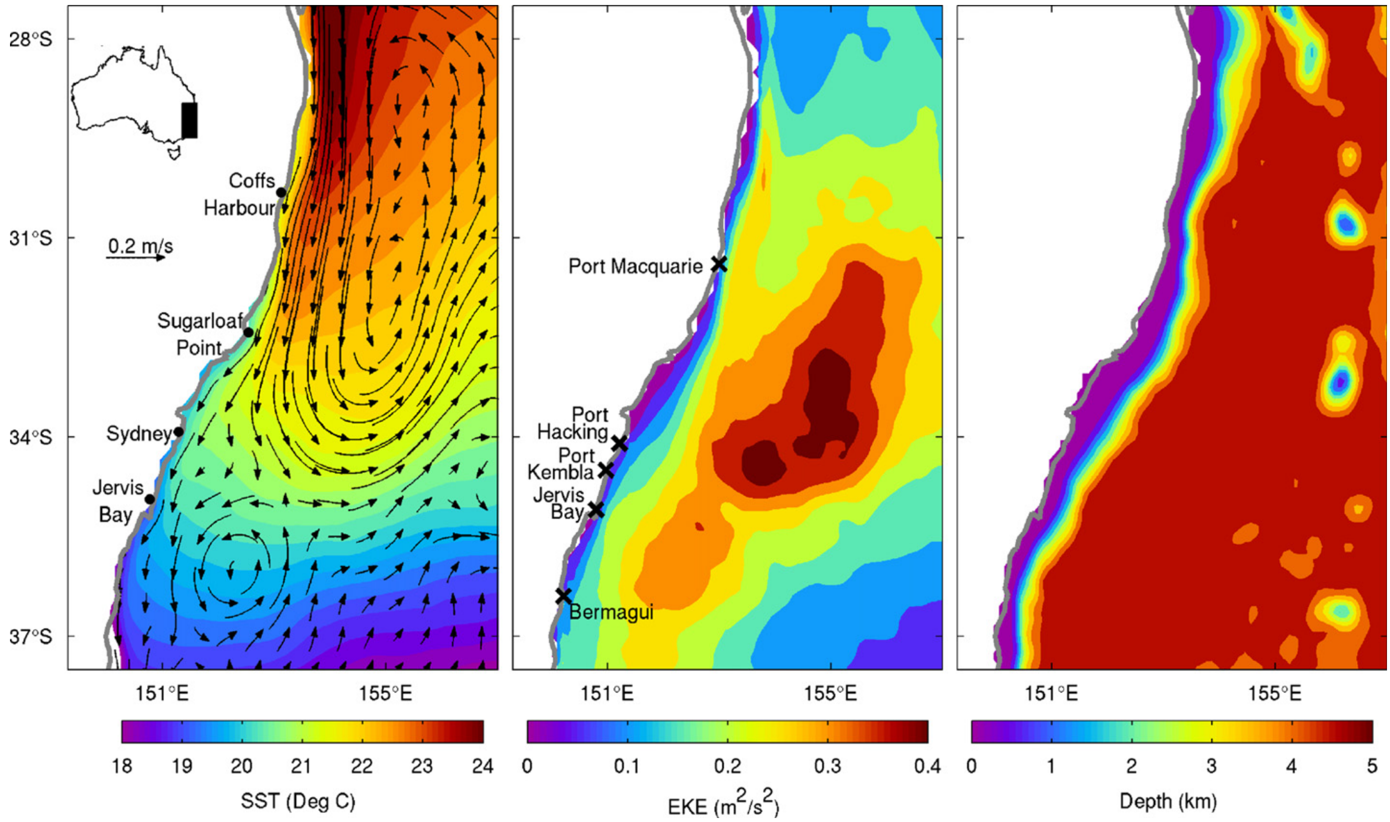

Fig. 1. Thirteen-year average (1993–2006) SST and surface velocities (left), eddy-kinetic energy (EKE; middle) computed from daily mean fields of surface velocity, from BRAN2p1, and model topography (right). The inset on the left panel shows the location of the region of interest off south eastern Australia. The crosses on the middle panel denote tide gauge locations referred to in Fig. 3.

Bluelink ReANalysis (BRAN) system (Oke et al., 2005, 2008; Schiller et al., 2008). Briefly, BRAN involves the integration of a global ocean model that is eddy-resolving around Australia and the sequential assimilation of altimeter, sea-surface temperature (SST) and in situ Argo temperature (T) and salinity (S) observations. Despite the regional focus, the assimilation is performed globally, using all available observations.

2. Reanalysis system

The Bluelink ReANalysis (BRAN) system that is used here is comprised of a global ocean general circulation model, called the Ocean Forecasting Australia Model (Schiller et al., 2008), and an ensemble data assimilation system, called the Bluelink Ocean Data Assimilation System (Oke et al., 2008). The Bluelink system is run operationally at the Bureau of Meteorology for the production of forecasts (Brassington et al., 2007) and has been used for several scientific studies (Oke et al. 2005, 2008, 2009; Oke and Schiller, 2007; Schiller et al., 2008, 2009, 2010).

The Bluelink ocean model is a configuration of the Modular Ocean Model (Griffies et al., 2004; version 4.0d). The model grid has 10 m vertical grid spacings over the top 200 m, and 1/10° horizontal grid spacing in the 90°-sector centred on Australia and south of 16°N. This translates to zonal and meridional resolution of about 11 km and 9–10 km (at 26-36°S), respectively. The horizontal grid spacing is 0.9° across the Indian and Pacific Ocean and 2° in the Atlantic Ocean. To accommodate the inhomogeneous resolution, the horizontal viscosity is resolution- and state-dependent, based on the Smagorinsky-scheme (Griffies and Hallberg, 2000). The bottom topography was constructed from a range of different sources, as documented by Schiller et al. (2008). The turbulence closure model used here is a version of the hybrid mixed-layer scheme described by Chen et al. (1994). For long model runs, such as free spin-up runs and BRAN experiments, the model is forced by 6-hourly heat, freshwater and momentum fluxes from ECMWF, using fields from ERA-40 (Kallberg et al., 2004) for the period prior to August 2002, and 6-hourly operational forecasts thereafter.

The Bluelink assimilation system uses an Ensemble Optimal Interpolation (EnOI) scheme that draws on a 120-member ensemble of intraseasonal model anomalies. The ensemble is generated from a long non-assimilating integration of the model. The ensemble is stationary in time, acting as a time-invariant database that is intended to define the sub-space of the ocean model. Using ensemble data assimilation techniques (see Oke et al., 2008), the model-observation misfits (the background innovations) are projected onto the model sub-space, to compute an increment, or correction, to a model background field during each weekly assimilation cycle. Thus, the assimilation system is multi-variate, using the statistics of the ensemble to interpolate and extrapolate model-observation misfits onto the full-model grid, and for all model variables. So for example, an observation of one variable, say temperature, is compared to the model background field, and the difference is projected onto the model state, using the ensemble, yielding an increment not just for temperature, but also salinity, velocity, and sea level. In practice, many observations of different types are assimilated simultaneously at each assimilation step. In this case, the assimilation system solves an analysis equation, using explicit estimates of the observation errors to weight their relative impact, together with the ensemble statistics, to compute a weighted least-squares analysis that