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Coastal upwelling by wind-driven forcing in Jervis Bay, New South Wales: A numerical study for 2011

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ABSTRACT

The Princeton Ocean Model (POM) was used to investigate an upwelling event in Jervis Bay, New South Wales (SE Australia), with varying wind directions and strengths. The POM was adopted with a down-scaling approach for the regional ocean model one-way nested to a global ocean model. The upwelling event was detected from the observed wind data and satellite sea surface temperature images. The validated model reproduced the upwelling event showing the input of bottom cold water driven by wind to the bay, its subsequent deflection to the south, and its outcropping to the surface along the west and south coasts. Nevertheless, the behavior of the bottom water that intruded into the bay varied with different wind directions and strengths. Upwelling-favorable wind directions for flushing efficiency within the bay were ranked in the following order: N (0°; northerly) > NNE (30°; northeasterly) > NW (315°; northwesterly) > NE (45°; northeasterly) > ENE (60°; northeasterly). Increasing wind strengths also enhance cold water penetration and water exchange. It was determined that wind-driven down-welling within the bay, which occurred with NNE, NE and ENE winds, played a key role in blocking the intrusion of the cold water upwelled through the bay entrance. A northerly wind stress higher than 0.3 N m^{-2} was required for the cold water to reach the northern innermost bay.

1. Introduction

Jervis Bay (JB) is a semi-closed embayment located on the east coast of Australia (35° 04′S, 150° 44′E; Fig. 1). It has a north-south extent of 15 km, a west-east extent of 8 km, an average depth of 15 m, and an area of 126 km^2. The width and depth of the bay entrance, are 3.75 km and 40 m, respectively (Wang and Symonds, 1999). The rate of water exchange with offshore water is higher than in nearby bays, while nutrients and biological productivity are lower (Joyce et al., 2010).

The marine environment of the JB has been exposed to pollutant problems from anthropogenic development (Yamamoto, 2003; Anderson et al., 2008). Eutrophication is a common phenomenon that has been frequently stimulated by nutrients such as phosphorus and nitrogen released from rivers, ground water and catchment sewage systems. Because the exchange rate between JB and offshore water is low, the accumulated pollutants within the bay take a long time (10–74 days) to be flushed out varying with the tidal flow (Holloway et al., 1992b). Furthermore, eutrophication events may lead to the occurrence of Harmful Algal Blooms (HABs) within the bay, deteriorating water quality. Eutrophication can therefore have an adverse impact on the marine ecosystem and limit human activities (e.g., leisure sports and tourism).

Given the above, coastal upwelling events in Jervis Bay can play an important role, not only in flushing out nutrient material accumulated in the bay, but also in importing nutrients into the bay from offshore water and therefore in producing algal blooms; this is all the more so because river inflows into JB (e.g., Currambene Creek, Callala Creek, and Moona Moona Creek) are negligible (Blackburn and Cresswell, 1993; Kai et al., 1999; Oke and Middleton, 2001; Pritchard et al., 2003; Lee et al., 2007; Anderson et al., 2008; Trainer et al., 2000). Understanding the coastal upwelling intrusion into JB is therefore a key, but still poorly investigated, research and management challenge.

The influence of East Australian current (EAC) and its eddies on the hydrographic properties of this area is instead well known. The

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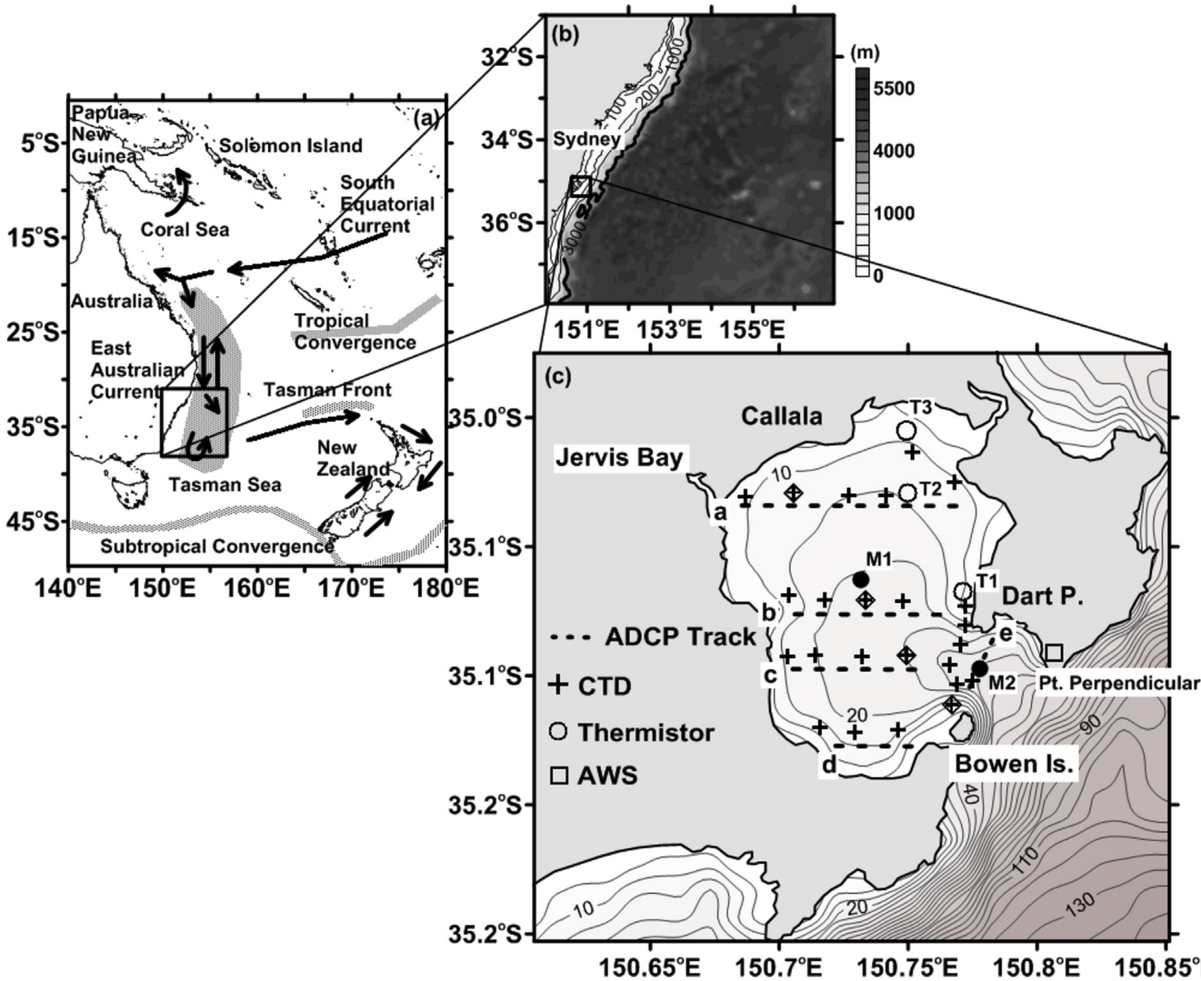

Fig. 1. Map of the study area: (a) schematic view of ocean circulation and fronts of the Southwest Pacific Ocean region along the coastline of Australia, (b) the model domain with bottom topography, and (c) a topographic map of the area around Jervis Bay in m. The contour interval is 5 m. The three open circles (T1, T2, and T3) indicate the stations where thermistors were moored from March to August 2011. Solid black circles indicate the location of sites M1 and M2 referred to in Fig. 8. Superimposed are ADCP tracks (a–e) and CTD stations (+) for June 26, 1998. Open diamonds with black crosses are stations for vertical section of temperature from Callala to Bowen Island in Fig. 3g and g′.

EAC flows poleward off the east coast and separates around Sugarloaf Point (32.4°S), which is where it typically generates anticyclonic warm core eddies. In summer, it can advect warm surface waters down to Tasmania. The Tasman Front forms the interface between the warm Coral and the cool Tasman Seas (Fig. 1a). At times, baroclinic Rossby waves triggered by oscillations of the Tasman Front travel toward the east coast of Australia, producing a small cold-core (cyclonic) eddy (Marchesiello and Middleton, 2000). Since the cold water from the Tasman Sea approaches the bay entrance, the formation of eddies near the bay mouth affects the circulation within the bay (Holloway et al., 1991; Joyce et al., 2010). Aside from the EAC, density driven currents, tidal processes, and coastal trapped waves (CTW) influence circulation patterns. During the summer season, bay circulation is dominated by sub-inertial baroclinic flows that are created as a baroclinic response of the bay to the scattering of CTWs in the form of internal Kelvin waves (Middleton, 1994; Wang and Wang, 2003).

In JB, the M_2 semi-diurnal tidal current is dominant but weak, with a speed of 0.02 m s^{-1} (Holloway et al., 1992b). Accordingly, circulation and shelf upwelling intrusion are the main physical mechanisms. In particular, it is worth determining how coastal upwelling on the shelf intrudes into the bay and how this intrusion varies with time and space. It is known that coastal upwelling near JB is mainly driven by two factors: 1) the warm EAC and its eddies (Tranter et al., 1986; Huyer et al., 1988; Holloway et al., 1992a; Blackburn and Cresswell, 1993; Hallegraeff and Jeffery, 1993); and 2) upwelling-favorable winds (Smith, 1968; Lewis, 1981; Rochford, 1984; Schahinger, 1987). In the southern hemisphere, winds blowing in a poleward direction along a western boundary tend to cause upwelling. Alongshore currents (Huyer et al., 1988; Gibbs et al., 1997) and bottom Ekman-transport convergence (Herzfeld and Tomczak, 1999) are considered to be minor factors driving upwelling events along the east and south coasts of Australia.

Although upwelling can be driven by onshore encroachment of the EAC near the Sydney shelf (McClean-Padman and Padman, 1991; Roughan and Middleton, 2004), wind-driven upwelling is more significant (Gibbs et al., 1997; Marchesiello and Middleton, 2000). This has been confirmed by analysis of NOAA-11 remote Sea Surface Temperature (SST) images (Gibbs et al., 1997) and by numerical analysis (Marchesiello and Middleton, 2000). Meanwhile, Gibbs et al. (1998) suggested that the formation of baroclinic instability by the EAC off the east coast of Australia prior to upwelling-favorable winds could more actively trigger coastal upwelling. Nevertheless, it is presumed that upwelling-favorable wind is the primary forcing mechanism driving upwelling in JB and plays an important role in transporting nutrients to the coast