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Intermittent dense water outflows under variable tidal forcing in Shark Bay, Western Australia

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ABSTRACT

Hydrodynamic data (time series of tidal velocities and vertical stratification) were collected during the winter of 2009 in Shark Bay, Western Australia, to document water exchange between the bay and the ocean. The net loss of freshwater through evaporation causes salinity levels in Shark Bay to be higher than the adjacent ocean, leading to its classification as an inverse estuary. The observations revealed pulses of near-bed dense water outflows (velocity ~0.10 m s^{-1}) at weekly to fortnightly intervals, associated with periods of turbulent mixing when tidal velocities and winds were both weak. Although tidal mixing appeared to be the main control on the formation of the outflows, wind mixing during strong wind events was also sufficient to destratify the water column and interrupt the density-driven circulation. These data represent the first direct measurements of exchange flows in the entrance channels of Shark Bay and reveal a mechanism to maintain the balance of salinity as well as contribute to the exchange of material (e.g., larvae) between the bay and the ocean.

1. Introduction

In arid climates, such as in Shark Bay Western Australia, density-driven currents can represent an important mechanism for estuary–ocean exchange. In these systems, an excess of evaporation and highly intermittent freshwater input causes the bay waters to become more saline than the adjacent shelf waters. The resulting density gradient drives a circulation that is the reverse, or inverse, of a classical estuarine system, with denser inshore waters flushing out of the bay along the bottom and fresher ocean waters flowing in at the surface (Pritchard, 1967; Nunes and Lennon, 1986; Bowers and Lennon, 1987; Lennon et al., 1987).

In these 'inverse estuary' systems the longitudinal density gradient, and thus density-driven circulation, is often weaker than in classic estuaries with freshwater input. This can increase their vulnerability to ecological problems such as hypoxia and accumulation of pollutants. Inverse estuaries are particularly susceptable to changes in the balance of buoyancy inputs, both naturally and due to human impacts; for example, due to droughts, changing climatic conditions, and the damming of rivers (Largier et al., 1997; Largier, 2010).

Globally, water bodies that exhibit inverse estuarine characteristics are common across a variety of scales and examples include: the Arabian Sea (Banse, 1997), northern Gulf of California, Mexico (Lavin et al., 1998), West Australian coastal waters (Shearman and Brink, 2010; Pattiaratchi et al., 2011), Spencer Gulf, Australia (Nunes et al., 1990); Shark Bay, Australia (Logan and Cebulski, 1970); Laguna San Ignacio, Mexico (Winant and de Velasco, 2003); Hervey Bay, Australia (Ribbe, 2006); Puttalam Bay, Sri Lanka (Arulananthan et al., 1995); and Bahia de Guaymas, Mexico (Valle-Levinson et al., 2001). Largier (2010) provides a review of 'low-inflow' estuaries that seasonally exhibit inverse estuarine circulation, and emphasizes that they are likely even more common than classic estuaries. Perhaps because the arid climates that induce inverse estuarine conditions occur to a large part in areas of low population density and/or in developing countries, there is a comparative void of literature on these systems.

In estuaries the gravitational circulation is driven by a longitudinal density gradient which provides a buoyancy flux for stratification of the water column that is then controlled by mixing (or destratification) effects due to turbulence generated by winds and tidal currents. Enhanced periods of gravitational circulation in inverse estuaries are associated with pulses of dense saline water flowing out of the estuary along the seabed, referred to here as 'dense water outflows'. It is usually during periods of reduced mixing that dense water outflows develop (Linden and Simpson,

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1988). Much knowledge of these processes has been gained through idealized laboratory experiments (e.g. Linden and Simpson, 1986, 1988) and through extensive observational studies in areas such as Spencer Gulf and Gulf St. Vincent in South Australia (Nunes and Lennon, 1986; Nunes and Lennon, 1987; Samarasinghe and Lennon, 1987). In these regions, the inshore salinity increases substantially during the summer due to intense evaporation, which is released as pulses of higher salinity water, particularly during autumn and winter when cooling further increases longitudinal density gradients. The frequency of these pulses are regulated by a fortnightly variation in tidal currents through the spring–neap cycle (Lennon et al., 1987).

In Shark Bay, Western Australia (hereinafter referred to as the Bay; Fig. 1) strong longitudinal salinity gradients have been documented since the 1970s, but the detailed dynamics of its density-driven circulation remain unknown. The 'Shark Bay Outflow' was inferred through measurements of sea floor sediments on the shelf (James et al., 1999), hydrographic survey data (Woo et al., 2006), and numerical modeling (Nahas et al., 2005), but little was known about the mechanism or frequency of the release of water from the Bay. In this paper, measurements of current velocity, density, and temperature profiles in one of the main entrance channels to Shark Bay are presented with the aim of describing the dynamics of the export of dense water from the Bay that have previously only been indirectly observed.

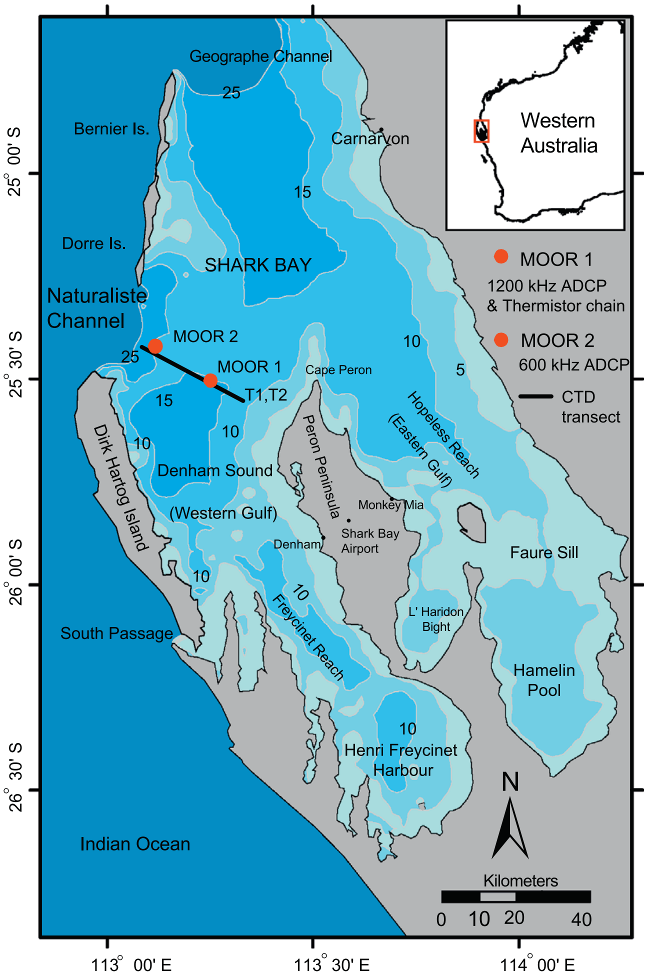

Fig. 1. Map of the study area showing the locations of the two moorings (MOOR 1 and MOOR 2) and the location of CTD transect T1 measured in June. The location of the transect measured in July (T2) was similar to T1, though slightly extended on either end. Depth contours at 5,10,15, and 25 m are shown.

2. Study area

Climate, tides and winds are the major physical factors influencing the oceanographic environment of Shark Bay, a large, shallow, hypersaline Bay located along the arid northwest coast of Western Australia between 24°30′ and 26°45′S. Shark Bay is the largest semi-enclosed water body in Australia with a north–south length of ~250 km, width ~100 km, and average depth of only 10–20 m. The southern part of the Bay consists of an Eastern Gulf (Hopeless Reach) and Western Gulf (Freycinet Reach) divided by the Peron Peninsula (Fig. 1). Exchange with the Indian Ocean can occur only between the three offshore islands that semi-enclose the Bay. This study focuses on flow through the Naturaliste Channel (width ~25 km), one of Shark Bay's two main entrances. Other connections to shelf waters include the Geographe Channel (width ~35 km) to the north and much smaller South Passage (width ~2 km) (Logan and Cebulski, 1970; Burling et al., 2003; Nahas et al., 2005). The slope of the seabed is quite steep through its main channels (Naturaliste and Geographe) in contrast to the rest of the Bay, which is relatively flat and shallow. Shark Bay is a UNESCO World Heritage site. Here, some of the largest seagrass beds in the world, a diversity of marine mammals, and stromatolite 'living fossils' must coexist with a salt mining operation, an aquaculture industry, and important commercial prawn, scallop, snapper, crab, and whiting fisheries (DASETT, 1990).

2.1. Climate and geography

Local annual rainfall is ~200 mm, with most precipitation falling during the passage of winter cold fronts, or occasional summer cyclone events (Logan and Cebulski, 1970). Relatively strong southerly winds (mean ~8 m s^{-1}) blow consistently during spring and summer (October–March) and are weaker (mean ~5 m s^{-1}) and more variable during autumn and winter (April–September) (Pattiaratchi et al., 1997; Burling et al., 1999; Woo et al., 2006).

The combination of strong winds and high summer temperatures causes the mean annual evaporation (~2000 mm) to exceed precipitation (~200 mm) by a factor of 10, resulting in hypersaline conditions, particularly in the inner reaches. In the innermost portion of the Eastern Gulf, where Faure Sill restricts flow into Hamelin Pool (Fig. 1), the salinity level is ~65 thus nearly twice that of the adjacent ocean (Burling et al., 1999). Two rivers occasionally empty into the Bay, but are thought to make an insignificant contribution to the mean salinity regime, as they are dry most years and flow only during cyclone events (Logan and Cebulski, 1970). Logan and Cebulski (1970) and later Smith and Atkinson (1983) found that the Bay maintained its salinity structure both seasonally and inter-annually, with generally vertically well-mixed conditions in most of the Bay.

An important feature of the Bay is the presence of density fronts in both Geographe and Naturaliste Channels that separate Bay water from intruding shelf waters. A weaker frontal feature (Fig. 3b) extends across the entrances to both gulfs and northwards along the eastern shoreline (Logan and Cebulski, 1970; Smith and Atkinson, 1983; Nahas et al., 2005). Nahas et al. (2005) suggested that the location of the frontal systems at the ocean entrances are a result of the balance between tidal mixing and gravitational circulation and may be predicted using the Simpson–Hunter parameter (Simpson and Hunter, 1974). The front across the middle of the Bay is more influenced by wind. The well-defined semi-circular fronts in the Naturaliste and Geographe Channels are easily identified in satellite sea surface temperature images throughout the year; however, differential heating/cooling of the Bay due to the shallow depths causes a seasonal reversal in temperatures across the fronts (Figs. 2 and 3). In winter, Shark Bay