Marine Pollution Bulletin 105 (2016) 277–285

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Research paper

The density-driven circulation of the coastal hypersaline system of the Great Barrier Reef, Australia

Gerry G. Salamena [a,*], Flávio Martins [b], Peter V. Ridd [c]

[a] College of Marine and Environmental Science, James Cook University, Townsville, Queensland 4811, Australia
[b] CIMA-EST/UAlg., Campus da Penha, P8000-117, Faro, Portugal
[c] Marine Geophysics Laboratory, College of Science Technology and Engineering, James Cook University, Townsville, Queensland 4811, Australia

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form 30 January 2016
Accepted 4 February 2016
Available online 12 February 2016

Keywords:
Density-driven circulation
Hypersaline waters
Great Barrier Reef
Flushing time

ABSTRACT

The coastal hypersaline system of the Great Barrier Reef (GBR) in the dry season, was investigated for the first time using a 3D baroclinic model. In the shallow coastal embayments, salinity increases to *c.a.* 1‰ above typical offshore salinity (~35.4‰). This salinity increase is due to high evaporation rates and negligible freshwater input. The hypersalinity drifts longshore north-westward due to south-easterly trade winds and may eventually pass capes or headlands, e.g. Cape Cleveland, where the water is considerably deeper (*c.a.* 15 m). Here, a pronounced thermohaline circulation is predicted to occur which flushes the hypersalinity offshore at velocities of up to 0.08 m/s. Flushing time of the coastal embayments is around 2–3 weeks. During the dry season early summer, the thermohaline circulation reduces and therefore, flushing times are predicted to be slight longer due to the reduced onshore-offshore density gradient compared to that in the dry season winter period.

1. Introduction

The existence of hypersaline waters in coastal zones of continental shelves is caused by the excess of evaporation over precipitation and river runoff (de Silva Samarasinghe and Lennon, 1987; Gräwe et al., 2009; Heggie and Skyring, 1999; Lavín et al., 1998; Wolanski, 1986). Hypersaline systems in continental shelves have been studied in numerous locations particularly around the dry continent of Australia, for example, in northern Australia (Wolanski, 1986), gulfs in the Southern Australia (de Silva Samarasinghe, 1989; de Silva Samarasinghe and Lennon, 1987; Nunes and Lennon, 1986, 1987), Hervey Bay, Australia (Gräwe et al., 2009) and coastal zones of Great Barrier Reef (GBR), Australia (Andutta et al., 2011; Wang et al., 2007; Wolanski, 1981). The extent of the hypersalinity depends upon the freshwater balance of the region which is highly associated with seasonal characteristics e.g. during the dry season summer (e.g. in Gulf of California, Lavín et al. (1998)) and the dry winter in the GBR (Walker, 1981b). One important hydrodynamical effect of the hypersaline waters is to produce a thermohaline circulation by which the saltier water masses will sink and be flushed out seaward along the sea-bed (Fig. 1) (Gräwe et al., 2009; Heggie and Skyring, 1999; Lennon et al., 1987b; Wolanski, 1986). As a result, this thermohaline circulation is an important oceanographic aspect in the hypersaline coastal waters of the continental shelf.

The degree of hypersalinity on the continental shelf is not only influenced by the freshwater balance, but is also affected by the exchange of the coastal hypersaline waters with oceanic salinity from offshore (Wang et al., 2007). This exchange transport process is likely affected by turbulent diffusion, thermohaline circulation and large scale advection (Wang et al., 2007). Due to this exchange transport role, some authors have conducted studies connecting this transport process with the flushing time of the coastal hypersaline waters (de Silva Samarasinghe and Lennon, 1987; Hancock et al., 2006; Heggie and Skyring, 1999; Largier et al., 1997; Wang et al., 2007).

The hypersaline system of the GBR shelf is different to most other hypersaline environments due to its aspect ratio. It is a continental shelf system 2000 km in the long-shelf direction and between 50 (further North) and 100 (further South) km across shelf. This contrasts with most other reported hypersaline systems which are bays, gulfs, or inverse estuaries and are smaller in the long-shelf direction than across shelf direction. Due to this morphological difference, along shore currents become important for the GBR (Andutta et al., 2011). In contrast, for waters in narrow bays, it is the cross shelf tidal currents which predominate e.g. Gulf of St. Vincent (de Silva Samarasinghe and Lennon, 1987), Gulf of California (Lavín et al., 1998), Shark Bay (Nahas et al., 2005) and San Diego Bay (Largier et al., 1997). Thus, along-shore currents of the GBR enables the hypersaline waters in the GBR to be transported alongshore from one coastal embayment to another (Andutta et al., 2011).

There has been considerable works on residence or flushing times of the GBR waters due to the potential influence of residence time on pollutant build-up in the GBR lagoon (Andutta et al., 2013; Choukroun

* Corresponding author at: LIPI's Centre for Deep Sea Research, Indonesian Institute of Sciences (LIPI), Jl. Y. Syaranamual, Guru-Guru, Poka, Kota Ambon, Provinsi Maluku 97233, Indonesia.
E-mail address: gerry.salamena@my.jcu.edu.au (G.G. Salamena).

http://dx.doi.org/10.1016/j.marpolbul.2016.02.015
0025-326X/

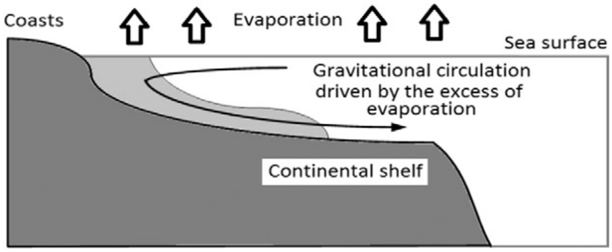

Fig. 1. Schematic diagram of evaporation-driven circulation. The light grey indicates plume of hypersaline water. This figure is drawn based on Fig. 2d of Wang et al. (2007).

et al., 2010; Hancock et al., 2006; Mao and Ridd, 2015; Wang et al., 2007). For the inshore hypersaline system in the GBR, it is probable that a combination of longshore currents and cross-shelf transport including via the thermohaline circulation can significantly affect the exchange process between inshore and offshore waters. This contrasts with the situation in narrow bays and estuaries where the effects of longshore currents are negligible (Largier et al., 1997) and hence, the narrow waters are likely to have longer residence time (Kämpf et al., 2010). Recent studies investigating cross-shelf transport in the GBR's coastal hypersaline system, which used 1D-models of the diffusion of salt, indicate short residence times (a few weeks) of these coastal zones, despite being approximate in nature and ignoring longshore transport (Hancock et al., 2006; Wang et al., 2007).

The recent studies to investigate the dynamics of hypersalinity in the GBR have significant limitations. For instance, the 1D cross-shelf exchange and diffusion models neglect longshore gradient of the salinity of the bays in the coastal zones of the GBR (Hancock et al., 2006; Wang et al., 2007). In addition, the 2D vertical integrated-models (Andutta et al., 2011) ignore baroclinic force driving thermohaline circulation (Nunes and Lennon, 1986) even though they have successfully duplicated the spatial distribution of hypersalinity along the GBR coast lines (Andutta et al., 2011); these 2D models required considerable manipulation of model diffusion coefficients to produce results comparable to field data.

Ideally, a 3D model description of the circulation is required in order to simulate the baroclinic forcing, the general wind and tidal barotropic flow especially along the shelf. Furthermore, this 3D-model can also simulate the influence of the Coriolis Effect on the baroclinic flow, i.e. the sub-surface hypersaline flow might be deviated by Coriolis Effect in the near-bottom layer as reported observationally (Lavín et al., 1998). This deviation of the salt transport cannot be described by 1D-model and 2D-model due to the absence of longshore and vertical aspects, respectively.

The objectives of this study are to (a) simulate 3D-features of the dynamic of hypersalinity in the coastal zones of GBR, (b) investigate the density-driven circulation in this area and (c) calculate the flushing time of the hypersaline water in selected bays in association with the prevailing transports in the coastal waters (i.e. longshore and the cross-shore transports).

In order to keep the computational cost of the 3D model reasonable, and due to limitations on the availability of coastal salinity data to be used for model validation, a subsection of the GBR lagoon was chosen. The area of interest for this numerical study is the shallow-water environment situated from Bowling Green Bay to Halifax Bay (Fig. 2b) of the central GBR region (Fig.2a). This area is in the dry tropics region of the GBR and hypersaline conditions are a regular feature of the dry season (Walker, 1981b; Wolanski and Jones, 1981b).

2. Physical description of the study area

During the dry season (April to November), the central GBR (Fig.2a) is dominated by the south-east trade wind (Wolanski, 1982) with average evaporation rate over the ocean of 5 mm/day (Da Silva et al., 1994; Gibson et al., 1999; Kalnay et al., 1996) and negligible precipitation (Wang et al., 2007). Semi-diurnal tides prevail in these coastal zones with the surface elevation ranging from 0.5 m to 3.8 m (Hamon, 1984; Lou, 1995). Coastal zone oceanography is affected by oceanic inflows from the Coral Sea (Brinkman et al., 2002) and this inflow is significantly affected by the complex bathymetry of this region (Brinkman et al., 2002; Wolanski, 1994). The residual circulation is affected by the oceanic inflow and also by the SE trade winds which produce a generally longshore transport near the coasts (Wolanski, 1994).

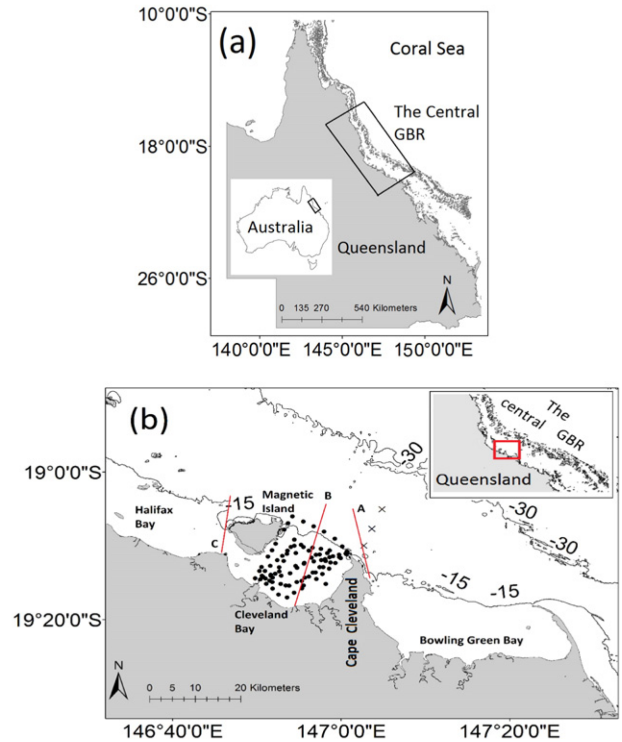

Fig. 2. (a) The central GBR, and (b) one of coastal zones of the central GBR including Halifax Bay, Cleveland Bay and Bowling Green Bay; (•) represents oceanographic stations from routine measurements using Seabird SBE 19 (i.e. 19–21 September 2009, 18 September 2010, 10–11 September 2011, 7–9 September 2012 and 5–7 October 2013); (×) describes oceanographic stations of Wolanski and Jones (1981b); transects A, B and C represent cross-shelf transects of eastern Cape Cleveland, Cleveland Bay and western Magnetic Island, respectively for which model results are calculated.

Cleveland Bay and Bowling Green Bay in the central GBR (Fig. 2b) have been the focus of numerous surveys of coastal hypersalinity (Walker, 1981b, 1982; Wang et al., 2007; Wolanski, 1994; Wolanski et al., 1981). Furthermore, the routine salinity measurements for this coastal hypersalinity have also, recently, been conducted inside the Cleveland Bay (Fig. 2b). Geomorphologically, Cleveland and Bowling Green Bays are 25 km and 80 km wide, respectively and, relatively 15 m deep at their seaward edge (Fig. 2b) (Lou, 1995; Wolanski and Jones, 1981a).

3. Material and methods

3.1. The MOHID model

The 3D-model used in this study was the MOHID model (www.mohid.com). MOHID is the 3D water modelling system developed by the Marine and Environmental Technology Research Centre (MARETEC) (Mateus and Neves, 2013; Mateus et al., 2012). MOHID has been used not only in Portugal (Cancino and Neves, 1999; Martins et al., 2001; Vaz et al., 2007) but also in other regional areas including the Ria de Vigo, Spain (Taboada et al., 1998), Western Europe margin (Coelho