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Assessing water renewal time scales for marine environments from three-dimensional modelling: A case study for Hervey Bay, Australia

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Abstract

We apply the three-dimensional COupled Hydrodynamical Ecological model for REgioNal Shelf seas (COHERENS) to compute water renewal time scales for Hervey Bay, a large coastal embayment situated off the central eastern coast of Australia. Water renewal time scales are not directly observable but are derived indirectly from computational studies. Improved knowledge of these time scales assists in evaluating the water quality of coastal environments and can be utilised in sustainable marine resource management. Results from simulations with climatological September forcing are presented and compared to cruise data reported by Ribbe (2006. A study into the export of saline water from Hervey Bay, Australia. Estuarine Coastal and Shelf Science 66, 550–558). A series of simulations using idealised forcing provides detailed insight into water renewal pathways and regional differences in renewal timescales. We find that more than 85% of the coastal embayment's water is fully renewed within about 50–80 days. The eastern and western shallow coastal regions are ventilated more rapidly than the central, deeper part of the domain. The climatological simulation yields temperature and salinity patterns that are consistent with the observed situation and water renewal time scales in the range of those derived from idealised model studies. While the reported simulations involve many simplifications, the global assessment of the renewal time scale is in the range of a previous estimate derived for this coastal embayment from a simpler model and observational data.

Keywords: Estuaries; Water renewal; Residence time; Flushing; Hervey Bay; Coastal management; Water quality; Impact assessment; Ocean modelling; COHERENS; Sustainability

1. Introduction

With about 50% of the global population living within the coastal zone (e.g. Cohen et al., 1997), the influence of human activity upon coastal marine environments is immense. An important quantity that aids the classification of the environmental state of estuaries, large coastal embayments, shelf seas, but also ocean basins from regional to global scales is that of the water renewal time scale, sometimes also referred to as the flushing or ventilation time scale (e.g. Wolanski, 1986; Takeoka, 1984; Luketina, 1998; Greyer, 1997; England, 1995; Gómez-Gesteira et al., 2003; Koutitonsky et al., 2004; Liu et al., 2004; Shen and Haas, 2004; Andrejev et al., 2004; Banas and Hickey, 2005; Guyondet et al., 2005; Ribbe, 2006). Marine and aquatic scientists refer to this physical attribute when estimating the time it takes to replace all water within a confined region. For sustainable estuarine and coastal management purposes, this concept is applied to assess the health of aquatic and coastal systems impacted upon by coastal population growth and constructions, industries, fishing, tourism, agricultural runoff, aquaculture, and associated potential pollution.

The quantity 'renewal time scale' is not observable or measurable directly. In its simplest form, it is estimated indirectly from the ratio between the domain's volume and the

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volumetric throughflow. In this instance, it is a first-order description of the physical transport mechanisms (Fischer et al., 1979) without any detail knowledge of the physical processes that lead to the renewal of water being required (Monsen et al., 2002). Briefly summarised, all the techniques used to estimate time scales include simple concepts such as the tidal prism based on volume and salinity budgets (e.g. Wolanski, 1986; Luketina, 1998; Gillibrand, 2001; Ribbe, 2006), box models (e.g. Gómez-Gesteira et al., 2003), depth- or laterally-averaged two-dimensional ocean circulation models (e.g. Gillibrand, 2001; Bilgili et al., 2005) and complex three-dimensional general circulation models (e.g. Andrejev et al., 2004; Liu et al., 2004; Shen and Haas, 2004; Guyondet, 2005; Banas and Hickey, 2005) employing Lagrangian particle or Eulerian methods to track the passage of passive tracers. In particular, the application of these three-dimensional ocean general circulation models has become popular in recent times and highlighted the deficiencies of simple methods employed (e.g. tidal prism) to estimate renewal time scales (e.g. Guyondet et al., 2005). The models provide a complete description of the physics that drive the oceanic circulation. It is the physical processes that cause the flow and exchange of water which in turn control marine environmental conditions. Additional insight, for example, into the spatial distribution of renewal time scales is gained and the models allow studying the impact of different physical processes such as wind, tides, mixing, evaporation, precipitation, and river runoff upon the derived overall renewal time scale.

In this paper, we aim to determine water renewal pathways and to assess regional differences in renewal time scales for Hervey Bay, Australia (Fig. 1), from three-dimensional ocean general circulation modelling studies with simplified topography and idealised forcing. The model adopted in this work is the COupled Hydrodynamical Ecological model for REgioNal Shelf seas (COHERENS) which is publicly available and includes excellent documentation (Luyten et al., 1999). The application of the model focuses upon Hervey Bay which has long been recognised as an important marine ecological system. It provides a resting place for humpback whales migrating between the tropics and the Southern Ocean (Chaloupka et al., 1999), and it is home to a large number of residential dugongs and sea turtles listed as vulnerable to extinction by the International Council for the Conservation of Nature and Natural Resources. Hervey Bay is also a spawning region for many species of temperate pelagic fish (Ward et al., 2003) and supports a fisheries industry that is worth several tenths of millions of dollars with aquaculture developing recently into a significant industry (ABARE, 2004). The region is vulnerable to extreme climate events such as severe subtropical storms and cyclones (Preen and Marsh, 1995; Preen et al., 1995). Coastal population growth in the Hervey Bay region is exceptional and is one of the largest in Australia during the last 10 years (LPG, 2004). No rigorous assessment of the physical oceanography and circulation of this particular bay has been provided in the past. The only recent insight into the physical settings of the bay is presented in Ribbe (2006) who estimates from field observations a basin-integrated residence time scale of about 90 days.

The simulations reported in this paper provide insight into the spatial distribution of basin to regional water renewal times aiding the better management of this important marine environment. Time scales are assessed from a series of studies utilising idealised as well as climatological forcing. The basin average time scale is found to be in the range of the previous estimate derived for this coastal embayment from observational data (Ribbe, 2006). The simulated temperature and salinity patterns are consistent with those observed during the hydrographic survey reported by Ribbe (2006). In Section 2 of this paper, we describe the physical oceanographic settings of the area simulated, outline the model employed and detail the objectives of the computational studies performed. The results are discussed in Section 3 and focus upon basin-scale estimates, spatial pattern of simulated renewal time scales from idealised model experiments, and results from one simulation with climatological forcing. Section 4 presents a brief discussion, summary, and conceptual model of renewal time scales derived for the bay.

2. Method

2.1. Domain and model description

The model is applied to Hervey Bay which is a large coastal embayment off the central east coast region of Australia (Fig. 1a). The bay is situated at the southern end of the Great Barrier Reef. It is bowl shaped with an area of about 4000 km^2 and is connected to the open shelf ocean via an approximately 80 km wide northward facing main opening. The eastern boundary of the bay is formed by Fraser Island, the world largest sand island (Boyd et al., 2004), and a narrow, shallow channel provides a small connection to the open ocean in the south. Maximum depths in the bay are about 25–30 m. Water to be exchanged with Hervey Bay is potentially supplied by (i) the East Australia Current that flows along the shelf break transporting up to 16 Sv southward (Ridgway and Godfrey, 1997) and (ii) derived from northern parts of the shelf (Wolanski, 1994). Middelton et al. (1994) conducted a hydrographic survey in the region describing the circulation to the east and north off Hervey Bay. The tidal regime for a region to the north of Hervey Bay has been described from current meter measurements as primarily semidiurnal or mixed-semidiurnal which agreed well with previously published results from tidal modelling (Griffin et al., 1987). With the exemption of a hydrographic survey reported by Ribbe (2006), no work on the physical oceanography of the bay itself has been carried out. All previous studies focused on biological aspects of the bay since it was identified as an important marine ecological system and whale sanctuary (Chaloupka et al., 1999). Several studies dealt with the catastrophic loss of sea grasses, an important feeding ground for protected dugongs, due to severe weather events and associate extreme high river runoff (Preen et al., 1995).

In order to investigate bay water renewal time scales and the exchanges of bay water with the surrounding coastal and open ocean, COHERENS is adopted in this study. A full description of the model is provided by Luyten et al. (1999) which is publicly available on CD-ROM at http://www.mumm.ac.be/~patrick/mast/documentation.html. COHERENS is a multi-purpose three-dimensional hydrodynamic model that solves the continuity, momentum, temperature and salinity transport equations using finite-differences on an Arakawa-C staggered Cartesian, sigma-coordinate grid. The hydrodynamic model can be coupled to biological, resuspension and contaminant models. The user has the choice of several state-of-the-art advection schemes for momentum and scalars, and the model allows for various parameterisation of turbulent motion including a variety of turbulence closure schemes. For details