Assessing Water Renewal Time Scales for Marine Environments from Three-Dimensional Modelling: A Case Study for Hervey Bay, Australia

(*)Joachim Ribbe, (**)Jörg-Olaf Wolff, (**)Joanna Staneva, and (**)Ulf Gräwe

(*) Corresponding Author:
University of Southern Queensland
Department of Biological and Physical Sciences
Email: Joachim.Ribbe@usq.edu.au
Ph.: +61 2 4631 1452
Fax.: +61 2 4631 1530

(**) University of Oldenburg
Institute for Chemistry and Biology of the Marine Environment
Oldenburg, Germany

Final manuscript prepared for submission to
Environmental Modelling and Software

Toowoomba, February 15th, 2008

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 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 times 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.

Key words: 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 run-off, 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 volumetric throughflow. In this instance, it is a first-order description of the physical transport mechanisms (Fisher, 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 theses 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 times 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 times scales is gained and the models allow studying the impact of different physical processes such as wind, tides, mixing, evaporation, precipitation, and river run-off 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 (Figure 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 (Figure 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, 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 semi-diurnal 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 run-off (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 hydro-dynamic 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 see Luyten et al. (1999). The model was systematically tested and applied in several studies (Umgiesser et al., 2002; Luyten et al., 2003; Lacroix et al., 2004; Marinov et al., 2006) and model intercomparison projects (Moll and Radach, 2003; Delhez et al., 2004).

[Insert Figure 1]

The key model configurations adopted for the experiments using idealised forcing are summarised in Table 1. The domain of interest is resolved with a horizontal grid spacing of about 1.8 km in both north to south and west to east direction. Ten vertical sigma levels were chosen. The model started from rest and the circulation within the bay is in a quasi-steady state after only a few days. We do not apply an additional spin-up period. Due to an average renewal time of about 90 days, an initial spin-up will only slightly change the renewal time and is not considered as significant. Since wind and tide are considered to be the main drivers of the circulation within the bay, we are using the barotropic version of the model and no heat and freshwater fluxes are specified. For one final experiment carried out to compare observational and simulated data, these forcing conditions are replaced with climatological values described in Section 3.4.

[Insert Table 1]

At the northern and southern boundary (if opened, see model experiments) a conservative scalar quantity is specified at all vertical and horizontal boundary grid points and set to a constant value of 100. Its initial value within the interior of the domain is zero ($C_{t=0} = 0$). This passive Eulerian tracer is transported into the model domain and is used to determine renewal time scales. We define the renewal time scale $T_{renewal}$ as the time when the initial tracer concentration at a certain point within the domain exceeds a certain threshold value:

$$T_{renewal} = T(C(t) > C_{threshold})$$

Several preliminary computational experiments were conducted in order to evaluate the impact of the various horizontal and vertical mixing schemes upon the renewal flow and time scale. For a detailed description of these schemes, it is referred to Luyten et al. (1999). No significant changes in times scales were found for the various vertical mixing schemes, therefore, all experiments reported here applied the Pacanovski and Philander (1981) scheme for both momentum and the Eulerian tracer. The assessment of the impact of the horizontal diffusion schemes is, however, important and results from several sensitivity studies are reported. In the following section, we described how forcing and horizontal mixing is varied between individual computational experiments.

2.2 Computational Studies

The computational studies reported in this paper are motivated by our deficient knowledge of the physical processes that operate within an important coastal environment. Due to the limited database for model forcing and validation most of the experiments use idealised forcing in order to provide a first assessment of renewal pathways, overall basin-averaged renewal time scales, and identify distinct domains with different renewal characteristics under variable wind conditions. These experiments provide an impetus to improve our knowledge of the physical oceanography through year-round observational work in the future. Only the data reported by Ribbe (2006) allow a first assessment of water renewal characteristics for a particular, realistic situation and one experiment using climatological September forcing yields temperature and salinity pattern as well as water renewal time scales.

[Insert Table 2]

The results from a total of twenty five computational experiments are reported in this paper. The differences in model settings are briefly summarised in Table 2. The model is forced with a constant wind varying only in direction from westerly, easterly, northerly through to southerly in the first set of experiments (E1-E4). The second set of experiments (E5-E8) is carried out with the same wind forcing, yet a sinusoidal northern boundary current with magnitude 0.5 $m \cdot s^{-1}$ and a specified period of 43.200 s is applied. This represents an approximation and simplification of the primarily semi-diurnal tide region of the region including average tidal flows across the northern domain opening. The forcing is uniform in space across the northern boundary. Comparison between these sets of experiments allows evaluating the impact of both wind and quasi-tidal forcing upon the watermass renewal of the chosen domain. For the next series of computational experiments (E9-E12), identical forcing to that of the above experiments is chosen, but this time the southern boundary is opened. This facilitates the exchange of water with the open ocean at this location and illuminates the impact of the southern inflow upon the bay and its chosen renewal pathway.

The final series of simple experiments (E13 - E24) is conducted with the same forcing (wind, sinusoidal tide) as above but with variations to horizontal mixing from the standard Smagorinsky (1963) scheme to constant horizontal mixing of different magnitude. This particular series of experiments assesses the effect of the parameterisation of horizontal mixing upon the renewal time scales and pathways. The values chosen for horizontal mixing are well within the range of those reported for coastal waters (Fisher et al., 1979). A final simulation applies September climatological forcing (see section 3.4).

All numerical experiments are carried out for a total period of 180 days as some preliminary experiments demonstrate that complete renewal in most parts of the bay is achieved within this period. The circulation within the bay is in a quasi-steady state after only a few days of this period.

3. Results

In the following sections, results from all twenty five experiments are discussed and renewal time scales are summarised in Tables 3 and 4. To elucidate the renewal process with different wind pattern, the renewal pathways are shown and discussed for the first twenty days of the integration in Section 3.1. This is the time scale upon which most rapid and complete renewal of large areas of the domain occurs (>50 %, see Figure 6). This is followed by section 3.2 in which basin-wide renewal times scales are presented. In section 3.3, spatially varying renewal time scales are discussed in some detail in order to characterise distinct regions within the bay and finally, section 3.4 present results from the final computational experiment that applies climatological forcing.

3.1 Circulation and renewal pathways

Experiments E1-E8 assess renewal pathways with wind only (E1-E4) and with both wind and sinusoidal forcing at the northern boundary (E5-8). The renewal pathways from the latter four experiments are presented in Figure 2 to Figure 5. These are similar to those in E1-4, however, since the chosen horizontal Smagorinsky-type mixing scheme for momentum and tracer in these computational experiments is flow-dependent, horizontal diffusion of the tracer is larger in E5-E8. This in turn reduces basin-wide (see Figure 6) as well as spatially varying renewal time scales if compared to E1-E4 with wind-forcing only.

The distribution of the passive Eulerian tracer transported into the domain via the northern boundary is captured for each of the experiments during the first twenty days of the simulations. After this period, about 50 % of the domain is fully ventilated. The sequence of tracer distributions identifies the pathway of new water entering and flowing throughout the domain. Only the surface circulation and renewal pathway is shown which is indicative of the depth integrated flow throughout the bay. The circulation is in a quasi-steady state and represented after a completion of a full sinusoidal forcing cycle, hence the pattern of the indicated circulation is not changing.

A westerly wind (Figure 2) results in a quasi-steady state circulation which is anti-clockwise, i.e. anticyclonic throughout the domain. Shaded is the distribution of the transported Eulerian tracer that is used as a measure for the amount of "new water" transported into the domain. Entry is primarily confined to the shallower western coastal regions of the bay where surface currents are strongest and outflow occurs along the eastern section of the northern boundary.

[Insert Figure 2]
[Insert Figure 3]

Due to spatially uniform northern boundary forcing, entry of new water is observed across the whole of the northern boundary, and the impact of the wind-induced circulation leads to a more rapid anti-cyclonic renewal along the western boundary of the bay.

With easterly wind forcing (Figure 3), a primarily clockwise, i.e. cyclonic circulation is established throughout the bay, and the renewal pathway or entry of new water follows the shallow eastern regions of the bay. With both westerly and easterly wind forcing, it is the centre of the bay that is clearly the least rapid ventilated region (see below for further discussion).

Northerly wind forcing only (Figure 4) leads to a separation of the flow in into two individual circulation cells and the establishment of two rapid renewal pathways along the shallow edge of the bay. The western and eastern part of the bay are characterised by anticyclonic and cyclonic flows respectively. Outflow of water from the embayment occurs along the central north to south axis of the bay.

[Insert Figure 4]
[Insert Figure 5]

With southerly wind (Figure 5), a reversal of the flow field is evident from the established renewal pathways, with inflow primarily confined to the central interior north to south axis and outflow along the eastern and western boundaries of the domain.

In addition to the experiments (E1-E8) discussed in this section, a further seventeen (E9-E24, C) experiments were conducted to determine renewal time scales. The impact of the various changes in forcing and mixing parameterisation upon basin-averaged renewal time scales is discussed in section 3.3 and 3.4.

3.2 Basin renewal

The temporal evolution of the renewed water volume [%] within the bay is shown in Figure 6 for experiments E1 - E12 (wind only, wind and periodic boundary forcing, southern boundary open) and in Figure 7 for experiments that test sensitivity of the renewal time scale to the parameterisation of horizontal mixing and the chosen mixing coefficients (E13 - E24).

In Table 3, renewal time scales from all the experiments are presented with renewal assumed to be achieved when 90 % of the domain is ventilated, i.e. the initial concentration is larger than the threshold value of 90. These values correspond to those presented in Figures 6 and 7 which show the temporal evolution of the total renewed water mass [%] within the bay. The values in Table 3 vary from about 48 days to larger than 180 days, i.e. in the latter case complete renewal of the whole domain is not achieved within the simulated period.

The comparison of E5-E8 and E13-E24 demonstrates that the Smagorinsky (1963) scheme for horizontal momentum and tracer mixing produces the longest renewal time scales and that renewal time scales decrease with increasing constant diffusion coefficient. The range of simulated renewal time scales is found to be much smaller for experiments with easterly and westerly wind compared to those using northerly and southerly wind forcing. No further information on the spatial distribution of renewal time scales is presented for E13-24, however, the Smagorinsky (1963) scheme results in the sharpest gradients within highly dynamic regions. These gradients are weakened and smoothed using constant and increasing diffusion coefficient.

[Insert Figure 6]

[Insert Figure 7]

Largest changes in renewal time scales are obtained for northerly wind forcing. In all cases, renewal time scales are found to be longest except in those experiments when only wind-forcing is applied (E1 - E4). Constant horizontal mixing coefficients have also the most significant impact upon renewal time scales with northerly wind increasing by almost 50 % with a smaller diffusion coefficient. The opening of the southern boundary has the largest impact in experiments with northerly and southerly wind forcing, but affects least renewal time scales simulated with easterly and westerly wind forcing.

[Insert Table 3]

3.3 Regional renewal

The simulated renewal pathways shown in Figure 2 to Figure 5 reflect the general circulation within the bay under varying wind forcing. It is possible to identify three key regions that exhibit distinct ventilation characteristics: (i) the eastern region, i.e. east of 152.8^o E and north of 25.25^o S, (ii) the western region, i.e. west of 152.8^o E and north of 25.25^o S, and (iii) the southern region south of 25.25^o S. The values represented in Table 4 are obtained as area averages from all experiments. Renewal is again assumed when 90 % of water within the domain had been replaced.

The two regions identified as western and eastern to the north of 25.25 ^{o}S, represent about 90 % of the bay volume. It is this combined eastern and western region of the bay that is least impacted upon by any water entering the domain from the south in experiments with westerly and easterly wind forcing. The eastern region is ventilated within 23-24 days and the western region within 65-68 days with easterly winds. With westerly wind, both regions were ventilated within 68 days (eastern region) and 84-88 days (western region) respectively. This means that the inflow of water from the south affects less than 10 % of the bay as indicated by almost equal renewal time scales obtained in all simulations.

With southerly wind and an open southern boundary, the renewal pathway for water of southern origin is found in the eastern region, i.e. additional southern water flows through the eastern region, lowering renewal time scales from 116 days to 85 days but leaving the western region almost unaffected (51 days and 54 days). With northerly wind and an open boundary, the renewal pathway for water of southern origin is found in the western region, i.e. additional southern water moves through the western region, lowering renewal time scales from 161 days to 114 days, but leaving the eastern region unaffected (117 days and 112 days). It is evident and not surprising that the southern region of the bay is most impacted upon by a closing and opening of the southern boundary, however, since the domain comprises less than 10 % of the bay, its impact upon the system as a whole is very small.

[Insert Table 4]

3.4 Temperature, Salinity, and Renewal with Climatological Forcing

Renewal time scales computed and reported in the previous sections are not directly observable. The only data available for a direct comparison with simulations is a September 2004 hydrographic survey which was reported and used by Ribbe (2006) in order to determine a basin-wide flushing time scale of about 90 days. This value is within the range of spatially varying renewal time scales reported from the idealised simulations above. In this section, we discuss the results from an application of the model with climatological September forcing to simulate the observed temperature and salinity pattern and derive water renewal time scales under more realistic conditions.

Data for air temperature (22 ^{o}C), humidity (68 %), cloud cover (40 %), precipitation (50 mm month^{-1}), and easterly wind (5.5 m$\cdot$s^{-1}) are from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/averages/tables/cw_039085.shtml). The data is also used by the model to internally calculate evaporation rates. September mean river runoff is specified for the Mary River (6 m^{3}s^{-1}) and Burnett River (2 m^{3}s^{-1}). Tidal forcing in the model region is obtained from a tidal gauge time series near Bundaberg located at the northwest coast of the bay (Australian Bureau of Meteorology; contributed by the National Tidal Centre). Only the M_2 tidal constituent is used and the amplitude tuned to the Bundaberg measurements. The forcing data determine the exchange of heat, freshwater, and momentum between the ocean and atmosphere driving the circulation within the bay. The model is initialised from rest. Initial temperature and salinity and boundary values are climatological data from the EAC to the east of the bay. The model is then integrated for a period of twelve months and the resulting mean temperature and salinity distribution along the boundary is then prescribed for the September simulation discussed below. For the boundaries we are using a zero-gradient condition. Using this climatological September forcing, the model is integrated for a period of seven months and data are presented as mean values from the last month of that simulation.

The observed salinity and temperature pattern (Figure 8a) reported by Ribbe (2006) is compared with the simulated pattern (Figure 8b). The overall pattern simulated is consistent with the observed situation in September 2004. Temperature minima are located within the interior of the bay and values increase toward the shallow coastal areas of the bay. In both cases, temperature minima are about 20.6 ^{o}C. The simulated salinity pattern is characterised by a northeast to southwest gradient with increasing salinity toward the shallow western coast of the bay. This is consistent with the observed pattern. Simulated salinity is about 0.1-0.2 larger than the observed value.

[Insert Figure 8]

The corresponding renewal time scales are represented in Figure 9. Lowest values are found toward the northwest and northeast of the Bay. These are regions were new water enters the Bay due to river runoff in the west and easterly driven open ocean water in the east of the Bay. The overall basin-wide renewal time scale is about 28 days, but varies spatially throughout the domain with values ranging from several days to about 120 days within the interior of the Bay. Renewal time scales using climatological forcing are within the range of those obtained from experiments with simpler forcing reported above.

[Insert Figure 9]

4. Summary and Conclusion

The aim of this study is to assess renewal pathways and time scales for a large coastal ocean embayment using a three-dimensional general ocean circulation model with idealised boundary forcing. The renewal pathways represented in Figs. 2 to 4 and the interpretation of the spatial distribution of renewal time scales allows for a schematic description of the circulation in the bay and its renewal characteristics (Figure 10). It takes into account that the southern inflow impacts only marginally upon the bay as a whole. The bowl shaped bathymetry of the bay, its orientation with its main opening facing northward, and the prescribed idealised wind-driven forcing leads to the establishment of cyclonic and anticyclonic steady state circulation cells within the bay. The parameterisation of horizontal mixing impacts upon the overall, basin-wide renewal time scales discussed above, and increases or decreases the transition (i.e. the gradient) between rapidly and less rapidly ventilated regions of the bay, but affects only little the overall circulation pattern within the bay.

[Insert Figure 10]

Our experiments demonstrate that the use of a simple basin-averaged renewal time scale may be appropriate for many natural resource management enquiries. However, the modelling experiments reveal that renewal time scales vary spatially and management questions that focus on local, smaller-scale issues are better served by taking into account the spatial variability in renewal time scales. These findings are based on simple forcing and idealised experiments that require in the future validation through year-round field observations for model validation.

While many simplifications are made in this study, the general circulation patterns established and the pathway taking by renewing water shall provide the coastal management community, aquatic industries and fisheries with some new insight into the dynamics of the bay. Future modelling needs to take into account seasonal, annual and interannual variability in wind-forcing, better prescription of tidal flows and improved bathymetry in order to narrow down the range of renewal time scales obtained from this study. A limitation of our study is the data (temperature, salinity and current) available for model validation and forcing. Yet, the survey reported by Ribbe (2006) allows us to apply the model in a particular situation. We found that the model captures the observed September temperature and salinity pattern well and the spatial pattern of the water renewal time scale is judged to be close to reality. It is this simulation that is most realistic and applicable. In the future, work will need to focus on obtaining further observational data to validate and improve model simulations.

Acknowledgment

The authors would like to thank the Hanse Institute for Advance Study, Germany, and the University of Southern Queensland, Australia, for financial support of this project. The Burnett Mary Regional Group (Australia) is assisting with funding in establishing a field program for Hervey Bay. We would like to thank Luyten et al. (1999) for providing access to the COHERENS code and the developers of the FERRET program which was used for data analysis and graphics presented in this paper. Ferret is a product of NOAA's Pacific Marine Environmental Laboratory.

5. References

ABARE, 2004. Australian Fisheries Statistics 2004, Canberra.

Andrejev, O., Myrberg, K., Lundberg, P. A., 2004. Age and renewal time of water masses in a semi-enclosed basin – application to the Gulf of Finland. Tellus 56A, 548-588.

Banas, N. S., Hickey, B. M., 2005. Mapping exchange and residence time in a model of Willapa Bay, Washington, a branching, macrotidal estuary. Journal of Geophysical Research 110, 11011-11011.

Bilgili, A., Proehl, J. A., Lynch, D. R., Smith, K. W., Swift M. R., 2005. Estuary/ocean exchange and tidal mixing in a Gulf of Maine Estuary: A Lagrangian modelling study. Estuarine, Coastal and Shelf Science 65, 607-624.

Boyd, R., Ruming, K., Davies, S., Payenberg, T., Lang, S., 2004. Fraser Island and Hervey Bay - a classic modern sedimentary environment. In: Boult, P.J., Johns, D.R., Lang, S.C., (Eds.), Eastern Australian Basins Symposium II. Petroleum Exploration Society of Australia, Special Publication, pp. 511-521.

Chaloupka, M., Osmond, M., Kaufman , G., 1999. Estimating seasonal abundance trends and survival probabilities of humpback whales in Hervey Bay (east coast Australia). Marine Ecology Progress Series 184, 291-301.

Cohen, J. E., Small, C., Mellinger, A., Gallup, J., Sachs, J., Vitousek, P. M., Mooney, H. A., 1997. Estimates of coastal populations. Science 278, 1211-1212.

Delhez, É. J. M., Damm, P., de Goede, E., de Kok, J. M., Dumas, F., Gerritsen, H., Jones, J. E., Ozer, J., Pohlmann, T., Rasch, P. S., Skogen, M., Proctor, R., 2004. Variability of shelf-seas hydrodynamic models: lessons from the NOMADS2 Project. Journal of Marine Systems 45, 39-35.

England, M. H., 1995. The Age of Water and Ventilation Time scale in a Global Ocean Model. Journal of Physical Oceanography 25, 2756-2777.

Fischer, H. B., List, E. J., Kho, R. C. Y., Imberger, J., Brooks, N. H., 1979. Mixing in Inland and Coastal Waters, Academic Press, New York, 483p.

Gillibrand, P. A., 2001. Calculating Exchange Times in a Scottish Fjord Using a Two-dimensional, Laterally-integrated Numerical Model. Estuarine, Coastal and Shelf Science 53, 437-449.

Gómez-Gesteira, M., deCastro, M., Prego, R., 2003. Dependence of the water residence time in Ria of Pontevedra (NV Spain) on the seawater inflow and the river discharge. Estuarine, Coastal and Shelf Science 58, 567-573.

Greyer, W. R., 1997. Influence of Wind on Dynamics and Flushing of Shallow Estuaries. Estuarine, Coastal and Shelf Science 44, 713-722.

Griffin, D. A., Middelton, J. H., Bode, L., 1987. The Tidal and Longer-period Circulation of Capricornia, Southern Great Barrier Reef. Australian Journal of Marine and Freshwater Research 38, 461-474.

Guyondet, T., Koutitonsky, V. G., Roy, S., 2005. Effects of water renewal estimates on the oyster aquaculture potential of an inshore area. Journal of Marine Systems 58, 35-51.

Koutitonsky, V. G., Guyondet, T., St-Hilaire, A., Courtenay, S. C., Bohgen, A., 2004. Water renewal estimates for aquaculture developments in the Richibucto estuary, Canada. Estuaries 27, 839-850.

Lacroix, G., Ruddick, K., Ozer, J., Lancelot, C., 2004. Modelling the impact of the Scheldt and Rhine/Meuse plumes on the salinity distribution in Belgian waters (southern North Sea). Journal of Sea Research 52, 149-163.

Liu, Z., Wei, H., Liu, G., Zhang, J., 2004. Simulation of water exchange in Jiaozhou Bay by average residence time approach. Estuarine, Coastal and Shelf Science 61, 25-35.

LPG 2004. Population Growth - Highlights and Trends, Wide Bay Region. Queensland Government, Brisbane, Australia, pp.17.

Luyten, P. J., Jones, J. E., Proctor R., 2003. A Numerical Study of the Long- and Short-Term Temperature Variability and Thermal Circulation in the North Sea. Journal of Physical Oceanography 33, 37-56.

Luyten, P. J., Jones, J. E., Proctor, R., Tabor, A., Tett, P., Wild-Allen, K., 1999. COHERENS – A Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas: User documentation, MUMM report, 914 pp., Management Unit of the Mathematical Models of the North Sea. Brussels.

Marinov, D., Norro, A., Zaldivar, J.-M., 2006. Application of COHERENS model for hydrodynamic investigation of Sacca di Goro coastal lagoon (Italian Adriatic Sea shore). Ecological Modelling 193, 52-68.

Middelton, J. H., Coutis, P., Griffin, D. A., Macks, A., McTaggart, A., Merrifield, M. A., Nippard, G. J., 1994. Circulation and Water Mass Characteristics of the Southern Great Barrier Reef. Australian Journal of Marine and Freshwater Research 45, 1-18.

Moll, A., Radach, G., 2003. Review of three-dimensional ecological modelling related to the North Sea shelf system – Part 1: models and their results. Progress in Oceanography 57, 175-217.

Monsen, N. E., Cloern, J. E., Lucas, L. V., 2002. A comment on the use of flushing time, residence time, and age as transport time scales. Limnology and Oceanography 47, 1545-1553.

Pacanovski, R.C., Philander G., 1981. Parameterization of vertical mixing in numerical models of the tropical ocean. Journal of Physical Oceanography 11, 1442-1451.

Preen, A., Marsh, H., 1995. Response of dugongs to large scale loss of seagrass from Hervey Bay, Australia. Wildlife Research 22, 507-19.

Preen, A. R., Lee Long, W. J., Coles, R. G., 1995. Flood and cyclone related loss, and partial recovery, of more the 1000 km^2 of seagrasses in Hervey Bay, Queensland, Australia. Aquatic Botany 52, 3-17.

Ribbe, J**.,** 2006. A study into the export of saline water from Hervey Bay, Australia. Estuarine, Coastal and Shelf Science 66, 550-558.

Ridgway, K. R., Godfrey, J. S., 1997. Seasonal cycle of the East Australia Current. Journal of Geophysical Research 102, 22921-22936.

Shen, J., Haas, L., 2004. Calculating age and residence time in the tidal York River using three-dimensional model experiments. Estuarine Coastal and Shelf Science 61, 449-461.

Smagorinsky, J., 1963. General circulation experiments with the primitive equations: I. The basic experiment. Monthly Weather Review 91, 99-164.

Takeoka, H., 1984. Fundamental concepts of exchange and transport time scales in a coastal sea. Continental Shelf Research 3, 311-326.

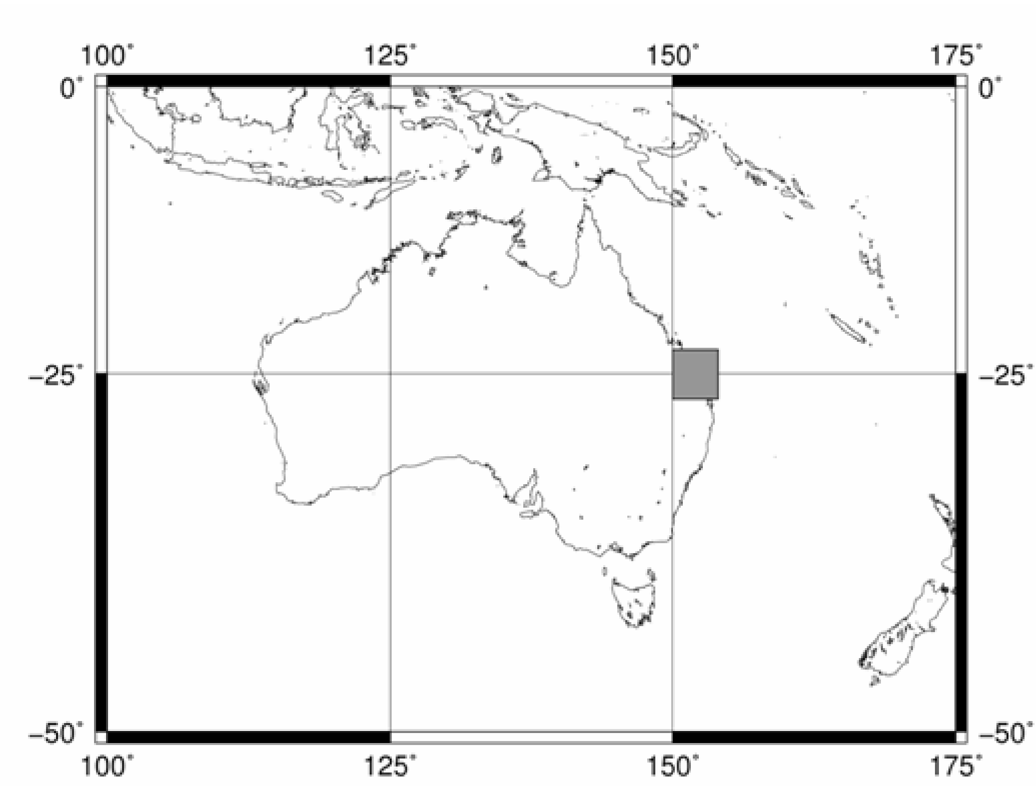
Umgiesser, G., Luyten, P., Carniel, S., 2002. Exploring the thermal cycle of the Northern North Sea area using a 3-D circulation model: the example of PROVESS NNS station. Journal of Sea Research 48, 271-286.

Ward, T. M., Staunton-Smith, J., Hoyle, S., and Halliday, I. A., 2003. Spawning patterns of four species of predominantly temperate pelagic fishes in the subtropical waters of southern Queensland. Estuarine, Coastal and Shelf Science 56, 1125-1140.

Wolanski, E., 1994. Physical Oceanographic Processes of the Great Barrier Reef. Marine Science Series, CRC Press, Boca Raton, FL, 194pp.

Wolanski, E., 1986. An evaporation-driven salinity maximum zone in Australian tropical estuaries. Estuarine, Coastal and Shelf Science 22, 415-424.

Figures



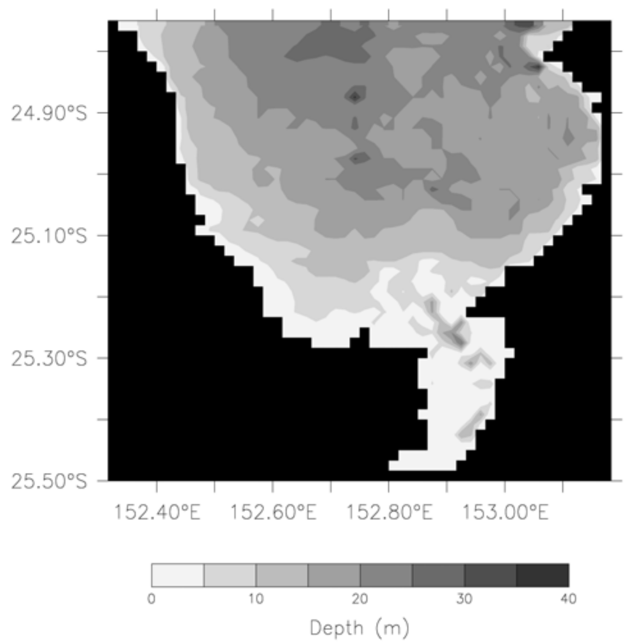


Figure 1: (a): Map of Australia indicating the region of interest, (b): Bathymetry and model domain. Shading is in 5 m depths intervals. Average depth of the total domain is about 20 m, with the southern region of the Strait less than 5 m deep. Horizontal and vertical lines indicate the three key regions east, west, and south which are used to assess regional difference in renewal time scales.

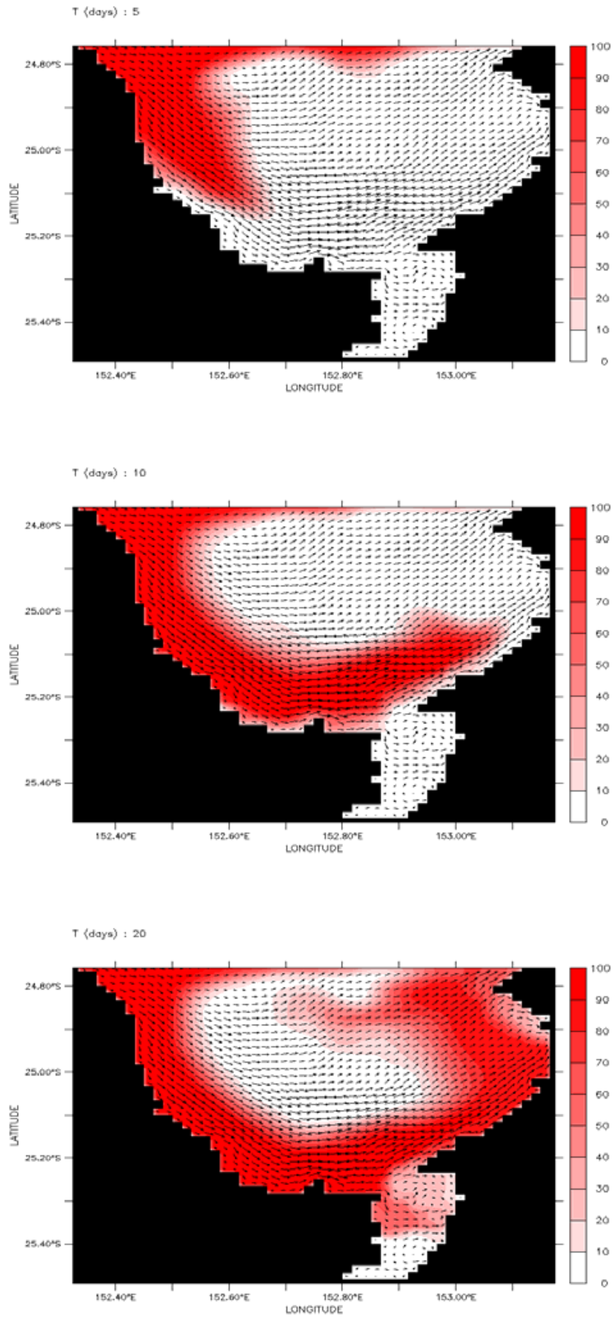


Figure 2: Renewal pathways with westerly wind and sinusoidal tidal forcing at the northern boundary (vertically averaged and plotted after 5 days, 10 days, and 20 days). Arrows indicate steady state surface flow. The shaded region represents ‘new’ water with a value of ‘100’ indicating complete renewal.

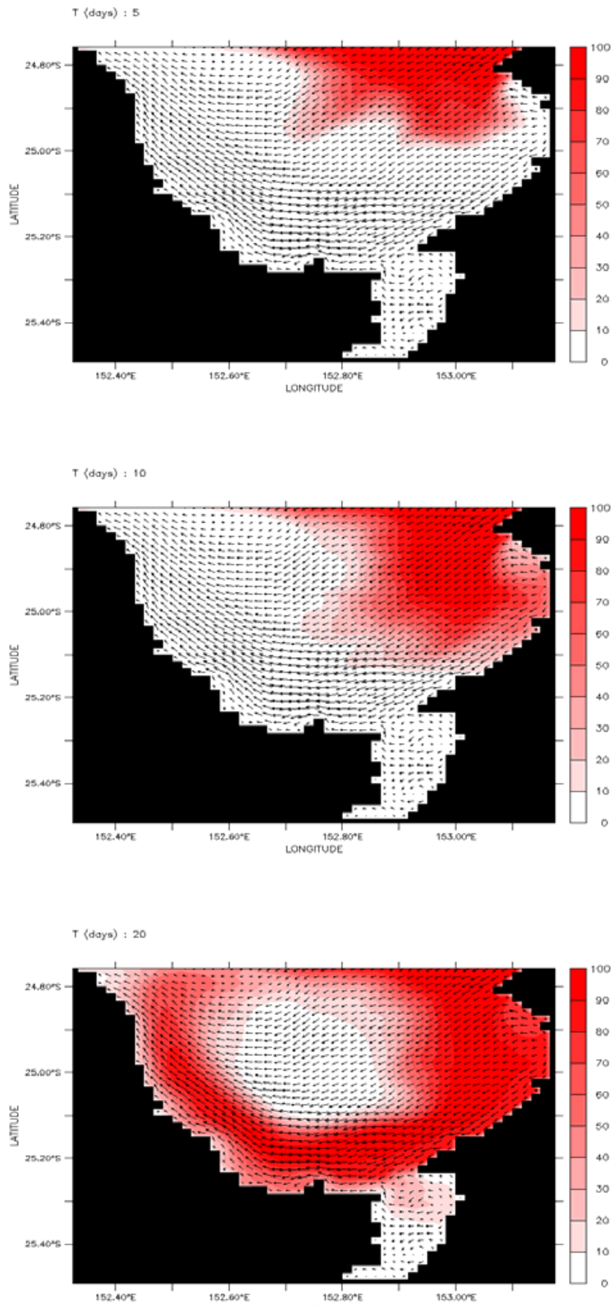


Figure 3: As Figure 2 but for easterly wind.

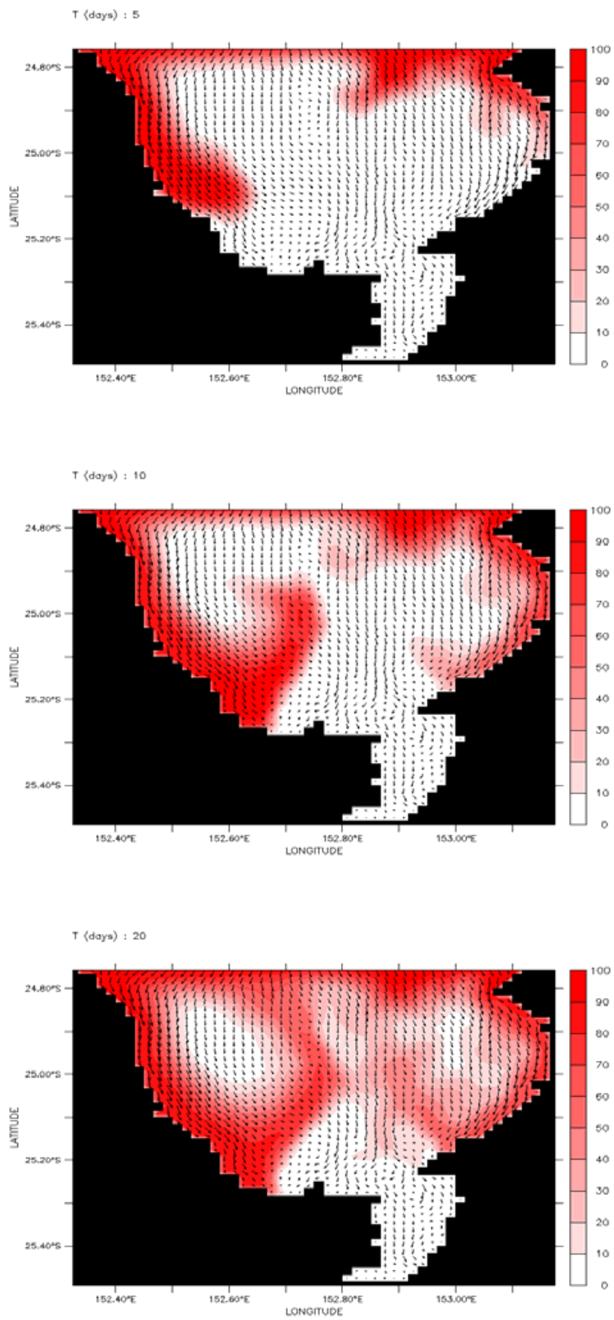


Figure 4: As Figure 2 but for northerly wind.

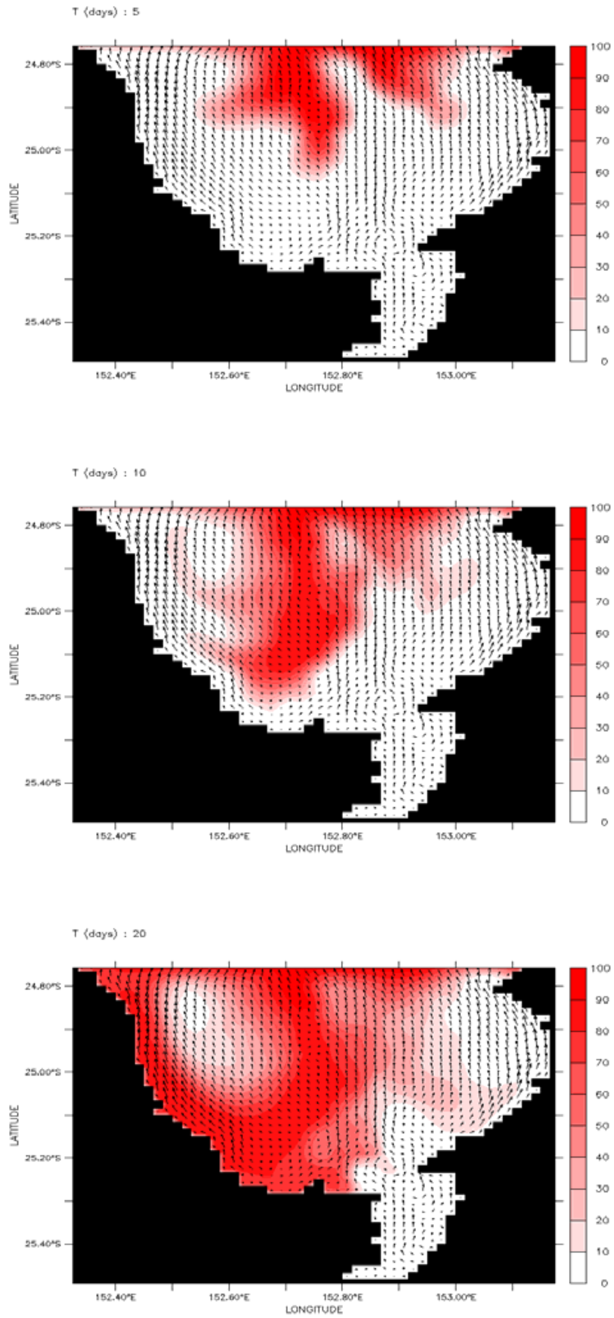
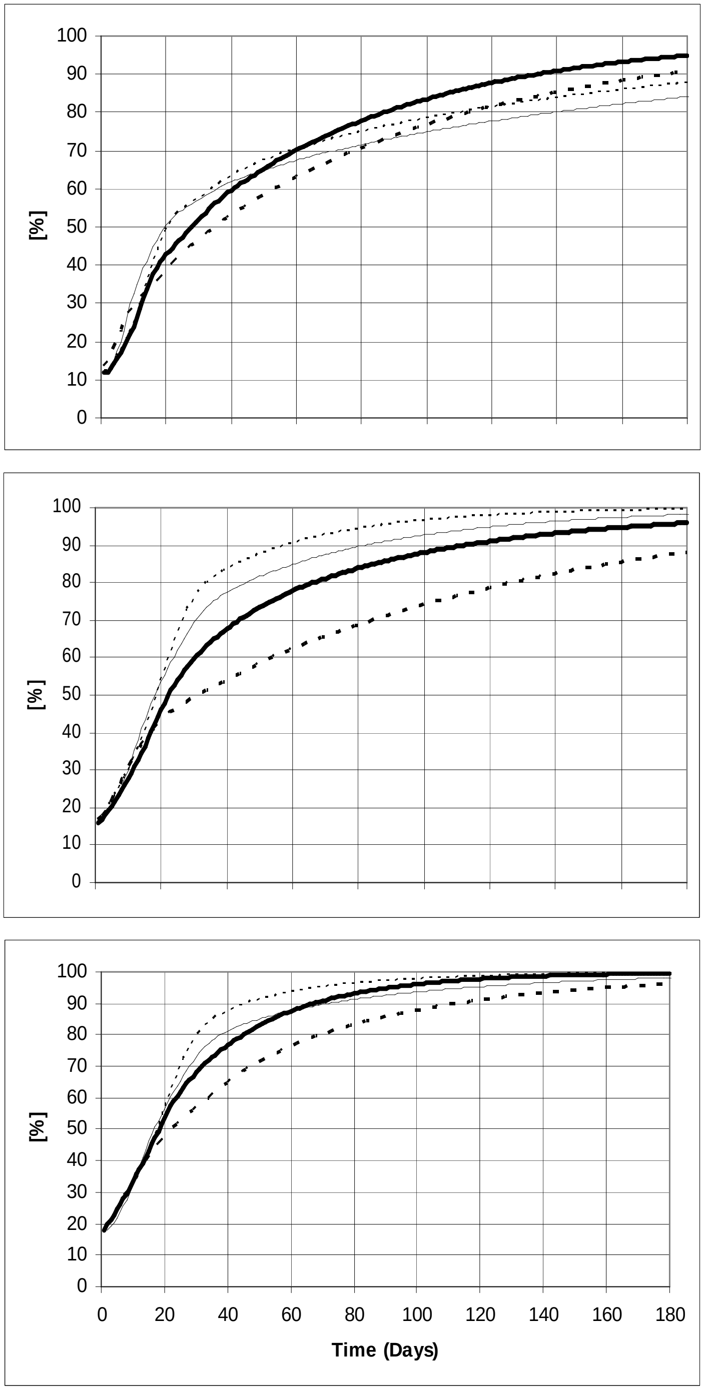
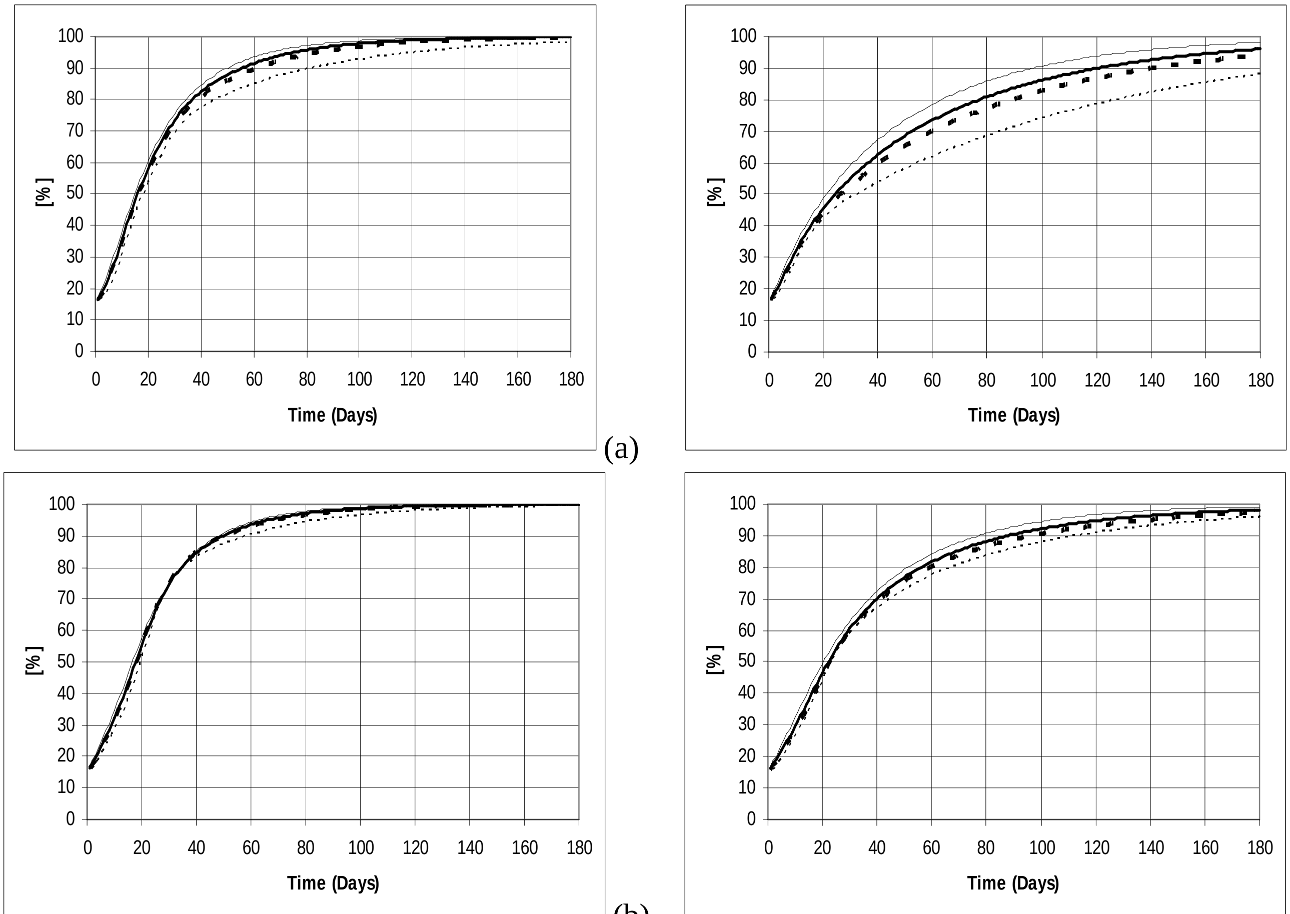


Figure 5: As Figure 2 but for southerly wind.



(a) (b) (c)

Figure 6: Temporal evolution of the renewed water volume [%] within the bay: (a) E1-E4 results with wind forcing only, (b) E5-E8 with wind and tidal forcing, and (c) E9-E12 results with open southern boundary and westerly (thin solid line), easterly (thin dashed line), northerly (thick dashed line) and southerly wind (thick solid line).



(a) (c) (b) (d)

Figure 7: Temporal evolution of the renewed water volume [%] within the bay using varying horizontal mixing parameterisation from E13-E24, (a) westerly wind, (b) easterly wind, (c) northerly wind, and (d) southerly wind; Pacanovski and Philander (1987) scheme (thin dashed line), K_h =100 $m^2 \cdot s^{-1}$ (thin solid line); K_h =50 $m^2 \cdot s^{-1}$ (thick solid line); K_h =25 $m^2 \cdot s^{-1}$ (thick dashed line).

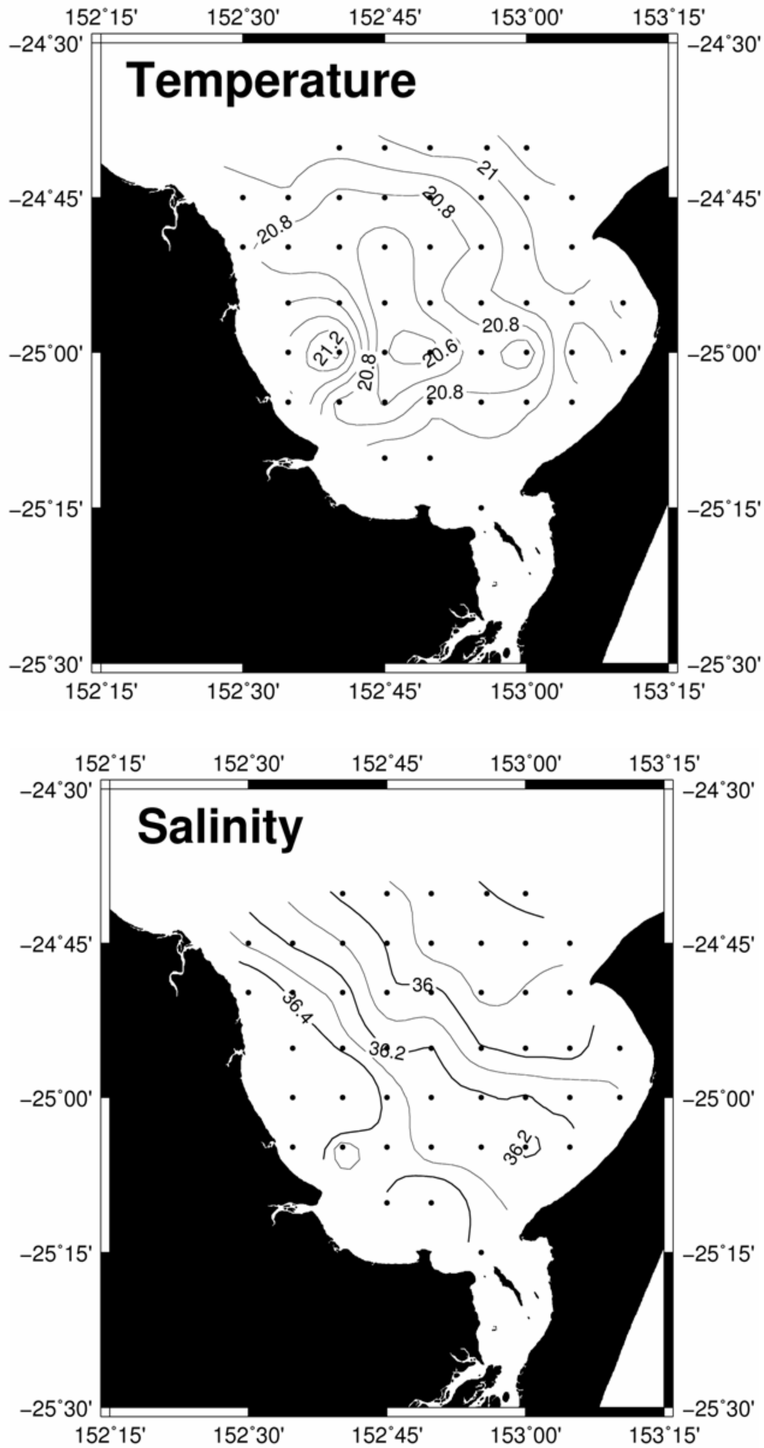
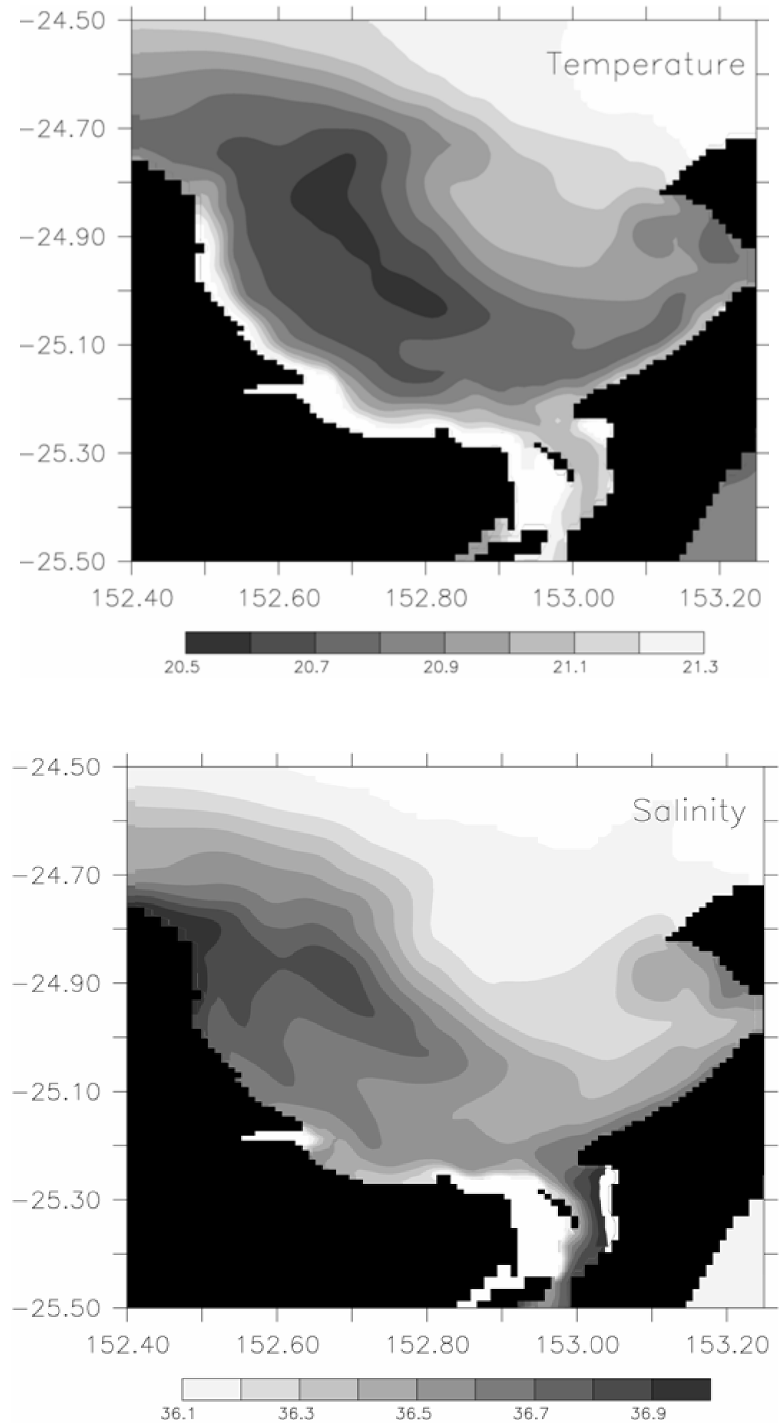


Figure 8: (a) Observed temperature [^{o}C] (top panel) and salinity pattern (bottom panel) reported by Ribbe (2006) and



(b) simulated pattern.

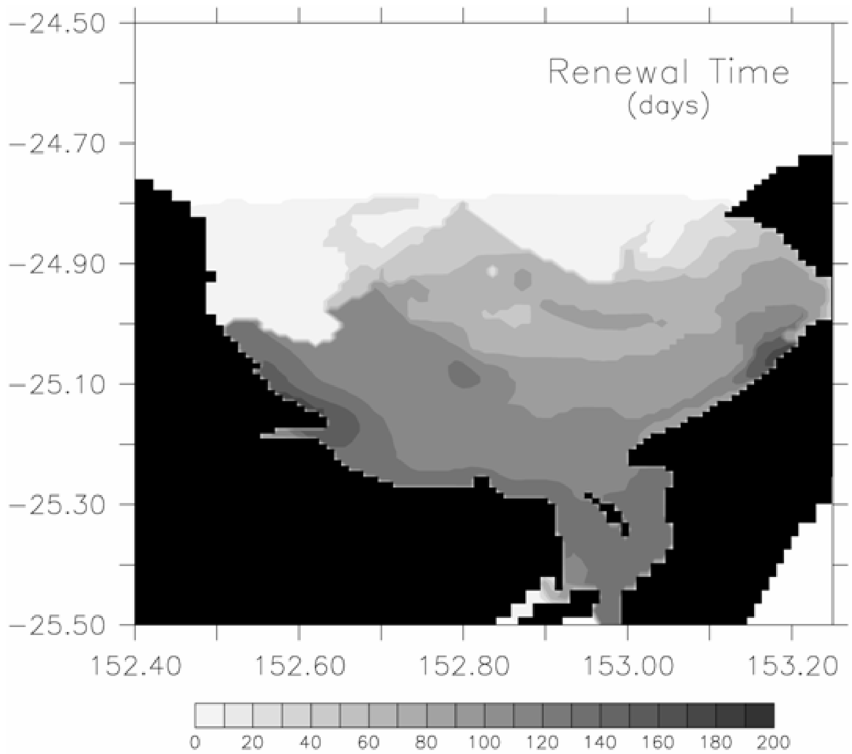


Figure 9: Renewal time scale [days] using idealised wind forcing.

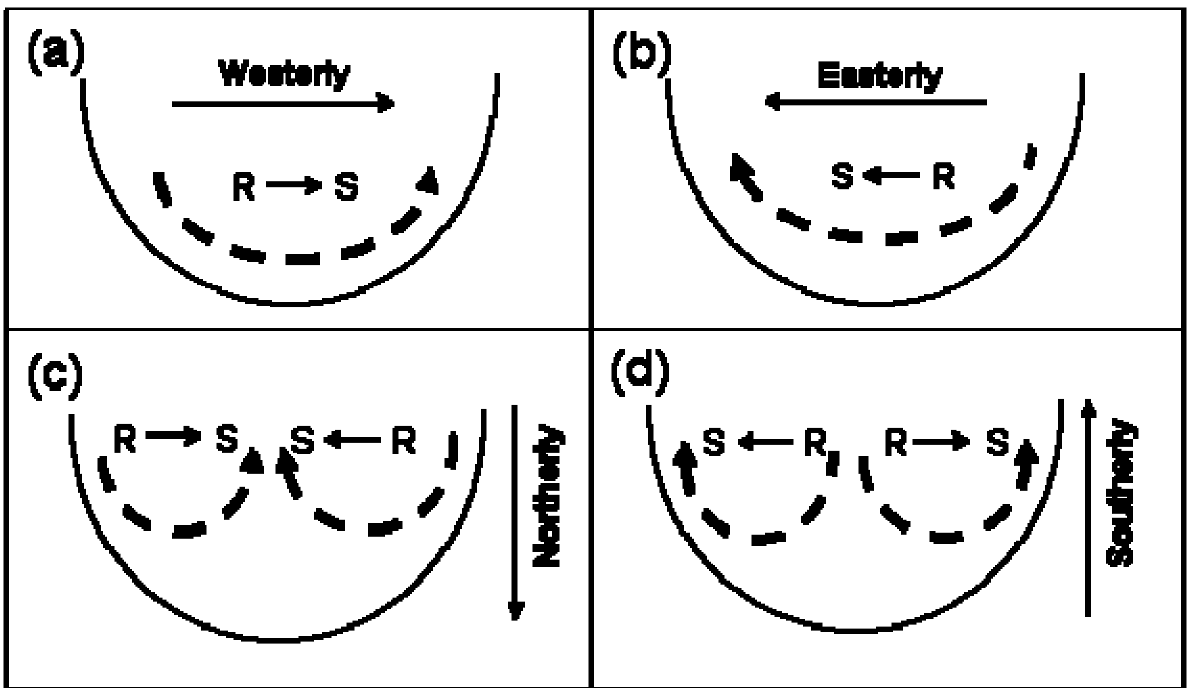


Figure 10: Schematic depiction of renewal pathways and time scales for Hervey Bay, a large coastal embayment off the central eastern coast of Australia; R = rapid renewal, S = slow renewal. Renewal pathway and main flow indicated as dashed arrows. Solid arrows indicate wind direction, (a) westerly, (b) easterly, (c) northerly and (d) southerly.