Multigrain seabed sediment transport modelling for the south-west Australian Shelf

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Abstract. With increasing concerns about climate change and sea-level rise, there is a need for a comprehensive understanding of the sedimentary processes involved in the erosion, transport and deposition of sediment on the continental shelf. In the present paper, long-term and large-scale seabed morphological changes on the south-west Australian continental shelf were investigated by a comprehensive sediment transport model, Sedsim. The investigated area covers the continental shelf and abyssal basins of the south-western region. The regional seabed is sensitive to environmental forces and sediment supply, and most terrigenous sediment carried down by major rivers is trapped in inland lakes or estuaries. Only a small fraction of fine-grain sediment reaches the continental shelf. The simulation has also confirmed that the Leeuwin Current and high-energy waves play the most important roles in regional long-term seabed evolution. Although the numerical implementation only approximates some forcing and responses, it represents a significant step forward in understanding the nature of potential long-term seabed change as a response to possible climate change scenarios. The 50-year forecast on the seabed morphological changes provides a reference for the management of coastal and offshore resources, as well as infrastructure, in a sustainable way.

Additional keywords: climate change, continental shelf, morphological change, seabed.

Introduction

The Australian continental shelf has been of research interest for many decades. A large number of research vessel cruises have sampled seabed sediment for different reasons. Long-term and continuous satellite observation records of winds, waves and imaging of ocean temperatures have been accumulated and made available for general research. Most importantly, the development of the Bluelink system, Ocean Forecasting Australia (Oke \textit{et al.} 2005, 2008; CMAR 2008), has significantly improved the level of our knowledge about the waters surrounding Australia. In addition, many other seabed-related data and knowledge are available in the fields of civil engineering, oceanography and geology. The aim of the present paper was to build links between the environmental forces and seabed responses, and to test our understanding of modern seabeds to answer the fundamental questions: (i) what does the sediment consist of; (ii) why is the sediment distributed in these locations; (iii) are the sediments relict or modern; and (iv) how will the type and distribution of sediments respond to reasonable assumptions of climate change?

Most seabed areas consist of both relict and modern sediment. The relict sediment was deposited during or before the previous geological cycle and has not been modified by modern environmental conditions. By contrast, modern sediment is sensitive to the effects of waves, tides and ocean currents. The first two questions posed above, which are not trivial, could be addressed by a combination of discrete seabed sampling, mapping, interpolation, observations of environmental forces and modelling of ocean currents. However, forecasting the future trend of seabed change is not possible without a numerical sediment transport model.

Sedsim is a comprehensive process-based stratigraphic forward model initially developed under a consortium at Stanford University in the 1980s. Since the 1990s, the program has been systematically redeveloped. Sedsim has now been tested for sediment transport over long periods controlled by many of the major erosional, transport and depositional processes, including fluvial, aeolian, shallow and deep marine, coastal waves and storms, carbonate growth, slope failure, turbidity flows and deep ocean geostrophic currents (Tetzlaff and Harbaugh 1989; Koltermann and Gorelick 1992; Martinez and Harbaugh 1993; Griffiths \textit{et al.} 2001; Li \textit{et al.} 2003, 2005a, 2005b, 2006a, 2006b, 2007).

In Sedsim, the Navier–Stokes equations and the continuity equation are simplified and solved by using a marker-in-cell technique in two horizontal dimensions. Flow velocity and sediment load are represented at points that move with the fluid. A two-dimensional square grid is used to represent the depth of flow.
Seabed sediment transport modelling

Marine and Freshwater Research

and elevation of the water–sediment interface. At each time step, each fluid element’s position and velocity are recalculated. This technique combines the advantages of Eulerian and Lagrangian representations of fluid flow.

To allow for the computation of seabed morphological evolution on time scales of decades and spatial scales of hundreds of kilometres, substantial simplification schemes are essential because full-scale, direct simulation of all involved processes is not feasible. Major model assumptions include: (i) morphological seabed change has a negligible effect on deep ocean currents, tides and waves; and (ii) oscillatory water movement caused by waves and tides creates negligible long-term net sediment transport in deep water. The oscillatory water movements are only responsible for mobilising sediment and making sediment available for transportation by large-scale ocean circulation.

Understanding the geomorphological changes and sedimentary processes that are occurring on the seabed and the shoreline is becoming increasingly important to manage coastal and offshore resources and infrastructure in a sustainable way. The present paper discusses the future state of the seabed in south-west Australia based on an extrapolation of the present-day wave, tide and current climate.

Geomorphology of the south-west Australian continental shelf

The simulation area covers the south-west Australian continental shelf and abyssal basins (Fig. 1), which includes the Rottnest Shelf, the Perth Canyon, the Albany Canyons, the Great Australian Bight, the Lincoln Shelf, the Spencer Gulf, the Gulf St Vincent, and part of the Lacepede Shelf. The region roughly extends from 30°S to 39°S and from 110°E to 139°E.

The south-west Australian continental shelf is a narrow, high-energy open shelf on a passive margin (James et al. 1994). The steep continental slope is incised by Perth, Albany and Murray Canyons (Exon et al. 2005), leading to a 4000-m deep abyssal plain. The continental shelf and coastline have been mainly shaped by Holocene sea-level fluctuation. A rapid post-glacial transgression to a high hydrodynamic energy level with low terrigenous input has limited carbonate productivity and reworked the transgression surface (Pleistocene limestone and sandstone), developing retrograding sand dune systems. A subsequent fall in the sea level started a continuing progradation of shell beds and dunes to the present day. The seabed of the Rottnest Shelf is covered by a thin blanket (0–4 m) of relict sediment, mainly bryozoans and bivalve skeletons (cool water carbonates), on top of the Pleistocene basement (Collins 1988; James et al. 1992, 2001). Holocene to recent calcareous/quartzose sand dunes, Pleistocene consolidated calcarenite and sandstone, and Tertiary limestone cliffs are the main features of the south-west coastline, sometimes outcropped by Precambrian igneous rocks.

The Leeuwin Current has been influential since at least the last interglacial period. McGowran et al. (1997) reviewed evidence of the Leeuwin Current during the Cainozoic era and concluded that the current has been active and fluctuating since...
the later middle Eocene. The seabed of continental shelves is constantly evolving, subject to processes such as sedimentation, hydrodynamic movement, slope failure and biological activity.

Existing sediment sources

Seabed sediment

Based on the comprehensive auSEABED sediment database (Jenkins et al. 2003), the grain size and sediment compositions are interpolated onto the whole grid from the available samples (Fig. 2a). The map of median sediment grain size, d<sub>50</sub>, shows that coarse grains (>0.5 mm) occur mainly within and around the Great Australian Bight, the Spencer Gulf, the Gulf St Vincent and part of the Lacepede Shelf. Medium grains (0.25–0.5 mm) occupy slightly larger areas around the coarse-grained facies. Fine-grained facies (<0.01 mm) tend to occur at water depths greater than 200 m on the continental slope and abyssal basin (Fig. 2b). Gravel and exposed rock-head are frequently found in two different areas. One is the narrow shelf from Lancelin to Esperance of Western Australia, and the other is in the deep Southern Ocean south-west of Cape Leeuwin, where the water depth is more than 4000 m.

The grain sizes and sediment compositions from available observations are interpolated onto the computational grid and are broken into four representative clastic grain sizes. The four grains imported into Sedsim are: very coarse sand (3 mm), medium to coarse sand (0.5 mm), very fine sand (0.1 mm) and silt (0.01 mm).

Sediment thickness estimations have been carried out for the Rottnest (Collins 1988) and Lacepede Shelves (James et al. 1992). A reworkable sediment thickness of 0–1 m has been found for the inner shelf (0–60 m depth), and 0–4 m for the outer shelf (60–170 m depth) where wave abrasion is less efficient and carbonate production more important (bryozoan sands and muds). The thickness of loose sediment on the shoreline (beaches and dune systems) is estimated from stratigraphic information of the west coast superficial formation, ‘Safety Bay Sand’ (Australian Stratigraphic Units Database, Geoscience Australia). With a maximum thickness of 6 m, this recent unit forms most of the beaches and mobile dune systems. We make the assumption that this thickness is representative of the loose sediment stock over the studied coastline. From this information, a simple input file for the initial seabed loose sediment thickness has been built according to water depth (shoreline, inner and outer shelf) and the rock exposure parameter in the auSEABED database. For the onshore and near-shore area, with Australian height datum (AHD) from +20 m to −10 m, the loose sediment thickness is assumed to be 5 m. For the inner shelf (−10 m to −60 m AHD), the thickness is given as 1 m. For the outer shelf, −60 m and deeper, a 4-m pre-deposit is assumed between the seabed surface and the rock substrate. On top of these rough estimates, the sediment thickness is corrected to 0.1 m.
Seabed sediment transport modelling

The amount of sediment carried by rivers to the coastal area is closely related to catchment area, rainfall and vegetation. In the south-western region, 17 major river and inlet systems have been identified and evaluated in terms of their annual sediment carrying capacity (under present climate conditions) at their mouths (Table 1; Fig. 3).

<table>
<thead>
<tr>
<th>Source</th>
<th>No.</th>
<th>Name of the source</th>
<th>Q (m³ s⁻¹)</th>
<th>C (kg m⁻²)</th>
<th>Latitude (S)</th>
<th>Longitude (E)</th>
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<tr>
<td>WA</td>
<td>1</td>
<td>Moore River</td>
<td>12.68⁶</td>
<td>0.052⁶</td>
<td>31°21’20”</td>
<td>115°30’41”</td>
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<td></td>
<td>2</td>
<td>Swan-Canning River</td>
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<td>0.265</td>
<td>31°57’49”</td>
<td>115°50’44”</td>
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<td>3</td>
<td>Leschenault Inlet</td>
<td>10.00</td>
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<td>32°35’10”</td>
<td>115°46’12”</td>
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<tr>
<td></td>
<td>4</td>
<td>Peel-Harvey Estuary</td>
<td>19.60</td>
<td>0.02</td>
<td>33°18’20”</td>
<td>115°41’37”</td>
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<tr>
<td></td>
<td>5</td>
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<td>0.35</td>
<td>0.146</td>
<td>33°36’51”</td>
<td>115°25’22”</td>
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<tr>
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<td>6</td>
<td>Margaret River</td>
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<td>0.033</td>
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<td>114°59’21”</td>
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<td>7</td>
<td>Hardy Inlet</td>
<td>29.33</td>
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<td>115°11’31”</td>
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<td>115°49’51”</td>
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<td>116°45’10”</td>
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<td>34°59’23”</td>
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<td>34°58’50”</td>
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<td>0.135</td>
<td>34°33’02”</td>
<td>138°20’26”</td>
</tr>
</tbody>
</table>

⁶Estimated value.

River input
The amount of sediment carried by rivers to the coastal area is closely related to catchment area, rainfall and vegetation. In the south-western region, 17 major river and inlet systems have been identified and evaluated in terms of their annual sediment carrying capacity (under present climate conditions) at their mouths (Table 1; Fig. 3).

Hydrodynamic forcing under present-day climate conditions
Wind climate
Wind climate data in a monthly form were provided by the Defence Oceanographic Data Centre (DODC). The data consist of mean and maximum wind speed and wind direction. The original wind data cover the time period from July 1999 to May 2005 at a resolution of 0.25°.

The wind climate of the Australian south-west is mainly controlled by the position of a high pressure ridge over the Great Australian Bight. In summer (November–March), the high pressure ridge is located over the south of the Great Australian Bight. High pressure systems generally move eastwards along the ridge, but have a favoured position south of the Great Australian Bight (~38°S). Consequently, the most frequent air stream across southern Australia during this period is from the south-east. In winter (June–September), the high pressure belt weakens and moves northward over the Bight. Frontal systems associated with depressions travelling eastwards across the ocean move north (around 30°S), highly influencing the weather over south-western Australia. The whole region is subjected to strong westerly winds, with a mean speed of 20–30 kn (12–15 m s⁻¹), and frequent storms.

Wave climate
The wave climate is extracted from both the DODC’s 14-year multi-satellite data and from CSIRO Wave Analysis Model (WAM) wave hind-cast results (Hayes et al. 2005). The CSIRO data comprised six-hourly predictions of significant wave height, period and mean wave direction, gridded at a 0.1° spatial resolution, for the period of March 1997 to February 2002 inclusive.

The wave climate in the region is strongly related to the south-west wind regimes – west to south-west in winter and south to south-east in summer (Lemm et al. 1999). The south-west continental shelf is a high wave-energy environment. In winter, waves with a mean significant wave height (SWH) of up to 3 m and a mean period of approximately 9 s are observed. The maximum wave height can reach 8–9 m in the Bight. The summer values are lower, with a mean SWH of approximately 2 m, a mean period of 7–8 s, and maximum wave heights of 6 m.

Tidal currents
South-western Australia has micro-tidal, mixed and predominantly diurnal tides. The maximum tidal range along the coast from Perth to Esperance is less than 1 m and rises to 1.8 m at the Head of the Bight, and to 3.5 m at the tip of Spencer Gulf. The tidal range and depth-averaged tidal current speeds for spring tides in the region were provided by the National Tidal Centre, Bureau of Meteorology. The highest tidal range and speed appears in the Spencer Gulf. Except for this area, tidal current plays a marginal role in the mobilisation of seabed sediment in this region.

Leeuwin Current and El-Niño Southern Oscillation
The dominant boundary current off south-western Australia is the Leeuwin Current, which flows along the south-west shelf, bringing warm water to the south and east. The bottom current fields simulated by the Ocean Forecasting Australia Model
OFAM) are used as an input into the Sedsim model. The OFAM (Oke et al. 2005, 2008) is the global model used by Bluelink; it has 0.1° resolution around Australia. The model data provided by CSIRO Marine and Atmospheric Research is in the form of monthly averages of the OFAM output between 1991 and 2005.

The bottom current velocities show strong seasonal variation. The Leeuwin Current starts to strengthen in March–April, forming a narrow jet with a peak velocity of 0.45 m s\(^{-1}\). During May–August, the Leeuwin Current broadens, with the 0.10-m s\(^{-1}\) southward velocities extending to almost 114°E (Fig. 4). With speeds of 0.1–0.25 m s\(^{-1}\) on the shelf, the current may not be strong enough to mobilise sediment. However, it can efficiently transport particles that have been suspended by wave action.

Inter-annually, the Leeuwin Current is distinctly stronger during a La Niña year and weaker during an El Niño year. The annual average poleward geostrophic currents in normal El Niño and La Niña years are 3.4, 3.0 and 4.2 Sv (1 Sv = 10\(^6\) m\(^3\) s\(^{-1}\)) respectively (Feng et al. 2003).

**Multigrain sediment transport modelling by Sedsim**

**Sediment entrainment and seabed mobility**

High-frequency water movements caused by waves and tides are the major factors affecting local seabed sediment availability to long-term and large-scale transport, although the net sediment movement by waves and tides may be negligible, at least in deep water. The seabed mobility index, \(r\) (Eqn 1), is defined as the ratio between the value of wave- and current-combined skin-friction Shields parameter, \(\theta_{cws}\), and the critical Shields parameter, \(\theta_{cr}\). It serves as an indicator of the level of intensity and frequency of seabed sediment available for movement

\[
r = \frac{\theta_{cws}}{\theta_{cr}} = \frac{\text{combined Shields parameter}}{\text{critical Shields parameter}}.
\]

Details about the calculation of the skin-friction Shields parameter, \(\theta_{cws}\), and the critical Shields parameter, \(\theta_{cr}\), have been discussed by Li and Amos (2001).

In fair weather conditions, the mobility index value is lower than 1.0 on most of the continental shelf, except for some isolated nearshore areas in both summer and winter seasons, shown in Fig. 5. However, in storm conditions the index is much higher, particularly in an Australian winter (Fig. 6b). Although the higher the mobility index value the more likelihood of sediment movement, where \(r\) is < 1 there is still potential for sediment movement. The existing sediment on the seabed is composed of different grain sizes; thus, the median grains are stationary, but the finer fraction may be transported.

**Estimated long-term, large-scale sediment transport rate by near-bottom circulation**

Virtually all sediment transport occurs either as bedload or as a combination of bedload and suspended load (Soulsby 1997) (suspended load rarely occurs in isolation). The combined load is known as the total load. In practice, it is very difficult to separate bedload from suspended load. For this reason, we chose the
total load approach to estimate the sediment transport rate in the present study.

Li and Amos (2001) considered five equations applicable to sediment transport on a continental shelf. Of these, the Bagnold equation provides the best fit to the sediment characteristics in the south-west Australian shelf. Bagnold (1963) assumed that waves cause sediments to be stirred up, but it is the steady currents that cause net sediment transport. For combined wave–current flows, the maximum (not the instantaneous) skin-friction combined shear stress, $\tau_{cws}$, is used to compute the net sediment transport rate from:

$$q = K \tau_{cws} u_{100}/[(\rho_s - \rho)g]$$  \hspace{1cm} (2)

where $q$ is the volumetric rate of sediment transport, $u_{100}$ is the bottom current velocity at 1 m above the seabed, $\rho_s$ and $\rho$ are the densities of sediment and sea water, respectively, and $K$ is the proportionality coefficient described by the empirical equation of Sternberg (1972):

$$K = M \exp[0.7(\tau_{cws} - \tau_{cr})/\tau_{cr}]$$  \hspace{1cm} (3)

where the empirical coefficient $M$ has a value of 0.005. The transport direction is assumed to be that of the steady current. Given the relationship of Shields parameter and bottom shear stress:

$$\theta_{cws} = \frac{\tau_{cws}}{(\rho_s - \rho)gD}$$  \hspace{1cm} (4)
Eqn (2) can be written as:

\[ q = M \cdot u_{100} \cdot \theta_{cws} \cdot D \cdot \exp\left\{0.7(\theta_{cws} - \theta_{cr})/\theta_{cr}\right\} \]

(5)

where \( D \) is the sediment grain diameter. The bottom circulation velocity data extracted from OFAM was assumed to represent the velocity 1 m above the seabed, \( u_{100} \).

Sediment transport prediction is at a much lower level of certainty than the modelling of waves and flows (Whitehouse et al. 2000). With the large uncertainties in the input data and the simplifications of the numerical modelling, seabed change predictions at any one location should be considered as indicative rather than definitive.
Multigrain representation of the sediment mixture

Transport-rate measurements showed that armouring of fine sand by coarse sand gives rise to a significant reduction in the transport rate of the fine sand (de Meijer et al. 2002). The armouring effects are too significant to be neglected in most analyses of shelf and near-shore sediment transport (Reed et al. 1999), and this is particularly relevant for models that are dealing with large-scale and long-term sedimentary regimes. The armouring process can occur at relatively low stress conditions, when the coarser particles are not mobilised, but also at relatively high stress conditions, when all material can be transported.

In the present study, sediment is represented by a mixture of four grain sizes, which are coarse sand (3 mm), coarse to medium sand (0.5 mm), very fine sand (0.1 mm) and silt (0.01 mm). The total sediment transport rate (both suspended load and bedload) is estimated by a total load equation (discussed in the previous section). A transport capacity/efficiency fraction method (Tetzlaff and Harbaugh 1989; Wu et al. 2003) is used in the calculation of fractional sediment transport. In this method, the total load is computed using an appropriate equation, and then the fractional transport rates are determined by distributing the total load into size groups through a transport capacity distribution function. The transport capacity distribution function is related to both hydraulic conditions and sediment properties.

Simulating the results of seabed morphological change

Simulation of the sediment erosion–transport–deposition process uses the method of Martinez and Harbaugh (1993). The regional seabed and its deposit layer are converted to a Cartesian coordinate system by Lambert projection. The research area is then represented by a $1061 \times 341$ grid with a spatial resolution of 2.4 km. The environmental factors considered in the present model are sediment-laden river flows, waves, tides, geostrophic currents, sea-level change, submarine slope failure and turbidity currents. The model predicts changes of seabed morphology, sediment grain composition and seabed mobility.

Figs 7 and 8 summarise the bottom ocean current circulation patterns in winter (May–September) and summer (October–April), respectively, based on OFAM output at 1991 to 2005. The regional continental shelf is characterised by two shelf breaks,
an inner shelf break at \( \sim 50 \text{ m} \) followed by a second break at \( \sim 200 \text{ m} \) water depth. Under the influence of this terrace-like structure, the local ocean currents on the inner shelf are very different from the current on the outer shelf. In summer, the former, recognised as the Cape Current (Gersbach et al. 1999), flows northward, whereas the Leeuwin Current flows southward on the outer shelf. In winter, the Cape Current vanishes and the Leeuwin Current flows on both the inner and outer shelf. From south of Cape Leeuwin to Roe Plain, the prevailing circulation feature on the shelf is the eastward-flowing Leeuwin Current in all seasons. The current covers the entire shelf, but is strongest at the edge of the shelf. In summer, as the Leeuwin Current is weaker towards the east, the local water is partially replaced by the westward coastal current in the shallow water between Eucla and Roe Plain.

Direct discharges of sediment from fluvial sources are mainly from the Swan and Moore Rivers. Discharge is usually limited by the occurrence of estuaries impounded behind coastal ridges or semi-permanent mouth bars. Thus, most of the riverine sediment is retained in the less turbulent estuarine environments. However, rare high-flow and large-scale coastal erosion can occasionally bring some fluvial sediment into the marine systems.

Fig. 9 shows the Sedsim predicted seabed morphological change over the next 50 years under an extension of the current climate. The model predicts a broad erosion area on the inner shelf for water depths less than 80 m. This is well-supported by existing seabed sediment samples; relict sediment could be 17 000 years old (James et al. 1992, 2001). Wave abrasion is strongest on the mid shelf (50–90 m), and little contemporary sediment would accumulate in this high-energy environment (James et al. 1994).

The most severe erosion/accretion occurs in the vicinity of the shoreline. The erosion/accretion is strongest when the shelf is narrower because it is more open to the swell and to current movement (off the Cape Leeuwin and the coast between Albany and Esperance). Most of the shoreline suffers from erosion, particularly the coast facing south-west or south (from Cape Naturaliste near Margaret River to Albany). This erosion appears...
as an offshore sediment movement. The eroded material is generally redistributed by currents to water depths beyond 80 m, which is below the normal wave abrasion limit. Other areas, such as Perth beach, Rockingham beach and Geographe Bay, suffer from less erosion or even deposition with the protection from Rottnest Island and Garden Island and their orientation to the wave and current direction. These sheltered environments are acting as sediment traps. Exposed areas often experience a coarsening of the sediment, and fining is observed along sheltered coastlines.

According to Collins (1988), the sediment blanket on the outer shelf is thicker than on the inner part, and a ridge of algal nodules pavement is observed on the edge of the slope. These observations are consistent with our result; even if the initial seafloor conditions, such as the sediment thickness and lithology, are not exact, the system adjusts quite well to the hydrodynamic conditions and reaches a state that is close to the observed actual morphology.

The simulation created a noticeable amount of patchy sediment accumulation at the foot of the continental shelf near Perth Canyon, Parryville Spur, Denmark Canyon and Albany Canyon. These deposits are most likely transported down the slope by turbidity currents and slope failures, assisted by the Leeuwin Current.

A study of superficial sediments in the Great Australian Bight (GAB) (James et al. 2001) reveals that Holocene sedimentation can be directly related to modern oceanography on this predominantly down-welling shelf. The shelf from 50 to 100 m depth is sediment-starved because of strong wave abrasion along the southern Australian margin (Li et al. 1999).

The shelf in the eastern part of the simulated area is broader (GAB) and sediment movement is less intense (Figs 7b, 8b and 9b). Although the Bight is still open to the Southern Ocean long period swell, it is more sheltered than the south-west corner. Morphological changes increase from east to west. Accumulations of sediment are found down-slope. Shore erosion is widespread along the cliff coast. Sediment accumulation is predicted in the deep-water area enveloping the bottom current (Fig. 9).
Acknowledgements

The authors wish to thank Martin Rutherford (Defence Oceanographic Data Centre) for meteorological data. Peter Harris and Alix Post (Geosciences Australia) provided useful discussions on the data and model verification. Special thanks to Donna Hayes and Peter Oke (CSIRO Marine and Atmospheric Research) for the wave hindcast data and bottom current data. Also thanks to James Chittleborough (National Tidal Centre) for the tidal range and tidal current data. The National Oceans Office provided encouragement over the life of the project, and the Directors of the Wealth from Oceans Flagship, Craig Roy and Kate Wilson, have supported this work from its inception. Finally, we would like to thank the editor and three anonymous reviewers for their constructive comments and suggestions.

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Manuscript received 25 February 2008, accepted 15 February 2009

http://www.publish.csiro.au/journals/mfr