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Highlights

Marine Geology xxx (2013) xxx–xxx

The influence of coastal reefs on spatial variability in seasonal sand fluxes

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- Investigated how coastal reefs cause spatial variability in seasonal sand fluxes
- Revealed alongshore 'zones' with alternating spatial and seasonal modes of flux
- Zone boundaries determined by reefs, headlands and longshore current jets
- Seasonal variability in fluxes driven by littoral drift, wave power and sea level

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The influence of coastal reefs on spatial variability in seasonal sand fluxes

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ABSTRACT

The effect of coastal reefs on seasonal erosion and accretion was investigated on a 2 km-stretch of sandy coast. The focus was on how topography drives alongshore variation in the mode and magnitude of seasonal beach erosion and accretion; and the effect of intra- and inter-annual variability in metocean conditions on seasonal sediment fluxes. This involved using monthly and 6-monthly surveys of the beach and coastal zone, and comparison with a range of metocean conditions including mean sea level, storm surges, wind, and wave power. Alongshore 'zones' were revealed with alternating modes of sediment transport in spring and summer compared to autumn and winter. Zone boundaries were determined by two mechanisms: (1) reefs and headlands blocking littoral drift; and (2) longshore current jets constricted by the reefs. In spring and summer, constant sand resuspension and northerly littoral drift due to sea breezes allowed a sand ramp to form in the South Zone so that sand overtopped the reef to infill the lagoon. This blocked the main pathway for sand supply to downdrift zones which subsequently eroded. In autumn and winter, with the dominance of northwesterly storms and reversal in the direction of littoral drift, the South Zone eroded and sand travelled through the lagoon in the current jet to nourish the northern beaches. Combined inter-annual and seasonal variation in sea level, variation in storm frequency and intensity, and pulsational effects of local sand fluxes at Yanchep due to inter-seasonal switching in the direction of littoral drift determined marked differences in the volumes of seasonal sand transport. These seasonal 'sediment zones' highlighted interesting and unexplored parallels (and differences) between coasts fronted seaward by coral reefs and rocks.

1. Introduction

Perched beaches are underlain or fronted seaward by hard structures that are shallowly buried or outcrop above the sediment (Gallop et al., 2012a). 75% of the world's coast is rocky (Davis, 1996) and global estimates of the area of coral reef coverage range between 112,000 to 393,0000 km^2 (Spalding and Grenfell, 1997). Beaches can be perched on all types of rock, for example on beachrock that occurs in tropical as well as temperate regions such as Australia, Greece, Brazil, Israel and the Seychelles (e.g. Vousdoukas et al., 2007); and limestone such as in southwestern Australia (Playford et al., 1975; Gallop et al., 2011a). Many beaches that are perched on structures in the cross-shore direction also have lateral structural boundaries that form embayed and pocket beaches. These beaches are associated with interrupted longshore supply of sediment due to their indentation; trapping-effects and hence limitations in sediment exchange to adjacent beaches (Storlazzi and Field, 2000; Ranasinghe et al., 2004; Bowman et al., 2009). The presence of reefs and platforms, and the lithological mix is a key determinant of coastal complexity (Porter-Smith and McKinlay, 2012) and there is a large gap in knowledge of how reefs and platforms affect with sediment transport (Larson and Kraus, 2000; Stephenson and Thornton, 2005; Naylor et al., 2010). McNinch (2004) stated that while many coastal geologists have suggested that framework geology plays a key role in determining large-scale and long-term shoreline behaviour (e.g. Demarest and Leatherman, 1985; Riggs et al., 1995; Kraus and Galgano, 2001); it is unknown how framework geology influences shorter-term coastal morphodynamics. And while it is obvious that it plays a key role in determining beach morphology, the extent, and mechanisms are still unclear. For example, in Hawaii, many beaches are eroding creating a societal hazard while others are accreting despite an increase in mean sea level (Norcross et al., 2002). Moreover, often eroding and accreting beaches are adjacent to each other (Fletcher et al., 1997). Therefore, to investigate how coastal reefs influence coastal morphodynamics over scales of months and seasons, the current research focused on Yanchep Lagoon in southwestern Australia, where sandy beaches are perched on calcarenite limestone reefs and platforms.

The coast of southwestern Australia consists of low bluffs and extensive limestone reefs and platforms alternating with sandy beaches (Bird,

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1985; Semeniuk and Searle, 1987; Collins, 1988). Spring and summer are dominated by strong, southerly sea breezes that blow parallel to the coast and result in northerly littoral drift. Winter is dominated by storms, often from the northwest which can reverse the direction of littoral drift (Kempin, 1953; Masselink and Pattiaratchi, 2001). There are limited records of beach morphology in Western Australia, but it has been suggested that a key driver of beach growth and recession is cumulative longshore winds (Clarke and Eliot, 1983), such as the cumulative of daily wind speeds at a certain time for a given period (Eliot and Travers, 2011). The rate of northerly littoral drift in southwestern Australia due to the longshore energy flux driven by wind waves was estimated as 150,000 m^3 yr^{-1} by Pattiaratchi et al. (1997), and between 138,000 and 200,000 m^3 yr^{-1} by Tonk (2004). On a beach perched on a limestone platform in Cottesloe (Fig. 1a), plentiful sediment supply in summer in combination with smaller and less-steep waves and less storm surges causes the limestone platform to be covered in sand. This sand is eroded in autumn and winter due to more frequent storm-surges, steeper waves, and northwesterly winds (Doucette, 2009). On a finer temporal scale, the influence of sea breezes and storm events on sand transport was investigated hourly and daily at Yanchep Lagoon in 2010 (Gallop et al., 2011a, 2012a). Longshore variation in reef topography had a dominant influence on the mode and magnitude of cross-shore and longshore sand transport alongshore due to wave refraction, current jets and scour-steps due to the reefs. Research reported in the current paper examines the cumulative effect of sea breezes in spring and summer; and of storm events during autumn and winter on the coastal morphology at Yanchep Lagoon.

The aim was to investigate the effect of reefs on seasonal erosion and accretion. The objectives were to: (1) examine how alongshore variation in reef topography drives alongshore variation in the mode and magnitude of seasonal beach erosion and accretion; and (2) understand the effect of intra- and inter-annual variability in metocean conditions on seasonal sediment fluxes. To achieve this, sub-aerial beach surveys were undertaken monthly for two years, and hydrographic surveys were measured five times during late summer and winter, out to 10 m above MSL. Numerical models using XBeach (Roelvink et al., 2009, 2010) were used to determine how the coastal reefs influence currents at Yanchep.

2. Study area

2.1. Geological setting

The coastal bathymetry of southwestern Australia is dominated by a series of shore-parallel reefs of calcarenite limestone. These reefs are present from 20 km offshore (Fig. 1a; Playford et al., 1975; Semeniuk and Johnson, 1982), to the coast such as at Yanchep, located 60 km north of the City of Perth (Fig. 1a, b). The sandy beaches of Yanchep Lagoon face southwest and consist of well-sorted medium sand with d_{50} of 0.4 mm (Murphy, 2011) made of mostly quartz and skeletal material (Semeniuk and Johnson, 1982). The topography of the reefs varies alongshore, with higher, more continuous reefs in the south that enclose a coastal lagoon; and deeper, patchy reefs towards the north (Fig. 1b). There is a 'bombora', defined as a small shallow reef that creates a surf break, north of the lagoon exit that focuses wave energy on the reef where they break; and forces swell to refract. At the northern end of the beach, the Club Capricorn groyne was built in 1971.

2.2. Climatology

Southwestern Australia is influenced by three wind systems: sea breezes; low-pressure storms; and high-pressure calm periods (Steedman and Craig, 1983). Spring and summer (September to February) are dominated by strong and persistent south–southwesterly sea breezes. On a typical sea breeze day, morning winds are easterly with

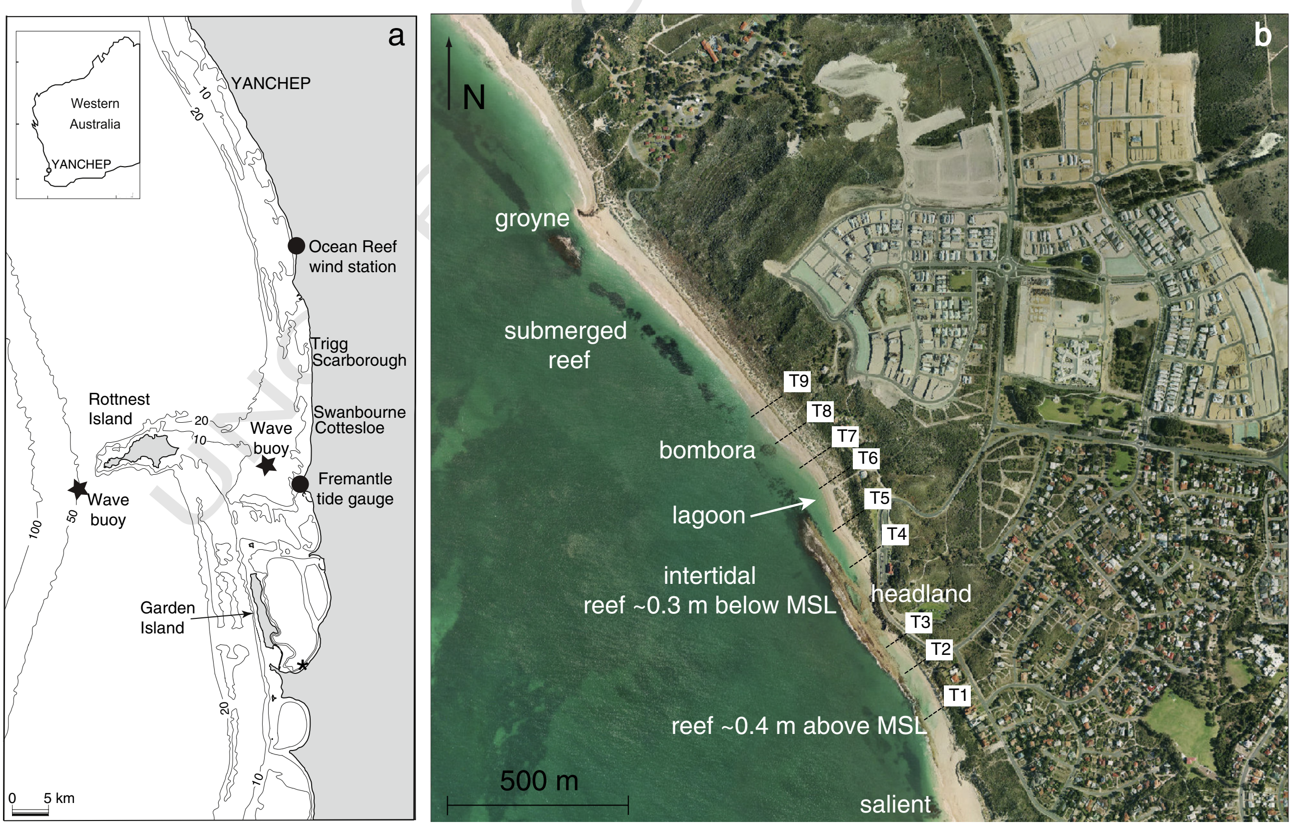

Fig. 1. (a) Western Australia and sites of interest; and (b) sub-aerial beach transects at Yanchep Lagoon that were surveyed monthly (photo source: Landgate).

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relatively low speeds of around 5 m s^{-1}. In the late morning to early afternoon, wind speed rapidly increases, generally from 10 to 15 m s^{-1} and the direction changes from south to southwesterly. Frontal storms can occur throughout the year but are more frequent as part of mid-latitude depressions in winter from June to August. Approximately 15 to 30 frontal storms of 1 to 5 days duration occur annually (Verspecht and Pattiaratchi, 2010). During these storms peak wind speeds reach 20 m s^{-1} and are generally southerly in summer and northwesterly in winter. High-pressure systems occur throughout the year (Gentilli, 1972) and are commonly associated with easterly winds of less than 5 m s^{-1}. These systems can last for 1 to 15 days and during which coastal hydrodynamics are driven mainly by density gradients and longshore currents rather than wind and tides (Steedman and Craig, 1983).

2.3. Sea level

Southwestern Australia is microtidal (mean spring tidal range of 0.6 m) with mainly diurnal tides (Department of Defence, 2012). Sea level is generally higher in the winter, with average annual amplitude of 0.22 m (Pattiaratchi and Eliot, 2009) and also varies inter-annually in relation to the Southern Oscillation Index (SOI) (Feng et al., 2004). Variability of sea level would affect the amount of wave dissipation occurring on offshore and coastal reefs, and may determine the frequency of inundation at different elevations on reefs and hence on any perched beach it supports.

2.4. Waves

The wave climate of Western Australia is dominated by swell from the Southern Ocean. In the offshore, mean annual significant wave height (H_s) is 2.14 m and annual mean peak period (T_p) is 13.5 s. Summer waves are typically 40% smaller than winter waves and H_s exceeds 4.0 m 10% of the time (Bosserelle et al., 2012). Offshore limestone reefs attenuate up to 80% of the incident swell (Masselink and Pattiaratchi, 2001). At Yanchep Lagoon there was general agreement with these results with measured wave heights of 1 to 2 m with periods of 5 to 8 s in summer and during winter storms, swell wave height attenuation was 80% for 5 m swell (Gallop et al., 2011a, 2012a).

2.5. Littoral currents

In spring and summer, northerly energy flux is created by wind waves generated by strong sea breezes which drive longshore currents (Gallop et al., 2012b) and sediment transport (Masselink, 1996; Tonk, 2004). It has been suggested that the direction of littoral drift reverses annually as a result of northwesterly storms (Kempin, 1953; Masselink and Pattiaratchi, 2001). More locally, the coastal lagoon at Yanchep is impounded by the continuous limestone reef (Fig. 1b) and contains a northerly current that can exceed 1 m s^{-1} (Gallop et al., 2011a).

3. Methodology

3.1. Sub-aerial beach surveys

Nine sub-aerial beach transects (T1 to T9) were surveyed monthly on a 1 km-long stretch of coast from February 2010 to March 2012 (Fig. 1b). Profiles were surveyed from temporary benchmarks at the top of the frontal dune ridge to instantaneous sea level to Australian Height Datum (AHD) where zero AHD corresponds to MSL. Due to the low tidal range (mean of 0.45 m during the study period), the level of the tide at the time of survey was negligible. Transect 4 (T4) was located seaward of the main access path to the beach (Fig. 1b) and on several occasions during the monitoring period engineering works took place so results (Figs. 3f and 4f) are treated with caution.

3.2. Hydrographic surveys

Five hydrographic surveys were done from MSL to 10 m above AHD in late summer and winter (Fig. 6), with cross-shore and longshore resolutions of 5 m and 50 m. Volume differences were calculated between the 6-month periods (Fig. 7). The accuracy of the surveys was ±0.10 m.

3.3. Metocean data

Sea level measured at the Fremantle tide gauge (Fig. 1a) was divided into three components: (1) a 30-day running MSL; (2) tide using the T_Tide Harmonic Analysis Toolbox (Pawlowicz et al., 2002); and (3) storm surge calculated as the difference between the observed and predicted sea level. Wind was measured 10 m above the ground at a coastal weather station at Ocean Reef, 25 km south of Yanchep (Fig. 1a). Wind data from 9 to 14 January 2011 and 29 February 2012 were missing so data from Swanbourne 50 km south of Yanchep (Fig. 1a) were used. The variability of the wind and littoral drift was estimated using approximately monthly cumulatives of 3 pm daily wind speed in the cardinal directions, similar to the method of Eliot and Travers (2011). Cumulated winds were calculated for the periods between the monthly surveys and 3 pm winds were used because sea breezes dominate the coastal processes in summer and are generally strongest in the mid-afternoon (Masselink, 1996; Verspecht and Pattiaratchi, 2010; Gallop et al., 2012b).

Wave height, period and direction were measured by a Wave Rider buoy 5 km off Cottesloe (Fig. 1a). Wave power was calculated for swell ($T_p > 9$ s) and sea ($T_p < 9$ s), using equations for wave power (P) and the energy density spectrum (E) described by (Hughes and Heap, 2010; Kamphius, 2000; Nielsen, 2009). P was calculated in the cardinal directions of x and y as:

$$P_x = \left(EC_g\right)\cos(270-\theta) \quad (1)$$

$$P_y = \left(EC_g\right)\sin(270-\theta) \quad (2)$$

where C_g is the group speed of the waves; and θ is the incident wave angle. E was given in terms of H_s representing the natural spectrum as:

$$E = {}^{1}/_{16}\rho g H_s^{\,2} \quad (3)$$

where ρ is water density and g is acceleration due to gravity. C_g was calculated as:

$$C_g = C\left(\frac{0.5 + (Kh)}{\sinh(2Kh)}\right) \quad (4)$$

where C is the wave speed ($C = L/T_p$, where L is the shallow water wave length), K is the wave number ($K = 2\pi/L$), and h is the water depth. Shallow water wave length (L) was approximated by:

$$L = L_o.\tanh\left(\left(\frac{\sigma^2 h}{g}\right)^{3/4}\right)^{2/3} \quad (5)$$

(Fenton and McKee, 1990), where L_o is the deep water wavelength ($L_o = 1.56{T_p}^2$) and σ is the angular frequency (Dean and Dalrymple, 1991). Using the dispersion relationship for linear waves:

$$\sigma^2 = \left(\frac{2\pi}{T_p}\right)^2 \quad (6)$$

and deep water wave length (L_o) was calculated as:

$$L_o = 1.56{T_p}^2. \quad (7)$$

Monthly cumulates of the daily 3 pm wave power was determined. Rates of longshore sediment transport (Q_l) relate to the magnitude of wave power, such as by:

$$Q_l = \frac{KP}{(\rho_s - \rho)ga'} \quad (8)$$

(CERC, 1984), where ρ_s is the sediment density. In southwestern Australia, longshore sediment transport is predominantly driven by the longshore energy flux exerted by wind waves (Tonk, 2004).

3.4. Numerical modelling with XBeach

Only short records (days) with sparse spatial coverage were available of hydrodynamics at Yanchep Lagoon (Gallop et al., 2011a, 2012a), hence numerical modelling was used to provide a broader-geographic understanding of the circulation pattern due to the reefs. A numerical model using XBeach was run with idealised forcing to indicate general current speeds and directions at Yanchep Lagoon. XBeach is an open-source, numerical model for nearshore processes, originally developed to model coastal morphology during time-varying storm and hurricane conditions. The model contains formulations for the propagation of short-wave envelopes, non-stationary shallow-water waves, sediment transport, and bed updating (Roelvink et al., 2010). XBeach has been validated with various analytical, laboratory and field data. A full description of XBeach is provided in Roelvink et al. (2009) and in the user manual (Roelvink et al., 2010). The grid used to apply XBeach had a resolution of 5 m extending 2.8 km alongshore and 1.7 km cross-shore. The grid was rotated by 26° to face the southwest (Fig. 2) so that the offshore boundary was normal to the incoming wave to optimize the extent of the grid. Stationary wave conditions were used, representative of the summer conditions observed by Gallop et al. (2011a) who measured wave heights of 1 to 1.2 m with periods of 5 to 8 s periods coming from south to southwest during sea breezes at Yanchep Lagoon.

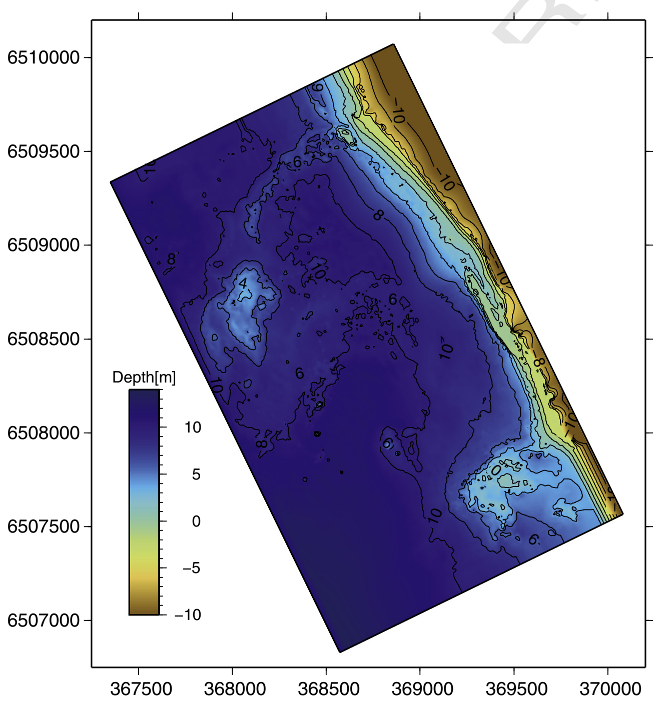

Fig. 2. XBeach model bathymetry of Yanchep Lagoon to AHD with x and y coordinates in UTM.

4. Results

4.1. Sub-aerial beach volume

Alongshore variability in reef elevation, placement and longshore continuity was expected to lead to modifications in beach morphodynamics. This expectation was confirmed by a marked degree of spatial variation in the mode and magnitude of seasonal sand transport along the kilometre long-stretch of coast. The beachface landward of the reef was consistently less than 50 m wide (Fig. 3a–f) while the beach perched on the reef in the South Zone ranged up to 100 m wide (Fig. 3g–i) between the vegetation line at the toe of the dune ridge and sea level. The beach perched on the reef in the South Zone had the greatest volume in March and lowest in October or November (Figs. 4g–i, 5). In contrast, the beach in the lee the reefs (T4 to T9) had the lowest volume in March and greatest in October or November (Figs. 4a–f and 6). This part of the beach accreted and developed a berm in the winter (Fig. 3a–f). Profiles T6 and T7 were perched on submerged reef and located near the exit of the lagoon and had the largest seasonal variation. Low seasonal variation occurred: at the northern-most profile (T9) furthest from the lagoon exit and not fronted directly to seaward by reefs; T5 on the salient near the end of the lagoon; and T8 landward of the bombora (Fig. 1b).

4.2. Sediment zones

The greater volume of beach perched on the reef in the South Zone in summer is apparent in Fig. 6a, c, and e, as is its eroded state in winter (Fig. 6b and d), and vice-versa on the beach landward of the lagoon. Further, four clearly-defined zones were revealed by seasonal changes in sand elevation in the nearshore and ranged in size from 67,400 to 673,000 m^2. There was an 'Offshore Zone' and three 'Coastal Zones' that had open boundaries and sand exchange between them. These boundaries were defined by the mode of sand transport relative to the adjacent areas between the five surveys (Fig. 7a). During autumn and winter the South, North and Offshore Zones eroded while the Middle Zone accreted (Fig. 7a and c). In spring and summer, the South, North and Offshore Zones accreted while the Middle Zone eroded (Fig. 7b and d). Most of the sand transport occurred landward of the reefs in the three coastal zones. The division between the South and Middle Zones comprises a pattern of updrift accretion and downdrift erosion in the direction of littoral drift.

4.3. Currents at Yanchep

The strong current jet in the lagoon turns offshore after exiting (Fig. 8a). There is also a southerly current from the groyne to the northwards current jet that converges with the lagoonal jet as it turns seaward near the bombora. The location of the northwards lagoonal current is consistent with GPS-drifter tracks recorded by Gallop et al. (2011a, 2012a; Fig. 8b). Additionally, XBeach predicted current speeds of more than 0.8 m s^{-1} in the lagoon (Fig. 8b) consistent with measurements reported by Gallop et al. (2011a) of 0.7 to 1.65 m s^{-1}. With south–southwest waves, the division between the Middle and South Zones corresponds to the division between the northwesterly lagoonal current and the southerly current from the groyne.

4.4. Inter-seasonal variability

The South Zone eroded in autumn and winter and accreted in spring and summer and had the greatest inter-annual variability (Fig. 9). In autumn and winter 2011, there was four times the erosion of 2010 while in spring and summer 2010–2010 there was only half the

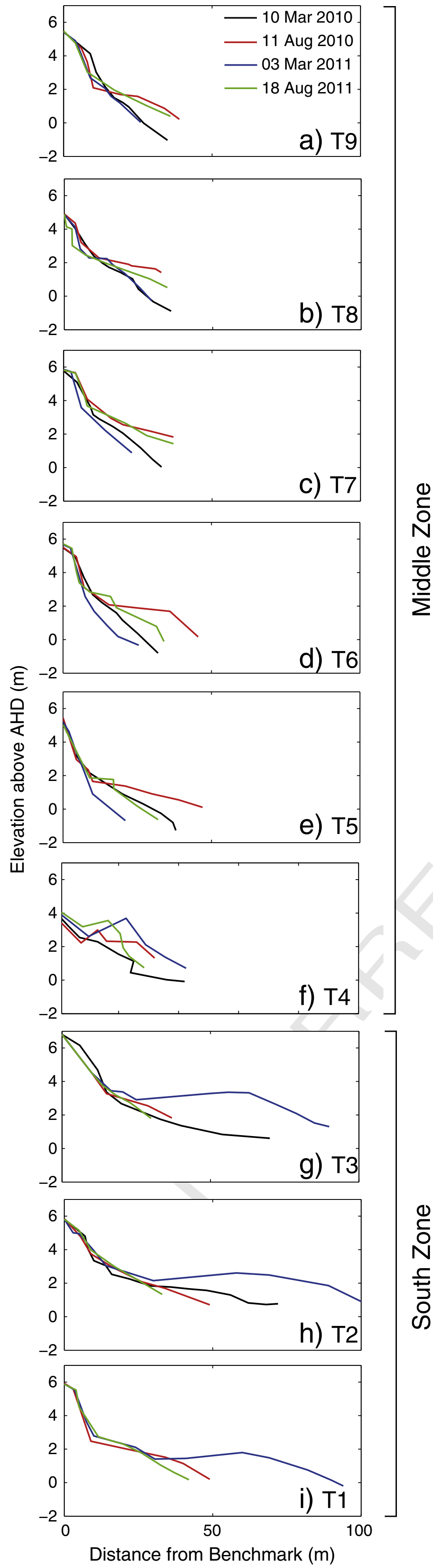

Fig. 3. Sub-aerial beach profiles from summer and winter in 2010 and 2011 to AHD.

accretion of the previous year (Table 1). The Middle Zone, in contrast to the other two coastal zones, accreted in autumn and winter and eroded in spring and summer (Fig. 9). It accreted by 12,500 m^3 more in autumn and winter 2011 compared to 2010. Also, in spring and summer 2011–2012, this zone eroded by only half the amount of the previous year (Table 1). The North Zone eroded in autumn and winter and accreted in spring and summer and had the least inter-annual variability in the volume of seasonal sand (Fig. 9). Generally the sand volume changed by 41,000 to 42,000 m^3 except in spring and summer of 2011/2012 when it accreted by 50,000 m^3 (Table 1). This suggested that the 'saturation volume' of the groyne, reflecting its ability to trap littoral drift, is between 40,000 to 50,000 m^3. In the Offshore Zone, while there was consistently erosion in autumn and winter and accretion in spring and summer, the normalised seasonal changes were an order of magnitude lower than the coastal zones (Table 1; Fig. 9). In autumn and winter in 2010 the Offshore Zone lost just 4110 m^3. However, during the other seasons sand fluxes were an order of magnitude greater. In spring and summer 2010 to 2011 the Offshore Zone gained 43,500 m^3 of sand then in the following autumn and winter lost 86,500 m^3. Subsequently, in spring and summer 2011 to 2012 the Offshore Zone gained 50,000 m^3.

5. Discussion

5.1. Sediment zones formed by the reefs

Four seasonal 'sediment zones' were identified, with boundaries formed by two mechanisms: (1) nearshore reefs acting as obstacles in the longshore to littoral drift; and (2) the convergence zone between the northwesterly current jet exiting the lagoon and a southerly current starting at the groyne (Fig. 8b). The division between the South and Middle Zones at the headland was also identified by Stul (2005), who defined sediment cells of Perth beaches based on alongshore variation in topography, bathymetry, geology and beach type. However, the boundary due to the current jet from the lagoon was not identified.

Modes of seasonal sand transport in the zones alternated between erosion and accretion. Updrift accretion and downdrift erosion around obstacles are common in southwestern Australia and reverses with seasonal changes in wind direction (Masselink and Pattiaratchi, 2001). In spring and summer when intense sea breezes drive northerly littoral drift, sand overtops the reef in the South Zone to infill the lagoon. Consequently, sand can no longer travel through the lagoon northwards to the Middle Zone which then erodes. Northwesterly storms may occur in autumn and winter and waves and currents erode sand from the South Zone that is more exposed from the northwest (Fig. 7). The storms also provide a source of sand to profiles in the lee of the reef beach by eroding sand from the North Zone that accreted in spring and summer (Fig. 7b, d). The seasonal shift in the widest section of beach has some similarity to beach rotation that occurs on pocket beaches, defined as the periodic shifting of sediment towards one end of a beach embayment with variation in wave direction (Short, 2010). However the mechanism is somewhat different because at Yanchep, the driver of the 'rotation' is due to sediment overtopping the limestone reef blocking the coastal lagoon in spring and summer (and vice versa in autumn and winter) rather than sediment accreting against one of the lateral boundaries with changing direction in seasonal wave climate.

Topographic rip currents ('headland rips' or 'topo-rips') are common on beaches with lateral boundaries (Short, 2010; Gallop et al., 2011b) but generally head seaward (e.g. Short, 1985). The current jet at Yanchep is generated by wave set-up over the coastal reef and is predominantly orientated alongshore. In addition to the zone boundary formed by updrift accretion and downdrift erosion via the coastal lagoon, the boundary between the Middle and North Zones was located where the current exiting the lagoon converged with a southerly current from the groyne (Fig. 8b). This is a feature that to our knowledge has not been observed before on pocket beaches. These results show

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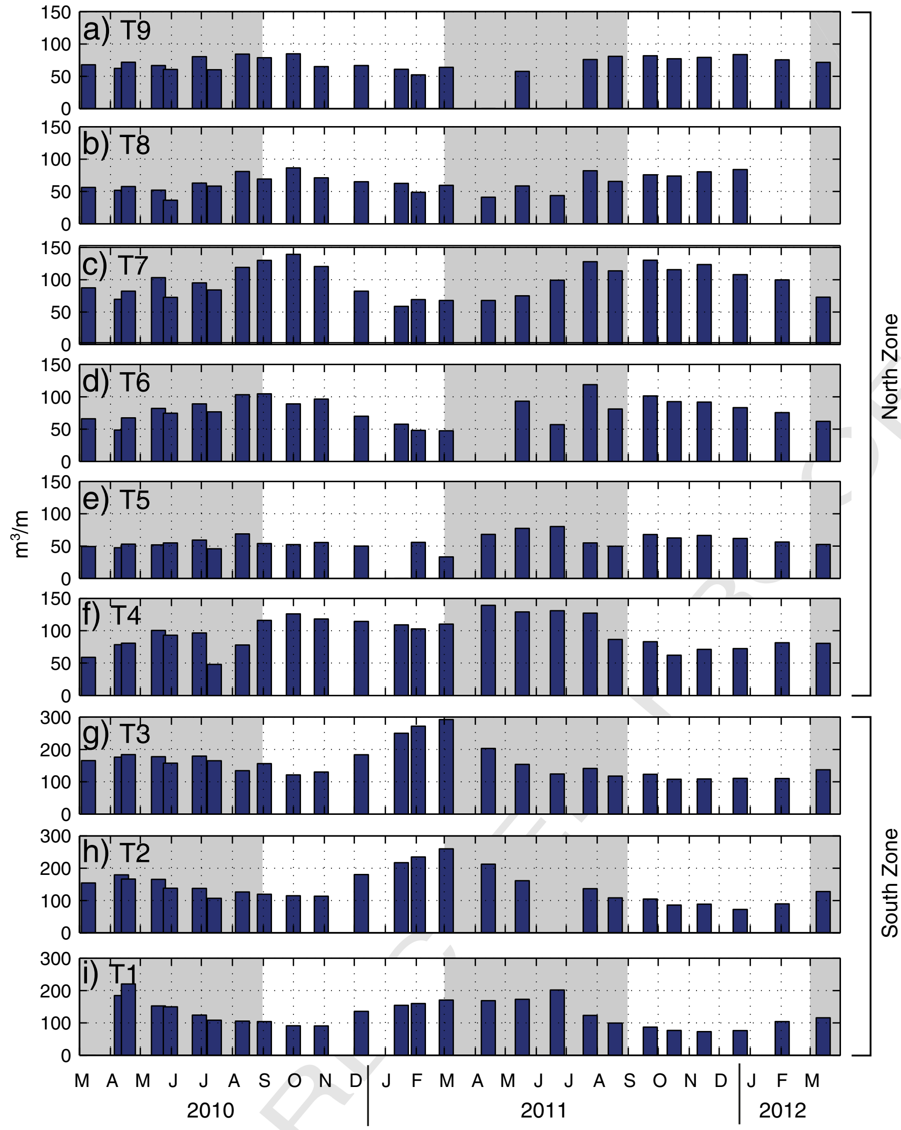

Fig. 4. Volume ($m^3\ m^{-1}$) of the sub-aerial beach profiles at Yanchep Lagoon. Grey shaded areas are autumn and winter months and unshaded are spring and summer months. Note the different scales on the y axis for the beach in the South Zone.

that on perched beaches, obstacles to littoral drift as well as seasonal blockages to local sediment transport pathways and converging current jets can create adjacent areas of seasonal erosion and accretion.

To our knowledge, the only other study in a reefed environment with extensive longshore coverage investigating spatial variability in seasonal changes beach morphology was at Kailua Beach, on Oahu, Hawaii. Kailua Beach is broadly embayed and fronted by a wide fringing reef with significant variations in the topography and continuity alongshore. From a 70 year record, seasonal variations in morphology dominated the variability in response to changing seasonal wind and wave states and directions (Norcross et al., 2002). Although the mechanism responsible is somewhat different at Yanchep, there were four distinct alongshore zones, or 'behavioural groups' of alternating modes of seasonal erosion and accretion. Norcross et al. (2002) suggested that the main reason for this was due to interaction of the paleostream sand channel that bisects the reef in the middle of the bay although the actual mechanism was unclear. This similarity, and also the differences in the mechanisms that created the seasonal sediment zones at Yanchep and Kailua highlights some of the interesting, and largely unacknowledged and unexplored similarities between beaches perched on reefs made of rocks and coral. It also highlights that the large degree of spatial variability alongshore e.g. in the seasonal mode of sand transport on adjacent sections of beach at Kailua and Yanchep, is a widespread occurrence that requires further research. Particularly to understand the effect of sea level rise and coral reef degradation which may cause adjacent sections of beach to erode or accrete depending on reef topography and directions and magnitudes of littoral drift.

5.2. Inter-annual variability in volumes of sand transport

Inter-annual variability in the magnitude of seasonal sand fluxes in the zones was driven by a combination of factors including sand supply, and the interaction of reef topography with sea level oscillations and changing wave conditions. Sub-aerial beach profiles in the South Zone had much larger monthly changes in volume than in the Middle Zone. This could be because in the Middle Zone cross-shore sand transport was inhibited less in the cross-shore and sand was more free to erode and form a sandbar perched on submerged reefs. The bar subsequently became a source that resupplied the beach when conditions allow. During a winter storm, sub-aerial beach profiles at T7 (perched on submerged reef) and T9 (not fronted directly to seaward by submerged reef; Fig. 1b), eroded less overall during winter storms than the beach

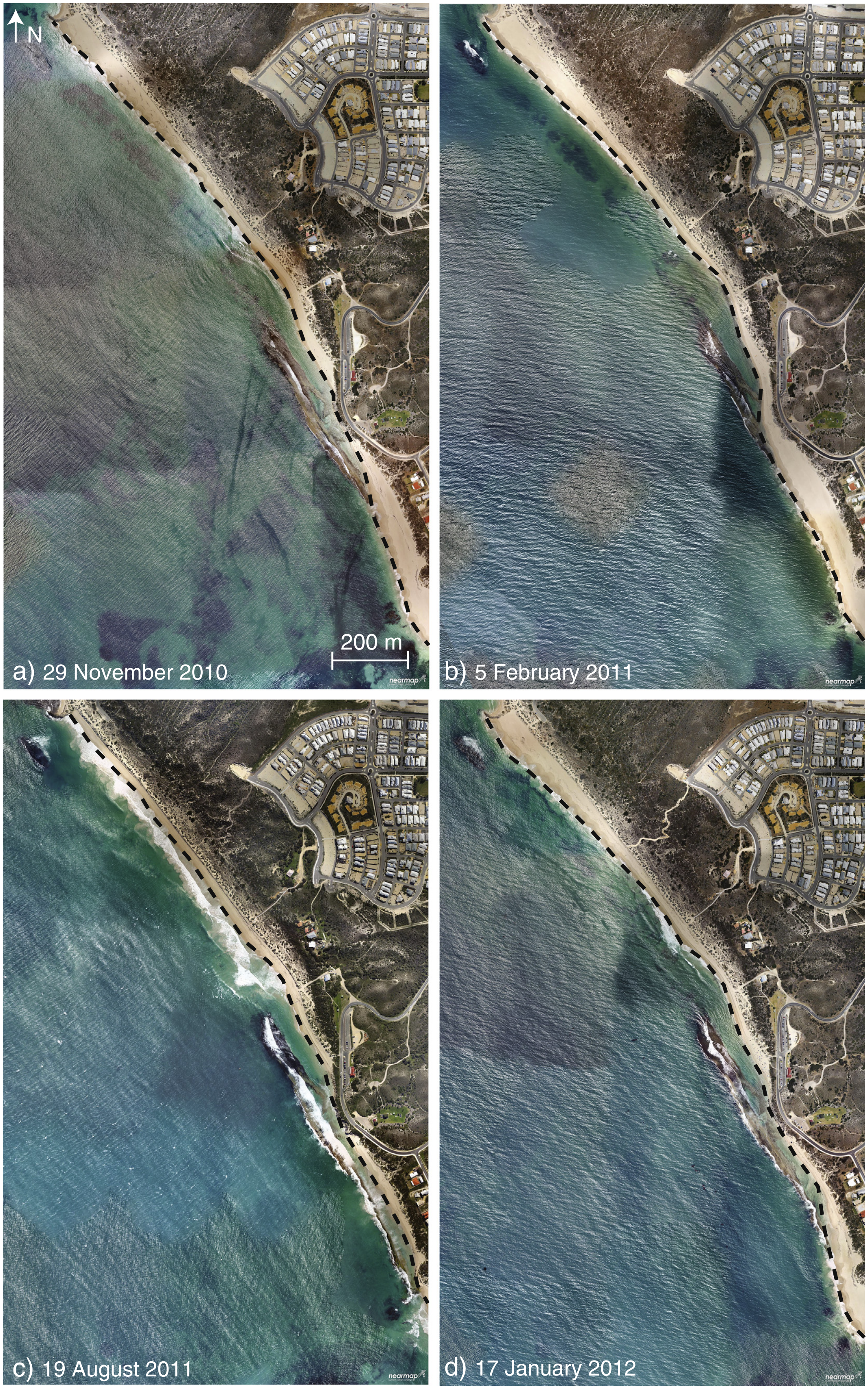

Fig. 5. Aerial photos of Yanchep Lagoon (photo source: Nearmap).

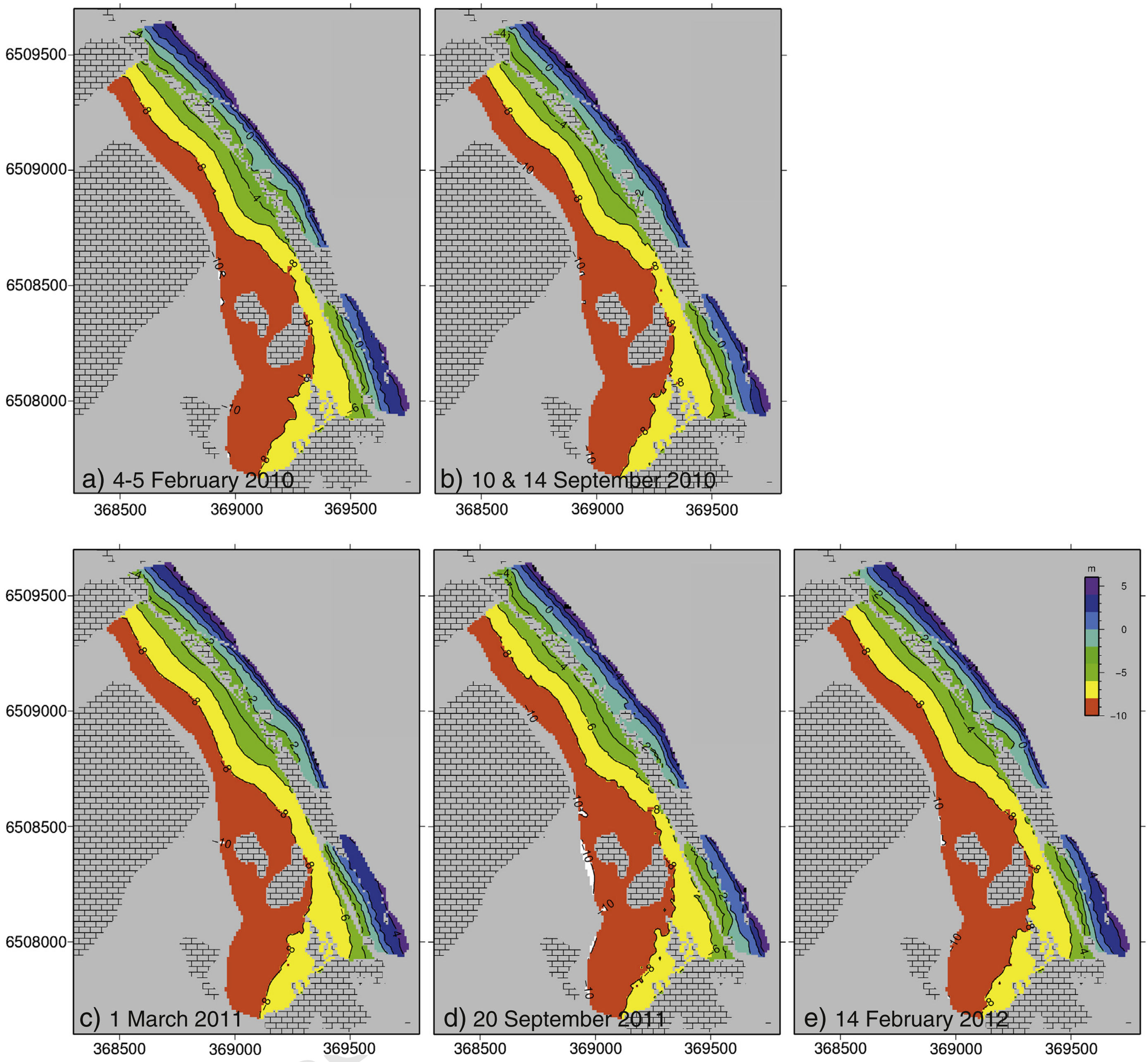

Fig. 6. Bathymetry of Yanchep Lagoon to AHD with x and y coordinates in UTM on (a) 4–5 February 2010; (b) 10 and 14 September 2010; (c) 1 March 2011; (d) 20 September 2011; and (e) 15 February 2012. Resolution is 10 m and hatching indicates outcrops of limestone reef and grey areas are dry land and areas outside the survey zone.

profile at T3 (perched on the reef) (Gallop et al., 2012a). This may be because cross-shore sand transport at T7 and T9 was not significantly inhibited by the reefs. Hence during periods of decreased storm activity the erosion was buffered by short periods of onshore sand transport. Additionally, sand eroded from the South Zone was transported through the lagoon to supply profiles in the Middle Zone. These results show that intra and inter-annual variations in metocean forcing can interact with coastal reefs to increase erosion in some areas, and decrease it in other areas.

Seasonal variation in beach morphology at Yanchep Lagoon is largely driven by longshore sediment transport, in agreement with other studies such as by Clarke and Eliot (1988) at a pocket beach in New South Wales, Australia and Norcross et al. (2002) at Kailua in Hawaii. A combination of forcings contributed to accretion in spring and summer of the South Zone while the other zones erode (Fig. 7). The constant resuspension of sediment (Verspecht and Pattiaratchi, 2010) and littoral drift during the south–southwest sea breezes (Kempin, 1953; Masselink and Pattiaratchi, 2001) in combination with generally lower MSL (Fig. 10g) and less storm surges (Fig. 10f) allowed the formation of a sand ramp seaward of the reef in the South Zone. Suspended sand travelled up this ramp with waves and over the reef to build up the beach (Bosserelle et al., 2011). As the beach in the South Zone infilled, this blocked the dominant sand transport pathway to the Middle Zone which then eroded due to the current jet. In autumn and winter, the Offshore and South Zones eroded while the Middle Zone accreted due to a combination of reduced northerly littoral drift and possible reversal due to northwesterly storms (Fig. 10a; Kempin, 1953; Masselink and Pattiaratchi, 2001). In addition, winter is generally associated with higher MSL (Fig. 10g) and more storm surges (Fig. 10f). As the South Zone eroded, this re-opened the coastal lagoon and the opening of the coastal lagoon in the South Zone and the dominant sand transport pathway to the Middle Zone which then accreted.

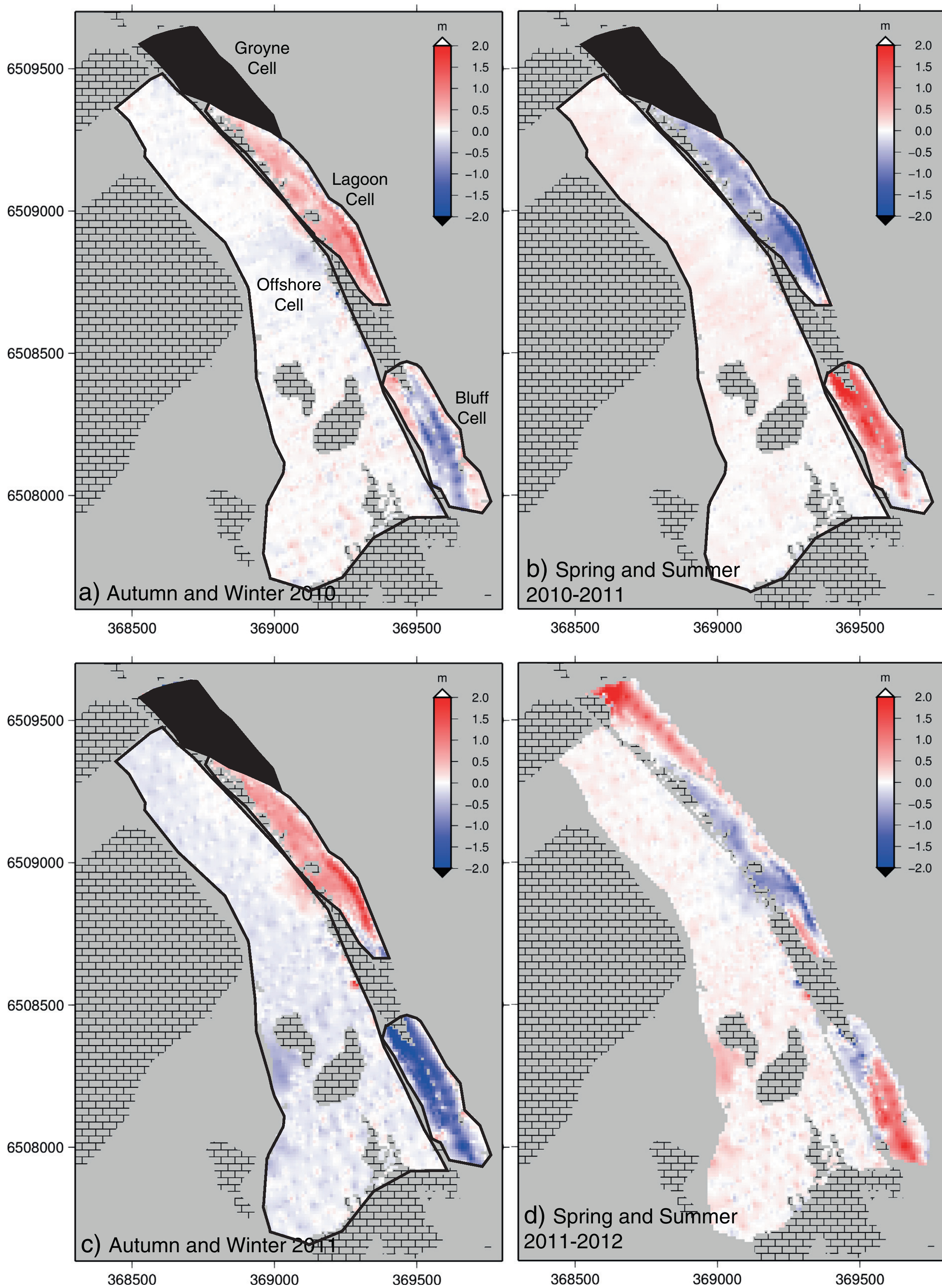

Fig. 7. Change in sand elevation between: (a) February 2010 and September 2010; (b) September 2010 and March 2011; and (c) March 2011 and September 2011; and (d) hatching indicates reef outcrops and grey areas are dry land and areas outside the survey zone with x and y coordinates in UTM.

The seasonal sand transport processes mentioned above are affected by inter-annual variations in meteorological conditions, sea level, wave regimes and sand availability to Yanchep Lagoon. In spring and summer 2011 to 2012, the South Zone accreted by half as much as 2010 to 2011 (Figs. 5 and 9). In spring and summer 2011 to 2012 there were more storm surges, with 13 events greater than 1 m (Sampling Period 4;

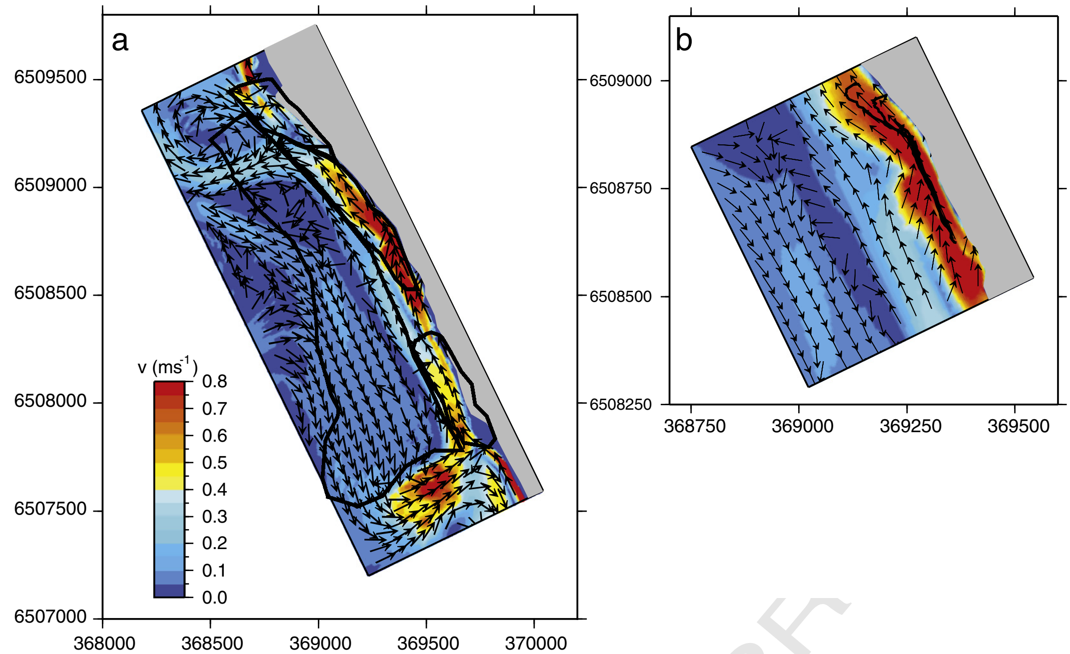

Fig. 8. XBeach model of current speeds (colour) and directions (arrows) at Yanchep Lagoon for 1 m, 8 s south–southwest waves from 220°. b. Shows zoom in with GPS-drifter paths (from Gallop et al., 2011a,b) in black. Grey area is land and the four seasonal sediment zones identified by hydrographic surveys are shown in white with x and y coordinates in UTM.

Fig. 10f) compared to just 5 in the previous spring and summer (Sampling Period 2; Fig. 10f). In spring and summer 2011 to 2012, cumulative monthly southerly wind and wave power were lower (Sampling Period 4; Fig. 10a) which decreased littoral drift and sand supply to the South Zone. Cumulative longshore winds are suggested to be a key driver of beach growth and recession in southwestern Australia (Clarke and Eliot, 1983; Masselink and Pattiaratchi, 2001; Eliot and Travers, 2011). Less accretion of the South Zone in spring and summer 2011 to 2012 resulted in less erosion in the Middle Zone because the main sand transport pathway through the coastal lagoon was partially blocked. In autumn and winter 2010 (Sampling Period 1; Fig. 10g) MSL was 0.2 m higher than 2010; and there was more northerly wave power (Sampling Period 3; Fig. 10b) which led to more erosion of the Southern Zone that is partially protected from the south by a submerged reef (Fig. 7). This was evident in four times more in autumn and winter 2011 compared to 2010 (Figs. 7 and 9). This process also occurs at the platform beach at the northern end of Cottesloe (Fig. 1a; Doucette, 2009). Increased erosion in autumn and winter of the South Zone led to more sand supply to the Middle Zone which subsequently accreted more in autumn and winter 2011 than 2010.

6. Conclusions

This research focused on the effect of reefs on seasonal erosion and accretion, in particular how alongshore variation in reef topography drives alongshore variation in the mode and magnitude of seasonal beach erosion and accretion; and the effect of intra- and inter-annual variability in metocean conditions on seasonal sediment fluxes. Inter-annual variability in sea level, variation in storm frequency and intensity, together with seasonal switching in the direction and magnitude of wave power and hence also littoral drift and pulsational effects on sand movement caused marked differences in seasonal sand fluxes. Four seasonal sediment transport zones were identified, with boundaries determined by two mechanisms: (1) reefs and headlands blocking littoral drift; and (2) longshore current jets created by the reefs. In spring and summer, northerly littoral drift and constant sand resuspension allowed a sand ramp to form in the South Zone so that sand overtopped the reef to infill the lagoon. This blocked the main pathway for sand supply through the lagoon to the zones in the north which erodes in spring and summer. In autumn and winter, with the reduction and sometimes reversal in littoral drift and northwesterly storms, the South Zone is eroded and sand can then travel through the lagoon in the current jet to nourish the northern beaches. These seasonal 'sediment zones' highlighted interesting and unexplored parallels (and differences) on coasts fronted seaward by coral reefs and rocks.

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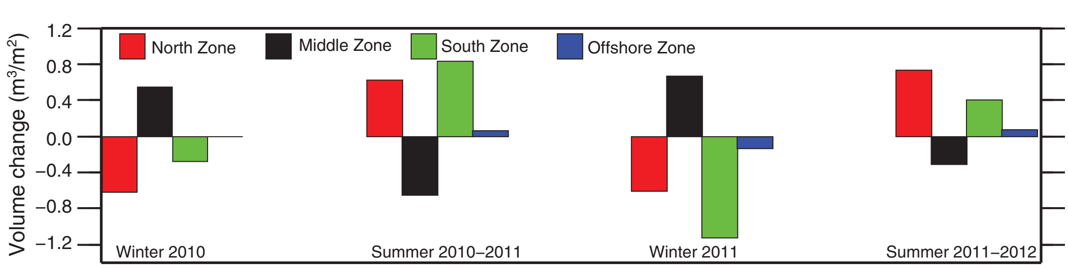

Fig. 9. Normalised seasonal changes in volume in the sediment zones at Yanchep Lagoon. Positive changes are accretion, and negative are erosion.

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Table 1
Seasonal changes in sediment volumes at Yanchep Lagoon.

Cell	Area (m^2)	Feb 2010–Sep 2010		Sep 2010–Mar 2011		Mar 2011–Sep 2011		Sep 2011–Feb 2012	
		m^3	m^3 m^2	m^3	m^3 m^2	m^3	m^3 m^2	m^3	m^3 m^2
Groyne	67,380	−41,940	−0.62	+41,710	+0.62	−41,000	−0.61	+50,070	+0.74
Lagoon	100,390	+54,990	+0.55	−65,470	−0.65	+67,550	+0.67	−31,620	−0.31
Bluff	82,760	−0.28	−2,780	+68,580	+0.83	−93,970	−1.13	+33,590	+0.41
Offshore	672,990	−4,110	0.00	+43,620	+0.06	−86,510	−0.13	+49,920	+0.07

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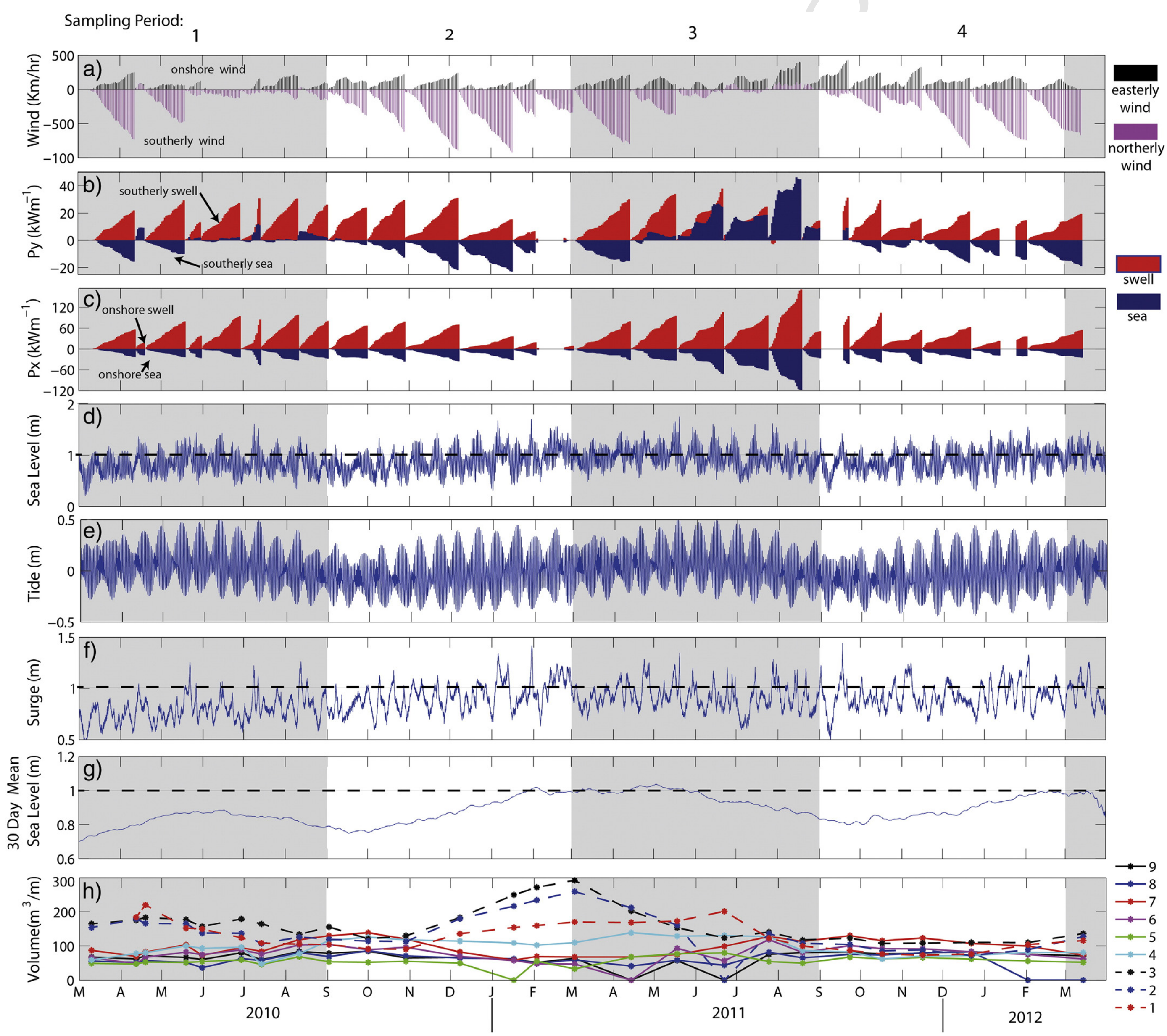

Fig. 10. (a) Monthly cumulative of 3 pm winds; (b) monthly cumulative longshore component of 3 pm wave power; (c) monthly cumulative cross-shore component of 3 pm wave power; (d) sea level; (e) tide; (f) storm surge where dashed line is at 1 m; (g) sea level; and (h) beach profile volumes. Dashed line shows 1 m threshold for total sea level, surge and sea level. Note numbered 6-monthly sampling periods at the top of the figure.

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