SEA LEVEL VARIABILITY

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ABSTRACT

Coastal sea level variability occurs over timescales ranging from hours to centuries. Sea level data from Fremantle, which has one of the longest time series records in the southern hemisphere, and other sea level recording stations in Western Australia are presented to highlight the different processes, such as seiches, tsunamis, tides, storm surges, continental shelf waves, and annual and inter-annual.

1. INTRODUCTION

Coastal regions experience rise and fall of sea level which vary at timescales of hours, days, weeks, months, annually and so on, governed by the astronomical tides, meteorological conditions, local bathymetry and a host of other factors. Globally, the astronomical forces of the Sun and the Moon are the dominant forcing which results in the tidal variability with periods of 12 and 24 hours. In many regions, the effects of these tides dominate the water level variability; however, in regions where the tidal effects are small other processes become important in determining the local water level. In this paper, sea level data from Fremantle (Figure 1) which has one of the longest time series records in the southern hemisphere, are presented to highlight the different processes ranging from seiches, tsunamis, tides, storm surges, continental shelf waves, annual and inter-annual variability (Table 1). The auto spectrum of water levels recorded at Fremantle over three years indicated several peaks, ranging from hours to seasonal timescales reflecting these processes (Figure 2). The contribution from each of these processes, which includes both direct and remote forcing to the total sea level variability is of the same order of magnitude and thus is equally important.

Sea level variability is important for a range of activities including navigation, coastal stability and coastal planning. The significance of coastal sea level change for coastal management has been recognised, effective for both gradual change and intermittent fluctuations (Komar and Enfield, 1987; Allan *et al.*, 2003). In order to interpret historic patterns of coastal management and predict possible future needs, it is necessary to document both short and long-term trends and fluctuations of sea level.

Fremantle is located along the western-coast of Australia at latitude 32°S (Figure 1). Weather systems impacting on the region are dominated by anti-cyclonic high-pressure systems with periodic tropic and mid-latitude depressions and local seasonal sea-breezes (Eliot and Clarke 1986). Anticyclones move to the east and pass the coast every 3-10 days (Gentilli 1972). The peak occurrence of mid-latitude depressions is in July and the strongest winds in the system are the north-westerlies (Gentilli, 1971; Lemm *et al.*, 1999). Tropical cyclones track down from the Northwest coast infrequently during late summer and can have significant impact on the coastline (Eliot and Clarke, 1986). The seasonal movement of the high-pressure systems results in a strong seasonality in the wind regime. During the summer southerly winds prevail whilst in winter there is no dominant wind direction although the strongest winds are north-westerly during the passage of frontal systems.

Sea breezes, which are stronger during the summer dominate the coastal region with offshore (westward) winds in the morning and strong (up to 15 ms^{-1}) shore parallel sea breezes commencing around noon and weakening during the night (Pattiaratchi *et al.*, 1997; Masselink and Pattiaratchi, 2001).

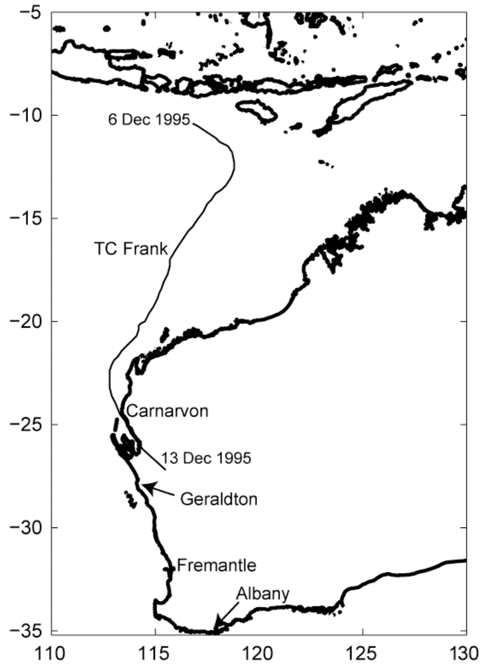

Figure 1 – Location of tide gauges used in the present study and the track of the tropical cyclone Frank.

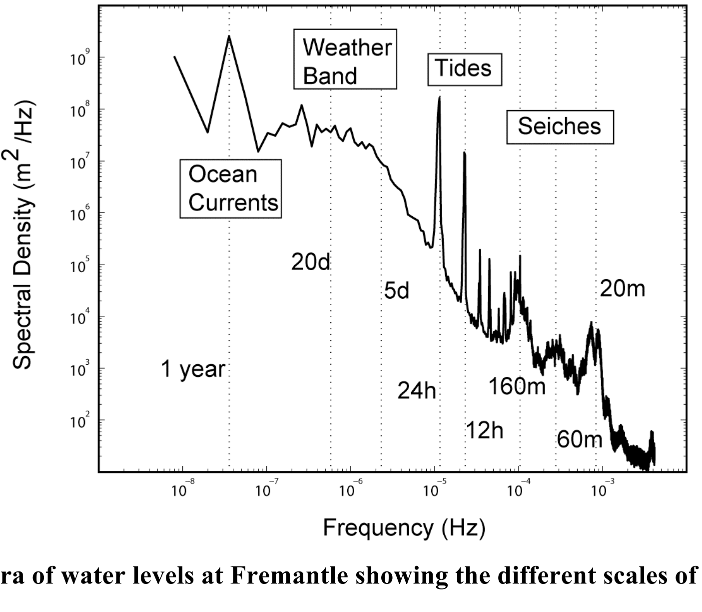

Figure 2 – Spectra of water levels at Fremantle showing the different scales of variability

Table 1 - Water level components

Process	Duration	Scale (m)	Reference
Wave action	2–20 sec	~ 5	Lemm *et al.* (1999)
Wave set-up	5–30 mins	~ 0.3	Bode and Hardy (1997)
Seiches	30–90 mins	~ 0.2	Ilich (2006)
Pressure surge	1–3 hours	~ 0.2	Reid (1990)
Wind set-up	3–6 hours	~ 0.2	Pugh (1987)
Tidal conditions	12–24 hours	~ 0.8	Easton (1970)
Sea breezes	24 hours	*	Pattiaratchi *et al.* (1997)
Pressure systems (cycle)	1–10 days	~ 0.8	Hamon (1966)
Continental shelf waves	3–10 days	~ 0.6	Fandry *et al.* (1984)
Oceanic currents	Seasonal	~ 0.3	Pattiaratchi and Buchan (1991)
Nodal tide	18.6 years	~ 0.15	Pugh (1987)
Climate variability	Decades	~ 0.2	Pariwono *et al.* (1986)
Climate change	10^{3+} years	~ 10	Wyrwoll *et al.* (1995)

During winter, the region is subject to the passage of mid-latitude depressions and associated frontal systems, and ~30 storm wave events are experienced (Lemm *et al.* 1999). During the passage of a frontal system, the region is subject to strong winds (up to 25–30, ms^{-1}) from the north through west, which rapidly change direction towards west through southwest then progressively more southerly over 12–16 hours. South to south-westerly winds gradually weakens over two to three days, and calm, cloud-free conditions prevail for another three to five days prior to the passage of another frontal system.

2. DATA

Data presented here was recorded at the long-term tide station located at Fremantle and maintained by the WA Department for Planning and Infrastructure. The sampling intervals vary between 2 minutes and 1 hour. In addition, monthly mean data from the same gauge was obtained from the Permanent Service for Mean Sea Level, located at Proudman Oceanographic Laboratory, Liverpool, UK (www.pol.ac.uk/psmsl/).

3. SEICHES

A free oscillation in an enclosed or semi-enclosed body of water, similar to the oscillation of a pendulum where the oscillation continues after the initial force has stopped, is defined as a seiche (Miles, 1974). Several factors cause the initial displacement of water from a level surface, and the restoring force is gravity, which tends to maintain a level surface. Once formed, the oscillations are characteristic only of the system's geometry (length and depth) and may persist for many cycles before decaying under the influence of friction or energy leakage.

In the auto-spectrum (Figure 2), 3 seiche periods were identified: 2.8hrs, 1hr and 20mins. The seiches have amplitudes between 10 and 40 cm and contained 40%-70% energy relative to the main 24hr diurnal tidal oscillation. Ilich (2006) found that the maximum amplitudes of the 2.8hr and 20min seiches to be ~45cm and ~12cms respectively although the 45cm seiche amplitude could be due to the superposition of all three seiches.

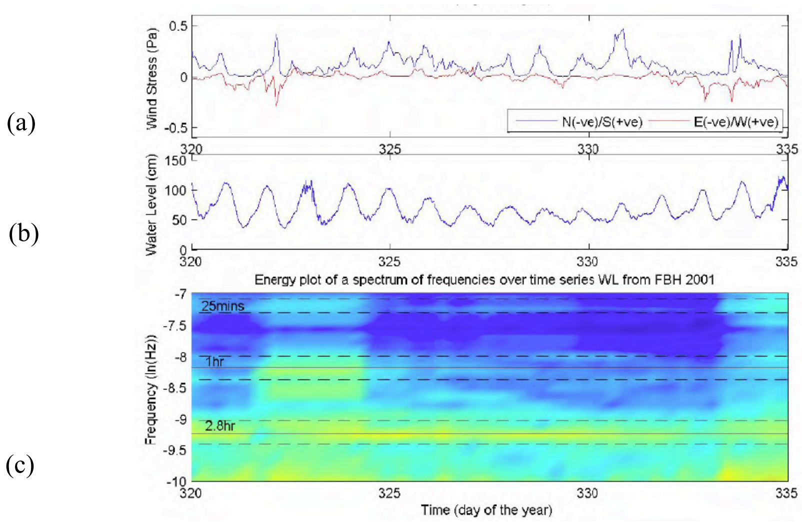

Figure 3 – Time series of (a) wind stress; (b) water level; and, (c) time-frequency diagram for a 15 day period in November 2001 showing that onshore winds (-ve easterly) initiates seiching (from Ilich, 2006).

Ilich (2006) found that changes in direction of the wind stress initiate seiching (Figure 3). In particular: (a) strong wind events onshore or offshore components initiate seiching at the 1hr and to a lesser extent, the 20min seiche; (b) strong southerly (shore-parallel) events seldom cause excitation; (c) sea breeze patterns occurring for more than two days decrease spectral energy of the entire spectrum.

4. TSUNAMIS

The Indian Ocean region experienced its most devastating natural disaster through the action of a tsunami, resulting from an earthquake off the coast of Sumatra, on 26th of December 2004. This was followed by tsunamis in March 2005, June 2006 and July 2007 and tide gauges in Western Australia recorded sea level oscillations related to all 4 tsunamis but did not result in large scale property damage (Pattiaratchi and Wijeratne, 2009).

The tide gauge data along the west coast indicated that the tsunami waves incident at Geraldton (0720), Carnarvon (0740) and Fremantle (0740). The initial waves all indicated an increase in the water level, corresponding to leading elevation waves, and the heights along the west coast ranged from 0.33 m at Fremantle to 1.650 m at Geraldton (Figure 4 and Table 2). Examination of the residual time series, maximum wave heights, and the elapsed time between the initial and maximum waves indicated that: (1) the maximum wave heights recorded at Carnarvon, Geraldton, and Fremantle (Table 2), all exceeded the mean spring tidal range at these locations; (2) at Geraldton, although initial oscillations due to the tsunami waves were observed at 0720 UTC, there was a lag of five hours before the highest water level (2.6 m relative to datum) was reached at 1210 GMT, which coincided with the tidal high water (Figure 4). However, the highest waves (trough to crest) were recorded ~10 hours later and were associated with a wave group (see Figure 4 below). The water levels recorded at Geraldton during this event were the highest and lowest levels recorded at this station, which has been in continuous operation for more than 40 years; (3) The residual time series indicated the arrival of a group of waves with higher wave heights at Geraldton some 13–15 hours after the arrival of the initial wave (Table 2) suggests a reflected wave from the island of Madagascar or the Mascarene ridge (Pattiaratchi and

Wijeratne, 2009); and, (4) the tsunami set-up seiching along the continental shelf with periods of 4 and 2.7 hours at Geraldton and Fremantle, respectively (Figure 4). These periods were the same as those excited by the meteorological effects (Section 3).

Table 2 – Characteristics of the 26 December 2004 tsunami as recorded by tide gauges

Station	Initial wave		Maximum wave	
	Arrival time/date (UTC)	Wave height^{+}	Elapsed time (number)	Wave height
Carnarvon	07:40 26/12/04	0.38 m	15 h 20 m (25)	1.14 m
Geraldton	07:20 26/12/04	0.13 m	15 h 15 m (19)	1.65 m
Fremantle	07:40 26/12/04	0.33 m	7 h 20 m (9)	0.60 m

+ Maximum wave height is listed as the trough to crest height.

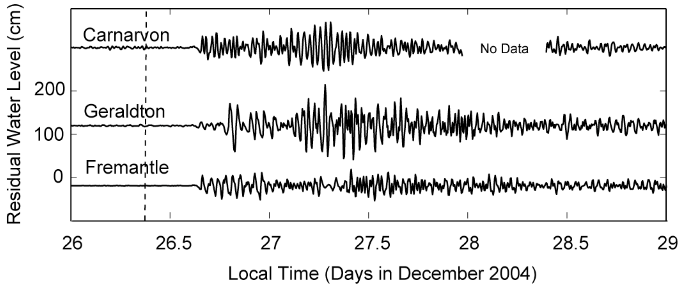

Figure 4 – Time series of residual sea level from coastal stations located along the west coast of Australia. The dashed line shows the time of the earthquake. (Note: local time is +8 hrs UTC.)

5. TIDES

Astronomic tides are the most widely recognised phenomena affecting water levels. These tides are the harmonic fluctuations of water level developed through the gravitational attraction from astronomic bodies (mainly the sun and moon). The tides at Fremantle tide station is generally representative of the tides experienced along south-western Australia. The four largest constituents are associated with diurnal and semidiurnal effects of the sun and moon (Table 2). The relative position of the sun and moon develops a monthly cycle of enhanced (spring) and lowered (neap) tidal ranges as the principal constituents move in and out of phase.

Table 2 – Principal Tidal Constituents for Fremantle

Constituent	Amplitude	Period	Description
K_1	0.165 m	23.93 hr	Principal Lunar Diurnal
O_1	0.118 m	25.82 hr	Principal Solar Diurnal
M_2	0.052 m	12.42 hr	Principal Lunar Semi-diurnal
S_2	0.047 m	12.00 hr	Principal Solar Semi-diurnal

Along south-western Australia, the tide's diurnal component has a range of 0.6 m, and the semidiurnal tide has a range of only 0.2 m. The semidiurnal tidal range is related to the lunar cycle, with the maximum tidal range occurring close to the full and new moons, and minimum tidal ranges occurring close to the lunar cycle's first and last quarter's—the spring–neap cycle. Diurnal tides are related to the declination angle of the moon's orbital plane. The diurnal and semidiurnal tides oscillate at a frequency of 13.63 and 14.77 days, respectively. This phase difference, of 1.14 days, between the two tidal signals modulates the resultant tide over an annual cycle, causing the diurnal and semidiurnal tides that are in phase during the solstice (resulting in a maximum "spring" tidal range) and out of phase at the equinox (resulting in a minimum "spring" tidal range). This means the highest tidal range (the "spring" tide) does not always correspond with the full/new moon cycle. The above also means that daily tidal range varies biannually, with solstice tidal peaks (December–January and June–July) producing a tidal range that is about 20% higher than during equinoctial troughs (February–March and September–October).

During the solstice, when the diurnal and semidiurnal tides are in phase, the maximum tidal range corresponds with the full/new moon cycle; during the equinox, the maximum tidal range does not correspond with the full/new moon cycle. Mixed tides occur during "neap" tides closest to the equinox, with two high and low waters commonly observed over a tidal cycle. Hence, in a diurnal tidal system, such as along south-west Australia, definitions such as *spring* and *neap* tides do not always relate to phases of the moon, as is the case for semidiurnal tides.

Another consequence of the diurnal tides is the seasonal change in the times of high/low water. During the summer, the low water generally occurs between 4 am and 12 pm, depending on the phase of the moon, with high water in the evening. As summer progresses, the low water occurs earlier; as winter starts, the low water occurs later at night, becoming progressively earlier in the evening (with high water occurring in the morning).

6. COASTAL-TRAPPED WAVES

The power spectra of sea level (Figure 2) indicates a broad peak in energy in the 'weather' band (5-20 days) and these are generally due to atmospheric effects. Closer examination and comparison of the tidal residuals with local meteorological data revealed that a number of significant tidal residuals that were not fully explained by local synoptic conditions but was a combination of locally generated and remotely generated signals, the former through local changes in atmospheric pressure and local wind. The remote signal is characteristic of a long period coastally trapped shelf wave, travelling anti-clockwise relative to the Australian coast.

A coastally trapped wave is defined as a wave that travels parallel to the coast, with maximum amplitude at the coast and decreasing offshore. Examples of these waves include continental shelf waves (CSWs) and internal Kelvin waves (Le Blond and Mysak, 1978), which are governed through vorticity conservation (Huyer, 1990). Coastally trapped waves need a shallowing interface and may develop a range of modes according to the shelf structure (Tang and Grimshaw, 1995). They travel with the coast to the left (right) in the southern (northern) hemisphere. Along the Australian coast, shelf waves propagate anti-clockwise relative to the landmass. All these wave types propagate along the coastal boundary, with the wave signal reducing in amplitude with distance offshore.

Continental shelf waves (CSWs) depend on only the cross-shelf bathymetry profile and the vertical density profile controls the structure of an internal Kelvin wave (Huyer, 1990). The alongshore component of wind stress usually generates CSWs, which are active along the Western Australian coast, first reported by Hamon (1966). Provis and Radok (1979) demonstrated that these waves propagate anti-clockwise along the south coast of the Australian continent over a maximum distance of 4000 km at speeds of 5–7 ms^{-1}.

Along the west Australian coastline, the continental shelf waves are generated through the passage of mid-latitude low-pressure systems and tropical cyclones. The continental shelf waves can be identified from the sea level records by low-pass filtering (i.e. removal of the tidal component). An example is shown on Figure 5 for tidal records from Geraldton, Fremantle and Albany (Figure 1). Several CSWs with amplitudes ranging from 0.1 to 0.5 m can be identified. For example, between days 290 and 295, an increase of ~0.5 m in the sub-tidal water level was observed at Geraldton. The same variation in water level signal was seen at Fremantle and Albany, and could be attributed to the passage of a CSW. The correlation coefficients between sub-tidal water levels at these three locations were all greater than 0.8, despite observations being several hundred kilometres apart. The propagation time of the CSW between Geraldton and Fremantle was 23 hours, and between Fremantle and Albany it was 17 hours, yielding a mean propagation speed of ~500 km day^{-1} (~6 ms^{-1}). The period of the continental shelf wave range between 3-10 days and corresponds to the passage of synoptic systems from west to east across the west Australian coastline.

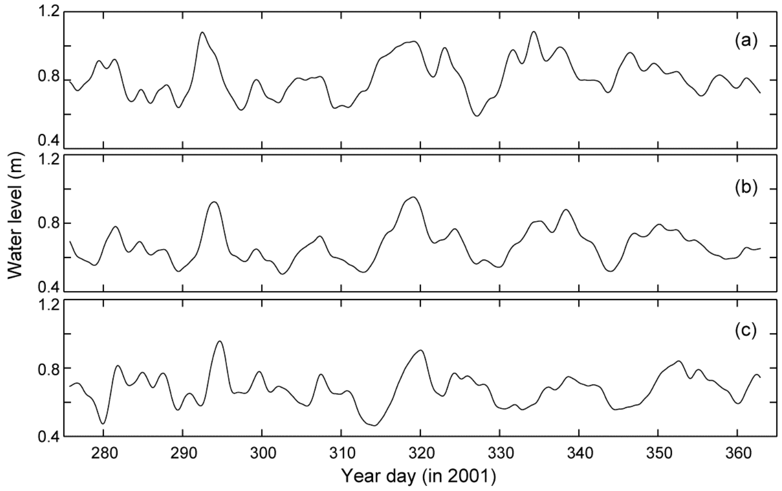

Figure 5: Low-frequency water levels at (a) Geraldton, (b) Fremantle, and (c) Albany for days 275 to 365 in 2001 showing the presence of continental shelf waves (from O'Callaghan *et al.*, 2007).

Tropical cyclones are intense low pressure systems which form over warm ocean waters at low latitudes and are associated with strong winds, torrential rain and storm surges (in coastal areas). They may cause extensive damage as a result of strong winds and flooding (caused by either heavy rainfall and/or coastal storm surges). The impacts of tropical cyclones on the North-West region of Australia are well known with several severe cyclones impacting this region over the past few years. The most noticeable impacts of these cyclones are normally restricted to the region of impact of the cyclone, and hence the direct effect of cyclones on south-western Australia is rare. Fandry *et al.* (1984) identified 1 to 2 m amplitude peaks in sea level propagating southwards with speeds ranging between 400-600 km day^{-1}. These were associated with tropical cyclones travelling southward and were attributed to a resonance phenomenon when speeds of the southward component of the cyclone speeds were close to the southward propagating continental shelf wave.

Sea level records at Fremantle indicate remote forcing due to tropical cyclones. Comparison between the low frequency component of sea level records along the west and south coasts of Western Australia with the occurrence of tropical cyclones in the North-West shelf region has revealed that every tropical cyclone, irrespective of its severity and path, generated a southward propagating sea level signal or a continental shelf wave (Eliot and Pattiaratchi, 2009). The wave can be identified in the coastal sea level records, initially as a decrease in water level, 1-2 days after the passage of the cyclone and has a period of about 10 days. As an example, water level record at Fremantle for the period 1-19 December 1995 is shown on Figure 6. Tropical cyclone Frank was declared as a category 1 cyclone on 7 December and developed into a category 4 cyclone by 11 December and crossed the coastline near Carnarvon on 12 December. The evidence of the continental shelf wave becomes evident on 8 December when the water level starts to decrease and reaches a minimum level on 10 December and a maximum peak on 14 December. The wave height (trough to crest) was 0.55 m, higher than the tidal range during this time (Figure 6).

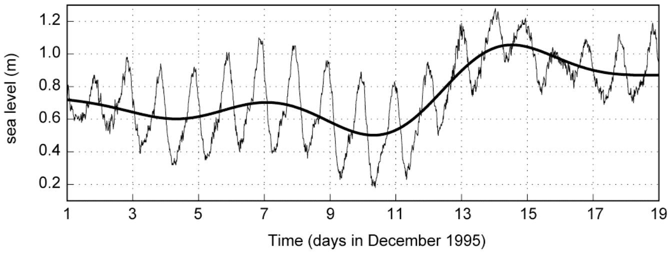

Figure 6: Sea level record at Fremantle (thin black line) during December 1995 showing the low-frequency water level variation (thick-line) induced by Tropical Cyclone Frank.

7. SEASONAL CHANGES

Mean sea level varies in an annual cycle averaging 0.22m with water levels reaching a maximum in May-June and minimum October-November (Figure 7). This variation is attributed to changes in the strength of the major ocean current in the region, the Leeuwin Current (Thompson 1984; Pattiaratchi and Buchan, 1991; Feng *et al.* 2004).

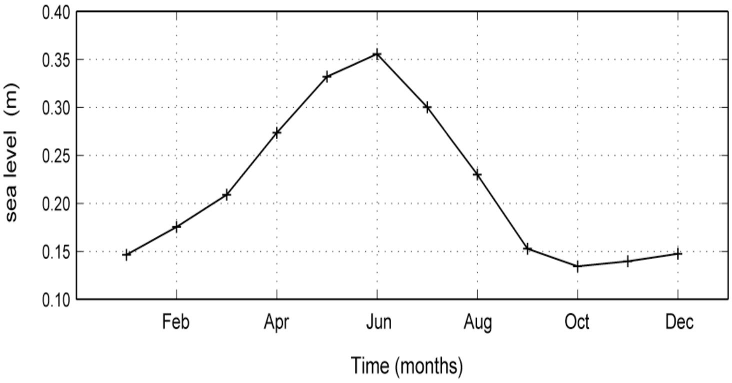

Figure 7: Mean monthly sea levels at Fremantle for the period 1943-1988.

The Leeuwin Current is a shallow (< 300 m), narrow (< 100 km wide) poleward boundary current flowing off the West Australian coast. It transports relatively warm, lower salinity water of tropical origin southward generally along the 200m depth contour (Pattiaratchi and Woo, 2009). During October to March the Current is weaker as it flows against the maximum southerly winds, whereas between April and August the Current is stronger as the southerly winds are weaker (Godfrey and Ridgway, 1985). The Leeuwin Current is driven by the large-scale density field in the eastern Indian Ocean and is in geostrophic balance (Woo and Pattiaratchi, 2008) and hence, along the Western Australian coast, a southward flow generates onshore motion. This onshore motion, which is dependent on the strength of the current, creates a set-up of the water level at the coast. This channels the flow along the shelf edge, with a sea surface gradient balancing the tendency for shoreward motion. Thus sea level is higher when the Leeuwin Current is stronger (April to August due to lower southerly wind stress) and lower between October and January when the Current is weaker (higher southerly wind stress).

8. INTER-ANNUAL CHANGES

Inter-annual changes in sea level, with amplitudes up to 20cm (Figure 8), are also linked to the strength of the Leeuwin Current (section 5). During La Nina events the Leeuwin current is stronger (higher sea level) whilst during El Nino events the Current is weaker (lower sea level). This also implies a strong correlation between mean sea level and the Southern Oscillation Index (SOI), an index reflecting El Nino/La Nina events (Pattiaratchi and Buchan 1991; Feng *et al.* 2004).

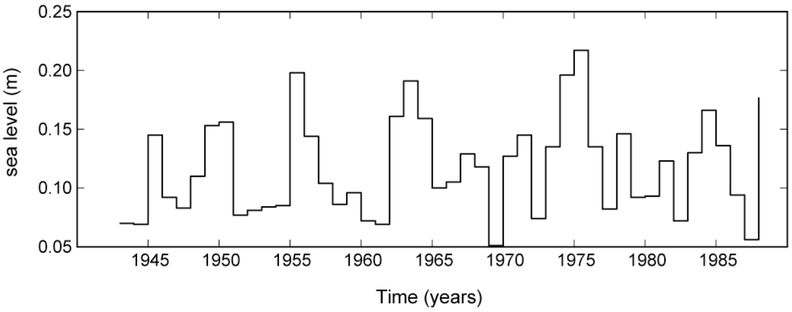

Figure 8: Time series of mean annual sea levels at Fremantle for the period 1960-1990.

9. DECADAL CHANGES

The moon, in making a revolution around the earth once each month, passes from a position of maximum angular distance north (23.5±5°) of the equator to a position of maximum angular distance south (23.5±5°) of the equator during each half month. This is termed a tropical month and has a period of 27.32 days (Pugh, 1987). This angular distance is defined as the lunar declination and twice a month the moon crosses the equator. The cycle of variation from 18.5° (23.5°-5°) to 28.5° (23.5°+5°) is defined as the nodal cycle and has a period of 18.61 years. This cycle modulates the tide generating forces and in particular influences the diurnal tides. Analysis of the tidal record from Fremantle indicates that the lunar nodal cycle has a range ~15 cm in the region (Figure 9).

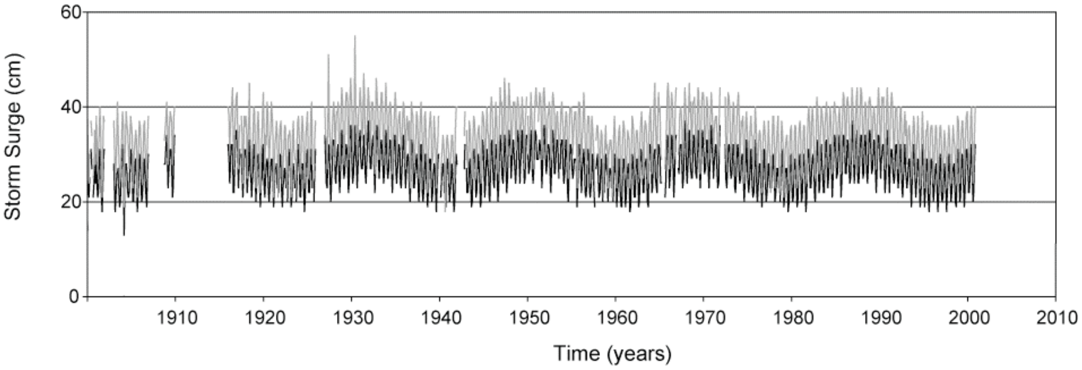

Figure 9: The 99% (grey) and 95% storm surge exceedance curves showing the 18.61 nodal cycle (from Eliot and Pattiaratchi, in prep).

10. GLOBAL SEA LEVEL PROCESSES

Relevant global sea level processes can be considered from two time-scales: (1) the era inferred from geological evidence, particularly over the last 20,000 years; and, (2) the historic record, largely determined from coastal tide gauge measurements.

Sea level rise in the west Australian region over recent geological time frames has been inferred from geological records (Wyrwoll *et al.* 1995). This behaviour largely corresponds to global analysis of sea level records with rapid sea level rise subsequent to the last Ice Age, reaching present levels approximately 6000 years before present, then subsequently staying largely constant (Figure 10).

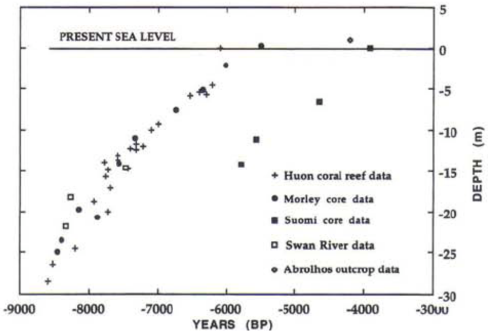

Figure 10 – Sea Level Event Data for Western Australia (from Wyrwoll *et al.* 1995)

Sea level has been recorded at Fremantle continuously since 1897 and is the longest sea level data record in the southern hemisphere. This record indicates that there has been a mean rate of sea level rise of 1.54 mm per annum (Figure 11). This rate of increase is similar to that observed globally, which has been estimated to range between 1.1 to 1.8 mm per annum (Douglas, 2001; Church *et al*., 2004). Although there has been an increasing trend over the past 100 years, there have been periods, which are revealed when the linear trend is removed, where the rate of mean sea level change varied with time. These variations were dominated by the inter-annual variability of sea level linked to the ENSO phenomenon. From 1900 to 1952 there were cyclic periods of sea level increase and decrease ranging between 10 to 14 years. Between 1952 and 1991, there was a decreasing trend, but in combination with the mean sea level rise resulted in almost constant mean sea level. A reversal of this trend occurred between 1991 and 2004, producing an apparent rapid mean sea level rise at a rate of 5 mm per annum - a rate more than 3 times the trend over the previous 100 years (Pattiaratchi and Eliot, 2005). This resulted in Fremantle recording maximum sea levels in 2003 and 2004.

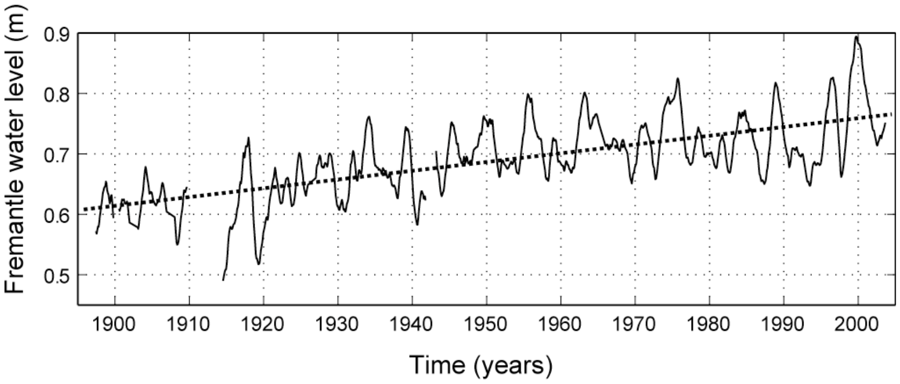

Figure 11: Time series of Fremantle sea level (one year running mean) with the linear trend of 1.54 mm per annum shown with dashed line.

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