

5th Western Australian State

COASTAL CONFERENCE 2009

*Whose Coast Is It?
adapting for the future*

Storm Waves and Their Temporal and Directional Distribution, Perth, 1994–2008

8B:

Before and
After the Storm:
11.25–11.55am
Friday 9th
October 2009
Pleiades Room

PRESENTER:

Dr Fangjun Li

Department of Transport, WA

CONTACT DETAILS:

Phone: +61 (8) 92168213

Email: Fangjun.li@transport.wa.gov.au

Postal Address: Marine House, 1 Essex Street, Fremantle WA 6160

CO-AUTHORS:

Lucya Roncevich

Department of Transport, WA

Charlie Bicknell

Department of Transport, WA

Reena Lowry

Department of Transport, WA

Karl Ilich

Department of Transport, WA

Introduction

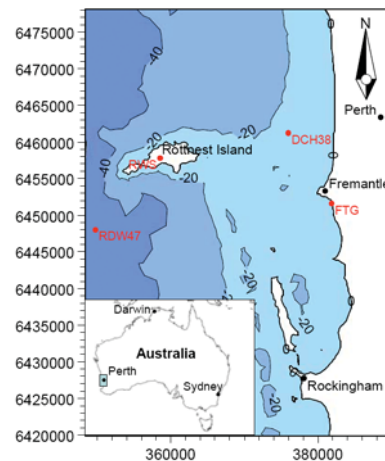
The Perth metropolitan coast is located at the south-western margin of the Australian Continental Shelf, Figure 1. High energy and long period waves from the Indian and Southern Oceans arrive at the edge of the continental shelf (west of Rottnest Island) without encountering any obstruction. As a result, the south-west coast of Australia has the most energetic wave climate around the continent with local mean significant wave heights significantly greater than elsewhere on Australia's coasts (Hemer *et al.* 2007).

To estimate appropriate setback distances for coastal development the Western Australia State Coastal Planning Policy (WAPC, 2003) requires the prediction of storm-induced acute shore erosion. To meet the 100 yr planning time frame a storm wave sequence with 100 yr average recurrence interval (ARI) is required. With a lack of long-term wave data the policy currently allows estimation of 100 yr ARI storm erosion by running cross-shore sediment transport models, such as SBEACH (Larson and Kraus, 1989, Wise *et al.* 1996), with three successive runs of the most severe storm event recorded. In 2003 when the State Coastal Planning Policy of WA was developed the most severe storm recorded along the Perth metropolitan coast was considered to be the storm that occurred from 15 to 19 July, 1996.

The deep water wave data was collected by a waverider buoy (marked RDW47 in Figure 1) deployed since 1991 south-west of Rottnest Island in a water depth of 48m. The early data was six-hourly with poor continuity and season losses. Hourly continuous data become available from February 1994 onwards. Wave

data at an intermediate water depth of 17 m has also been collected since 1994 offshore from Cottesloe Beach (marked DCWH38 in Figure 1). After computational quality controlled the data was spectrally analysed to determine the significant wave height, peak period and mean period of the total wave. Using a split at 8 second the data was further broken down into the significant wave height, peak period and mean period of sea and swell waves. The sea comprises waves with period below 8s and the swell comprises waves with period greater than 8s.

Figure 1 Perth coast (Western Australia) showing the locations of wave buoys, wind station, and tide gauge used in this study. Map projection: MGA-50, Datum: Australian Height Datum (+0.756m above CD), unit: metre. DCH38: Cottesloe Waverider, FTG: Fremantle Tide Gauge, RWS: Rottnest Wind Station, RDW47: Rottnest Directional Waverider.



The wind climate in Perth has a strong seasonal variation. In winter, the region experiences strong westerly and northwesterly winds, blowing with a mean speed of 10 to 15 m/s (40 to 55 km/h), and frequent storms. In summer, there are fewer storms and the wind has more south and south-westerly occurrences (Figure 2). The area is subjected to one of the strongest and most consistent sea breeze systems in the world (Pattiaratchi *et al.* 1997, Masselink and Pattiaratchi, 2001). The sea breeze velocities frequently exceed 10 m/s in the summer months when the sea breeze system is best developed.

The Perth region has micro-tidal, mixed but predominantly diurnal tides with a tidal form factor of 2.87. The Fremantle tide gauge has one of the longest Australian tidal records with data being collected since 1897. The records show a tidal range of about 1.1 m with non-tidal variations having the same order of magnitude as tidal variations.

Storm-associated water level surges, high energy waves, and high winds cause beach erosion, jetty and breakwater damages, and coastal flooding. With unprecedented public concerns on the impact of climate change it is important to provide stakeholders and the general public with credible analysis on the natural variability of Perth storms and the climatic trend of storminess.

This study examined if the current selection of the severe storm in July 1996 is still the most appropriate one for planning using quality-assured Rottnest wave buoy records up to September 2008. The results provide coastal engineers with the statistical background for the extreme storm sequence selection.

Available wave data

Significant wave height (H_s), spectral peak wave period, spectral mean wave period for total waves, swells and seas south-west of Rottnest Island ($32^{\circ} 05' 39''S$, $115^{\circ} 24'28''E$) have been collected since the early 1990s by the Department of Transport, Western Australia.

The wave dataset is hourly and covers exactly 14 years for non-directional wave data by the selection of an analysis time window from 21 Sep.1994 to 20 Sep. 2008. The directional wave dataset is analysed from 21 Sep.2004 to 20 Sep. 2008.

As will most wave recordings the Rottnest wave dataset has gaps. The data recovery statistics indicate that on average the recovery rates were 95 % and 87 % for nondirectional and directional data respectively. For small gaps (less than one day), the relatively slow-varying nature of the Rottnest wave data allows linear interpolation to provide a best fit to fill in the gaps. However, there are 31 gaps with missing data longer than one day, including nine large data gaps longer than three days. The maximum 35-day gap occurred

from 25 Aug. to 15 Sep. 2005. Ignoring these data gaps would severely compromise the quality of annual storminess analysis and damage the comparability of inter-annual storminess.

To fill gaps longer than one day with credible substitutes the correlations of wave height with wind speed, non-tidal water level residual, and the nearby Cottesloe wave height were explored. Among those candidates the Cottesloe wave height gave the highest correlation coefficient (CC), 0.90 for total Hs, against all available Cottesloe directional wave records (from 14th Feb. to 31st July, 2008 with 3975 valid hourly wave records). So the Rottneest data gaps longer than one day was filled with data calculated from the Cottesloe records.

Storm definition and storminess indices

In the past, arbitrary criteria were commonly used as the threshold for storm identification. For example Hs > 4.0m (Lemm, 1999), Hs >1.5 m (Dolan and Davis, 1992), Hs >5.0 m (Ferreira, 2005), Hs >0.75 m (Dorsch, *et al.* 2008). The threshold values generally corresponded to a low percentage of exceedance in their datasets, even without this explicitly given as a reason. In this study the selection of thresholds for different datasets follows the statistical method used by Zhang, *et al.* (2000) which chose a storm surge greater than two standard deviations as the criterion to determine a major storm event.

Three criteria have to be satisfied for a data sequence to be classified as a storm:

- The event consists of at least one sample over its peak threshold value, $H_{s_storm_peak}$ (the dataset mean + two standard deviations); The storm continues while the total Hs remain above H_{s_dur} (dataset mean + standard deviation);
- The interval between two consecutive storms (storm peak to storm peak) is not less than 30 hours. Otherwise they are regarded as the continuation of a single storm (Morton, *et al.* 1997, Lemm, 1999);
- The storm break, the end of previous storm to the beginning of current storm, is not shorter than three hours; otherwise they are regarded as the continuation of one storm.

Figure 2. Storms defined as event during which the significant wave height exceed 4.09 m and duration calculated as the Hs above 3.13 m.

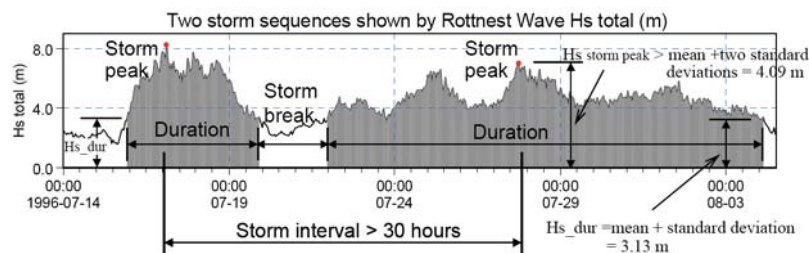


Figure 2 uses the Rottneest July 1996 wave records as an example to graphically illustrate the definition of a storm, storm duration, and the terminology used in this study. The total wave power (TWP) for each storm sequence is defined as:

$$(1) P = \sum(Hs_{total_Rottneest}^2 * \Delta t)$$

where $Hs_{total_Rottneest}$ is the hourly significant wave height in metres, Δt is the wave data interval in days, for an hourly dataset, $\Delta t = 1/24$ day. This index was first introduced by Dolan and Davis (1992). It was proved to be a good measure of storm strength, and a good indicator for shoreline movement and beach erosion evaluation. In the absence of significant current, wave energy flux is generally accepted to be responsible for long-shore and cross-shore sediment transports (Larson and Kraus, 1989).

In this study three of the most commonly used indicators were calculated and compared. They are:

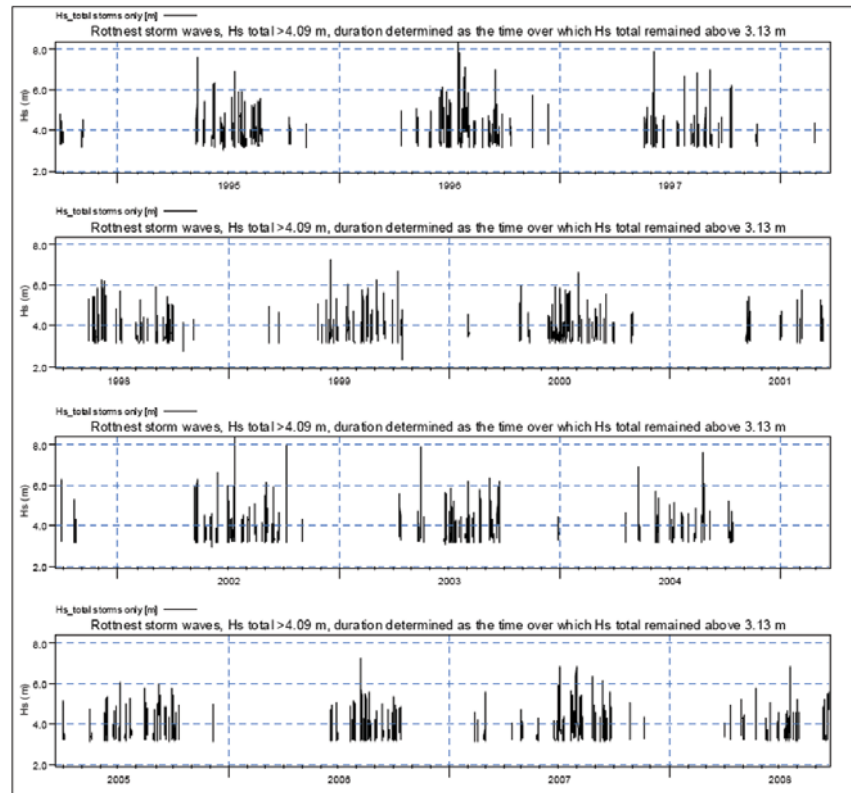
- 1) Annual number of storm events determined by Rottneest wave height, $H_{s_dur} = 3.13$ m and $H_{s_storm_peak} = 4.09$ m.
- 2) Annual storm hours determined by Rottneest total significant wave height $H_s > 4.09$ m at storm peak.
- 3) Annual total storm wave power (ATWP) m^2/day

Temporal distribution of storms

Most storm systems in Perth are characterised by strong fronts and intense lows that are associated with sustained gale-force winds and severe gusts over a widespread area. Figure 3 presents the identified storm sequences from the wave dataset. The temporal variability of storm event distribution from 1994 to 2008 is significant.

Among the 254 storms identified from the 14 year dataset, 233 occurred in the cool season (May – October) and only 21 occurred in the warm season (November – April). There have been no cyclones impacting the Perth coast between 1994 and 2008, although historically the annual frequency of cyclone occurrence in Perth is around 0.15 events per annum (BoM, 2008). Maximum wave heights during summer storms are significantly lower than those in winter storms.

Figure 3. Identified storm sequences from the hourly Rottnest total significant wave height dataset (from 21 Sep. 1994 00:00 am to 20 Sep. 2008 23:00 pm) $H_{s_storm_peak}=4.09$ m, $H_{s_dur}=3.13$ m.



The storm duration was calculated by the time the total significant wave height remained above 3.13 m. Figure 4 plots total wave power (TWP) in m^2 day for each individual storm sequence. The figures revealed a high level of consistency of the two indices in representing the intensity of individual storms. The top three most powerful storms between 1994 and 2008 all occurred in July, and the stormiest season is in June, July, August and September. Conversely, from 1995 to 2008, no storm occurred in January. The months from November to March contained the least storms. There is no evidence to suggest an increase in extreme storm wave power in Perth and in the study period (1994 to 2008).

To make comparisons easier the storminess indices are standardized by dividing by their mean value. In Figure 5, the three normalised annual storminess indices calculated from Rottnest wave dataset are compared. It shows a consistency amongst the storminess indices defined by number of storm events, storm hours, and storm wave power. The stormiest year is 1996 and the least stormy year is 2001 in terms of storm hours, number of storm events, and annual total storm power.

Figure 4. Total storm power index, P, in m²day based on the hourly Rottneest significant wave height dataset (from 21 Sep. 1994 00:00 am to 20 Sep. 2008 23:00 pm) Hs_{storm_peak}=4.09 m, Hs_{dur}=3.13 m.

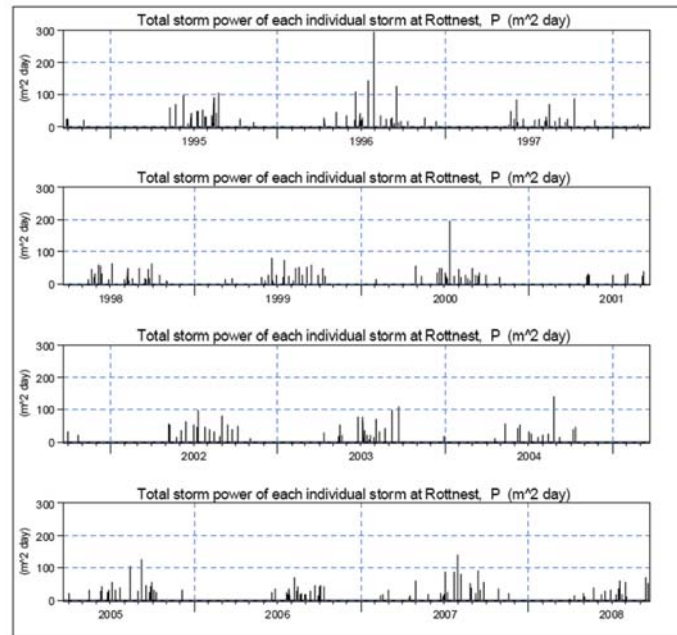
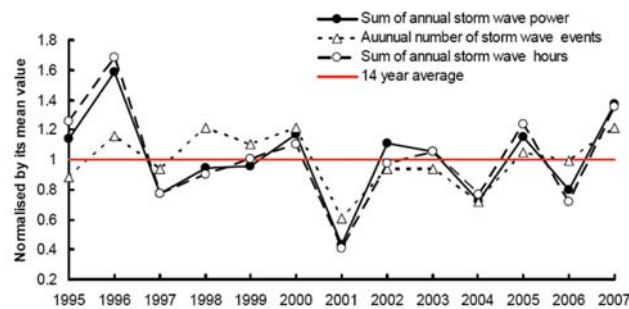


Figure 5. Normalised annual (calendar year) wave storminess indices, i.e. annual value divided by its 14-year (from 21 Sep. 1994 to 20 Sep. 2008) mean value.



Directional distribution of wave height

Four years of directional wave data from Rottneest were analysed. Figure 6 plots the joint occurrence probability (%) of Hs and the directions for swell and sea waves at Rottneest. The radius represents the significant wave heights in meters, and the coloured contours represent the percentage of wave occurrence. The most frequently occurring swells are from 250°, with significant wave heights between 1.0 to 1.5 m (Figure 6), which is in a good agreement with the previous assumed 250° to 257° in wave modelling (DPI, 2004, MRA, 2000). The most frequently occurring sea direction is 240°, with Hs between 0.5 to 1.0 m. This contrasts with the west in winter and south in summer sea wave directions that were usually inferred from local wind direction (Lemm, 1999). Figure 6b has basically ruled out of any prevailing sea occurrences from either west or south in any season.

Figure 6. Joint occurrence probability of significant wave heights and wave incident directions based on 21 Sep. 2004 to 20 Sep. 2008 hourly wave dataset. (a) swell Hs & Direction, (b) sea Hs & Direction (colour scale unit: %; Meteorological wave direction convention, i.e. 270 is a wave from the West).

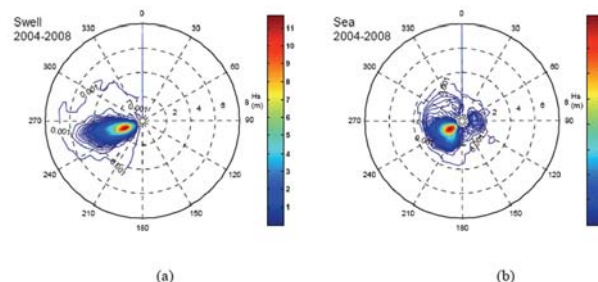
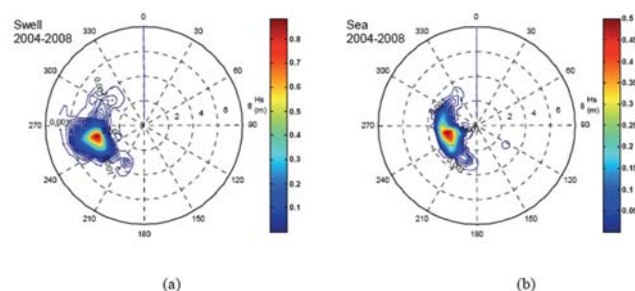


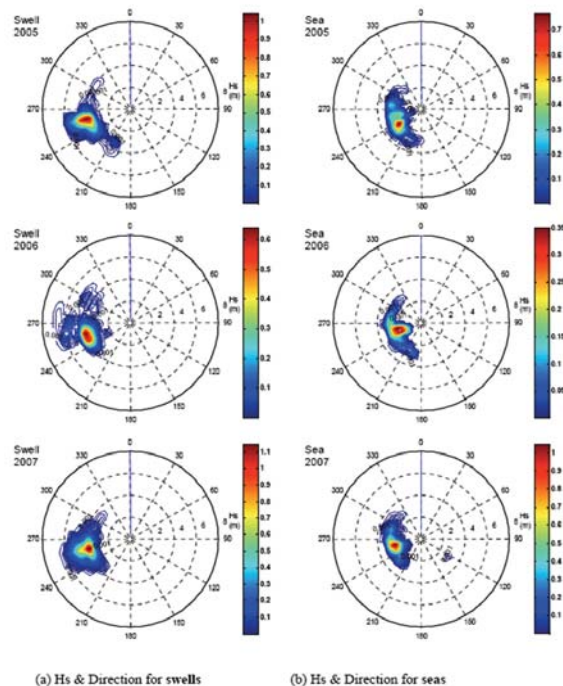
Figure 7. Joint occurrence probability of storm wave heights (H_s total > 4.09 m) and storm incident directions based on 21 Sep. 2004 to 20 Sep. 2008 hourly wave dataset. (a) swell H_s & Direction, (b) sea H_s & Direction (colour scale unit: %).



The swell density rose shows a single peak mode, while the sea density plot shows a secondary peak at 70° ENE, which is in the opposite direction of the first peak. There is the possibility that this secondary peak could be further north if the short-period seas arriving at the RDW47 wave buoy were not blocked by Rottneest Island which is about 10km to its northeast (Figure 1).

For engineering purposes the directional distribution of large storm waves is a major concern. Figure 7 plots the storm-wave-only ($H_s > 4.09\text{m}$) dataset, where the total wave H_s lower than 4.09 m is not deleted but marked as empty (Not-a-Number in data processing). So the density values in the Figure 6 and Figure 7 are comparable.

Figure 8. Joint occurrence probability of storm wave heights (H_s total > 4.09 m) and storm incident directions for 2005, 2006, and 2007 at Rottneest (colour scale unit: %).



Comparing the occurrence probability plots of the full wave dataset and the stormwave-only dataset ($H_s > 4.09\text{m}$) shows that the dominant wave direction for storm waves is ten degrees more north-west than waves from the full wave dataset for both swells and seas (Figure 6). The highest swells ($H_s > 6\text{m}$) are from 250° to 280° and the highest seas ($H_s > 3\text{m}$) appear to be from 290°.

Figure 8 shows the inter-annual variability of storm waves for 2005 to 2007 inclusive. Storm wave directions in 2006 are wider spread than in 2005 and 2007. This coincides with a relatively calm year in storm wave events, storm hours and total storm power, as indicated in Figure 5.

Top ten extreme storms ranked by different indicators

In previous studies wave records were frequently ranked by the maximum H_s of a storm, Table 1. In addition to the maximum H_s ranking Table 2 lists the top ten most powerful storms ranked by TWP. The 15 to 19 July 1996 storm, recommended by the Western Australia State Coastal Planning Policy (WAPC, 2003) for acute beach erosion calculation, only ranked the third. The following storm from 21 July to 4 August 1996 had a

much longer duration, approximately 13 days, and contains more than twice the wave power of the 15–17 July storm. In addition the tables include comprehensive details about each storm event, such as maximum Hs, total storm wave power, storm duration, wind direction and Fremantle non-tidal residual (NTR) at the time of storm peak, and the times when the storm started, peaked, and ceased.

Table 1. Top ten storms ranked by the significant wave height at the peak of a storm

Rank	Hs total at storm peak (m)	Total wave power (m ² day)	Storm duration (day)	Wind dir. at storm peak (deg)	NTR* at storm peak (m)	Storm started at	Storm peaked at	Storm ended at
1st	8.37	96.82	3.46	260°	0.29	10/07/2002 2:00	12/07/2002 2:00	13/07/2002 13:00
2nd	8.31	144.22	4.00	310°	0.60	15/07/1996 22:00	17/07/1996 3:00	19/07/1996 22:00
3rd	7.95	46.71	1.54	260°	0.51	5/10/2002 12:00	5/10/2002 22:00	7/10/2002 1:00
4th	7.89	51.14	1.75	270°	0.62	15/05/2003 20:00	16/05/2003 10:00	17/05/2003 14:00
5th	7.88	83.21	3.13	240°	0.22	3/06/1997 2:00	4/06/1997 15:00	6/06/1997 5:00
6th	7.61	137.84	4.75	240°	0.17	22/08/2004 14:00	25/08/2004 11:00	27/08/2004 8:00
7th	7.59	57.29	2.00	330°	0.31	10/05/1995 22:00	11/05/1995 14:00	12/05/1995 22:00
8th	7.27	69.63	2.42	280°	0.33	7/08/2006 1:00	7/08/2006 21:00	9/08/2006 11:00
9th	7.24	78.15	4.33	260°	0.24	15/06/1999 17:00	18/06/1999 17:00	20/06/1999 1:00
10th	7.09	293.92	13.17	280°	0.31	21/07/1996 23:00	27/07/1996 18:00	4/08/1996 3:00

* NTR : non-tidal residual NTR = Observed sea level (t) - Tide (t) .

It is believed that elevated water levels and large waves associated with storms are a major cause of severe beach erosion. There are a number of other factors which affect the impact of storms on the coastline, particularly with respect to their erosive capability. Storm duration, the incidence of high tides during and immediately after a storm are important examples.

To explore the likelihood of energetic waves coinciding with elevated water levels on the Perth coast the hourly Fremantle NTR data is plotted against the Rottnest significant wave height in Figure 9. The joint occurrence probability contours in Figure 9 show that in general the higher the wave the more likely it coincides with a high NTR. The largest waves (Hs > 7 m) generally correspond to positive NTR up to 0.7m, and the highest NTR surges (NTR > 0.6m) correspond to 3 ~ 7.5 m large waves.

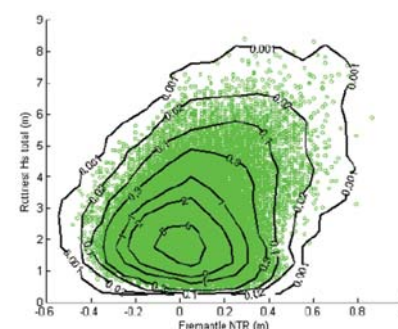


Figure 9. Joint Probability of occurrence (%) between Rottnest significant wave height and Fremantle NTR water level.

Table 2. Top ten storms ranked by total storm wave power (TWP)

Rank	Total wave power (m ² day)	Hs total at storm peak* (m)	Storm duration (day)	Wind dir. at storm peak (deg)	NTR at storm peak (m)	Storm started at	Storm peaked at	Storm ended at
1st	293.9	7.09	13.17	280°	0.31	21/07/1996 23:00	27/07/1996 18:00	4/08/1996 3:00
2nd	195.9	5.74	9.38	230°	0.25	10/07/2000 7:00	11/07/2000 8:00	19/07/2000 16:00
3rd	144.2	8.31	4.0	310°	0.60	15/07/1996 22:00	17/07/1996 3:00	19/07/1996 22:00
4th	137.8	7.61	4.75	240°	0.17	22/08/2004 14:00	25/08/2004 11:00	27/08/2004 8:00
5th	137.5	6.8	5.67	270°	0.44	27/07/2007 18:00	30/07/2007 15:00	2/08/2007 10:00
6th	124.7	6.0	5.71	290°	0.50	4/09/2005 9:00	6/09/2005 3:00	10/09/2005 2:00
7th	123.6	6.95	5.63	290°	0.39	14/09/1996 1:00	15/09/1996 17:00	19/09/1996 16:00
8th	109.0	6.11	4.88	290°	0.23	17/06/1996 14:00	19/06/1996 16:00	22/06/1996 11:00
9th	108.8	6.18	4.88	240°	0.14	20/09/2003 1:00	23/09/2003 1:00	24/09/2003 22:00
10th	105.5	5.74	5.63	230°	-0.07	13/08/2005 6:00	14/08/2005 2:00	18/08/2005 21:00

* definition of storm peak is in Figure 2.

Conclusions

All wave storminess indices for the Perth coastal region show significant variability over the past 14 year period from September 1994 to September 2008. Over the 14 year period there are, on average, around 18 wave storms per year. The severe storm recommended by the Western Australia State Coastal Planning Policy that occurred from 15 to 19 July 1996 is not the most powerful one.

The most severe storm sequence in terms of the total storm power occurred from 21 July to 4 August 1996 with approximately 13 days duration and wave power index of 293.9 [m^2day]. Four of the top ten most powerful storms occurred in 1996. Further investigation is required to examine which storm actually caused the most severe erosion along the Perth coast.

The most frequently occurring sea direction is consistently 240° through the seasons, with significant wave height between 0.5 to 1.0 m, as opposed to the west in winter and south in summer usually assumed by previous wave climate descriptions (Lemm, 1999). The swell density rose shows a single peak mode, while the sea density rose shows a secondary peak at 70° ENE in the opposite direction of the first peak. This phenomenon is largely created by the easterly morning component of summer sea breezes.

The joint occurrence probability between the Rottnest significant wave height and the Fremantle NTR indicates that in general the higher the wave the more likely it occurs coinciding with a high NTR.

The 14-year data span is still too short to detect a climate change trend. There is no convincing evidence of any increase in the intensity or frequency of Perth storms over the period of 1994 to 2008.

Most coastal engineering issues are linked to the storm wave power. Structural damage and erosion/siltation problems are dependant on the amount of energy reaching the shore. Future research and data analysis are required to explore the link between global climate change and climate variability indices and the local wave climate in the Perth region. The outcome may help to extend our relative short wave records with the much longer wind and Southern Oscillation Index records.

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References

- BoM, Bureau of Meteorology. 2008. Tropical Cyclones Affecting Perth.
<http://www.bom.gov.au/weather/wa/sevwx/perth>.
- Dolan, R., and R. E. Davis, 1992 An intensity scale for Atlantic coast northeast storms. *J. Coastal Res.*, 8, 352–364.
- Dorsch, W. Newland, T., Tassone, D., Tymons, S. and Walker, D. 2008. A Statistical Approach to Modelling the Temporal Patterns of Ocean Storms. *Journal of Coastal Research* vol. 24, 1430–1438.
- DPI. 2004. Port Beach Coastal Erosion Study, Technical Report, Report No. 427, Department for planning and infrastructure, Western Australia.
- Ferreira, O., 2005. Storm groups versus extreme single storms: predicted erosion and management consequences. *Journal of Coastal Research*, Special Issue No. 42, pp. 221–227.
- Hemer, M. A., Church, J. A., and Hunter, J. R. (2007). Waves and climate change on the Australian coast. *Journal of Coastal Research*, (50): 423–437.
- Larson, M. and Kraus, N. 1989. SBEACH: Numerical Model for Simulating Storm-Induced Beach Change. Tech. Report CERC-89-9, US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS, USA.
- Lemm, A.J.; Hegge, B.J., and Masselink, G., 1999. Offshore wave climate, Perth (Western Australia): 1994–1996. *Marine and Freshwater Research*, 50, 95–102.
- Masselink, G. & Pattiaratchi, C. B. 2001b, 'Characteristics of the sea breeze system in Perth, Western Australia, and its effect on the nearshore wave climate', *Journal of Coastal Research*, vol. 17, no. 1, pp. 173–187.
- Morton, I.D.; Bowers, J., and Mould, G., 1997. Estimating return period wave heights and wind speeds using a seasonal point process model. *Coastal Engineering*, 31, 305–326.
- MRA. 2000. *Port Beach Coastal Management, R083 Rev 0*. Prepared for Fremantle Port Authority.
- Pattiaratchi, C., Hegge, B., Gould, J. & Eliot, I. 1997, 'Impact of sea-breeze activity on nearshore and foreshore processes in southwestern Australia', *Continental Shelf Research*, vol. 17, no. 13, pp. 1539–1560.

- Pattiaratchi and Eliot 2008 Sea Level Variability in South-West Australia: From Hours To Decades Proc. of the 31st ASCE International Conference on Coastal Engineering, Hamburg, Germany 2008.
- Schmith, T., Kaas, E., Li, T.-S., 1998. Northeast Atlantic winterstorminess 1875–1995 re-analysed. *Climate Dynamics* 14, 529–536.
- WAPC (Western Australian Planning Commission), 2003. State Planning Policy 2.6 State Coastal Planning. <http://www.wapc.wa.gov.au/Publications/139.aspx>.
- Wise, R A, Smith, S J & Larson, M 1996. SBEACH: Numerical Model for Simulating Storm-Induced Beach Change. Report 4, Cross-shore transport under random waves and model validation with SUPERTANK and field data. Technical Report CERC-89-9 rept. 4. Coastal Engineering Research Centre, Vicksburg, MS.
- Zhang, K., Douglas, B.C. and Leatherman, S.P. 2000. Twentieth-Century storm activity along the U.S. East Coast. *Journal of Climate* 13: 1748–1761.