

Australian Height Datum (+0.756m above Chart Datum), unit: metre. DCH38: Cottesloe Waverider, FTG: Fremantle Tide Gauge, RWS: Rottnest Wind Station, RDW47: Rottnest Directional Waverider.

Wind climate in Perth has a strong seasonal variation. In winter, the region experiences strong westerly and north-westerly winds, blowing with a mean speed of 10 to 15 m/s and frequent storms. In summer, there are fewer storms and the wind has more south and south-westerly occurrences. The area is subjected to one of the strongest and most consistent sea breeze systems in the world (Pattiaratchi et al, 1997). The sea breeze velocities frequently exceed 10 m/s in the summer months. Half-hourly wind data from Rottnest Island wind station (marked RWS in Figure 1), with mean wind speed and direction at 10 m above sea level, was obtained from the Bureau of Meteorology.

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 that tidal range of about 1.1m with non-tidal variations having the same order of magnitude as tidal variations.

Most Australian storminess studies have focused on east coast (Short and Treneman, 1992, Lord and Kulmar, 2000, Goodwin, 2005, Phin, 1992, You, 2005, Patterson, 2007). On the Western Australian coast the published research is scarce (Lemm, 1999, Barr, 2004, Travers, 2007). In the past, due to the absence of extended wave datasets, water level residuals and wind hindcast data were often used as a storminess proxy (Lemm, 1999, Pattiaratchi and Eliot 2007). However, the appropriateness of such substitution remains to be verified. The Rottnest Island wave dataset and the availability of wind, air-pressure and water level datasets for the same time period provide us with a unique opportunity to address this issue. This study reviewed and compared the Perth storminess by different indicators. It marks the first step of a Department for Planning and Infrastructure (DPI) project intending to improve our understanding of storminess and its inter-annual variability around the Western Australian coast. The correlation analysis of

the common used storminess indices provides an objective assessment on the appropriateness of using other datasets to extend the relatively short wave records. It will also help to validate/invalidate the climate change hypotheses.

Available data

Four datasets were selected for Perth coastal region storminess analysis:

- a) significant wave height (H_s) for total waves, collected southwest off Rottnest Island ($32^{\circ} 05' 39''S$, $115^{\circ} 24' 28''E$), by the DPI, Western Australia;
- b) 10-minute-mean wind speed and direction data at 10 m above sea level on Rottnest Island ($32.0069^{\circ}S$, $115.5022^{\circ}E$), obtained from Bureau of Meteorology;
- c) 10-minute-mean air-pressure data at mean sea level (MSL) on Rottnest Island ($32.0069^{\circ}S$, $115.5022^{\circ}E$), obtained from Bureau of Meteorology;
- d) Water level data collected at a tide gauge inside Fremantle Fishing Boat Harbour ($32^{\circ} 03' 56''S$, $115^{\circ} 44' 53.3''E$) by DPI.

Considering the availability of the wave, wind, air-pressure, and water level records, and avoiding the bias that can result from missing data or superfluous counting of extra seasons a maximum of 14 years was selected for this analysis. For wind and water level data the time window selected is from 1st Sep. 1994 to 31st Aug. 2008. The cut-off date for the wave and air-pressure datasets is from 21st Sep.1994 to 20th Sep. 2008. This selection secures a four year directional wave dataset from 21st Sep. 2004 to 20th Sep. 2008.

Data preparation

As will most wave recordings the Rottnest wave dataset has gaps. 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 with the missing data lasting longer than three days. The maximum 35-day gap occurred from 25 Aug. to 15 Sep.

2005. Ignoring these data gaps would have 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).

The selected wind and water level datasets largely cover the same period of wave and air-pressure data, with 99.6% overlapping. The wind dataset is in its original half-hour time interval. The Fremantle Non-Tidal Residual (NTR) is calculated by subtracting the predicted tidal signals from the observed half-hourly water levels. The calculated NTR is affected by storm surges, changes in mean sea level (MSL), atmospheric pressure, continental shelf waves, baroclinic flow, barotropic flow, the Leeuwin Current, temperature and ENSO.

The continuity of wind, pressure and water level datasets is better than the wave data. Therefore only linear interpolation was used for filling the gaps in these datasets.

Storm identification and storminess indices

Coastal storminess is a widely used indicator for coastal erosion and climate change. However, so far there is no universally accepted definition. Most meteorologists use the number of storm/cyclone systems with wind speed greater than a certain threshold or central air-pressures of less than 1000hPa. Coastal engineers commonly use numbers of hours, or number of storm events, when wave height is higher than a certain value (Barr, 2004, Lemm, 1999, Goda, 1988). Others use the number of hours, or number of events, when water level is higher than a certain level (Pattiaratchi and Eliot 2007, Zhang, 2000, Eliot et al 1986).

In the past, arbitrary criteria were commonly used as the threshold for storm identification. For example $H_s > 4.0\text{m}$ (Lemm, 1999), $H_s > 1.5\text{m}$ (Dolan and Davis, 1992) wind speed $> 15.3\text{ m/s}$ (Lozano, et al 2004), wind speed $> 15\text{ m/s}$ (Travers, 2007). These threshold values generally corresponded to a low percentage of exceedance in their datasets. In this study the selection of thresholds for different datasets follows the statistical method used by Zhang, et al. (2000), which chose storm surge greater than two standard deviations as the criterion to determine a major storm event. The use of a statistical threshold simplifies the comparison of storminess indices across the four datasets.

If the datasets were normally distributed then two standard deviations away from the mean would account for approximately 95 percent of the samples. However, none of our four datasets are strictly in a normal distribution. For our four datasets two standard deviations above the mean roughly equals 5 % exceedance.

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

- 1) 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);
- 2) 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;
- 3) 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.

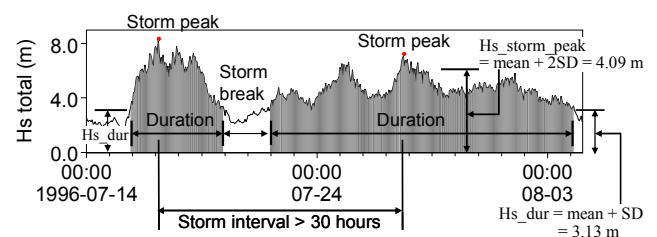


Figure 2. Storms defined as events during which the significant wave height exceed 4.09 m and duration calculated as the Hs above 3.13 m

Figure 2 uses the Rottneest July 1996 wave record 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:

$$P = \sum (H_{S_{Rottneest}}^2 * \Delta t) \quad (1)$$

where $H_{S_{Rottneest}}$ is the hourly significant wave height in metres, Δt is the wave data interval in days, for hourly dataset, $\Delta t = 1/24$ day. This index was first introduced by Dolan and Davis (1992) and 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.

In this study nine of the most commonly used storminess indices based on wave, wind, air-pressure and water level data 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 number of storm events determined by Rottneest wind speed, $V_{10_dur} = 10.7$ m/s and $V_{10_storm_peak} = 13.85$ m/s.
- 3) Annual number of storm events determined by Rottneest air-pressure at MSL, $PP_dur = 1010.0$ hPa and $PP_storm_peak = 1003.8$ hPa.
- 4) Annual number of storm events determined by Fremantle NTR, $W_dur = 0.17$ m and $W_storm_peak = 0.31$ m.
- 5) Annual storm hours determined by Rottneest wave height $H_s > 4.09$ m.
- 6) Annual storm hours determined by Rottneest wind speed $V_{10} > 13.85$ m/s.
- 7) Annual storm hours determined by Rottneest MSL air-pressure $PP < 1003.8$ hPa.
- 8) Annual storm hours determined by Fremantle NTR data $W > 0.31$ m.

9) Annual total storm wave power (ATWP) m^2/day calculated by Eq. (1).

Storminess analysis results

Figure 3 presents the identified storm sequences from wave dataset. The temporal variability of storminess calculated by each dataset is significant both seasonally and inter-annually.

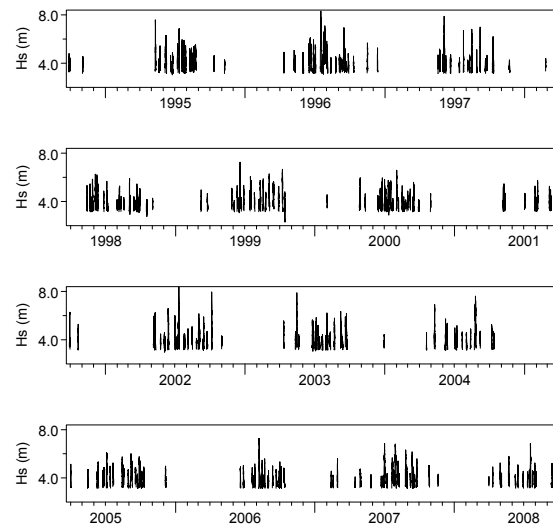


Figure 3. Identified storm sequences from the hourly Rottneest total significant wave height dataset (from 21 Sep. 1994 00:00 am to 20 Sep. 2008 23:00 pm) $H_{s_storm_peak} = 4.09$ m, $H_{s_dur} = 3.13$ m.

Intra-annually the Rottneest Island wave dataset shows that the stormiest season is in June, July, August, and September. From 1995 to 2008 no storms occurred in January, with the relatively calm season occurring from November to March (Figure 3). The storms defined by the Rottneest Island wind dataset are more spread out through the seasons. However, the strongest winds clearly occur more frequently in June, July and August. The same trend applies to Fremantle NTR dataset. The only exception to this trend is for storm events identified by the Rottneest air-pressure. More low-pressure systems appear during the summer, although the storms in winter tend to be stronger in terms of having lower air-pressures.

Figure 4 plots total wave power (TWP) in an unit of $[m^2/day]$ for each individual storm sequence based on the Rottneest total significant wave height dataset. This index is a good measure of single storm intensity.

Although under the pressure of sea level rise and temperature rise there is no evidence showing any trend for increased extreme storm power over the studied time period.

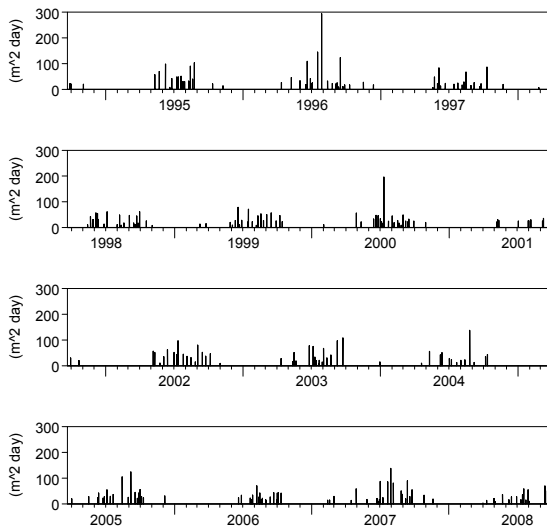


Figure 4. Total storm power index, P , in m^2 day based on the hourly Rottnest significant wave height dataset (from 21 Sep. 1994 00:00 am to 20 Sep. 2008 23:00 pm) $H_{s_storm_peak}=4.09$ m, $H_{s_dur}=3.13$ m.

Figure 5a shows inter-annual variability of annual storm hours identified by four different datasets. Over the study period there is no consistent trend of change in those annual storm hour indices except the annual low air-pressure hour index. There is a convincing trend of decline in the annual low pressure hours from 1995 to 2007 calendar year. This is in consistent with the trend of rainfall decline in WA. The most variable dataset is the index of annual total NTR storm surge hours, with the stormiest year 1999, having 628.5 surge hours. The correlation between the storm hours defined by Fremantle NTR and the storm hours defined by Rottnest total wave heights is weak.

The numbers of annual storm event indices are presented in Figure 5b, which exhibit less variability than the annual storm hour indices. The least variable index is the storm wind event. It rarely varies more than 20% from its mean value of 47 storms per year. On average the Perth region experiences 18 wave storm events, 21 NTR surges, and 47 strong wind storms annually. The region also experiences 432, 344, 176 and 240 storm

hours per year in term of wave height, wind speed, air-pressure and NTR respectively. In general, the comparison provides little evidence that a storminess index based on Fremantle NTR is indicative of Perth region wave storminess.

The 1996 is ranked as the stormiest year by three out of nine indices. Year 2000 and 2007 also frequently appear in the top rankings of different indices. On the other hand, year 2001 and 2006 are regarded as relative calm by many of the indices.

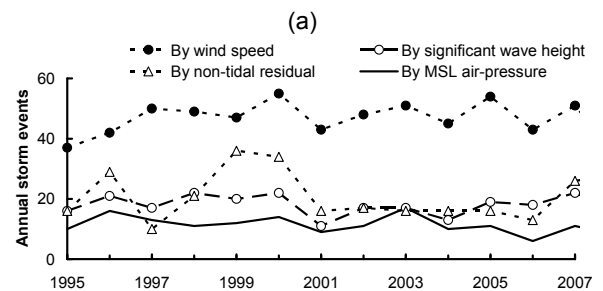
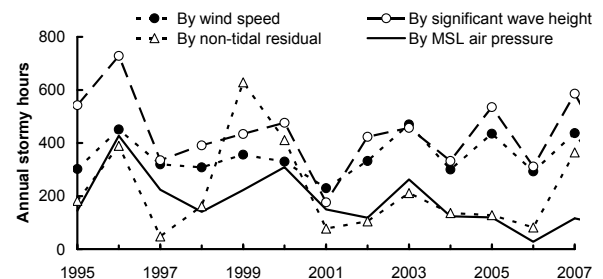


Figure 5. Annual storminess defined by a) stormy hours, b) number of storm events. Storm is determined by i) half-hourly mean wind speed at Rottnest exceeding 13.85 m/s (mean+2SD), ii) hourly total significant wave height at Rottnest exceeding 4.09 m (mean+2SD), iii) hourly MSL air-pressure at Rottnest lower than 1003.8 hPa (mean-2SD), iv) half-hourly non-tidal residual water level at Fremantle fishing harbour exceeding 0.31 m (mean+2SD).

To make comparisons easier the storminess indices are standardized by dividing by their mean values. In Figure 6, three normalised annual storminess indices calculated from the Rottnest wave dataset are compared. This comparison reveals a consistency among the storminess indices defined by annual number of wave storm events, annual storm wave hours, and annual total storm wave power. The close correlation between annual total storm wave power and the storm wave hours confirms that ATWP is a good measure of annual storminess for the Perth coast.

Similarly the normalised annual NTR surge hours and number of NTR surge events also correlate well, as shown in Figure 7. Remarkably, from 2001 to 2006, there were six consecutive years of lower than average storminess in both indices of NTR surge events and NTR surge hours (Figure 7).

Finally, the storminess indices defined by Rottnest wind and air-pressure records have a much poorer consistency. In the 1996 calendar year the storm wind hour index shows 30% more hours than average, however, the wind storm event index indicates 11% lower than average storminess.

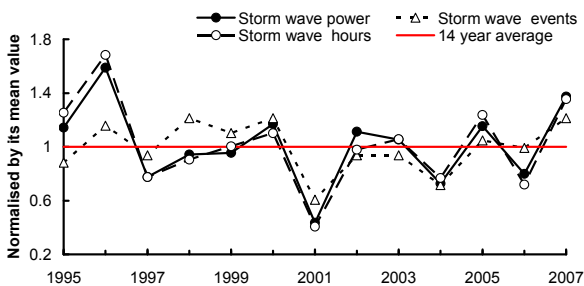


Figure 6. Normalised annual (calendar year) wave storminess indices, i.e. annual value divided by its 14-year (from 21 Sep. 1994 to 20 Sep. 2008) mean value.

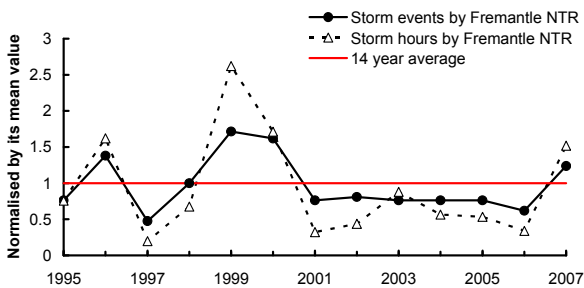


Figure 7. Normalised annual (calendar year) NTR storminess indices, i.e. annual value divided by its 14-year (from 1st Sep. 1994 to 31 Aug. 2008) mean of Fremantle NTR records.

Correlations across datasets and links with Southern Oscillation Index

As a preliminary study a linear correlation analysis between the annual storminess indices, as well as the Southern Oscillation Index (SOI), was conducted. The SOI is a widely used index describing an irregular fluctuation of the atmospheric circulation system across the Indian-Pacific region. It

was found that four pairs of indices have strong correlations, which are: i) Annual total storm wave power and Annual total storm wave hours, $CC=0.98$; ii) Annual total storm wave hours and Annual total storm wind hours, $CC=0.77$, (Figure 8) ; iii) Annual total storm wave power and Annual total storm wind hours, $CC=0.76$, (Figure 8); and vi) SOI index and Annual total NTR surge hours, $CC=0.71$ (Figure 9);

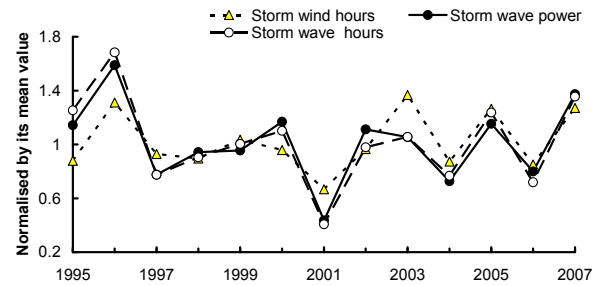


Figure 8. Correlation between normalised annual wind storm hours and the annual total storm wave power.

The strong link between the SOI index and Annual total NTR surge hour index confirms the speculation that the Fremantle NTR is also strongly affected by ENSO, as is the Fremantle mean sea level (Feng et al, 2004). Feng, et al (2004) found that there are high Fremantle sea levels during positive SOI (with more frequent La Niña events) and low sea levels during negative SOI (with more frequent El Niño events). Our preliminary results show that the annual Fremantle NTR surge hour index is also well synchronized with SOI index (Figure 9). There are decreased hours of NTR surge in El Niño years (2002 to 2006, for example) and increased hours in La Niña years (2000 and 2007, for example)

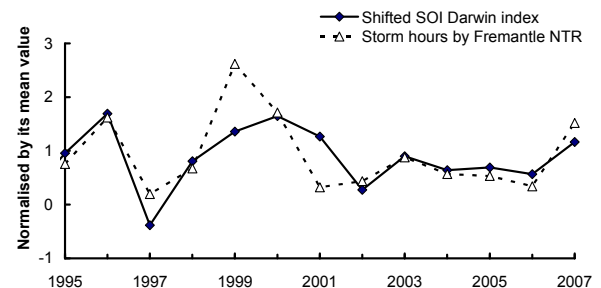


Figure 9. Correlation between the reversed SOI index and the normalised annual storm surge (NTR) hours at Fremantle.

Caution must be taken when using NTR indices for storm surge analysis. NTR data does contain storm surge information but it also contains many processes that do not relate to storminess. In the Perth region, for example, continental shelf waves and the Leeuwin Current variability are significant contributors to the non-tidal sea level fluctuations.

Conclusions

The temporal distributions of storms in the Perth region are documented by analysing different type of datasets. All storminess indices for the Perth coastal region show significant inter-annual variability over the 14 year period from 1994 to 2008. The variations are up to $\pm 60\%$ in term of annual storm wave hours, 160% in term of annual NTR surge hours, and $\pm 35\%$ in terms of annual wind storm hours.

Annual storm wave hours and annual storm wind hours at Rottnest are closely correlated. However, the annual storm hour index, based on Fremantle NTR, does not follow the same trend.

The four indices of annual number of storm events, defined by Fremantle NTR, Rottnest Hs, Rottnest air-pressure, and wind speed, are less variable than the storm hour indices. Again the annual storm event numbers based on Fremantle NTR are more variable than those based on significant wave height and wind speed. For a 14-year average there are 47 wind storms, 21 NTR surge storms, 18 wave storms, and 11 low-pressure storms every year by the chosen storm identification method.

From 2001 to 2006 there were six consecutive years of lower than average storminess in both NTR surge events and surge hours. The Fremantle NTR records clearly indicate an increase of NTR surge from 2007 after seven consecutive calm years followed the previous storm surge maximum in 1999.

The close correlation between annual total storm wave power and the storm wave and wind hours has confirmed that annual total storm wave power is a good measure of annual storminess for the Perth coast.

The 14-year data span is still too short to detect climate change trend. There is no convincing evidence that a consistent trend of change in Rottnest storm intensity (TWP) and frequency (number of annual wave storm events), except the storm hour index defined by air-pressure data, which is obviously in a decline trend.

The temporal consistency of wave storminess indices with their NTR counterparts is limited. The correlation between the storm hours defined by Fremantle NTR and the storm hours defined by Rottnest total wave heights is weak.

Further research and data analysis are required to explore the link between global climate change and climate variability indices and the local wave climate in Perth region. And the outcome may help to extend our relative short wave records with the much longer wind and SOI indices

Acknowledgments

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Biography

Fangjun Li is a Project Manager at Department for Planning and Infrastructure, WA. She is responsible for research and advice on climate change with respect to future coastal engineering solutions and coastal vulnerability in WA. Before joining DPI she worked with CSIRO Petroleum Resource for seven years as a Research Scientist and Project Leader. She obtained her PhD (Civil Engineering) at the University of Western Australia in 2001, Master of Coastal engineering at Dalian University of Technology, China in 1988.

Fangjun has experience in coastal and offshore engineering, sediment transport modelling, geomorphology and oceanography. From 2003 to 2008 she was heavily involved in a CSIRO Wealth from Oceans Flagship Program for assessment of long-term Australian seabed responses to climate change. She has authored and co-authored over 30 fully refereed journal and conference papers and several CSIRO reports on a wide range of engineering and scientific topics.