NSW Coastal Storms and Extreme Waves

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Abstract

The NSW coast is subject to a generally moderate wave climate periodically affected by large wave events originating from coastal storm systems. Such events, particularly when they occur coincidently with high water levels, may cause coastal inundation, beach erosion, damage to property and marine structures, and risks to public safety.

Following a series of intense and damaging storms in 1974, a network of wave buoys was incrementally established along the NSW coast by the NSW Department of Public Works. Data from this wave buoy network now extends up to 35 years, providing a valuable long-term record of wave climate and extreme events. A recent study undertaken by the Water Research Laboratory (WRL) and Macquarie University (Shand et al., 2010), with support from the NSW Dept. of Environment, Climate Change & Water (DECCW) and Manly Hydraulics Laboratory (MHL), has sought to classify coastal storms affecting the NSW coastline over this time and to estimate the statistical distribution of extreme storm wave heights for a range of storm durations.

This paper presents a summary of study findings including discussion of the climatology of major storm systems causing large wave events on the NSW coast and trends in the spatial and temporal distribution of these storms.

Introduction

The NSW coast is subject to a generally moderate wave climate predominantly from the south to south-east. Previous studies have found an average offshore significant wave height of between 1.5 to 1.6 m and average peak period of 9.4 to 9.7 s (Lord and Kulmar, 2000). This generally moderate wave climate is periodically affected by large wave events originating from coastal storm systems. These storms vary both spatially and temporally in their genesis, intensity and track. Very large storm events such as occurred in 1974 (*'Sygna Storm'*), 1997 (*'Mothers Day Storm'*) and 2008 (*'Pasha Bulker Storm'*) occasionally impact the coastline and, particularly when they are co-incident with high water levels, may cause widespread coastal inundation, beach erosion, damage to property and marine structures, and risks to public safety (Figure 1). Accurate estimation of the likelihood and magnitude of large wave events is essential for the quantification of extreme beach erosion and inundation, design of nearshore structures, and longer term coastal hazard assessment.

After a series of intense and damaging storms in 1974, a network of wave buoys has been incrementally established along the NSW coast with the present network consisting of seven buoys. Data from these buoys is collected by MHL for the DECCW. Analysis of wave records, collected over a sufficient time period, allows quantification of extreme wave heights and, using appropriate extreme values analysis, characterisation of large, low probability wave events. These low probability events are generally described by either their average recurrence interval (ARI) or return period (RP), both of which describe the average time interval between events exceeding a particular magnitude.

There have been several studies undertaken to estimate extreme wave heights along the NSW coast. (PWD, 1985; 1986) evaluated historical storm events between 1880 and 1985 based on historical charts, weather bulletins and reports, newspapers and other studies. Derived extreme wave heights were found to generally increase from south to north, with the derived 100 year ARI significant wave height on the north coast estimated at between 12.3 and 12.6 m depending on the selection of extreme value distribution. Lord and Kulmar (2000) presented an analysis of wave buoy data at all buoys up until 1999 including evaluation of extreme wave heights for Byron Bay, Sydney and Eden for events of between one and 24 hour duration. The estimated 100yr ARI, significant wave height with a one hour duration for Byron Bay is 7.8 m, for Sydney is 8.6 m and for Eden is 9.3 m. This indicates a reverse spatial trend from the PWD (1985; 1986) studies and a significant reduction in design wave height.

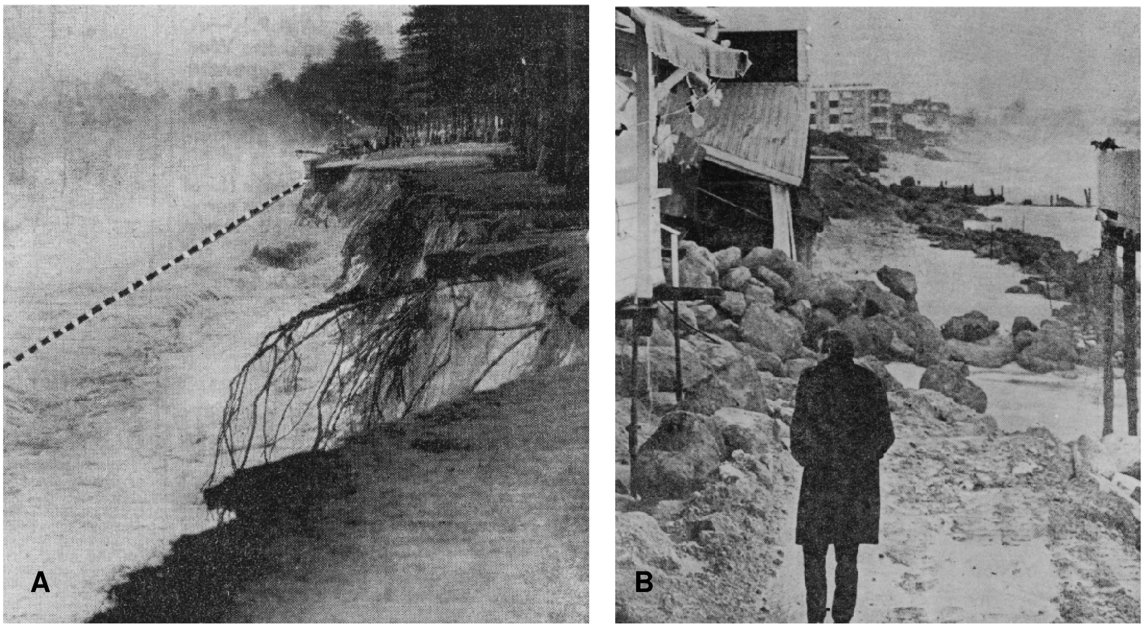

Figure 1: (A) Erosion at North Steyne during June Storms in 1950 (Daily Telegraph, 27/06/1950); (B) Erosion at Collaroy Beach, 1967 (The Sun, 05/09/1967)

COASTAL WAVE DATA

Sources of data used to provide quantitative information on wave heights along the NSW coast included nine wave buoys spanning 1971 to present (seven administered by DECCW, one by Sydney Ports and one by Queensland DERM), the (US) Oceanic and

Atmospheric Administration (NOAA) Wavewatch III Numerical Hindcast spanning 1997 to present and the European Centre of Medium-Range Forecasting (ECMRF) WAM-cycle 3 ERA-40 Hindcast spanning 1957 to present. Locations of these wave buoys and numerical grids are shown within Figure 2.

Wave buoy locations, date range, data capture rate (%) and effective record length (product of the total record length and the total data capture) are presented within Table 1. Data has been captured by the wave buoy network at intervals of 12, 6 and 1 hour since commission, although from 1984 all MHL wave buoys captured data at 1 hour intervals. The total data capture rate for the wave buoys ranges from 73.1% at Byron Bay to 89.7% at Batemans Bay.

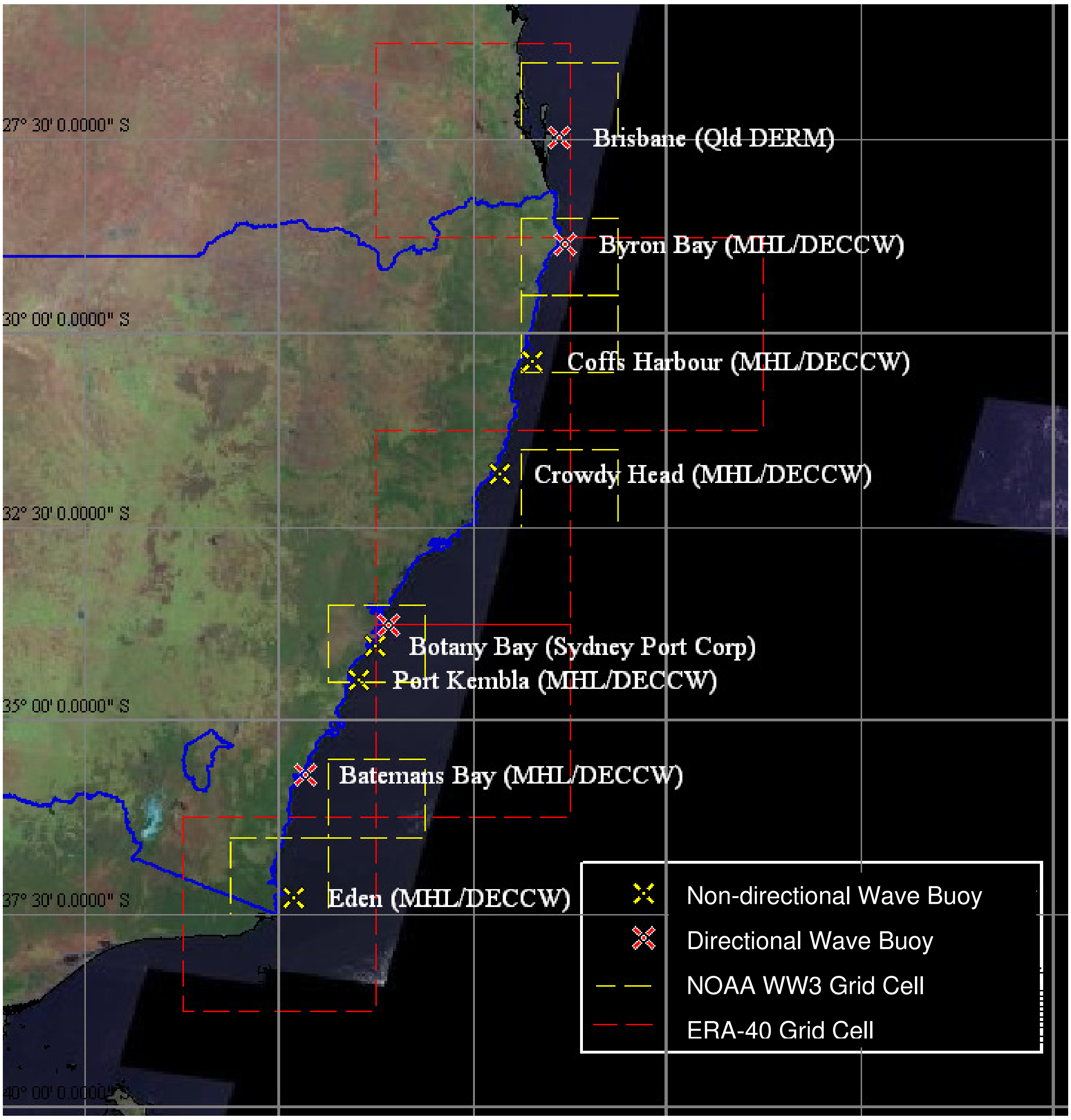

Figure 2: Location of nine wave buoys and numerical output grids on the NSW and SE Queensland Coast.

Table 1: List of Wave Buoys and Locations used within the Present Study

Site	Present Location	Water Depth (m)	Administered by	Buoy Type	Date Range	Total Capture (%)	Effective Record Length (yrs)
Brisbane	153° 37.5' E 27° 28.1' S	76	Queensland DERM	Directional Waverider	Oct 1976 – Dec 2009	85.9	28.5
Byron Bay	153° 42.1' E 28° 51.2' S	62	MHL/DECCW	Directional Waverider	Oct 1976 – Dec 2009	73.1	24.3
Coffs Harbour	153° 16.1' E 30° 21.4' S	72	MHL/DECCW	Waverider	May 1976 –Dec 2009	84.7	28.5
Crowdy Head	152° 51.6' E 31° 49.5' S	79	MHL/DECCW	Waverider	Oct 1985 – Dec 2009	85.6	20.7
Sydney	151° 25.0' E 33° 46.3' S	92	MHL/DECCW	Directional Waverider	Aug 1987 –Dec 2009	84.5	19.0
Botany Bay	151° 15.1' E 34° 02.3' S	73	Sydney Ports Corporation	Waverider	Apr 1971 – Dec 2009	87.7	34.0
Port Kembla	151° 01.6' E 34° 28.5' S	80	MHL/DECCW	Waverider	Feb 1974 – Dec 2009	85.1	30.6
Batemans Bay	150° 20.6' E 35° 42.2' S	73	MHL/DECCW	Directional Waverider	May 1986 –Dec 2009	89.7	21.2
Eden	150° 11.1' E 37° 18.1' S	100	MHL/DECCW	Waverider	Feb 1978 – Dec 2009	83.5	26.6

Descriptive Statistics

Wave height exceedance plots for all buoys are presented within Figure 3 and seasonal and mean significant wave height (A), peak spectral period (B) and peak spectral direction (C) are presented in Figure 4.

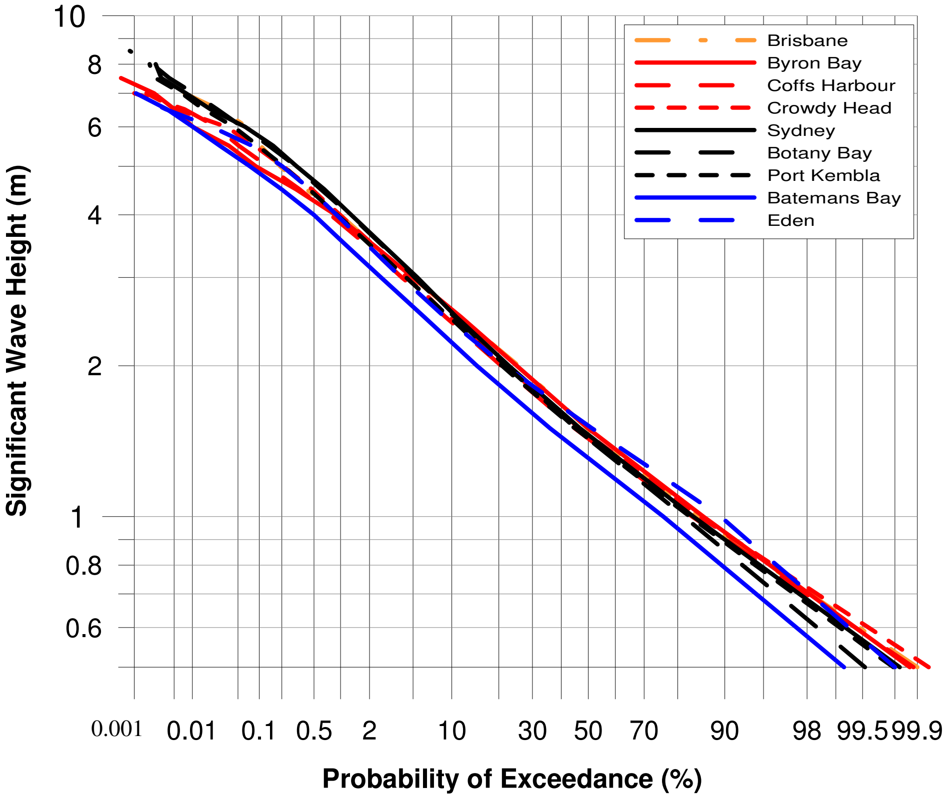

Figure 3: Hourly Significant Wave Height Exceedance for New South Wales and Brisbane Wave Buoys

While a more complete statistical description of the NSW wave climate is provided within Shand et al. (2010), Figure 3 shows that the median (50% exceedance) significant wave height along the NSW coast ranges from 1.30 m at Batemans Bay to 1.52 m at Eden. With the exception of Batemans Bay, all buoys are relatively uniform. More significant along-coast variation in mean H_{sig} is observed seasonally, with larger waves occurring in the north during autumn and lower waves occurring during spring and summer. Wave height in the south is more uniform year-round. The 1% exceedance and maximum observed H_{sig} are highest at Sydney and Botany Bay, with a maximum H_{sig} of 8.86 m observed at Botany Bay, followed by Sydney and Port Kembla at 8.43 m.

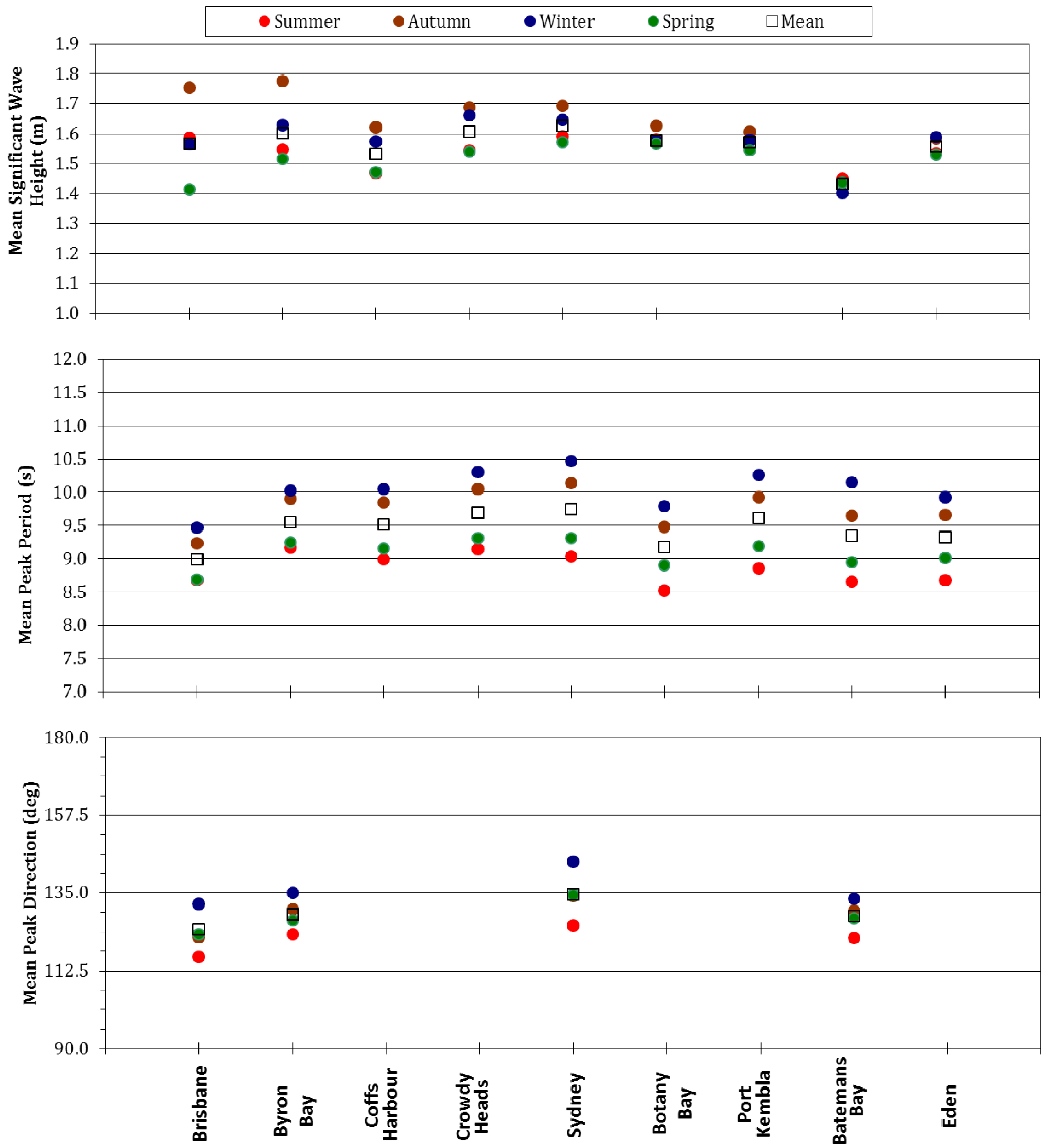

Figure 4: Seasonal And Overall Mean Wave Statistics

Mean peak wave period (T_{p1}) is relatively consistent along the NSW coast ranging from around 9.3 s to 9.7 s although it displays seasonal variation of 1.0 to 1.5 s. Period increases at all buoy locations during autumn and winter and decreases during spring and summer. This change is representative of the seasonal changes in wave generation systems further discussed in following sections.

Mean peak wave direction is more easterly at the northern buoys (123° at Byron Bay) and becomes slightly more southerly at the southern buoys (135° in Sydney). Seasonal variation of 10 to 20° is observed, with a more southerly mean peak wave direction in winter and a more easterly direction in summer. Waves of greater than 5 m occur more commonly from the east to east-south-east in the northern buoys and from the south-south-east to south-east in the southern buoys. This is reflective of the storm systems responsible for generation of large waves discussed further in the following sections.

Defining Storm Events

A key component of this present study is evaluating the distribution of extreme, long-duration storm events rather than simply the yearly maxima. The peaks over threshold (PoT) method was therefore used to analyse the wave data and define storm events. An initial PoT analysis was undertaken for H_{sig} > 2.0 m with a minimum exceedance duration of three days. A second PoT analysis was then undertaken with a higher threshold of H_{sig} > 3.0 m. Thus storms with H_{sig} > 2.0 m and duration greater than three days were identified, as well as storms of any duration with H_{sig} > 3.0 m. This ensures that enough long duration storm events were captured for extrapolation of extreme wave heights and avoids generation of an excessive number of small and short duration events. You (2007) found the estimated extreme wave height to be largely insensitive to variation in the adopted threshold of between 3.0 and 4.5 m. A minimum interval between storms was set at one day. This prevents single storms being split into two or more events if wave height temporarily drops below the threshold.

While missing data within a storm event has been noted, no new data was synthesised as this would introduce a somewhat subjected component to the dataset. Only data missing during the largest events is expected to substantially influence the estimated extreme wave climate This may have occurred at Byron Bay where a number of large events may have been excluded or reduced values obtained, possibly due to buoy submergence under steep wave crests (Bettington and Wilkinson, 1997).

A summary of detected storm events for each of the NSW wave buoys is presented within Table 2 and Figure 5. A complete *Storm History Table* detailing storm characteristics for each storm event detected on the NSW Coast by wave buoys between 1971 and 2009 is presented by Shand et al. (2010). Figure 5 shows the central NSW coast to be subject to the highest number of storm events per year as well as the largest mean and maximum storm peak height. The largest storm on record is the *'Mother's Day'* storm which occurred in May 1997. The storm peaked during the night of the 10^{th}-11^{th} May, with H_{sig} reaching 8.43 m at both Sydney and Port Kembla and 8.86 m at Botany Bay. Peak H_{sig} decreased to the north and south, reaching 5.9 m at Eden and 5.6 m at Coffs Harbour. The Batemans Bay buoy did not log data between 11pm on 8^{th} May and 2 pm on 14^{th} May, 1997. The largest storm event by total storm power was the 'Pasha Bulker Storm' which occurred in June 2007 (Watson et al., 2007). This storm reached a peak H_{sig} of 6.90 m in Sydney but remained elevated over 3 m for 8 days and over 5 m for nearly 2 days.

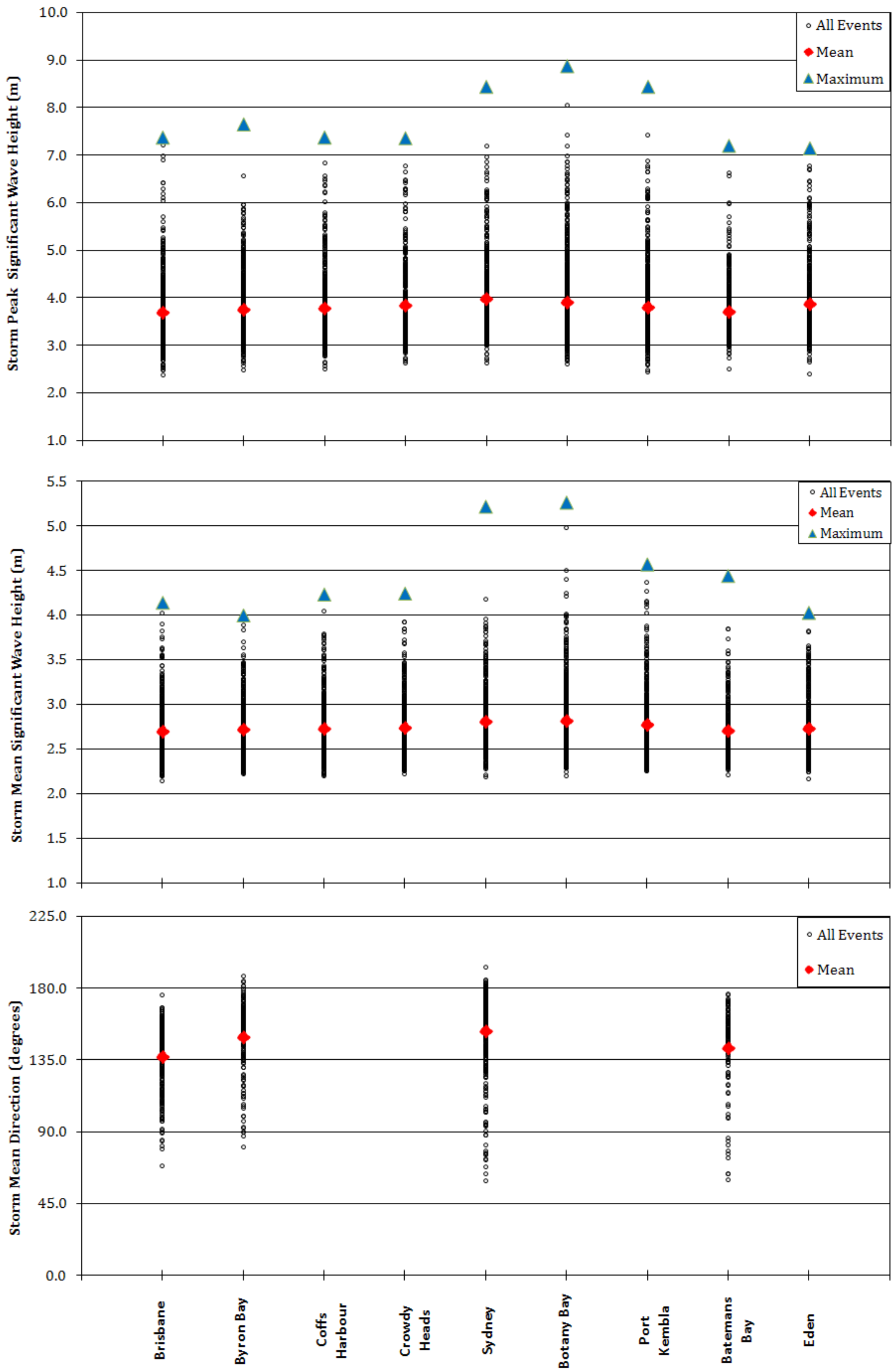

Figure 5: Storm Peak (A) and Mean (B) H_{sig} and Mean Spectral Direction (C)

Table 2: Summary of Storm Events Detected at Each Wave Buoy

Data source	Number of detected storm events	Effective Record length (years)	Average number of storms/ year	Maximum storm peak wave height $(H_{sig})_{peak}$	Mean storm peak wave height $(H_{sig})_{peak}$	Mean storm duration (hours)
Brisbane	456	28.5	16.0	7.36	3.69	90
Byron Bay	495	24.3	20.4	7.64	3.75	74
Coffs Harbour	454	28.5	15.9	7.37	3.78	72
Crowdy Head	390	20.7	18.8	7.35	3.84	73
Sydney	451	19.0	23.7	8.43	3.98	64
Botany Bay	751	34.0	22.1	8.87	3.91	63
Port Kembla	594	30.6	19.4	8.43	3.80	64
Batemans Bay	318	21.2	15.0	7.19	3.71	57
Eden	441	26.6	16.5	7.14	3.87	68

NSW COASTAL STORM CLIMATOLOGY

The NSW coast spans the southern Coral Sea to the Southern Tasman Sea across the sub-tropical to mid-latitude zone. Extreme wave energy is mainly generated within the Coral Sea and Tasman Sea window, but can also be generated from outside this zone: in the South – West Pacific tropics; and, in the Southern Ocean in the extra-tropics. Aspects of the modal wave climate for the NSW coast have been previously described by Short and Trenaman (1992), Lord and Kulmar (2000), numerous NSW PWD and MHL reports, including an annual wave climate summary, Hemer et al. (2007) and Callaghan and Helman (2008) amongst others.

Due in part to their rapid intensification and complexity, East Coast Cyclones (ECC) have proven difficult to both forecast and categorise. The Australian Bureau of Meteorology (BOM) used seven different storm categories to compile their NSW maritime low database, while the PWD report used a different six categories. Holland et al. (1987) discussed three types of ECC events and Hopkins and Holland (1997) used a different eight classifications. As there is no broad consensus on what constitutes an ECC, discrepancies exist between these reports. Definitions used to classify storms in this study was based on the synoptic classification in Browning and Goodwin (in review) that resulted in 8 storm types that are presented in Table 3.

The synoptic type was assigned to each defined event using the NCEP-NCAR Reanalysis (NCEP) pressure dataset from 1948 to 2009 (Kalnay et al., 1996). The types were determined using the 1000 hPa (surface) and 500 hPa pressure field data. The assigned type for each storm event was based on the synoptic genesis of the storm and the synoptic pattern at the time of the observed peak wave climate. The storm types often are transformed as they move eastwards or southwards in the Tasman Sea region. Whilst most synoptic type classifications were unambiguous, some were complicated by factors such as change in storm type during wave generation, multiple simultaneous swell generating weather systems.

Table 3 Storm Type Definitions

Number	Abbrev	Full Name	Description
1	TC	Tropical Cyclone	Swell related to named Tropical Cyclones forming in the Coral Sea between 5-10° latitude.
2	TL	Tropical Low	Low pressure systems forming in the Coral Sea but not reaching the low pressure intensity of a named tropical cyclone
3	AI	Anti-Cyclone Intensification	Form when a high across the Tasman Sea directs onshore E to SE winds to the coast
4	ETL	Easterly Trough Low	Primary type of ECC. Cyclonic depressions that initially form as a trough in the easterly flow along the Queensland / Northern NSW coast. These storms move parallel to the coast and often intensify rapidly causing significant damage
5	CL	Continental Low	Storms originating in Western Australia of the Great Australian Bight and moving overland, often re-intensify upon crossing the east coast
6	ITL	Inland Trough Low	Originate in the quasi-permanent low pressure trough over inland Qld, their movement to the east coast is often associated with STL
7	SSL	Southern Secondary Low	Form as a cut off low in the wake of a cold front in the mid-latitude westerly circulation
8	STL	Southern Tasman Low	Major lows in the southern ocean south of 38°S

Spatial Trends

The spatial variation in storm types is presented by percentage for each wave buoy in Figure 6A and for storms with a peak H_{sig} > 5m in Figure 6B. It shows major storm events (> 5 m) on the northern NSW coast are a mixture of tropical cyclones, tropical lows and easterly trough lows while on the central NSW coast, major storm events also include inland trough lows and southern secondary lows. Along the southern NSW coast, major storm events are mainly associated with a combination of easterly trough lows, inland and continental lows and southern secondary lows, with a number of Southern Tasman lows causing waves in excess of 5 m.

Temporal Trends

The total number of storms observed yearly by storm type is presented within Figure 7 with the year of wave buoy commission indicated and the Southern Oscillation Index (SOI) as provided by the Bureau of Meteorology included for reference. Storms observed only at the Botany Bay buoy were not assigned storm types in this study. The average number of *storms* observed along the NSW coast (by one or more buoy based on the criteria described above) has remained largely constant since all wave buoys were commissioned in 1987 at around 32 storms per year, with a slight increase observed during the late 1990s. This may be related to the change in phase of the Interdecadal Pacific Oscillation (IPO) (Goodwin and Browning, in prep) from El Niño-like to La Niña-like in the early to mid 2000s.

The relationship between storm frequency and the El Niño-Southern Oscillation (ENSO) was examined by You and Lord (2008), who found correlation between average yearly storm intensity and Southern Oscillation Index (SOI) indicating more severe storm events during La Niña years. The Sydney wave buoy was found to detect an average of 23.7 storms per year (Table 2) meaning that the Sydney coastline is affected, based on the adopted H_{sig} threshold, by around 75% of all storm wave events on the NSW coast. However, it is important to note that the available buoy data only span the El Niño-like phase of the IPO together with a few recent years of the La Niña-like phase. Hence, it is probable that any trends and relationships between storm type, frequency and severity, ENSO and the IPO are biased towards the El Niño-like phase, where interannual El Niño events are stronger and more persistent over multi-years, and La Niña events weaker and less persistent. Goodwin and Blackmore (in prep) will report the results of hindcasting NSW wave climate over the La Niña-like phase of the IPO prior to the buoy measurement period.

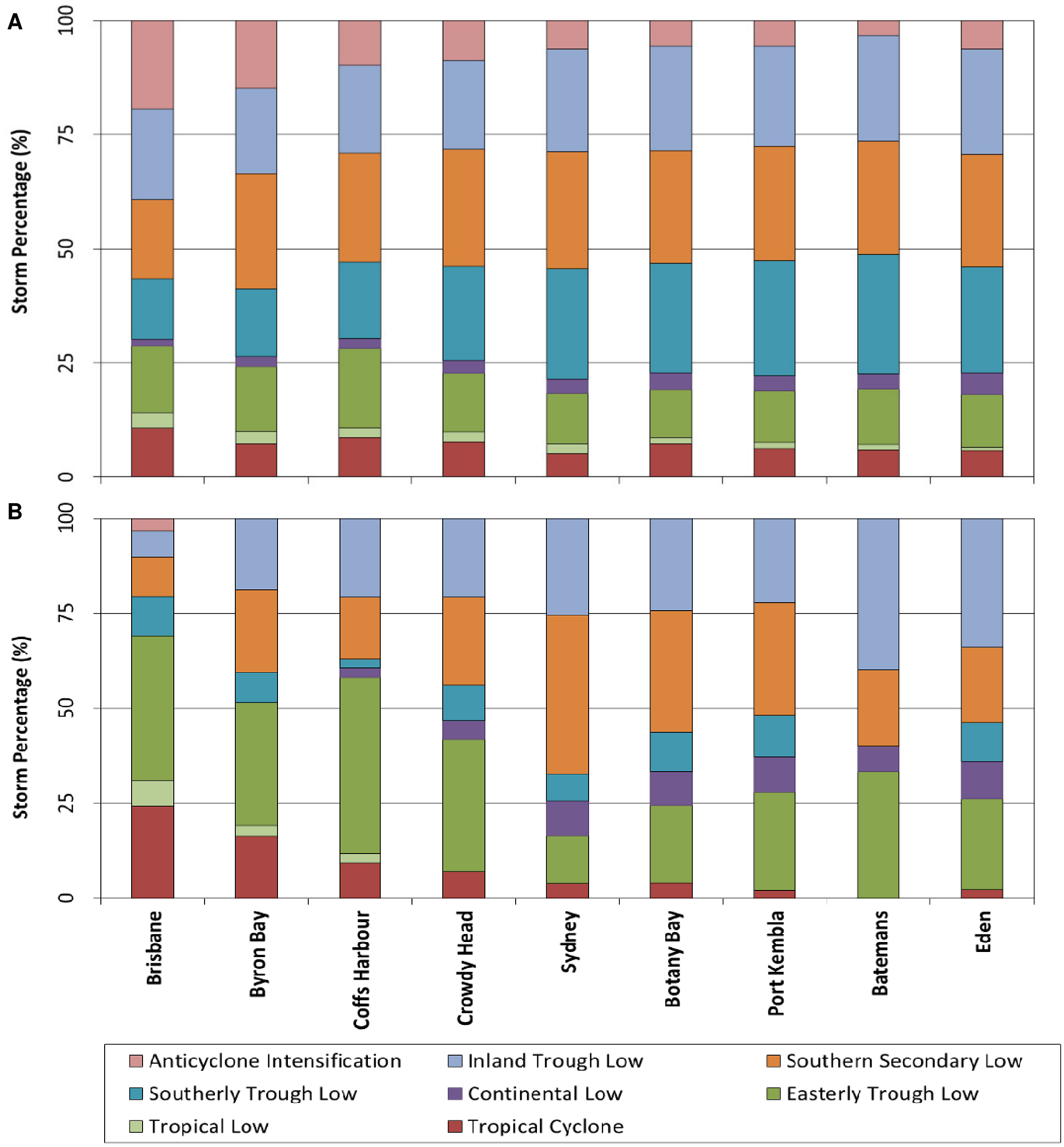

Figure 6: Storm Types by Percentage for Each Wave Buoy over their Respective Record Length for All Storms (A) and for Storms Greater Than 5 m (B)

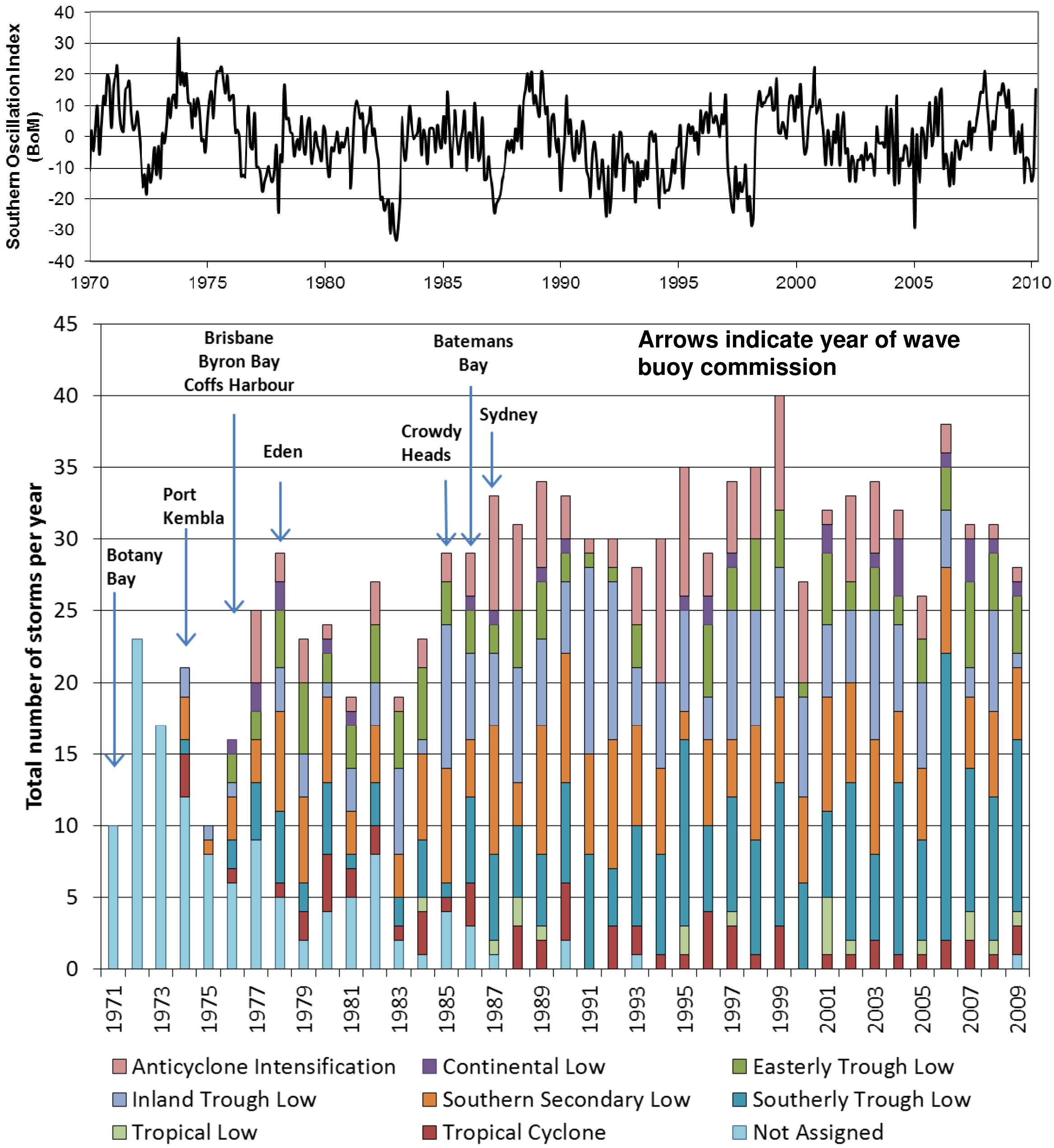

Figure 7: Total Number of Storms Types Observed Yearly with the Southern Oscillation Index as provided by BoM.

Seasonal Trends

Seasonal changes in the occurrence of various storm types along the NSW coast as observed by the wave buoy network are shown within Figure 8. March, July and October are the stormiest months, with November, December and January being the least stormy. Inland trough lows and southern secondary lows exhibit strong negative-correlation, with greater numbers of southern secondary lows occurring between April and October and larger numbers of inland trough lows occurring between October and March. Tropical cyclones and lows are restricted to December to April with most occurring between January and March. Easterly trough lows are concentrated between April and August. Both anticyclone intensifications and Southern Tasman lows occur throughout the year, although anticyclone intensification events tend to be more concentrated and produce larger wave events between January and June and Southern Tasman lows are concentrated and produce larger wave events between July and December.

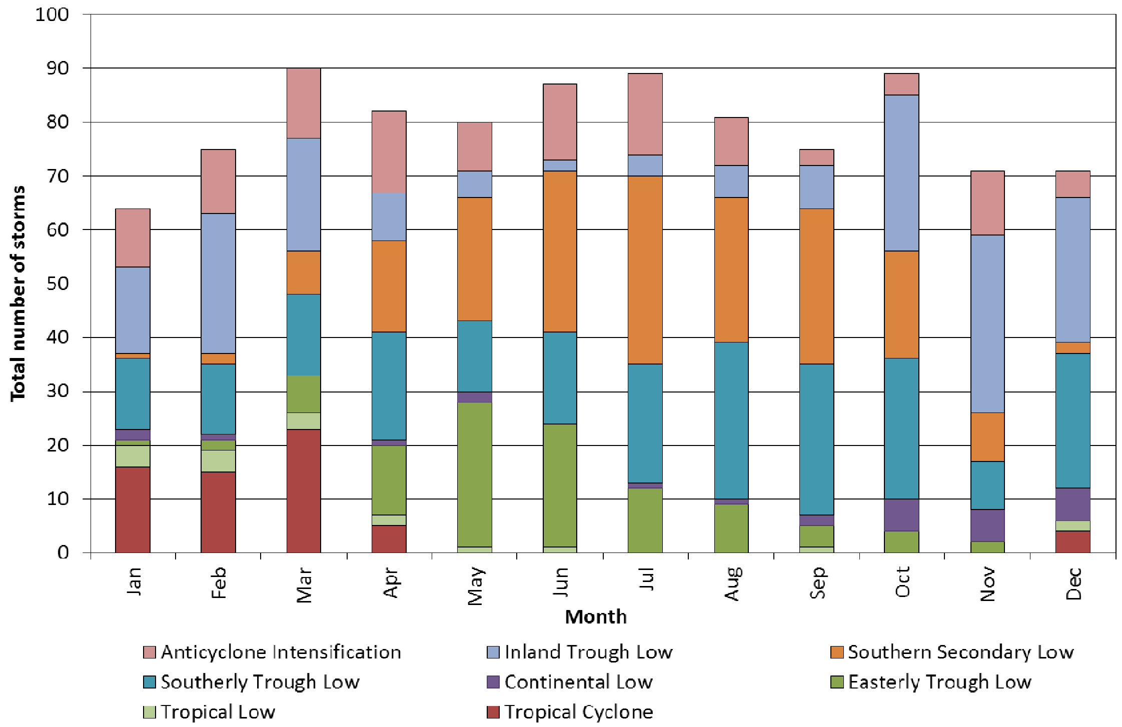

Figure 8: Total Number of Storms Observed along the NSW Coast for Each Month

Extreme Value Analysis

While estimated extreme values derived from the extracted data are not available within this paper, they can be found in the final report of Shand et al. (2010).

Conclusions

This study has reviewed characteristics of storms which impact the NSW coastline using data collected over the past 22 to 38 years. Results of this study will have useful and highly practical application in a number of important areas including:

- Evaluation of the contribution of extreme waves to elevated coastal water levels;
- Design of offshore and nearshore structures and infrastructure;
- Providing boundary conditions for study of beach response to extreme wave events;
- Improved understanding of extreme storm climatology leading to large wave events on the NSW coast.

Acknowledgments

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