NSW EAST COAST LOW EVENT – 3 TO 7 JUNE 2016 WEATHER, WAVE AND WATER LEVEL MATTERS

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Abstract

An upper-level trough moved over southeast Australia on Friday 3rd and Saturday 4th of June 2016. Combined with a strong high pressure system in the south Tasman Sea and heightened moisture levels across central Australia, the system amplified as it approached the NSW east coast resulting in the development of a complex East Coast Low (ECL). Winds strengthened as the trough deepened along the coast on Saturday with gale force north-easterly winds blowing over a long fetch across the NSW coast reaching peak gusts of 100-120 km/h. A combination of the long northeasterly fetch and the passage of intense mesoscale low pressure centres during this complex ECL event resulted in the highest individual wave ever recorded along the NSW coast of 17.7m at 4.30am offshore of Eden on Monday 6th June. In addition to the widespread heavy rainfall, strong north-easterly winds and massive ocean waves, the ECL event was coincident with the winter solstice Spring Tide (King Tide), and together with a positive tidal residual of up to +0.34m (storm surge), resulted in substantial and widespread erosion and damage to the NSW coast.

Introduction

Some of the most significant weather impacts on the east coast of NSW are associated with East Coast Lows (ECLs). These very intense low pressure systems can bring torrential rain, gale force winds and phenomenal seas to NSW coastal regions. During 3 – 7 June 2016, an intense ECL caused loss of life and major damage to the New South Wales (NSW) coastline, including the Sydney Metropolitan region. Of meteorological note, impacts from the ECL included:

- Extreme hourly rainfall rates between 100mm and 150mm at places along the coast. Woolgoolga and Wooli River Caravan Park, located to the north of Coffs Harbour, recorded 113mm and 105mm within an hour on the afternoon of the 5th of June. The intense rainfall exceeded the 1% Annual Exceedance Probability (AEP) for a 1-hour duration.
- Widespread event rainfall totals in excess of 250mm along most of the NSW coast (**Figure 4**), with over 500mm falling in places along the far northern NSW and the coast south of Sydney. The maximum recorded falls were: Wooli Caravan Park 524mm, Robertson 617mm (of which 462mm fell within 24 hours) and Macquarie Pass 580mm (306 mm fell within 24 hours). The Sydney area also received prolonged heavy rain. Picton (Stonewarry Creek) near the George River received 332mm during the event. Camden received 289mm over the event, which exceeded the 1% AEP for a 48-hour duration.
- 21 catchments along the NSW coast experienced flooding during this event, with nearly all of the east-flowing rivers affected. The riverine flooding included major flooding of the Georges River in Sydney and moderate flooding of the

Hawkesbury/Nepean in Sydney. The flood waters were responsible for three fatalities, two in New South Wales and 1 in the Australian Capital Territory.

- Periods of sustained gale force winds (over 63km/h) with damaging wind gusts (over 90km/h) along parts of the NSW coastal fringe. Sydney Harbour saw wind gusts of 116km/hr and Port Kembla saw 100 km/hr gusts.
- Tides near to the Highest Astronomical Tide along the NSW coast combined with pressure induced sea level anomalies and large north-easterly waves resulted in local inundation of low-lying areas and widespread coastal erosion (examples of these are described later in the paper).

ECLs are not uncommon to Australia and the Bureau's weather records show that over the past 50 years, systems of comparable severity have affected the populated areas of Wollongong, Sydney and Newcastle about once every 10 years on average. The most notable recent event was the April 2015 ECL which resulted in gale force winds and rainfall in excess of 200mm in the Hunter and Illawarra districts. This event also caused extensive flooding, coastal erosion and fatalities.

The June 2016 event was particularly notable with respect to the spatial extent of the heavy rainfall and range of significant coastal impacts. ECLs are typically small-scale systems whose major impacts are confined to a few hundred kilometres of the coastline. For example in the case of the April 2015 ECL, rainfall in excess of 200mm was largely confined to areas from the Hunter to the Illawarra regions of NSW, with only light falls north of Taree.

Synoptic Scale Meteorology

The initial development of the June 2016 system closely followed the upper-tropospheric precursor scenario described by Mills et al. (2007), with an amplifying upper ridge developing over the west of the continent by late on the 2nd of June while a positively tilted upper cut-off low developed in the vicinity of Adelaide. The upper cut-off low deepened and became more negatively (towards the northeast) tilted during the 3rd of June, and provided a forcing mechanism for pressure falls at the surface. This led to the initial surface low development over the southern inland of Queensland (**Figure 1**).

At this stage of development in a typical ECL, continuing amplification of the upstream upper ridge leads to a strengthening of the surface high pressure ridge to the south and southwest of eastern Australia. This inhibits the southward movement of the developing coastal low and tends to lead to a situation where coastal impacts are confined to a relatively small stretch of the coastline on the southern flank of the low. In the case of the June 2016 ECL, the upstream upper ridge started to weaken on the 3rd, and an amplification of the downstream upper ridge over the Tasman Sea commenced. This lead to the main area of surface high pressure rapidly shifting to be centred over New Zealand, with the maximum analysed pressure steadily increasing and reaching 1040 hPa by 00 UTC on the 6th (**Figure 1f)**.

As this intensification of the high pressure centre to the southeast was occurring, the upper cut-off low over southern Australia continued to stretch and become more negatively tilted, gradually shifting eastwards towards the NSW coastline during the 4th of June. On the night of the 4th a new cold-cored upper cut-off low sheared off from the apex of this feature and tracked across southeast Queensland to be offshore from the southeast Queensland coast by the morning of the 5th of June. This cut-off was associated with a region of strong cyclonic Isentropic Potential Vorticity (IPV) advection (**Figure 2a**). IPV advection is associated with enhanced ascent in the atmosphere and this to pressure falls at the surface (Dowdy, 2011). It was at this stage of the event, that a series of embedded low centres began to develop within the broader surface trough. **Figure 1d** shows that there was a significant low centre just to the south of the strongest upper IPV advection at 00 UTC on the 5th of June.

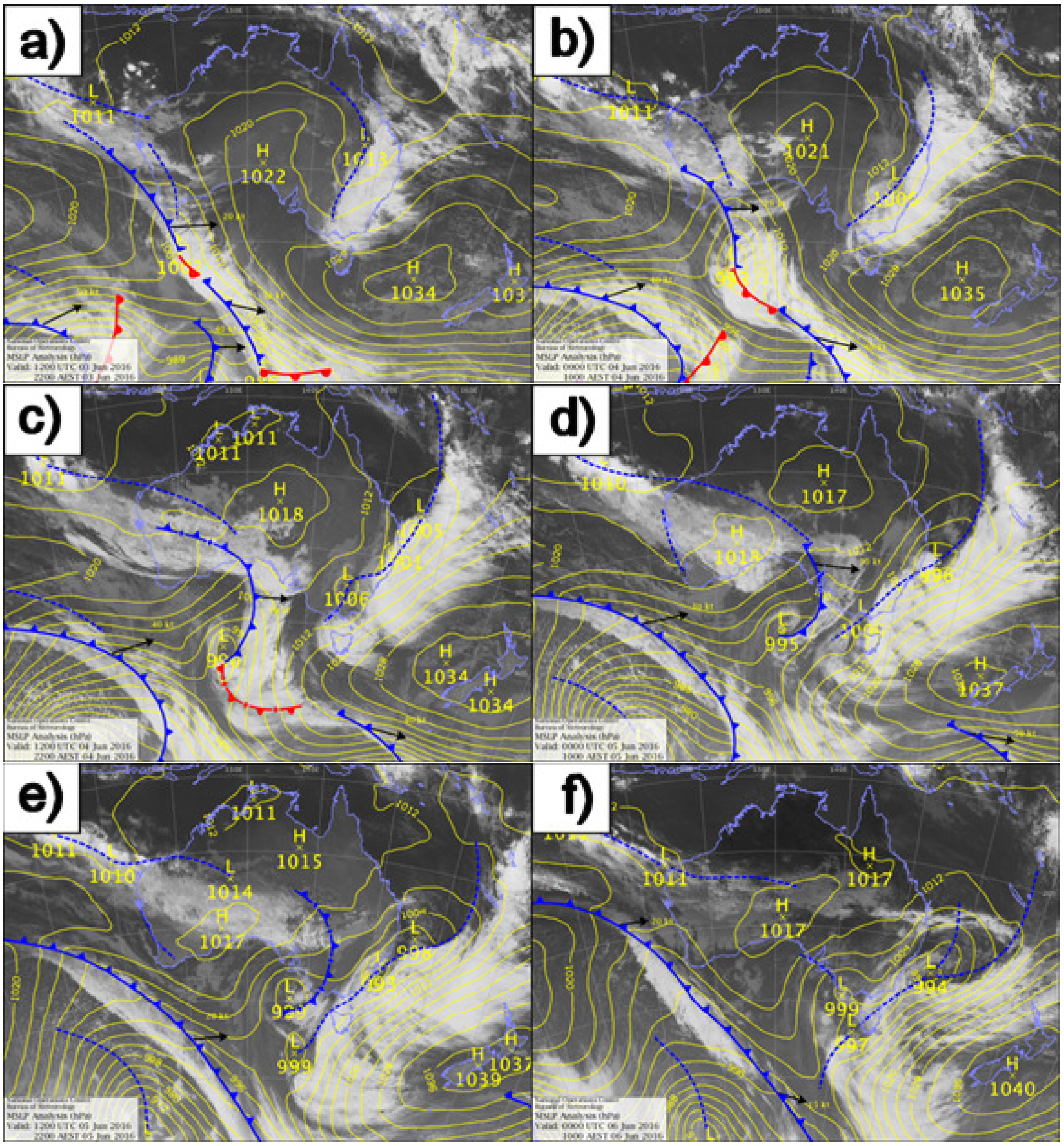

Figure 1: Synoptic development of ECL pressure system. Shown are mean sea level pressure analyses with (yellow) contours every 4hPa, with infrared satellite imagery overlaid. Low pressure troughs are marked with dashed blue lines, cold fronts as blue lines with triangular barbs and warm fronts are red lines with circular barbs. Times shown are: a) 12 UTC on 03/06/16, b) 00 UTC on 04/06/16, c) 12 UTC on 04/06/16, d) 00 UTC on 05/06/16, e) 12 UTC on 05/06/16, f) 00 UTC on 06/06/16

By this time an extremely tight pressure gradient had developed across the Tasman Sea between the New Zealand high pressure system and the embedded low off the NSW north coast (**Figure 1d** and **Figure 2b**). This created a long fetch length of gale force north-easterly winds, from just south of Noumea to the southern half of the NSW coastline (the blue area in **Figure 2b**), which in turn produced the storm surge and large waves which combined to cause significant damage to coastal infrastructure in southern NSW.

Between the morning of the 5th of June and the evening of the 7th of June the strong upper ridge remained quasi-stationary over the western Tasman Sea and acted as a block to any further eastwards progression of the cut-off upper low. During the 5th and 6th of June the upper low pressure system took a southward track, remaining just offshore from the NSW coast, resulting in a series of embedded meso-scale surface low pressure centres developing in the surface trough. These in turn tracked south-westwards back across the NSW coastline, steered by the north-easterly mid-level winds on the western flank of the upper ridge.

The slow southward progression of surface trough during the 5th and 6th (**Figure 1e** and **Figure 1f**) prolonged the exposure of the NSW coast to the long fetch, and large waves, for up to 48 hours, and the embedded low centres resulted in some of the heavier rainfall totals and strongest winds being located along the coast just to the south of their crossing points. By the evening of the 6th, the upper cut-off low that was providing the forcing for surface meso-low development had weakened and reached far enough south that the focus for heavy rain and strong winds had shifted to north-eastern Tasmania.

Overall, as the initial development occurred within the inland trough over southern Queensland, this event most closely resembles an inland trough low in the synoptic typing proposed by Speer (2009) or a type-1 low in the synoptic typing proposed by Holland et al. (1987). However, the subsequent intensification of the upper ridge over the Tasman Sea and the blocking nature of the high pressure system near New Zealand, led to a sequence of lows that affected a broader area than is typical of ECL events. The orientation and strength of the pressure gradient over the Tasman Sea, in conjunction with near highest astronomical tides also meant that impacts on coastal infrastructure from large waves and storm surge were greater than for many other ECL events.

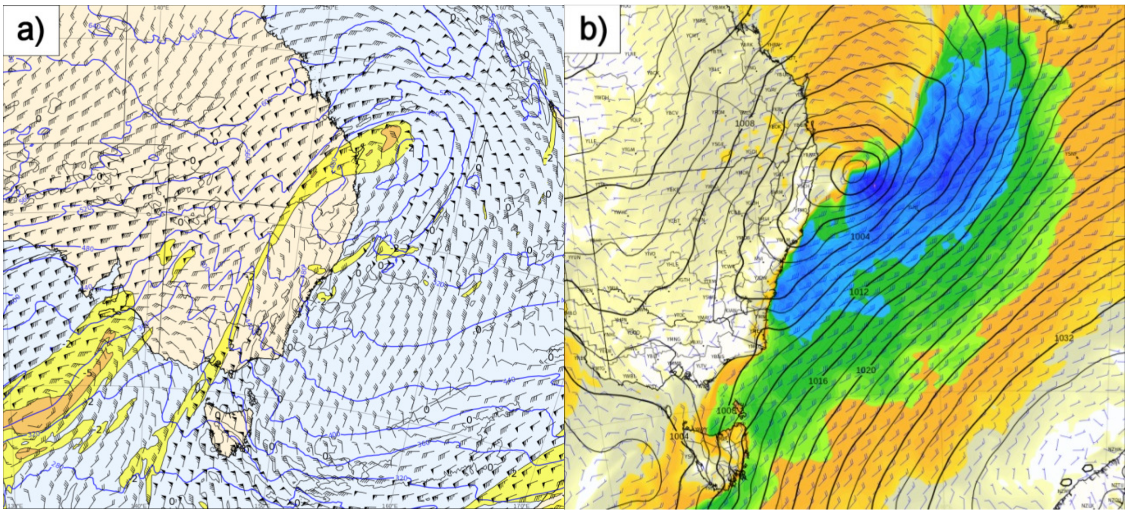

Figure 2: ACCESS-R model analyses at 00 UTC on 5th June 2016:

a) Potential vorticity (shaded) and pressure (contours) on a 320K isentropic surface. IPV contours are at -2 (yellow) and -5 (orange) and pressure contours are every 40hPa. Also shown are wind barbs at the 320K isentropic level; and

b) Surface mean sea level pressure (black contours, every 2hPa), surface wind barbs, and surface isotachs (shaded). Isotach colour ranges are orange (8 to 13m/s), green (13 to 17m/s), blue (17 to 25m/s) and red (greater than 25m/s).

Rainfall Impacts

One consequence of the slow southward moving nature of the ECL was that it led to a deep intrusion of humid tropical air into higher latitudes. Both Sydney Airport and Williamtown RAAF base recorded their highest daily precipitable water (a measure of the total humidity within an atmospheric column) on record of 40.5mm and 39.7mm respectively on the morning of the 5th of June. The daily series of precipitable water values at Hobart Airport on the evening of the 6th (**Figure 3**) shows how far outside the climatological range this event was.

This extremely humid air was ascending on the eastern and southern flank of the surface trough, and this led to the development of an extensive cloud band (**Figure 1a-f**), that produced very heavy rainfall totals along much of the eastern sea board (**Figure 4**). Almost all of the coastal river catchments in NSW experienced flooding, with riverine floodwaters contributing to and exacerbating coastal inundation issues stemming from high tides and storm surge into low-lying coastal areas.

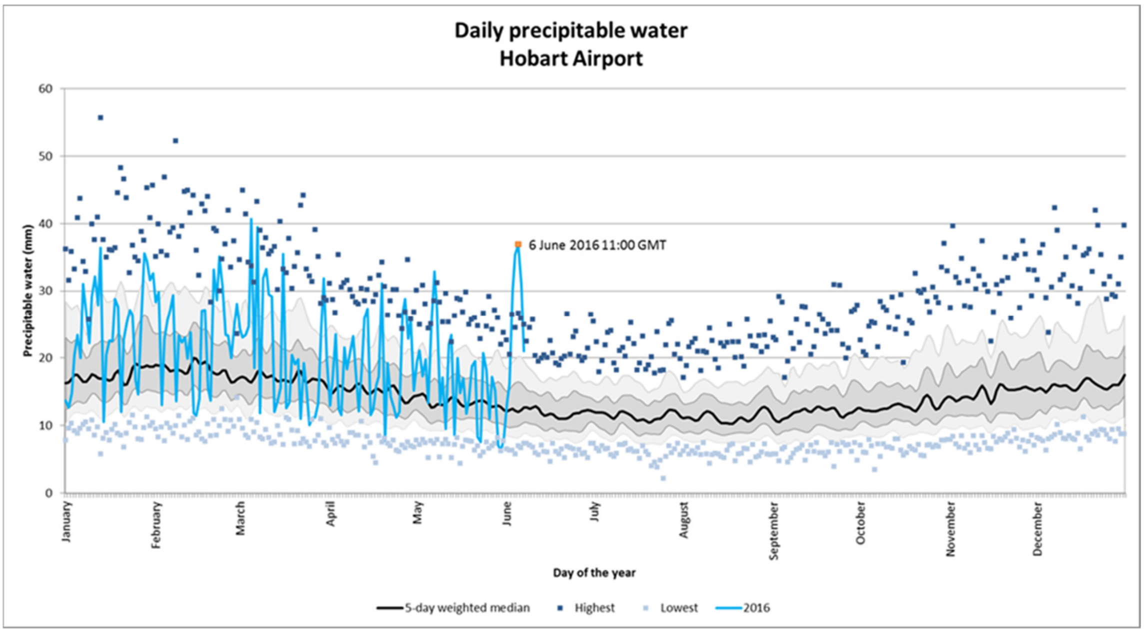

Figure 3: Daily series of total precipitable water at Hobart Airport (from Bureau 2016). The thick black line shows the 5-day weighted median, the blue dots show the daily maxima on record, and the orange highlighted dot shows the value from 6th June 2016. The darker grey shading is the 25th to 75th percentile. The lighter grey shading is the 10th to 90th percentile.

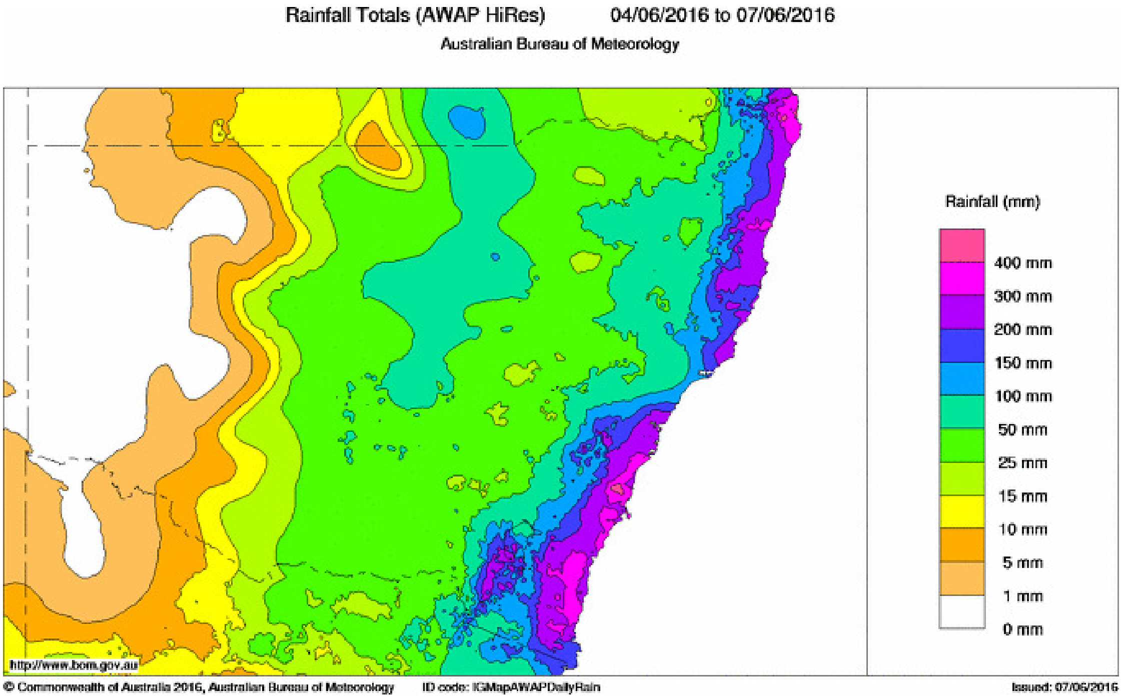

Figure 4: Four day rainfall totals for NSW from the 4th the 7th of June 2016

Sea Surface Temperature

Energy transfer from the ocean to the atmosphere is one of the key factors in the formation of barotropic low latitude weather systems such as tropical cyclones. While the atmospheric response to sea surface temperature anomalies is not as strong for mid-latitude (baroclinic) cyclogenesis (Webster 1980), numerical modelling has shown that it still can have a significant effect on the intensity of the low, and the resultant extent and strength of high wind and rainfall. McInnes et al. (1992) found that a sea surface temperature increase of 2°C to 3°C off the east coast of Australia could lead to deeper low central pressures by 1-2hPa on average, and increases in peak rainfall by 45 to 80 percent.

Figure 5 shows that on the 5th of June there was a pronounced area of warm water extending along the NSW coast, with an associated tongue of 21°C to 22°C water reaching as far south as Ulladulla associated with the East Australian Current (EAC). This translated to a region with sea surface temperature anomalies of between +2°C and +3.5°C extending from offshore from the Great Lakes region to approximately Batemans Bay. It seems likely that this pronounced sea temperature pattern could have been a contributing factor in both the intensification of the embedded low pressure centres and the increased rainfall rates seen during the June 2016 ECL event.

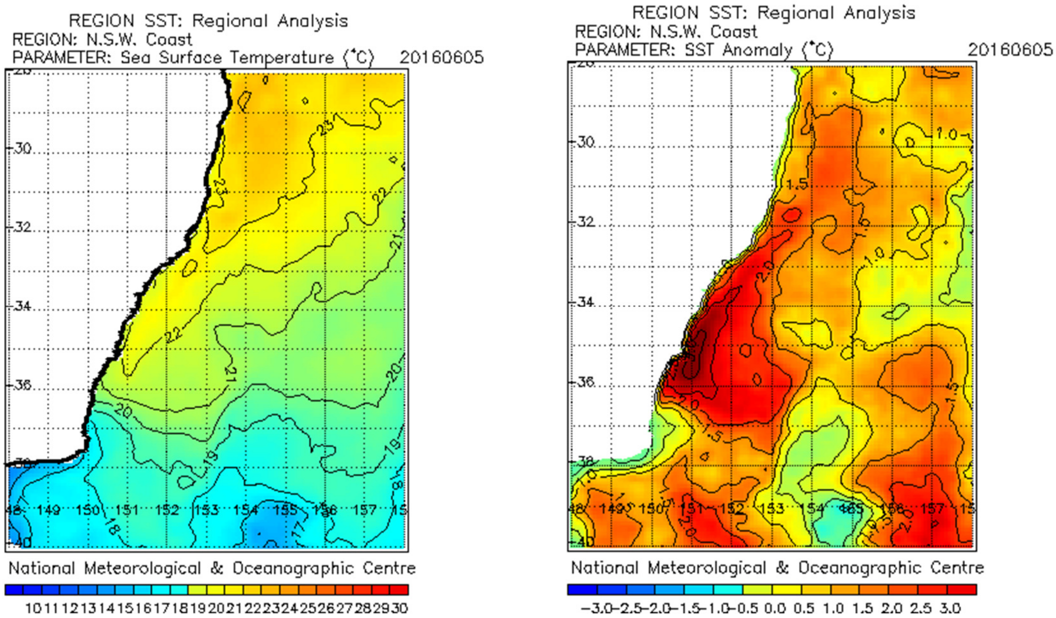

Figure 5: Regional Sea Surface Temperature (left) and Sea Surface Temperature anomaly (right) analyses. Shown are temperatures in contours of 1°C and anomalies in contours of 0.5°C

Ocean Water Levels

The occurrence of this ECL event coincided with a Winter Solstice Spring Tide (colloquially, King Tide). These Spring Tides occur biannually during winter and summer solstice periods when the Earth, Moon and Sun are aligned both with the perigee and perihelion. Despite this, however, the tide levels observed along the NSW coastline were not altogether unusual for an ECL event. Tidal time series for Tweed River, Sydney and Eden during the June ECL are presented in **Figure 6**. The highest tidal peak of 1.29m AHD occurred at Sydney on the 5th at 20:15 hours. This peak included a 204mm tidal residual (storm surge) and corresponds to a 1:2.5 year water level (**Figure 7**). The tidal peak at Eden was of a similar level (1.21m AHD) although occurring a full tidal period later and the tidal peak at Tweed River was much higher (1.56m AHD), and occurred 24 hours before the Sydney peak, but was influenced by rainfall runoff in the river and hence is not necessarily representative of the ocean level at that time.

The most unique aspect of the June ECL from a tidal perspective was the scale and duration of the event. Historic ECL events, as mentioned previously, tend to be spatially localised around a few 100kms of coastline and persist at most a few days. The stationary strong upper ridge produced storm conditions along the majority of the NSW coastline in the June event and the slow moving nature of the trough induced an event that lasted more than four (4) full tidal cycles from the beginning of the storm at Byron Bay to the tail end at Eden. This created a variating effect along the coast as the peak of the storm coincided with different stages of the tidal cycle. The coincidence of elevated ocean water levels and high waves, winds and to a lesser extent rainfall was reflected in the magnitude and distribution of coastal damage caused by the event.

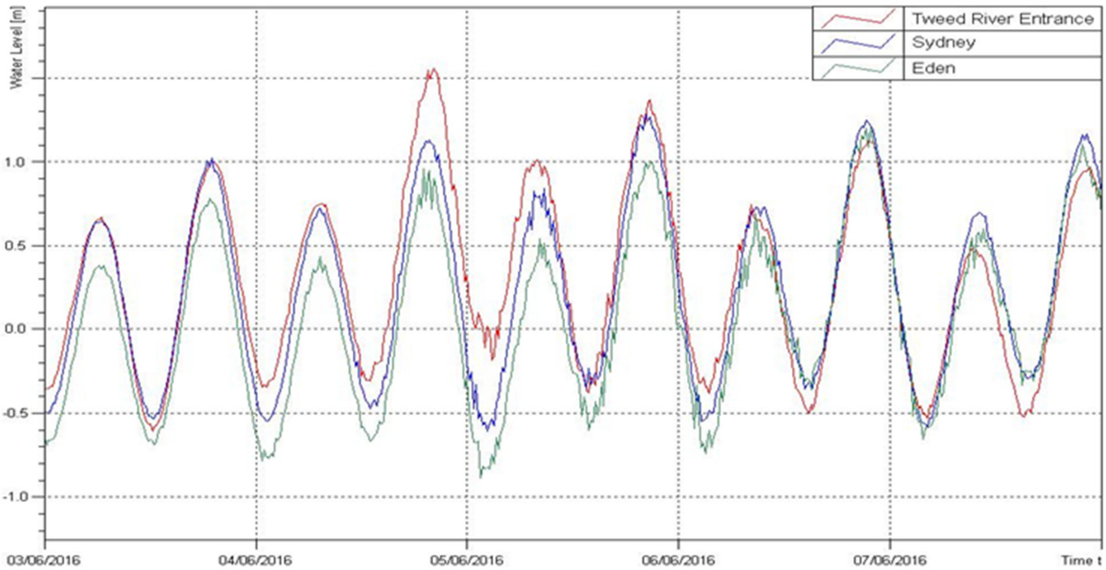

Figure 6: Ocean tide levels at Tweed River (includes flooding), Sydney and Eden between 3rd and 8th June, 2016 (OEH Coastal and Flood Data Program managed by MHL)

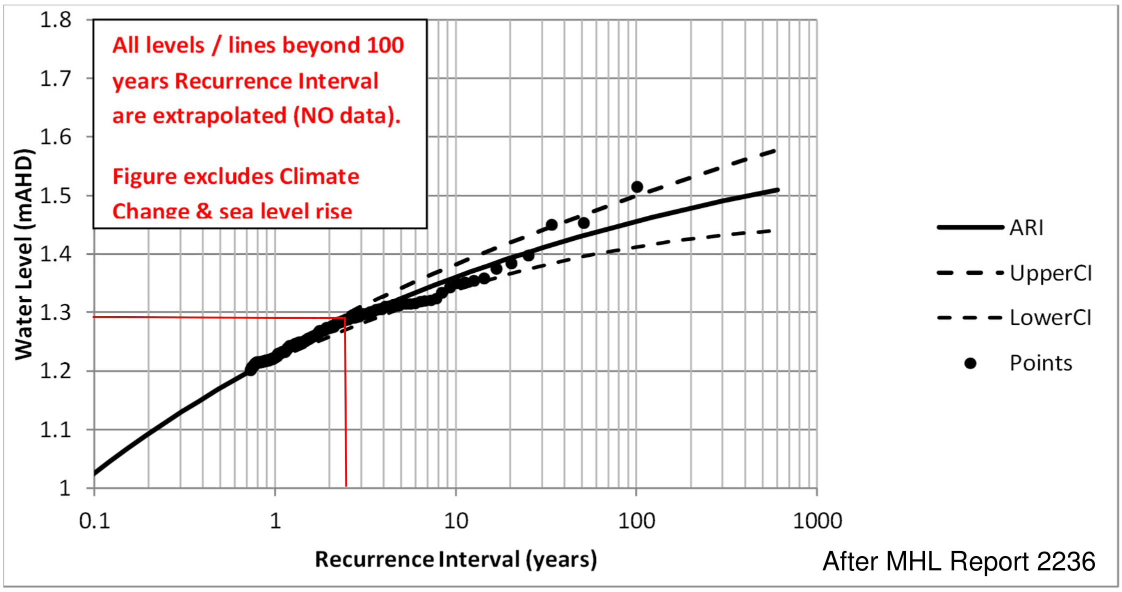

Figure 7: Sydney peak tide level exceedance probability (after MHL, 2016)

Offshore Wave Conditions

Offshore wave data for the June, 2016 ECL were captured by Manly Hydraulics Laboratory's (MHL's) seven (7) Datawell directional Waverider buoys. These buoys are located off the NSW coast at water depths of approximately 100m near Byron Bay, Coffs Harbour, Crowdy Head, Sydney (Long Reef), Port Kembla, Batemans Bay and Eden. Combined, they have recorded over 230 years of wave data since the 1970s and 1980s with three of the stations recording over 15 years each of directional data to-date. A summary of the record lengths for each buoy is presented in **Table 1**.

Table 1: Record length summary of MHL's offshore Waverider buoys

Wave Station	Date Site Commissioned	Directional Buoy Deployed
Byron Bay	14-Oct-1976	26-Oct-1999
Coffs Harbour	26-May-1976	14-Feb-2012
Crowdy Head	10-Oct-1985	19-Aug-2011
Sydney	17-Jul-1987	03-Mar-1992
Port Kembla	07-Feb-1974	20-Jun-2012
Batemans Bay	27-May-1986	23-Feb-2001
Eden	08-Feb-1978	16-Dec-2011

During the 4-days of the event, five of the seven buoys were able to capture >97% of the data despite an often noisy signal caused by storm interruptions to radio signals. The computer responsible for data collection of the Batemans Bay buoy had experienced a failure on the 18th of May and was unavailable to record any data for the event. The Port Kembla buoy was unable to record any data between 10:00 hours on the 4th of June and 17:00 hours the following day (5th) due to signal interference and is therefore unlikely to have recorded the peak wave conditions of the event which is estimated to have passed through Port Kembla between 15:00 hours and 16:00 hours on the 5th.

Data collected from the Waverider buoys between the 4th and 8th June 2016 reflect the meteorological observations presented previously. A wind fetch of ~1500km NE from the Coral Sea produced the large swells which grew in size as they travelled south, leading to a general increase in coastal storm severity along the NSW coastline from north to south. As such, Byron Bay experienced the smallest waves, peaking at H_s= 5.2m at 15:00 hours on the 5th, equivalent to less than a 1:1 year Average Recurrence Interval (ARI) event (peak H_s). Eden experienced the largest waves, reaching a peak H_s = 8.5m at 04:00 hours on the 6th which is equivalent to a 1:85 years ARI event based on extreme value statistics prepared by Shand et al. (2011). Additionally, the Eden buoy recorded the largest single wave (H_{max}) ever measured in NSW at around 04:30 hours on the 6th, of 17.7m. The sea surface trace of this wave is presented in **Figure 8** along with the previous largest ever wave recorded at Sydney of 14.9m in April 2015.

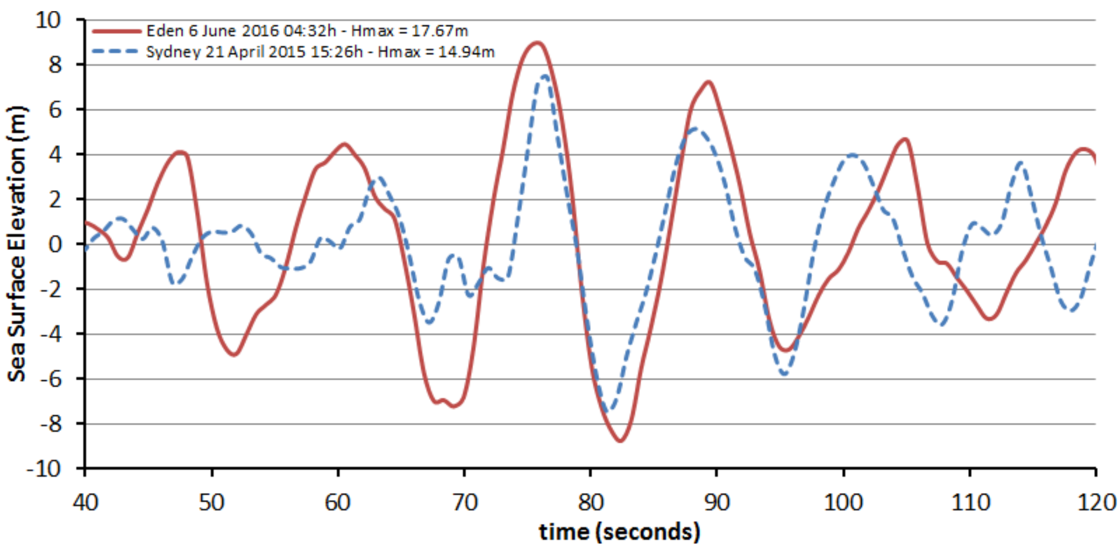

Figure 8: Sea surface trace of 17.7m wave offshore of Eden and 14.9m wave recorded April 2015 at Sydney

Sydney recorded a moderate H_s = 6.5m at the peak of the ECL corresponding to about a 1:2 years ARI (based on Shand et al., 2011). A complete summary of the storm statistics is given in **Table 2**, with plots of hourly significant wave heights recorded at the seven stations over the storm duration presented in **Figure 9**.

Table 2: 2016 ECL offshore wave statistics summary

	Storm Peak H_{max} (m)	Peak H_{max} Date/Time	Storm peak H_s (m)	Peak H_s Date/Time	Storm Avg T_p (s)	Storm Avg Dir (deg)	Approx peak H_s ARI** (years)	% Data Capture
Byron	11.6	5/06/2016 1:00	5.02	5/06/2016 15:00	12.5	100 (E)	< 1:1	99.4%
Coffs	11.2	5/06/2016 3:00	6.35	5/06/2016 2:00	12.8	90 (E)	1:4	100.0%
Crowdy	13.3	5/06/2016 8:00	6.72	5/06/2016 9:00	13.0	93 (E)	1:7	100.0%
Sydney	12.0	5/06/2016 15:00	6.53	5/06/2016 15:00	13.5	103 (ESE)	1:2	98.8%
Port Kembla*	11.1	5/06/2016 23:00	5.83	5/06/2016 23:00	13.5	96 (E)	1:2	63.9%
Eden	17.7	6/06/2016 4:30	8.46	6/06/2016 4:30	15.1	77 (ENE)	1:85	97.5%

* Storm peak may have been missed before reliable records commenced at 17:00 hours at Port Kembla

** ARIs after Shand et al. 2011 based on 1hr exceedance, excludes consideration of wave directions – refer also to Updated Extreme Value Wave Height Analysis below

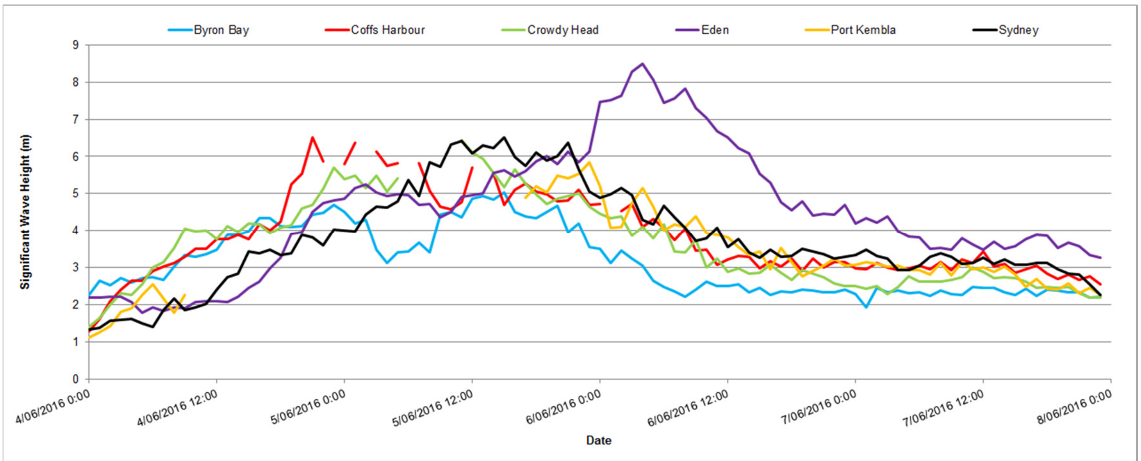

Figure 9: Hourly significant wave heights recorded at each of MHL's offshore Waverider buoys, 4th to 7th June 2016

Open Coast Damage Characteristics & Historical Context

While beach erosion associated with the June ECL was widespread along the NSW coastline, the impacts were most apparent at Collaroy-Narrabeen Beach in Sydney, and Wamberal Beach on the Central Coast, where development has occurred in vulnerable locations. The erosion at Collaroy-Narrabeen Beach was prominently featured in the media and in published literature and included major damage and undermining of both commercial and residential buildings. At Wamberal an erosion escarpment in excess of 4m high exposure old ad-hoc protection works and undercut several residential decking structures. **Figure** shows typical locations suffering erosion and/or damage during the ECL event, included Coffs Harbour's northern breakwater and boat harbour, Collaroy-Narrabeen Beach, Manly Beach towards Fairy Bower, Wollongong Harbour, Moruya breakwater and the Eden chip mill wharf.

Figure 10: June 2016 Storm Damage – Coffs, Collaroy, Manly, Eden, Moruya and Wollongong (clockwise from top left).
Source: ABC Coffs Harbour, MHL and Department of Industries, Lands personnel and the Eden Magnet.

The wave effects superimposed upon elevated mean water levels enabled run-up to be significant with debris lines typically measured between 4 and 6.5 m AHD on most beaches. The maximum measured run-up levels surveyed for this event reached an elevation of 7.5m AHD at Maroubra. Waves overtopped and/or damaged many coastal structures in the Sydney and Central Coast region and impacted lower lying buildings including many surf clubs. Coogee surf club sustained significant damage while many others suffered minor damage to building and equipment. Typically the worst affected sites were in the southern corners of beaches which are normally protected from larger swell waves (e.g. Manly, Terrigal etc.).

The increase in wave height from north to south would usually pair with an associated increase in coastal damage. However the coincidence of peak tide levels with the development of intense multi-cell low pressure systems (see **Figure 1c**, **d**, **e** and **f**), and with it maximum seas, combined to produce extremely damaging conditions in more locations than just Eden. As mentioned above, the peak tide at Sydney was on the 5th of June at 20:15 hours at which time the significant wave heights were still in excess of 6m (**Figure 9**). Comparatively, the Eden peak occurred at 4:30 hours on the 6th when the tide was reasonably close to MSL and by the time the peak tide came around on the evening of the 6th, the seas had dropped to $H_s < 5m$, lessening the severity of the damage. To the north, tidal peak coincidence with the peak of the storm on the evening of the 4th combined to cause significant damage to Coffs Harbour's northern breakwater and surrounding coastline (**Figure**). These results highlight the complex interactions of various oceanographic and meteorological phenomena which, when taken in isolation, have clearly defined and well understood consequences and yet can behave dynamically and unpredictably when acting in conjunction with one another in real-world situations.

Placing the June 2016 ECL in context of prominent ECL storms of the past reveals the areas in which it was unique as well as those in which it was typical or less severe than others. In June 2007, a series of five ECL events swept the NSW coast, focusing between the Hunter and Illawarra regions. The first and most damaging of these was named the Pasha Bulker storm for the 40,000-tonne bulk carrier which ran aground on Nobbys Beach in Newcastle (Verdon-Kidd et al., 2010). The wave heights for this storm were estimated somewhere between 1:4 and 1:10 years ARI at the time (Watson et al., 2007). If the same storm occurred today, the wave heights recorded during the Pasha Bulker storm would be classified as around a 1:3 years ARI event (refer to Updated Extreme Value Wave Height Analysis below). The damage caused in the June 2007 event was far more severe than the June 2016 ECL and was more characteristically concentrated in a smaller area (typical of ECL systems). Most of the June 2007 storm damage occurred due to extreme wind and rainfall rather than ocean conditions, which were not as intense as the June 2016 event.

The May-June ECL events of 1974 included the May 26th 'Sygna' storm which would become the catalyst for research into beach response to storm erosion, identification of the need for coastal emergency management plans, and the deployment of Waverider buoys up and down the NSW coastline. The 1974 storms caused extreme, widespread damage along much of the NSW coastline, well in excess of the June 2016 ECL, primarily because of the extreme ocean levels experienced comprising the highest tidal anomaly and highest water level ever recorded in Sydney of 1.5m above AHD (compared with 1.3m AHD for the June 2016 event). Although reliable wave data was unavailable at the time, it was generally accepted that the severity of the event was in the vicinity of a 1:100 years ARI event (Lord & Kulmar, 2000). Some further analysis performed a quarter century later placed the storm closer to 50 years to 70 years ARI, depending on the duration considered. Reliable estimates of the peak significant wave height for the May 1974 storm vary between 9m (Lord & Kulmar, 2000) and 7.5m (from ERA-40 hindcasting). Using the updated extreme value wave height analysis for Sydney (see below), the peak intensity of that storm indicates an ARI in the vicinity 1:10-1:50 years; the smallest of which is still far larger and more damaging than the recent June 2016 ECL.

Updated Extreme Value Wave Height Analysis

The NSW storm history database (defined by $H_s > 3m$) held by MHL was updated to include all storms since the last extreme value analysis of the NSW wave climate undertaken by Shand et al. (2011). This paper presents the results of the updated extreme value wave height analysis for Sydney and Eden only. The complete results and more details of this updated analysis (including results for different statistical distributions) will be presented by MHL at Coasts & Ports (2017).

Results of the updated extreme value wave height analysis are consistent with the results obtained by Shand et al. (2011), albeit affected by several major storms recorded since December 2009 as shown in **Figure** for Eden and Sydney. These events are indicated by black shading in **Figure** which also shows the prior extreme value analysis results from Shand et al. (2011) for comparison.

The largest difference presents for Eden due to the addition of five (5) top ranking major storms between 2010 and 2016 comprising June 2016, March 2012, June 2012, May 2010 and September 2013 storms (from 1st to 5th ranking). These additions to the recorded storm wave heights significantly impact the extreme value distribution tail and hence the resulting peak H_s ARIs.

The occurrence of large storms in April 2015 and June 2012 similarly changed extreme value analysis ARI values for the Sydney monitoring station. These two storms now rank as the 2nd and 3rd largest recorded at Sydney. Using these updated statistics, the ARI of the June 2016 ECL for Eden updates from approximately 1:85 years (with data up to December 2009) down to approximately 1:30 years ARI and about 1:2 years for Sydney (**Figure**). As discussed below, however, these extreme value statistics do not take into consideration the effect of wave direction (for which more limited data exists).

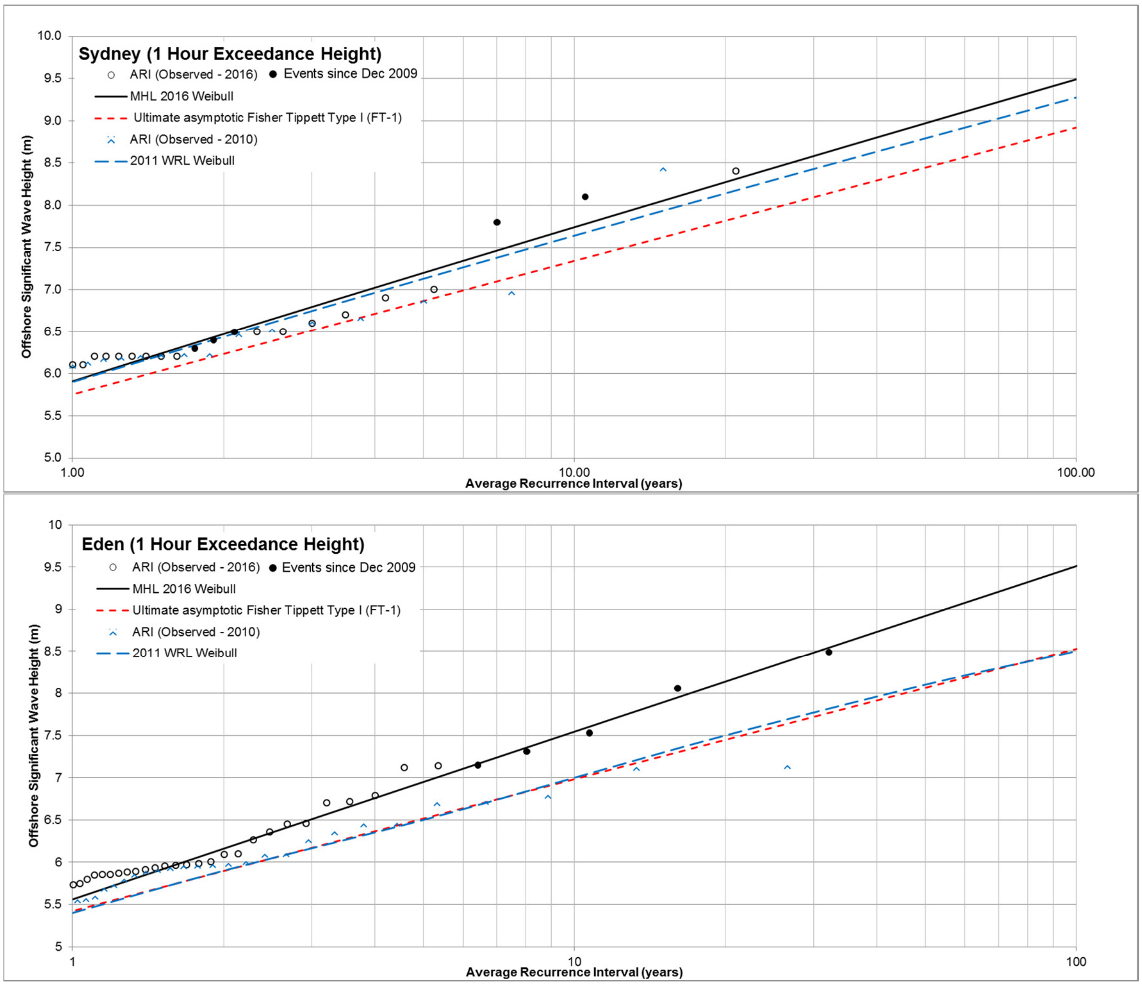

Figure 11: Updated extreme value analysis for peak H_s (equivalent to 1 hour duration) at Sydney and Eden

A preliminary directional exceedance analysis for Sydney is presented in Error! Reference source not found.**2.** The 4-year directional dataset for Eden is not sufficiently long to provide valid predictive statistics which have hence been omitted from this report. The June 2016 ECL event created the largest waves ever recorded from the northeast to east quadrant for Eden and east to southeast for Sydney. The majority of storm events at these locations come from the southeast to south (Sydney) and south to southwest (Eden) quadrants, which provides less data for exceedances in the directions observed in the June ECL. Given that wave directions on the NSW coast are affected by inter-annual and inter-decadal cycles (such as SOI and ENSO), which occur over periods of up to 60 years, reliable extreme value analysis is expected to require at least 50 to 60 years of record length.

For Sydney, the June 2016 event fits within the non-directional distribution more closely due to the 24 years of directional data available. Notwithstanding a more reasonable record length, directional wave statistics for Sydney should not be used given very few major events being recorded for several directions which may be due to inter-decadal dependencies not yet experienced during the time of directional records.

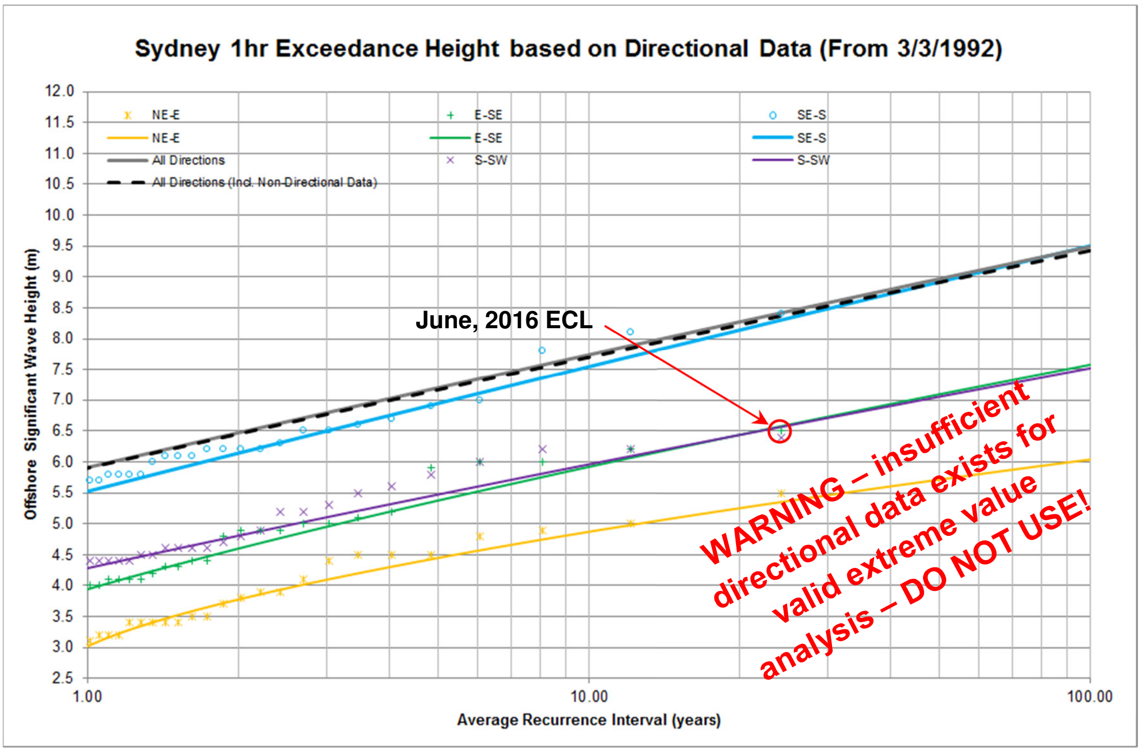

Figure 102: Directional extreme value analysis for Sydney buoy (1992-2016) – Caution: insufficient data exists for reliable results

Contrasting directional wave statistics for Eden and Sydney displays the importance of continuing to collect directional wave data in order to make more accurate predictions and accommodations for design. Changes in extreme storm wave intensity-frequency relationships over the past 5 years further highlights the need for ongoing quality controlled directional wave data collection and careful analysis. Climate change further emphasises the importance of ongoing data collection given the non-stationary environment we live in. Coastal structures, protection works and beach environments are all highly dependent upon understanding and adapting to changing design storm conditions (especially when coincident with high ocean levels) and this work adds to the growing bank of evidence pointing to the inadequacies of traditional methods of calculating these design conditions moving into an uncertain future.

Conclusions

The June 2016 ECL was noteworthy for its magnitude, duration and location compared to recorded events in the past. This event was one of the most well documented coastal ECLs ever with advanced warning systems allowing impacts to be observed immediately prior and following the storm along a large stretch of the NSW coastline. The ~1500km fetch from the northeast allowed massive waves to form at NSW's central and southern coastal regions with the largest single wave of 17.7m ever recorded in NSW measured at Eden on June 6th. Coincidence of Winter Solstice tides with high seas caused extensive damage along the NSW coast, concentrated around Sydney's northern beaches. The storm, while not the most damaging on record, was large enough to alter the statistics of extreme wave values for Eden and will provide much data on beach response, emergency management efficiency, ECL development and dynamics, in the coming years. It is the finding of this paper that extreme weather, waves and water levels all matter, but their coincidence matters even more.

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