

ARTICLE

Ocean Affects from Severe Weather Systems in Coastal Areas

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ABSTRACT

Severe weather systems can generate large waves and storm surges which can cause many fatalities in coastal areas. In extreme circumstances a single cyclone caused up to 500,000 fatalities in the Bay of Bengal in 1970. Adaption by authorities in that region from evacuations and construction of storm shelters have significantly reduced the number of such fatalities there. The effects of Hurricane Sandy in 2012 in New York City and surrounding areas is examined to show how ocean effects can cause many casualties. Scrutiny of a European storm shows how a slight error in analysis can fail to detect a deadly increase in intensity which caused many fatalities. World record wave height events are examined, and the historical Australian east coast events are investigated. The impacts from long period waves emanating from distant storms are shown to be a forecasting problem.

1. Introduction

This paper is part memoir and part research as the author worked with the Bureau of Meteorology from 1965 to 2008 first as an observer but mostly as a forecaster. From 1995 to 2008 my position was leader of the Queensland, Australia Severe Weather Section. My work since 2008 has been as a Meteorological Consultant but also writing 23 peer reviewed severe weather related papers. My marine experience comes from 60 years as a surf lifesaver with the Kirra (Gold Coast) surf lifesaving club for which I am a life member. This period of service includes two awards for an ocean rescue during Severe tropical cyclone Dinah (see details Section 6) as it was located off the Gold Coast on 30 January 1967. Other

marine experience includes six Antarctic voyages during service with the Australian Antarctic Expeditions 1965/66, 1969/1971 and 1983/84.

Large waves reaching the coast can cause significant impacts such as coast erosion and saltwater inundation, damage to infrastructure and loss of life. Hurricane Sandy in 2012 has been selected here as a benchmark study as it caused 96 fatalities and widespread damage in the New York City/New Jersey area mainly from the effects of ocean waves and storm surge. It becomes a benchmark in a study like this to compare it with other storms which stir up the ocean. A European storm is studied for such a comparison and displays a serious forecasting problem. A world record individual wave height event generated by the trapped fetch phenomena and measured by an

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Australian rescuing helicopter pilot in 1998 is discussed. This follows many discussions with the Captain of the Yacht which encountered the wave. The wave is compared with World Meteorological Organisation ratified significant wave height record in a severe weather system off Scotland. Weather systems developing large waves along the Australian sub-tropical east coast are scrutinised. The impacts from long period waves are assessed. The author has had extensive experience with these events having prepared an online forecasting module for the Severe Weather staff and in preparing a report for the coroner for a deadly event in 2001. An exceptionally intense winter storm in the Pacific is presented including its unexpected impact from waves in the Marshall Islands from an unknown origin (at the time). The Queensland Severe Weather Section was involved in forecasting this event. Adaption strategies appear to be reducing the number of fatalities from deadly storm surge events in the Bay of Bengal.

2. Data

Surface wind data over the ocean was obtained from the quikSCAT satellite data available from QuikSCAT/SeaWinds Data products (noaa.gov).

Wave data were obtained from the Queensland Government Environment Protection Agency's web site at: http://www.epa.qld.gov.au/environmental_management/coast_and_oceans/waves_and_storm_tides/wave_monitoring/ and the Manly Hydraulics laboratory web site at:

http://mhl.nsw.gov.au/www/wave_data_plot.htmlx.

Radiosonde data used came from Bureau of Meteorology archives and from the Wyoming University web site: <http://weather.uwyo.edu/upperair/sounding.html>.

Microwave imagery came from the U.S. Naval Research Laboratory Monterey web site: https://www.nrlmry.navy.mil/tc_pages/tc_home.html.

Synoptic observations were sourced from Bureau of Meteorology archives and the excellent web site www.meteomanz.com/?l=1.

3. Hurricane Sandy 2012

Large waves, storm surge carry debris impacted Long Beach Island, New Jersey; Mantoloking, New Jersey; Staten Island, New York; Queens, New York; and Westerly, Rhode Island. The worst effects were found in Long Beach Island and Mantoloking^[1,2]. Many of the above locations were 2 metres or less above mean sea level which helps explain the devastating damage. Estimates from the New Jersey Governor's office found

around 346,000 housing units were damaged or destroyed in that state, with 22,000 of those units uninhabitable. The New York governor's office found around 305,000 homes were destroyed in the state, mostly caused by storm surge. The hurricane caused 43 deaths in the state of New Jersey. In New York City 53 civilians died because of the hurricane.

Note the storm force observations near New York City with the northernmost from JFK and the two southern buoys just off the New York Harbour entrance (right frame Figure 1). The wind speeds measured at the buoys were at 5metres above sea level (msl) with high energy waves (peak period 15 seconds) reaching 9.9metres significant wave height and therefore producing extreme surface roughness. Therefore, the best track peak wind speed at landfall of 70knots (one-minute average) appears justified. Also supporting this wind intensity was a measurement from a Texas Tech University Tower near Long Beach, New Jersey, where a 1-minute mean wind of 53 knots (27.3m/s) at a height of 2.25 metres at 0000 UTC 30 October was recorded. This observation can be adjusted to a 10-metre wind of about 68 knots (35.0m/s) using standard adjustment factors. After landfall the hurricane moved inland and quickly weakened.

The tide gauge at Battery Park New York City recorded a record water level of 14.06 feet (4.285 metres) above mean low water level at 0140UTC 30 October 2012 close to the time of the highest storm surge and peak astronomical tide. Therefore, these severe wind and wave conditions at landfall had an almost immediate effect on New York City. On the western end of Long Island Sound a gauge at Kings Point recorded 14.31feet (4.362metres) above mean low water level at 0200Z 30 October 2012 with the peak storm surge of 12.65 feet (3.856metres) at 2250Z 29 October 2012 (which was the highest storms surge measured) and the peak tide there occurred at 0410Z 30 October 2012.

The hurricane force strength winds were averaged over a 1-minute period for Sandy would probably only be assessed a Category 2 cyclone in Australasia where sustained winds are measured over a 10-minute period. Additionally, the population density of New York City and New Jersey is far greater than many coastal locations across the world at the present time. Lessons could be learned from the impact of Sandy in the general expectation that ocean levels and population density will increase in many coastal locations around the Globe over the next century.

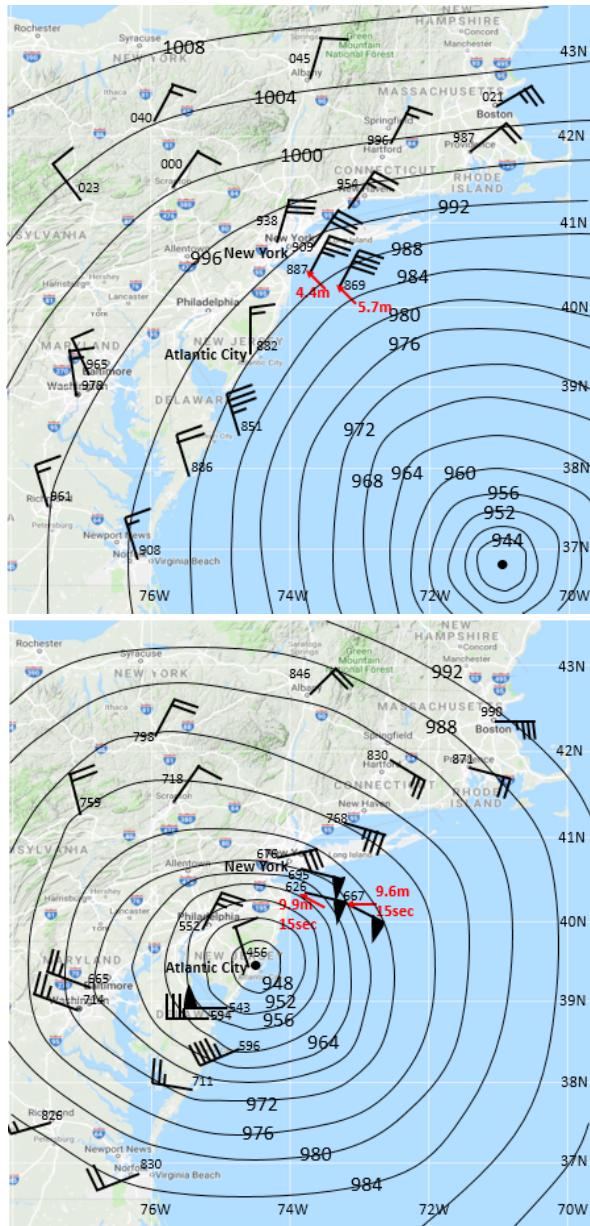


Figure 1. Mean Sea Level (msl) analyses, one-minute wind plots, msl pressure readings last three digits to one decimal place and wave observations (in red) of significant wave height and peak period for 1200UTC 29 October 2012 (Top) and 0000UTC 30 October 2012 (Bottom).

4. Recent Deadly Storm Surge from Xynthia in Europe

A violent windstorm in Western Europe on 26-28 February 2010 was code named *Xynthia*. In France the storm caused at least 51 fatalities with 12 more said to be missing. The French President, Nicolas Sarkozy, expressed alarm that families could be surprised in their sleep and die drowned in their homes. Many victims

drowned in their homes, early Sunday 28 February 2010 as surging waters bashed through aged sea walls.

The La Rochelle area experienced a one in 100-year storm tide. From ^[3] the largest storm surge value of 1.5 metres, which was the largest since 1949, was recorded in La Pallice at La Rochelle around 0300UTC 28 February 2010. The corresponding total water level (during the spring high tide) reached 8.01 m above marine chart datum in La Pallice. From historical data this gave a return period larger than 100 years. On Friday evening 26 February assessment of the storm's potential prior to its impact led to a warning in France for people to stay off beaches and coastal roads. However, this did not warn people that they would be surprised in their homes in the middle of the night by surging waters that smashed through aging sea walls.

Open ocean waves up to 7.5 m high, hitting at high tide, smashed through the sea wall off the coastal town of L'Aiguillon-sur-Mer (see Figure 2). The waves reaching the normally sheltered waters of L'Aiguillon-sur-Mer of course would be much smaller with significant wave height in the order of 2.5 metres. The waves and wind generated a powerful storm surge which smashed through the ancient sea wall. The wall was built in the period of Napoleon. Observations from nearby Pointe De Chassiron (elevation 23 metres) on Oléron Island just to the south of the town at 0300UTC 28 February 2010 reported sustained winds of 46 knots from the west southwest at 0300UTC and sustained winds of 50 knots from 210 degrees at 0200UTC. The wave rider buoy is located around 35 km southwest of Pointe De Chassiron. The buoy registered significant wave heights of Hsig 7.5 metres between 0300UTC 28 February and 0430UTC February and 6 metres or greater between 0130UTC and 0730UTC with waves from 210 degrees turning to 260 degrees over this latter period and peak periods reaching 8.4-8.7 seconds with the largest waves. The peak storm tide at La Rochelle was 8 metres (1.5 metre Storm surge) around the same time at 0300UTC 28 February coincident with high tide.

Note that the pressure gradient for this event peaked in intensity right on the coast near the coastal town of L'Aiguillon-sur-Mer when the high tide occurred (Figure 3). The magnitude of the event must not have been anticipated as the area was not evacuated. On 27th February 2010 the warning bulletins of Météo France announced storm Xynthia. They warned for the possibility of rising water in coastal areas but although various camping sites in the Charente Maritime were evacuated no large-scale evacuation was carried out. In this event, an evacuation of a few thousand people around about 300 to 500 meters from the sea would have saved most of the

lost lives.

Meteorological Factors Leading to the Deadly Storm Surge

Much has been written about the contribution of the aging sea walls and the urbanisation of the area in causing the large number of fatalities but here we look at a crucial period as Xynthia struck the coast as the main meteorological effect.

The 0000UTC 28 February MSL analysis was well forecast by the models particularly the EC and the various tracks show Xynthia at 0600UTC 28 February much

where it lies in Figure 3 but the stalling of the system between 0000UTC and 0300UTC was not highlighted and the NCEP NCAR reanalysis for 0300UTC 28 February does not stall the system (Figure 4). The movement of Xynthia was very slow between 0000UTC and 0300UTC 28 February with 10hPa pressure rises in the Bordeaux area (45degrees N) in the three hours and this caused an intense pressure gradient around the La Rochelle area at 0300UTC. This was when the largest waves and storm surge were recorded in this area.

A report of this event ^[4] used European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalyses

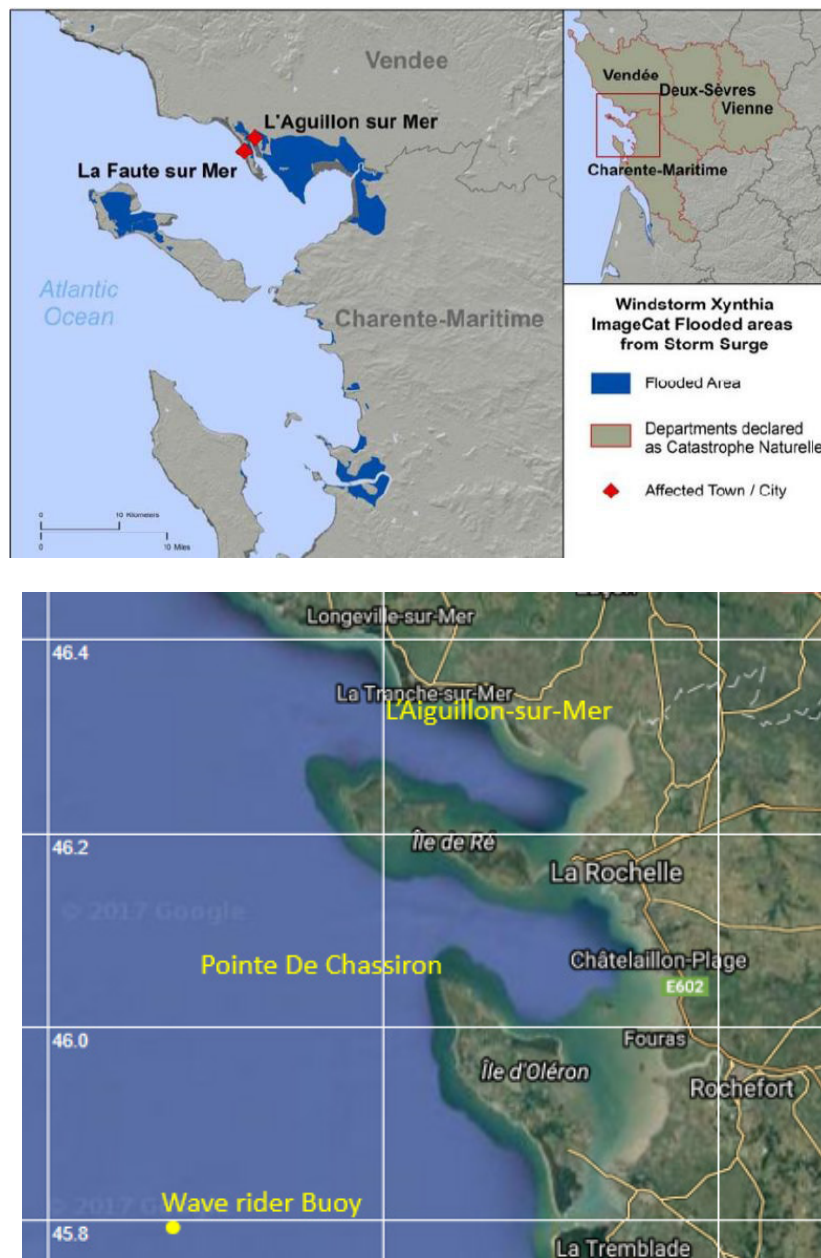
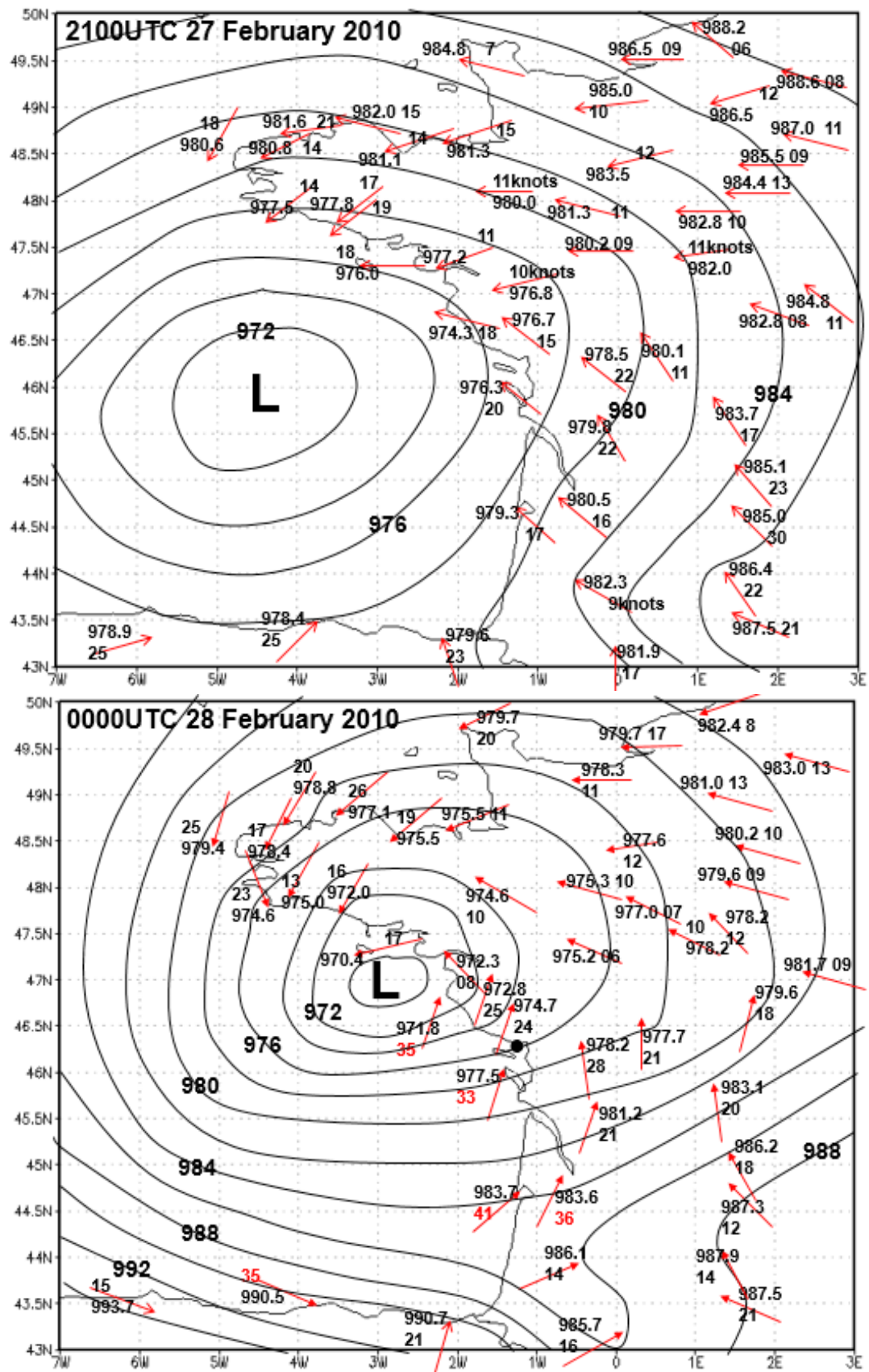


Figure 2. (Top) Worst of the storm surge areas and (bottom) location map.



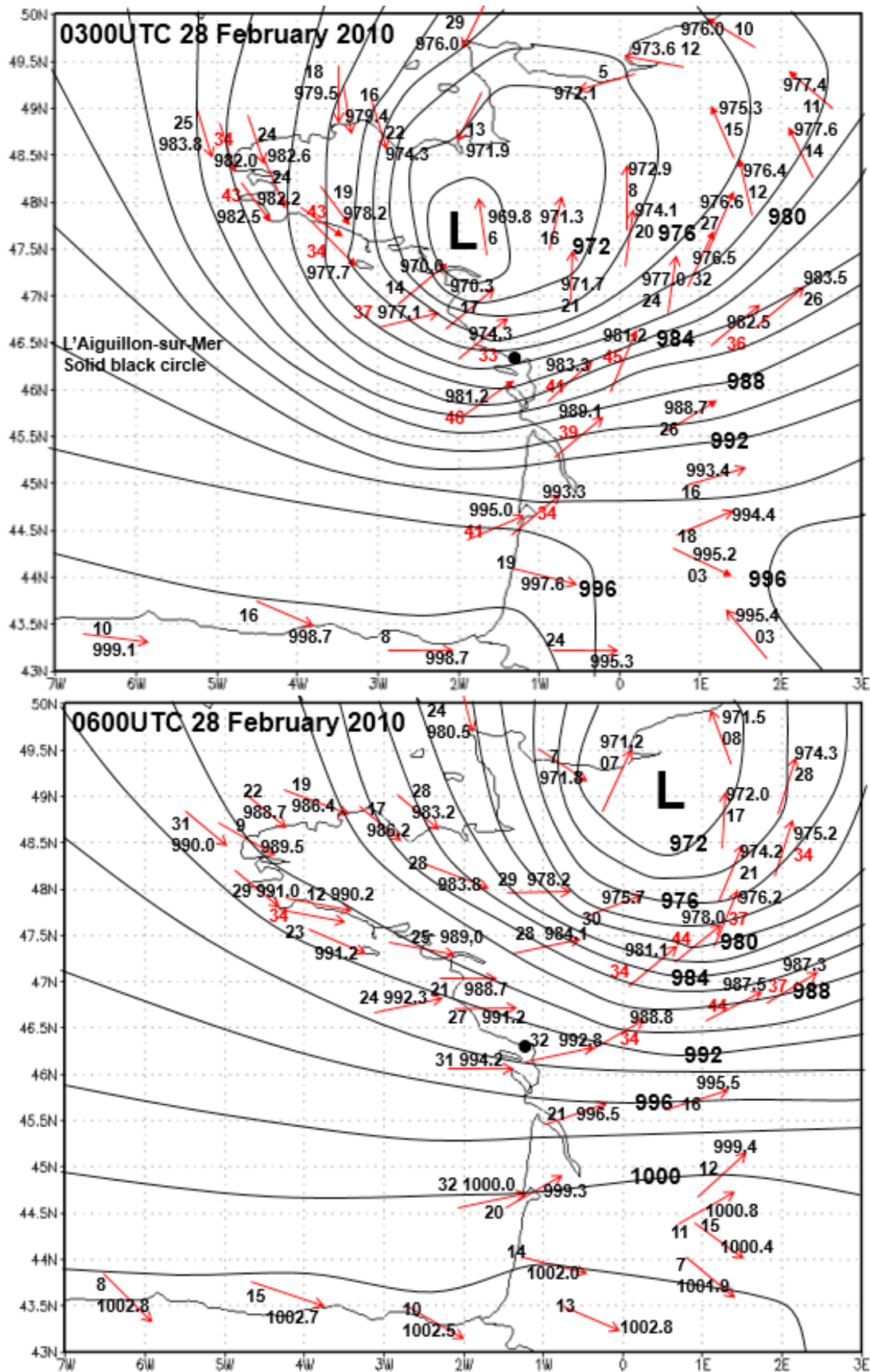


Figure 3. Sequence of the severe extra tropical cyclone X

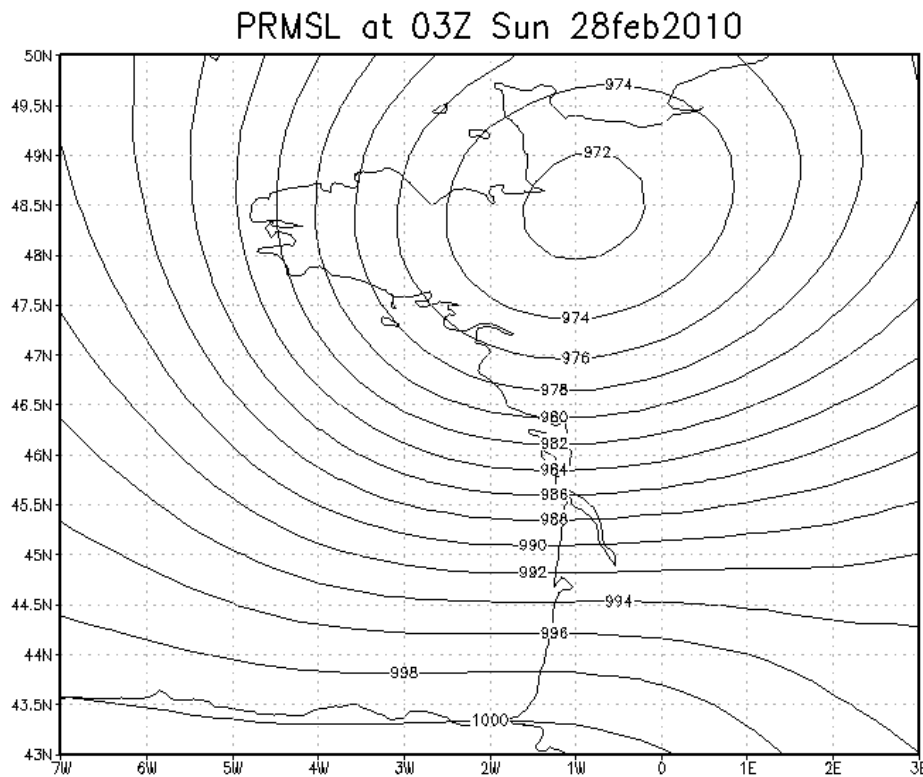


Figure 4. NCEP/NCAR Reanalysis mean sea level pressure analysis for 0300UTC 28 February 2010.

(ERA Interim) at full temporal (six-hourly) so have missed the critical 0300UTC analysis.

Xynthia striking France during February 2010 red arrows highlight the surface wind direction with the mean winds in knots on the arrow tail and gales highlighted in red.

5. World Record Wave Heights

The largest waves ever recorded appear to be associated with fast-moving systems, where the wave generating winds move at similar speeds to the developing wave train, thereby building the waves to phenomenal heights in a process called “resonance”.

Some examples:

1979 UK Fastnet Yacht Race Storm 15 lives lost.

1993 Tropical cyclone *Nina* 3 lives lost Solomon Islands.

1997 Hurricane *Martin* northern Cook Islands 20 lives lost.

1998 Hurricane *Danielle* (marginal Australian Category 3 cyclone) generated significant wave heights to 15.8 metres measured on a Canadian buoy.

2004 Tropical cyclone *Heta* destroyed a village located on a 20metre cliff in Niue.

Using a theoretical model wave resonance was first identified as a serious threat in 1987^[5]. In their theory

there must be large waves present before the theory could work. The low trajectory must have a straight part larger than the horizontal extent of the enhanced wind field and the ratio of V/U in the direction of motion of the low should satisfy $0.25 < V/U < 0.5$ where V is the velocity of the low and U is the component of wind velocity in the direction of motion.

5.1 Sydney to Hobart Storm 1998

Previously, the largest individual wave of 34.1 metres was measured by a qualified observer aboard the USS Ramapo in a typhoon in 1933. The measurement was made by triangulation.

Daryl Jones, pilot of a rescuing helicopter and his crew risked their lives to rescue five sailors from Bass Strait during the ill-fated 1998 Sydney to Hobart Yacht Race. Their story was told to the coroner probing the deaths of six men in the disastrous race. The Coroner, Mr John Abernethy, later said it had been “the most amazing morning I have ever spent on the bench”. But as Sergeant Key, the recuing swimmer explained: “There were people dying out there. We had to have a go.” Senior Constable David Key, Senior Constable Jones and Constable Barry Barclay left Melbourne in bright sunshine that afternoon, heading for Mallacoota. But then the clouds came down and the helicopter was hurled across Bass Strait

at 420kmh, propelled by the vicious storm battering the Hobart fleet.

What he found out later was that Senior Constable Jones was struggling to keep the helicopter above him - flying it at 85 knots just to stay still. He was 30 metres above the water and had a Doppler-based radar system which was bouncing a radio wave off the water and back to the helicopter. He became aware of something coming across the sea towards him, told Constable Barclay to let out more cable, and went up to 45.7 metres. The mass of water which he said was about 300 metres across and looked like a giant plateau passed under him. The altitude instrument went from 45.7 metres to three metres. Thereby the height of the wave was measured as 42.7 metres.

Down in this was Sergeant Key, who said he popped out the back of the wave and free-fell around nine metres, knocking the wind out of himself in the process. Campbell, the person being rescued, suddenly appeared in front of him, injured and almost dead from exposure. "I grabbed his underpants and gave him the biggest wedgy ever and put him in the harness."

Jones was an extremely talented pilot and a highly decorated police officer receiving many awards during his career including the Victoria Police Valour Award, the Australian Federal Group Citation for Bravery, the American Captain Kossler Award for Bravery, the Royal Life Saving Society Bravery Cross and a commendation for Brave Conduct. Therefore, there is little reason to doubt his observations.

A peer reviewed paper ^[6] describes this world record wave height (42.7m), which occurred during this race. These were the highest waves of the event, and photographs were presented in Joubert's paper where waves appear to be as high as 80 feet. Joubert was a highly qualified individual being a retired Professor of Fluid Dynamics from Melbourne University, designer of many yachts in which he competed in the Sydney to Hobart race over the years and a former World War II fighter pilot. His latter experience led him to influence the introduction of seat belts in motor vehicles around the world thus saving countless lives.

There was a pre-existing swell in Eastern Bass Strait leading into the event with Kingfish B wave rider buoy reporting the following significant wave heights from the southwest:- 0100UTC 26 December 1.75metres, 0900UTC 26 December 2.5metres and 1300UTC 26

December 3.2metres.

Figure 5 covers the life of the storm and a low developed near Wilsons Promontory by 6am 27 December 1998. By 3pm the low had moved 237km or 128nm and heading towards a bearing of 80° and Mills ^[7] showed that the storm had reached Beaufort Scale Force 12. This is a forward speed of 16 knots and from ^[5] at this speed of movement resonance can be effective for winds up to 4 times this speed i.e., greater than 60knots. Additional factors which help resonance are for large waves to be present before the event (this was the case) and for an elongated straight line wind field in the wave generation zone, which from Figure 5 this condition was also met. Therefore, in addition to the large waves which were present in Bass Strait that day, a localised zone of extreme waves was generated in the area immediately north of the low and moved with the low and continued to grow in this zone.

5.2 WM0 World Record Wave Height (Significant Wave Height from a Buoy)

World Meteorological Organization expert committee has established a new world record significant wave height of 19 meters (62.3 feet) measured by a buoy in the North Atlantic. The significant wave height (H_s) is defined usually mean wave height (trough to crest) of the highest third of the waves ($H_{1/3}$). A more precise definition is four times the standard deviation of the surface elevation - or equivalently as four times the square root of the zeroth-order moment area of the wave spectrum. The symbol H_{m0} is usually used for that latter definition. The significant wave height may thus refer to H_{m0} or H_s ; the difference in magnitude is negligible for practical purposes.

The Buoy 64045 is located at latitude 59.10 degrees North and longitude 11.401degrees West. On 4 February 2013 0600UTC the buoy reported the mean wind as 260/43knots, msl pressure as 986.7hPa and the significant wave height as 19.0m with an average period was 15 seconds. The weather charts leading up to the record wave height are shown in Figure 6.

The WMO Commission for Climatology's Extremes Evaluation Committee classified it as "the highest significant wave height as measured by a buoy". The Committee consisted of scientists from the United Kingdom, Britain, Canada, the United States of America, and Spain.

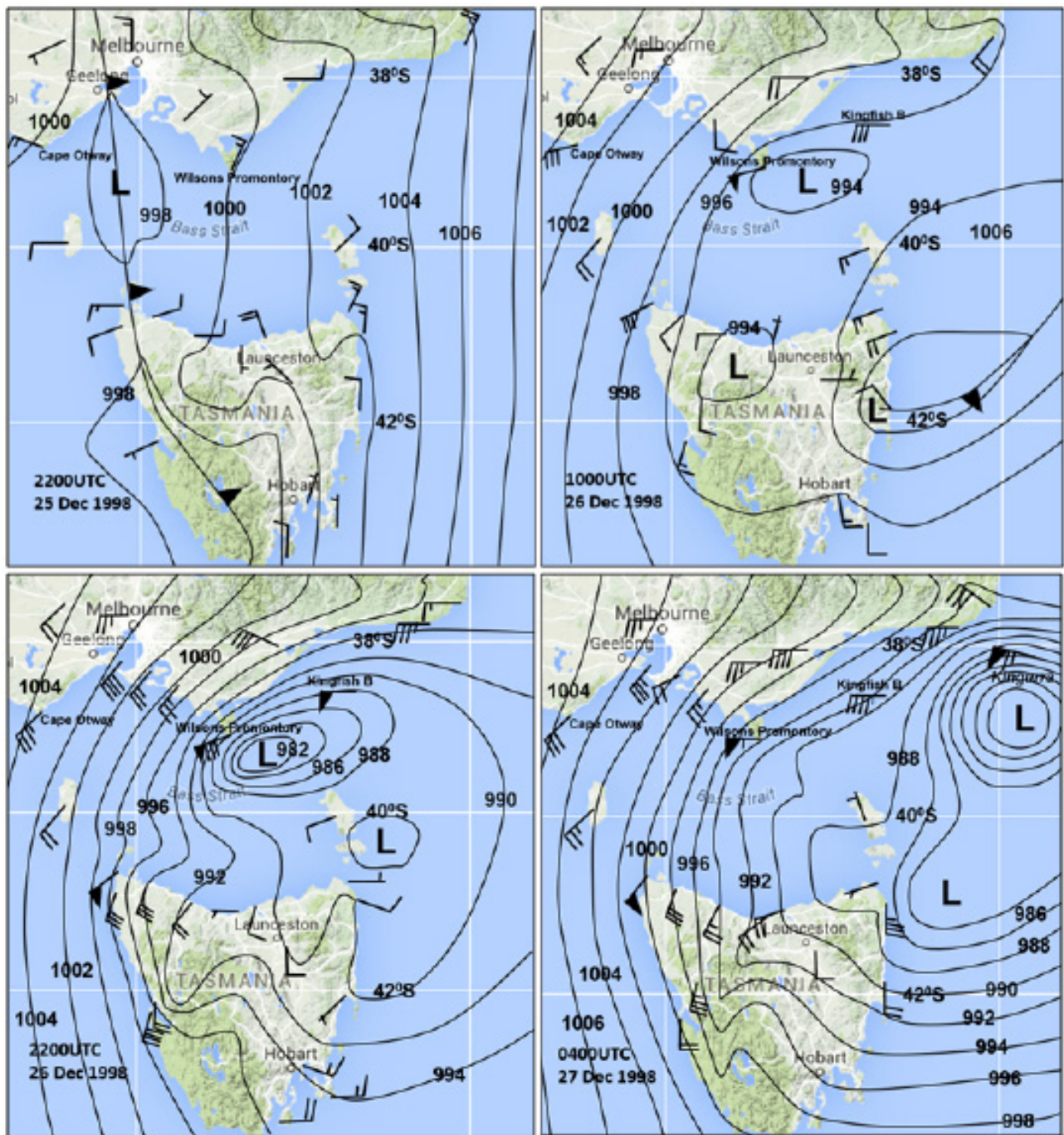


Figure 5. MSL pressure analyses with observations over Tasmania and Victoria from 9am EDT 26 December 1998 to 3pm 27 December 1998. The wind observations near the centre of the low in the bottom right frame is from Joubert's boat the Kingurra.

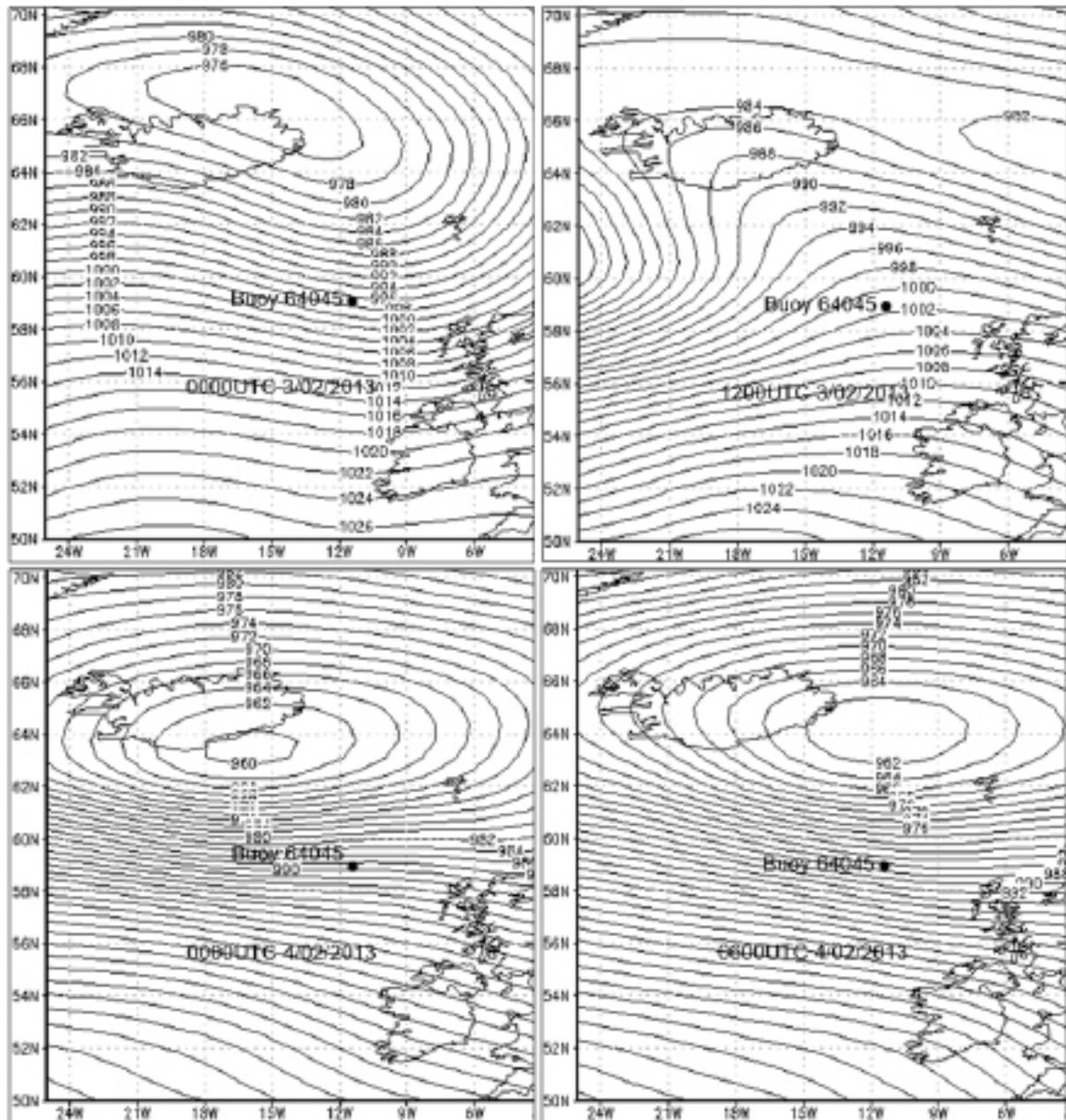


Figure 6. Mean Sea Level Pressure distribution from 0000UTC 3 February 2013 to 0600UTC 4 February 2013 during the period when Buoy 64045 measured the record significant wave height.

6. Australia East Coast Wave and Storm Surge Damage

Around the Australian coast, many houses are vulnerable to wave attack. Nearly 39 000 buildings are located within one hundred metres of sandy coastlines and therefore at risk from erosion from large waves Coastal Erosion | Geoscience Australia (ga.gov.au). The New South Wales coast is particularly vulnerable from east coast lows (ECLs) and tropical cyclones (TCs).

6.1 1967 Events Tropical Cyclone Dinah January 1967

From a study of normalised insurance losses ^[8] from 1966 to 2017 showed that TC Dinah January 1967 when it crossed Fraser Island and came close to the Gold Coast caused losses of 4,685 millions of normalised Australian Dollars (AUD) placing it a close second in TC impacts just behind the infamous Tracy which struck Darwin on Christmas Day 1974.

Dinah 24-31 January 1967 probably generated the largest waves observed over Southeast Queensland over

the last century. *Dinah* caused severe damage at Heron Island initially on its passage south from the tropics and then passed over Fraser Island recording a central pressure of 944.8 hPa at Sandy Cape Lighthouse. Although well off the coast many trees were blown down from Rockhampton to Grafton in Northern New South Wales (see MSL analyses in Figure 7). Houses were unroofed and crops damaged from Bundaberg to Northern New South Wales.

Renowned surfer Bob McTavish in his autobiography reported he just escaped with his life when wave run up from *Dinah* engulfed him and his friends on the top of a cliff 25metres high near Noosa. Around Sandgate in Moreton Bay seawater 1.5 metres deep came into houses. More than one hundred homes suffered saltwater

inundation in the Bayside suburbs of Brisbane and at Cribb Island one house was washed into the sea. At nearby Nudgee beach the sea wall was destroyed, and houses were flooded with 0.66 metres of salt water. Storm surges also affected the Gold Coast and water lapped the decking of a bridge which was about 1.5 metres above the highest astronomical tide. A road fronting Surfers Paradise Beach on the Northern Gold Coast collapsed from attack by large waves and wave run up came over the Road at Snapper Rocks and caused damage at Rainbow Bay on the Southern Gold Coast. A similar storm surge occurred on the Tweed River in Northern New South Wales isolating Fingal with six houses awash. The msl sequence (Figure 7) shows the incredible pressure gradient of *Dinah* as it passed Southeast Qld and Northern NSW.

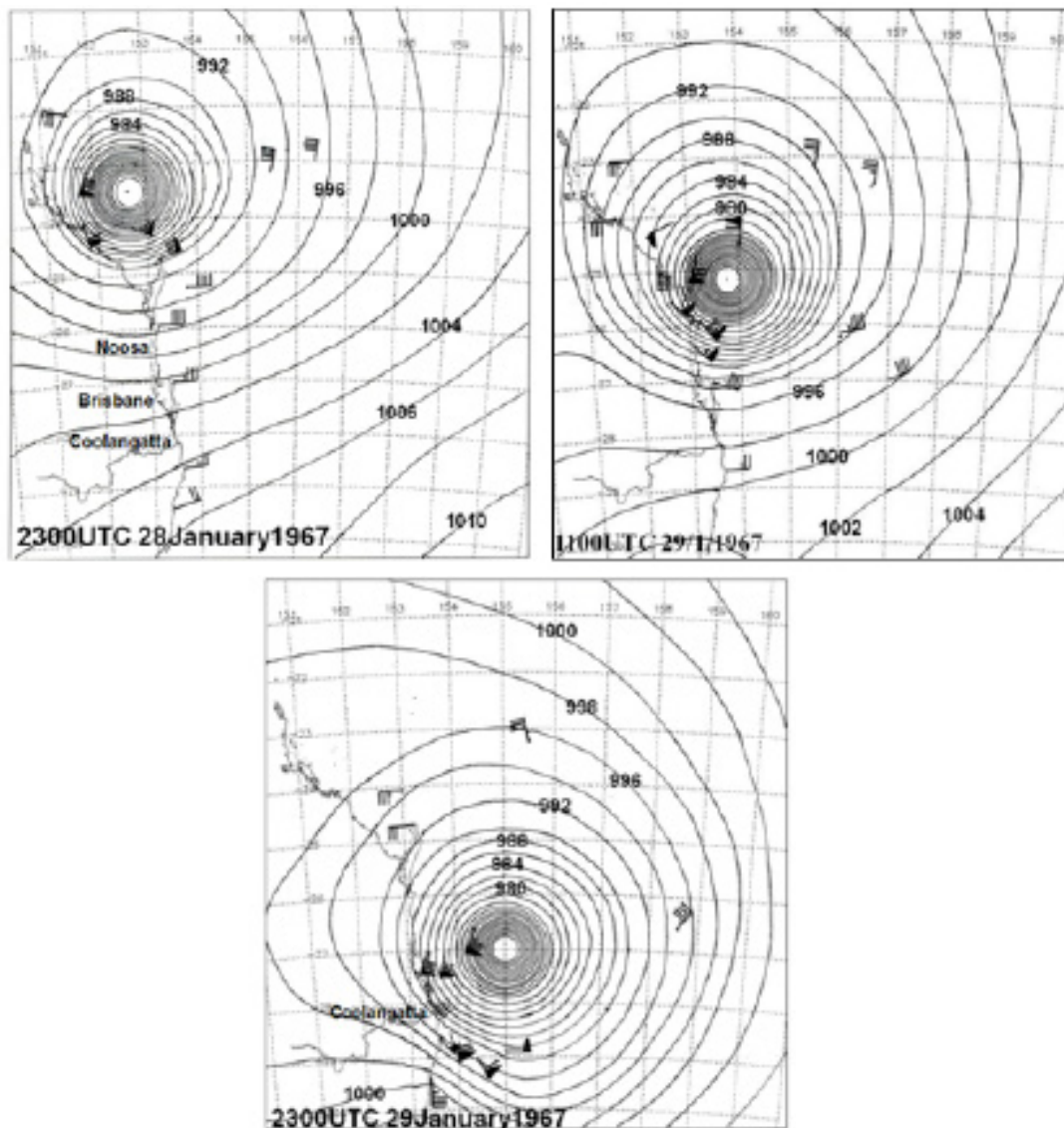


Figure 7. MSL pressure analyses for Severe tropical cyclone *Dinah* from 2300UTC 28 January 1967 to 2300UTC 29 January 1967. Coolangatta marks the position of the God Coast.

Following Dinah an ECL on 26 June 1967 four tropical cyclones then three June East Coast Lows (ECLs) produced unprecedented erosion on the Gold Coast. The ECL on 26 June 1967 (see Figure 8) was the culminating storm surge event and the whole series resulted in 9 billion normalised Australian dollars (AUD) insurance losses^[8] making it the worst series of Australian weather events in a year over the period since 1966. During the ECL of 26 June 1967 a volunteer army of 5000 people placed around 100,000 sandbags along the foreshore of the Gold Coast to protect houses from the raging ocean waves.

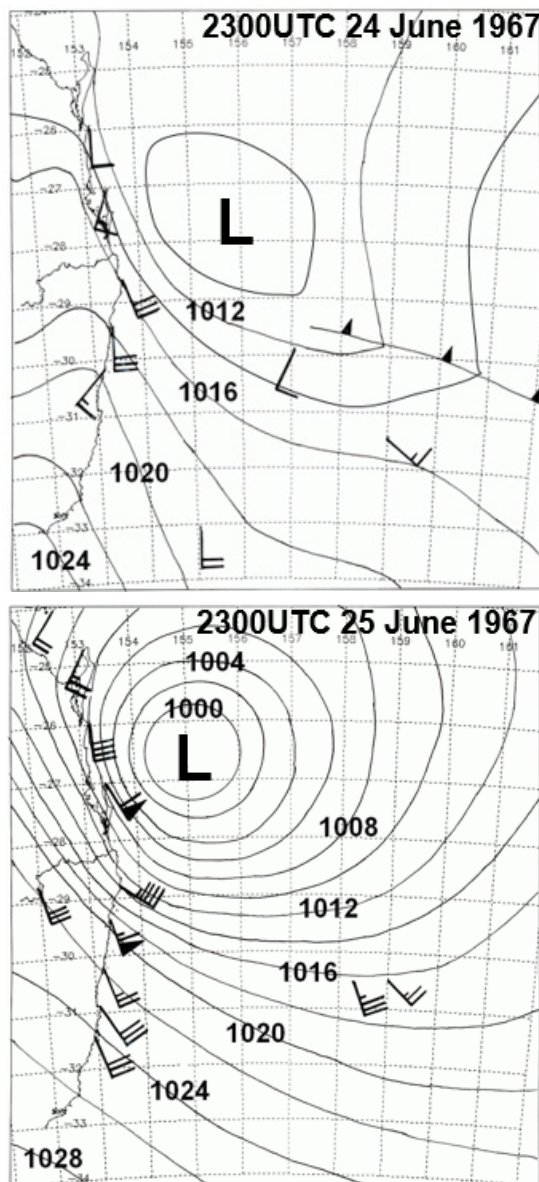


Figure 8. Mean Sea level pressure analyses with mean wind observations for 2300UTC 24 June 1967 (Top) and for 2300UTC 25 June 1967 (Bottom). Normal wind plotting convention is used here and in following figures where half barb, barb and flag representing 2.5 m/s, 5 m/s, and 25 m/s.

Another series of disastrous storms occurred over Southeast Queensland during the late nineteenth century^[9]. Following this a sand spit began to extend northwards along the northern parts of the Gold Coast extending today up to South Stradbroke Island. It is about 200 to 400metres wide and 5 to 10metres in elevation. The average linear growth of the Spit from 1910 to 1968 was 61metres per year or 6km/century^[9]. The supply of sand for this spit can be explained by ocean currents. A boundary current, the East Australian Current, moves down the east coast of Australia transporting warm water from the Coral Sea southwards. The meandering current pinches off eddies and the current speeds at the edge of these eddies can be up to 4 knots. An inshore northward current generated largely by wave action brings sand to the southern Gold Coast and then removes it from the northern Gold Coast. This was found from the Delft Report^[10] in their investigation into the disastrous beach erosion on the Gold Coast in 1967. The results from this report showed that the littoral transport was mainly directed northwards and extended seawards out to about 900metres from the shore. South of the Tweed River near the Gold Coast southern border the net northward transport was calculated as 500,000 cubic metres per year which is of the same order of the sediment supply of the nearest NSW Rivers. The 1967 storms removed 8 million cubic metres of sand from Gold Coast beaches.

6.2 Sygna Storm May 1974

An ECL on 26 May 1974 affected the Collier Sygna waiting for a load of 50,000 tonnes of coal with measured winds gusting to 171 km/h (92 knots) and was driven ashore on Stockton Beach. The storm resulted in unprecedented beach erosion around Sydney and the New South Wales (NSW) South Coast Ocean beaches including beaches inside Sydney Harbour and Botany Bay^[11]. Figure 9 shows the intensification of the storm.

Wind observations from anemometers near Newcastle:

92 knot gust at Nobby Signal Station 1610UTC 25/5/1974

78 knot gust at Munmorah Lake Macquarie 1613UTC 25/5/1974

85knot gust at Kooragang Island at 1610UTC 25/5/1974

also 70 knot gust Mascot (Sydney).

There were at least 9 deaths One a nurse in a traffic accident at Wollongong in torrential rain, another a 19-year-old youth who was swept from his car into the ocean at Terrigal on the central coast, a 24-year-old man who was swept into a flooded creek at Mulgoa, near Liverpool in Sydney's outer western suburbs, and a man whose body was picked up by a freighter near Newcastle

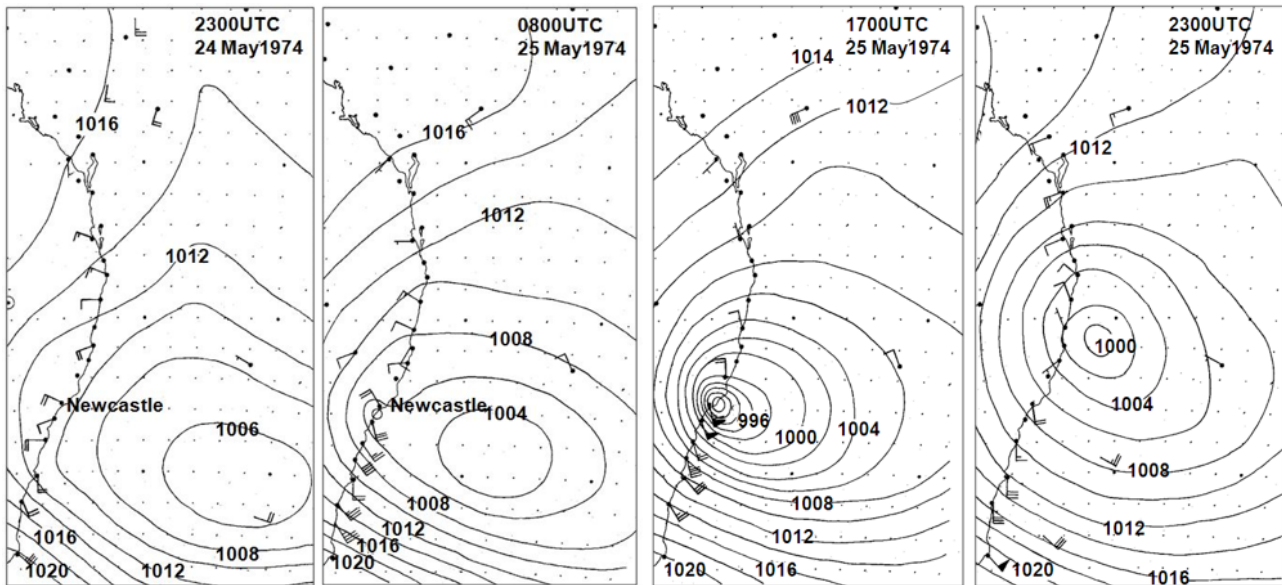


Figure 9. Mean Sea level pressure analyses with mean wind observations for 2300UTC 24 May 1974 (left), 0800UTC 25 May 1974 (second from left), 1700UTC 25 May 1974 (second from right) and 2300UTC 25 May 1974 (right).

this afternoon after the one-man yacht *Elsie* was wrecked. Bodies were washed up at Copacabana Beach on Tue 28th, Taronga Zoo, Gosford on Monday 27th and two were lost on the yacht *Nimbus II*.

Hundreds of homes were wrecked, hundreds more unroofed and scores of small boats were driven aground and smashed. Two freighters were driven aground at Newcastle, and one, the 52,000-ton Norwegian freighter *Sygn* broke up on the beach. One of the worst-hit areas was Manly, where the famous swimming pool and its beachfront were wrecked.

At Kiama on the South Coast police evacuated homes fronting the sea, as wind driven seas, combined with a high tide, crossed the road into housing areas.

The storm, which lasted only a few hours in the Newcastle area, destroyed several houses and a hotel. One house was burnt down, and a light aircraft was wrecked at Hexham Airport.

At nearby Morrisett, the Church of England was lifted by winds and moved 6 metres (20ft) off its foundations. Three houses in the Lake Macquarie area were demolished and one brand new home at Swansea “disappeared” at the height of the storm. Parts of the house and its foundations were found more than a mile away.

From a study of weather charts, it was estimated significant wave heights in the Sydney area reached 9.2 metres. Storm surges were large with a surge of 0.59 metres at Fort Denison, Sydney was measured at 1600UTC 25 May 1974 (2am EST 26th). Later a storm surge of 0.57m was recorded at Coffs Harbour at

0600UTC 28 May 1974 (4pm 28th EST).

7. Long Period Waves from Distant Storms

Figure 10 shows how long period waves affect the number of rock fisher deaths. Tropical cyclone forecasters should be aware of the danger associated with long period waves arriving from distant storm. Over the years these waves have caused many deaths in Pacific Islands and on the Australian east Coast.

These waves can be extremely dangerous for the following reasons:

- (1) They can double in height if they encounter a bar or reef which is steeply sloping seaward.
- (2) Vessels approaching a coastal bar from the sea will not notice the danger as the deep water height may be 3m and the wave length 400m resulting in just a gentle roll.
- (3) There is often a long time between the larger sets in these events which make swimmers and boaters think it is quite calm only to be engulfed by a large set after they have swum off or steamed out to sea.
- (4) The rips are much worse than normal as wave set up is much higher with greater volumes of water moved around. People have been swept out to sea from very shallow water or even in some cases just walking along the waters edge in sloping beaches.
- (5) They often occur in sunny light wind conditions which encourages marine activity.

Here we describe an Indian Ocean even which caused loss of life and widespread damage throughout the tropical Indian Ocean region.

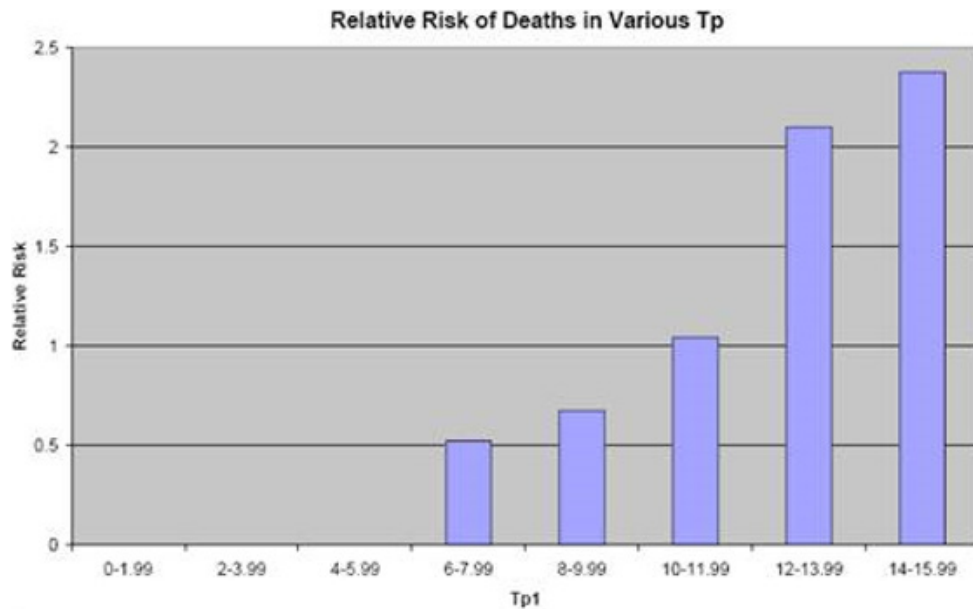


Figure 10. Graph of rock fisher deaths vs peak period, based on 10 years of New South Wales mortality data. The analysis was done by Ray Rice (Cardno) for the NSW Marine Consultative Committee.

7.1 Indian Ocean Impacts

Waves with heights reported to reach up to 11 metres devastated France's Reunion Island in the Indian Ocean when it slammed into the southern port of Saint Pierre on 12 May 2007. Wavelength ranges of 350 - 433 meters corresponding to periods of 15-17 seconds were observed. The waves smashed the southern port of Saint Pierre, leaving two fishermen missing, causing several piers to collapse, and flooding several homes and businesses. Six people disappeared at sea in Mauritius and Rodrigues Islands.

In Indonesia high waves hit coastal areas of Indonesia devastating houses, expelling tourists from beaches, preventing fishermen from going out to sea, and at least one person was lost.

Over the Maldives, based on an assessment conducted by the government, wave surges had resulted to flooding of the islands. This led to the evacuation of approximately 1649 people, damage to 217 housing units, destruction of 43 vegetation sites, damage to 15 sea vessels, and partial damage to several harbour and jetties, in addition to eroding some coastlines.

7.2 Synoptic Situation

The weather system which generated these waves is shown in Figure 11 and it consisted of a very intense pressure gradient between a high-pressure ridge over southern Africa and a low pressure/trough system near 50 degrees South. This pressure gradient produced very large

fetches of gale to storm force winds along a great circle path towards the tropical Indian Ocean.

7.3 Long Period Wave Event July 2001

Long period waves generated from a low between New Caledonia and New Zealand impacted on the New South Wales Coast and Southern Coast of Queensland early in July 2001. The synoptic situation is shown in Figure 12. Wave-rider buoy data at Brisbane and Sydney are shown in Figures 13 and 14.

The 11-metre cruiser "Just Cruisin" was found wrecked on Spitfire Bank near the entrance to Moreton Bay near Brisbane. The boat had been flipped over by the large breakers on 6 July 2001 and the bodies of the crew of four were never found.

A yacht was wrecked by large waves on a sandbar near Fraser Island north of Brisbane and the lone yachtsman was never found. Also, a woman was reported missing after being swept off her dinghy on the 7th of July near Jumpinpin Bar (Southern Moreton Bay). Farther east, a French yachtsman was found drowned near his stricken yacht in the Norfolk Island area. In New South Wales 2 rock fisherman were swept to their deaths, one on the South Coast at Twofold Bay and the other near Cronulla in Sydney.

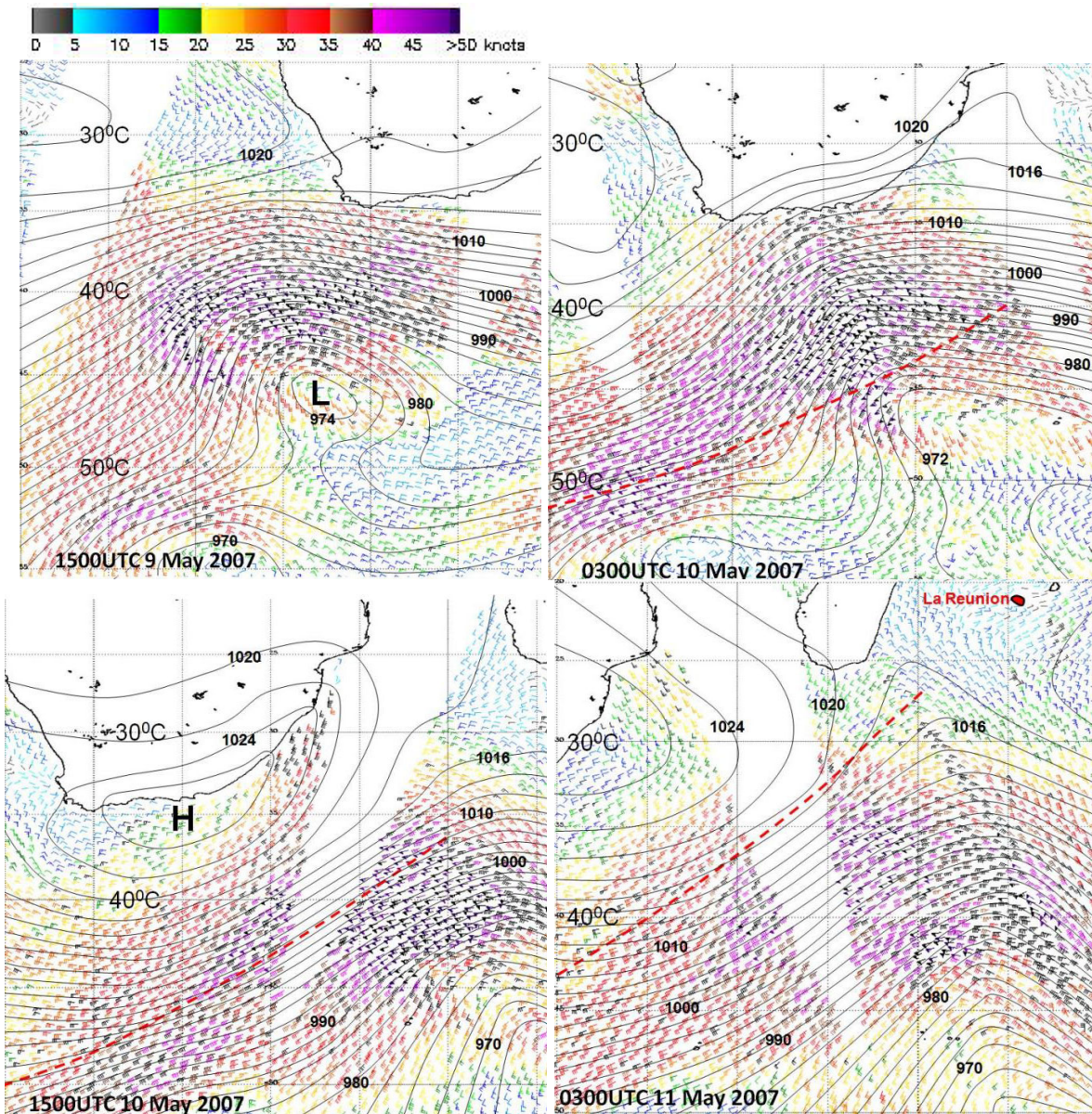


Figure 11. Mean sea analyses overlaid on quikscat images from 1500UTC 9 May 2007 to 0300UTC 11 May 2007. The dashed red line is a great circle path to La Reunion Island.

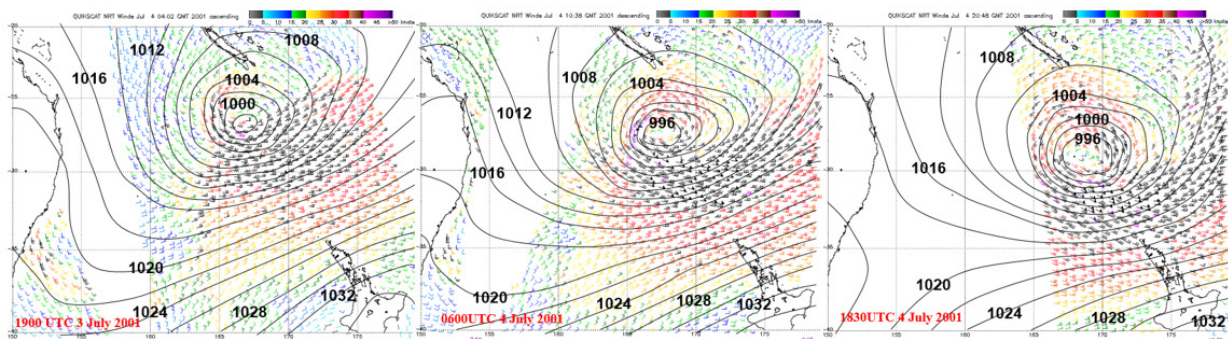


Figure 12. MSL sequence overlaid on Quikscat imagery 1800UTC 3 July 2001 (1900UTC Quikscat) to 1800UTC 4 July 2001 (1830UTC Quikscat).

Date/time UTC July 2001	Hsig (metres)	H max (metres)	Peak energy period
05/0000	2.1	3.5	10.5
05/0300	2.0	3.6	12.1
05/0600	2.5	4.1	11.5
05/1200	2.8	4.9	13.3
05/1800	3.4	5.4	14.5
05/2300	4.0	6.5	15.1
06/0530	3.7	5.7	15.9
06/0600	4.2	7.9	15.0
06/0800	4.3	5.4	15.0
06/0900	3.9	6.6	15.1
06/1130	3.7	5.8	15.6
06/1700	3.7	6.0	15.9
06/2000	3.8	5.5	14.6
07/0000	3.4	5.1	14.3
07/0600	2.9	4.9	14.0

Figure 13. Brisbane wave-rider buoy data showing the largest long period waves arriving on the morning of the 6 July 2001 local time and lasting through the 7 July 2001.

7.4 Storm Surge from Large-long Period Waves at Majura in the Marshall Islands

A huge southerly swell was generated by a severe winter storm (Figure 15). On the 7-8 June 1994 large southerly surf eight to 10 feet high (3.7m to 4.6m) struck the

Marshall Islands north of the equator (Figure 16). Damage was substantial at Majuro due to seawater inundation of one to 3 feet (30 to 91cm) with accompanying ocean floor debris. The sea flooded 120 dwellings, damaged infrastructures and closed the airport for 48 hours. The high surf lasted for two days and was especially intense during several high tides. The path taken by the southerly swell is shown in Figure 16.

A local Government High Surf Evaluation on June 9 and 10, 1994 stated that on June 9 and 10, 1994 unpredicted high surf compounded by high tides ravaged the Majuro Atoll. This caused severe damage to the airport seawall, long term damage to 30% of the airport water catchment system, significant debris, the landfill (build on the ocean side of the atoll), housing and roads.

7.5 Other Effects from the June 1994 Event

A fleet of yachts were hit by the intense low between Auckland and Tonga. In an epic rescue mission 21 persons were rescued. However, seven yachts were abandoned and three people tragically lost their lives. The yacht *Destiny* read wind speeds, from an electronic anemometer, of 75 to 80 knots. The New Zealand Air Force's rescue Orion P3 aircraft calculated the surface wind speeds as 70 to 80 knots. This aircraft flew at an elevation of 200 feet where they calculated that the highest waves reached 30m which was like the estimates from the stricken yachts.

MHL Sydney: 7 July 2001

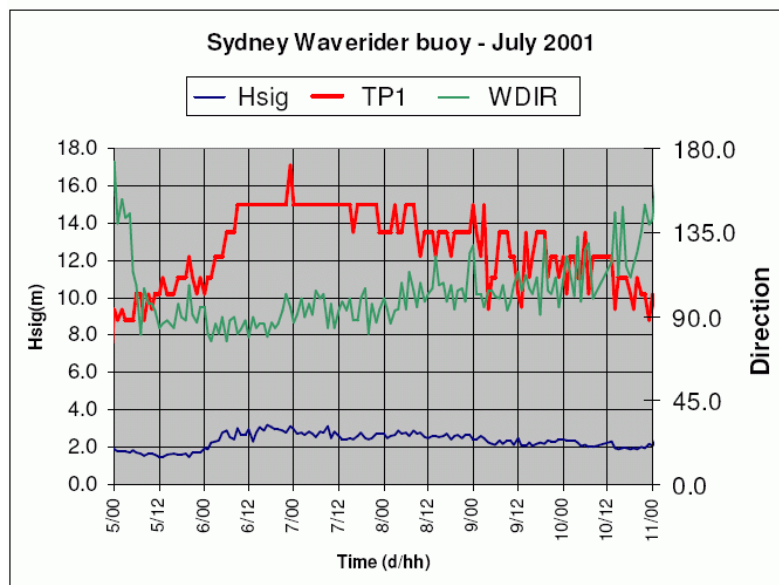


Figure 14. The long period swell reached Sydney around noon on the 6th local time and was maintained through the 7 July 2001.

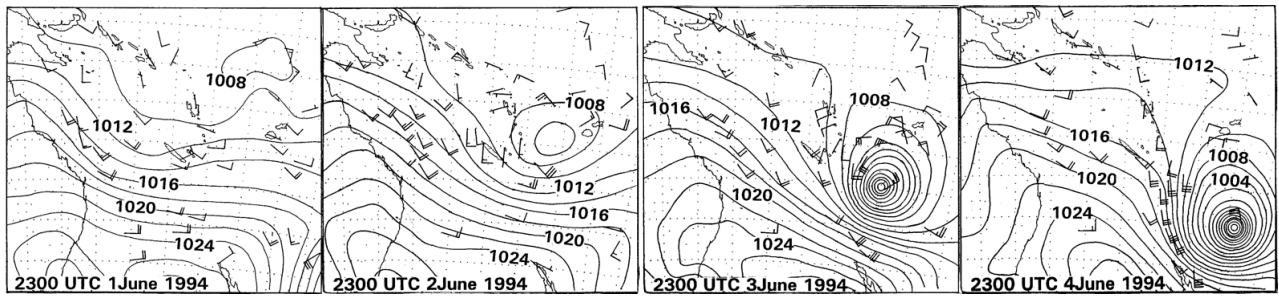


Figure 15. Mean Sea level pressure distribution and mean wind observations 2300UTC 1 June 1994 to 2300UTC 4 June 1994.



Figure 16. Path of the strong Southerly swell.

8. Bay of Bengal Cyclones

The worst known fatalities from ocean effects occur when tropical cyclones make landfall in the Bay of Bengal. The concave shape of Bays ensures water gets concentrated or funnelled as the cyclone moves into the bay. What makes matters worse in the Bay of Bengal are high sea surface temperatures, which can trigger extremely strong cyclones.

The deadliest cyclone there was the 1970 Bhola cyclone that struck East Pakistan (present-day Bangladesh) and India's West Bengal on November 11, 1970. At least 500,000 people lost their lives in the storm, primarily because of the storm surge that flooded much of the low-lying islands of the Ganges Delta.

Preparedness has improved since then and when the Cyclone Amphan approached the Bay of Bengal in May 2020 approximately 4.2 million people were evacuated in coastal India and Bangladesh, with roughly 2 million from

India and 2.2 million from Bangladesh.

An estimated storm surge 5 metres (16 ft) inundated a wide swath of coastal communities and communications were severed. The greatest inundations were expected in the Sundarbans, where flooding could extend 15 km (9.3 mi) inland. Due to the evacuations and storm shelters fatalities from storm surge were almost eliminated. At least 86 people died in West Bengal most of the fatalities were due to electrocution or the collapse of homes. In Bangladesh at least twenty people died in storm-related incidents. Figure 17 shows a microwave image of Amphan as it approached Sagar Island and Figure 18 shows critical observations at Sagar Island, Nimpith and Canning as the cyclone moved into the coast. At 4.00pm (1010UTC) the centre of Amphan was close to Sagar Island with a central pressure of 948.5hPa. At 6:00pm (1210UTC) it was near Nimpith at 953.0hPa and at 7:20pm (1330UTC) it was near Canning at 965.0hPa.

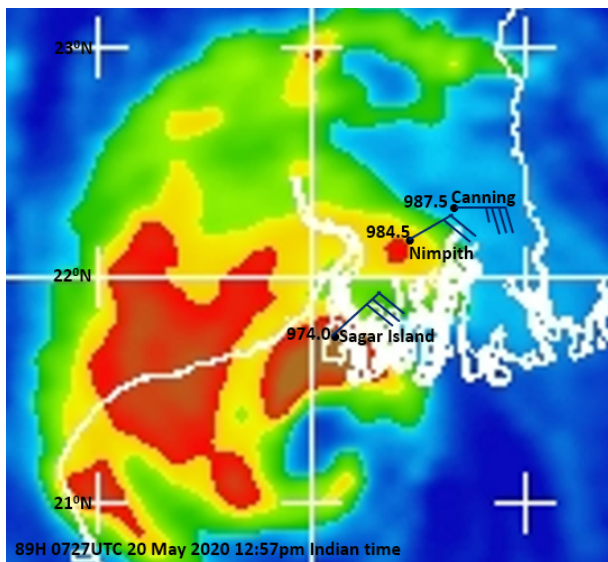


Figure 17. Microwave image 0727UTC 20 May 2020 with sustained wind observations and MSL pressure (hPa) at Sagar Island, Nimpith and Canning.



Figure 18. Observations at Sagar Island, Nimpith and Canning from anemograms.

9. Conclusions

The author's involvement and interest with the above storms were listed in the introduction. Large waves and storm surges reaching the coast can cause significant damage and loss of life. This was the case with Hurricane Sandy in 2012 which caused massive damage and loss of life in New York City and New Jersey with 96 fatalities. It has become a benchmark study for events around the globe in coastal areas which are expected to be affected by rising sea levels with increasing population in the coming decades. A European storm was studied for such a comparison and displayed a deadly forecasting problem when these storms intensify right on the coast. A world record individual wave height event generated by the trapped fetch phenomena and measured by an Australian rescuing helicopter pilot in 1998 is discussed and compared with World Meteorological Organisation ratified significant wave height record in a severe weather system off Scotland. Weather systems developing large waves along the Australian sub-tropical east coast are scrutinised. The impacts from long period waves are assessed as well as an unexpected impact from waves in the Marshall Islands of unknown origin (at the time). Adaption strategies appear to be reducing the number of fatalities from deadly storm surge events in the Bay of Bengal.

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