



CYCLONE TESTING STATION



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Natural Hazards Research Australia

TC Narelle, Queensland, NT, WA Damage to Structures

CTS Technical Report No 72



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TC Narelle, Queensland, NT, WA Damage to structures

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TC Narelle, Queensland, NT, WA – Damage to structures

1. Tropical cyclone 2. Wind speed 3. Damage to buildings 4. Damage to buildings – Natural disaster effects
5. Wind damage 6. Wind-driven rainwater

LIMITATIONS OF THE REPORT

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Executive Summary

Severe TC Narelle crossed Cape York Peninsula in Queensland, Eastern Arnhem land in the Northern Territory and near North West Cape in Western Australia. The most significant wind gusts over land were in the North West Cape in WA and these were measured at 61 m/s (around 71% of the design wind speed for importance level 2 buildings such as houses in this area). There was also damage at Coral Bay where the wind speed was estimated at 50 m/s (65% of the design wind speed for houses). The damage was less at Carnarvon, which is now in wind region C where the wind gusts were measured at 42 m/s (63% of the design wind speed for houses).

A significant number of buildings in the investigation area showed signs of rainwater ingress. Water in houses that were free of structural damage came through flashings, overflowing box gutters and valley gutters. Water also came through undamaged windows through defective seals and through weepholes. In some cases, water came around the edge of windows where the seals between the window frame and the building had been omitted or were no longer effective.

Fewer had structural damage. Structural damage to some buildings was observed where there had been some deterioration of structural components. This was particularly prevalent in verandas where posts had deteriorated near ground level or light gauge metal connectors had rusted. Where verandas had detached, they often damaged the house causing significant water ingress. More recent buildings had water damage to linings and contents. A few structures were damaged due to internal pressure.

A number of roof mounted attachments had failed due to the winds in TC Narelle. In some cases, it was because of deterioration, and this highlighted the need for corrosion protection on attachments to match the site. This particularly applied to satellite dishes and air conditioners. Where the attachments were only attached to the roof sheeting, it caused damage to the roofing which led to water ingress problems.

All roof attachments in cyclone areas should be rated for cyclone winds. This includes solar panels and their attachment systems. Some evidence of deterioration of solar panel fixings due to low cycle fatigue was seen. Solar panels also became wind borne debris that has affected neighbouring properties.

Some smaller shade structures were seen in towns and associated with buildings. Larger shade structures were associated with agriculture near Carnarvon. Where shade structures were taken down, they could be replaced and returned to function soon after the passage of the cyclone, but where they were not taken down, they were generally no longer functional and may have presented a hazard for nearby structures.

While there were relatively few habitable buildings that were structurally damaged in the region investigated, there were many that had some level of water damage. Any water coming into the roof space above the ceiling caused ceiling damage, even if the hole through which the water entered was very small. Water damage can cause loss of functionality of buildings even if wind speeds are less than the serviceability wind speed and there is no structural damage to the building. There were some cases in which water damage seen after TC Olwyn in 2015 was repeated in TC Narelle. This underlines the importance of rectifying the water entry point (e.g. fix flashings, seals, gutters, etc.) and not just repairing the interior damage such as replacing damaged linings.

Acknowledgements

The authors thank the residents of the affected Pilbara and Gascoyne communities who generously assisted with this study by volunteering information and inviting the authors onto their properties, and to the staff of SES and DFES stationed in Geraldton, Carnarvon, Exmouth and Karratha for arranging logistics that facilitated the investigation in WA.

The authors also thank staff from Queensland SES, QPD, QFD and Cook Shire for providing images, data and information on effects of the tropical cyclone in Cape York Peninsula, and for NT SES for providing information on effects in the NT.

During this investigation, the CTS team worked closely with Building and Energy, and the Department of Fire and Emergency Services (DFES) WA. The collaboration between the three organisations enabled a coordinated, efficient, and effective approach to the investigation that increased the amount of data and information gathered. The authors particularly acknowledge the support given by:

- **Building and Energy** – particularly Paul Da Costa.
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- **The Bureau of Meteorology** – especially Joe Courtney for providing feedback and the BoM summary information.

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1. Introduction

This report covers damage to structures from Severe Tropical Cyclone Narelle that crossed the Cape York Peninsula coast in Queensland on 19/03/2026 as a category 4 tropical cyclone, Eastern Arnhem land on 21/03/2026 as a category 3 tropical cyclone and near NW Cape in Western Australia on 27/03/2026 as a category 4 tropical cyclone. All three crossings were as a severe tropical cyclone. The path of TC Narelle as the last advice issued by the Bureau of Meteorology on 28/03/2026 is shown in Figure 1-1.

Issued at 5:43 am AWST Saturday 28 March 2026.

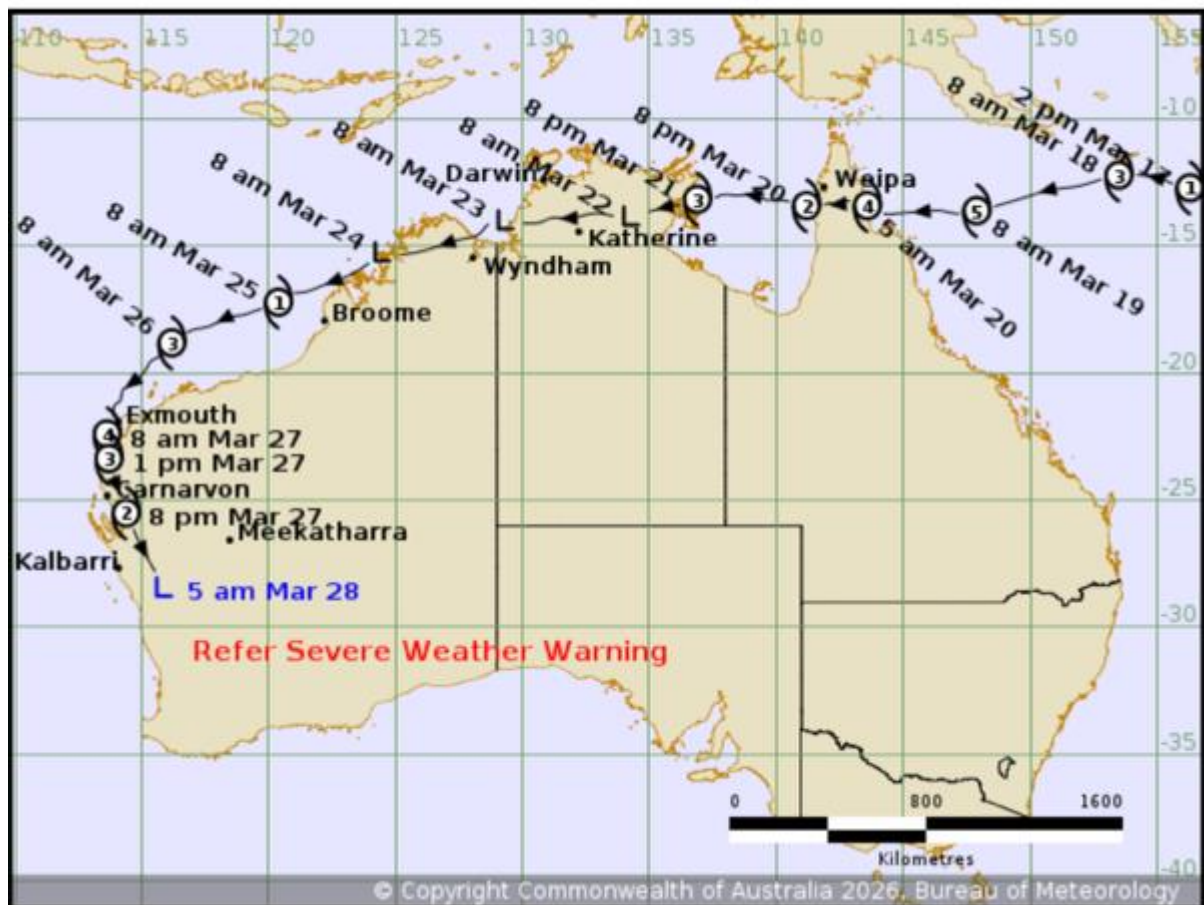


Figure 1-1 Track map of TC Narelle 28/3/2026 (Bureau of Meteorology, 2026)

The area affected by the three land crossings of TC Narelle when it was classed as a tropical cyclone were Cape York Peninsula (wind region C), Groote Eylandt and Eastern Arnhem Land (wind region C) and Coral Bay in WA (wind region D). The path relative to Australia's wind regions is shown in Figure 1-2.

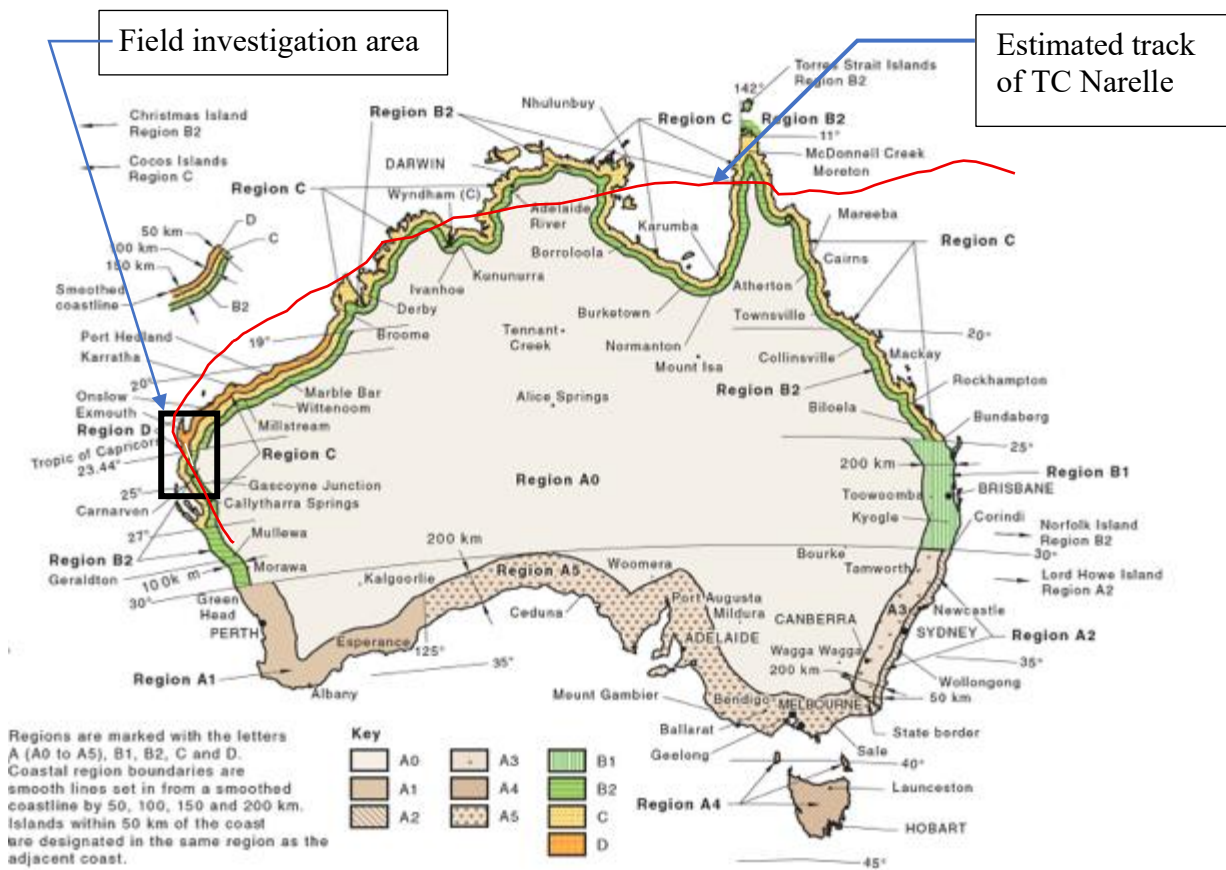


Figure 3.1(A) — Wind regions — Australia 

Figure 1-2 Estimated track of TC Narelle superposed on wind regions (from AS/NZS 1170.2:2024)

1.1. Meteorological overview of TC Narelle

The following information was provided from the Bureau of Meteorology (2026) from preliminary information on their web page. It is used with permission. The web page also contained the preliminary track map shown in this report as Figure 1-3.

Severe Tropical Cyclone Narelle was a long-lived event that crossed the coasts of far north Queensland, Northern Territory and Western Australia at severe TC intensity, only the second cyclone to do so following Ingrid (2005).

Tropical Low 34U formed near the southern Solomon Islands on 15 March and moved on a general westerly track over following days. Tropical Cyclone Narelle was named on 17 March and reached category 3 intensity the following day, then began a period of rapid intensification to peak at category 5 intensity on 19 March. Narelle weakened slightly to category 4 intensity as it crossed the Far North Queensland coast, passing between Lockhart River and Coen on the morning of 20 March.

Narelle weakened as it moved over Cape York Peninsula and emerged into the Gulf of Carpentaria near Aurukun, south of Weipa, at category 2 intensity late on 20 March. The tropical cyclone continued on a steady westward track, redeveloping into a severe tropical cyclone before crossing the Northern Territory coast between Nhulunbuy and Groote Eylandt early on 21 March at category 3 strength.

Despite soon weakening below tropical cyclone intensity, the system produced heavy rain over previously flooded catchments in the Northern Territory, especially the Daly and Victoria River regions. On 23 March, the low moved across Joseph Bonaparte Gulf and the north Kimberley before moving offshore on 24 March.

Narelle redeveloped into a tropical cyclone northwest of Broome early on 25 March and quickly reached severe category 3 intensity later that day, north of Port Hedland, as it moved west southwest parallel to the Pilbara coast. The system had developed into a large circulation and despite being located about 150 kilometres to the north of the Pilbara coast, many coastal locations experienced a prolonged period of gale force winds as it moved west.

On 26 Narelle turned to the southwest and moved closer to the west Pilbara coast as it reached category 4 intensity. The tropical cyclone then turned south and passed just west of Exmouth early on 27 March. Narelle then turned south southeast and made landfall just to the south of Coral Bay, passing to the east of Carnarvon. The tropical cyclone quickly weakened as it accelerated to the south southeast and was downgraded to below tropical cyclone intensity early on 28 March as it moved over land east of Kalbarri and Geraldton.

Severe Tropical Cyclone Narelle was the tenth tropical cyclone and the seventh severe tropical cyclone in the Australian region for the 2025/26 season. Narelle was the first tropical cyclone to impact Queensland, Northern Territory and Western Australia since Severe Tropical Cyclone Ingrid in 2005. Tropical Cyclone Advises were first issued on 17 March for the Queensland coast and continued through to 28 March over Western Australia. This is believed to be the longest continuous period of advises for any tropical cyclone in Australia.

*Note: A comprehensive report will be issued for this event upon completion of a post event reanalysis. All information relating to intensity and track is preliminary information and subject to change following post analysis.

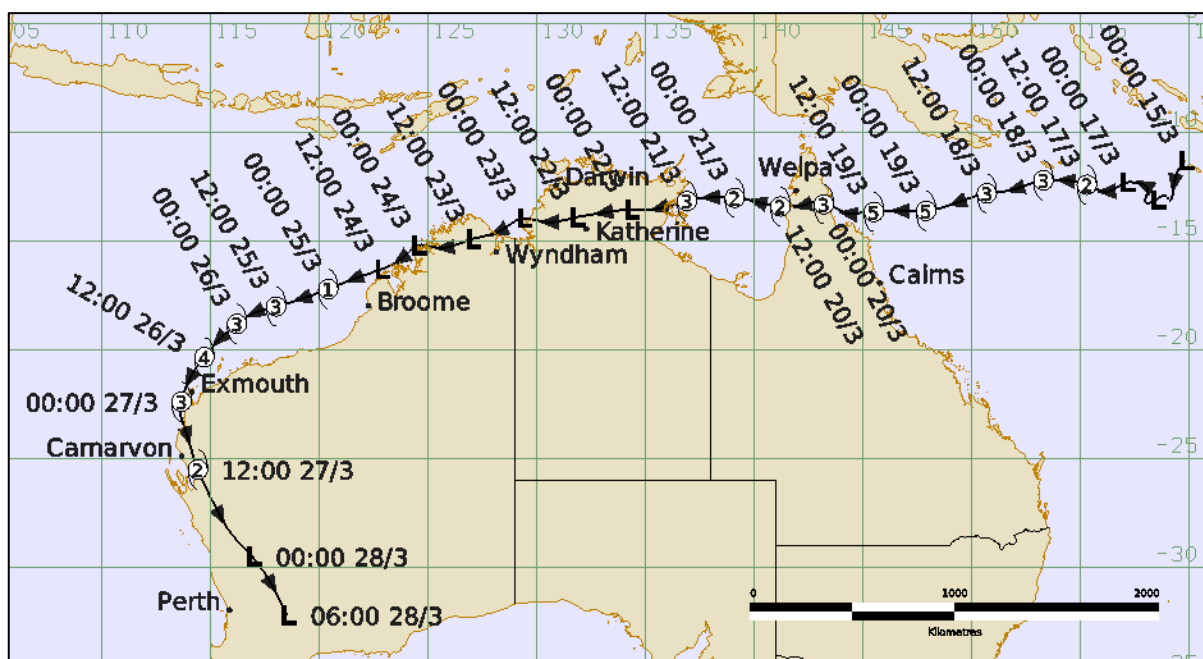


Figure 1-3 Preliminary TC Narelle track map (Bureau of Meteorology, 2026)

In general Narelle caused a large swathe of rainfall in excess of 200 mm across Far North Queensland, Northern Territory, and northwest of Western Australia as shown in the maps of weekly rainfall in Figure 1-4.

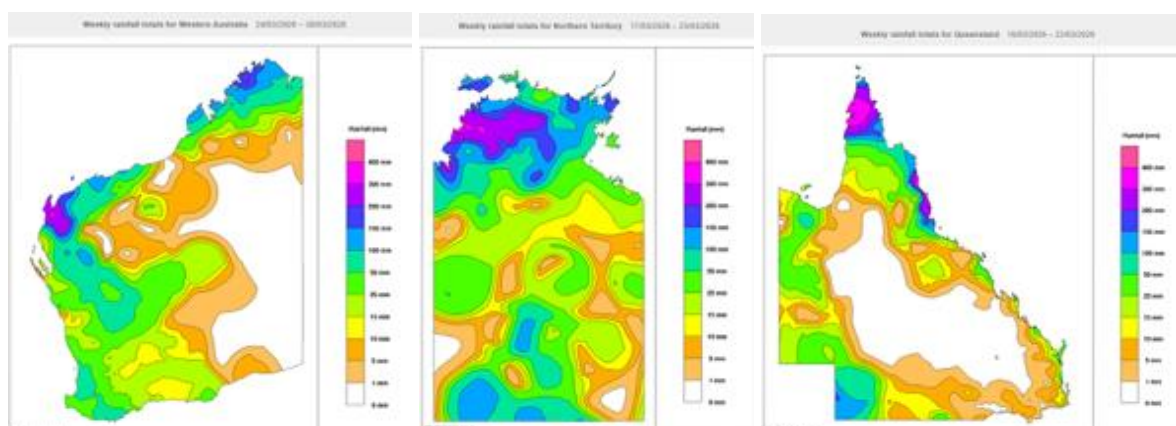


Figure 1-4 Weekly rainfall totals in WA, NT and Queensland (Bureau of Meteorology, 2026)

1.2. Purpose of the report

This report presents the outcomes of the field investigation of the joint Cyclone Testing Station (CTS), the Department of Local Government, Industry Regulation and Safety's Building and Energy Division (Building and Energy), and the WA Department of Fire and Emergency Services (DFES). The aim of the investigations was to learn from damage to structures in the affected area and to estimate the wind speeds at locations in which structures were examined.

1.3. Investigations

The progress of TC Narelle was monitored across Queensland, Northern Territory (NT) and Western Australia (WA):

- While approaching Queensland and after crossing communities in Cape York Peninsula, the CTS was in regular contact with Queensland State Emergency Service (SES) and Queensland Fire Department (QFD) as well as local councils to obtain information on the extent of damage. Preliminary assessments of wind damage indicated that there was little structural damage, and a field investigation was not undertaken.
- Emergency Services in NT were contacted to establish the extent of damage in TC Narelle's passage through the NT. While there was flood damage from the rain from TC Narelle, reports of wind damage to buildings were sparse, so a field investigation in NT was not mounted.
- Contact with the WA Department of Fire and Emergency Services was established as TC Narelle crossed into WA. Damage as it progressed through the Kimberley and down the Pilbara coast was monitored. Early indications were that there was a significant level of damage to buildings in the Exmouth to Carnarvon regions in WA. This took in communities at Exmouth, Learmonth, Coral Bay, Carnarvon and near Gascoyne Junction. The field study focused on these areas.

The field study commenced on Sunday, 29 March 2026 and was completed on Friday, 3 April 2026. For that period, one team was based primarily in Carnarvon, and a second team primarily in Exmouth.

Figure 1-5 shows the focus of the investigation in the Western Pilbara and the Western Gascoyne regions of WA. The yellow lines indicate the roads taken by the teams and the red line, the estimated track of the cyclone. Both teams were able to cross the eye of the cyclone. Towns discussed in this report are located on Figure 1-5.



Figure 1-5 Localities visited in the investigation and estimation of the path of the cyclone.

2. Observations in TC Narelle

As TC Narelle was moving generally east to west across Australia as indicated in Figure 1-3, The data from the closest anemometers was collected. For each station, the terrain and topography was evaluated for the 16 wind directions and modified by the terrain/ topographic corrections in AS/NZS 1170.2 (Standards Australia, 2021). This enabled a consistent method of comparing windspeeds when adjusted to standard conditions – 10 m measurement height over flat open terrain (Terrain Category 2). Corrections to give 0.2 second gusts were made using the factors published by Holmes and Ginger (2012).

The plots of wind speed in this report are all relative to the standard conditions. Where the wind speed is reported as a 0.2 second gust, it uses the dimensions m/s to be compatible with the design winds speeds presented in AS/NZS 1170.2. Where the wind speed is reported as a 3 second gust, it uses the dimensions km/h to be consistent with the reporting periods used by the World Meteorological Office and the Bureau of Meteorology in Australia.

Storm tide can be measured by tide gauges, but in some locations affected by the storm tide there were no gauges. Also wave runup increases the height of the water and can top walls and dunes above the nominal storm tide height.

2.1. Gust wind speeds from TC Narelle in Queensland

Figure 2-2 shows Bureau Automatic Weather Stations (AWS) close to the cyclone track in Queensland. The track from Figure 1-3 has been superposed as a red line in Figure 2-1. The coloured circles in Figure 2-1 correspond with the coloured lines in Figure 2-2.

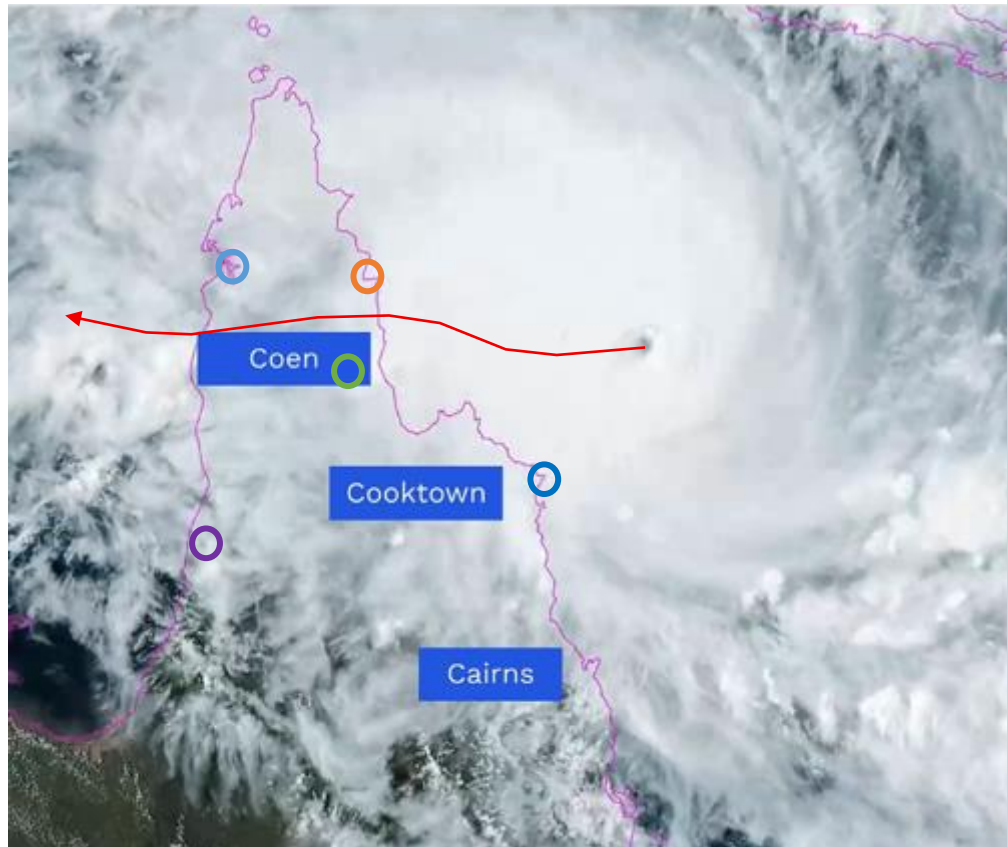


Figure 2-1 Locations of AWS in Cape York peninsula (Satellite image from BoM, 2026).

Unfortunately, the Coen AWS stopped transmitting at 0235 AEST on 20/03/2026 and did not start transmitting until 1234 AEST on 20/03/2026. This was the period of maximum winds and lowest atmospheric pressure over Coen. The area without record is highlighted by the green rectangle in Figure 2-2 and means that there is no record of the peak gust or lowest atmospheric pressure as TC Narelle passed Coen.

The dark blue circle represents the Cape Flattery AWS, the orange circle represents the Lockhart River AWS, the dark green circle the Coen AWS, the light blue circle the Weipa AWS, and the purple circle, the Kowanyama AWS. The vertical lines in Figure 2-2 mark the time of the lowest pressure at each station. Data for these stations and some others has been summarised in Table 1 with the same-coloured circles shown.

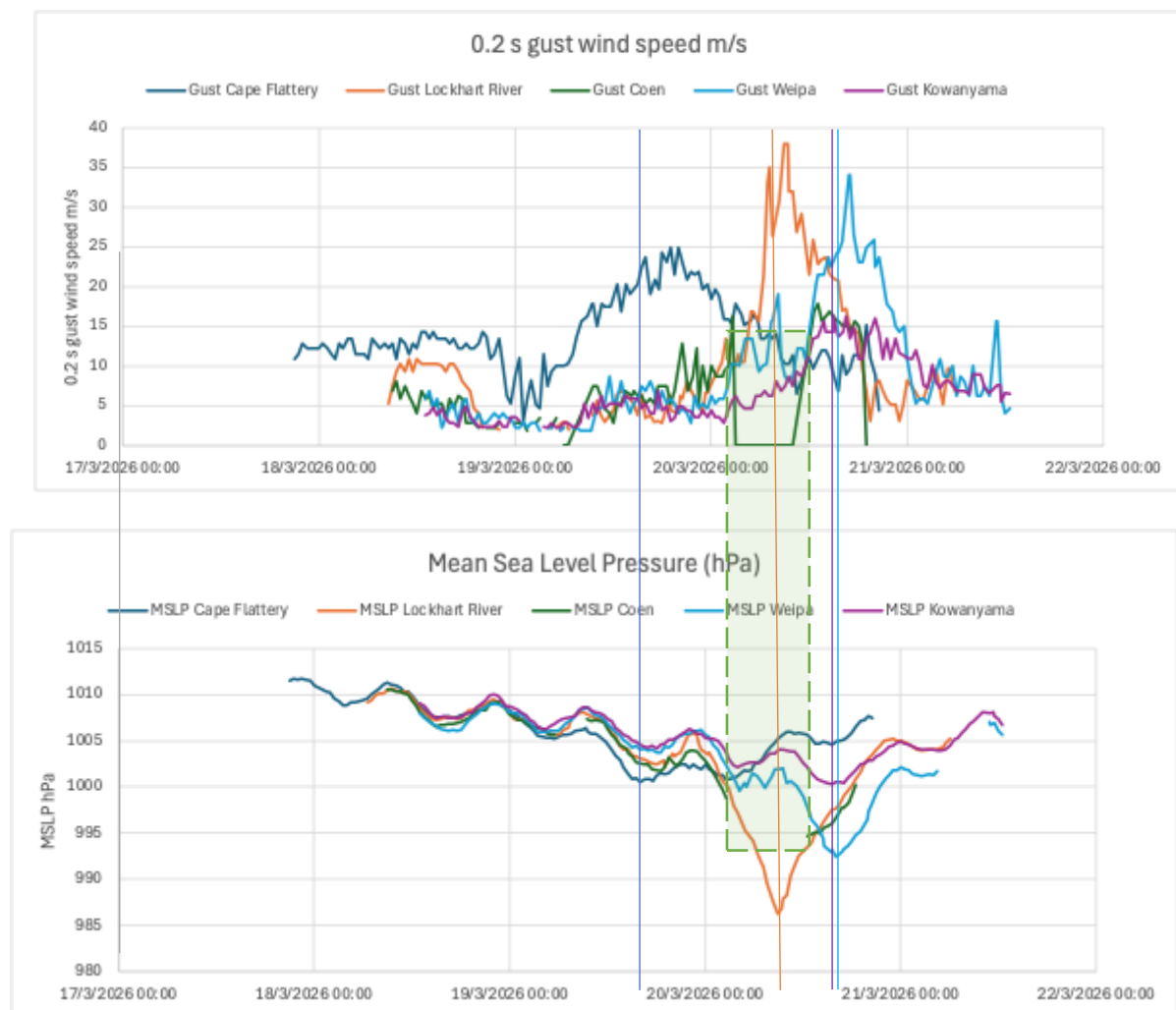







Figure 2-2 Selected Queensland AWS data presented as 0.2 s gust relative to standard conditions.

Figure 2-2 shows that the peak gust was experienced at each AWS at around the same time as the minimum Mean Sea Level Pressure. The highest recorded gust wind speed was at Lockhart River. The peak gust data corrected for terrain and topography is summarised in

Table 1 with % V_{IL2} as the % of the Regional Design wind speed (V_R) for Importance Level 2 buildings in NCC2025 and AS/NZS 1170.2: 2024.

Table 1 Summary of standardised wind data for TC Narelle in Queensland

Station	peak 0.2 s in m/s	peak 3 s in km/h	Bearing	Date and time	%V _{IL2}
Cape Flattery	 25.0	80	135	19/3/2026 20:00	38%
Cooktown	21.5	69	135	19/3/2026 23:45	33%
Lockhart River	 38.0	121	315	20/3/2026 09:26	58%
Coen*	 (17.8)	(57)	90	20/3/2026 13:00	(27%)
Sherger	22.1	70	337.5	20/3/2026 16:00	33%
Weipa	 34.0	109	315	20/3/2026 17:00	52%
Kowanyama	 16.2	52	135	20/3/2026 16:30	25%

* Part of the Coen AWS data was missing, and the recorded peak wind data missed the period when TC Narelle was closest to Coen.

The highest recorded gusts were at Lockhart River and Weipa, both of which were to the north of the track. The peak gust experienced at Coen would have been higher than the peak recorded before the AWS went off-line. The stations at Kowanyama and Cape Flattery were further from the track than the stations at Lockhart River and Weipa. There is no AWS at Aurukun which lay very close to the track as the cyclone moved into the Gulf of Carpentaria.

Table 1 shows that the measured peak gusts were less than 60% of the design wind speed for importance level 2 buildings. The wind loads were therefore less than 35% of the design wind loads for importance level 2 buildings in this area. The Bureau's SAR output showed that the cyclone was very compact as it approached Cape York Peninsula, so the small radius of maximum winds may have missed all of the operational AWS shown in Figure 2-1. However, higher winds may have been experienced in localities between Coen and Lockhart River such as Archer River.

2.2. Gust wind speeds from TC Narelle in the Northern Territory

Figure 2-3 shows AWS close to the cyclone track in the Northern Territory. The track from Figure 1-3 has been superposed as a red line in Figure 2-3. The coloured circles in Figure 2-3 correspond with the coloured lines in Figure 2-4.



Figure 2-3 Locations of AWS used in this report in the Northern Territory (Satellite image from NASA Worldview, 2026).

The dark blue circle represents the Gove AWS, the orange circle represents the Groote Eylandt AWS, the dark green circle the Bulman AWS, the light blue circle the Central Arnhem Plateau AWS, the purple circle, the Douglas River AWS and the light green circle, the Wadeye AWS. Data for these stations and some others has been summarised in Table 1.

The anemometer data in Figure 2-4 and has been adjusted for approach terrain and topography and converted from a 3 second gust to a 0.2 second gust compatible with the wind speed data presented in AS/NZS 1170.2. The vertical lines in Figure 2-4 mark the time of the lowest pressure at each station.

The highest wind speeds were recorded at Gove and Groote Eylandt, near where the tropical cyclone that had been rated as a category 3 event crossed the coast. Figure 2-3 shows that the track steered between these two AWS but crossed much closer to other stations as it crossed the Northern Territory as a tropical low.

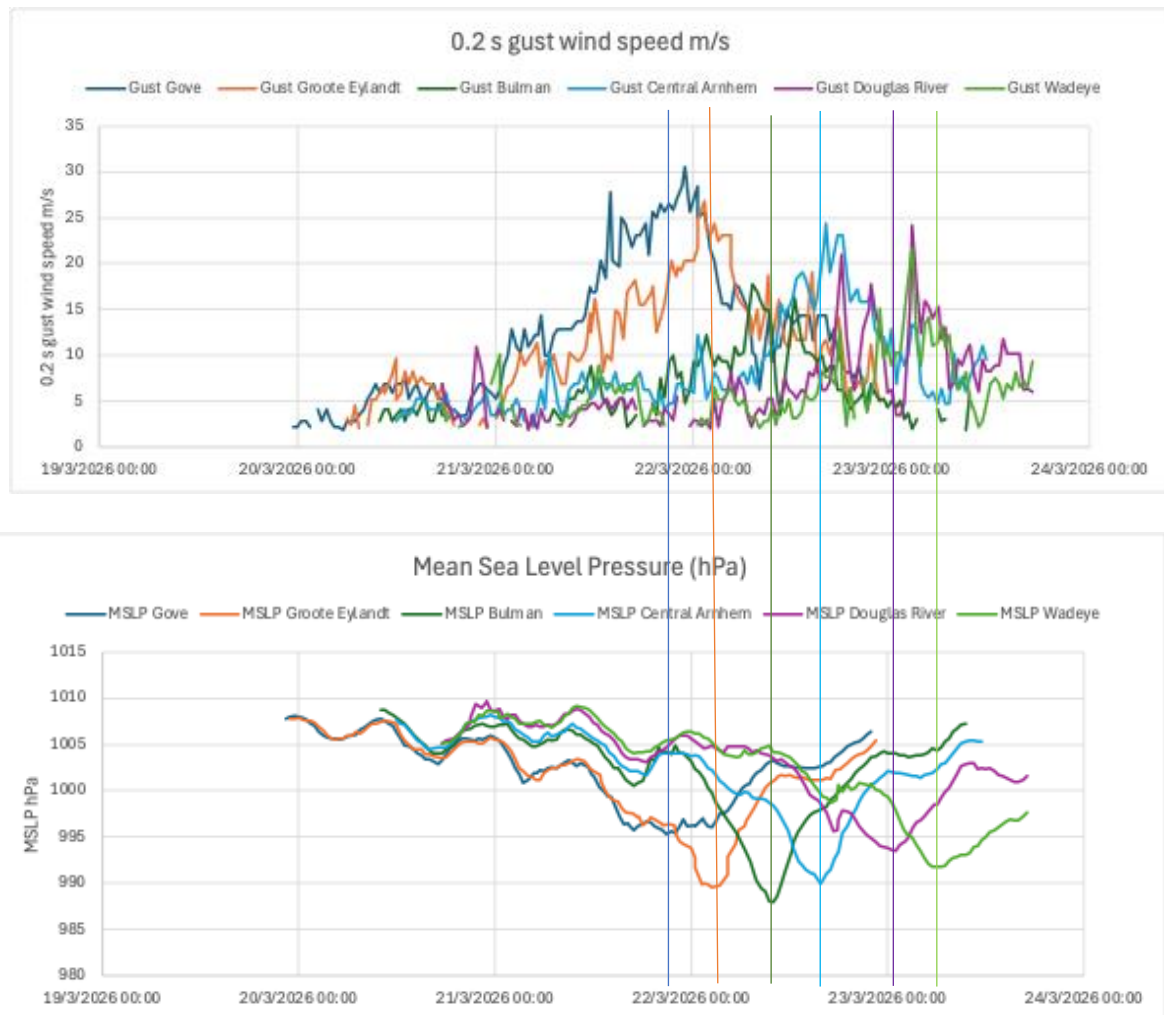


Figure 2-4 Selected Northern Territory AWS data presented as 0.2 s gust relative to standard conditions.

Table 2 Summary of standardised wind data for TC Narelle in the Northern Territory

Station	peak 0.2 s in m/s	peak 3 s in km/h	Bearing	Date and time	%V _{IL2}	Region
Gove	30.6	98	292.5	21/3/2026 23:00	46%	C
Groote Eylandt	26.8	85	112.5	22/3/2026 01:19	41%	C
Ngukurr	22.4	71	112.5	22/3/2026 09:30	39%	B
Bulman	17.8	57	225	22/3/2026 07:11	40%	A
Central Arnhem	24.3	78	315	22/3/2026 16:00	54%	A
Jabiru	18.0	57	315	22/3/2026 17:00	32%	B
Tindal	24.3	78	112.5	22/3/2026 20:12	54%	A
Mt Bundy S	18.6	59	315	22/3/2026 18:26	33%	B
Douglas River	24.2	77	0	23/3/2026 02:30	54%	A
Wadeye	21.7	68	202.5	23/3/2026 02:30	33%	C

Table 2 shows that in the Northern Territory, the measured peak gusts were less than 55% of the design wind speed for importance level 2 buildings. The wind loads were therefore less than 30% of the design wind loads for importance level 2 buildings in this area. This was a lower percentage of design load than that experienced in Cape York Peninsula. However, higher winds may have been experienced in coastal localities between Nhulunbuy and Numbulwar. There are not many communities in this area.

2.3. Gust wind speeds from TC Narelle in Western Australia

Figure 2-5 shows AWS close to the cyclone track in Western Australia. The track from Figure 1-3 has been superposed as a red line in Figure 2-5. The coloured circles in Figure 2-5 correspond with the coloured lines in Figure 2-6.

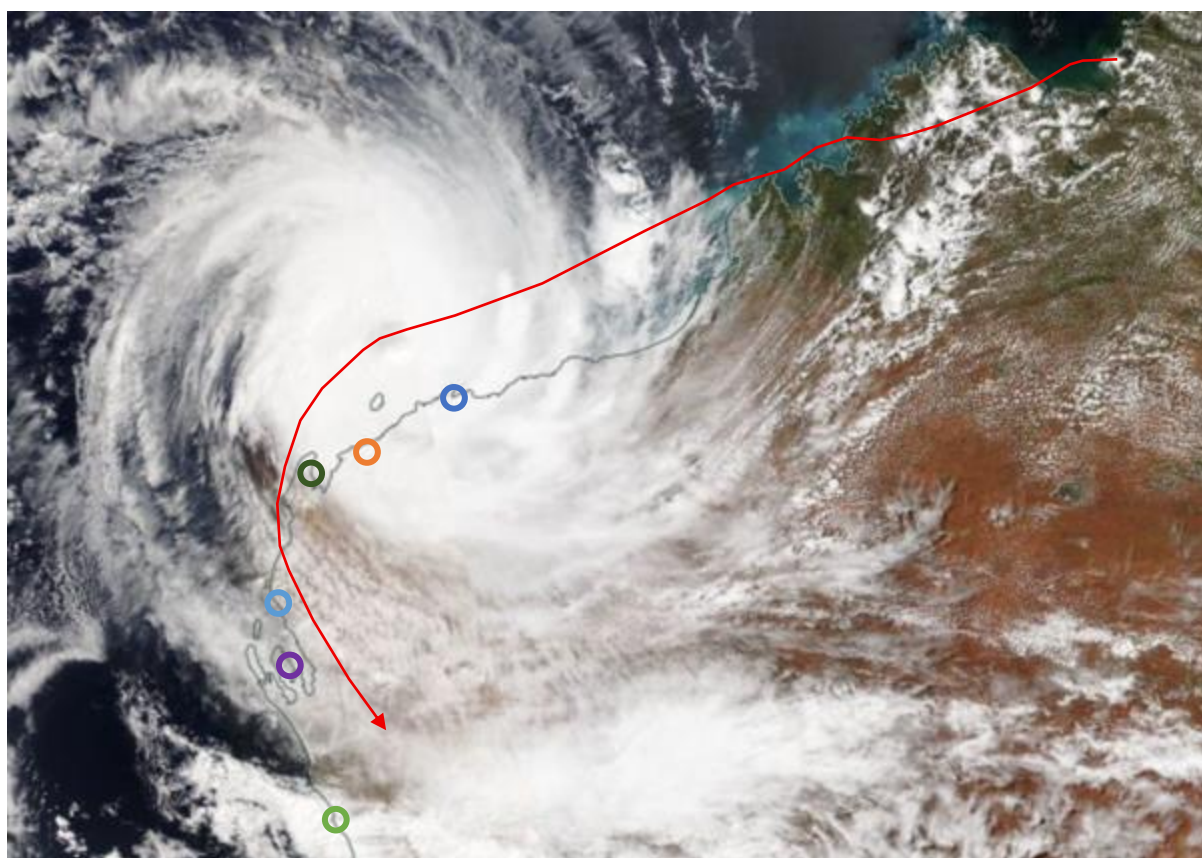


Figure 2-5 Locations of AWS used in this report in Western Australia (Satellite image from NASA Worldview, 2026).

The anemometer data in Figure 2-6 and has been adjusted for approach terrain and topography and converted from a 3 second gust to a 0.2 second gust compatible with the wind speed data presented in AS/NZS 1170.2. The vertical lines in Figure 2-6 mark the time of the lowest pressure at each station.

The highest wind speeds were recorded at Learmonth which was where the tropical cyclone that had been rated as a category 3 event was approaching the coast.

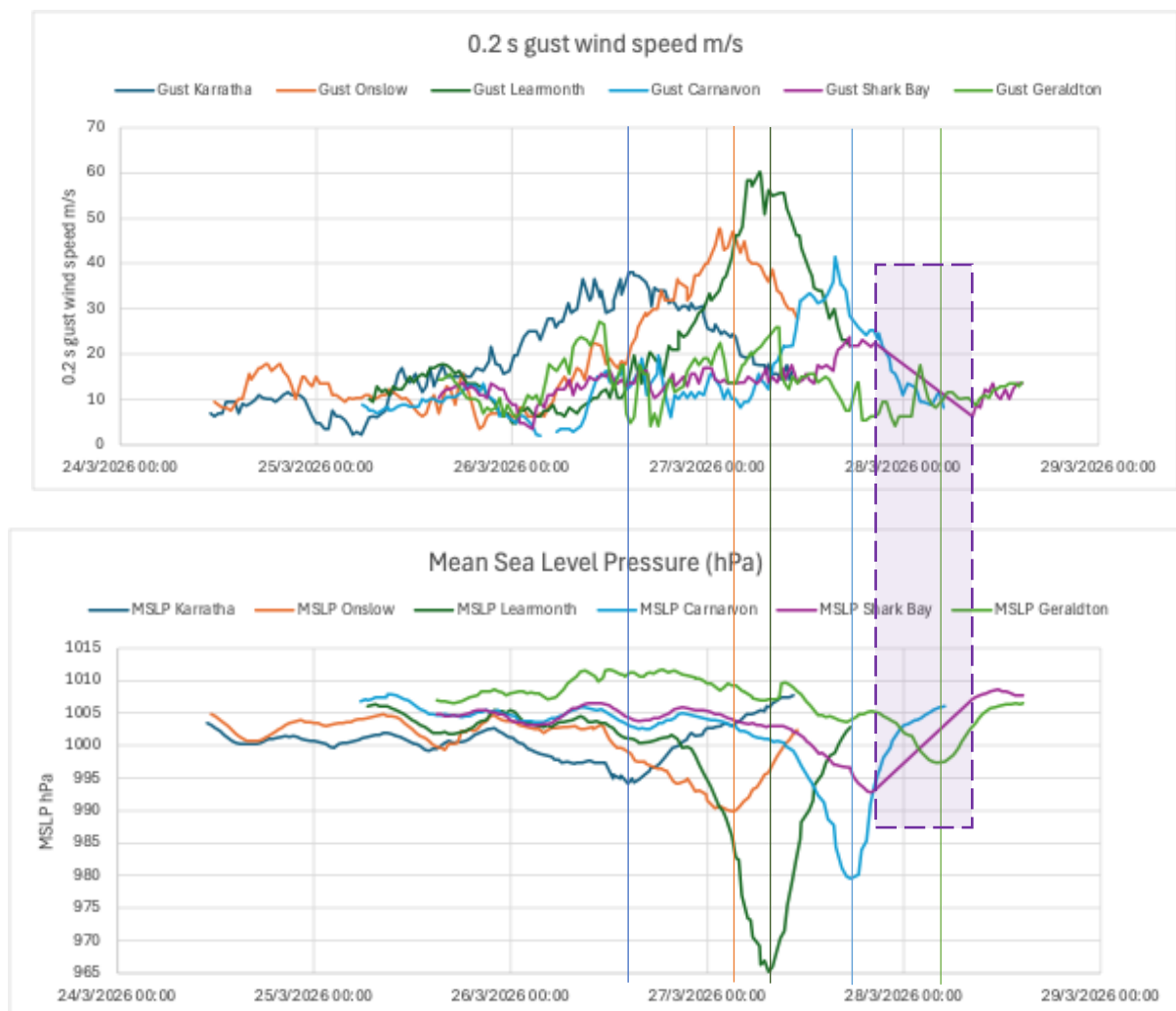








Figure 2-6 Selected Western Australian AWS data presented as 0.2 s gust relative to standard conditions.

Unfortunately, the Shark Bay airport AWS stopped transmitting at 2030 AWST on 27/03/2026 and did not start transmitting until 0830 AWST on 28/03/2026. This was the period of maximum winds and lowest atmospheric pressure over Shark Bay. The area without record is highlighted by the purple rectangle in Figure 2-6 and means that there is no record of the peak gust or lowest atmospheric pressure as TC Narelle passed Denham or Shark Bay.

Figure 2-5 shows that TC Narelle's track went closest to Learmonth and Carnarvon. These two AWS recorded the lowest atmospheric pressure. Learmonth recorded the highest gust wind speed and Onslow the second highest. Figure 1-3 shows that even though TC Narelle

was well offshore when it passed Onslow, the bureau had rated it a Category 4 event at that point. It had decayed to a Category 3 tropical cyclone as it passed Learmonth (see Figure 1-3) and was continuing to reduce in intensity as it passed Carnarvon. The Bureau's SAR output from this part of the track showed that the band of maximum winds was very broad, so it is likely that the maximum wind speeds extend over 100 km from the track in the region between Exmouth and Carnarvon.

Table 3 Summary of standardised wind data for TC Narelle in Western Australia



Station	peak 0.2 s in m/s	peak 3 s in km/h	Bearing	Date and time	%V _{IL2}	Region
Kununurra	20.3	65	112.5	23/3/2026 14:30	36%	B
Wyndham	19.7	63	90	23/3/2026 20:38	30%	C
Kalumburu	15.6	50	0	24/3/2026 11:06	24%	C
Koolan Island	27.0	86	0	25/3/2026 05:28	41%	C
Lombadina	23.0	73	0	25/3/2026 01:30	35%	C
Broome	23.7	76	90	25/3/2026 03:11	36%	C
Rowley Shoals	40.6	134	0	25/3/2026 18:19	61%	C
Bedout Island	42.0	139	45	26/3/2026 08:22	49%	D
Port Hedland	30.0	96	45	26/3/2026 10:13	35%	D
Karratha	 38.1	122	90	26/3/2026 14:50	45%	D
Onslow	 47.8	153	45	27/3/2026 01:30	56%	D
Learmonth	 60.2	193	67.5	27/3/2026 06:22	71%	D
Carnarvon	 41.5	133	112.5	27/3/2026 15:40	63%	C
Shark Bay*	 (23.7)	(76)	(90)	(27/3/2026 17:29)	(36%)	C
Geraldton	 27.2	87	45	26/3/2026 10:44	48%	B

* Part of the Shark Bay AWS data was missing, and the recorded peak wind data missed the period when TC Narelle was closest to Shark Bay.

The wind speeds at Learmonth can be compared with recorded wind speeds at the same location in a number of other recent tropical cyclones. This data is shown in Table 4. The wind speed data for Carnarvon has been compared with the design wind speed for wind region C as Carnarvon is located in wind region C following boundary changes in 2024.

Table 4 shows that the wind speeds in TC Narelle were comparable with those in TC Olwyn (Boughton et al, 2015) but stronger than those in TC Mitchell earlier in 2026. For Learmonth, a comparison with TC Vance is also shown referencing the Dynes anemometer data from (Reardon et al., 1999). The wind speeds in both TC Narelle and TC Olwyn were significantly less than those recorded in TC Vance. (Note that the Dynes anemometer records very short duration gusts and the data from it was taken as a 0.2 s gust. An equivalent 3 second gust for TC Vance was derived from the Dynes data.)

Table 4 Gust wind data at Learmonth and Carnarvon for recent tropical cyclones

TC	peak 0.2 s in m/s	peak 3 s in km/h	Bearing	Date and time	%V _{IL2}	Region
AWS Learmonth						
TC Narelle	 60.2	193	67.5	27/3/2026 06:22	71%	D
TC Mitchell	37.2	119	90	8/2/2026 23:30	44%	D
TC Olwyn	57.5	180	22.5	13/3/2015 02:32	68%	D
TC Vance	74.2	(243)	225	22/3/1999 11:45	88%	D
AWS Carnarvon						
TC Narelle	 41.5	133	112.5	27/3/2026 15:40	63%	C
TC Mitchell	33.4	107	90	9/2/2026 15:37	51%	C
TC Olwyn	46.6	146	45	13/3/2015 13:30	71%	C

2.4. Tide records for Exmouth

Figure 2-7 shows an excerpt from the tide gauge at Exmouth. It shows a storm surge of 3 m and the storm tide around 1.5 m higher than the Highest Astronomical Tide. The datum used for this plot is different to the AHD datum used for other plots of storm tide in this document.

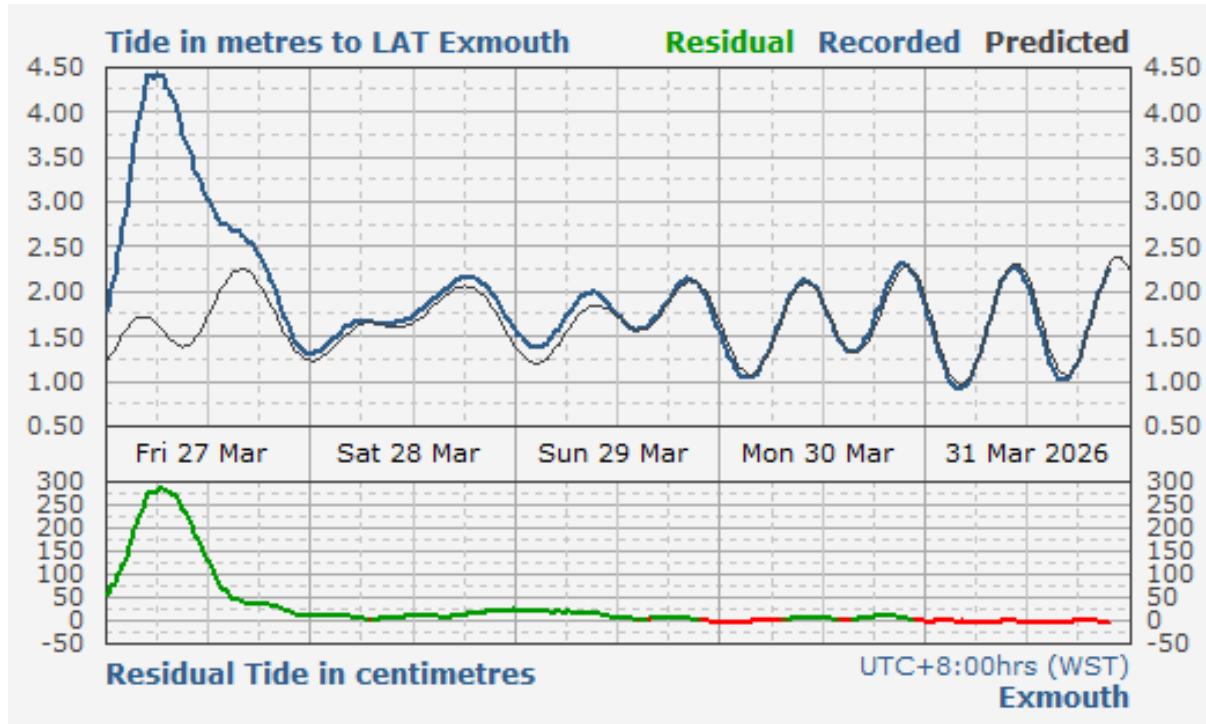


Figure 2-7 Excerpt from Exmouth tide gauge (WA Dept. Transport).

The tide gauge at Exmouth is just inside the Marina and sheltered from direct wave action by its location and the main breakwater on the boat harbour. Observations of where the storm tide came to in the marina supported this level of storm tide. In some locations, just south of Exmouth, the storm tide broke through the coastal dune and flooded low lying land inland from the dune. Further detail on the effects of the storm tide is given in Section 7.

3. Wind field in the investigation area

Throughout the investigation area, structures were assessed for their performance under wind or the combination of wind and rain. Therefore, it is important to estimate the peak wind gusts that each of these structures were subjected to. This required developing a wind field for the investigation area by using the anemometer data outlined in Section 2, results of ‘windicator’ analyses and a numerical wind field model.

3.1. ‘Windicator’ analysis

‘Windicators’ are simple structures that can be used to estimate the wind speed at that location. 39 road signs were measured as windicators to obtain wind speed estimates closer to some of the communities where there are no anemometers. Figure 3-1 shows two of the road signs that were used to estimate the wind speeds associated with the tropical cyclone. The left photo shows a sign that was still vertical i.e. the pole had not failed. This indicates that the wind forces had not been strong enough to cause a plastic hinge in the pole. By calculating the speed required to cause a hinge, an upper bound of the wind at the location could be found.

The aerodynamic drag on a sign is similar for wind directions within 45° of perpendicular to the plane of the sign. Signs were only selected where the plane of the sign was nearly perpendicular to the direction of maximum winds. The direction of maximum winds was identified by damage to nearby buildings or structures or damage to vegetation. These directions were confirmed with the numerical model of the wind field.

The right photo shows a sign that had developed a plastic hinge in the pole, so the same calculations on this sign gave a lower bound of the wind speed at the location. i.e the wind speed had to be greater than the wind speed calculated for the poles on this sign, as it had caused plastic hinges.



Figure 3-1 Road signs used as windicators

3.1.1. Wind speeds near Exmouth

As the anemometer at Learmonth on NW Cape was 33 km south of the town of Exmouth, windicators in the Exmouth area were used to estimate the wind speed in Exmouth relative to the wind speed in Learmonth. Additional windicators were measured near Learmonth to confirm that the windicators and the anemometer showed similar wind speeds. Figure 3-2 shows the results of windicator analyses near Exmouth and Learmonth. It shows a spread of upper and lower bound windicators near Exmouth and some at Learmonth near the anemometer. The location of an anemometer operated by the Australian Institute of Marine Science (AIMS) is also shown in Figure 3-2.

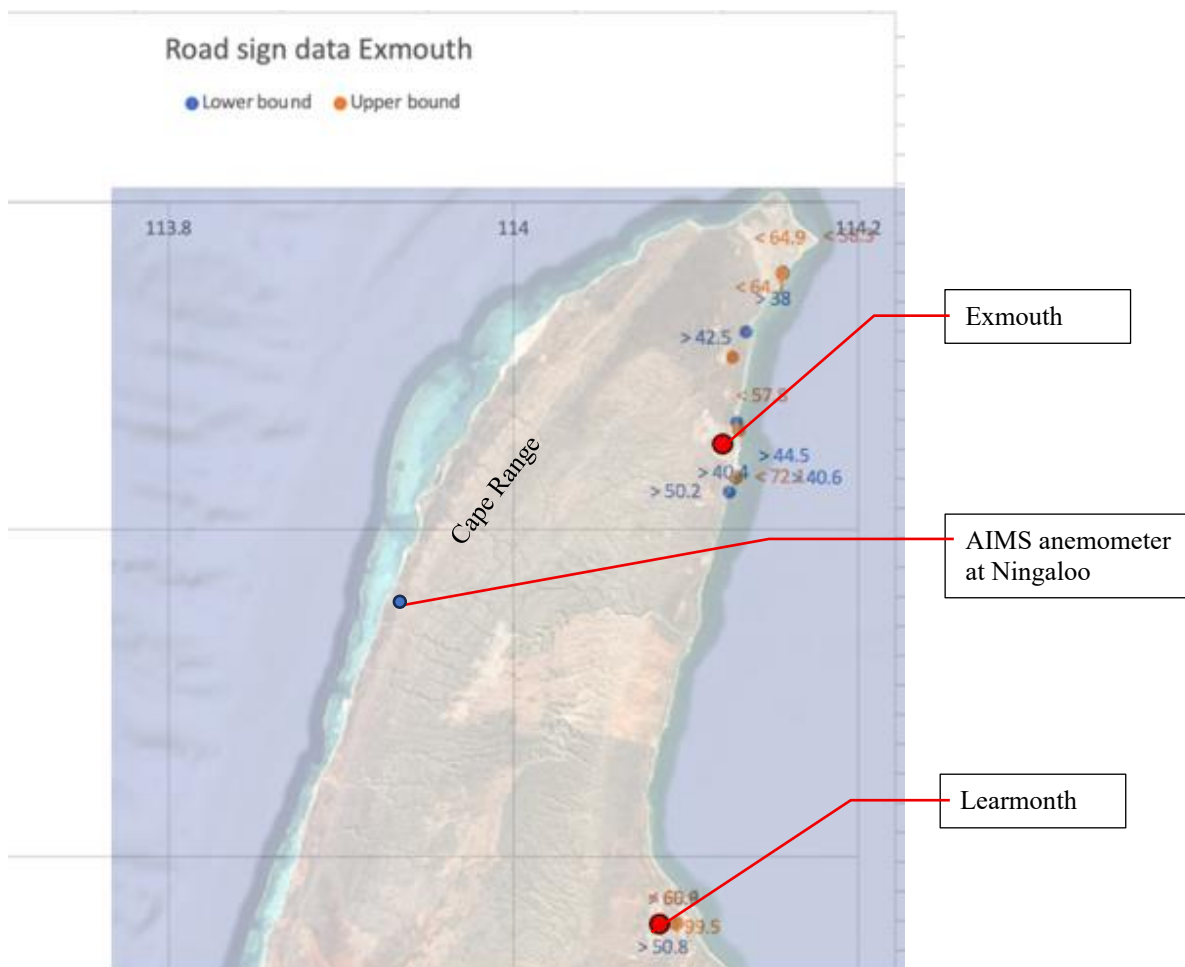


Figure 3-2 Results of windicators near Exmouth

The windicators at Learmonth estimated 0.2 sec peak gust wind speeds between 60 m/s and 70 m/s. This estimate is compatible with the anemometer nearby returning 60.2 m/s.

The windicators near Exmouth estimated 0.2 sec peak gust wind speeds between 50 m/s and 58 m/s. This may be slightly lower than the wind speeds at Learmonth, but not significantly different from wind speeds at Learmonth. The estimated wind speeds at Exmouth were not higher than the wind speeds at Learmonth.

The record for the AIMS anemometer at Ningaloo showed erroneous data for the wind direction, so it was not possible to correct the data for terrain and topography. The uncorrected peak gust recorded was 48 m/s equivalent to a 0.2 sec gust. This was significantly lower than the wind speeds recorded at Learmonth at around the same time. The

winds at Learmonth were from the ENE which meant that the Ningaloo anemometer would have been immediately in the lee of the Cape Range. This may have offered some protection and led to a lower reading than the anemometers on the upwind side of the range.

The Bureau SAR output when TC Narelle was near NW Cape indicated that the cyclone had a very broad area of maximum winds, so it likely that the whole of NW Cape from Learmonth to Exmouth experienced similar magnitude maximum wind gusts, compatible with the windicator data.

Wind speeds in Exmouth were very similar to those recorded in Learmonth at around 70% of the design wind speed for Importance Level 2 structures.

3.1.2. Wind speeds near Coral Bay

Coral Bay is approximately 140 km SSW of Exmouth and 110 km from Learmonth. The track of the cyclone crossed the coast near Coral Bay, but the cyclone had travelled for around 140 km after it had been primarily affecting Exmouth before it crossed the coast so the wind speeds may have been significantly different at Coral Bay.

Windicators were used to estimate the wind speed at Coral Bay. Figure 3-3 shows the windicators used near Coral Bay.

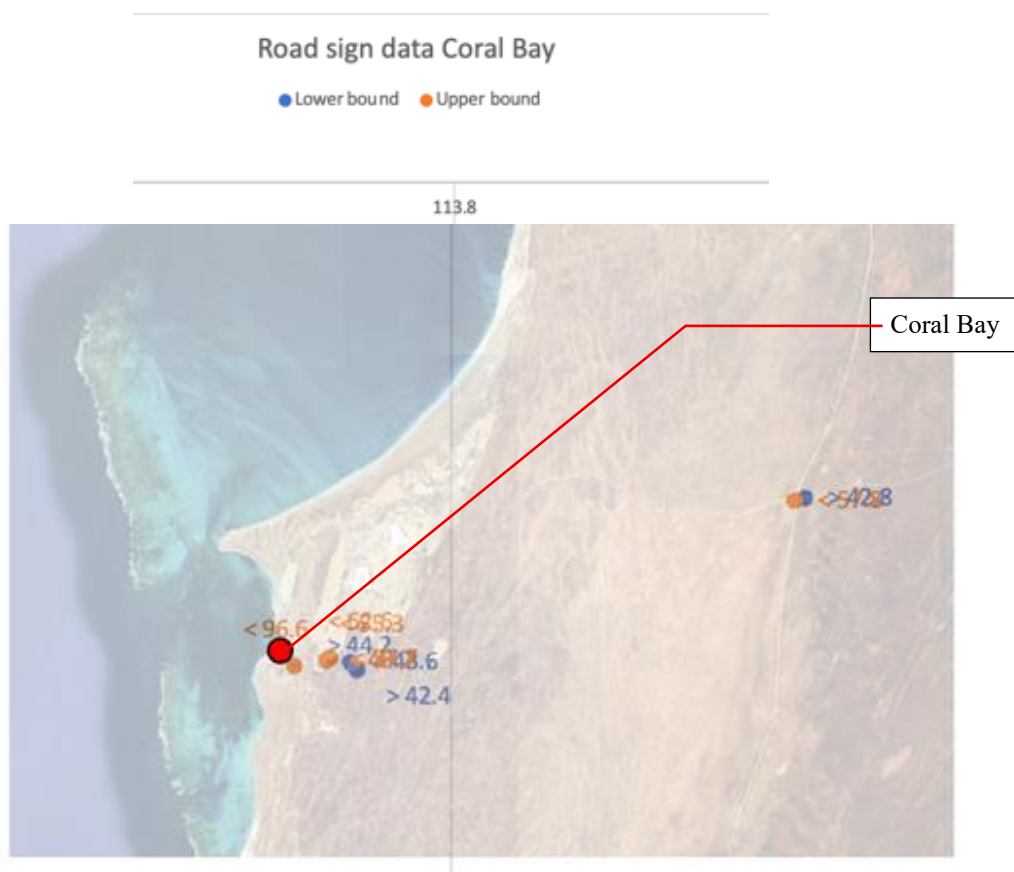


Figure 3-3 Results of windicators near Coral Bay

The result of the lower bound and upper bound windicators in this region is that the estimated peak gust wind speed was between 49 m/s and 50 m/s. While the potential errors are higher than this range, there is some confidence that the peak gust wind speeds were less than

around 55 m/s. This makes the wind speeds at Coral Bay less than those estimated for Exmouth and Learmonth.

This finding is compatible with the observations of tree damage, which was a little less than that for the same species in Exmouth and the fact that the strength of the tropical cyclone was decreasing as it approached NW Cape.

Wind speeds in Coral Bay were lower than those recorded in Learmonth at around 65% of the design wind speed for Importance Level 2 structures.

3.1.3. Wind speeds near Gascoyne Junction

Structures were assessed in both Carnarvon and Gascoyne Junction. While there was an active AWS in Carnarvon, there is not one in Gascoyne Junction. Windicators were recorded near both Carnarvon and Gascoyne Junction as shown in Figure 3-4. The track of TC Narelle passed between Carnarvon and Gascoyne Junction.

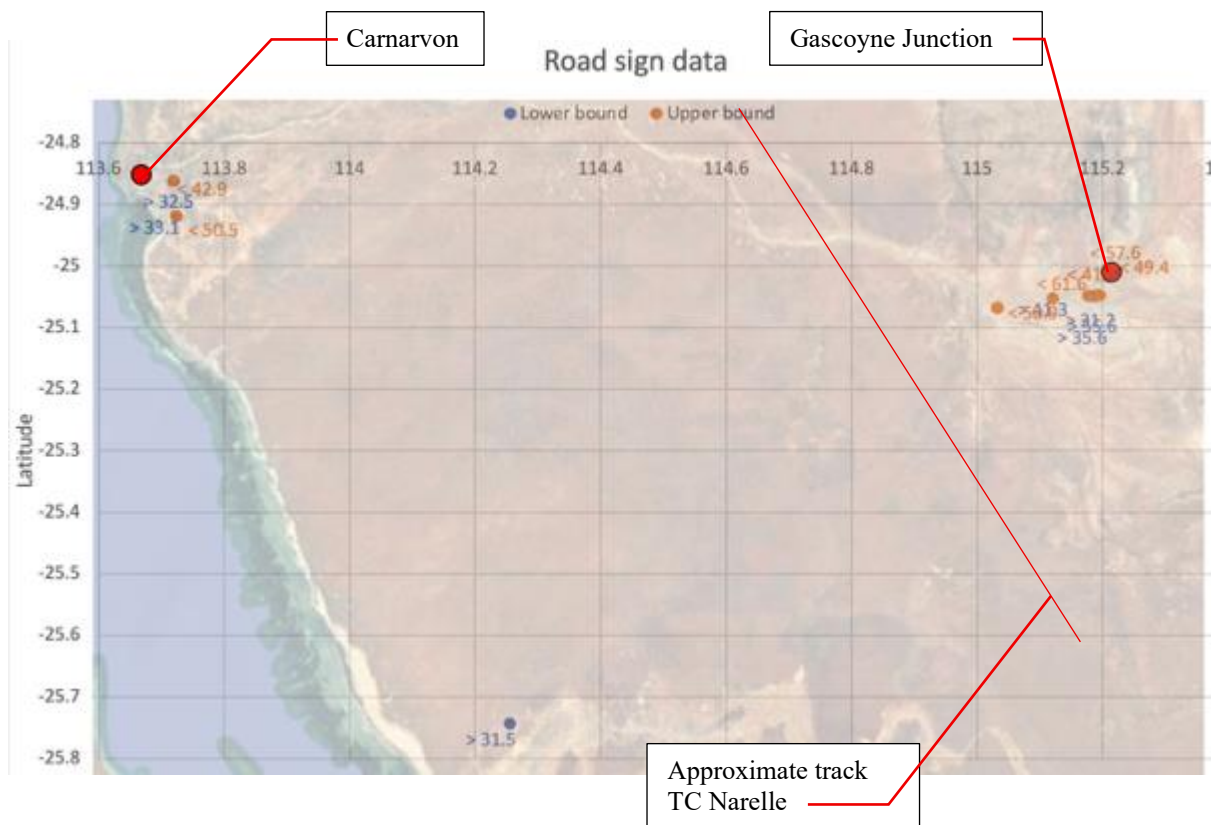


Figure 3-4 Results of windicators near Carnarvon

The windicators near Carnarvon indicate that the maximum wind gust was between 33 m/s and 42 m/s. This is compatible with the 41.5 m/s 0.2 sec gust from the AWS at Carnarvon Airport. Carnarvon is now classified as being in wind region C and the measured wind speed in Carnarvon was lower than the design wind speed for Importance Level 2 buildings at around 63% of the design speed.

The windicators near Gascoyne Junction indicate that the maximum wind gust was between 51 m/s and 56 m/s. This indicates that the wind speed at Gascoyne Junction was a little higher

than that at Carnarvon. This is to be expected as Gascoyne Junction was closer to the track of the cyclone compared to Carnarvon. However, Gascoyne Junction is around 130 km from the smoothed coastline which means it is currently classified as being in wind region A. Design wind speed for Importance Level 2 structures in region A is 45 m/s, which means that the estimated wind speed is between 113% and 124% of the design wind speed for Importance Level 2 structures. Many of the buildings in Gascoyne Junction may have been designed for region B wind speeds which is close to the speeds experienced in TC Narelle.

3.2. Numerical wind field model

The Australia-wide version of the SEAtide model (SEA, 2020) was used to both forecast and hindcast the wind field and storm tide response of TC Narelle at its land fall in Queensland, NT and WA. The wind and surface pressure swath was calibrated using selected AWS sites from Table 1, Table 2 and Table 3. The BoM preliminary analysis track based on the Broome radar provided the base reference for an estimated minimum central pressure (MSLP) and V_{\max} (V 10-min).

SEAtide uses a ‘double Holland’ parametric wind and pressure formulation that can adjust the storm structure to accommodate expected changes at landfall as the inner core typically tends to decay and expand as the surface energy flux decreases. The modelled results for $V_{0.2\text{-sec}}$ peak gusts in Terrain Category 2 at 10 m height (standard conditions) as used in AS/NZS 1170.2 (Standards Australia, 2021) have been used for comparison with observed building damage.

SEAtide also uses the wind field over the ocean and the atmospheric pressure to evaluate estimated storm surge. This can be added to the astronomical tide to obtain estimations of the storm tide at the coast.

3.2.1. Numerical model for winds at landfall in Queensland

Figure 3-5 shows a contour plot of the maximum 0.2 sec peak gust along the track of TC Narelle as it crossed Cape York Peninsula. The wind gusts reduced in speed over a short distance to the south of the eye which gave a low expected peak gust wind speed at Coen, the closest major town to the track on the east side of the peninsula. The peak gusts expected in Coen were around 30 m/s – around the same speed expected at Aurukun on the west coast of the peninsula on TC Narelle’s track.

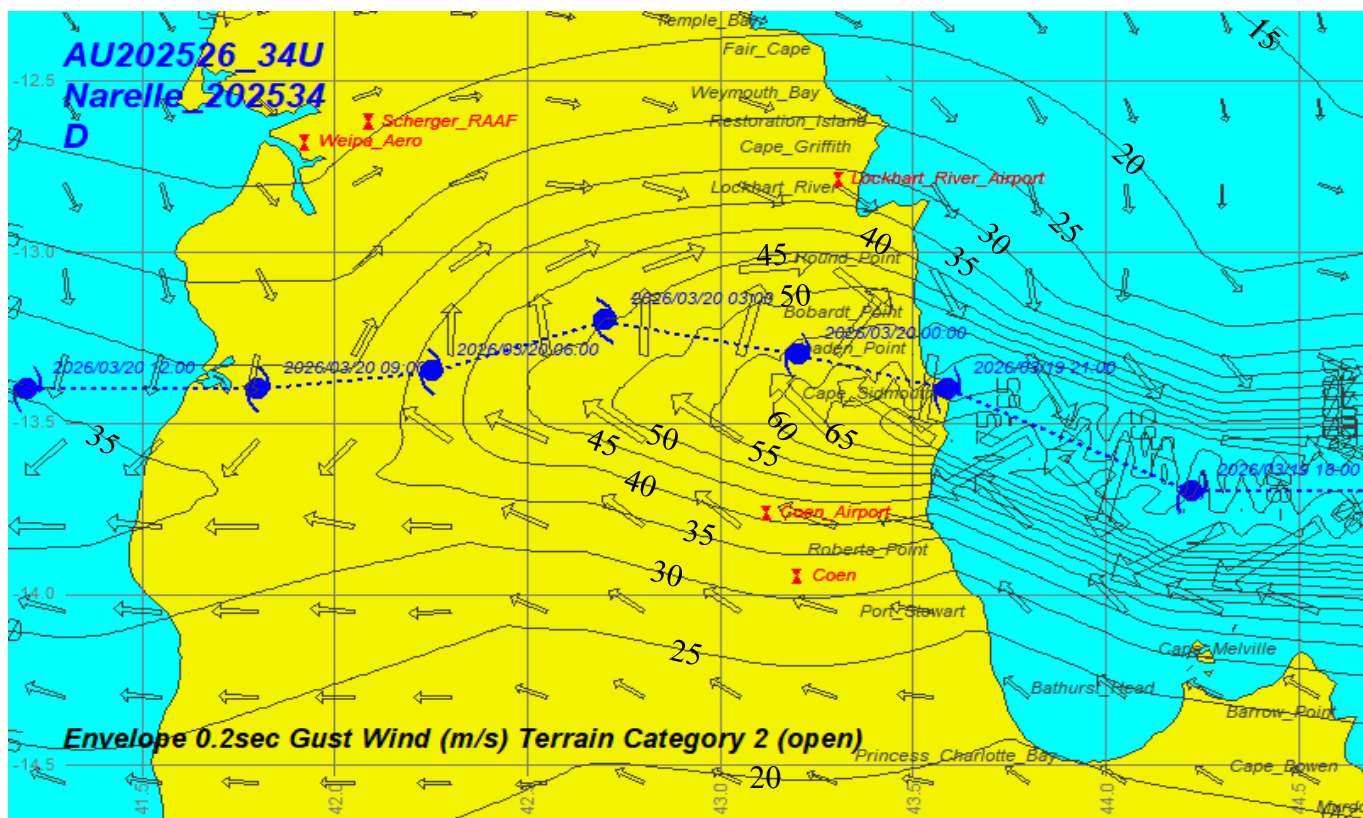


Figure 3-5 Numerical wind field TC Narelle in Queensland (SEA 2026) – peak 0.2 sec gust in m/s

The very tight peak gust wind gradient is compatible with the very compact cyclone shown in the Bureau's SAR output. The tight gradient also made it more difficult to match anemometer data far from the track e.g. Lockhart River and Weipa.

3.2.2. Storm tide from TC Narelle in Queensland

Severe TC Narelle achieved estimated Cat 5 strength about 250 km before landfall near the isolated Cape Sidmouth. The forecast track over the open sea and estimated intensity largely played out as forecast over the several days of approach, with the time of landfall rarely shifting away from the high tide on the morning of 20 March. The only outpost in the area at Port Stewart, which is located about 65 km south of the track, was expected to experience a storm tide of about 4.5 m AHD, being a 2.6 m surge delivered on the 1.2 m high tide as shown in Figure 3-6. This would be over 1.5 m above the Highest Astronomic Tide at the site, which together with wave runup would likely cause significant beach erosion to the sandy shoreline. The settlement itself is expected to have been protected to some extent by being inside the barred Stewart River entrance at an elevation of about 8 m AHD. The estimated peak storm tide of 5.5 m was expected 30 km to the north of Port Stewart and 30 km south of track, consistent with the estimated radius to maximum wind.

Figure 3-6 presents estimation of storm tide from modelling.

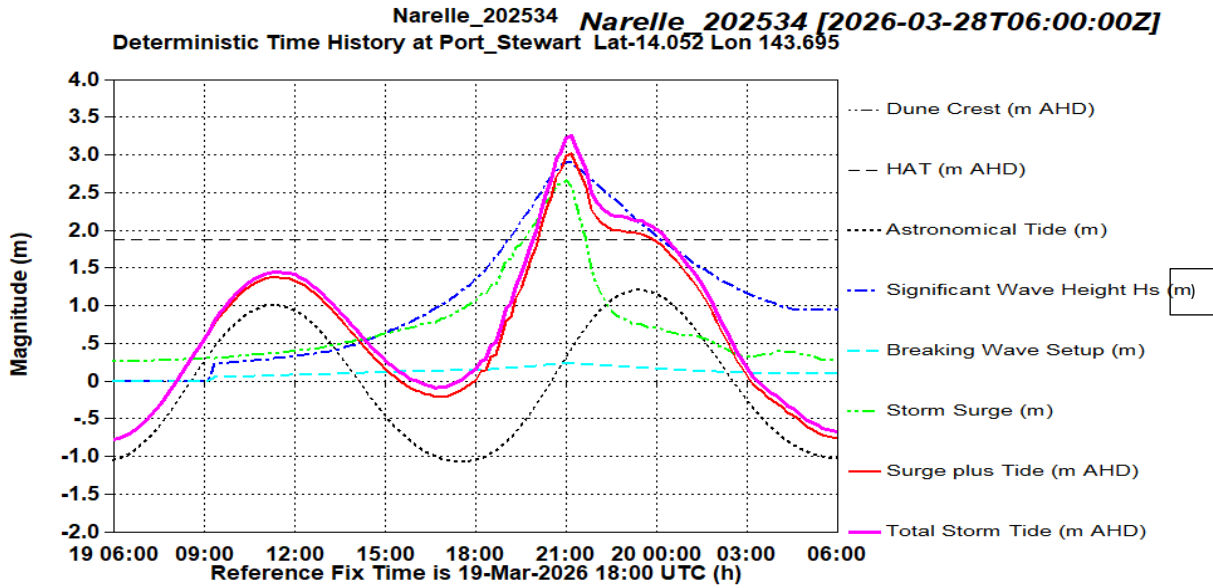


Figure 3-6 Storm tide data for Port Stewart, Cape York Peninsula, Queensland (SEA).

3.2.3. Numerical model for winds near landfall in Northern Territory

Figure 3-7 shows a contour plot of the maximum 0.2 sec peak gust along the track of TC Narelle as it crossed near Groote Eylandt into east Arnhem land. The tropical cyclone had a lower intensity than when it approached the Queensland coast and peak wind gusts were lower than those shown in Figure 3-5. The analysis showed that peak gusts expected in larger communities – Nhulumbuy, Groote Eylandt and Bulman were around 30 m/s or less – around the same speed expected at Coen and Aurukun on Cape York Peninsula.

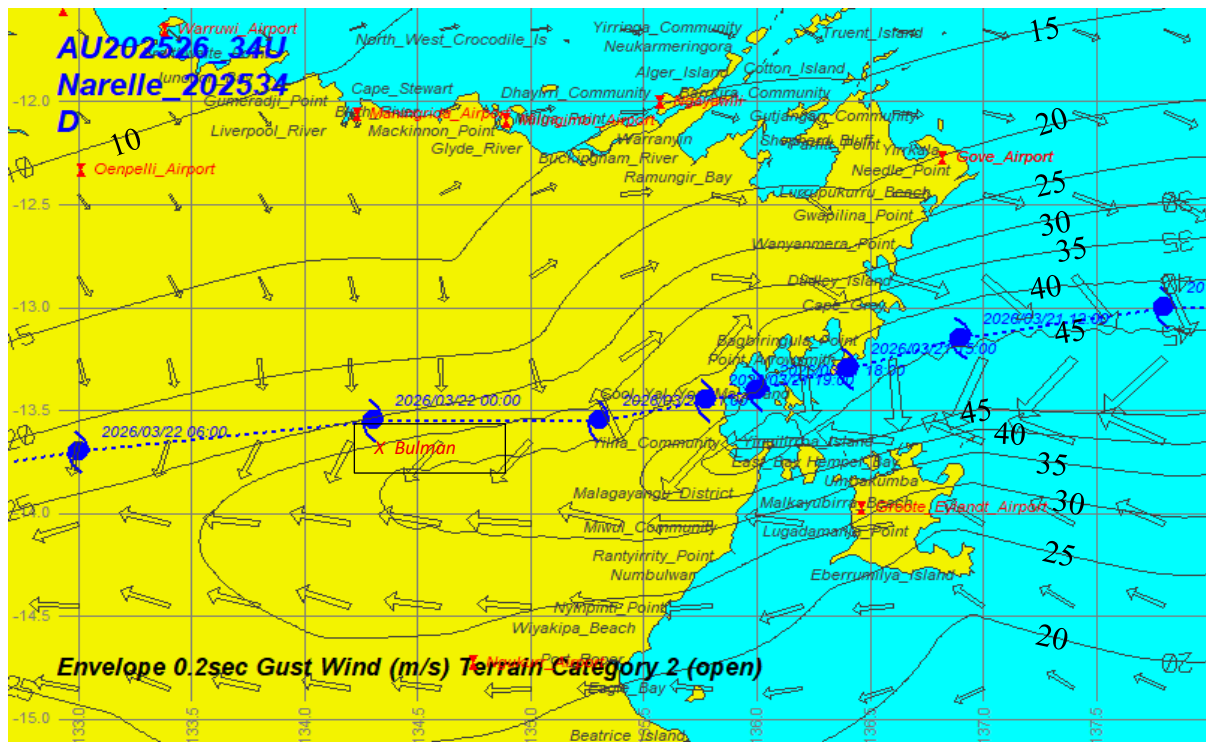
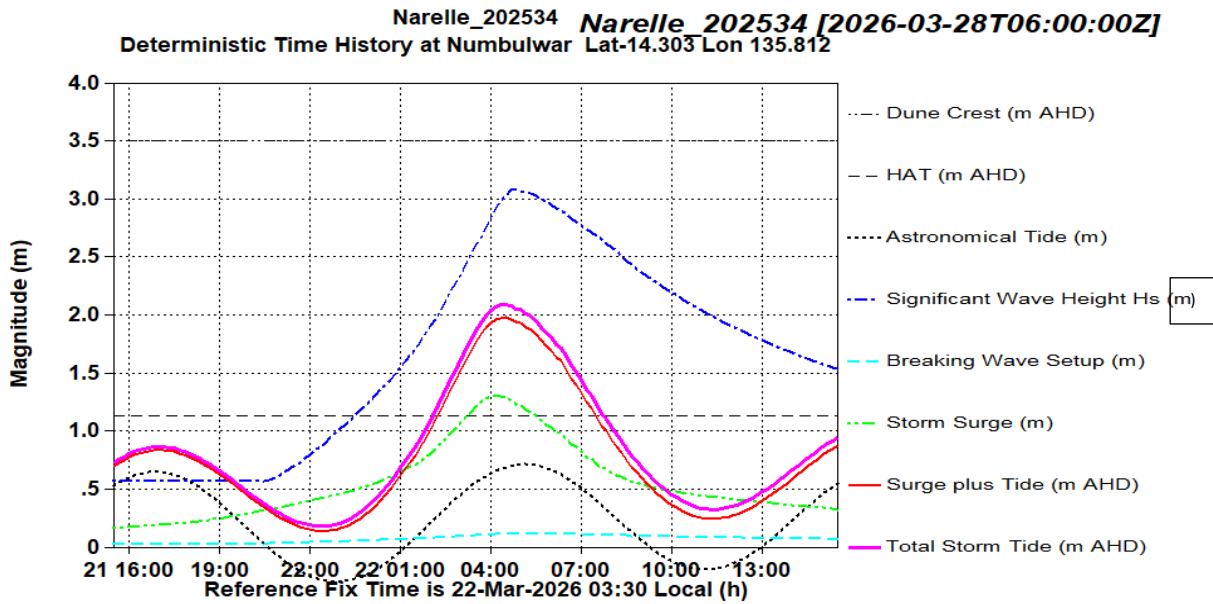


Figure 3-7 Numerical wind field TC Narelle in East Arnhem land (SEA 2026) – peak 0.2 sec gust in m/s

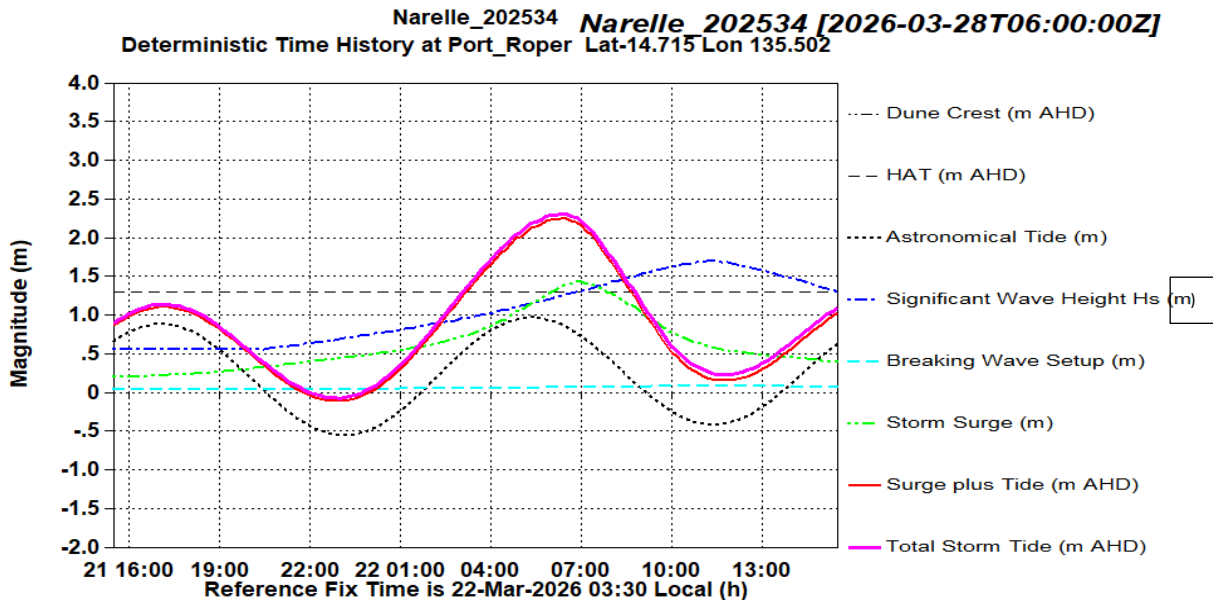
3.2.4. Storm tide from TC Narelle in the Northern Territory

A storm tide analysis showed that it had the potential to push the water level around 1 m above Highest Astronomical Tide (HAT) at locations on the East Arnhem coast south of Groote Island. Figure 3-8 (a) shows storm tide effects at Numbulwar based on modelling of winds and tide expectations. It shows that breaking waves may have pushed a little over 1 m above HAT but well short of the dune crest.

Port Roper (Figure 3-8 (b)) is a little further south from Numbulwar and experienced slightly higher storm surge, but lower breaking wave setup.



(a) Numbulwar



(b) Port Roper

Figure 3-8 Storm tide data for Numbulwar and Port Roper in east Arnhem land, NT (SEA).

3.2.5. Numerical model for winds near landfall in Western Australia

Figure 3-9 shows a contour plot of the maximum 0.2 sec peak gust along the track of TC Narelle as it approached the WA coastline. It had previously travelled from the western Kimberley down the Pilbara coast and had increased in intensity to a category 4 event but was decaying as it approached the coast.

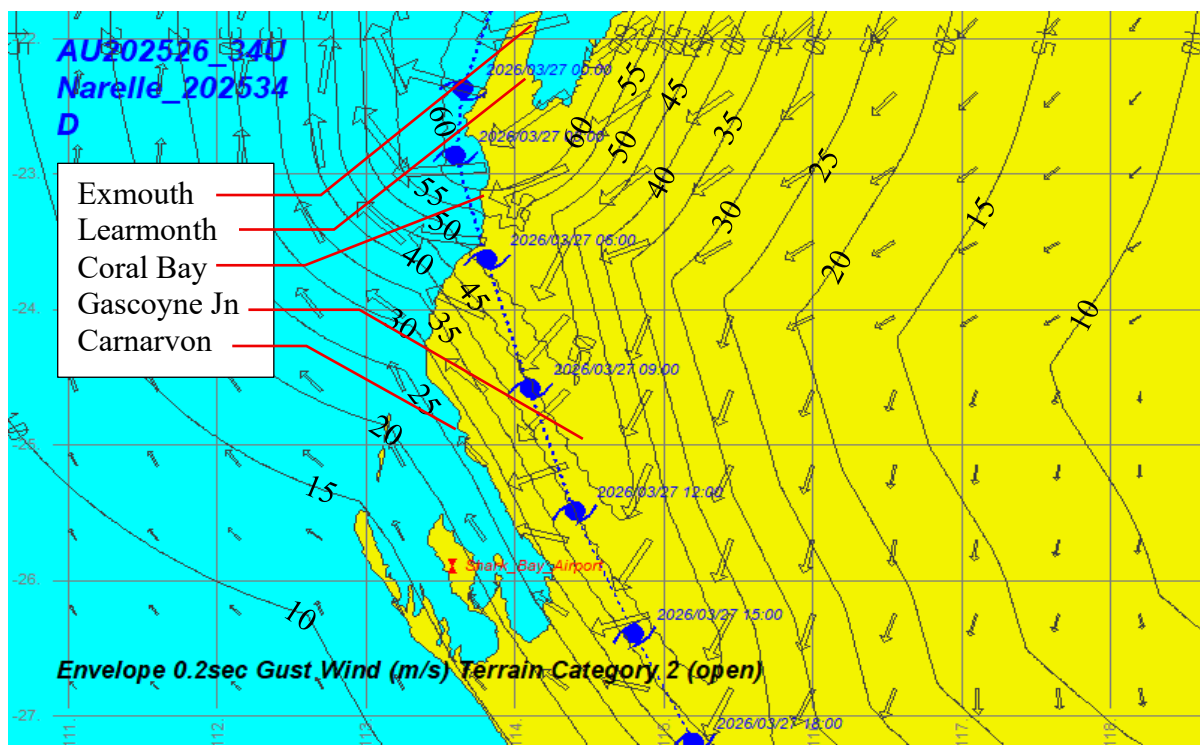


Figure 3-9 Numerical wind field TC Narelle in Western Australia (SEA 2026) – peak 0.2 sec gust in m/s

Figure 3-9 shows that the wind speeds in Exmouth town were greater than 55 m/s. It is likely that the winds were closer to the upper bound wind speed obtained from the windicators in Exmouth – 58 m/s. Likewise the peak wind gusts shown in Figure 3-9 are compatible with the measured wind speed at Learmonth of 61 m/s.

The estimated wind speeds in Coral Bay from the windicators are also compatible with the 50 m/s shown in Figure 3-9. However, as the cyclone moved further south the measured speeds were higher than those shown in the modelled wind field.

3.2.6. Wind field for the area covered in the field investigation

Information from the anemometer data, the windicators and the numerical model based on preliminary information on TC Narelle from the Bureau of Meteorology was combined to give the wind field map plotted as Figure 3-10. This map gives close agreement between the records from the anemometers and the windicator data and its basic shape was based on that from the numerical model.

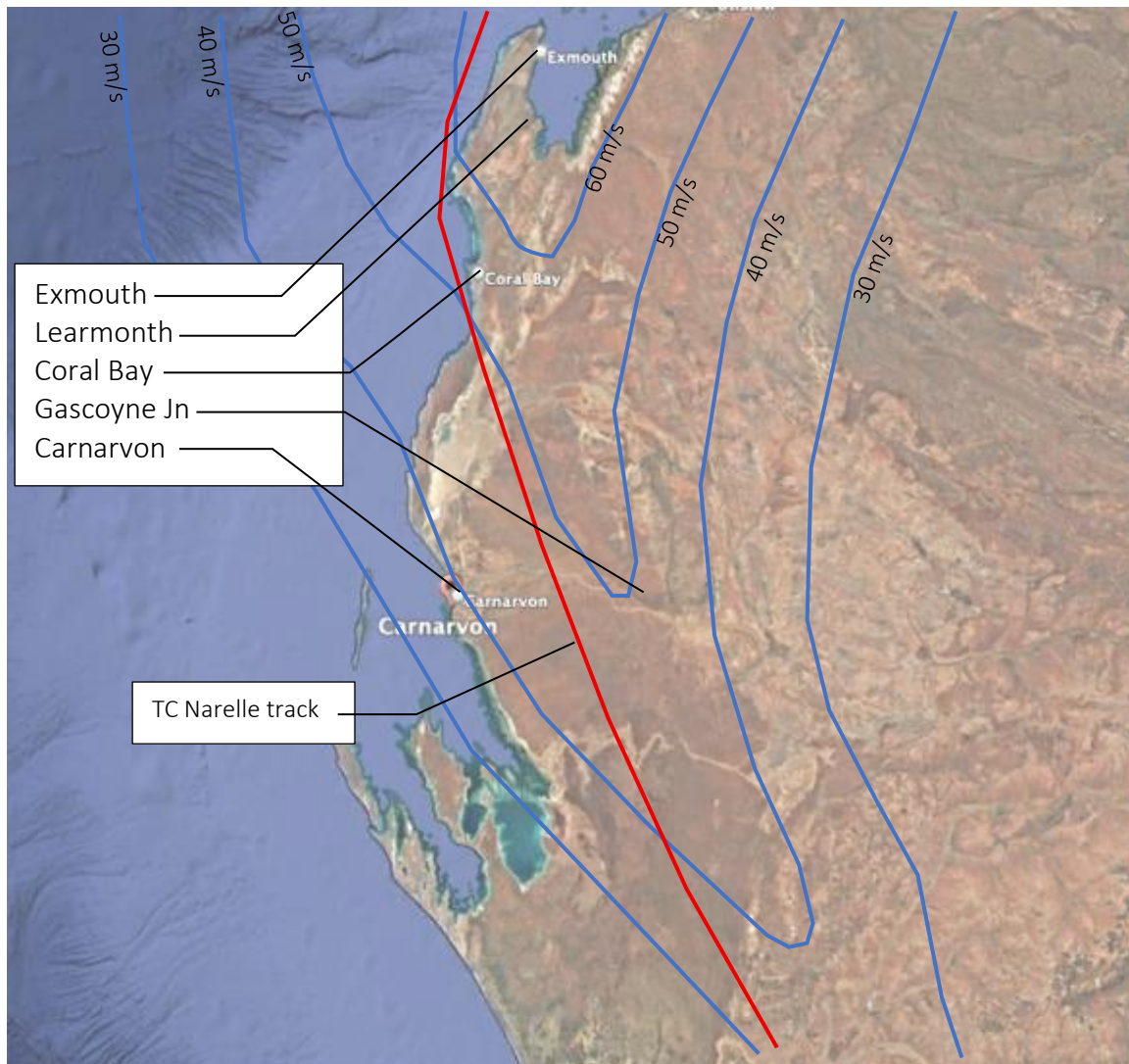
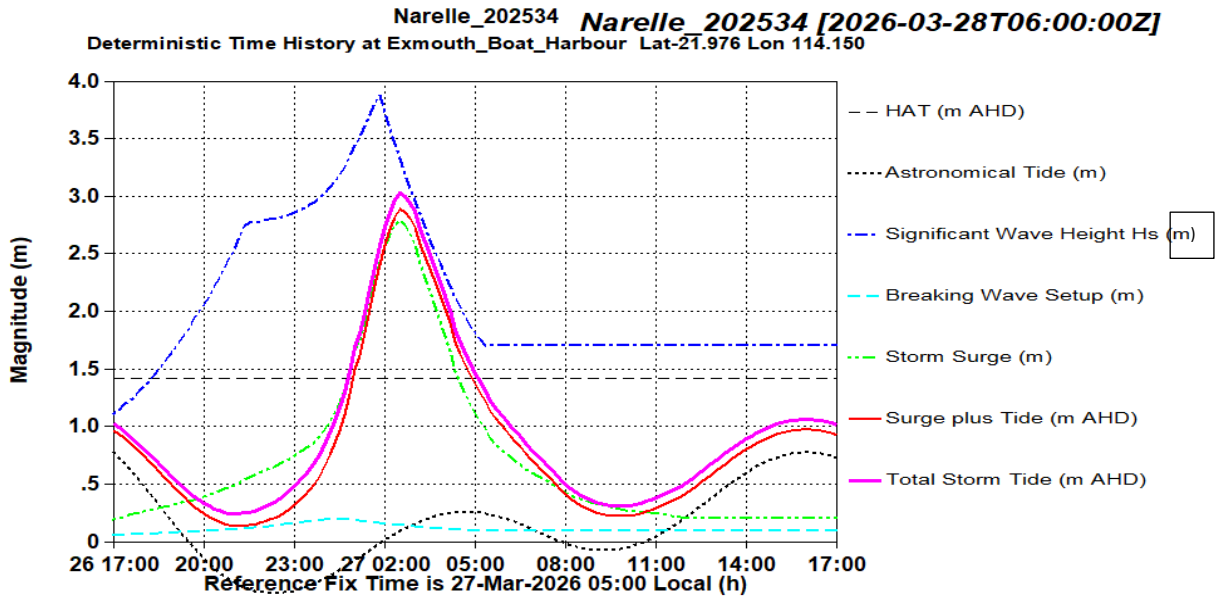


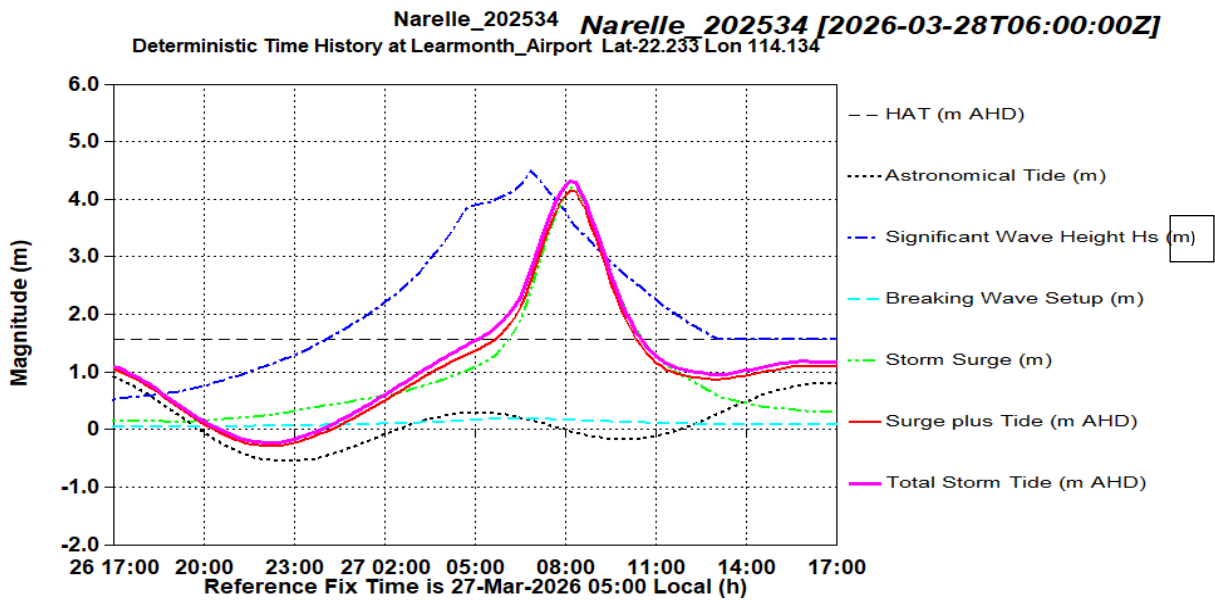
Figure 3-10 Wind field for field investigation of TC Narelle in WA as 0.2 sec maximum gust

3.2.7. Storm tide from TC Narelle in Exmouth Gulf

Figure 3-9 shows that the peak winds in the Exmouth Gulf were from the NE. This wind direction drove water into the Gulf and onto the eastern shore of NW Cape. The shallow water depth in the gulf and the gentle slope onto the shore contributed to a substantial storm surge. Figure 3-11 shows modelling of the storm tide at Exmouth (in the northern part of the gulf) and at Learmonth (in the southern part of the gulf).



(a) Exmouth marina



(b) Learmonth

Figure 3-11 Storm tide data for Exmouth Gulf, WA (SEA).

The storm tide modelling at Exmouth follows the recorded storm tide at the Exmouth Tide Gauge shown in Figure 2-7 and gives confidence in the modelling of storm tide in this area. The storm tide at Learmonth was significantly higher at around 4 m. This level of storm tide was above the dune level in places and allowed significant volumes of water to cross the dunes and fill low-lying areas of land around the airport.

4. Observations of wind damage in Queensland

The media focused on TC Narelle as a Category 5 event and presented it as the strongest cyclone to affect Cape York Peninsula for many years, in some reports, 100 years.

Media showed some photos of trees that had fallen and some videos of people outside while the wind was buffeting the trees. Little structural damage was reported. The lack of reported damage is consistent with the wind speeds at 30% to 60% of the design wind speed for housing (

Table 1). This equates to wind pressures of 10% to 35% of design wind pressures. Figure 4-1 and Figure 4-2 show some photographs harvested from media showing reported damage. We did not receive any reports from Port Stewart which was near the east coast crossing point and may have been subjected to very severe winds.



Figure 4-1 Social media images of damage from Weipa



Figure 4-2 Media images of a fallen tree and power lines in Aurukun and a damaged shed in Coen (ABC news)

Extensive imagery from the SES survey of Coen was examined by the Cyclone Testing Station. The lack of observed damage to fences, undamaged street signs, and very slight leaf loss on trees, indicates that the peak gusts were likely to be below 100 km/hr. Figure 4-3 shows a comparison of the leaf cover before and after TC Narelle in Coen from the before and after drone footage taken by the SES in Coen.



(a) Leaf index before TC Narelle in Coen

(b) Leaf index after TC Narelle in Coen

Figure 4-3 Comparison of leaf cover before and after TC Narelle in Coen showed little change

The light leaf loss was also observed in photos from Aurukun. Slightly more leaf loss was observed in some photos from Archer River, north of Coen and close to the path of the cyclone shown in Figure 2-1. A media image from Archer River is shown in Figure 4-4. The leaf loss and tree damage in this photo is compatible with peak wind speeds around 120 km/h.



Figure 4-4 Media images of tree damage in Archer River and a shed roof lifting in Lockhart River (ABC news)

5. Observations of wind damage in the Northern Territory

There were few reports of structural damage due to wind in the Northern Territory. The media showed some photos of trees that had fallen and some more shade cloth off structures as shown in Figure 5-1 and Figure 5-2. Both Gove and Groote Eylandt were population centres near the approach of the tropical cyclone to the East coast of Arnhem land.

However, Table 2 showed that the wind speeds in those locations were well below the design wind speed and the damage observed was appropriate for wind speeds at 41% to 46% of the design wind speed for housing (Table 1). This equates to wind pressures of 17% to 21% of design wind pressures.



(a) tree damage near Gove

(b) tree damage on Groote Eylandt

Figure 5-1 media photos of damage in TC Narelle near landfall (ABC News)



Figure 5-2 Media images of a shade cloth failures near eastern Arnhem land (ABC news)

However, the more significant damage in the NT was flooding caused by ex TC Narelle.

6. Observations of wind damage in Western Australia

The damage investigation focused on the area from Exmouth to Carnarvon. This region had the most significant wind and wind-driven rain damage.

6.1. A roof retrofit

A large building had a roof upgrade after TC Olwyn. We were told that this was because the building leaked and the roofing banged during TC Olwyn. The initial roofing system was a concealed fixed roofing system that utilised clips that anchored two cladding ribs each. The clips had been screwed to hot-rolled purlin sections, but the original screws had clearly corroded. Some of them may have broken through completely which would have caused banging during TC Olwyn.

The retrofit entailed removing the roofing, and the original sheeting clips. Then the same roofing was replaced with screws through each of the cladding ribs at each purlin crossing. This effectively transformed the same roofing from a concealed fixed system to a pierce fixed system.

A similar failure (loud banging and water ingress) was experienced during TC Narelle. The barge flashing had come off many edges of the roof as shown in Figure 6-1. The loss of flashing in Figure 6-1 (a) happened prior to the loss of the roof sheeting. The flashing shown in Figure 6-1 (b) was new flashing fitted at the time of the refurbishment. Holes in the roofing at that edge showed that the previous flashing had been screwed to the sheeting at every second rib, but the new flashing was fastened with pop rivets every fourth rib. Widespread flashing failure on this building was due to the inadequacy of the fixing methods.



(a) Flashing parallel to ribs
Figure 6-1 Missing flashings

(b) Flashing perpendicular to ribs

The failure of the flashing shown in Figure 6-1 (a) allowed the wind to get under the edge of the sheet on the left side of the photo and it would have started to flap. (The wind at that stage was coming from left to right in the photo.) However, the reason for the roof failure was that three of the four screws that held the lap joint of the edge sheet had broken years ago. It is likely that the screws broke on installation into the hot rolled purlins, but were held tight by the double layer of sheeting at the lap. One of these screws was removed by hand and is shown in Figure 6-2. Figure 6-2 also shows the purlins with the very badly rusted small gauge screws that held the initially installed clips and corroded failure surfaces on the new screws associated with failure at the time of installation.

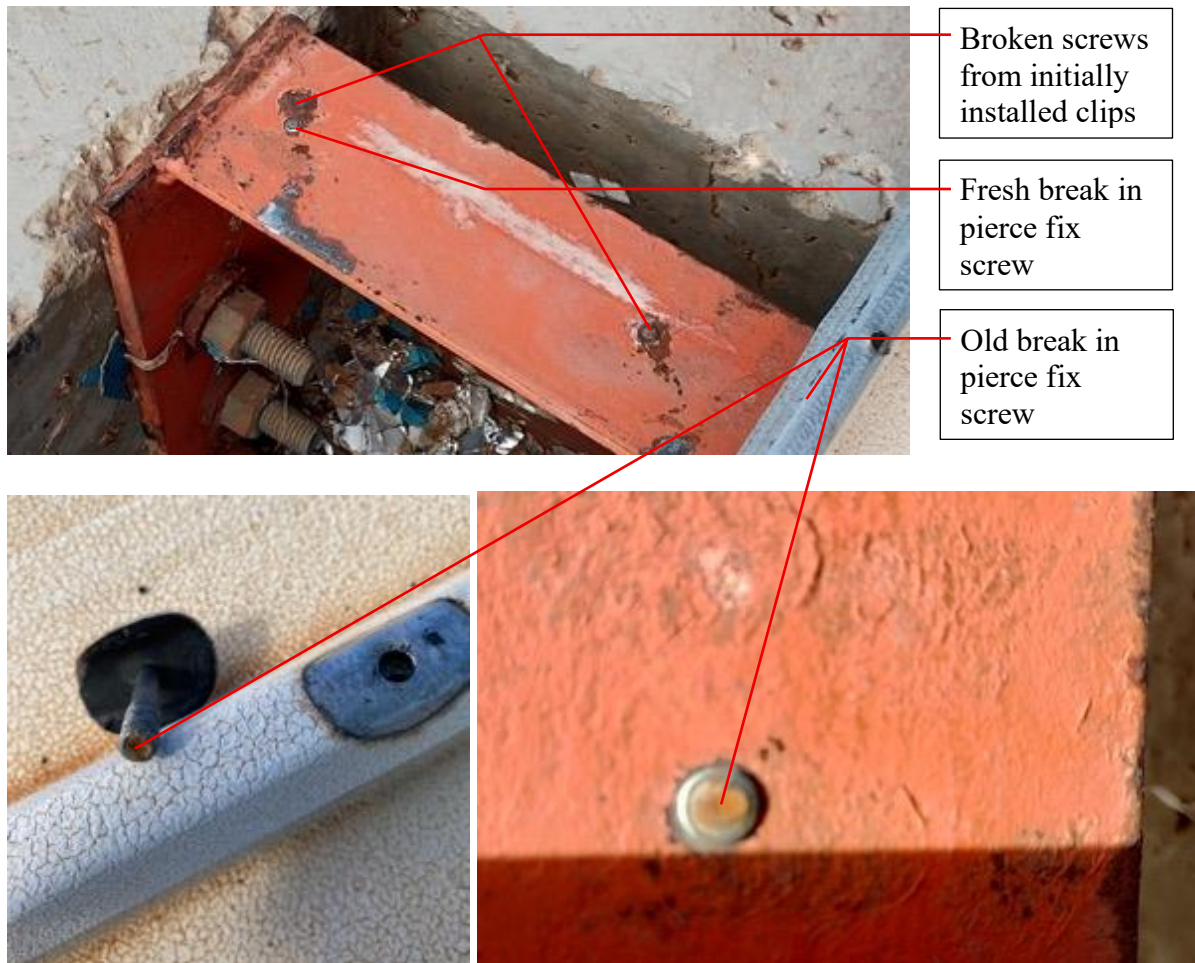


Figure 6-2 Broken screws from pierced fixed roofing

The roofing had detached except for one end and had folded back as shown in Figure 6-3 (a). The detached portion of roofing had flapped across the top of the roof and eventually broken the end of the sheet off, leaving the gap shown in Figure 6-1 (a). Water was blown in through this gap and under the missing flashing on that edge. It caused water damage to the ceiling underneath as shown in Figure 6-3 (b).



(a) Damaged roofing

(b) Internal water damage including ceiling loss

Figure 6-3 Roofing loss

6.2. Concealed fix roofing

An older building lost its entire roof. The roofing was an older concealed fix system and some of the clips were bent down. It is highly likely that they were bent down at the time of installation, by not engaging properly with the rib on the piece of sheeting as it was pressed down.

The roof is shown in Figure 6-4 together with a photo showing a normal clip on the left and a bent clip on the right.



Figure 6-4 Loss of older concealed fixed roofing

A newer building had a contemporary concealed fix roof, but a part of the roof was lost. While it was not possible to perform a detailed inspection of the failure, the clips bent upwards in a way that indicated that one connection between the purlin and the clip may not have been fastened. The failure is illustrated in Figure 6-5.

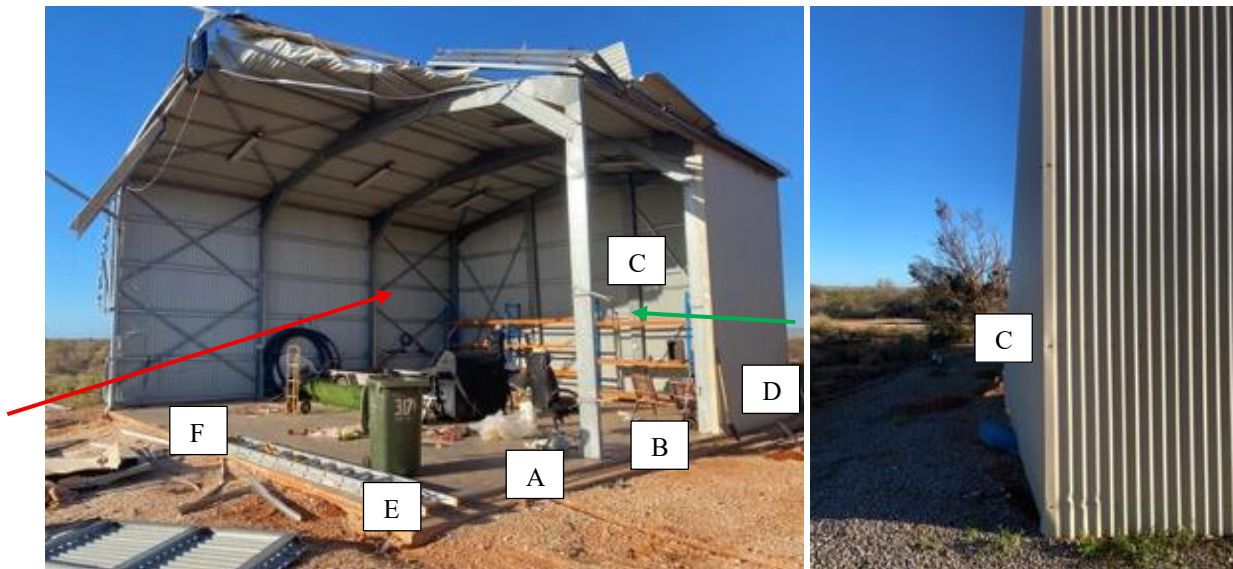


Figure 6-5 Failure of contemporary concealed fix roofing

6.3. Internal pressures

Figure 6-6 shows a shed that had experienced multiple failures:

- The doors on the right side of the shed had blown off (A and B).
- One end wall had bowed outward (C).
- The base of one portal had lifted around 250 mm (D) – also shown in Figure 6-7.
- A different portal leg had broken away from the footing folded back onto the roof (E)
- The other end wall had blown out of the building (F)



The red arrow indicates the wind direction when doors came off. The green arrow indicates the wind direction for the maximum winds.

Figure 6-6 Shed failures

One of the doors was found around 240 m from the shed and the path it took gave the wind direction when the doors were lost. The bent flashing over the top rail indicated that the doors had folded upward and over the top of the building. The wind direction at this stage is shown by the red arrow and the doors would have been on a side wall with very significant suction forces. The wind was from this direction early in the passage of the tropical cyclone.

The loss of these doors would have created a large opening which would have been on the windward face for the maximum winds experienced in this location. Once the wind had shifted by 90° after the loss of the doors to the direction shown by the green arrow, the shed would have been subjected to very high internal pressure. The high positive internal pressure would have caused outwards pressures on the two end walls. It would also have contributed to higher uplift forces in the portal legs. Lateral forces would also have contributed to tension in the legs on the windward side of the shed. The high tensions in the legs that were part of the in-plane bracing of the end walls gave failures near the base of the portal legs.

For leg (D), the failure was a footing failure and for leg (E) it failed the bolts in the baseplate. Figure 6-7 shows the lifting of the footing under leg (D)

As at least one of the end posts had been compromised and the support for the girts at one end removed, the end wall (F) was blown out of the building. The wind speeds that caused this damage were around 70% of the design wind speed for importance level 2 structures. The wind loads on this shed were around 50% of the region's design wind loads.



Figure 6-7 lifting of footing under an end portal leg

A large and lined building had vents from a redundant air conditioning system into the area above the ceiling space. Wind and rain was able to get through the vents and cause water damage under the vents, but also pressurise the whole ceiling space. In areas not under the open vents, the dry ceiling had been blown downwards by the high internal pressure in the ceiling space.

Figure 6-8 (a) shows the redundant air conditioning vents that allowed pressurisation of the ceiling space in the building. Where the ceiling had been blown into the building under the vents, the insulation was obviously wet, but Figure 6-8 (b) shows ceiling collapse some distance from the vents where the insulation remained dry. These failures could have been avoided by replacing the redundant vents with sealed wall cladding.



(a) Redundant vents (b) collapse of dry ceiling

Figure 6-8 Internal pressurisation in the ceiling space

All structures in the cyclone regions (B2, C and D) including sheds need to be designed to accommodate high internal pressures.

Internal pressure was also instrumental in the failure of roofs on older buildings once windows on the windward wall had failed. In many cases, inadequate tie-down may also have

contributed to the failures, but where there were similar buildings side-by-side it was only the ones that had windward wall failures that had significant roof damage. Figure 6-9 shows a transportable building (donga) that had been well tied down to concrete blocks, but where windward wall windows had broken, the internal pressure had caused roof loss, while neighbouring dongas without window damage retained their roofs. While these buildings were in region A and were not required to be designed for internal pressure, the failure of the roof associated with a windward wall window breaking, confirmed that internal pressure can arise in any wind region.



Figure 6-9 Roof loss in one donga that had damage to a windward window

6.4. Roof tie-down

Some buildings had failure within the roof tie-down chain. Elements within the tie-down chain include

- Roofing fasteners – which tie the roofing to the battens or purlins,
- Batten/purlin fasteners – which tie the battens or purlins to rafters or trusses
- Roof system anchors that tie the roof structure to the walls.

In some cases, appropriate fasteners had not been installed, by omission or because they were not documented in framing manuals at the time of construction. In other cases, they had deteriorated so that they were no longer fit-for-purpose.

6.4.1. Roofing fasteners

Figure 6-10 (a) shows partial failure of an older roof where the fasteners at the edge of the roof had corroded. This had caused the edge of the roof sheets to lift. Figure 6-10 (b) shows a more recent roof. In this case, the saline coastal environment for this site had caused corrosion of some fasteners on the veranda and they had been weakened. Their failure in this case had not precipitated roof loss as the broken fasteners were not at the edge of the roof. Figure 6-10 (c) is a photo that also shows corrosion, this time on wall cladding fasteners that were only a few years old.

Coastal environments require more frequent maintenance or specification of cladding fasteners with higher levels of protection.



(a) Partial roof failure due to deterioration of roofing fasteners



(b) Corrosion of cladding fasteners leading to fastener failure

(c) Corroded wall sheeting fasteners

Figure 6-10 Deterioration of cladding fasteners

6.4.2. Batten or purlin fasteners

In previous tropical cyclones in this area (TC Vance in 1999 and TC Olwyn in 2015), there had been a number of cases of nailed batten to rafter connections failing. The absence of these types of failures in this event suggests that most of the older buildings had been demolished or upgraded as a result of the effects of previous events. Figure 6-11 shows an older building with nailed purlin to truss connections where many of them had failed in TC Narelle. In this case, the building had been re-roofed, but the underlying connections were not upgraded while the roofing was off.



Figure 6-11 Failure of some purlin to truss connections

Nailed batten or purlin to trusses or rafters should be upgraded to connections that comply with AS 1684.3 in cyclone areas. The ideal time to perform this upgrade is when roofing is replaced.

6.4.3. Roof to wall connection

A recently constructed building lost a complete section of roof due to connection failure between the roof and the walls. The walls were reinforced blockwork with filled cores. Figure 6-12 (a) shows that the roof from the veranda beam to the ridge line is missing. The original position of the veranda beam is indicated by the red rectangle and missing blocks at the end connection are highlighted by the oval. At the other end of the veranda beam masonry anchors had pulled out of the reinforced cores as shown in Figure 6-12 (b). At this end, the reinforcement could be seen in the cores, but there was no sign of it at other end.



(a) Roof loss



(b) Detail of connections

Figure 6-12 Roof loss at roof to wall connection

The large portion of roof was carried around 80 m and caused damage to at least 2 other houses as it landed.

All connections from the roof to the ground need to be adequately sized. The larger the tributary area for the connection, the higher the load it will need to carry.

6.5. Windows

Some windows were broken by either wind-borne debris or by wind pressure. Figure 6-13 (a) shows a float glass window that failed by differential pressure from the inside of the building to the side wall. The glass failure created a hole in the building envelope and spread large pieces of sharp broken glass nearby. Figure 6-13 (b) shows some debris damage to a laminated glass sliding door. Though the glass had broken, it remained in place and had not caused an opening in the building and had not spread broken glass.



(a) Float glass



(b) laminated glass

Figure 6-13 Glass failures



(a) Frame moved from brickwork



(b) frame moved from timber framing

Figure 6-14 Window frames removed from the wall

Figure 6-14 shows two examples of windows where the window frame was not correctly fitted to the building. In Figure 6-14 (a), the red ellipse highlights the gap between the brickwork and the window frame. It had blown into the building under differential pressure, and the window in Figure 6-14 (b) had been sucked out.

Laminated glass provides more resilience in windows.
Correct fixing of window frames to the building is necessary for them to continue to remain fit-for-purpose.

6.6. Verandas

The inspection investigated 12 buildings in which verandas had failed. In nearly all, cases, the reason for the failure was deterioration of connections, defects in veranda posts or deterioration of the base of the veranda posts. It should be noted that for these failures, the wind loads were only around 50% of the design wind loads for the region.

Figure 6-15 (a) shows a veranda post that had broken off at the ground level. Here the corrosion had almost completely eroded the thickness of the steel walls of the post. Figure 6-15 (b) shows a brick column supporting the veranda roof that had a steel post embedded in the column. There were signs of rust up the full height of the column, but at the base, the post was completely corroded with only a small portion of one side of the SHS visible. (See the red ellipse.) In both of these cases, because most of the veranda posts were in this condition, the posts had failed causing the whole veranda to lift. As they tore away from the structure, they damaged the edge of the roof causing water ingress to the main building. The veranda also became wind-borne debris that caused damage to other parts of the roof and neighbouring properties.



(a) Steel veranda post

(b) Steel post inside brick column

Figure 6-15 Corroded steel veranda posts

Figure 6-16 shows some timber veranda posts with significant rot near the ground line. There was evidence that the steel bolts from posts to the stirrups had corroded and been recently replaced with new steel bolts and the posts had been recently repainted. However, as the timber had rotted at the base of the veranda post, most of the posts failed in spite of the maintenance work.



Figure 6-16 Rotten veranda posts

Some verandas had corroded roofing, and others had corroded steel stirrups, nails and nailplates as shown in Figure 6-17.



Figure 6-17 Corrosion in steel elements of verandas

In some cases, details on the veranda itself can cause premature failure. Figure 6-18 shows some bolts in veranda beams that do not comply with the end distances in AS 1720.1. These details failed and caused loss of both a veranda and part of the house roof.



Figure 6-18 Insufficient end distance for bolts on veranda beams

Where verandas lift off, they can damage the house roof and/or the wall at the point of attachment of the veranda and this allows water in. This is illustrated in Figure 6-19. The veranda loss has created an opening at the top of the wall. It is generally above ceiling level, so wind-driven rainwater wets the ceiling which collapses. All of the cases of veranda failure illustrated in this report resulted in ceiling loss inside the house.



Figure 6-19 Water entry following veranda loss

Figure 6-20 (a) shows a recently repainted veranda. The nails in the batten to rafter connection had also been recently augmented with a heavily galvanised screw. However, a

number of timbers in this veranda had advanced rot, so rot in posts and battens caused failure under wind loads despite the recent maintenance.

Figure 6-20 (b) shows corrosion in a steel veranda post that was only 6 years old. It hadn't failed during TC Narelle, but if left unchecked, it may fail in a future tropical cyclone.



(a) Rot in batten

(b) Corrosion in veranda post

Figure 6-20 Maintenance of verandas

Maintenance of all aspects of verandas is important. Particular attention is needed for components in contact with the ground or concrete as corrosion or rot is greatest in these areas. These areas are frequently not easily visible. Elements with deterioration must be replaced. Painting will not give them their original strength.

6.7. Roof-top items

Figure 6-21 shows damage to roof top ventilators. An SES volunteer is putting a temporary patch on the roof where a ventilator had come off completely and left a hole that was allowing water in.



Figure 6-21 Damage to rooftop ventilators

Figure 6-22 shows from left:

- A kitchen extractor where the top cover has blown off. The loss of this cover has allowed water into the building and compromised the extractor.
- An evaporative cooler. Many evaporative coolers lost panels of fill. This allowed water to be blown into the unit and in some cases, find its way through the ducting into rooms below.
- An external condenser unit for a split system air conditioner that had broken its mounting. Not only was the system damaged, but it had created holes in the roof that had allowed water in.



Figure 6-22 Roof-top air conditioners and kitchen extractors

In addition to the items shown here, a number of roof-top satellite dishes had failed. Some dishes had bent or become detached and in one case, the support frame had been prised off and damaged the roof sheeting.

All roof-mounted attachments should be strong enough to withstand wind actions for the wind region and should be fastened securely to the roof structure – not just the roof sheeting. Mounting systems and hardware should have the appropriate coatings for the environment in which they will be used and then should be properly maintained.

6.8. Flashings

Figure 6-23 shows photos of damaged flashings in TC Narelle. They included external corner flashings between adjacent walls, barge flashings, flashings over parapets and apron flashings. Wherever a flashing is damaged, it allows water into the building. For lined buildings, this means damage to the linings and for any building it can cause damage to the contents.

Some of the barge flashings had been fastened to the roof with the roofing screws, but pop riveted to the walls or not fastened to the walls at all. There were many cases, in which the barge flashing had been screwed to the wall cladding at more than 500 mm centres.

Failure of apron flashings between either a wall and an eaves or a second storey wall and a first storey roof allowed water direct access to a ceiling and wall linings.



Figure 6-23 A collage of damaged flashings from TC Narelle

AS 1562.1 requires flashing to be fixed to each face of the building with screws at closer centres than 500 mm. Whenever flashings are replaced, they should be fixed to at least this standard. Pop rivets should not be used for large flashings (anything other than small flashings around penetrations).

6.9. Solar panels

Power in towns in the Pilbara and Gascoyne is supplied by local networks with generators in each town. Solar panels on roofs are becoming more common in these towns and some new solar generation facilities using ground-mounted panels are being connected to these local networks. In addition, remote communication towers require their own power and utilise solar arrays next to the towers.

This section presents observations of damage to both ground-mounted and roof-mounted solar panels that are similar to the observations made after TC Ilsa (Boughton et al, 2023). However, in TC Ilsa the observations related to wind loads at 80% or more of the design wind loads for Importance Level 2 structures in wind region D, but in this case the observations relate to wind loads of 50% or less of the design wind loads for Importance Level 2 structures in wind region D.

6.9.1. Ground mounted fixed solar panels

A number of ground mounted solar panels were investigated. Many of them had some clamp failures, and some showed glass damage.

Figure 6-24 (a) shows some ground-mounted panels where crazed glass was evident. (Panels with crazed glass are shown with dots). Figure 6-24 (b) shows that one panel failed by bending. Wind tunnel testing shows that the lower panels have the highest positive net wind pressures pushing on the upper surface of the panel and it was a lower corner panel that failed consistent with the wind tunnel results.

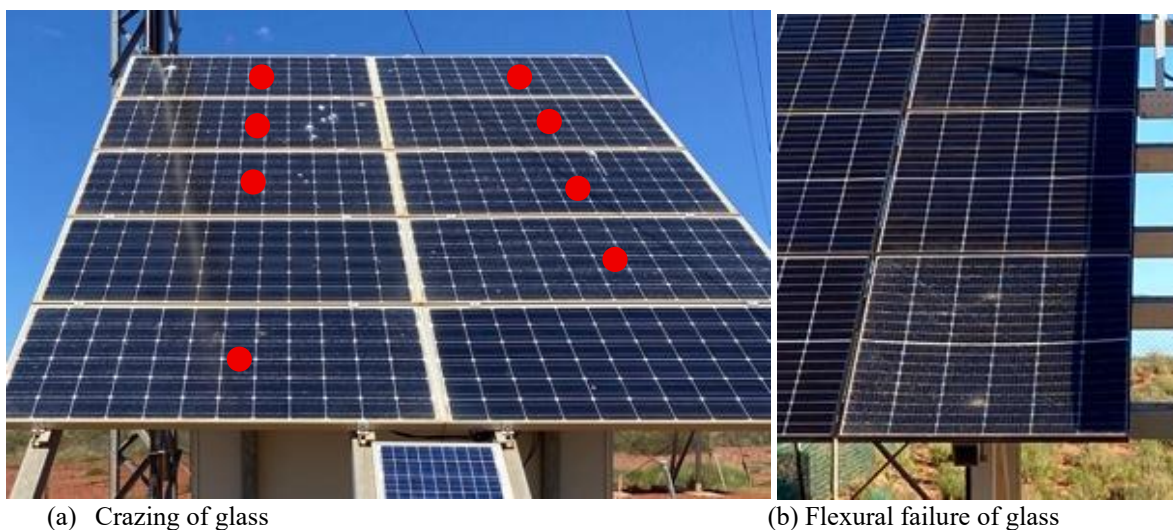


Figure 6-24 Glass failures in ground mounted solar panels

Some ground-mounted panels had become detached from their support frames. A number of different methods for fixing the panels were observed, with all methods having failures of some kind.

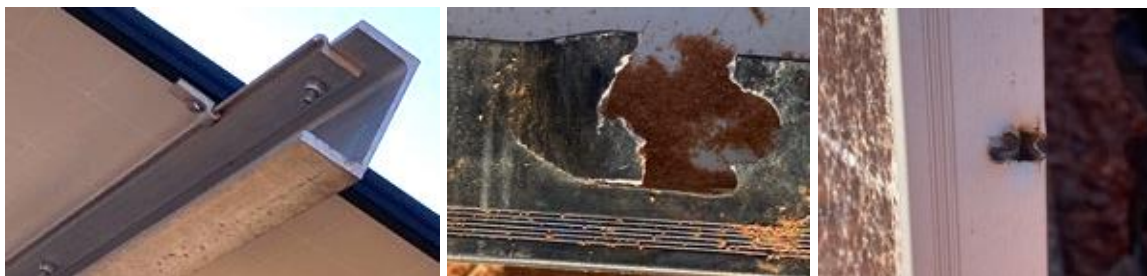
- Figure 6-25 (a) shows a clamped system in which the end clamps (circled) had been pried outwards and allowed a panel to become detached. The internal clamps that held that panel and the adjacent panel also moved which allowed a second panel to detach. Neither of these panels could be found. There was evidence that at least one of them had caused damage to the remaining panels as shown in Figure 6-26 (b).
- Figure 6-25 (b) shows a fastening system in which a bolt secures a clamp to the panel chassis as shown in the left photo. A few panels with this fastening system had failed.

The centre photo shows the damage to the chassis where the bolt has torn out a portion of the chassis. The failure surface indicates that fatigue may have been involved in the failure.

- The third photo in Figure 6-25 (b) shows another system in which the panels were bolted through the chassis, which also failed.



(a) Clamp movement



(b) Failure of bolts to chassis

Figure 6-25 Detachment of panels from frames

Where panels had become detached, they were sometimes difficult to find unless the panels were caught in the security fence around the compound. Figure 6-26 (a) shows a panel that travelled 250 m from its original location. In this case, the remote location did not have many other structures that could have been damaged by the detached solar panel. A detached solar panel with the potential to travel many hundreds of metres has significantly higher kinetic energy than the debris item listed in AS/NZS 1170.2.

Figure 6-26 (b) shows debris damage from a solar panel that had only travelled 3 metres from its point of detachment prior to bouncing off this panel. We could not find the panel that caused this debris damage.

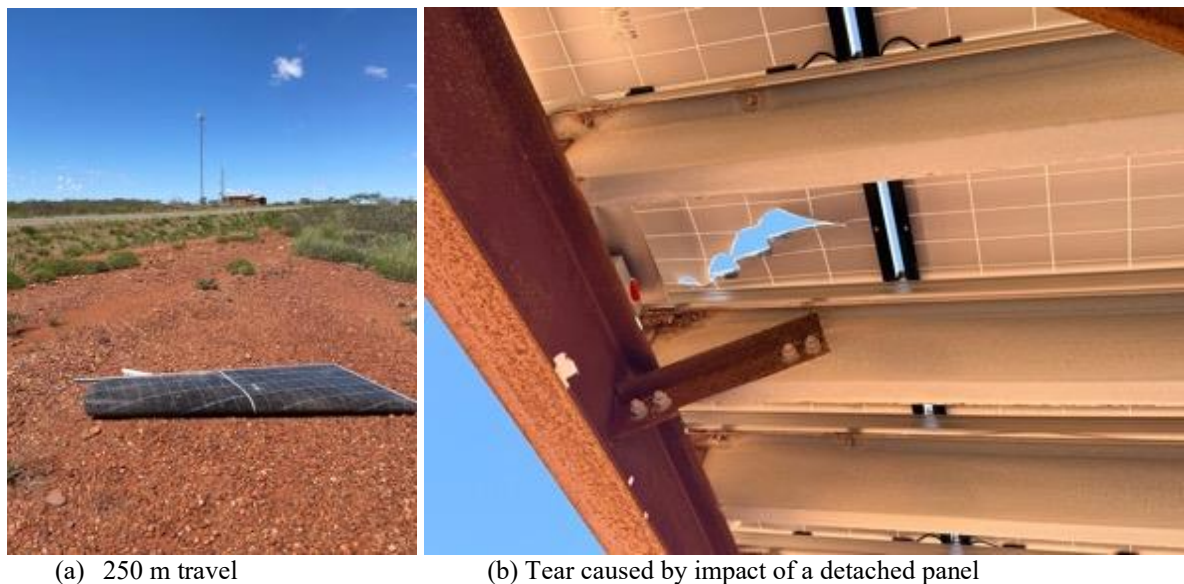


Figure 6-26 Panels lost from ground mounted arrays and damage from windborne panels

Wind causes lateral loads on cabinets associated with the solar panels. Figure 6-27 shows a cabinet that was blown over. In this case, the failure would have allowed wind-driven rain (from left to right in the photo) into the base of the cabinet and may have damaged circuitry inside even if it had survived the fall.



Figure 6-27 Damage to ground mounted cabinets

6.9.2. Roof mounted solar panels

There were many cases of roof-mounted solar panels that appeared to have no damage, but there were also around 15 installations that were observed to have some damage. They mainly involved detachment from the support rails. Figure 6-28 shows some examples:

- Figure 6-28 (a) shows a system where one panel has started to slide under the clamps.
- Figure 6-28 (b) shows a system where one panel has been disengaged from two of the clamps and slid under the other two but remained on the roof. Another panel has become completely disengaged and slid under the lower row of panels, and other panels have detached and been blown off the roof.
- Figure 6-28 (c) shows a couple of systems where the panels have been detached and left the roof completely.



(a) Panel moving in the clamps



(b) Some detached panels still on the roof



(c) Missing detached panels

Figure 6-28 Roof mounted panels detaching from rails

These systems all used clamps to secure the panels to the rails. Many clamps broke or the chassis of the solar panel moved, allowing it to pry or slip out of the clamp. Figure 6-29 shows a clamp that used barbs at the bottom to engage with the rail. The ellipse highlights that the barb on the right side is intact, but the barb on the left side has broken off.

A few clamps remained attached to the rails after the panels had been lost.

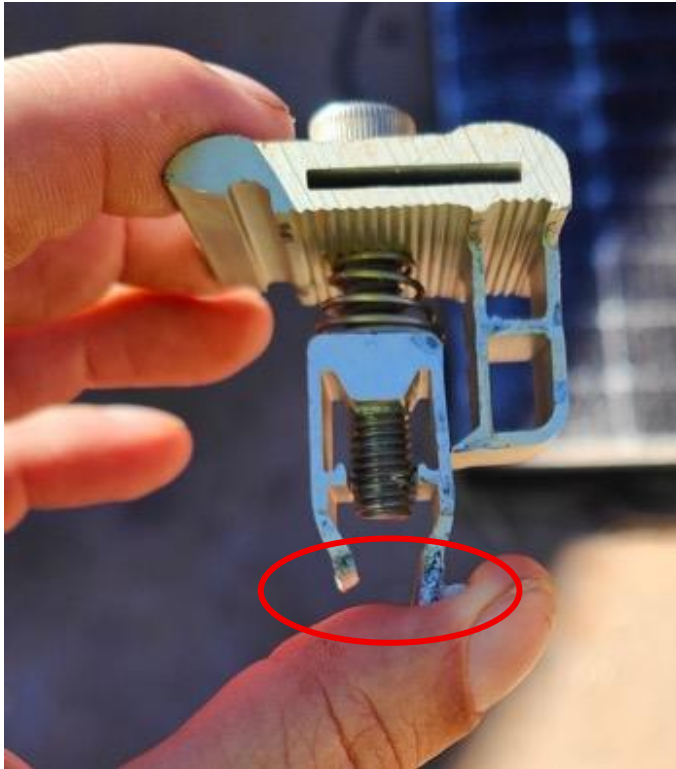


Figure 6-29 Clamp failure

Once the panels had become detached, then they became wind-borne debris. One panel was found 1.2 km from the house it had originally been installed on. Figure 6-30 shows photos of panels found on the ground in Exmouth.



Figure 6-30 A collage of photos of detached solar panels from Exmouth

All of the panels found on the ground had broken glass which would have come from the impact of the panel with the ground or other objects. In some cases, the glass fracture could

confirm that an edge impact had caused it to shatter, but in a few cases, the shatter was uniform and the broken glass was bowed upward indicating a differential pressure may have been involved in its failure.

There were reports of solar panels hitting other buildings and Figure 6-31 shows some damage caused by an impact from a windborne solar panel.



Figure 6-31 Debris damage on a garage door from an impact by a solar panel

Select an appropriate importance level for the installation based on expectation of functionality after severe events. Specify appropriate wind ratings for the panels themselves. Higher wind areas such as wind region D will require stronger panels. Design all elements of the support system for the differential pressure across the panels. Metal components of the support system should be tested for strength under repeated load and unload cycles (e.g. Low-High-Low testing as per AS4040.3).

6.10. Wind-borne debris

During this investigation a range of wind-borne debris was observed, including solar panels and other building components which had failed. This debris impacted neighbouring houses and caused damage, as shown in Figure 6-31.

A complete section of roof impacted two houses and caused significant damage as shown in Figure 6-32. Even though both of those houses did not sustain their own wind damage, the debris damage to them will require substantial repairs.



Figure 6-32 A section of roof as wind-borne debris

In addition to these wind-borne debris items which were significantly larger than the standard debris item specified in AS/NZS 1170.2, there were instances where pieces of timber penetrated the walls of buildings as shown in Figure 6-33.



Figure 6-33 Pieces of timber as wind-borne debris

While there are still examples of wind-borne debris of similar size and weight to the standard item referred to in AS/NZS 1170.2, there are also observations of much larger items of wind-borne debris. This includes portions of roof and solar panels. It may no longer be enough to justify design for low internal pressure by protecting the building envelope from impact by only the standard debris item.

6.11. Shade sails or shade cloth

In many of the towns, there were shade cloth structures on houses or commercial buildings to offer sun protection. In the Gascoyne region there were much larger agricultural shades used for either wind protection or to minimise evapotranspiration from crops. Domestic and agricultural structures will be discussed separately.

6.11.1. Domestic shade cloth

Many shade sails in towns had been taken down before the cyclone and were in the process of being re-erected at the time we were investigating damage. Figure 6-34 shows some shade sails still stowed after TC Narelle.

Where shade cloth structures had not been stowed, then the fluctuating wind pressures across the shade cloth tore it apart in most cases. Figure 6-35 shows some shade sail structures that were not stowed during TC Narelle and will now have to be completely replaced.



Figure 6-34 Shade sails still stowed after TC Narelle



Figure 6-35 Damaged shade sails that had not been taken down in preparation for the cyclone

6.11.2. Large agricultural shade cloth structures

In agricultural areas visited, shade cloth was used to minimise wind damage to crops under normal daily weather patterns and to reduce evapotranspiration losses to save on irrigation water.

- Wind breaks tend to be tall vertical structures which can be very long to protect a whole orchard. They reduce the impact of wind on the crop and also reduce damage to the fruit from wind-blown sand. These are illustrated in Figure 6-36. Some of these linear structures were configured so that the cloth could be dropped as preparation for a tropical cyclone.
- Water-saving shade cloth “green houses” were erected as draped structures across tension wires. They are illustrated in Figure 6-37. The farmers that provided information to the investigation noted that the construction/assembly precludes the shade cloth from being removed/lowered prior to approaching tropical cyclone.



(a) Torn wind breaks



(b) Lowered wind breaks

Figure 6-36 Agricultural wind breaks

While wind breaks are intended to protect crops from the effects of wind, they cannot resist tropical cyclone winds and Figure 6-36 (a) illustrates that. Where they have been lowered, the crops are unprotected, but the wind breaks can be raised again after the event to be functional for their intended design, which is to protect the crops during normal weather events experienced during the regular growing season.

An effective strategy for preserving wind breaks is to have the capacity to lower them as part of preparation for an approaching tropical cyclone. These types of structures are not designed to resist high wind events.

Figure 6-37 Shows a selection of agricultural crop covers intended to reduce evapotranspiration to reduce irrigation demand. The upper photo shows the least amount of damage and illustrates the tent-like structure with a roof and walls. Figure 6-37 shows increasing levels of damage in the lower photos. Those with significant damage will not reduce water demand at all. They require extensive repair to be fit-for-purpose again.



Figure 6-37 Agricultural crop covers

The complexity of the roof will make it very difficult to easily remove the shade cloth in preparation for an approaching tropical cyclone. Research on other methods of preparing them for severe winds may assist in their longevity.

Research should be undertaken on preparation of crop covers for an approaching tropical cyclone. Alternatively, research could establish ways of configuring these covers to reduce their wind loads.

7. Storm Surge

7.1. Storm surge damage in Queensland

Media reports also highlighted the combination of large swells and storm surge causing beach erosion and wave action over sea walls well south of the track of TC Narelle. Figure 7-1 shows some screen captures from media.

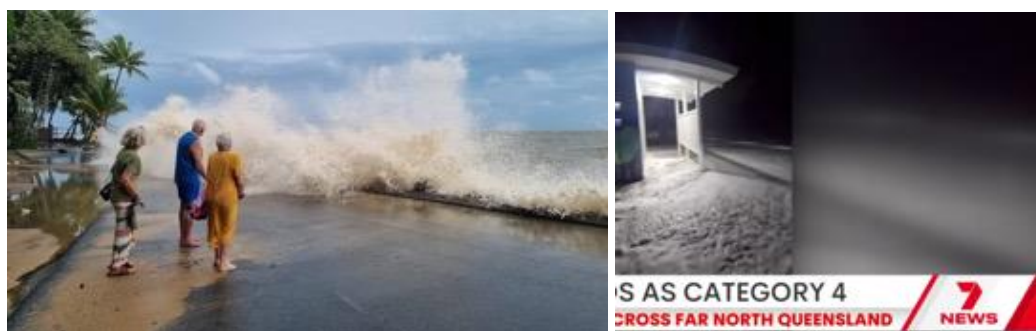


Figure 7-1 Media images of sea damage north of Cairns (ABC news and 7 News)

With a relatively tight estimated radius of gales of about 150 km, only Lizard Island to the south likely experienced close to gale force winds (65 kph). Elsewhere on the east coast, wind speeds were always well below gale force. Peak storm surge magnitudes south of Cape Melville are estimated to have been of order 0.5 m, which was the level recorded by the tide gauges between Cooktown and Cairns.

Although Highest Astronomical Tide was not exceeded at any of those sites, beach erosion is evident at several beaches north of Cairns. At Palm Cove, wave action on the high tides attacked the low dune and wave runup reached the esplanade. The nearby wave buoy registered maximum wave heights of 3 to 4 m during that time, likely forced primarily by the swell coming through the reef and on-shore winds coming from the eastern side of Narelle with the waves aligning with the inner-reef lagoon.

7.2. Storm surge damage in the Northern Territory

Media did not report on any NT damage from storm tide. The storm tide analysis illustrated in Figure 3-8 showed that it had the potential to push the water level around 1 m above Highest Astronomical Tide (HAT) at locations on the East Arnhem coast south of Groote Island. It shows that breaking waves may have pushed a little over 1 m above HAT.

No storm tide effects were reported along the northern Arnhem coast or at Darwin.

7.3. Storm surge damage in Western Australia

The tide gauge at Exmouth (Figure 2-7) showed a 3 metre storm surge on top of astronomical tides that were close to neap tides. The numerical models shown in Figure 3-11 also showed a 3 metre storm surge in Exmouth and a higher surge further south in Exmouth Gulf – 4 metres at Learmonth.

7.3.1. Storm surge in Exmouth

Figure 3-11 shows a 3 m storm surge that took the still water level around 1.5 m above the Highest Astronomical Tide. This level would still have been below the sea wall, but waves on top of elevated sea would broke over the sea wall. Figure 7-2 shows waves running across water lying on carparks behind the sea wall. (The vessel in the background was on hardstand, well above normal water level.)



Figure 7-2 Water behind sea wall at Exmouth Marina

The waves breaking over the sea wall dragged sediment including rocks over the carparks and surrounds of the marina. Figure 7-3 is a photo taken during our investigation looking across the car park shown in Figure 7-2. It shows marine debris including weed, sand and rocks that may have come from the sea wall. The sediment was more than 0.5 m deep in places.

Figure 7-3 also shows marine debris on the concrete floor of the toilet block shown. Significant cracking in the concrete column is also visible in this photo, but it was uncertain whether the crack existed before the passage of the cyclone.



Figure 7-3 Marine debris washed more than 40 metres from sea wall

The water spilling over the sea wall eventually found its way into the canals of the marina, which are shown in a still in Figure 7-4 from a social media video that was published by ABC news. The water level can be seen still below the slab level of the nearby buildings, but near the top of the pylons on jetties and floating wharfs. Water at this level damaged gardens in houses along the canals and flooded lower-level rooms such as boat storage rooms or basements. In some houses and ground level apartments in the marina area, it was reported that wave action took spray over the top of the retaining walls and into houses in the marina area.



Figure 7-4 Elevated water height in Marina, Exmouth (ABC news)

Much more significant damage to a building occurred on the commercial wharf in the boat harbour. Here, the water level was at least 1.8 m above the surface of the wharf as shown by the marine debris caught in the fence shown in Figure 7-5 (a). Nearby, an office/warehouse building had been impacted by waves at a height up to the red line shown in Figure 7-5 (b).

This level was around the same height as the debris caught in the fence. However, the damage to the office/warehouse indicated that significant wave action had impacted the building and its contents.



(a) Marine debris caught in fence at the commercial wharf



(b) Office warehouse

Figure 7-5 Wave height over commercial wharf at Exmouth

Figure 7-6 shows external views of the building with the cladding punched in by the wave action up to the second girt. The wave action had broken through the external cladding of the unlined warehouse and moved the contents around within the building and dragged some of it out of the building.

Where it hit the lined office portion of the building, it had broken through both the external and internal cladding and pushed all the contents including a heavy photocopier and built in cabinetry through an internal wall and into the warehouse space. The damage to the internal linings can be seen in the lower photo. (The trestle table visible in the photo had been placed into the kitchen/office after the event. The office and kitchen had been stripped bare when first entered after the cyclone and storm surge.)



Figure 7-6 Wave damage to office warehouse, Exmouth

It is difficult to design buildings to resist waves on top of storm tide. Rather than building to resist wave action, it is better to avoid building in storm tide risk areas.

South of Exmouth, the storm surge had broken through the coastal dunes in a number of places. Figure 7-7 (a) is a photo looking towards the dunes and gulf showing a gap created by storm surge, over-topping the dune 200 m away. At the time of the surge, sea water filled the

200 m up to the edge of the photograph. Marine debris was found on the track in the foreground of the photo.

Figure 7-7 (b) shows an ebb channel cut by the retreating water as it escaped back to the sea once the storm tide had dropped. This one had been filled with sediment from the ebbing flow.



(a) Break in dunes



(b) Ebb channel

Figure 7-7 Ebb tide channel, Exmouth

7.3.2. Storm surge in Learmonth

As the northerly wind pushed the water further into Exmouth Gulf, the sea surface was lifted even more. The SEAtide analysis showed that the storm tide was one metre higher at Learmonth than at Exmouth, and it overtopped a higher dune near Learmonth than the ones it cut through near Exmouth shown in Figure 7-7 (a).

Figure 7-8 (a) shows some photos of the area in which the storm tide overtopped 3.5 m high dunes. It flowed over the back of the dunes, across the road where it deposited sand and then spread out over the flat land adjacent to Learmonth airport shown in Figure 7-8 (b).

The ponded sea water spread out over the airport land, over runways and taxiways and the terminal carparks. It did not appear to enter the terminal, but it must have been very close to entering it.



Sea water breached dunes here.

(a) Looking towards Exmouth Gulf



Sand deposited on road.

(b) Looking away from the gulf towards the airport

Figure 7-8 Storm tide intrusion at Learmonth

Figure 7-9 shows marks on fences and cars at Learmonth airport.

- Figure 7-9 (a) shows water marks on the fence beside the access road to the main terminal building. It shows that water rose to a level just lower than the floor level of the terminal, but that it inundated roads to the airport and the terminal carparks.
- Figure 7-9 (b) shows water marks on the security fence around the airport near an auxiliary car park. The water mark on the car shows that the maximum water depth was over the wheels of the car.



Figure 7-9 Watermarks showing storm tide at Learmonth airport

8. Rain-water ingress

8.1. Rainwater ingress above ceiling

Extensive damage can be caused to interiors from just a small opening that allows wind driven rainwater to enter a building above ceiling level. Figure 8-1 effectively illustrates this. The damage can be considerable regardless of the size of the gap at roof level:

- Figure 8-1 (a) is a photo of damage to a furnished room that lost all the roof above the room. It shows water damage to the contents, loss of the ceiling and wet insulation.
- Figure 8-1 (b) is a photo of a damage to a furnished room that was on a wall that had lost its veranda. A new opening was created in the windward wall just above the ceiling level and rainwater gained access to the roof space through that relatively small hole. It also shows water damage to the contents, loss of the ceiling and wet insulation.
- Figure 8-1 (c) is a photo of damage to a partially furnished room that lost no roof or wall cladding. The water had entered only through a flashing. It also shows water damage to the contents, loss of the ceiling and wet insulation.

Even small apertures in the building envelope can permit enough water to come into a building to cause extensive damage.



(a) Missing roof

(b) missing veranda

(c) Missing flashing

Figure 8-1 Effects of water ingress above ceiling

The water above the ceiling came down through downlights or ceiling fans at first, and then as the ceiling softened, it caused more widespread ceiling collapse. In some cases, positive pressure in the roof space may have contributed to the loss of the ceiling.

Strong winds across the roof can transport water up the roof slope which can drive water:

- Along box gutters
- Up valley gutters to the top of the gutter
- Under ridge caps

Figure 8-2 shows water that has been driven up a roof slope leaving the top of the roof as a jet. This was in a location where the wind speeds were approximately 120 km/h or around 40% of the design ultimate wind speed for importance level 2 buildings.



Figure 8-2 Water driven up a roof slope in TC Narelle

A number of recently constructed buildings had used plasterboard for ceilings in external areas such as large balconies. Where water had leaked into the roof space above these external ceilings, they also sustained damage. Figure 8-3 shows damage to plasterboard in an outside ceiling on a balcony.



Figure 8-3 Water damage of external plasterboard ceilings

8.1.1. Box gutters

The potential for wind to move water as shown in Figure 8-2 means that where the wind direction blows parallel to the box gutter away from the rain head, it can move water away from the rain head and cause it accumulate at the other end where there is no opportunity for it to drain away. The build-up of water can overtop of the box gutter onto the ceiling.

Figure 8-4 shows ceiling damage in a house under the end of a relatively short box gutter (4.8 m long). The box gutter had overflowed from the end furthest from the rain head because the wind that was primarily across the line of the box gutter had a small component that was opposite to the normal water movement in the gutter.



Figure 8-4 Ceiling damage under a box gutter in a house

Box gutters should have overflows at each end of the box gutter. Overflows at the opposite end to the rain head will catch water that is blown up the gutter against the normal grade of the gutter.

Figure 8-5 shows a much longer box gutter in a commercial building. Here the box gutter had overflowed along its length with the wind almost at right angles to the box gutter. The overflowing water had damaged the plaster in the bulkhead and the ceiling around the bulkhead.



Figure 8-5 Ceiling damage under a box gutter in a commercial building

8.1.2. Valley gutters

Where the wind is directed up a valley gutter the water movement illustrated in Figure 8-2 is directing the water under the flashing at the top of the gutter. This allows the water to go under the flashing and directly into the roof space.

Figure 8-6 shows two photos supplied by the occupier of a building of water falling from the ceiling onto the floor during TC Narelle. These points in the house were under the top of valley gutters that were directing water into the roof space at different times during the passage of TC Narelle. After the event, the ceiling had been damaged despite of significant efforts to dry out the ceiling space.



Figure 8-6 Water falling from the ceiling under valley gutters during TC Narelle

Valley gutters can be sealed under the roof sheeting using closed cell foam to limit water ingress under the roof sheeting.

8.1.3. Leakage of windows and doors

There were many reports of water coming under, around and through doors and windows. Some people reported spray out of the tracks of windows and sliding glass doors typical of water being blown through weepholes. Observations showed that there was less water

through weepholes when the external weepholes were covered by a rubber flap that was in good condition. A few windows had torn rubber flaps and significant volumes of water came through those weepholes.

Figure 8-7 shows other places where water entered around windows and doors – between the blockwork and window frame, under bifold doors and under swinging doors without bottom seals.



(a) Water between window and blockwork (b) Water under bifold doors



(c) Water under swinging door

Figure 8-7 Water penetration at windows and doors

Some windows and doors were able to keep out all the wind-driven rain. The sealed window and the swinging door shown in Figure 8-8 had new seals and no water came through them even though they were on the windward wall during part of the passage of the cyclone.



(a) Swinging door

(b) Sealed window unit

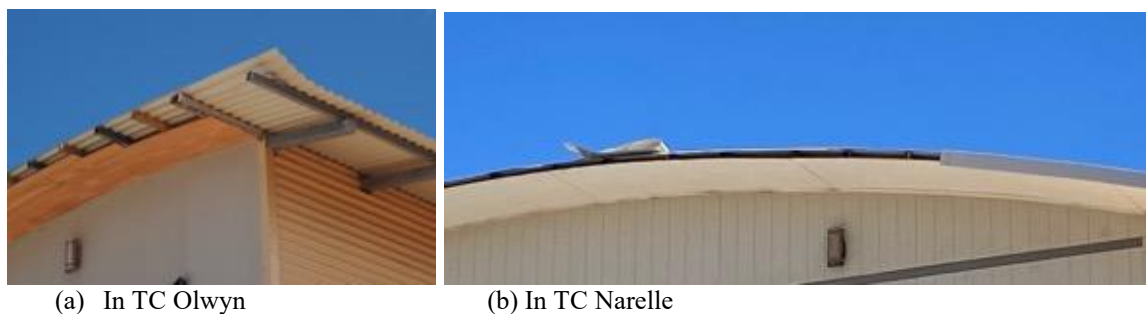
Figure 8-8 Windows and doors that performed well

New seals on windows and doors assist in limiting rainwater ingress through the doors and windows. Adequate flashing and waterproofing between the building and the frame is required to limit water passing between the window or door frame and the building.

8.2. Similar damage in TC Narelle to that in TC Olwyn

In Exmouth, the peak gust wind speed in TC Narelle was comparable with that in TC Olwyn as shown in Table 4. The wind direction was very similar as well. There were a number of buildings that had similar levels and types of damage. In these cases, the symptom was that there was water ingress into the building, but the cause of the water ingress was exactly the same after TC Olwyn and TC Narelle. This means that the point of entry of the water was not properly addressed in the repairs following TC Olwyn. These issues are illustrated in Figure 8-9 to Figure 8-13.

Figure 8-9 shows the same building where the flashing on the edge of the roof was inadequately fixed and was lost in both TC Olwyn and TC Narelle. This let water into the roof space above the ceiling and caused damage to the ceiling in both events. The minimum fastening requirements for flashings presented in AS 1562.1 will be sufficient to hold this edge flashing in place.



(a) In TC Olwyn
Figure 8-9 Damage to roof flashing

(b) In TC Narelle

Figure 8-10 shows a lightweight sliding glass door that was on the lee side of the house in both events. In TC Olwyn the frame had deformed outwards under the action of internal pressure and lee wall external suction. The deformation was permanent and in Figure 8-10 (a) the gap was enough to fit fingers. In TC Narelle with the wind coming from the same direction, the frame had also deformed outwards enough to allow the curtain to blow out through the gap. This time, the window came back in once the load had gone and trapped the curtain. This is certainly too large a deformation when the load is 50% of the ultimate load and lower than the serviceability load for these windows.

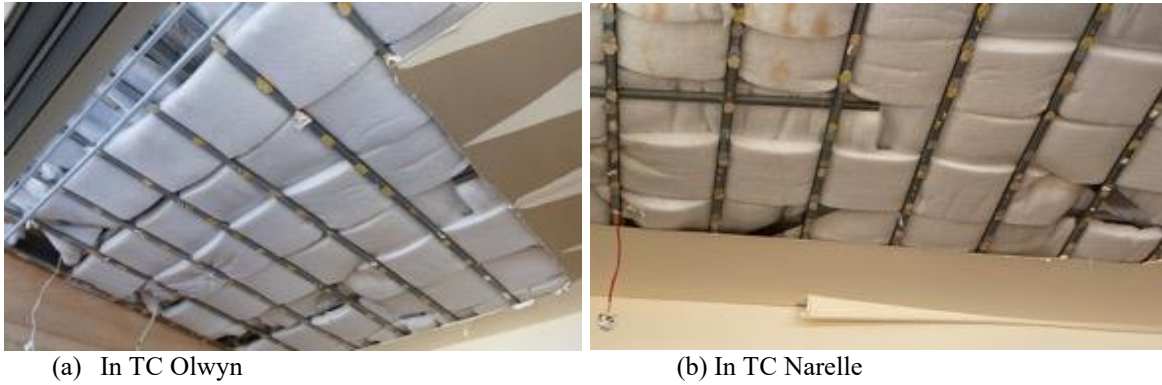


(a) In TC Olwyn

(b) In TC Narelle

Figure 8-10 Bowed lightweight window frames

Figure 8-11 shows a ceiling that is behind a join between a roof and a wall. Normally an apron flashing would seal this junction, but in this case it was missing and significant amounts of water came in during TC Olwyn. The ceiling had been repaired but the apron detail performed the same in TC Narelle. A new apron detail will be required to prevent the same damage in a future event.



(a) In TC Olwyn
Figure 8-11 Ceiling loss under a leaking apron detail

(b) In TC Narelle

Figure 8-12 shows the failure of an automatic sliding glass door in both TC Olwyn and TC Narelle. These doors are well supported at the top and at one point on the bottom at each side of the opening. The side edge is not well supported and the bottom edge is not supported at all in the centre. Before TC Narelle, a temporary brace had been fitted at mid-door height, but the bottom edge was still largely unsupported.



(a) In TC Olwyn
Figure 8-12 Failure of automatic sliding glass doors

(b) In TC Narelle

Figure 6-8 showed a redundant vent over a ceiling. Immediately under this vent is the ceiling shown in Figure 8-13. Water that came through the redundant vent saturated the ceiling and caused it to collapse in both TC Olwyn and TC Narelle. Replacing this vent with wall cladding will minimise the damage to the same ceiling in future events.



(a) In TC Olwyn
Figure 8-13 Water damage to ceiling

(b) In TC Narelle

In repairing damage, it is important to not only fix the damaged components, but also to address the cause of the damage so that future events do not cause the same problem.

9. Conclusions

Severe TC Narelle crossed Cape York Peninsula in Queensland, Eastern Arnhem land in the Northern Territory and North West Cape in Western Australia. It was very compact and its peak intensity was a category 5 tropical cyclone off the east coast of Queensland, but it weakened before crossing the Queensland coast. It caused local flooding, tree damage and minor structural damage in Queensland. It reformed over the Gulf of Carpentaria and crossed the east Arnhem land coast as a category 3 tropical cyclone and again contributed to flooding in the northern Territory, caused some minor structural damage and tree loss. It passed into the Kimberley in Western Australia as a tropical low and regenerated off the Kimberley and Pilbara coasts. It became a very large system with peak intensity in WA off North West Cape and passed close to the coast near Exmouth before crossing the coast just south of Coral Bay. It continued south-south-east through the Gascoyne region passing between Carnarvon and Gascoyne Junction.

The most significant wind gusts over land were in the North West Cape and these were measured at 61 m/s (around 71% of the design wind speed for importance level 2 buildings such as houses in this area). There was also damage at Coral Bay where the wind speed was estimated at 50 m/s (65% of the design wind speed for houses). The damage was less at Carnarvon, which is now in wind region C where the wind gusts were measured at 42 m/s (63% of the design wind speed for houses).

Structural damage was observed where there had been some deterioration of structural components. This was particularly prevalent in verandas where posts had deteriorated near ground level or light gauge metal connectors had rusted. Where verandas had detached, they often damaged the house causing significant water ingress. All structural components should be adequately protected from deterioration and regularly maintained, replacing them if they show signs of material degradation. Any nailed batten to rafter connections should be replaced with connections that satisfy AS 1684.3. All tie downs need to be sized for their tributary area. While maintenance is being done to the roof, the opportunity should be taken to check all tie downs.

A few structures were damaged due to internal pressure. In wind regions B2, C and D, designers are required to consider high internal pressures which should minimise failures due to internal pressure. Some debris items that were significantly larger than those specified in AS/NZS 1170.2 caused damage to buildings.

Laminated glass demonstrated that it could remain a barrier to water penetration even if broken and the broken glass did not become an injury risk. This makes it useful as the default glass for use in cyclone areas. The investigation saw cases where windows had not been fixed properly into the building, or sealing between the frame and the building was inadequate. Industry guidelines for installation of windows and doors should be followed.

Flashing failures were caused by inadequate fixings. AS 1562.1 has minimum fixing requirements and all the observed flashing failures had fixings that did not comply with this standard.

A number of roof mounted attachments were damaged by the winds in TC Narelle. In some cases, it was because of deterioration. This highlighted the need for corrosion protection on attachments to match the site. This particularly applied to both the roof-mounted item and its fixing. Examples include satellite dishes and air conditioners. Where the attachments were

only attached to the roof sheeting, it caused damage to the roofing and this caused water ingress problems. All roof attachments in cyclone areas should be rated for cyclone winds. This includes solar panels and their attachment systems. Some evidence of deterioration of solar panel fixings due to low cycle fatigue was seen. Evidence was also seen of solar panels becoming wind borne debris that has affected neighbouring properties.

Where shade structures were taken down, they could be replaced and returned to function soon after the passage of the cyclone, but where they were not taken down, they were generally no longer functional and may have presented a hazard for nearby structures. While this is possible for smaller shade structures, there were a number of very large agricultural shade structures where removal is not feasible. Research will be required to find ways of improving the functionality of these structures.

Water ingress happened in many buildings. Water in houses that were free of structural damage came through flashings, and from overflowing box gutters and valley gutters. Water also came through undamaged windows through defective seals and through weepholes. In some cases, water came around the edge of windows where the seals between the window frame and the building had been omitted or were no longer effective. There were some cases in which water damage seen after TC Olwyn in 2015 was repeated in TC Narelle. This underlines the importance of not only replacing the damage to the linings but fixing the cause of the water ingress and not just the symptom.

10. Recommendations

The following recommendations were made in this report:

10.1. Maintenance issues

- Check and maintain seals on windows including those between the window frame and the building to minimise the chance of water penetration during even low winds associated with storms or tropical cyclones. Correct fixing of the window and door frames to the building is necessary for them to continue to remain fit-for-purpose.
- Install seals on swinging doors to minimise water penetration under and around doors.
- Maintenance of all aspects of verandas is important. Particular attention is needed for components in contact with the ground or concrete as corrosion or rot is greatest in these areas. Elements with deterioration must be replaced. Painting will not give them their original strength.

10.2. Design and Construction issues

- All structures in the cyclone regions (B2, C and D) including sheds need to be designed to accommodate high internal pressures.
- Specify cladding fasteners with higher levels of protection or undertake more frequent maintenance in coastal environments. Ensure all tie downs including cladding fasteners are in good condition and comply with current requirements.
- AS 1562.1 requires flashing to be fixed to each face of the building with screws at closer centres than 500 mm. Whenever flashings are replaced, they should be fixed to at least this standard.
- It is difficult to design buildings to resist waves on top of storm tide. Rather than building to resist wave action, it is better to avoid building in storm tide risk areas.
- An effective strategy for preserving simple shade cloth structures such as wind breaks is to have the capacity to lower them as part of preparation for an approaching tropical cyclone. Research should be undertaken on preparation of crop covers for an approaching tropical cyclone. Alternatively, research could establish ways of configuring these covers to reduce their wind loads.

10.3. Photovoltaic solar panels

- All roof-mounted attachments should be strong enough to withstand wind actions for the wind region and should be fastened securely to the roof structure – not just the roof sheeting. Mounting systems and hardware should have the appropriate coatings for the environment in which they will be used and then should be properly maintained.
- Select an appropriate importance level for solar panel installations based on expectation of functionality after severe events. Specify appropriate wind ratings for the panels themselves. Higher wind areas such as wind region D will require stronger panels. Design all elements of the support system for the differential pressure across the panels. Metal components of the support system should be tested for strength under repeated load and unload cycles.

10.4. Minimising rainwater ingress

- Box gutters should have overflows at each end of the box gutter. Overflows at the opposite end to the rain head will catch water that is blown up the gutter against the normal grade of the gutter.
- Valley gutters can be sealed under the roof sheeting using closed cell foam to limit water ingress under the roof sheeting.
- In repairing damage, it is important to not only fix the damaged components, but also to address the cause of the damage so that future events do not cause the same problem.

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