CYCLONE
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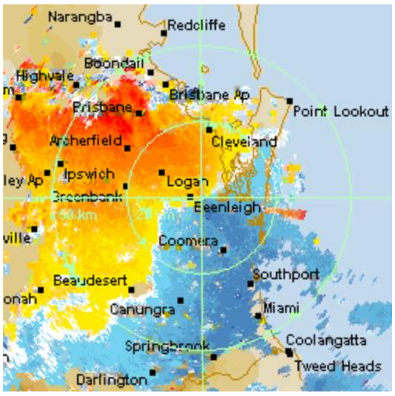
Investigation of Damage: Brisbane
27 Nov 2014
Severe Storm Event

CTS Technical Report No 60

February 2015



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COLLEGE of SCIENCE, TECHNOLOGY and ENGINEERING,
JAMES COOK UNIVERSITY

TECHNICAL REPORT NO. 60

Investigation of Damage: Brisbane, 27 November 2014 Severe Storm Event

By
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Summary

Between 2 and 6 pm the on the 27th of November 2014 severe thunderstorm activity was observed in the South-East Queensland region. Two adjoining storm cells moving in a northerly direction subjected Brisbane and neighbouring suburbs to severe hail, damaging winds and localized flooding. A maximum gust wind speed of 141 km/h was measured at Archerfield Airport, however speeds were estimated to be approximately 40 to 80 km/h in other affected suburbs. Severe hail accompanied the storm (40 mm diameter typical). Hail damage to windows and subsequent water ingress was particularly high especially for older housing, with older window glass performing poorly against the wind-driven hail as compared to newer window glass. Another contributing factor was most likely due to the significant horizontal component in the trajectory of the hail caused by the strong winds.

Most of the observed damage was due to hail, fallen trees and downed power lines. More than 105,000 homes were without power due to 642 downed power lines (ABC News, 2014). Damage estimates by the state government were initially on the order of $150 million however this was later revised to over $1.0 billion, with over 100,000 insurance claims submitted (Insurance Council of Australia, 2015).

A preliminary search of social media sites, including Facebook and Twitter, was performed to assess the types and severity of damage as well as their locations. Street and house surveys were conducted between the 28th of November and the 5th of December to assess structural damage and to compare overall impacts of the storm to what was reported by journalists and social media. A detailed examination of Doppler radar imagery was used to estimate the nature and extent of the wind field. Using data on housing damage from the QFES and CTS street surveys, an analysis of damage severity in relation to construction materials was performed allowing patterns of housing stock vulnerabilities to be examined.

The wind field analysis showed that the highest wind speeds occurred in the rear and forward flank downdrafts of the storm cell with the storm's maximum winds occurring in the vicinity of Archerfield Airport. The Doppler radar imagery showed that winds outside this area are unlikely to have been significantly higher than the 141 km/h (39 m/s) recorded at the site.

Hail damage was a significant contributor to losses, as evidenced by a large number of broken windows and subsequent contents damage due to water ingress. Additional research is needed to develop economic solutions and probability models for increased damage due to hail size and simultaneous severe winds.

Although winds were lower than design level, some cases of severe roof failure did occur. In many cases where significant roof damage had occurred, it was due to (i) building age with rot in timber roof members and/or corrosion of connections or (ii) installation of new roof cladding (in some cases replacing tile with metal cladding) without upgrading the batten to rafter or rafter to wall tie down connections to contemporary building standards. Roof structure damage was typically associated with a breach in the windward wall allowing a large increase in internal pressure and adding to the external suction loads on the roof. As such, it is recommended that all reconstruction and repairs should be carried out in accordance with current relevant Standards.

Acknowledgements

We appreciate the support and assistance of the Queensland Fire and Emergency Services, Bureau of Meteorology, Brisbane City Council and the Bushfire and Natural Hazards CRC (BNHCRC).

We also acknowledge the ongoing support of the Qld Dept. of Housing and Public Works. The CTS is very grateful to the residents who generously assisted this survey by volunteering information, answering questions and on occasions inviting the authors into their houses to inspect damage.

The Cyclone Testing Station is grateful for the ongoing support from its benefactors and sponsors. This untied research funding allows the CTS to continue its work in a number of ways, including: building community awareness, standards development, fundamental research, and support in post disaster damage investigations.

Benefactors

Contents

1. Introduction

Between 2 and 6 pm the on the 27th of November 2014 severe thunderstorm activity was observed in the South-East Queensland region. Two adjoining storm cells, shown in Figure 1, moving in a northerly direction subjected Brisbane and neighbouring suburbs to severe hail, damaging winds and localized flooding. A maximum gust wind speed of 141 km/h was measured at Archerfield Airport; however speeds were estimated to be approximately 40 to 80 km/h in other affected suburbs. Severe hail accompanied the storm (40 mm diameter typical). Hail damage to windows and subsequent water ingress was particularly high especially for older housing, with older window glass performing poorly against the wind driven-hail as compared to newer window glass. Another contributing factor was most likely due to the significant horizontal trajectory of the hail caused by the strong winds.

A preliminary search through social media sites including Facebook and Twitter was performed to assess the types and severity of damage as well as their locations. Following this, surveys were conducted on the 1st and 5th of December to assess structural damage and to compare the overall impact of the storm to what was reported by journalists and social media.

1.1 Objectives

Maximum wind speeds of 141km/h were recorded at the Bureau of Meteorology (BoM) Archerfield Airport automatic weather station (AWS). However, from the preliminary survey it was judged that the gust wind speeds in surrounding areas, where damage had occurred, were significantly lower. Data from amateur weather stations in surrounding suburbs were also found to indicate lower wind speeds. Most media reports had mainly cited only the 141km/h wind speed when reporting the impacts of the storm.

The objectives of this study are:

1. Estimate wind speeds in surrounding suburbs where damage occurred, using indicators such as leaf cover on trees, bent road signs and structural damage as well as an analysis of Doppler radar imagery.
2. Where structural damage was observed, determine the nature and likely causes; e.g. wind speeds exceeding design, poor connection details, aged timbers etc.

1.2 Survey Strategy

Based on a preliminary media search, as described in Appendix A, a shortlist of suburbs to be investigated was made. This list was further refined thanks to advice from the QFES and data from the TOM database, discussed in Section 3

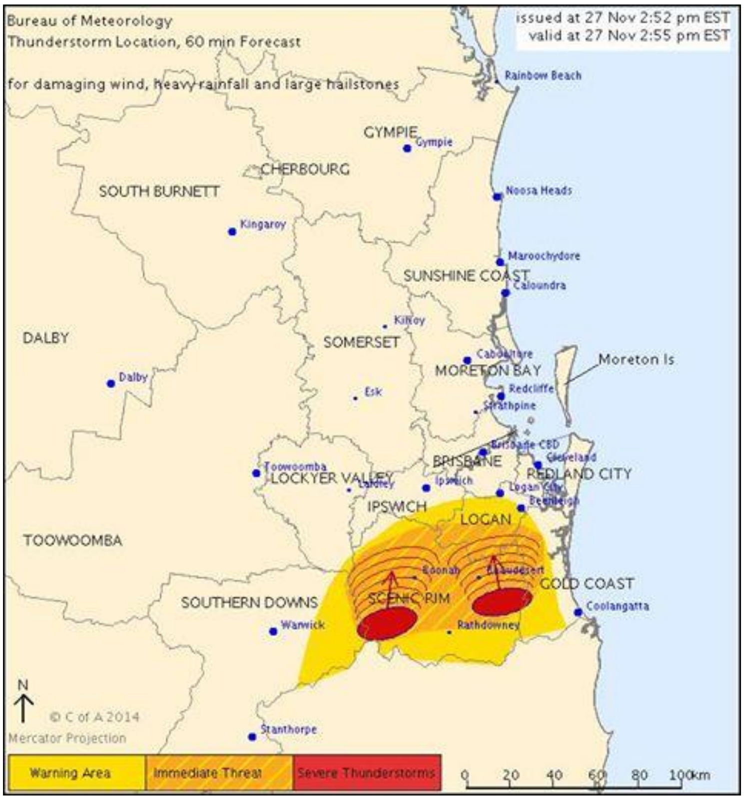


Figure 1: Estimated Storm Track
Source: Bureau of Meteorology

2. Estimated Wind Speeds

From field observations it was determined that the wind speeds in most affected areas were significantly below the 141 km/h measured at Archerfield Airport. Indicators used were damage to street signs and leaf coverage on trees. It was found that even in areas where complete roof failures occurred there was still considerable leaf cover including flowers and seed pods as well as relatively undamaged palm fronds. No failures or damage to official street signage was observed due to plastic hinge formation at the base. Additionally, apart from widespread hail damage to windows, severe roof failures were only localised, with neighbouring houses on the same street relatively undamaged.

2.1 Design Wind Speeds

The Australian Building Codes Board (ABCB) publishes the Building Code of Australia (ABCB, 2014) which stipulates design parameters for the majority of buildings in Australia. These requirements are met by compliance with a range of Standards relating to building construction (e.g. AS/NZS1170.2 (Standards Australia, 2011). Codes and standards have been used in the design and construction of engineered structures in Australia for several decades.

Brisbane and South East Queensland lie in region B as defined in AS/NZS1170.2, where the ultimate limit state design wind speed (in suburban terrain) is 47 m/s (170 km/h) at 10m height. The design wind speed at the roof height of the building is factored to account for the terrain, height and the topography. This factored design wind speed impacting on the building can be related to the pressures exerted on its elements through a series of coefficients defined in the wind loading standard, AS/NZS1170.2.

2.2 Wind Speed Measurements

Official winds speeds are measured at BoM Automatic weather stations (AWS) at 10m height, typically in open terrain. Wind speeds in suburban terrain are approx. 20% lower due to increased surface roughness. Due to the roughness of the earth's surface, wind speeds also vary with height being lowest at ground level. Wind speeds cited in this report are at the standard 10m height unless otherwise noted. It should also be noted that these 10m height speeds do not account for factors such as shielding or topography that can increase or decrease wind speeds experienced by structures.

Amateur weather stations have become popular in recent years and often upload their data to networks such as 'WeatherUnderground.com'. These can be useful to identify high wind speed areas however; the accuracy of results cannot be verified. It is likely that such home weather stations are installed lower than 10m in height and may well be affected by either shielding or accelerating effects on the wind flow from adjacent buildings.

2.3 Wind Field Assessment

A preliminary assessment of the surface wind field has been made based on a combination of 1-minute automatic weather station (AWS) wind speed and direction measurements, damage observations and BoM radar scans (Mt Stapylton rain and Doppler winds). The hypothesised wind field is also based on discussions with forecasters at the BoM. Subsequent information that may be released by the BoM, e.g. volumetric of dual Doppler scans, may provide greater insight into the wind field than deduced in this report.

The strongest winds for this event are believed to have occurred within the storm's Rear Flank Downdraft (RFD). More specifically they occurred during what appears to have been a re-intensification of the existing downdraft that occurred as a result of intense rainfall and hail. Figure 2 conceptually shows the downdraft structure of a supercell, with the location of the RFD and coupled, but less intense Forward Flank Downdraft (FFD) both shown. Unlike isolated microburst events, which have received much of the attention in wind engineering literature, Rear Flank Downdrafts occur over larger scales, e.g. 10-20 km, meaning they impact much larger areas than the former. Additionally, an RFD can generate a focused outflow that fans out primarily to one side of the storm, and often does not display a traditional omnidirectional divergence pattern. This said, smaller scale downdrafts are often imbedded within RFD outflows to generate small regions of high intensity winds.

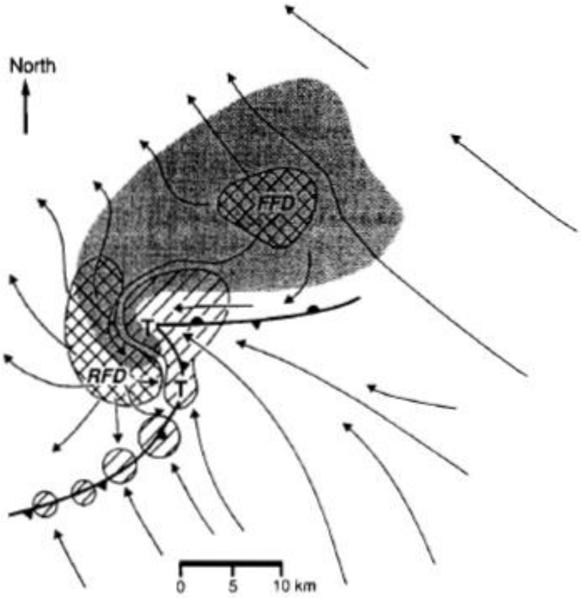
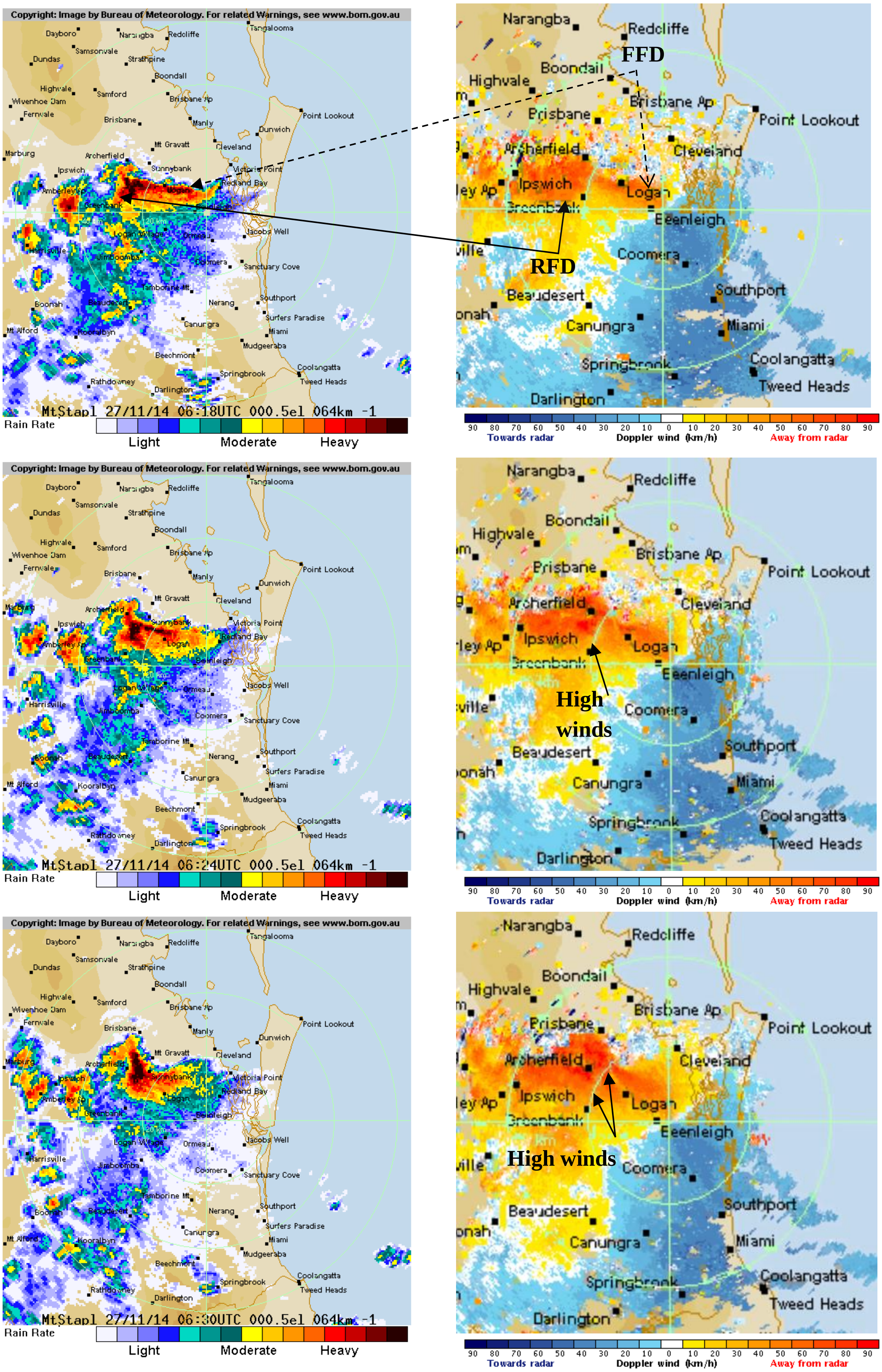


Figure 2 Schematic diagram of the location of the Rear Flank Downdraft (RFD) and Forward Flank Downdraft (FFD) within typical supercell. *Source: Wakimoto (2001)*

Figure 3 shows rain and Doppler radar images at 6 minute intervals between 4:18 pm and 4:48 pm (local time) as the RFD moved between Archerfield and the Brisbane Airport. Note that winds recorded by the Doppler radar differ from those reported by AWS anemometers in that they are measured at variable heights throughout the atmosphere—dependent on distance from the radar site—and are subject to some level of spatial and temporal averaging (refer to Leitch et al. (2009) for further discussion). For reference, Doppler-measured winds at Archerfield and Brisbane are at an elevation of approximately 670 m and 770 m, respectively. To complement these images, measured wind gust (V3,600) and mean wind speed (V600), direction, temperature, pressure and rainfall for the Archerfield Airport and Brisbane AWS stations are shown in Figure 4.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Rain Rate
Light
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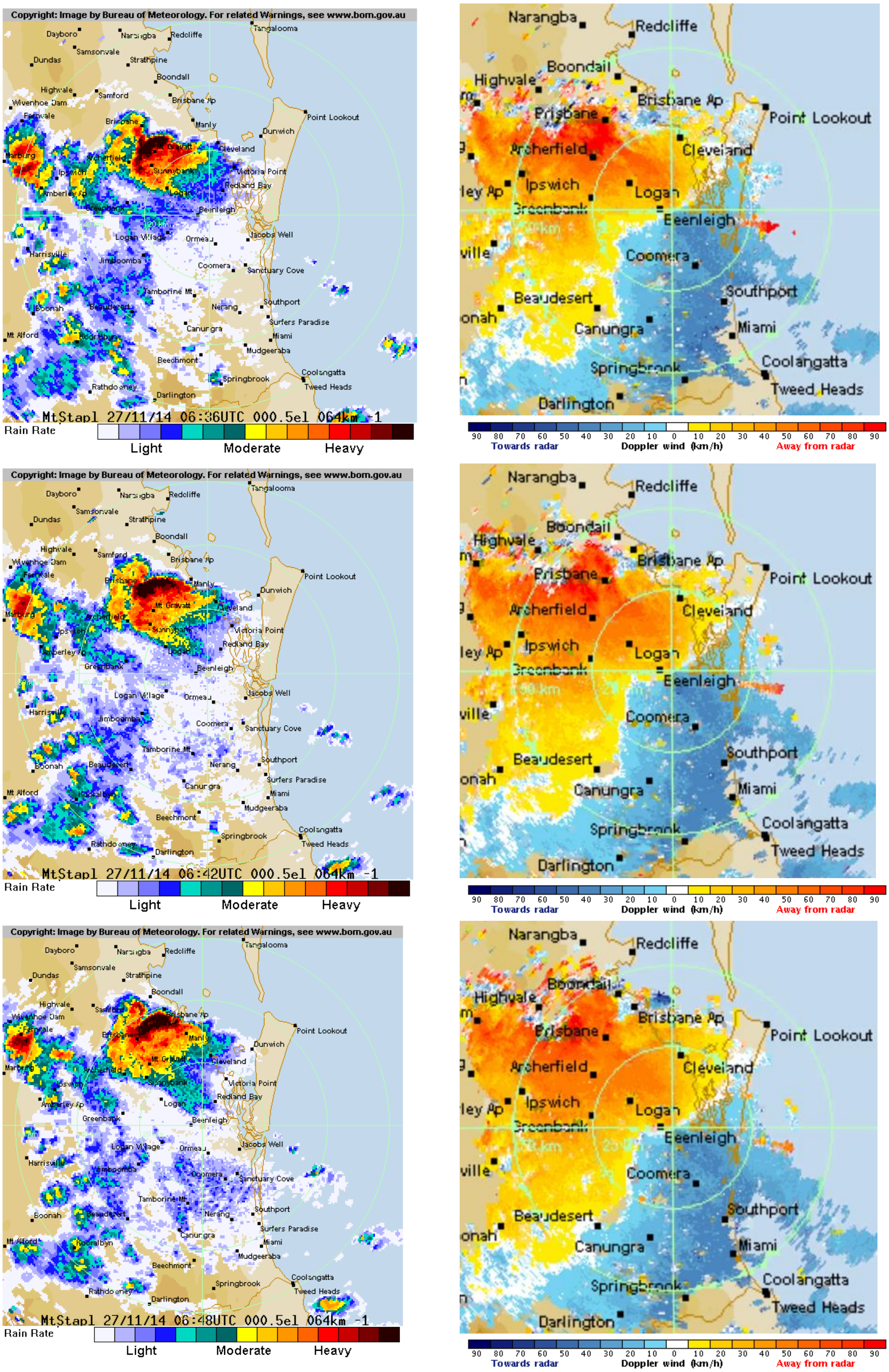
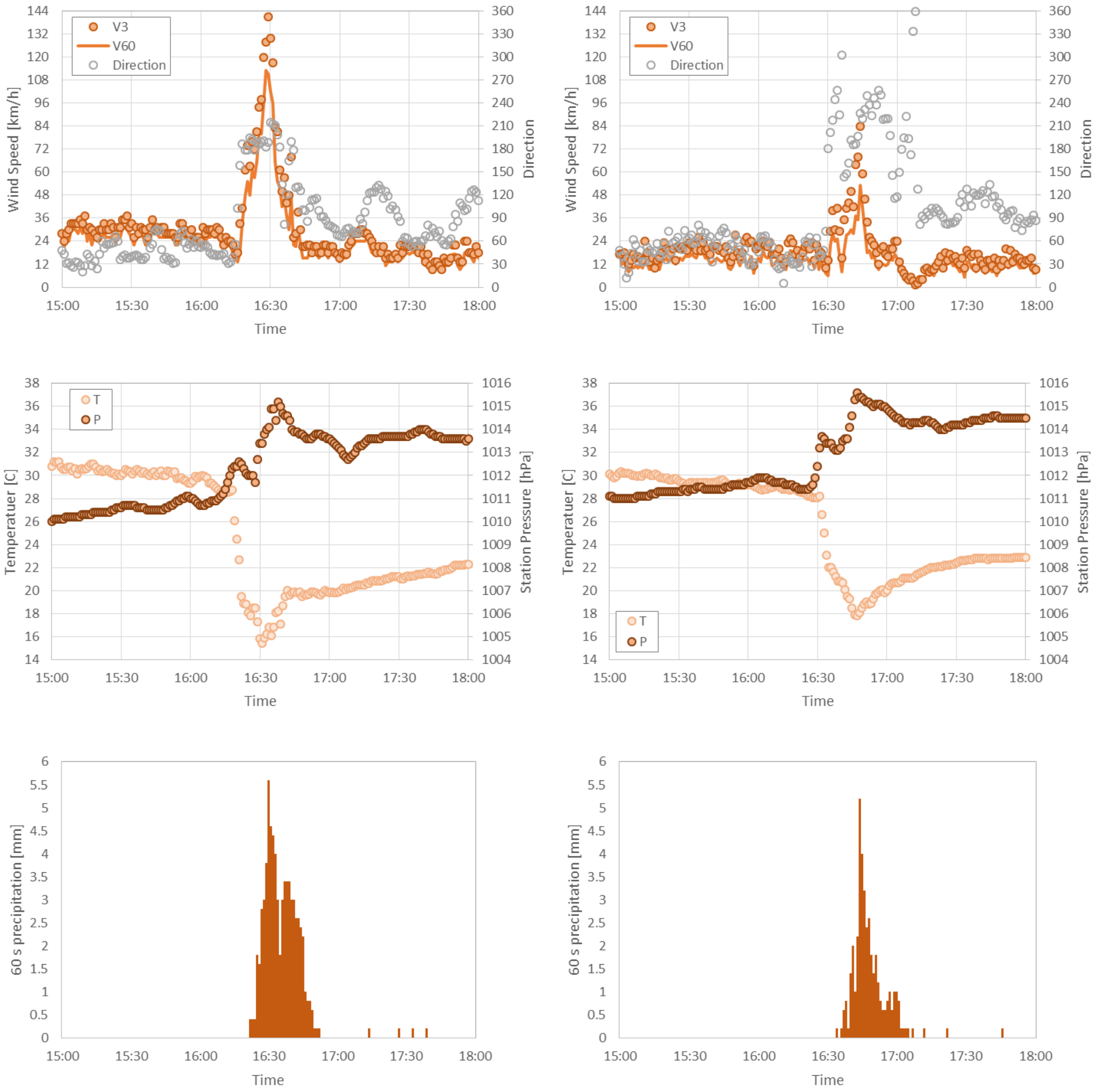


Figure 3 Rain rate (left) and Doppler wind (right) radar images from the Mt Stapylton BoM radar.



Archerfield Brisbane

Figure 4 Wind speed, direction, temperature, pressure and 1-minute precipitation recorded at the Archerfield Airport (left) and Brisbane (right) AWS stations.

Rear Flank Downdraft

Winds from the RFD are first viewed on the Doppler radar north of Beaudesert, with the outflow generating a diverging front that moves north and westward. There is some interaction of the outflow with existing outflow/s from previous storm activity in the area to the west of the developing supercell, but by 4:10 pm the outflow front reached Amberley Airforce Base west of Ipswich, generating a peak gust of 76 km/h [21 m/s] at the AWS station, and a concomitant drop in temperature of 10-15°C. Gust wind speeds around 70 km/hr [19 m/s] from between 120 and 140 degrees were maintained for approximately 13 minutes as the front passed through. While the outflow front diverged rapidly westward away from the storm, northerly movement of the front appears to keep pace with the 40-50 km/h translation of the storm, with little visible divergence in front of the storm itself.

By 4:15 pm the outflow front reached Archerfield Airport and there was a rapid increase in wind speed with an associated shift in wind direction from 30 degrees to 190 degrees as the anemometer went from seeing storm inflow to outflow (Figure 3 & Figure 4). A drop in temperature of nearly 10°C is also observed over a 5 minute period as the front moves through the station. At this time the westerly divergence of the outflow front continued, but little accurate information could be drawn from the Doppler imagery to ascertain its exact location.

At around 4:24 pm (06:24 UTC) the Doppler radar shows an intensification of wind speeds near the downdraft region of the RFD (Figure 3). This suggests a re-intensification of the downdraft and coincides with a significant change in the radar reflectivity in line with an increase in downdraft precipitation. The stronger outflow winds are felt almost immediately at Archerfield Airport, with an increase in wind speeds occurring over the following 5 minutes to the maximum mean (V600) and peak (V3,600) wind speeds of 113 km/h (31 m/s) and 141 km/h (39 m/s). Winds were predominantly from 180-210 degrees for both the initial outflow arrival and then the second intensification. The Archerfield AWS records also show a distinct double peak in surface pressure, with the first around 4:20 pm and the latter around 4:40 pm. It is evident that the second peak is associated with the passage of the downdraft and is as observed in experimental impinging jet tests as the jet itself moves over a point (e.g. Letchford and Chay (2002)). The double peak occurs due to the re-intensification process, and the passage of an internal front shortly following the initial outflow front. To the west, the AWS station at Gatton—approximately 70 km west of the RFD itself— recorded gusts reaching 60 km/h [17 m/s] and a drop in temperature of around 5°C.

By 4:30 pm the region of high winds seen on the Doppler scans has begun to spread north-westward, with a second region of high strength winds also observed. The latter appears to develop around (north-west around to east) the high precipitation region that has rapidly shot out to the north-west of the main precipitation zone. It is unclear from the available data whether these two regions are driven by a single large downdraft, or two distinctly separate ones. This point in time sees the maximum wind speeds recorded at Archerfield and sees the arrival of the initial outflow front at the Brisbane AWS station in Kangaroo Point/East Brisbane. Winds at the Brisbane AWS are initially from the south, but over the next five minutes become westerly as the site sees the easterly side of the curved outflow front. Wind gusts at Brisbane AWS only reach around 40 km/h (11 m/s) at this point, though local shielding from nearby trees and multi-storey housing to the south-west may influence observed results at this site (Figure 5). At this time winds gusting to around 50 km/h (14 m/s) from 120-150 degrees was observed at both Amberley and Gatton AWS sites.

A schematic diagram of the hypothesised wind field at around 4:30 pm over the greater Brisbane region is shown in Figure 6. This wind field structure changes rapidly with time, but it shows the initial RFD and FFD outflow fronts as well as a region of high winds spreading west to north-west from the Archerfield region, believed to be driven by a re-intensification of the downdraft, as well as a second region of high winds north of the main RFD, thought to be forced by the high levels of precipitation (which included hail at this time) over the Moorooka/Yeerongpilly area. [Note that the high wind speed regions were derived primarily based on Doppler radar images (i.e. 600-800 m elevation), which may not exactly align with the areas that experienced strong winds at ground level].

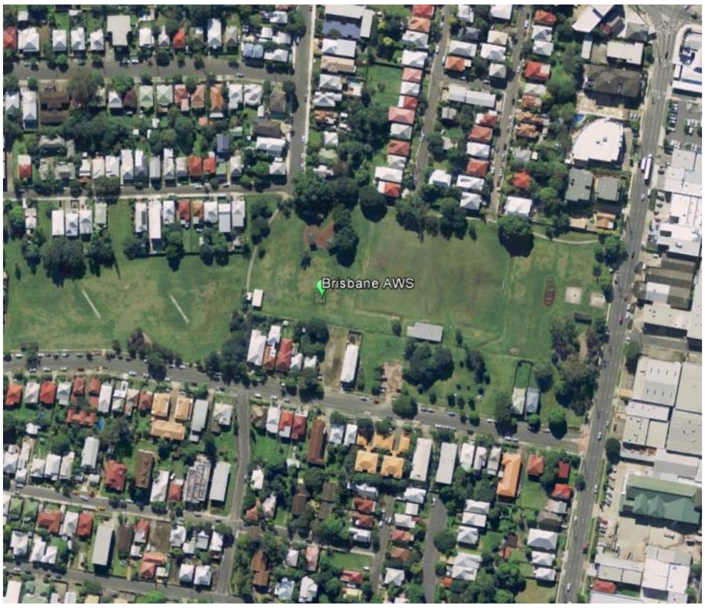


Figure 5 Brisbane AWS site and surrounding terrain. *Source: Google Earth 2014.*

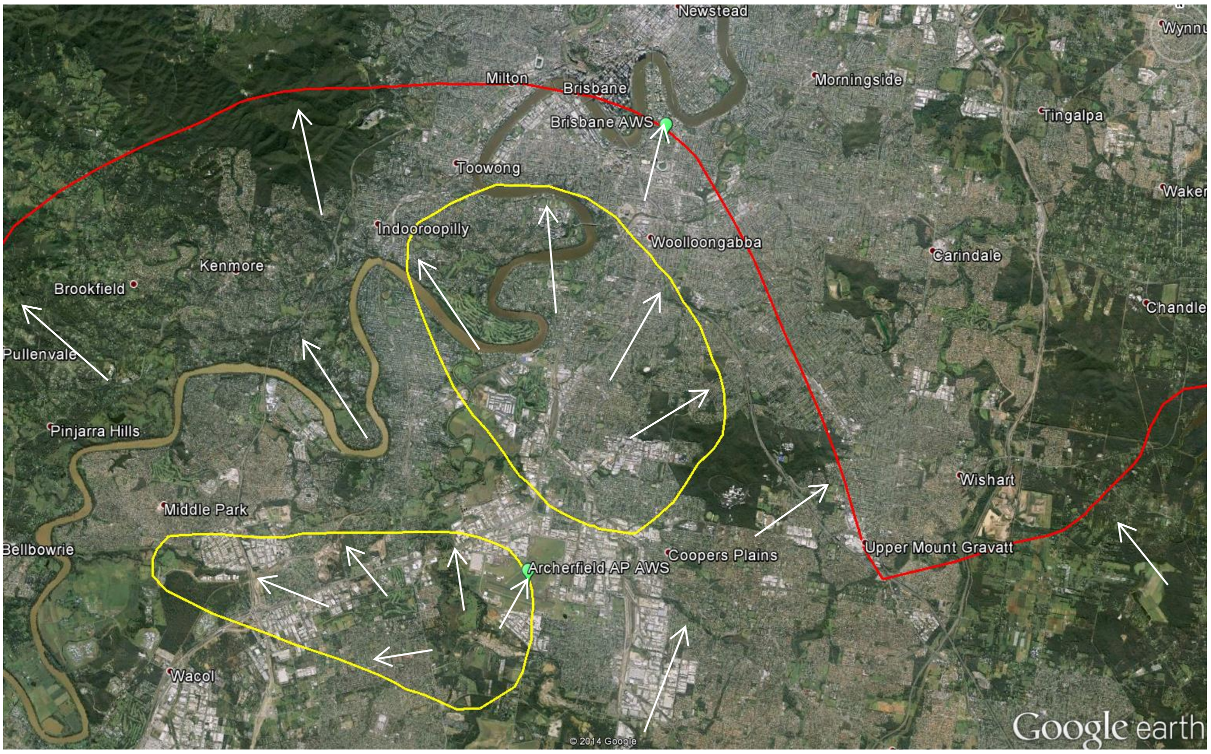


Figure 6 Hypothesised wind field at 4:30pm (06:30 UTC) with the red line indicating the approximate position of the initial outflow front and the yellow lines indicating the extent of the 'high wind zones' observed by the Doppler radar. Note that arrow length is arbitrary. *Base image source: Google Earth 2014.*

By the 4:36 radar scan the heavy precipitation that was over Moorooka in the previous image has moved northward and reduced in intensity. The two high velocity wind regions appear to intensify and combine, which produces a large swathe of strong winds from just north of Archerfield all the way to the CBD. Over much of this region the Doppler reflectivity is in the 90 km/h band, suggesting (given the Doppler only measures radial velocities) winds of greater than this magnitude occurred throughout the region—at the Doppler scan height. At this time the embedded outflow front reached the Brisbane AWS station, resulting in a shift in wind direction of around 150 degrees (Figure 4), but maximum wind speeds were not recorded for several minutes after this time.

Two distinct high wind speed regions are again visible at 4:42 pm, with the northern one moving northward through the Clayfield-Chermside area, just behind the progressing north-east flank of the outflow front. The second region of high winds diverged north-westward through the Indooroopilly-Toowong area and over the hills surrounding The Gap. The fact that these high wind speed regions are now wholly moving away from the storm itself suggests that the intensity of the downdraft feeding these outflows has most likely reduced. The reduction in precipitation in the downdraft regions (see radar imagery) corroborates this suggestion. Topographic speed-up and channelling may influence some of the observed wind speeds as the outflow moves over and through the hills around The Gap.

In the final Doppler image shown (4:48 pm), the northern high winds region continues to move with the outflow front but has largely dissipated. The north-westerly moving high wind speed region is shown to continue diverging over The Gap and surrounding suburbs, and still appears to maintain a reasonable wind speeds through the area. This is backed up by a gust wind speed of 95 km/h (26 m/s) recorded at a “Weather Underground” amateur weather station in Ashgrove (just near the entrance to The Gap). Note that this observation should be treated as indicative only as no information on the station’s elevation or exposure was available that would allow direct comparison with AWS measurements.

Forward Flank Downdraft

The FFD was initially seen on the Doppler radar as an intensification of winds west of Beenleigh between 3:30 and 4 pm, a similar time to the first RFD observations. Significant intensification does not occur until after around 4:10 pm, however. Figure 3 shows the FFD at 4:18 pm where it is evident that the outflow winds take on a roughly linear formation spanning for approximately 15 km and directly beneath the high reflectivity region on the matching radar scan. Despite no direct AWS measurements within the FFD it appears that wind speeds were less than those experienced within the RFD. This hypothesis is further justified when viewing the range of “Weather Underground” amateur weather stations throughout the affected region, where it is found that no wind speeds greater than 50 km/h were recorded (keeping the caveat discussed in the previous section in mind).

Unlike the RFD, the FFD does not diverge away from the precipitation region. Across the entire area the FFD generated winds were from the south-east quadrant and no divergence behind the storm is evident. This suggests that the predominantly south-east winds entering the storm are being forced downward, accelerating surface winds, but not substantially so.

Maximum Surface Wind Speeds

Winds from the supercell outflows were felt across most of Brisbane with relatively strong winds also spreading west onto the Toowoomba ranges. However, based on Doppler observations, damage reports and measured wind data, it appears the strongest winds were felt by the smaller area affected by the re-intensified RFD outflow, either to the west of the storm or propagating to the north of it. Figure 7 shows the broad area affected by winds greater than 90 km/h (at scan level), as observed by the Doppler radar. The direction of winds throughout this area would have varied depending on the location of the storm at the time, but the majority of strong winds appear to have come from the south-east through south-west quadrant. Damage observations throughout the impacted regions (discussed in Section 4) also suggest a strong southerly component to winds throughout this entire region. Without having detailed information on wind direction at the time of observed high winds it is difficult to estimate the total velocities at scan height, but it appears that winds were not moving directly towards or away from the radar, so stronger winds than those reported will have been present.

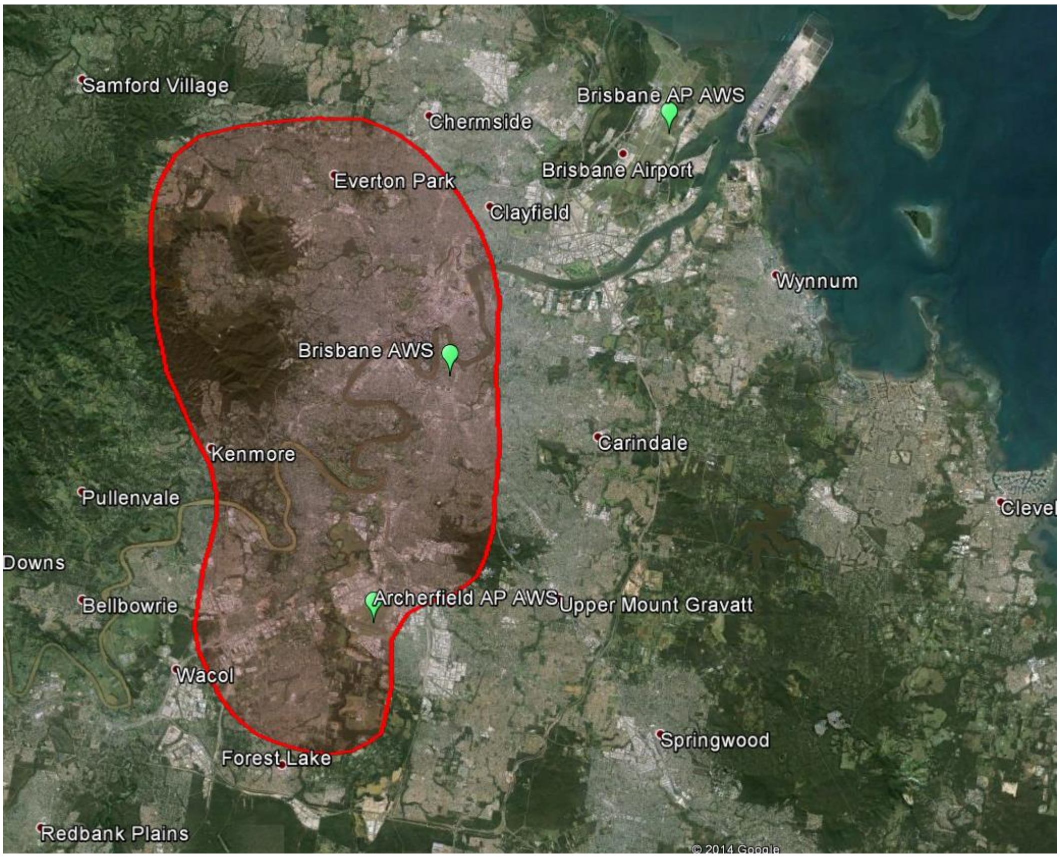


Figure 7 Envelope of areas with Doppler recorded wind speeds greater than 90 km/h.
Base image source: Google Earth 2014.

Despite the existence of Doppler measured velocities it is still difficult to make firm estimates of surface level winds based on these data alone. Thunderstorm outflows produce highly variable (spatially and temporally) vertical velocity profiles, and in general do not conform to the neutral boundary layer profile adopted by building codes. Studies (e.g. Gunter and Schroeder (2013)) show that depending on the outflow characteristics, surface winds can in fact be much stronger than those measured at elevations similar to the scan height. These very strong surface winds tend, however, to occur over small areas and for short periods of time. In addition, observational and experimental studies suggest that high surface winds can be associated with the impingement region of localised downdrafts within larger outflow wind fields. This is believed to have been the cause of the 39 m/s gust recorded at Archerfield AWS. It is believed that this type of phenomena may have also contributed to the localised region of structural damage near the southern end of Coronation Drive in Toowong.

Evidence suggests that the gust recorded at Archerfield was close to the maximum that occurred during the storm. Observations of damage to trees, signage, buildings and road signs around the airport show signs of diverging winds, suggesting downdraft impingement occurred in the area. Figure 8 shows the estimated direction of winds at a number of locations in the area. Some divergence to the east and west was evident, but no signs of complete reversal of winds (i.e. from the north) were found in the area. Similarly the Archerfield AWS did not record any reversal of flow. This is not uncommon for outflows that occur with fast moving storm systems, and/or within existing sheared environments (the latter can tilt the downdraft in the direction of flow). At the Archerfield AWS gust wind speeds greater than 100 km/h were sustained for 5 minutes, but dropped off rapidly as the outflow moved north of the site. Given there was no apparent intensification of wind speeds (as per Doppler imagery) as the storm moved north of this point, and that winds will have begun to be influenced by the rough suburban terrain, it is expected that wind speeds less than the 141 km/h recorded at Archerfield were recorded throughout the suburbs north of the airport. An absence of widespread structural failures also suggests this to be the case.

Figure 8 Estimates of direction of strong winds in the Archerfield Airport area based on observed damage to buildings, trees and signage. Note that arrow length is arbitrary. *Base image source: Google Earth 2014.*

More broadly, surface wind speeds at the initial RFD outflow front slow from around 70 km/h to 40 km/h as it moves between the Archerfield and Brisbane AWSs. The latter will have been influenced by the rougher suburban terrain in which it is imbedded, but even considering this the frontal winds decay significantly over this period.

The maximum wind speed recorded at the Brisbane AWS was 84 km/h. If it is assumed that a standard conversion can be applied to this—and considering the AWS site is in suburban terrain—this converts to a terrain category 2, 10 m wind speed of approximately 100 km/h. This site would have been close to where the high wind speeds associated with the northern protrusion of high reflectivity would have impacted the ground, and therefore are thought to represent the maximum winds in that region. It is therefore hypothesised that similar wind speeds, perhaps marginally higher, would have been felt to the south (e.g. Woolloongabba) of this site and also out to the west (e.g. West End/Taringa). Winds are expected to have decreased to the north as they were slowed (in part) through surface friction.

In summary, it is believed that the storm's maximum wind speeds would have occurred in the vicinity of the Archerfield Airport AWS, and are unlikely to have been significantly higher than the 141 km/h (39 m/s) recorded at that site. Given the observed gust of 84 km/h at the Brisbane AWS and similar, but less reliable, "Weather Underground" based observations at Bardon, Ashgrove and Fig Tree Pocket, it is believed that wind gusts up to 100 km/h (28 m/s) in open terrain and 80km/h in suburban terrain (22m/s) could have been felt throughout much of the 'high wind speed' region shown in Figure 7.

3. Damage Swath

Data from the QFES rapid damage assessment (RDA) was provided to give an indication of the spread of damage across the city. This preliminary assessment was undertaken in suburbs where emergency services received calls for help and was performed within hours of the event occurring. The RDA data is stored on a GIS capable database, Figure 9 shows locations of recorded damage indicated by blue ('minor'), yellow ('moderate') and red ('severe') coloured triangles. As the storm progressed in a northerly direction, impacted suburbs included, but were not limited to: Archerfield, Moorooka, Annerley, West End, Brisbane CBD, Spring Hill and Herston.

Over 2800 damaged properties were observed during the RDA; approximately 80% of these were houses. The RDA also classified such records as 'minor', 'moderate' and 'severe'. Of the damaged properties, approximately 92% of these were considered 'minor' damage, 7% 'moderate' and 1% 'severe'. Considering houses only: a similar breakdown of 94%, 5% and 1% of 'minor', 'moderate' and 'severe' damage was observed. For other building types such as commercial, Industrial, community halls and churches; a breakdown of 84% 14% and 2% was observed. This slightly higher percentage of moderate and severe damage is likely due to more time being spent surveying residential areas whereas industrial and commercial areas were likely surveyed only based on reports of significant damage occurring. During this event most 'minor' damage was from broken windows due to hail, 'moderate' and 'severe' damage from debris or tree impact and in a few cases roof failure due to wind load.

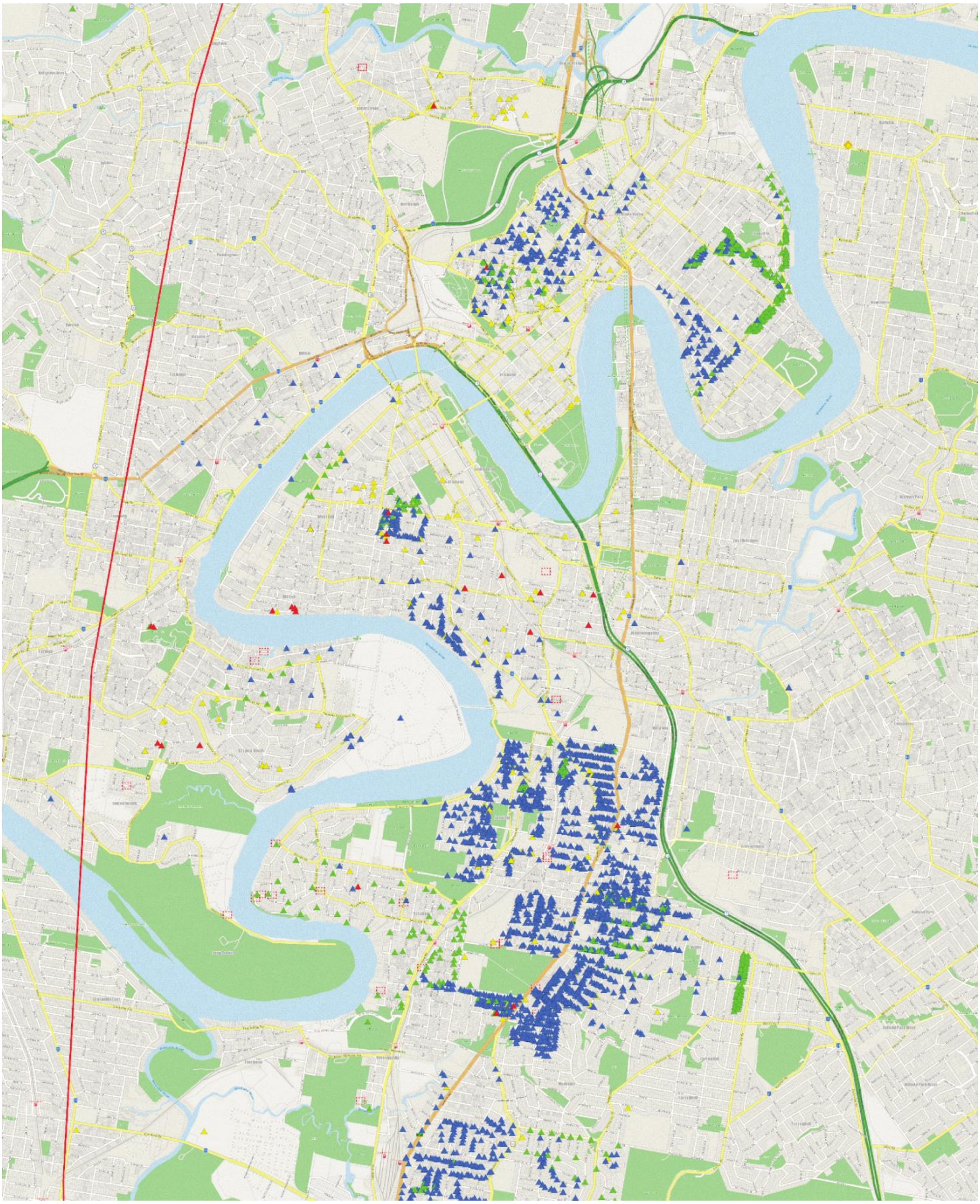


Figure 9: Records of damage from the QFES rapid damage assessment: blue triangles: minor damage, yellow: moderate and red: severe.

4. Overview of Damage

Teams from the CTS conducted surveys of streets and houses based on advice from the QFES, key observations included:

- Most of the damage observed was due to hail, fallen trees, roof damage from fallen trees and branches and downed power lines. More than 105,000 homes were without power due to 642 downed power lines (ABC News, 2014). Damage estimated by the state government was expected to reach $150m however this was later revised to exceed $1.0b (Insurance Council of Australia, 2015) This is likely to be mostly due to hail damage and water ingress as well as damage to cars.
- Damage to glass facades due to hail were observed in many locations as well as damage to cars. Flash flooding was observed in Bowen Hills and in other localized areas.
- Structural damage due to wind was observed in several locations including suburbs of Moorooka, Annerley and West-End. Roof damage was observed mostly on older housing, on some occasions with complete roof loss.
- The majority of damage to housing was window breakage due to hail, subsequently resulting in damage due to water ingress (indicated by water damaged items placed outside houses for collection). In some cases increases in internal pressure due to window breakage was the likely cause of roof failure.
- Generally little tile damage due to hail was observed, as most record of hail were smaller than the threshold for tile damage (50cm dia) (refer to section 4.3
- There was a noticeable difference in performance of new vs. old window glass in this event. In some cases houses with new windows experienced no hail damage, whereas immediate neighbouring houses with older windows had all windows broken on the southern side.

4.1 Roof Damage

Despite estimated winds being less than design wind speeds, several roof failures were observed. These were typically older structures including houses, units and churches. A common occurrence was failure of new roof cladding on older structures due to inadequate fixings. On several of these, tile roofs were replaced by new metal clad roofs fixed to the original battens, sometimes with the new cladding being connected to every alternate batten or in one instance: every 6th batten.

Complete roof loss had occurred to top floor units of some apartments. For one site that was surveyed, this had occurred due to window damage by hail and a subsequent dramatic increase in internal pressure. The timber roof of this apartment was observed to have insufficient tie down as hold down rods were only bent over top plates, no nuts were used.

Very often, neighbouring houses had little or no roof damage at all, indicating low wind speeds. Failures that did occur were largely due to pre-current building standard connection details or older degraded connections.

Figure 10: Loss of metal cladding and battens of an older house, original lead-headed nails were used to secure cladding to battens.

Figure 11: Loss of cladding and battens of a church hall. Originally a tile roof, new metal cladding was fixed to every 3rd existing batten

Figure 12: Loss of metal cladding and battens of a church. Originally a tile roof, the new metal roof was only secured to every 6th timber batten.

Figure 13: Loss of cladding and battens of an older home new cladding had been installed onto the original battens

Figure 14: An example of complete roof loss of the top storey unit of a 3 storey apartment building (New roofing currently being installed). Original timber rafters had inadequate tie down to withstand internal pressure due to the breakage of a large Southern facing window. The unit was also located on top of an escarpment (outlook shown in the lower photograph) and may have experienced slightly higher wind speeds.

4.2 Debris Damage

The preliminary media search indicated an extensive number of fallen trees and subsequent debris damage. Nearly all instances of roof failures had resulted in damage to neighbouring houses from debris impact often to roofs that appeared to be otherwise structurally adequate for wind loading.

Figure 15: Fallen trees were common, often causing damage to power lines and housing

Figure 16: Damage caused by debris originating from a neighbouring apartment building**.** The tile roof, including the large south (windward) facing gable, appears otherwise undamaged

4.3 Hail Damage and Water Ingress

The level of hail damage to homes was especially high, causing widespread window breakage and subsequent water ingress. This can be attributed the significant horizontal trajectory of hail and the relatively poor performance of older window glass. Many streets were surveyed that had the majority of windows on the windward side broken; resulting in damage due to water ingress. This could be observed by damaged furniture and goods that were placed outside of homes for collection. Apart from the widespread damage to cars from hail, it is likely that water ingress would be a large contributor to insurance claims from this event. Common hail damage to roofs observed during this event included dented metal cladding, dented roof vents and broken skylights. Additionally, hail damage to both commercial and domestic air-conditioning units are likely to have amounted to a large number of insurance claims.

The winds in the area had a significant influence on the direction of travel of hail and the impact on building performance. The most obvious evidence of this is that window damage far exceeded roof damage; suggesting that there was a significant horizontal component in the trajectory of the hail. Furthermore, windows on the windward side of the buildings (often to the south) were broken while windows on other sides were not. Even windows that were reasonably well protected by awnings were broken, again indicating the effect of wind on hail trajectory. It was also noted that where there was tile damage from hail, this was often on steeper tiled roofs. Once again this appears to illustrate that there was a significant horizontal component in the hail trajectory.

Reports varied greatly on the maximum diameter of hail during the storm, The BoM reported 40mm diameter hail (golf ball size) in most locations and up to 70-80mm diameter hail in the CBD. Based on the building performance observed it is believed that the hail impacting buildings in the areas studied were indeed up to 40mm in diameter. Some hail may have been slightly larger but the damage that occurred is not consistent with hail of 50mm diameter or greater. Previous studies on hail damage also indicate that damage to tile roofs from hail only occur with hailstones greater than 50mm in diameter (RMS, 2009).

It was observed in several instances that newer windows showed a better resistance than older thinner window glass. That is, there were examples of new homes or recently renovated homes with new windows having less to no window damage from the hail in the same streets where significant hail damage had occurred. Anecdotally, the installation of the new windows thereby reduced the vulnerability to damage by water ingress and structural damage due to internal pressures. Little literature is available regarding wind-driven hail (Carletta, 2010), thus it is recommended that additional research into hail size, density and relationships with wind velocity to be undertaken to allow for better material design and economic cost-benefit modelling. This will also require the collection of additional survey data including hail properties. From discussions on previous hail damage, another factor contributing to the much higher number of failures of older windows could be the older glass in the small casement panes is more rigid thereby not having as much energy absorption than the larger pane modern windows. It should be noted that newer thicker glass may not be able to be installed in the older casements due to rebate size and added weight on the casement sliders.

Figure 17: Hail damage from 'golf ball' sized hail (reported by resident) to the gable of a newer home

Figure 18: A common observation of many houses were several broken windows on the southern face as well as water damaged goods placed at the front for collection

Figure 19: A new apartment building in a storm affected neighbourhood, all windows on the exposed southern side were undamaged, indicating the improved performance of new window glass.

Figure 20: Typical hail damage to roof vent

Figure 21: Hail damage to windows and vinyl cladding of an older house. The proximity of the neighbouring house on the right and the size of the window shades suggest hail being driven at a sharp angle by the wind.

Figure 22: Significant hail damage to air-conditioning units of a newer apartment building. Note that all windows are undamaged, even those without overhanging eaves (far left), once again indicating the improved performance of new window glass in comparison to older windows in adjacent buildings.

5. Building Materials and Vulnerability

The rapid damage assessment data from the QFES can also give an indication of the general building stock in the affected areas. Approximately 40% of records on housing (just over 1000 samples) indicated wall and roof type. From this it can be clearly seen that approx. 80% of houses had timber clad walls, 10% double brick or brick veneer, the remainder other materials. Metal clad roofs were the most popular; making up 73% of the samples followed by 24% for tiles and 3% asbestos. Timber walled houses with metal roofs made up about 65% of all samples.

Examining the damage records for housing indicated that certain roof types may be more vulnerable in storm events. Higher proportions of asbestos and tile roofs incurred moderate or severe damage compared to metal clad roofs. Only 5% of metal clad roofs incurred moderate and severe damage as opposed to 30% and 20% for asbestos and tiled roofs respectively. From damage assessment comments recorded during the RDA it could be inferred in broad brush terms that for significant damage: metal roofs were mainly damaged by wind, tile roofs from tree or debris impact and asbestos roofs from hail or debris impact.

6. Conclusions and Recommendations

From field observations of damage and analysis of Doppler radar imagery it is estimated that wind speeds were generally less than 100 km/h for the surveyed area, significantly less than the 141 km/h maximum recorded at Archerfield Airport. Therefore, estimated wind speeds for the areas surveyed were less than the Australian wind loading standard design level for Brisbane.

Wind-driven hail had extensively damaged windows (predominantly from older housing) leading to damage to building interiors from the wind-driven rain. There was a noted difference in the performance of new window glass compared with older windows.

In many cases where significant roof damage had occurred, this was due to (i) building age with rot in timber roof members and/or corrosion of connections or (ii) installation of new roof cladding (in some cases replacing tile with metal cladding) without upgrading the batten to rafter or rafter to wall tie down connections to contemporary building standards. The roof structure damage was typically associated with a breach in the windward wall allowing a large increase in internal pressure and adding to the external suction loads on the roof.

Recommendations include:

- Reconstruction and repairs should be carried out in accordance with relevant Standards.
- For the rebuilding or upgrading of older housing, the complete load path from roofing to foundations needs to be considered, and not just from roof cladding to battens. This may not always be feasible so at the very least (pragmatic approach for partial solution) upgrade from roofing to top plates of walls. This includes the rafter to top plate connection and strapping from rafters and ridge plates to ceiling joists and tops of internal walls. Reference should be made to documents such as the Standards Australia handbook for the upgrading of older housing HB132.1 (1999). **This especially relevant when changing from a terracotta/concrete tile roof to a metal roof cladding.**
- Regular inspection of structural elements (including in the roof space) should be carried out to look for signs of deterioration (e.g. corrosion, rot, etc.). Although written for cyclone regions, some of the details in the CTS brochure “Is your house prepared for a cyclone?” contains further information: http://www.emergency.qld.gov.au/emq/css/pdf/cyclonebrochure-house.pdf
- Wind-driven hail was the primary cause of most window damage. It is recommended that this be the topic of further research as very little literature is available on the effects of wind driven hail on building components and associated water damage.

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Appendix A – Preliminary Social Media Search

A preliminary social media and online news search was performed on Friday the 28th of November to quickly assess the severity of the storm and to plan for the damage survey. A large and growing amount of content was available on a number of websites taken by journalists, storm chasers and members of the public, sometimes during the event itself. Selected photographs from these websites are presented in the following pages.

Initial observations were that cases of severe damage were mostly older houses. However, both new and old properties were affected by debris damage from fallen trees and failed roofing from other properties. Additionally, hail damage to cars and windows were widespread and included damage to glass facades in the Brisbane CBD.

Data from amateur weather stations was used to estimate the wind speeds that had caused damage that was recorded in these images. These included data from home weather stations that were contributing to the '*Weather Underground'* website as well as sites based at institutions such as the University of Queensland.

It should be noted that the reliability of this data cannot be determined as home weather stations may be installed incorrectly or poorly located and likely uncalibrated. Additionally, it is highly unlikely that these speeds are measured at a height of 10m. As such, this data is likely to underestimate the true wind speeds at 10m height. From this preliminary search it is estimated that peak gusts were between 60-80km/h in suburbs north of Archerfield, significantly smaller than the Terrain Category 3: 170km/h (47m/s) design wind speed for Brisbane.

Table A1. Recorded wind speeds at official and amateur weather stations, arranged approx. North to South

Station	Wind Speed (km/h)	Wind Gust (km/h)
Wavell Heights/Chermside*	43.6	56.2
Red Hill*	-	68.4
Brisbane CBD	37	83
University of Queensland		62
Fig Tree Pocket*	-	80.4
Holland Park West*	33.8	59.5
Darra*	28.5	56.2
Sunny Bank Hills*	30.6	43.4
Runcorn*	15.4	19.8
Archerfield Airport	113	141

*Data from amateur weather stations, source: www.weatherunderground.com

Storm Approaching Archerfield Airport, *Source*: Andy Barber, <https://www.facebook.com/SevereWeatherAustralia/photos/a.279133602504.146166.261100802504/10152877148677505/?type=1&theater>

Storm approaching the CBD, *Source:* Brisbane Times http://www.brisbanetimes.com.au/environment/weather/violent-storm-lashes-brisbane-thursday-november-27-20141127-11viro.html?aggregate=&selectedImage=0

The roof sheeting from this church has been torn off its battens. The roof appears to have been tiled before being replaced by metal sheeting. *Photographer*: Andree Withey. *Location*: Ipswich road, Annerley. *Source*: < http://www.abc.net.au/news/2014-11-28/roof-gone-in-brisbane-storm/5926234>

Roof sheeting attached to battens along with rafters have been torn off this worker's cottage. *Photographer*: Brad Schultz. *Location*: Ross St, Woolloongabba. *Source*: <https://twitter.com/superbrudd/status/537871622980382720/photo/1>

Roof sheeting with battens attached torn off building. *Photographer*: Brendan Fearn. *Location*: Woolloongabba. *Source*: <http://www.abc.net.au/news/2014-11-27/roofs-litter-the-streets-in-woolloongabba-after-the-storm/5923980>

Concealed fixed roof sheeting torn off clips, unit complex with river frontage. *Photographer*: Peter Doherty. *Location*: Toowong. *Source*: < https://twitter.com/peterdoherty7>

Damage aircraft hangar at Archerfield Airport, failure of a door, window or skylight may have contributed to the wall sheeting being blown off from the inside.
Source: Brisbane Times, http://www.brisbanetimes.com.au/queensland/brisbane-live-friday-november-28-2014-20141128-11vrwa.html

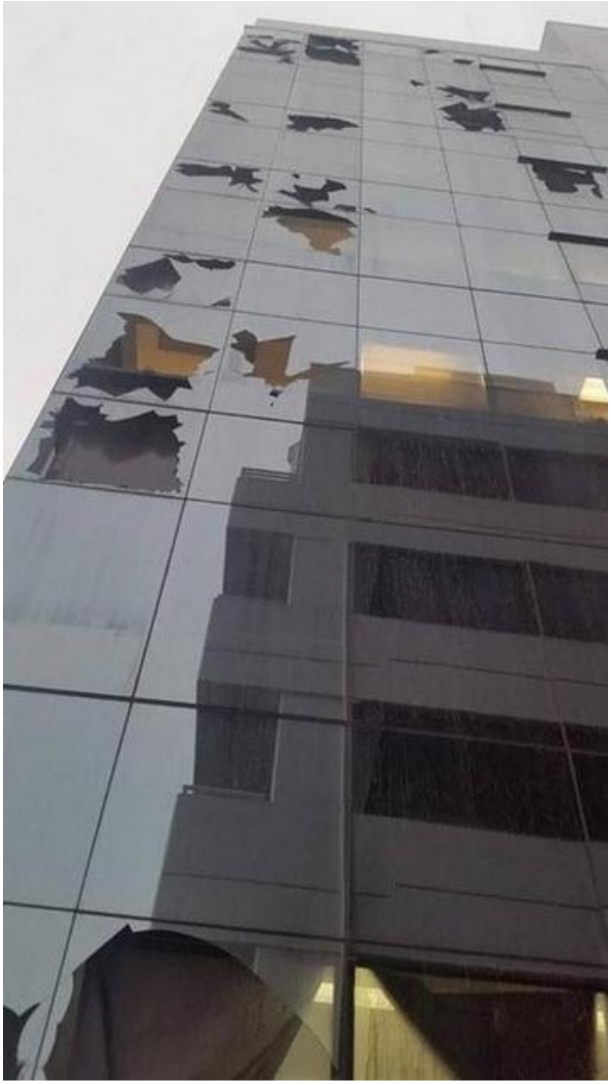
Perforated roller door failure of the XXXX Brewery, Milton. *Source*: Alex Tilbury, <https://twitter.com/hashtag/bnestorm?src=hash>

Severe debris damage to house at Herston. *Source*: Stefan Armbruster, <https://twitter.com/stefarmbruster>

Appartment door pieced by debris at Herston. *Source*: Nine News Brisbane, <https://twitter.com/9NewsBrisbane/status/538150543882194945/photo/1>

Flooding at Bowen Hills, of streets. *Source*: Darren England , The Courier Mail, http://www.couriermail.com.au/news/queensland/above-average-temperatures-as-southeast-prepares-for-supercell-storms

Shipping containers blown over onto carpark at the Port of Brisbane *Source:* Grant Spicer http://www.brisbanetimes.com.au/environment/weather/violent-storm-lashes-brisbane-thursday-november-27-20141127-11



Hail damage to glass façade, Turbot St, Brisbane CBD. *Source:* Jessy Sahota <https://twitter.com/JessySahota>

Planes flipped over. Photo: Higgins Storm Chasing Location: Archerfield Airport. *Source:* The Age, http://www.theage.com.au/environment/weather/violent-storm-lashes-brisbane-thursday-november-27-20141127-11viro.html

Orleigh Park West End Brisbane Times. *Source:* Brisbane Times http://www.brisbanetimes.com.au/environment/weather/violent-storm-lashes-brisbane-thursday-november-27-20141127-11viro.html

Robinsons Park Fairfield. *Source:* Brisbane Times

UQ St Lucia Campus. *Source:* Brisbane Times

Fallen trees on house, Orleigh Park West End. *Source:* http://www.brisbanetimes.com.au/environment/weather/violent-storm-lashes-brisbane-thursday-november-27-20141127-11viro.html

Tree blown over in Montague Street West End. *Source:* Brisbane Times, http://www.brisbanetimes.com.au/environment/weather/violent-storm-lashes-brisbane-thursday-november-27-20141127-11viro.html

Brisbane Times Turbot Street. *Source: Cameron Atfield*
http://www.brisbanetimes.com.au/environment/weather/violent-storm-lashes-brisbane-thursday-november-27-20141127-11viro.html

Brisbane storm from Ascot. *Source:* Brisbane Times
http://www.brisbanetimes.com.au/environment/weather/violent-storm-lashes-brisbane-thursday-november-27-20141127-11viro.html

Brisbane storm from Ascot. *Source:* Brisbane Times
http://www.brisbanetimes.com.au/environment/weather/violent-storm-lashes-brisbane-thursday-november-27-20141127-11viro.html

Truck overturned at Archerfield. *Source:* Higgins Storm Chasing