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Cyclone 'Yasi' windfield re-visited

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Introduction

The JCU-CTS report TR57 on Cyclone 'Yasi' (Boughton *et al.*, 2011) included an analysis of the windfield generated by 'Yasi' in relation to distribution of the maximum wind gusts over land, primarily in the zone affected by the strongest winds. A revised model and predictions of maximum gusts at key locations is presented herein, based on the well-known Holland (1980) model for hurricanes and tropical cyclones. The main difference in the re-analysis results from the separation of the 3-second moving average gusts obtained from the automatic weather stations and the much shorter duration' gusts obtained from the analysis of road signs ('windicators').

Holland model

The windfield model was based on the unmodified (single vortex) Holland model (Holland, 1980), which assumes the following expression for the static pressure variation from the centre to the edge of the storm.

$$\frac{p - p_c}{p_n - p_c} = exp\left(\frac{-A}{r^B}\right) \qquad (1)$$

where, p_c is the central pressure of the tropical cyclone
p_n is the atmospheric pressure at the edge of the storm
r is the radius from the storm centre
A and B are scaling parameters

Differentiating Equation (1) and substituting in the gradient wind equation gives for the gradient wind, U:

$$U = -\frac{|f|r}{2} + \sqrt{\frac{f^2 r^2}{4} + \frac{\Delta p}{\rho_a}\frac{AB}{r^B}exp(-\frac{A}{r^B})} \qquad (2)$$

where, $\Delta p = p_n - p_c$
f is the Coriolis parameter ($=2\,\Omega \sin\lambda$),
Ω is the angular velocity for the earth's rotation (rad/sec),
λ is the angle of latitude,
ρ_a is the density of air

Equation (2) requires a number of parameters to be provided:

- The central pressure of the cyclone, p_c. It was taken as 930 hPa, based on the measurement at Clump Point, close to the point of landfall of Cyclone 'Yasi'.
- The ambient pressure, far from the centre of the cyclone, p_n. An average value of 1007 hPa was used.
- Holland 'B' parameter. In the revised model a value of 1.2 was found to give the best fit to the recorded maximum gusts, as discussed in the following section.
- The radius of maximum winds, r_{max}. A value of 32.5 kilometres was estimated for r_{max}. In the Holland model r_{max} is closely approximated by $A^{1/B}$. With the value of B of 1.2 this leads to a value of A of 65.2 km.

Pressure profile

Figure 1 shows the lowest recorded values of barometric pressure measured at 8 locations, plotted against the radius from the centre of the storm at that time, and Equation (1) is also shown, with values of p_c, p_n, A and B given above. Good agreement is seen; this, together with the calibration against the recorded maximum wind gusts as described following, gives general validity to the modelling approach adopted.

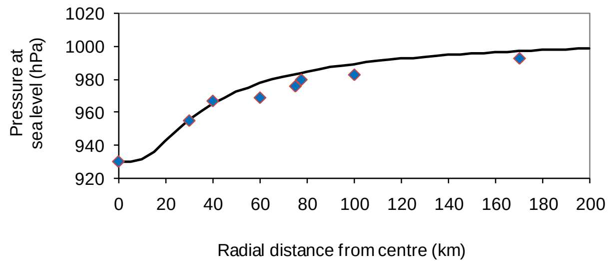

Figure 1. Comparison of recorded barometric pressures with modelled relation from Eq. (1).

Factors for the windfield

Equation (2) is an equation for the gradient wind, and requires factors to convert this to a 10-minute mean wind speed at 10 metres height, and a gust factor to convert the latter to a gust speed. There is also a change in direction from the gradient to the surface wind, towards the low-pressure centre of the cyclone.

In the present case, the ratio of 10-minute mean winds to gradient wind was taken as 0.7, and the gust factor was taken as 1.4 for overland winds, and 1.3 for overwater winds for 3-second moving-average gusts, and 1.65 and 1.55 respectively for 0.2-second gusts, as now proposed for AS/NZS1170.2:2011 (Standards Australia, 2011). The wind direction at the surface was adjusted by an 'inflow' angle of 30 degrees clockwise.

Once a cyclone makes landfall, there is an immediate weakening in strength as the eye collapses. This continues progressively as the storm moves further inland. In this case, the weakening factors in Table 1 were applied to the wind speeds, as a function of the distance of the centre of the storm from landfall. The factors in Table 1 are based on data from land-falling U.S. hurricanes analysed by Kaplan and de Maria (1995, 2001).

Distance from landfall (km)	Weakening factor
0	1.0
10	0.90
20	0.875
30	0.85
40	0.83

Table 1. Weakening factors after landfall

Outside the radius of maximum winds, the vortex gradient winds produced by the Holland model were summed vectorially, with a forward motion component taken as 10 m/s (36 km/h) in a direction 24 degrees south of west, based on observations of radar and satellite images of 'Yasi'.

Calibration of the windfield model

Table 2 shows values of the '1 square metre' gusts (i.e. approximately the 0.2-second gusts of AS/NZS 1170.2) derived from road signs. The values shown are averages of upper and lower limits from non-failed and failed road signs, respectively. This measurement technique is discussed in Boughton *et al.*, 2011, and in another presentation at this Workshop. All gusts in Table 2 have been corrected to 10 metres height in open terrain.

Location	Recorded gust (m/s) 1 sq. m.	Predicted gust (m/s) 1 sq. m.
Mourilyan	47.5	51.6
Tully-Birkala	62.5	51.6
Cardwell	58	65.1
Kurrimine	50.5	56.5
S. Mission Beach	63	60
El Arish	50	51.5
Silkwood	50	51.1
Halifax-Macknade	45.5	50.3
Bingil Bay	55	56.9
Kennedy	59	58.1
Dallachy-Bilyana	50	57.2

Table 2. Estimated maximum '1-square metre' gusts obtained from road sign 'windicators', and predicted values

Table 3 shows maximum gusts recorded by cup anemometers at seven locations during the event. Two of these were from offshore reefs – the cyclone passed between these two before landfall.

Location	Recorded gust (m/s) 3 sec.	Predicted gust (m/s) 3 sec.
South Johnstone	43.5+	43.8
Cairns	25.8	22.7
Townsville	37.5	30.7
Lucinda Point	45.9+	46.8
East Innisfail	43.3+	35.3
Holmes Reef	40.3	33.2
Flinders Reef	43.9	47.9

+ corrected for terrain, height and topography

Table 3. Maximum 3-second-averaged gusts recorded by anemometers compared with predicted values

All locations in Table 3, except for East Innisfail, are equipped with automatic weather stations operated by the Bureau of Meteorology, and the gusts recorded are 3-second-moving-average gusts, following World Meteorological Office practice (Beljaars, 1987).

Figure 2 shows the peak gusts from the model wind field, plotted against the measured values, with the latter consisting of a combination of anemometer and road sign readings.

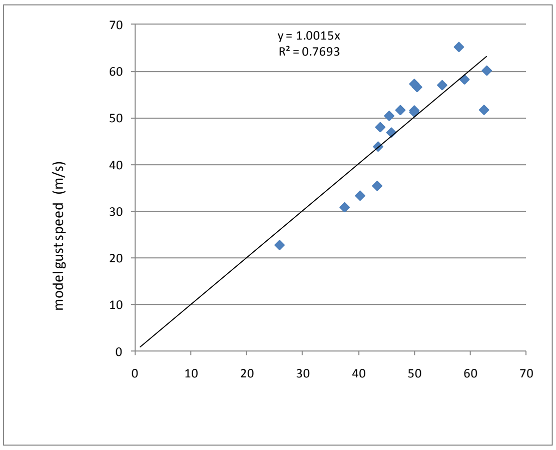

Figure 2. Cross-plot of measured and predicted maximum gust speeds

Generally good correlation is seen in Figure 2, with a correlation coefficient of 0.88, and a slope very close to 1.0, indicating no systematic bias in the model. This was achieved by adjustment of the '*B* parameter' in Equation (2) to obtain the best fit.

The model (Table 2) shows an underestimation of the maximum gusts at Tully, and an overestimation at Cardwell, compared with the measured values derived from the 'windicators'. Both of these differences may be the result of topographic effects with channelling between Mount Tyson and Mount Mackay producing an increase at Tully for north and south winds, and shielding from Hinchinbrook Island reducing gusts from easterly winds at Cardwell.

Reproduction of wind speed and direction histories

Histories of wind gusts and directions with time, and the position of the cyclone, were obtained by locating the centre of the cyclone at 10 kilometre intervals along its track, and evaluating the vectorial sum of the vortex speed and the forward speed of the storm. Nine positions of the storm were used, spanning 40 kilometres before and after the landfall, and a total time of more than two hours.

Figures 3 and 4 compare the calculated histories of maximum gusts and wind directions, with measured values from four automatic weather stations on land for which recorded values were available at intervals of 15-30 minutes. For the graphs, a coast crossing time of 12.45 am on February 3rd 2011 was assumed, and times for the other positions of the centre of the cyclone were estimated assuming a forward speed of 36 km/h (10 m/s).

The comparisons of maximum gusts (km/h) in Figure 3 are generally good; this is perhaps not surprising as the maximum gusts from these stations, together with the 'windicator' estimates, were used to optimize the model parameters. The measurements for Townsville indicate greater wind speeds after the eye of the cyclone made landfall; this feature was not reproduced by the model which incorporates weakening after landfall.

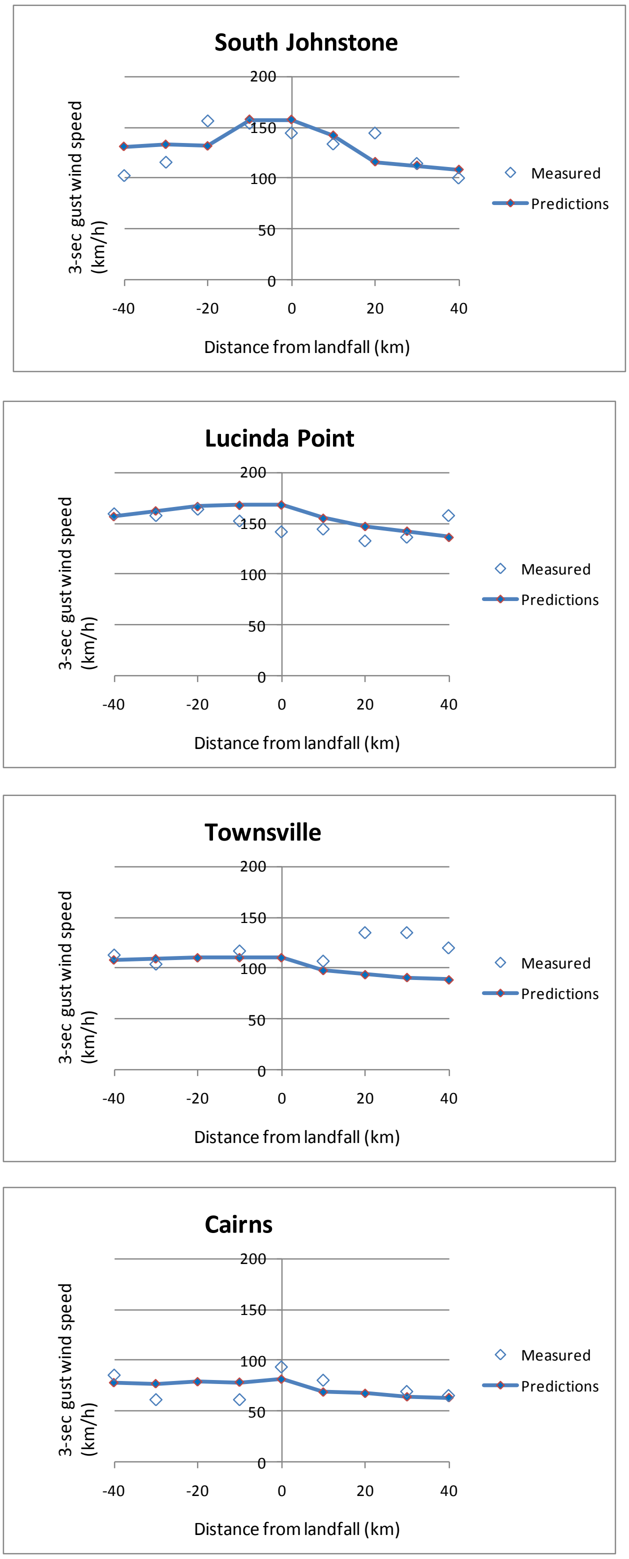

Figure 3. Comparison of measured and modelled maximum 3-second gusts (km/h)

Wind directions are compared in Figure 4 (except for Lucinda Point, for which the direction vane appeared to malfunction). The agreement is very good at Townsville. Although the general trend with time is similar, the measured directions at South Johnstone and Cairns appear to indicate somewhat greater inflow angles than the 30 degrees assumed in the model. Local topography may have influenced the wind directions at these measurement stations.

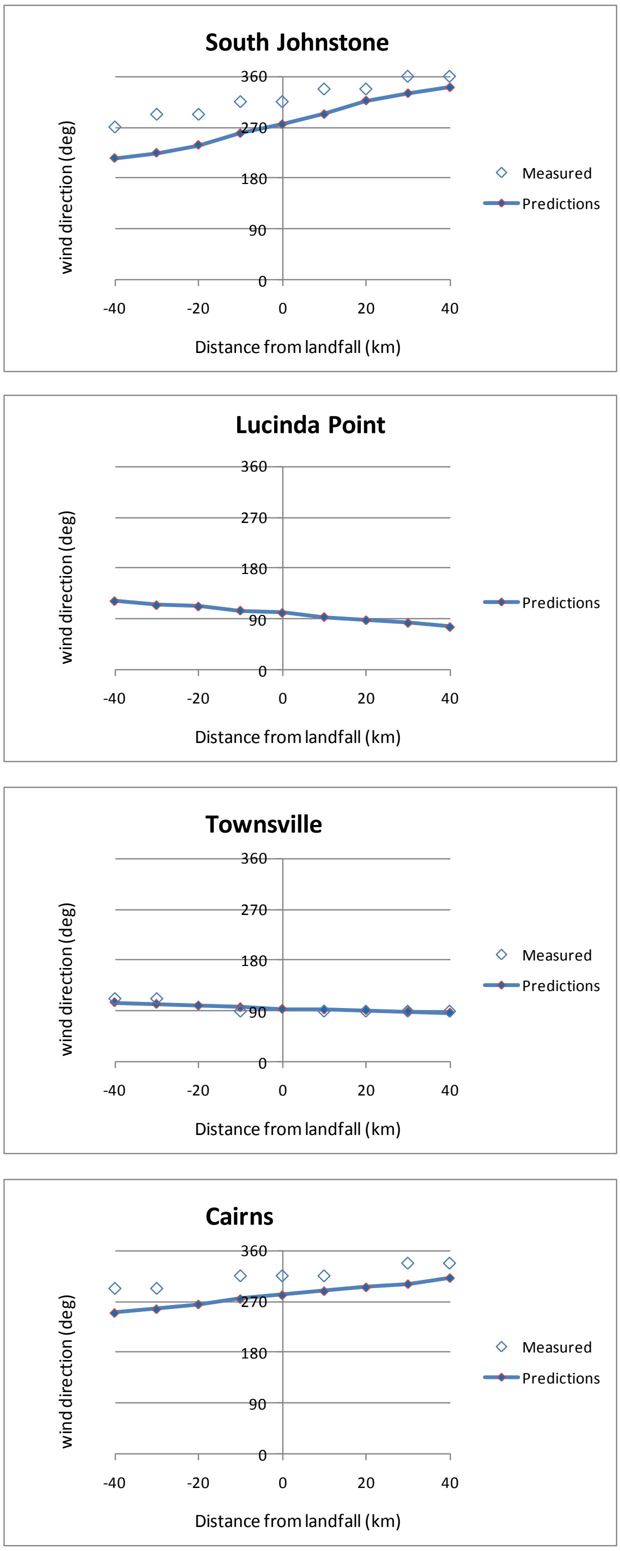

Figure 4. Comparison of measured and modelled wind directions

Table 4 shows the predicted maximum gusts produced by the model at 14 locations. The maximum *1-square metre* gusts anywhere in the event at 10-metres height, without any topographic effects, is predicted to have been 65 m/s (at Cardwell). However, the maximum *3-second* gust was about 55 m/s (200 km/h) - also at Cardwell.

Location	Predicted gust (m/s) *1 sq. m.*	Predicted gust (m/s) *3 sec. mov. avg.*	Predicted gust (km/h) *3 sec. mov. avg.*
Abergowrie	50.8	43.1	155
Bingil Bay	56.9	47.8	172
Cardwell	65.1	54.7	197
Dunk Island	59.4	47.8	172
El Arish	51.5	43.6	157
Ingham	47.8	40.6	146
Innisfail	41.7	35.3	127
Kurrimine	56.5	47.5	171
Lucinda	55.8	46.8	168
Mission Beach	56.9	47.8	172
Mourilyan	51.6	43.9	158
S. Mission Beach	60.0	50.3	181
Tully	51.6	43.9	158
Tully Heads	61.7	51.7	186

Table 4. Predicted maximum gusts at selected centres

Figure 5 shows approximate contours of estimated maximum gusts during 'Yasi' at 10 metres height over flat open terrain. These are *1 square metre* gusts, and closely equivalent to the *0.2 second* gusts used in AS/NZS1170.2. The boundaries of the region of maximum winds are defined approximately by the dotted lines in Figure 5.

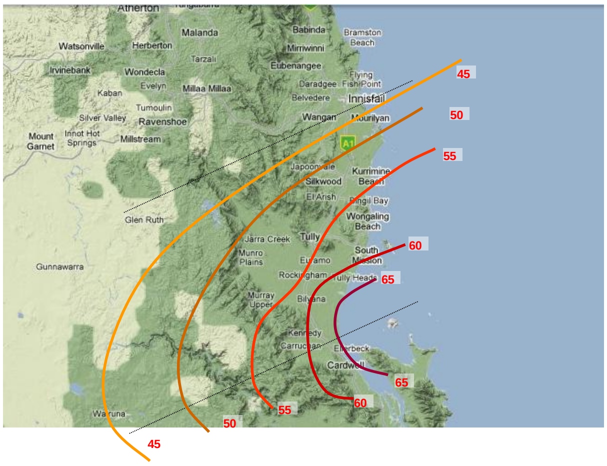

Figure 5. Approximate contours of maximum 0.2-second gusts at 10 m height in open terrain (in m/s) attained during 'Yasi' (local topographic effects not included) .

Conclusions

The approach used for the windfield modelling for Cyclone 'Yasi', based on the Holland model, has been validated by comparisons with recorded barometric pressures, and with time histories of wind speeds and directions at four automatic weather stations. Comparisons of the predicted variation of gust wind speeds, during the event, with the recorded values from South Johnstone, Lucinda Point, Townsville and Cairns are favourable, except the increase in wind gusts at Townsville, after the cyclone made landfall, cannot be reproduced.

Good agreement is achieved between the modelled and measured wind directions at Townsville. Less good agreement between modelled and measured wind directions at South Johnstone and Cairns is obtained, indicating greater inflow angles than are assumed in the model.

The maximum predicted gust of 65 m/s (234 km/h) in the Cardwell area is about 94% of the design value (V_{500}), for most buildings in Region C in AS/NZS 1170.2. However, predicted *3-second moving-average* gusts are 18-19% lower than the 1 square metre values, and do not exceed 200 kilometres per hour.

It should be noted that this work was directed to gust wind speeds over land, in the inner part of the cyclone, and the model was primarily calibrated to land-based measurements for that purpose. Modelling of the mean windfield offshore over the ocean, and for larger radii from the storm centre for storm surge prediction, may require a more complex model such as the double-vortex model (McConochie *et al.*, 2004)

Acknowledgments

The contributions and input of all the team members on the JCU-CTS investigations of Cyclone 'Yasi' is gratefully acknowledged, particularly the contributions of George Walker during the time-consuming collection of data from failed road signs (many more of the latter were checked and measured than were used for the modelling). The financial support of the Australian Building Codes Board during the field investigation is also acknowledged.

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