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Did Typhoon Haiyan have a new record-minimum pressure?

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Introduction

The intensity of a tropical cyclone is characterised by two main factors: the maximum sustained wind in the eyewall and the minimal atmospheric pressure in the centre of the eye (Merril, 1984). Since 23 October 2015, Hurricane *Patricia* officially holds the record for the highest maximum wind attributed to a cyclone, with 185kn (Kimberlain *et al.*, 2016; Rogers *et al.*, 2017). This value was estimated from the measurement of 182kn carried out by the Stepped Frequency Microwave Radiometer (SFMR) during aerial reconnaissance. Previously, the record was held by Typhoon *Haiyan*, with 170kn estimated from the satellite imagery on 7 November 2013 (Lander *et al.*, 2014). The minimum surface atmospheric pressure in *Patricia* was estimated between two aerial missions at 872hPa, just 2hPa from the world record of 870hPa recorded by dropsonde in Typhoon *Tip* on 12 October 1979 (Dunnavan and Diercks, 1980). In the absence of aircraft observation, the Regional Specialized Meteorological Centre (RSMC) at Tokyo and the Joint Typhoon Warning Center (JTWC) attributed a minimum pressure of 895hPa to Typhoon *Haiyan* (Lander *et al.*, 2014). In the western North Pacific, what explains a pressure of 25hPa less in Typhoon *Tip*, with winds estimated at 165kn, compared with Typhoon *Haiyan*, with 170kn winds? To try to better estimate Typhoon *Haiyan*'s minimum pressure at sea level, we used the pressures recorded at a Philippine meteorological station, which was on the outer edge of the eyewall. We also examined the example of two of the world's most intense cyclones that were the subject of aircraft reconnaissance, with pressure data taken outside and inside the eyewall and inside the eye itself.

Typhoon *Haiyan*: recorded data in the Philippines

Haiyan reached tropical storm stage with sustained winds of 35kn over 1min on 4 November 2013 (JTWC, 2014). At the time, the storm was located at 6.1°N, 151.5°E (Galvin, 2014). Intensifying very rapidly, *Haiyan* became a 65kn typhoon on 5 November and 130kn on 6 November at 0000 UTC. Moving west-northwest at 20kn, *Haiyan*, at 1800 UTC on that same day, entered the Philippines Area of Responsibility (west of 135°E and north of 5°N) with an intensity of 155kn. On 7 November at 1200 UTC, *Haiyan* reached its maximum intensity of 170kn (with pressure estimated at 895hPa), which was maintained until its landfall in the northern part of Leyte province (Figure 1). At 2130 UTC on 7 November, the centre of *Haiyan* passed 22km south of Guiuan aerodrome (11.035°N, 125.74°E), located in the extreme

southeast of Samar province. Before being destroyed, the anemometer recorded an average wind of 84kn over 10min, and a gust of 103kn at 2010 UTC. The eye, which was located precisely by the Guiuan radar, was just over 50km from the meteorological station (Table 1). The atmospheric pressure at sea level began to drop rapidly in Guiuan with the rapid approach of the typhoon: 955hPa at 2020 UTC (46km), 927hPa at 2045 UTC (34km), and 910hPa at 2100 UTC at a distance of 28km from the centre of the eye. This was the last pressure observed in Guiuan (Figure 2). The needle of the barograph was running off the paper which was removed just after 2100 UTC. The pressure was still falling rapidly, with a final reading at 908hPa, but the paper was not replaced, because the strong winds had begun to damage the windows of the station. According to the meteorological observation technician at Guiuan, the station was never inside the eye, and no period of calm was felt. Taking into account the 17km radius of *Haiyan*'s eye at the surface (34km in diameter) and the distance of 22km between the eye's centre and Guiuan (Figure 1 and Table 1), the station was in the northern part of the eyewall, about 5km from the outer edge of the eye, at 2130 UTC. The last image obtained at 2020 UTC before the destruction of Guiuan's radar (at the top of a hill, a few dozen metres above the plain) revealed Typhoon *Haiyan*'s structure when it neared the station (Figure 3). The northern part of the eyewall was about 11km wide. At 2057 UTC, the image from the NOAA 15 satellite located the eye's centre at 10.82°N, 125.87°E (Figure 1). At 2100 UTC, the Tokyo RSMC positioned the centre at 10.8°N, 125.9°E by means of the geostationary satellite MTSAT. Given the distance of 28km between the eye's centre and Guiuan at 2100 UTC, the station had begun to enter the north-northwestern part of the eyewall when the last pressure was measured at 910hPa (Table 1). This means that the pressure in the eye was much lower, and that its estimation involves a comparison with the pressure gradients of cyclones of comparable intensity.

Estimation of the minimum sea level pressure in the eye of *Haiyan*

Using a dropsonde, a pressure of 870hPa was observed in the eye of Typhoon *Tip* on 12 October 1979 at 0353 UTC (Dunnavan and Diercks, 1980). Probes were then used to measure the pressure in the eye only. It was not until the 1990s – with GPS sondes also released in the eyewall and in the central dense overcast of tropical cyclones (Hock and Franklin, 1999) – and the High Density Observation (HDOB) of airborne reconnaissance missions from the 2000s, that it was possible to define the pressure gradient more precisely. Therefore *Tip*'s pressure gradient is not known. The two cyclones chosen to facilitate estimation of the minimum pressure associated with Typhoon *Haiyan* are *Patricia* (2015) in the eastern North Pacific and *Megi* (2010) in the western North Pacific. There is still aircraft reconnaissance of hurricanes in the eastern North Pacific and in the North Atlantic when the North American coastline is threatened. Typhoon *Megi* was the subject of aerial missions as part of the Impacts of Typhoons on the Ocean in the Pacific (ITOP) campaign (D'Asaro *et al.*, 2014). As the intensity of *Patricia* was 180kn (Kimberlain *et al.*, 2016) and that of *Megi* was 160kn (JTWC, 2011) during aerial reconnaissance, these two cyclones are suitable for comparison, in terms of pressure gradient, with *Haiyan*, whose maximum winds were estimated at 170kn (JTWC, 2014). The comparison of pressures in *Patricia*, *Megi*, and *Haiyan* is shown in Table 2. The airborne observations displayed here were made in the southeastern part of Hurricane *Patricia* and in the northwestern part of Typhoon *Megi*. The minimum pressures were 879hPa at 0646 UTC on 23 October 2015 and 890hPa at 1305 UTC on 17 October 2010 in the eyes of *Patricia* and *Megi*, respectively. The pressure drop was more abrupt in Hurricane *Patricia* than in Typhoons *Megi* and *Haiyan*. Pressures of the order of 993–994hPa were measured 40km from the edge of *Patricia*'s eye, 81km from the edge of *Megi*'s eye, and 114km from the edge of *Haiyan*'s eye. Within the eyewall, the pressure gradient was strongest in *Patricia*, with 8.2hPa/km–1 over the last 4km (921 to 888hPa). At 12km from the edge of *Patricia*'s eye, the pressure change was at 77hPa

(888 to 965hPa), a gradient of 6.4hPa km^{-1} . In the last 8km inside the eyewall of *Megi*, the gradient was 4.6hPa km^{-1} (933 to 896hPa). In Typhoon *Megi*, over a distance of 14km around the eye, the pressure decreased by 59hPa (955 to 896hPa), giving a gradient of 4.2hPa km^{-1} . *Haiyan* had a greater extent pressure field than *Megi*, especially relative to that of *Patricia*, which was small in size. At 11km from the edge of the eye (28km from the eye centre), that is, at the entrance to the eyewall of *Haiyan*, Guiuan measured a pressure of 910hPa. At a comparable distance, an interpolation of reconnaissance data gives 945hPa in *Megi* and 960hPa in *Patricia* (see Table 2). When *Haiyan* approached from 34km to 28km with Guiuan station, a pressure drop of 17hPa (927 to 910hPa) was measured, that is, a gradient of 2.8hPa km^{-1} . This gradient was measured at the outer edge of the eyewall of Typhoon *Haiyan*. Within the last 11km of the eyewall, the pressure gradient was 6.5hPa km^{-1} for *Patricia* (960 to 888hPa) and about 4.5hPa km^{-1} for *Megi* (945 to 896hPa). An extrapolation for *Haiyan* would give a gradient of around 5.5hPa km^{-1} , a pressure of 850hPa at the edge of the eye, and a pressure of 845hPa inside the eye. Aerial reconnaissance showed a decrease in pressure of at least 5–6hPa in the eyes of *Patricia* and *Megi* (Table 2). However, as *Haiyan* was a wider cyclone than either *Megi* or *Patricia*, it is possible that the pressure gradient inside the eyewall of *Haiyan* was not as strong as that observed in *Megi* and *Patricia*. Our hypothesis is based on the testimony of one of the weather reconnaissance officers who measured the pressure of 870hPa on board the aircraft in Typhoon *Tip* (Iacovelli and Vasquez, 1998): *Usually, when a plane is flying inside a tropical cyclone, there is a big drop in the height of the 700hPa surface with the penetration in the eyewall. In the case of Typhoon Tip, there was a gradual slope all the way into the center.* Outside the eyewall, between 11 and 41km from the edge of the eye (between 28 and 58km of the eye centre), *Haiyan* had a more gradual pressure gradient than that of *Megi* or *Patricia*. We performed a satellite imagery comparison between *Haiyan*, *Tip*, *Patricia* and *Megi* (Figure 4). *Haiyan* had very cold cloud tops extending farthest and most symmetrically around the centre. *Tip* and *Megi* were comparable, though *Tip* had colder tops. *Patricia* also had very cold cloud tops, but they covered an area which was half of that found in the case of *Haiyan*. The images show that *Patricia* was a small hurricane with a very steep pressure drop around the eye (Table 2), while *Megi* and *Haiyan* were larger in size, and were associated with a faster pressure drop outside the eyewall. In the case of *Megi*, there was also a little less pressure drop in the eyewall. Since Guiuan could not record the pressure data when the station was in the middle of the eyewall at 2130 UTC on 7 November, it was therefore necessary to make assumptions in order to estimate the pressure at the centre of typhoon *Haiyan*. We devised three scenarios with different values of the pressure gradient in the eyewall (Table 3): 3.5, 4, and 4.5hPa km^{-1} . In the three scenarios, the minimum pressure estimated in the eye of *Haiyan* has values of 866.5, 861 and 855.5hPa, respectively – lower than the world record of 870hPa recorded in Typhoon *Tip* in October 1979. The most likely scenario for *Haiyan* would correspond to a rounded value of 860hPa. This pressure is also well below that of the 895hPa estimated by the Tokyo RSMC and the JTWC. In fact, even when there were regular aircraft reconnaissances in the western North Pacific until 1987, the only reliable factor measured was the atmospheric pressure at sea level (Kossin *et al.*, 2013). There were no microwave radiometers (Uhlhorn *et al.*, 2007) or GPS probes (Hock and Franklin, 1999) to measure maximum surface winds. Therefore sustained winds were adjusted on the empirical pressure–wind relationship developed by Atkinson and Holliday (1977). For a pressure of 872hPa, Table 4 shows that 8 of the world’s 10 deepest cyclones (whose pressure has been measured or partially estimated) were formed in the western North Pacific with a minimum pressure below 880hPa. However, in this basin, regular aircraft reconnaissance was discontinued in 1987, with the exception of specific on-and-off research missions, as in 2010 (D’Asaro *et al.*, 2014). It is possible that some typhoons, the pressure of which has not been measured since 1987, could have figured in Table 4. Note that 4 of the 8 typhoons with a pressure ranging from 860 to 879 hPa (*Tip*, *Nora*, *June*, *Rita*) were observed

in the decade 1970–1979. During this period, activity in severe cyclones of categories 4 and 5 of the Saffir–Simpson classification is considered one of the lowest in the western North Pacific since the early 1960s (Chan, 2008). In the same basin, a more recent study (Lin and Chan, 2015) indicates an increase in the intensity of the strongest typhoons despite a 30% decrease in the destructive potential of all typhoons, according to the Power Dissipation Index (PDI), since the pressure–wind relationship indicated a maximum wind of 160kn over 1min. It is on this basis that the maximum wind of 165kn was attributed to Typhoon *Tip* for an observed pressure of 870hPa. Since the late 2000s, a new pressure–wind relationship, that of Courtney and Knaff (2009), is in application in the western North Pacific. In the absence of aerial reconnaissance, maximum wind estimates from satellite pictures (Dvorak, 1984; Velden *et al.*, 2006) are considered the most reliable parameter. For a maximum wind of 170kn, the Courtney and Knaff (2009) pressure–wind relationship gives a pressure of 895hPa. This is the origin of the 895hPa pressure attributed to *Haiyan*.

The deepest tropical cyclones on Earth

The world's deepest cyclones, with the exception of *Haiyan*, are known thanks to aerial reconnaissance missions (Table 4), which began in the mid-1940s in the North Atlantic and then in the western North Pacific (Kossin *et al.*, 2013). They began later in the eastern North Pacific, early 1990s. Until the advent of technology which enables the measurement of pressure values in the majority of typhoons in the western North Pacific, and in the absence of precise measurement by a meteorological station, it will be difficult to attribute a pressure lower than the 870hPa observed in *Tip* or the 860hPa estimated in our study of *Haiyan*. This is especially true since, for a given maximum wind, the Courtney and Knaff (2009) pressure–wind relationship gives a higher pressure than that in the Atkinson and Holliday (1977) relationship, which is no longer applied today. In the eastern North Pacific, aerial reconnaissance episodically represents a minority of hurricanes that pose a threat to inhabited lands or islands. And these hurricanes do not necessarily reach their minimum pressure at the time of the aerial missions. In the North Atlantic Ocean, since the factors which govern cyclogenesis are more favourable in the western part of the basin (Landsea, 1993), there is a greater possibility of measuring the pressure in the most intense hurricanes by means of aircraft. This is also true for the eastern North Pacific, whose eastern part to the west of the Mexican coast is conducive to the formation of the deepest hurricanes in the basin. Hurricane *Patricia* is a good illustration of this phenomenon.

Conclusion

From the data observed at the meteorological station at Guiuan in the Philippines, as well as the data from aircraft reconnaissances measured in cyclones *Patricia* and *Megi*, it was possible to define the minimum surface atmospheric pressure at the centre of Typhoon *Haiyan* with a high degree of confidence. The scenario selected gives *Haiyan* a minimum pressure of 860hPa, below the world record of 870hPa held by *Tip* and the 872hPa pressure estimated in *Patricia*. The Tokyo RSMC and the JTWC had estimated the minimum pressure from *Haiyan* at 895hPa on the basis of the current application of the pressure–wind relationship. In a study aimed at estimating the intensity of the ten most intense cyclones of the satellite era, Velden *et al.* (2016) found an 878hPa pressure associated with a maximum sustained wind of 176kn for *Haiyan* using the Advanced Dvorak Technique. This pressure remains higher than the 860hPa estimated in our study of *Haiyan*. The next step will be to better estimate the maximum sustained winds generated by a typhoon whose pressure was around 860hPa. Indeed, Knaff *et al.* (2010) found a tendency to underestimate the maximum winds associated with the category 5 tropical

cyclones analysed using satellite imagery with the Dvorak technique (Dvorak, 1984) in the North Atlantic and the eastern North Pacific. Such a study has not been conducted in the western North Pacific following the cessation of the regular aircraft observations in 1987.

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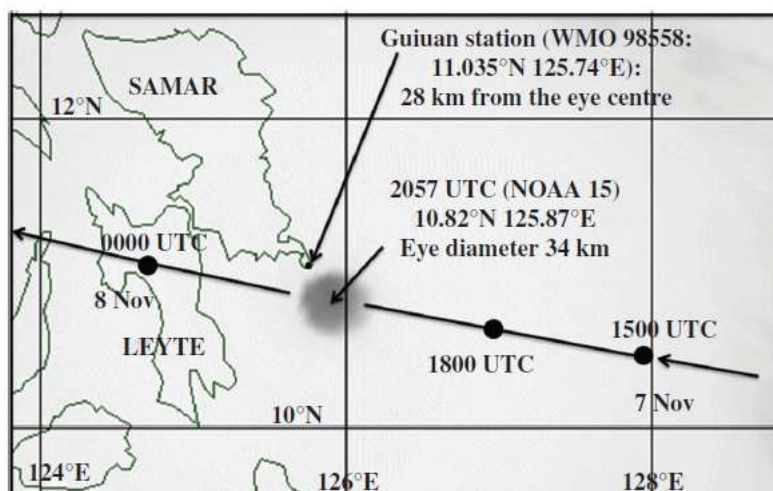


Figure 1. Haiyan track over the Philippines. (Source: compiled from a raw NCDC file (NOAA-15 image) and PAGASA and JMA data for the typhoon centre location.)

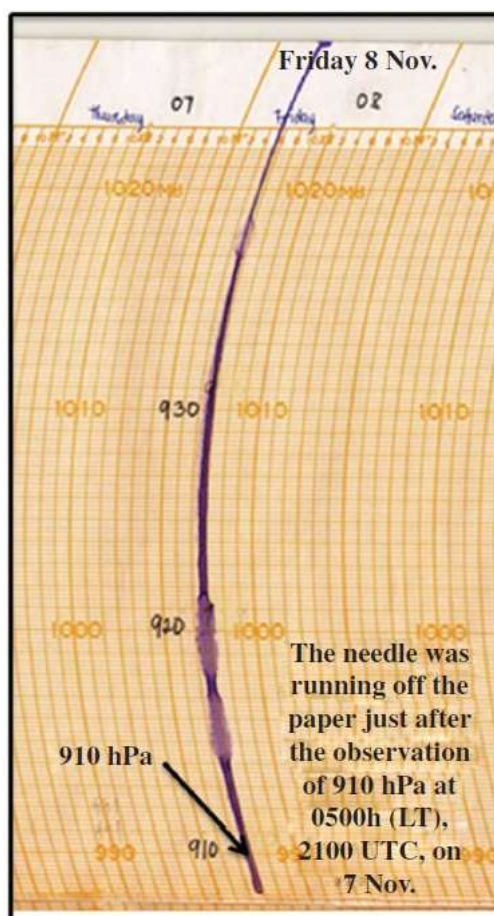


Figure 2. The barograph reading at Guiuan station during Typhoon Haiyan. (Source: PAGASA.)

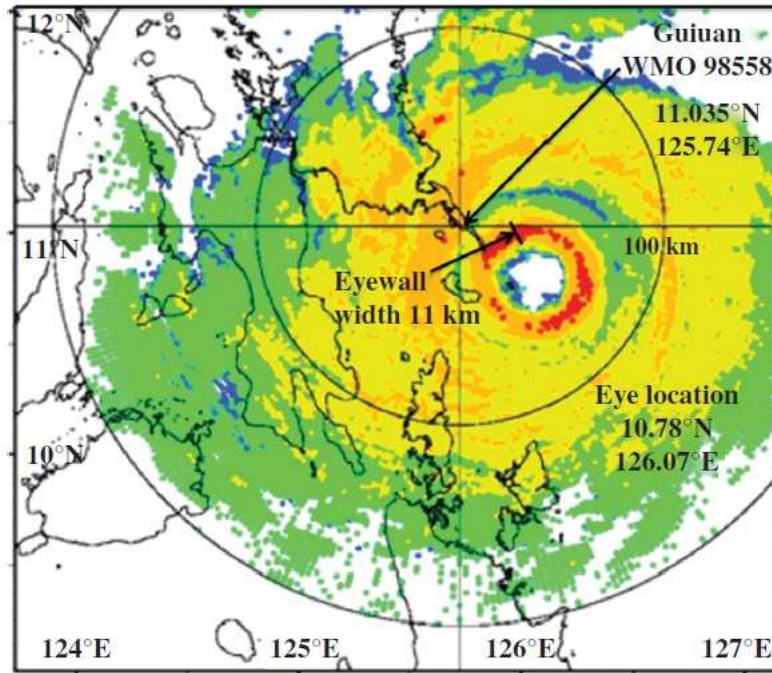
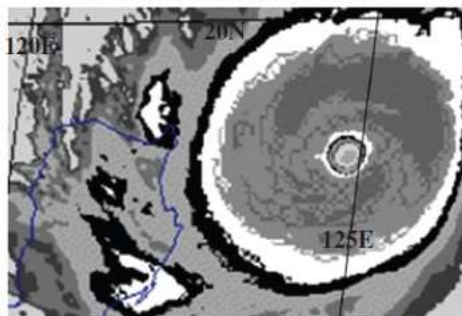


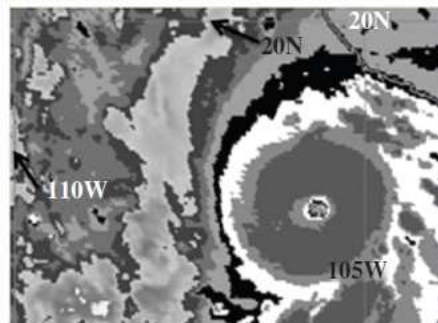
Figure 3. The Doppler radar picture of Typhoon Haiyan on 7 November 2013 at 2020 utc. (Source: PAGASA.)

Megi 10 Oct. 2010 1259 UTC MTsat
SLP measured: 890 hPa



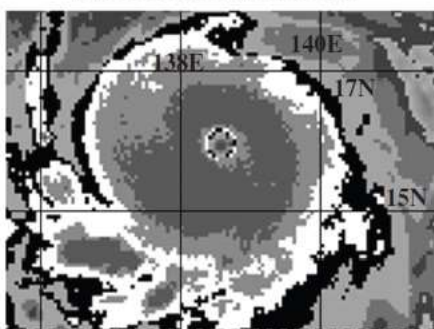
Source: treated from raw files of JMA

Patricia 23 Oct. 2015 1245 UTC Goes 13
SLP estimated: 872 hPa – measured 883 hPa



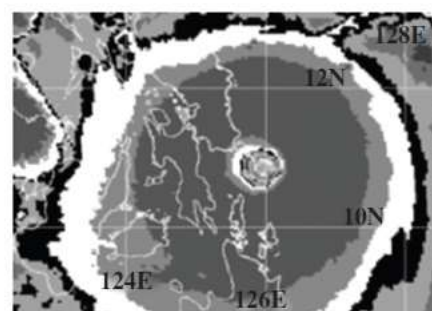
Source: Rogers et al. (2017)

Tip 11 Oct. 1979 2033 UTC GMS 1
SLP measured: 870 hPa



Source: JMA

Haiyan 7 Nov. 2013 2057 UTC MTsat



Source: NRL Monterey

Figure 4. The Basic Dvorak pictures of cyclones *Megi*, *Patricia*, *Tip* and *Haiyan*.

Table 1				
<i>The eye location of Haiyan, the distance to the station of Guiuan, and the pressure recorded on 7 November 2013.</i>				
Time (UTC)	Eye centre location		Distance (km) to Guiuan (11.035°N, 125.74°E)	Pressure (hPa) at Guiuan
	Lat (°N)	Long (°E)		
2130	10.84	125.70	22	^a
2100	10.82	125.87	28	910
2045	10.81	125.95	34	927
2020	10.78	126.07	46	955
2000	10.77	126.20	58	977
1900	10.70	126.53	94	989
1800	10.63	126.87	131	994
1700	10.57	127.23	171	997
1600	10.49	127.59	211	1000
1500	10.41	127.95	251	1003

^aPressure not recorded after 2100 UTC.
(Source: PAGASA data and satellite analysis.)

Table 2								
<i>The pressure gradient in Tropical Cyclones Patricia, Megi and Haiyan.</i>								
Hurricane Patricia 879hPa at 0646 UTC 23 October 2015			Typhoon Megi 890hPa at 1305 UTC 17 October 2010			Typhoon Haiyan 1800–2100 UTC 7 November 2013		
Pressure (hPa)	Distance to centre (km)	Gradient (hPa km ⁻¹)	Pressure (hPa)	Distance to centre (km)	Gradient (hPa km ⁻¹)	Pressure (hPa)	Distance to centre (km)	Gradient (hPa km ⁻¹)
888	5	Eye edge	896	13	Eye edge	[*]	17	Eye edge
921	9	8.2	933	21	4.6	910	28	^b
965	17	5.5	955	27	3.6	927	34	2.8
979	22	2.8	966	35	1.4	955	46	2.3
991	38	0.7	975	43	1.1	977	58	1.8
994	45	0.4	987	64	0.6	989	94	0.3
998	57	0.3	993	94	0.2	994	131	0.1

^{*}Pressure not recorded.
^bNo data in the eyewall.
(Source: aircraft reconnaissance data for Cyclones Patricia and Megi, and data at Guiuan for Haiyan.)

Table 3

The minimum sea level pressure in the eye of Typhoon Haiyan, for different gradient scenarios.

<i>Minimum sea level pressure in the eye</i>								
<i>Low scenario 866.5hPa</i>			<i>Probable scenario 861hPa</i>			<i>High scenario 855.5hPa</i>		
<i>Pressure (hPa)</i>	<i>Distance to centre (km)</i>	<i>Gradient (hPa/km⁻¹)</i>	<i>Pressure (hPa)</i>	<i>Distance to centre (km)</i>	<i>Gradient (hPa/km⁻¹)</i>	<i>Pressure (hPa)</i>	<i>Distance to centre (km)</i>	<i>Gradient (hPa/km⁻¹)</i>
871.5 ^a	17	Eye edge	866 ^a	17	Eye edge	860.5 ^a	17	Eye edge
910	28	3.5 ^b	910	28	4.0 ^b	910	28	4.5 ^b
927	34	2.8	927	34	2.8	927	34	2.8

^aThe pressure has been estimated at the edge of the eye from different gradient values estimated in the eyewall, which measured 11km in width, 5hPa has been subtracted in the eye to get the minimum sea level pressure.
^bThe three gradient values used.
 (Source: PAGASA data recorded at Guiuan station.)

Table 4

The deepest tropical cyclones estimated from aircraft reconnaissance or meteorological station data.

<i>Cyclone</i>	<i>Year</i>	<i>Pressure (hPa)</i>	<i>Basin</i>
<i>Haiyan</i>	2013	860	Western North Pacific
<i>Tip</i>	1979	870	Western North Pacific
<i>Patricia</i>	2015	872	Eastern North Pacific
<i>June</i>	1975	875	Western North Pacific
<i>Forrest</i>	1983	876	Western North Pacific
<i>Ida</i>	1958	877	Western North Pacific
<i>Nora</i>	1973	877	Western North Pacific
<i>Rita</i>	1978	878	Western North Pacific
<i>Vanessa</i>	1984	879	Western North Pacific
<i>Wilma</i>	2005	882	Western North Atlantic

(Source: aircraft reconnaissance data from JTWC and NHC, and PAGASA data.)