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Re-analysis of the Maximum Intensity of Super Typhoon Hato

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超強颱風天鴿最高強度的再分析

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摘要

二零一七年八月二十三日超強颱風天鴿(1713)吹襲香港期間，天文台需要發出最高級別的十號颶風信號。當天早上本港風力普遍達到烈風至暴風程度，南部地區及高地則持續受到颶風吹襲。天鴿吹襲香港期間，本港最少有 129 人受傷。適逢天文大潮及漲潮，天鴿所觸發的風暴潮導致本港及珠江口沿岸出現嚴重水浸及破壞。

天鴿橫過南海北部期間顯著增強，再分析顯示天鴿很可能在八月二十三日早上登陸前在香港以南水域短暫發展為超強颱風，中心附近最高的 10 分鐘持續風速估計為每小時 185 公里。本文利用所有可用的氣象資料如衛星、雷達及地面觀測來評定天鴿的最高強度。

Re-analysis of the Maximum Intensity of Super Typhoon Hato

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Abstract

Super Typhoon Hato (1713) necessitated the issuance of the highest tropical cyclone warning signal in Hong Kong, No. 10 Hurricane Signal, during its passage on 23 August 2017, with gale to storm force winds generally affecting Hong Kong and winds persistently reaching hurricane force over the southern part of the territory and on high ground that morning. At least 129 people were injured in Hong Kong and, coinciding with the high water of the astronomical tide, storm surges induced by Hato also resulted in serious flooding and damages in Hong Kong and over the coast of Pearl River Estuary.

Hato intensified rapidly as it traversed the northern part of the South China Sea and re-analysis suggested that Hato very likely attained super typhoon intensity for a short period over the sea areas south of Hong Kong on the morning of 23 August just before landfall, with an estimated maximum sustained 10-minute mean wind of 185 km/h near its centre. This study examines all available meteorological data such as satellite, radar and surface observations in determining the maximum intensity of Hato.

1. Introduction

Tropical Cyclone Hato (1713) necessitated the issuance of the highest tropical cyclone warning signal in Hong Kong, No. 10 Hurricane Signal, during its passage on 23 August 2017, and it was the first time since Severe Typhoon Vicente hitting Hong Kong in July 2012. Gale to storm force winds generally affected Hong Kong, and winds persistently reached hurricane force over the southern part of the territory and on high ground that morning.

At least 129 people were injured in Hong Kong during the passage of Hato, and there were over 5,300 reports of fallen trees and many incidents of falling objects. Coinciding with the high water of the astronomical tide, storm surges induced by Hato also resulted in serious flooding and damages in Hong Kong and over the coast of Pearl River Estuary. Figure 1 shows the maximum sea level (metres above Chart Datum, mCD) recorded at various tide stations in Hong Kong and flood reports from government departments, news and social media on 23 August 2017. In particular, the water level at Quarry Bay inside Victoria Harbour reached a maximum of 3.57 mCD, the second highest since instrument records began in 1954 and only lower than the record high of 3.96 mCD set by Super Typhoon Wanda in 1962.

The track of Hato is shown in Figure 2. Hato entered the northeastern part of the South China Sea on 22 August, intensifying into a typhoon and tracking west-northwest towards the coast of Guangdong. During the approach towards the Pearl River Estuary on the morning of 23 August, Hato showed sign of rapid intensification, with very intense convection and frequent lightning appeared near its eyewall and the cloud top reaching over 16 km to the top of the troposphere (Figure 3). This study aims to examine all available meteorological data on the morning of 23 August in determining the maximum intensity of Hato.

2. Re-analysis of Maximum Intensity

2.1 Satellite analysis

Dvorak technique analyzes the distribution and patterns of cloud top temperatures of a tropical cyclone. Incorporating with the statistical data summarized by Dvorak through a number of years, the intensity of a tropical cyclone can be deduced indirectly (Dvorak, 1975; Dvorak, 1984).

Satellite images of Himawari-8 Satellite on the morning of 23 August were examined in every 10 minute. Dvorak analysis using EIR technique showed that the Data T (DT) number of Hato rose rapidly, from 5.0 to 6.5, between 8:50 a.m. and 10:00 a.m. when an eye was forming, and dropped to 5.5 at 10:50 a.m. DT number of Hato reached momentarily of 6.5 around 10 a.m.

Assume FT and CI numbers are the same as the DT number obtained and ignore the constraint of the change of FT and CI numbers. CI number of 5.0 to 6.5 represent a 10-minute mean wind of 84 kt to 118 kt according to the conversion table used by the Hong Kong Observatory (Table 1). With highly varying DT numbers, extra care should be taken for the interpretation of the derived intensity (Burton, 2005). Nevertheless, the Dvorak technique depicted rapid intensification of the storm that morning. The maximum intensity of Hato was likely to reach super typhoon intensity for some time.

2.2 Radar Observation

Hato entered the surveillance range of Doppler radar operated by the Hong Kong Observatory on the morning of 23 August and the maximum intensity could be assessed by making reference to the maximum Doppler wind registered.

The maximum 0° PPI Doppler wind at Tai Mo Shan Weather Radar (TMSWR)

was 67.8 m/s, which was recorded at 10:54 a.m. (Figure 4). Using a conversion factor of 0.7 (Lee, 2010), the estimated 10 m wind would be around 92 kt, with a 95% confidence interval between 79 kt and 105 kt.

Moreover, radar observation also showed that degrade of the structure of Hato after making landfall in Zhuhai, with eye being filled shortly after noon time.

2.3 Surface Observations in Huangmao Zhou

The best way to assess the intensity of a tropical cyclone accurately is to collect and analyze wind speed information near the centre of the storm. Huangmao Zhou automatic weather station entered the eye of Hato on the morning of 23 August. In this section, we shall analyze the meteorological data observed in Huangmao Zhou.

2.3.1 Site Setting

Huangmao Zhou is an island at around 50 km south of Hong Kong (Figure 5). The meteorological measurement sensors were installed at a small house on the top of the island (Figure 6). There were two cup anemometers with wind vanes mounted on top of the house, and two pressure sensors each installed inside a metal enclosure in the house (Figure 7).

The Met-One wind system consisted of an anemometer and a wind vane, and the pressure sensor was an analog sensor for absolute pressure measurement (Figure 8). HMZ was the primary station and HM2 was the backup, still, they had the same models of wind and pressure sensors. HMZ and HM2 wind sensors were at the height of 67 m and 65 m above mean sea level respectively. And the wind mast of HMZ and HM2 were about 3.6 and 1.7 m respectively. The specification of wind speed and pressure measurement is shown in Table 2.

2.3.2 Data on 23 August

The pressure dropped and wind speeds picked up steadily as Hato approached in the early morning. There were missing data in HMZ wind and pressure between around 9:00 a.m. to 10:00 a.m., possibly due to data linkage problem. During that time, HM2 recorded a peak of mean wind stronger than 55 m/s, associating with the first encounter of the Hato's eye wall. Within the eye of Hato, the pressure fell to a minimum of 954.5 hPa at 9:52 a.m. and the winds moderated. After 10:30 a.m., pressure rose again and another peak of mean wind speed was recorded for the departure of eye. HMZ recorded the maximum mean wind of 70.9 m/s at 11:09 a.m., and HMZ was encountering the eastern part of the eyewall at that moment. However, HM2's maximum mean wind was about 10 m/s lower, with some bumpy values afterwards and maintaining a systematic bias with the wind speed of HMZ (Figure 9). HM2 was suspected to encounter a sensor problem.

2.3.3 HMZ Site aftermaths, including checking of instrument

A site inspection was made on Huangmao Zhou on 19 October 2017. Pressure sensors had operated normally but parts of the wind sensors were damaged after the passage of Hato (Figure 10). The wind vanes of both HMZ and HM2 were missing, and there was only one out of three cups left at HM2 anemometer. The anemometer at HMZ was observed to retain normal aftermath.

The HMZ wind system was brought back to the Hong Kong Observatory for instrument testing. It was confirmed that the field unit and the mechanical parts of the anemometer operated normally, reassuring the reliability of the wind data measured by HMZ during the passage of Hato.

2.3.4 Wind Reduction Factor

As the anemometer of HMZ is located at a height of 67 m above the sea level, it is necessary to convert the station wind speed to standard 10 m level to estimate the maximum intensity of Hato. The log wind profile recommended World Meteorological Organization (WMO, 2012) is widely adopted in meteorological community to correct winds taken at an elevated level to the equivalent 10-m winds.

$$\frac{u(z_1)}{u(z_2)} = \frac{u(z_1/z_0)}{u(z_2/z_0)}$$

where z_1 and z_2 are two heights at the same location, and z_0 is the surface roughness length parameters. WMO (2012) suggests different surface roughness length could be used in the log wind profile (Table 3).

For the site setting Huangmao Zhou (Figures 5 and 6), clearly the anemometer is not located at an open sea, nor crops bushes and parkland. Hence, a roughness length between 0.005 and 0.03 is considered to be suitable. The corresponding corrected 10-m mean winds is estimated between 104 kt and 110 kt.

2.3.4 Surface Observation in Macao and Zhuhai

There were a number of weather stations in the Pearl River Delta Estuary. The maximum sustained winds recorded in Macao and Zhuhai (corrected to 10 minute mean) were less than 90 kt and the minimum sea level pressure were generally above 960 hPa, and they do not support super typhoon intensity of Hato after landfall.

3. Discussion and Conclusion

Here we summarized the analysis in the previous section: (i) Dvorak analysis showed rapid intensification of Hato on the morning of 23 August, (ii) Doppler wind analysis estimated that the maximum intensity of Hato should be between 79 and 105 kt, (iii) the maximum 10-minute mean wind (corrected to 10 m) in Huangmao Zhou ranged between 104 and 110 kt, depending on different roughness length used in the correction, and (iv) winds and minimum sea level pressure reported in Macao and Zhuhai do not support super typhoon intensity after landfall.

Based on the information above, Hato attained super typhoon intensity for a short period over the sea areas south of Hong Kong on the morning of 23 August just before landfall, with an estimated maximum sustained 10-minute mean wind of 100 kt (i.e. 185 km/h) near its centre. Also, in view of the structure of radar and surface available observations in Macao and Zhuhai, Hato weakened into a severe typhoon after making landfall in Zhuhai. Figure 11 showed the time series of the maximum sustained wind speed near the centre of Hato.

Lastly we would also like to briefly discuss the results of a series of experiments on rapid scan using TMSWR conducted in the rain and typhoon seasons of 2017. A strategy of scanning at 0° PPI once every minute was adopted. Comparing to the normal volume scan of TMSWR with a repetition interval of six-minute, one-minute rapid scan provided more timely and frequent data which were expected to improve appreciation of storm evolution.

During the approach of Hato to the coast of Guangdong in the morning of 23 August 2017, TMSWR rapid scan showed better continuity in tracking of TC position. With higher update frequency and thus smoother animation, one-minute radar data revealed possibility of a new approach for estimating the

change rate of TC intensity based on spinning speeds of TC spiral rain bands between each radar imagery. The idea was to rotate the frame of reference in clockwise direction relative to TC centre at a suitable angular speed such that rain bands near the eye wall would appear stationary in the rotating frame. Together with the observed eye radius, tangential speed of the rain bands near the eye wall can be found. Applying this method in the event of Hato, one-minute radar data depicted increase of angular velocity of the rain bands from $3^{\circ}/\text{min}$ to $6.5^{\circ}/\text{min}$, and shrinking of Hato's eye from a radius of around 40 km to 25 km (Figure 12) in the period of 0500H to 0935H on 23 August 2017. This suggested a velocity change of rain bands near the eyewall from 126 km/h to 170 km/h, i.e. intensity change of +26% during the period. The result was reasonable comparing to the intensity change of 18% in HKO's best track over the same period.

The experiment would continue in 2018 to collect more TC data for verification of the new method in estimation of TC intensity change.

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WMO, 2012: Guide to meteorological instruments and methods of observation WMO-No. 8, 716 pp.

Table 1 Conversion table used by the Hong Kong Observatory

CI Number	10-min max wind (knots)
1.0	23
1.5	23
2.0	28
2.5	33
3.0	42
3.5	51
4.0	60
4.5	72
5.0	84
5.5	95
6.0	107
6.5	118
7.0	130
7.5	144
8.0	158

Figure 2 Specification of wind speed and pressure measurement in Huangmao Zhou

	Range	Accuracy
Wind speed (Met-One)	0 – 90 m/s (0 – 324 km/h)	± 0.5 m/s or $\pm 2\%$
Pressure (Setra)	800 – 1199 hPa	± 0.15 hPa

Table 3 Roughness length for different terrains as recommended by WMO (2012)

Terrain description	Roughness length z_0 (m)
Open sea, fetch at least 5 km	0.0002
Mud flats, snow; no vegetation, no obstacles	0.005
Open flat terrain; grass, few isolated obstacles	0.03
Crops, bushes, parkland	0.10 – 0.5
Regular large obstacle coverage (suburb, forest)	1.0
City centre with high- and low-rise buildings	≥ 2

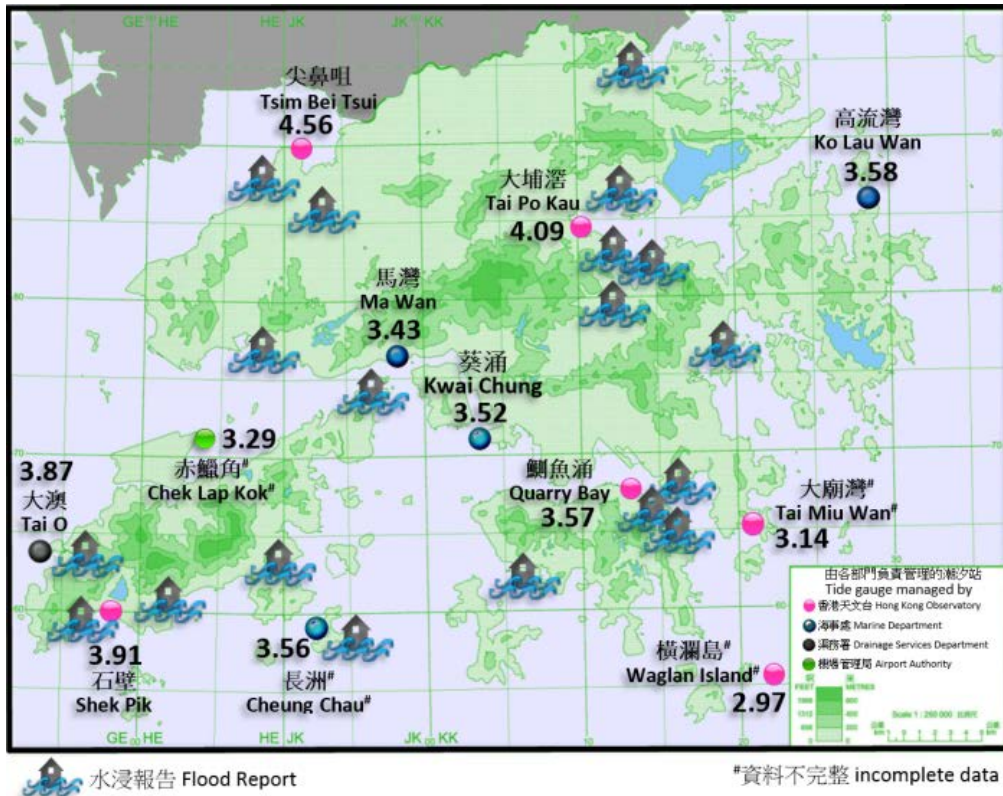


Figure 1 Maximum sea level (metres above Chart Datum) recorded at various tide stations in Hong Kong and flood reports from government departments, news and social media on 23 August 2017.

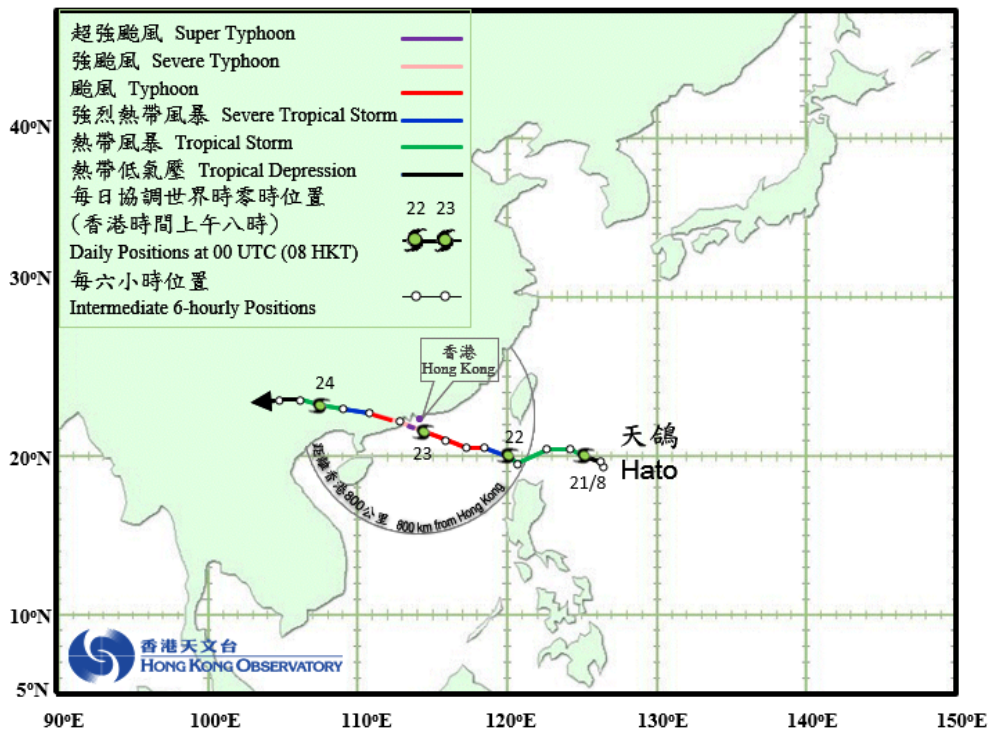


Figure 2 Track of Hato: 20 – 24 August 2017.

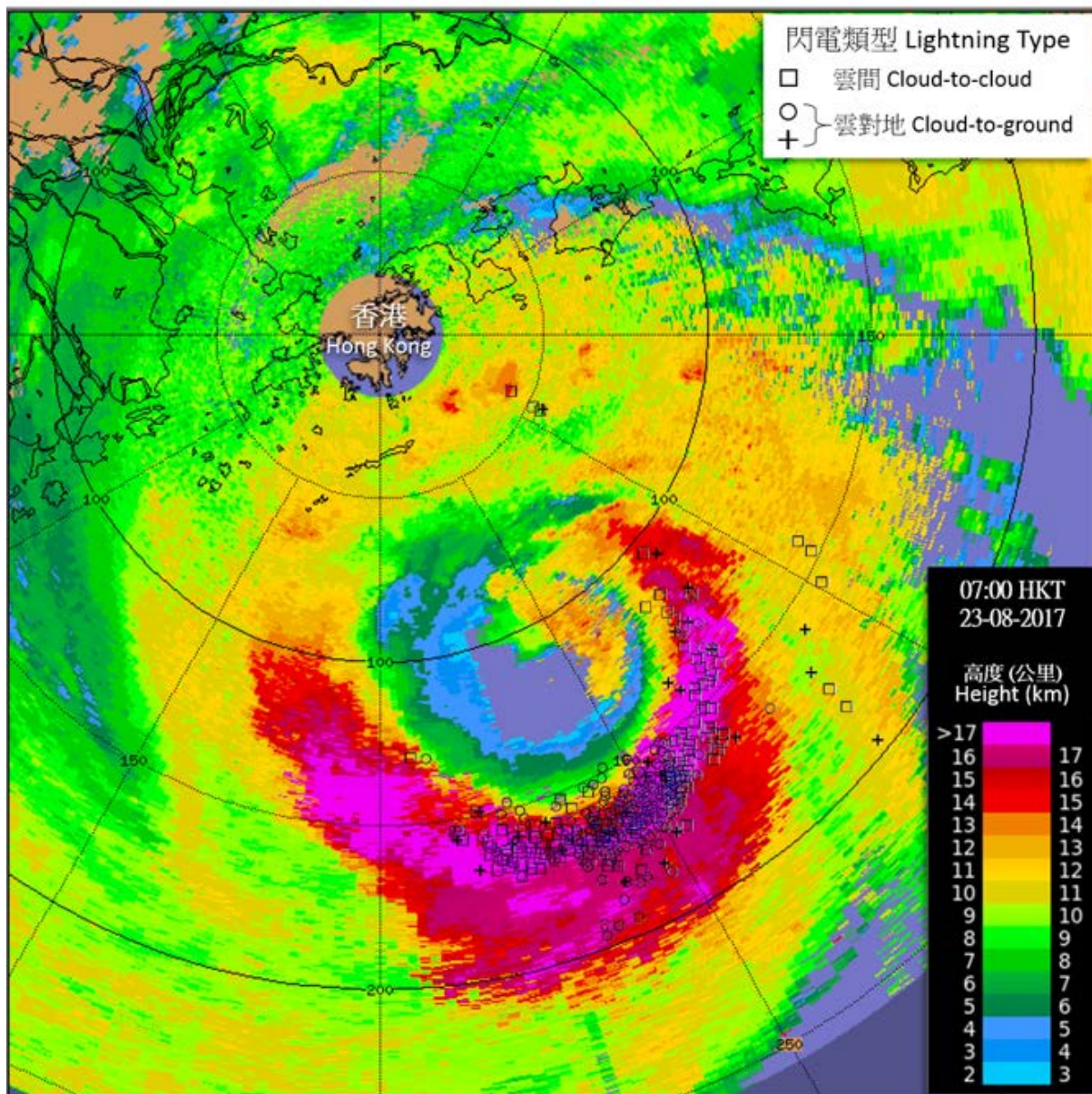


Figure 3 Image of cloud top height estimated using radar data at 7 a.m. on 23 August 2017, overlaid with lightning locations during the past 30 minutes. Very intense convection and frequent lightning appeared near the eyewall of Hato with the cloud top reaching over 16 km to the top of the troposphere.

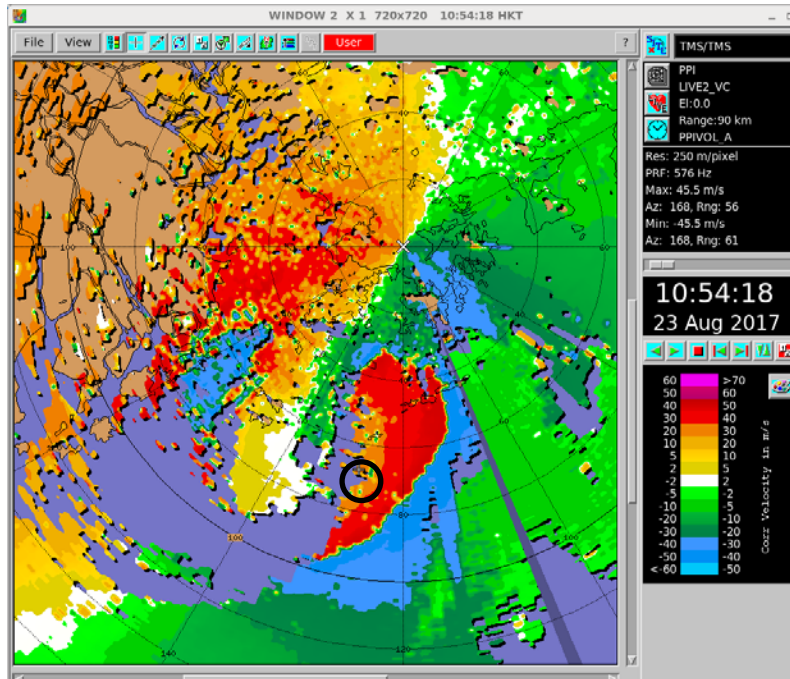


Figure 4 Radar imagery showing the Doppler velocity of Hato around 10:54 a.m. on 23 August 2017. With a Nyquist velocity of 45.9 m/s, there is velocity flowing in the figure. The highest Doppler Velocity of 67.8 m/s ($45.9 + 21.9$) was recorded (shown in black circle).

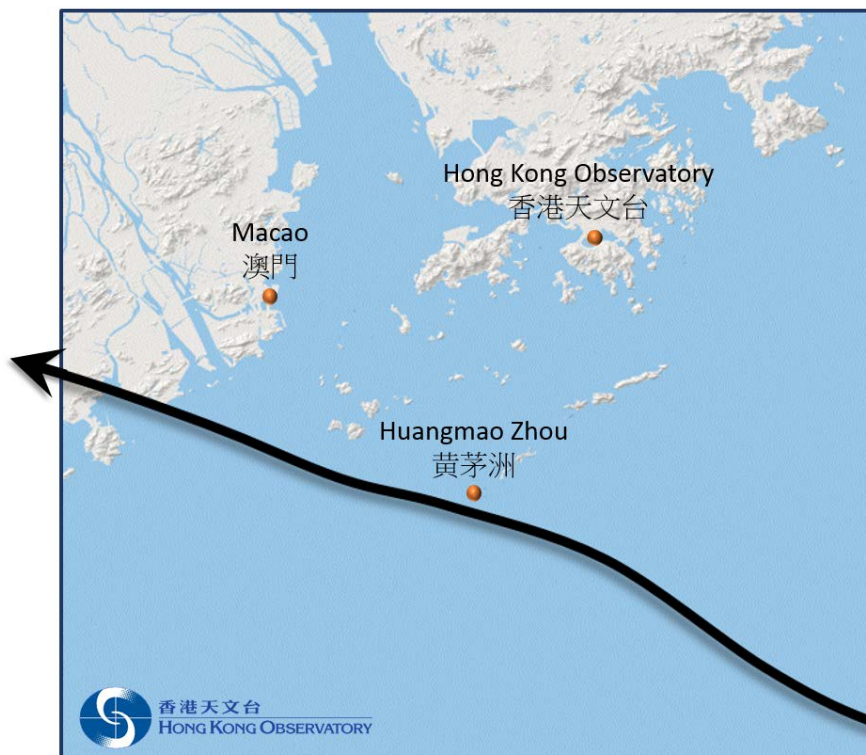


Figure 5 Location of Huangmao Zhou which is at around 50 km south of

Hong Kong. The track of Hato is shown in black line.



Figure 6 The small house on the top of Huangmao Zhou (indicated by the yellow circle).

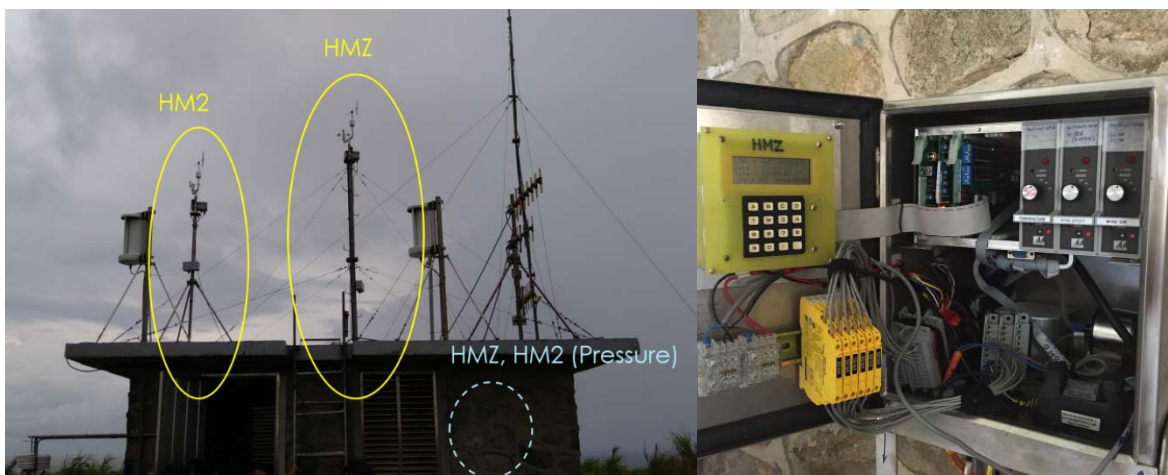


Figure 7 (Left) Wind sensors (HMZ and HM2) at the top of the house. (Right) Pressure sensor (HMZ) inside a metal enclosure in the house.



Figure 8 (Left) Met-One wind sensors system. (Right) Setra pressure sensor.

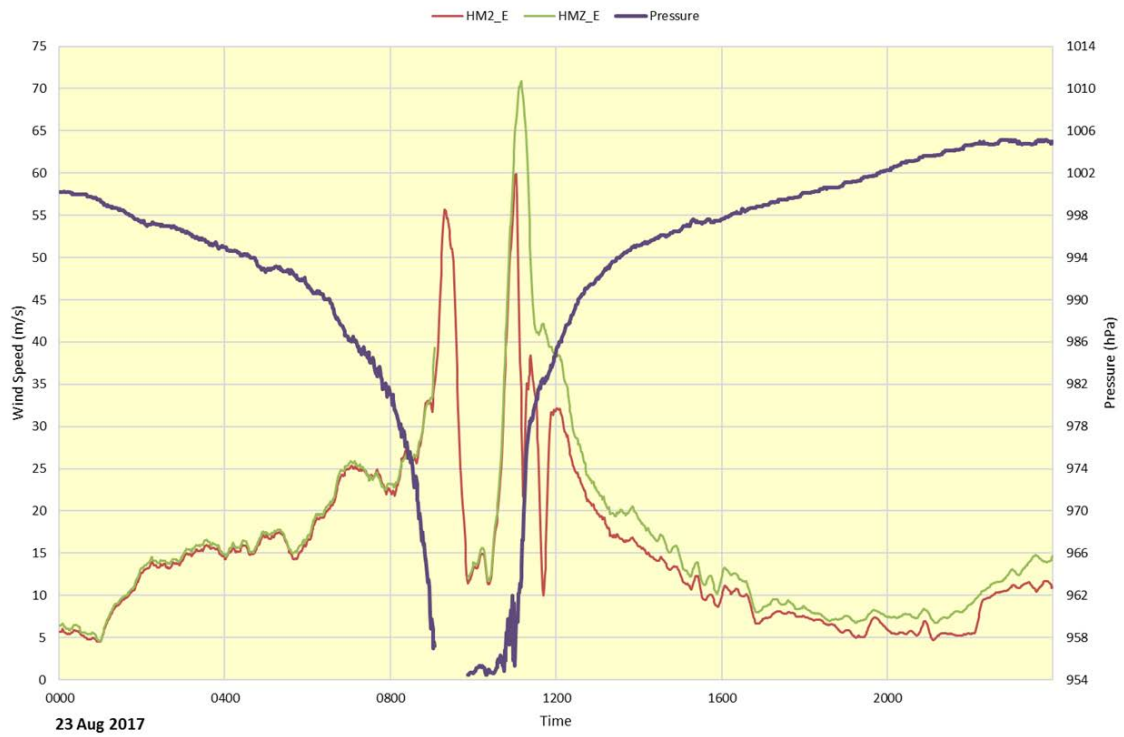


Figure 9 10-min mean wind speed at HMZ and HM2, and 1-min pressure at HMZ on 23 August 2017



Figure 10 Wind sensors at HM2 (left) and HMZ (right) during the site inspection on 19 October 2017.

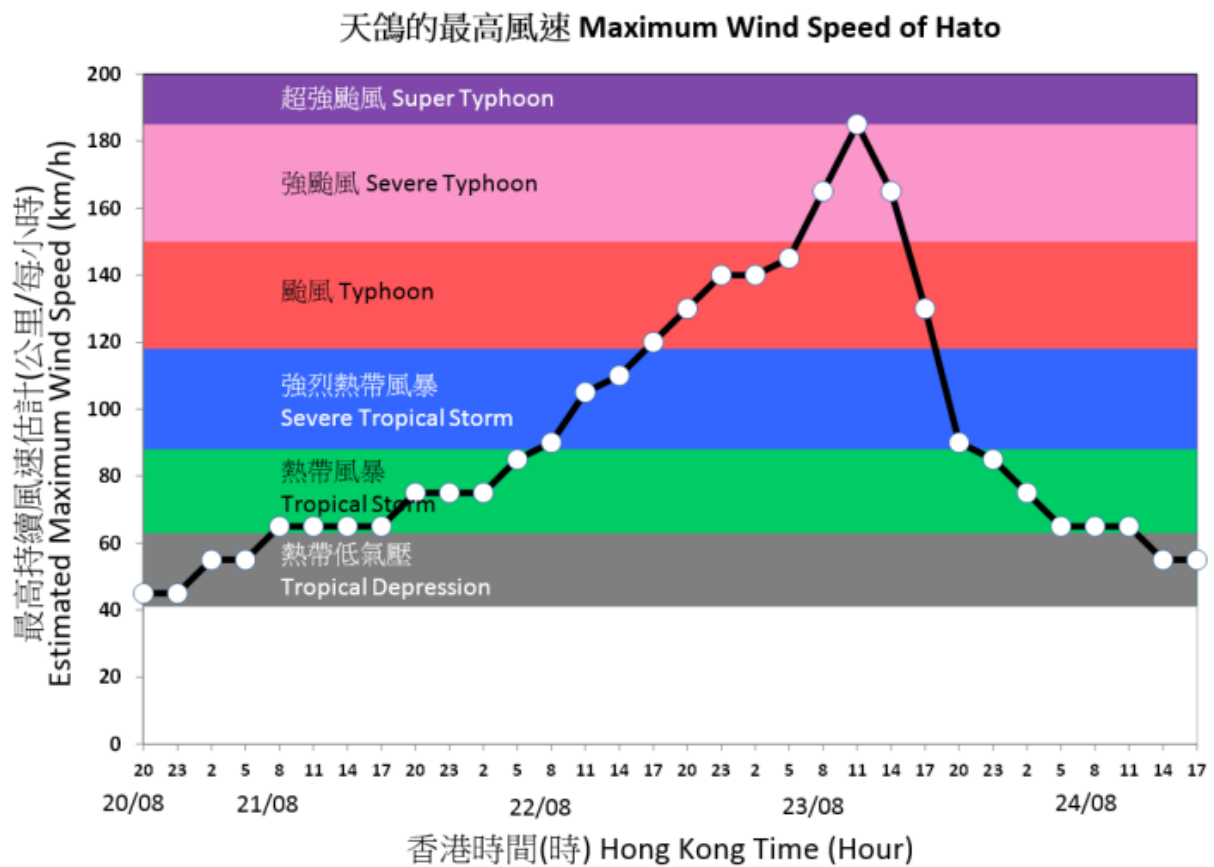
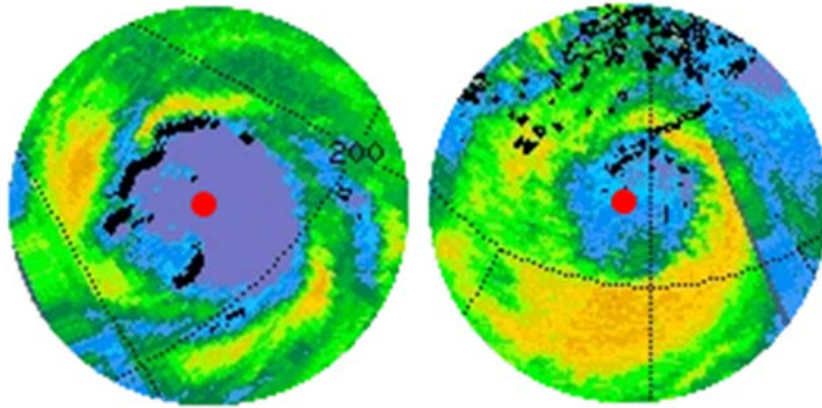


Figure 11 Time series of the maximum 10-minute sustained wind speed near the centre of Hato.



$$\begin{aligned}\omega &= \sim 3 \text{ deg/min} \\ &= \sim 3.14 \text{ rad/hr}\end{aligned}$$

$$R_{\text{eye}} = \sim 40 \text{ km}$$

$$V_{\text{eye}} = \sim 126 \text{ km/h}$$

$$\begin{aligned}\omega &= \sim 6.5 \text{ deg/min} \\ &= \sim 6.8 \text{ rad/hr}\end{aligned}$$

$$R_{\text{eye}} = \sim 25 \text{ km}$$

$$V_{\text{eye}} = \sim 170 \text{ km/h}$$

Figure 12 Eye of TC Hato at 5:00 a.m. (left) and 9:35 a.m. (right) on 23 August 2017. V_{eye} could be calculated by the product of R_{eye} and ω , with the conversion of units.