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"Convective Hot Tower" Analysis for Severe Typhoon Vicente (1208)

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Abstract

Severe typhoon Vicente (1208) was the first tropical cyclone that necessitated the issuance of No. 10 Hurricane Signal in Hong Kong since Typhoon York back in 1999. Hurricane force winds were recorded over the southwestern part of Hong Kong during the passage of Vicente. In the evening on 23 July 2012, “convective hot towers” appeared on the eyewall of Vicente and were captured on both radar imagery and lightning location map. The corresponding cloud top overshot 15 km up to the top of the troposphere, accompanied by cloud-to-ground lightning. Such observations signified that the associated updraft turned violent at the locations of convective hot towers. Shortly afterwards, Vicente intensified rapidly to a severe typhoon over the South China Sea to the south-southwest of Hong Kong around mid-night, reaching its peak intensity with an estimated maximum sustained wind of 155 km/h near its centre. This paper serves to document the above observational evidence on the signature of “convective hot towers” and as a reference for forecasters to monitor proximate typhoons for signs of rapid intensification in the future.

强台风韦森特（1208）的「对流热塔」分析

杨汉贤

香港天文台

摘要

强台风韦森特（1208）是自 1999 年台风约克袭港以来，第一个促使香港天文台发出十号飓风信号的热带气旋。韦森特吹袭期间，本港西南部风力达到飓风程度。2012 年 7 月 23 日入夜后，雷达及闪电位置图像显示韦森特风眼壁出现「对流热塔」现象，其云顶高度超过 15 公里，直达对流层顶部，并伴随有云对地闪电，显示该处上升运动转趋剧烈。韦森特其后在午夜时于香港西南偏南的南海上迅速增强为强台风，并达到其最高强度，中心附近最高持续风力达到每小时 155 公里。本文旨在记录上述显示「对流热塔」现象的观测实据以作为参考数据，方便日后预报员监测台风逼近时有否出现迅速增强的先兆。

（内文以英文编写）

1. Introduction

Severe Typhoon (ST) Vicente (1208) was the third tropical cyclone in 2012 that called for tropical cyclone (TC) warning signals in Hong Kong. It also necessitated the issuance of the first Hurricane Signal, No. 10 by the Hong Kong Observatory (HKO) since Typhoon York back in September 1999. Vicente grew into a tropical depression (TD) over the western North Pacific about 450 km northeast of Manila on 20 July. Drifting west-northwestwards, it made its way through the Luzon Strait that night and entered the northern part of the South China Sea in the morning on 21 July. Moving westwards, it intensified into a tropical storm (TS) that night. On 22 July, it became almost stationary over the South China Sea about 350 km south-southeast of Hong Kong. Vicente intensified into a severe tropical storm (STS) in the small hours of 23 July and embarked on a northwestward track during the morning, hinting that it would approach the coast of Guangdong thereafter. Fig. 1 shows HKO's best track for Vicente from 20 to 25 July 2012.

As shown in Fig. 2(a), Vicente's estimated maximum sustained winds kept increasing throughout the day on 23 July, reaching typhoon (T) intensity (the orange horizontal line refers) in the afternoon. During the evening, Vicente's intensification showed no sign of abatement while its distance from Hong Kong was decreasing. Around mid-night, Vicente intensified rapidly into a severe typhoon (ST) at a location about 130 km to the south-southwest of Hong Kong. Its peak intensity in terms of maximum sustained wind near its centre was estimated to be about 155 km/h. Locally, hurricane force winds were recorded over the southwestern part of Hong Kong during the closest approach of Vicente. As shown in Fig. 2(b), the 10-minute mean wind speed recorded at Cheung Chau exceeded hurricane force (demarcated by the horizontal red line) between 12:07 a.m. and 2:45 a.m. on 24 July, attaining its peak value of 140 km/h by 1:25 a.m. The Hurricane Signal, No.10, was issued for the period 12:45 – 3:45 a.m.

Before dawn on 24 July, Vicente accelerated towards the region west of the Pearl River Estuary and made landfall near the coastal areas of Taishan, about 130 km west-southwest of Hong Kong. Subsequently, it weakened below typhoon strength and took on a west-northwesterly track across western Guangdong that morning. Vicente continued to weaken while traversing Guangxi and became a tropical depression that night, dissipating eventually over the northern part of Vietnam on 25 July.

More details of Vicente can be found in the corresponding tropical cyclone report published by the Observatory [1]. In this short paper, focus is put on the rapid intensification of Vicente during the evening of 23 July. Observational evidence are collected and analyzed in detail for signatures of the so-called "convective hot tower" phenomenon. As proposed in the literature, it is considered a key precursor leading up to the rapid intensification of tropical cyclones. Sections 2 to 3 describe the observations captured in that evening by radar, satellite and lightning sensors respectively. The results are summarized and discussed with reference to other literature results in Section 5. Section 6 concludes this paper and outlines the significance of the results of the present study to operational TC forecasting.

2. Radar Reflectivity

As the name implies, "convective hot tower" (CHT) refers to some extremely tall structure of convections. In this paper, we refer CHT to those associated with the eyewall of a matured tropical cyclone. To detect such a phenomenon with the radar, one needs to aim up high in air near the tropopause. At such high levels, hydrometeors available are mostly crystallized and any reflectivity signal, if detectable, is expected to be relatively weak. For a single radar, observation availability and resolution at high altitudes are limited by the coarsening of radar beam elevation angles towards the zenith, a scanning strategy commonly found in operational radars. To maximize the chance of detecting the weak reflectivity signals from a CHT at high levels, the Guangdong-Hong Kong radar reflectivity mosaic made available under the SWAN (Severe Weather Automatic Nowcasting [2]) collaboration project was employed in this study. The SWAN mosaic comprises a maximum of ten radars from Guangdong and one from Hong Kong. The reflectivity data of the SWAN mosaic are routinely available every 6 minutes and provide improved coverage in the vicinity of Hong Kong, both in terms of geographical areas and vertical resolution. The latter is achieved through the use of multiple radar beams when calculating the reflectivity at any spatial location. More information on the SWAN mosaic is introduced in a separate paper also presented in this seminar [3].

Fig. 3 shows a sequence of 15.5-km CAPPI (constant altitude plan position indicator) images taken on 23 July 2012 from 13:30 to 15:30 UTC. On these images, the curved bands of gray pixels (representing signals of 0-20 dBZ) to the south or southwest of Hong Kong indicate the footprint of Vicente's eyewall. For easy appreciation of the rainband structure of Vicente, the corresponding 3-km CAPPI are also shown as insets. The cyan or grayish blue pixels (representing 20 dBZ or stronger reflectivity) embedded in the curved gray bands indicate the existence of a localized group of super-cooled water at that altitude. As aided by the red arrows in the plots, the locations of such super-cooled water can be traced with a cyclonic motion path over the eyewall. In terms of intensity, the maximum reflectivity was increasing during the first hour, attaining a maximum of about 28 dBZ and decaying afterwards. With the dissipation of the cyan pixels, a new group of super-cooled water appeared at 15:30 UTC near the Dangan Islands. Similar evolution trend can also be seen on the size/area of the group of super-cooled water. Such evolution in size and intensity suggested that this radar phenomenon did not happen by chance but a signature of some well-organized feature on the eyewall.

To better understand the spatial structure of such a radar signature, a vertical cross-section was made using the radar reflectivity mosaic valid at 10:30 p.m. on 23 July 2012. The vertical plane cuts along a line (the red dashed line labeled “AB” in Fig. 4 refers) through the area of strongest reflectivity at the 15.5 km level. As shown in Fig. 4(b), this group of reflectivity has an outstanding vertical extend (doubling the average height of echo top in other parts of the storm) and is narrow and upright in the form of a tall tower. Such features may be explained with a violent updraft that overshot the average cloud top and raised cloud water all the way to the tropopause. Together with other radar observations described in the previous paragraph, it is reasonable to ascribe the reflectivity tower to a CHT occurring on the eyewall of Vicente during the observation period. To complete with the identification of CHT, the cloud top properties of the postulated CHT are examined with satellite observations in the next section.

3. Satellite Channels

Fig. 5 shows a series of infrared (IR 1 channel) imageries from MTSAT during the period 13:32 – 15:32 UTC. To facilitate depiction by the naked eyes, a special colour lookup table was designed to highlight cloud pixels with very cold tops. As shown by the colour bar in Fig. 5(f), cloud tops with brightness temperatures below 204 degree Kelvin (K) are coloured from blue to brown to distinguish them from warmer clouds which are rendered in gray scales. For easy identification of the overshooting top of an emerging CHT, cloud pixels with brightness temperatures below 194, 193 and 192 K are highlighted in yellow, red and brown respectively. As shown in Fig. 5(a)-(c), a localized group of red/yellow pixels can be identified with locations closely matching with those seen in Fig. 3. During the latter stage, the overshooting cloud top spread out extensively (Fig. 5(d)-(e) refer). Interpreting together with the corresponding shrinking radar signatures depicted in Fig. 3(d)-(e), the extensive spreading of the overshooting could mean that the CHT is coming to the end of its lifecycle. Except for the initial stage (Fig. 5(a) refers), during which the coldest pixel of the emerging CHT is slightly above 194 K, brightness temperatures below 192 K can be identified throughout the evolution process.

Apart from its cold brightness temperature, an overshooting top also carries significant concentration of ice particles, which can be detected effectively using the polarization corrected brightness temperature (PCT) of microwave imageries in the 85-91 GHz channel [4]. Fig. 6 shows two SSMIS (Special Sensor Microwave Imager & Sounder) 91-GHz PCT images taken at 10:01 and 12:35 UTC on 23 July for Vicente. On both images, red colour refers to PCT at 192 K or below. From the 12:35-UTC image, a red spot can be identified on the southern flank of Vicente's eyewall. Comparing with the IR image shown in Fig. 5(a), the observed PCT feature at 12:35 UTC could be interpreted as a developing CHT which later caused the widespread outflow at 13:32 UTC on hitting the tropopause. Judging from the single PCT image at 10:01 UTC, the eyewall cloud was not so well organized and did not bear any red pixels. Unfortunately, there was not any PCT image available during the period when Vicente attained its peak intensity.

4. Lightning Detection

From forecasters' experience, it is rather uncommon to find lightning occurrence associated with tropical cyclones, especially in their inner-core or eyewall regions. Systematic study on tropical cyclone lightning is beyond the scope of this short article. It could be difficult to analyse historical cases due to the lack of lightning or other supporting observations in the past. As an alternative, we examined the Thunderstorm Warning records in Hong Kong for implication of lightning when tropical cyclones came close to Hong Kong. Since HKO's Thunderstorm Warning database began in 1967, there are a total of 65 TCs necessitating the hosting of the Gale or Storm Wind Signal, No.8 or higher. Among the 65 cases, 14 typhoons (including severe and super typhoons) necessitated the issuance of Signal No.9 or No.10. These typhoons all came within 120 km range of the Observatory. It is therefore reasonable to assume eyewall/inner-core lightning if Thunderstorm Warning was issued in Hong Kong. Yet, Vicente was the only case accompanied with a Thunderstorm Warning (16:15-21:15 UTC) amongst all the 14 typhoons.

As shown in Fig. 7, HKO's lightning detection network was able to pick up some cloud-to-ground (CG) lightning signals during the period 22:06 – 22:35 HKT (14:06 – 14:35 UTC) associated with Vicente. As indicated by the white square symbols, all the CG lightnings were located on the eyewall, shifting counter-clockwise as time progressed. Comparing with the corresponding images shown in Fig. 3 and Fig. 5, such eyewall lightnings align very well with the locations of the suspected hot tower depicted by radar and satellite.

5. Summary and Discussion

Summarizing the observations on the eyewall of Vicente as presented above in

Section 2 to 4, we have the following list of characteristics for the group of deep convections detected during the period 13:30 – 14:35 UTC:

(a) Strongest radar reflectivity $\geq$ 20-dBZ (maximum about 28 dBZ) at 15.5 km, horizontally localized, moving counter-clockwise, vertically stretched, upright and well exceeding the average echo top (20-dBZ) of the eyewall;

(b) Lowest brightness temperature of satellite IR-1 channel $<$ 192 K;

(c) C-G lightnings occurred at locations close to the group of deep convections captured in radar and satellite IR images; and

(d) Lifespan of about 2 hours.

Fig. 8 displays a schematic diagram illustrating the CHT conceptual model proposed by Kelley *et al*. in 2004 based on a study using TRMM observations [5]. The quantitative criteria for CHT signatures are also annotated on Fig. 8. Comparing with the above characteristics of Vicente's deep convections, both the radar and satellite IR criteria are satisfied. Although microwave 85-91-GHz PCT imagery is lacking during the period 13:30 – 14:35 UTC, the earlier image obtained at 12:35 UTC did meet the criterion of PCT $\leq$ 200 K.

As microwave imageries taken by polar orbiting satellites are not regularly and frequently available over a fixed region on the globe, the use of such data as a criterion for detecting CHT may not be the most effective in an operational environment. Recently, Jiang performed a similar study [6] and reported that while the minimum IR brightness temperature and the maximum 20-dBZ radar reflectivity are best associated with the rate of TC intensity change, the minimum 85-GHz PCT shows some ambiguities. On the other hand, Solorzano *et al*. [7] reported most recently that brightness temperature of microwave radiometer decreases with increasing lightning rate for all frequency channels from 37 to 183 GHz. Other recent studies [8]-[9] also found lightning a good indicator for rapid intensification of hurricanes. Despite the fact that an association between lightning and TC intensification was not found in the study by Kelley *et al*. [2] using the TRMM Lightning Imaging Sensor, we adopt here lightning observation as an alternative signature for the identification of a CHT when taking into account other supportive results by other researchers.

In summary, the observed group of deep convections on Vicente's eyewall is analyzed as a CHT satisfying three criteria on radar, satellite and lightning data as described above. Although the detailed mechanism for the formation and effects of CHT are still under active research, previous numerical simulation studies [10]-[12] suggested that CHTs in a vorticity-rich environment, known as "vortical hot towers", could provide a physically plausible mechanism to tropical cyclogenesis. Most recently, Hon *et al*. [13] performed numerical simulation studies on Vicente and found CHT-like development around the time when Vicente reached its peak intensity. Considering the chronological order of the observed events, it is reasonable to attribute the observed CHT as a trigger to Vicente's subsequent rapid intensification around midnight on 23-24 July.

6. Concluding Remark

Radar reflectivity, satellite IR, microwave 91-GHz channels and lightning data were analyzed and CHT signatures identified on Vicente's eyewall during the evening of 23 July. As suggested by the present case of Vicente and results found from the literature, CHT is considered a precursor to the subsequent rapid intensification of a typhoon. Forecasters on the bench shall therefore keep close monitoring on approaching TCs for such signatures. When predicting TC intensity change under such circumstances, reference can be made to the results presented in this paper. Based on the observed characteristics of Vicente's CHT, new alerting products combining different remote-sensing data sources may be developed in the future to facilitate forecasters' weather watch. Along this line, effective radar observation at high altitudes will be indispensible. When the timeliness and availability of the SWAN radar mosaic become suitable for operational use, this Guangdong-Hong Kong collaborative effort will bring invaluable benefits to TC operations in the region.

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Reference

[1]. HKO, 2012: Severe Typhoon Vicente (1208) 20 – 25 July 2012. *Hong Kong Observatory Tropical Cyclone Report*. (Available online at the website of HKO: http://www.hko.gov.hk/informtc/vicente/vicente.htm.)

[2]. Feng, Y., 2012: SWAN: A Severe Weather Nowcasting System. *The 92nd American Meteorological Society Annual Meeting*, 22-26 January 2012, New Orleans, LA, United States.

[3]. Ng, C.W. and H.Y. Yeung, 2013: Development of Radar-Satellite Blended QPE

Technique and Application to Rainfall Nowcasting. *The 27th Guangdong-Hong Kong-Macao Seminar on Meteorological Science and Technology*, 9-10 January 2013, Shaoguan, Guangdong, China.

[4]. Cecil, D. J., E. J. Zipser, and S. W. Nesbitt, 2002: Reflectivity, ice scattering, and lightening characteristics of hurricane eyewalls and rainbands, part I: Quantitative description, *Mon. Weather Rev.*, Vol. **130**, 769– 784.

[5]. Kelley, O.A., J. Stout & J.B. Halverson, 2004: Tall precipitation cells in tropical cyclone eyewalls are associated with tropical cyclone intensification. *Geophysical Research Letters*, Vol. **31**, L24112.

[6]. Jiang, H., 2012: The Relationship between Tropical Cyclone Intensity Change and the Strength of Inner-Core Convection. *Monthly Weather Review*, Vol. **140**, Issue 4, pp. 1164-1176.

[7]. Solorzano, N.N., J.N. Thomas, J.A. Weinman, W. Keane, M. L. Hutchins and R. H. Holzworth: WWLLN lightning and satellite microwave radiometrics at 37 to 183 GHz: Implications for convection and thundercloud charging in the broad tropics. *J. Geophys. Res.*, *submitted* August 2012.

[8]. Fierro, A.O., X.-M. Shao, T. Hamlin, J.M. Reisner, J. Harlin, 2011: Evolution of Eyewall Convective Events as Indicated by Intracloud and Cloud-to-Ground Lightning Activity during the Rapid Intensification of Hurricanes Rita and Katrina. *Monthly Weather Review*, Vol. **139**, Issue 5, pp.1492-1504.

[9]. DeMaria, M., R.T. DeMaria, J.A. Knaff, D. Molenar, 2012: Tropical Cyclone Lightning and Rapid Intensity Change. *Monthly Weather Review*, Vol. **140**, Issue 6, pp.1828-1842.

[10]. Hendricks, E.A., M.T. Montgomery and C.A. Davis, 2004: The Role of "Vortical" Hot Towers in the Formation of Tropical Cyclone Diana (1984). *Journal of the Atmospheric Sciences*, Vol. **61**, Issue 11, pp.1209-1232.

[11]. Montgomery, M.T., M.E. Nicholls, T.A. Cram and A.B. Saunders, 2006: A Vortical Hot Tower Route to Tropical Cyclogenesis. *Journal of the Atmospheric Sciences*, Vol. **63**, Issue 1, pp.355-386.

[12]. Lu, X., K.K.W. Cheung, Y. Duan, 2012: Numerical Study on the Formation of Typhoon Ketsana (2003). Part I: Roles of the Mesoscale Convective Systems. *Monthly Weather Review*, Vol. **140**, Issue 1, pp.100–120.

[13]. Hon, K.K., M.K. Or and W.K. Wong, 2013: Numerical Simulation Studies on Severe Typhoon Vicente. *The 27th Guangdong- Hong Kong-Macao Seminar on Meteorological Science and Technology*, 9-10 January 2013, Shaoguan, Guangdong, China.

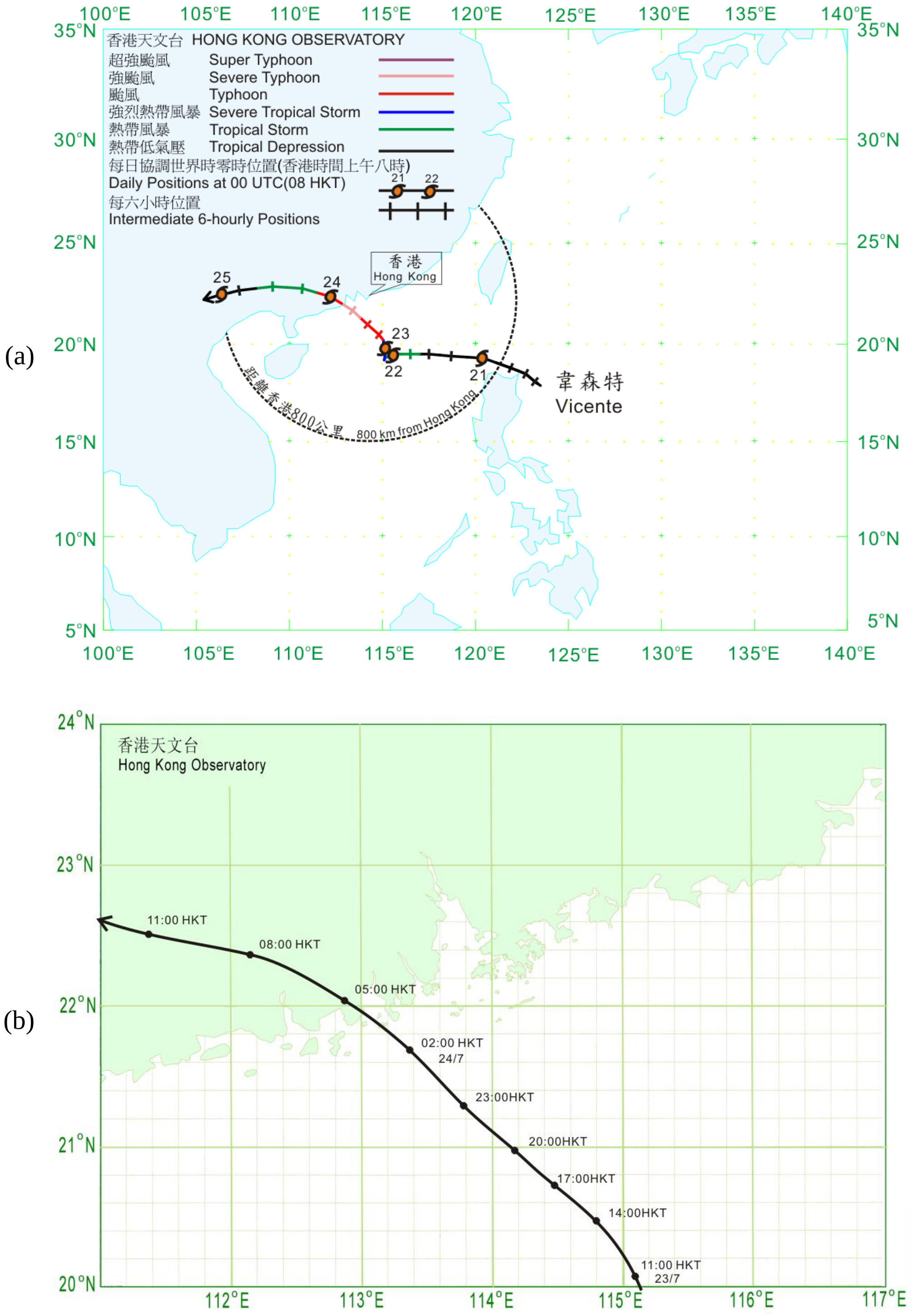

Fig. 1 Track of ST Vicente (1208) for: (a) 20 – 25 July 2012; (b) 11 am 23 July – 11 am 24 July 2012 durng its closest approach to Hong Kong.

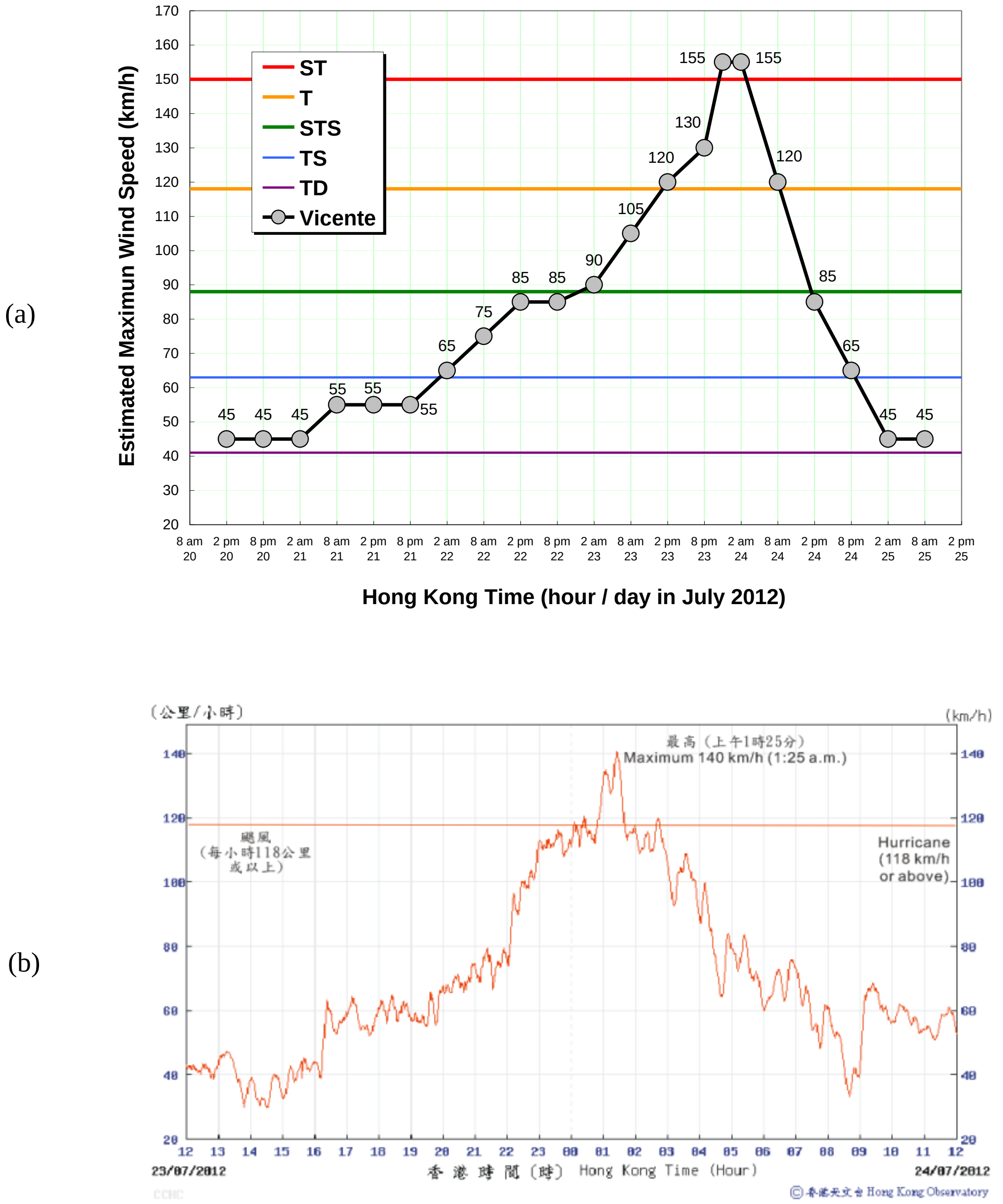

Fig. 2 (a) Time series of the estimated maximum sustained wind speed (10-minute mean) near the centre of ST Vicente (1208). The horizontal lines in red, orange, green, blue and violet colours represent intensity thresholds for classification as severe typhoon (ST), typhoon (T), severe tropical storm (STS), tropical storm (TS) and tropical depression (TD) respectively. (b) Time trace of 10-minute mean wind speed recorded at Cheung Chau on 23–24 July 2012. Hurricane force winds (indicated by the horizontal red line) were recorded at that station between 12:07 a.m. and 2:45 a.m. on 24 July.

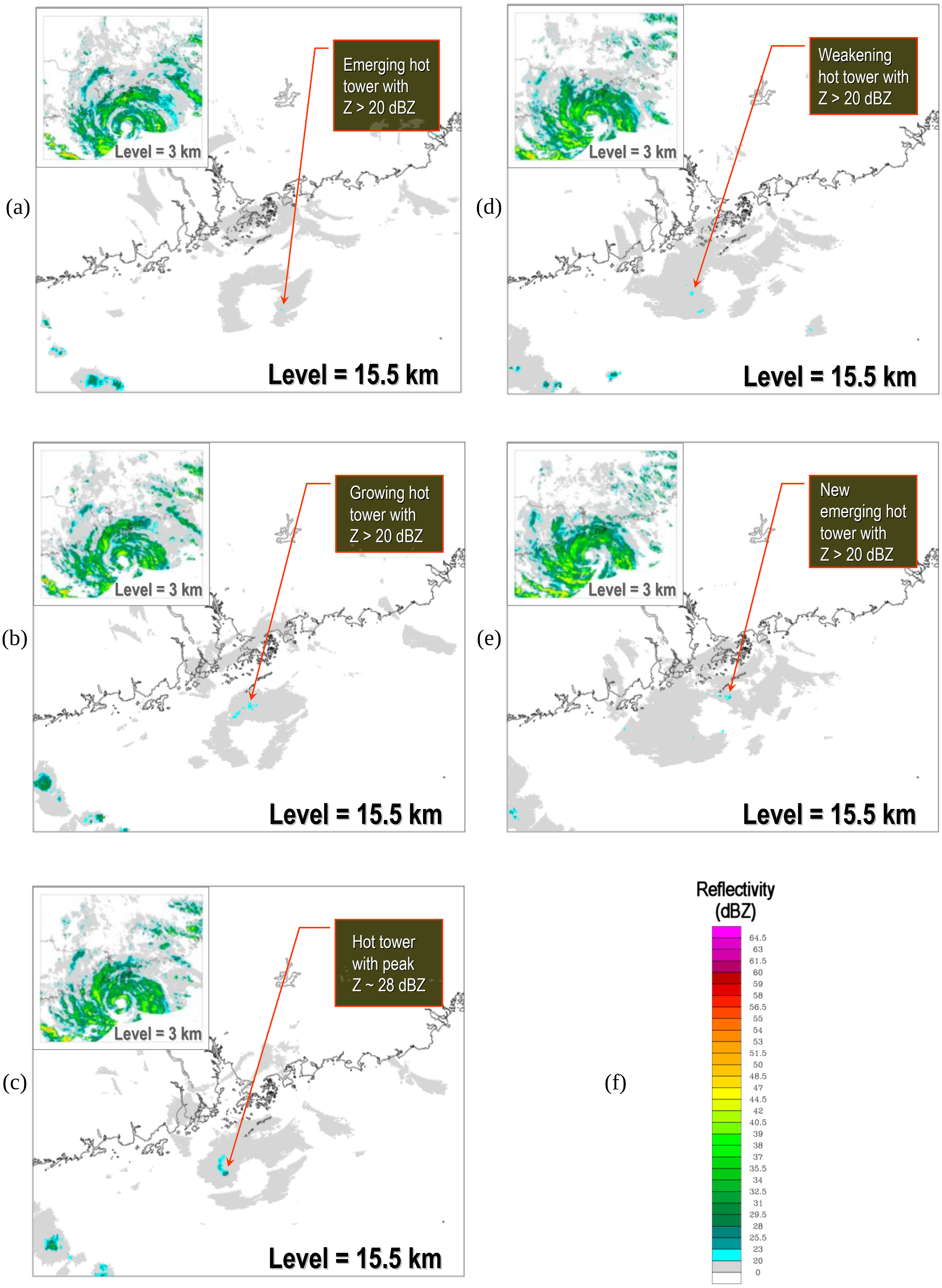

Fig. 3 CAPPI at the 15.5-km level taken on 23 July 2012 at: (a) 13:30 UTC; (b) 14:06 UTC; (c) 14:30 UTC; (d) 15:06 UTC; and (e) 15:30 UTC. The legend in (f) shows the colour scale of the reflectivity plots, in which grey represents signal less than 20 dBZ, cyan for 20-23 dBZ and other colours for stronger signals. Reflectivity pixels indicating the locations of hot tower are pinpointed by red arrows. Also shown as inset in each plot is the corresponding 3-km CAPPI image.

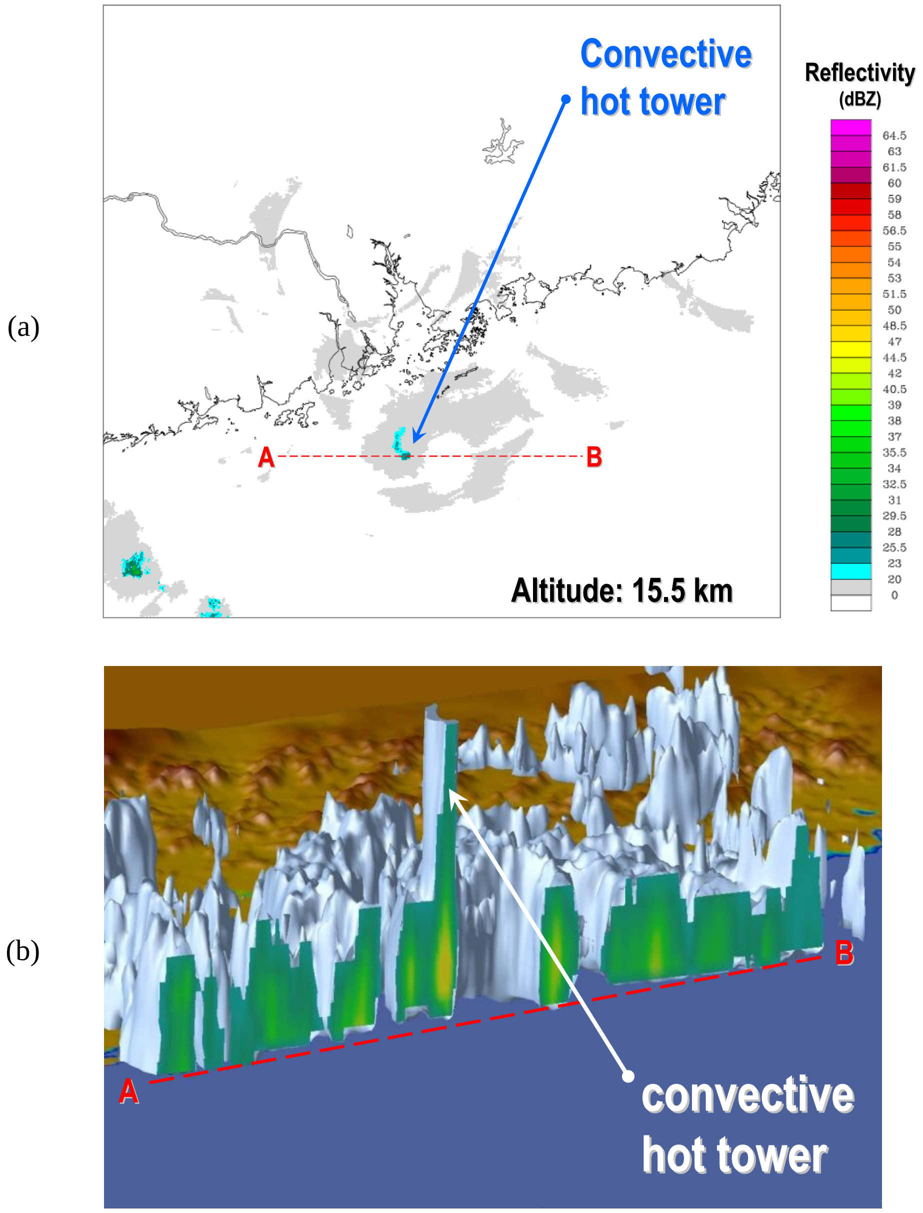

Fig. 4 Three dimensional structure of the convective hot tower observed on 23 July 2012 at 14:30 UTC: (a) CAPPI at 15.5 km and the dashed red line AB for making vertical cross-section; (b) vertical cross-section of radar reflectivity cut along the same dashed red line AB as in (a). The blue and white arrows pinpoint the location of the convective hot tower identifiable on the eyewall of Vicente (grey shadings south of Hong Kong in (a)). The arrow head in (b) indicates the altitude of 15.5 km.

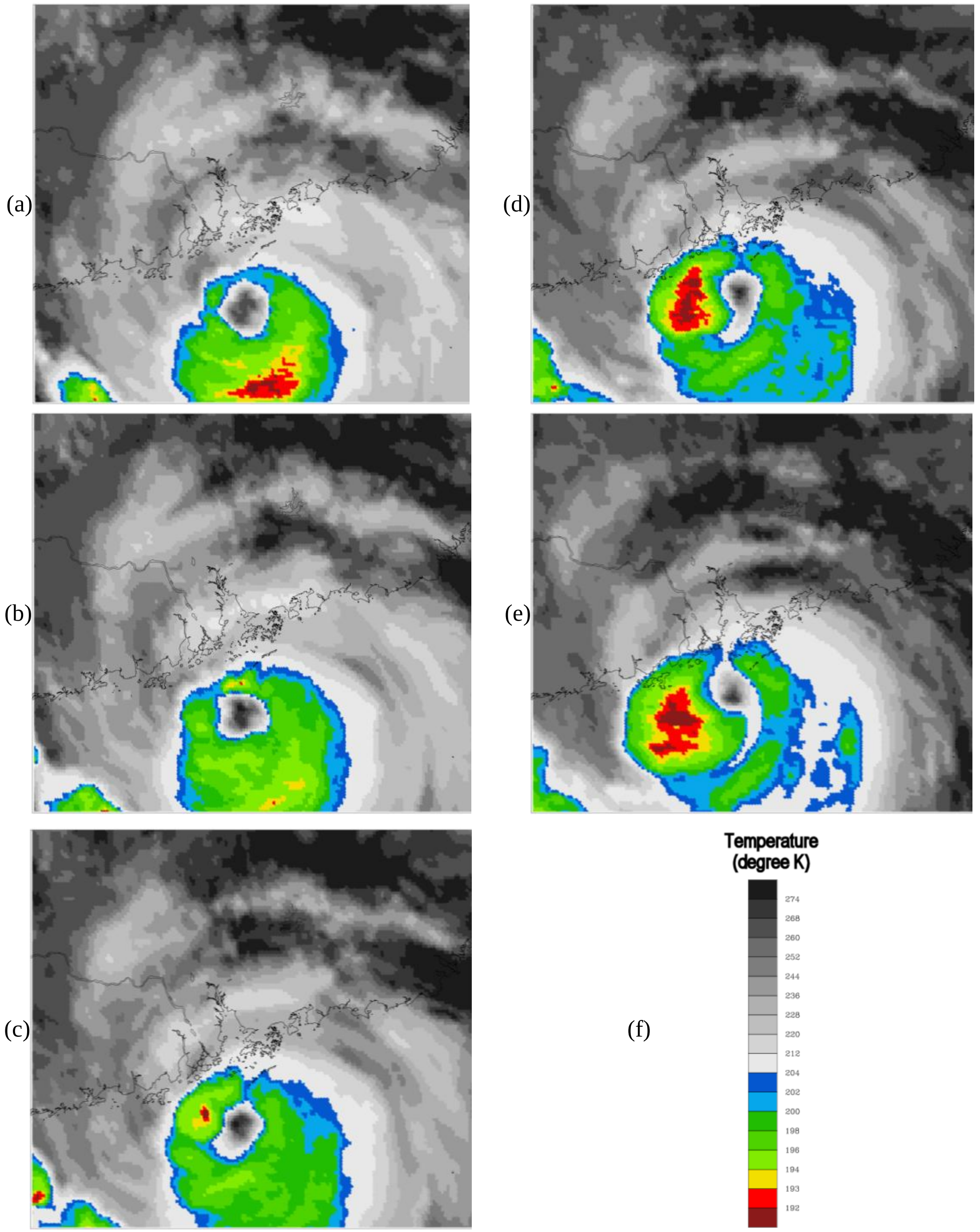

Fig. 5 MTSAT IR imageries taken on 23 July 2012 at: (a) 13:32 UTC; (b) 14:01 UTC; (c) 14:32 UTC; (d) 15:01 UTC; and (e) 15:32 UTC. The legend in (f) shows the colour scale of the IR plots in unit of degree Kelvin (K). Extremely cold cloud tops with brightness temperatures below 194, 193 and 192 K are highlighted in yellow, red and brown respectively.

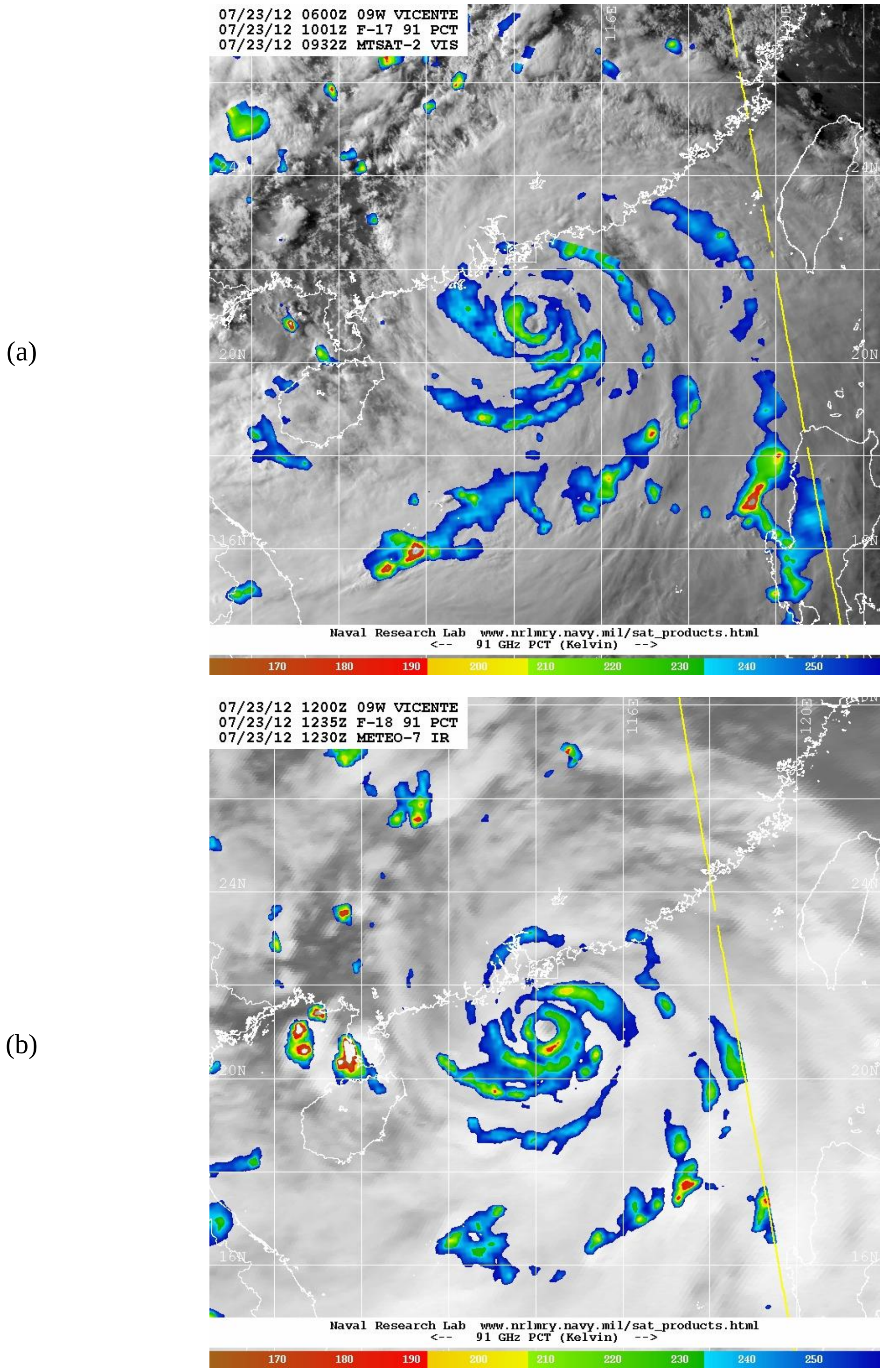

Fig. 6 Microwave 91-GHz PCT (Polarization Corrected Temperature) imageries of the Special Sensor Microwave Imager & Sounder (SSMIS) on 23 July 2012 at: (a) 10:01 UTC (overlaid on MTSAT-2 VIS); (b) 12:35 UTC (overlaid on METEO-7 IR). Red and deeper colours represent PCT at 192 degree Kelvin or below. (Image source: http://www.nrlmry.navy.mil/TC.html, Naval Research Laboratory, U.S.A.)

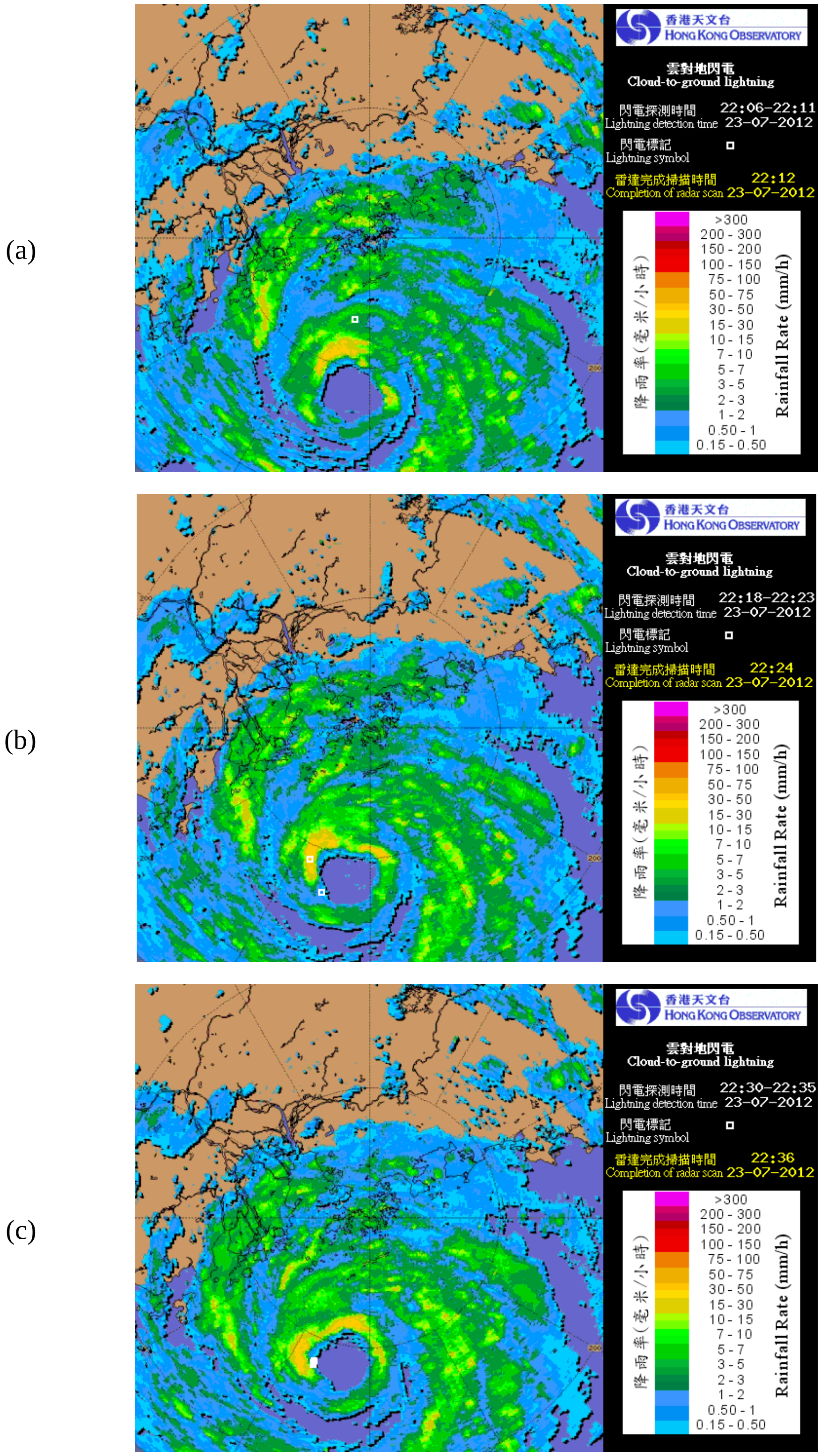

Fig. 7 Cloud-to-ground lightning observations (white squares) on 23 July 2012 at Hong Kong Time (HKT, 8 hours ahead of UTC): (a) 22:06–22:11 HKT; (b) 22:18–22:23 HKT; and (c) 22:30–22:35 HKT. These imageries span from 14:06 to 14:35 UTC, corresponding approximately to the time range in plots (b) and (c) in Fig. 3 and Fig. 5. Overlaid on the plots is the radar reflectivity expressed in rainfall rate unit.

CHT Signatures (based on TRMM) :

- **radar reflectivy: 20-dBZ ≥ 14.5 km**
- **satellite IR-1: Tb ≤ 192 K**
- **satellite microwave: 85-GHz PCT ≤ 200 K**
- **lightning: not always**

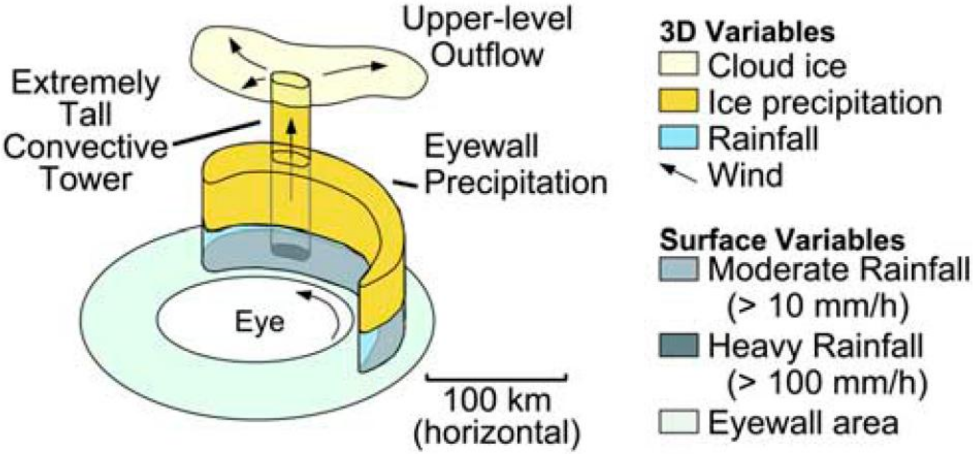

Fig. 8 Schematic diagram illustrating the concept of a convective hot tower (CHT) of a matured tropical cyclone. The annotated text in blue and orange summarized the criteria for CHT signatures following Kelley *et al.* 2004 [5].