



國立中央大學

大氣科學學系
碩士論文

使用地載與星載雷達分析颱風中雨滴的水
平分篩現象

Investigating the horizontal raindrop sorting
effect in tropical cyclone by ground-based
radar and space-borne radar

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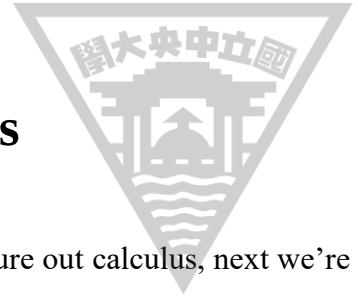
Chinese abstract

雨滴分篩現象(Hydrometeor size sorting)是一個受到雨滴終端落速不同產生的雲微物理現象。當強水平風存在時雨滴會受到水平應力而向下風處移動，大雨滴受到其質量大終端落速快的特性，會落在小雨滴水平風方向的相對上游處。這樣的現象在強風場如颱風、龍捲風下會更為顯著。本研究旨在使用雷達觀察颱風眼牆區域中的雨滴粒徑分類過程，分為使用地面雷達與衛星雷達。其中，差異反射率(Z_{DR})與質量權重粒徑(D_m)對於雨滴大小較敏感，而回波(Z_H/Z_e)則對雨滴數量更為敏感。本次研究利用四個地面雷達的個案，分別是凱米颱風(2024)、丹娜絲颱風(2025)、山陀兒颱風(2024)以及燦樹颱風(2021)。藉由分析颱風眼牆中回波與差異反射率之間的差異，結果顯示在逆時針旋轉的颱風眼牆中，高 Z_{DR} 偏向落在風場上游(順時針)處，而高 Z_H 則更偏向往下游(逆時針)延伸。除此之外，本研究利用數值方法量化水平雨滴分篩現象的程度。利用相關係數權重值代表 Z_H 與 Z_{DR} 之間的差異性。結果說明在絕大部分時間下，相關係數權重值都偏向正值，表示高 Z_{DR} 偏重在高 Z_H 上游處。但當 75 百分位 Z_{DR} 數值大於 0.7 時，權重值的大小會有更顯著的結果。將此方法套用至衛星雷達觀測結果時，發現權重值同樣為正值居多，但偏折數值相對減少許多，可能的因素為衛星雷達(GPM)解析度影響。未來也可繼續針對此方面問題作探討。



English abstract

Hydrometeor size sorting is a microphysical phenomenon driven by differences in raindrop terminal velocity. With strong horizontal wind, hydrometeors can be transported downstream as they fall. While big drops descent faster and tend to fall in the upstream area, small drops which fall slower, tend to propagate further downstream. Such a result can be more prominent in the presence of enhanced horizontal winds such as those in a Tropical Cyclone (TC) or tornado. This research aims to discover such a phenomenon within TC's eyewall region using both ground-based and space borne radar. With differential reflectivity (Z_{DR}) / mass weighted mean diameter (D_m) being more sensitive to bigger size of droplets and reflectivity (Z_H) being more sensitive to the concentration of drops, this research analyze the behavior of those polarimetric variables and discover the signature of size sorting within the eyewall region of TC. Four ground based cases were investigated in this study, including Gaemi (2024), Krathon (2024), Chanthu(2021) and Danas (2025). The result indicate that high Z_{DR} region is primarily located where it originated. At the same time, high reflectivity often seen in the downstream area, which rotates counterclockwise. Such a signature is more prominent at a lower altitude, where droplets have had sufficient time to be separated by the eyewall's tangential wind. Furthermore, an algorithm is developed to quantify the sorting effect using both Z_H and Z_{DR} . By comparing the signal distribution between Z_H and Z_{DR} . Results show that, most of the time, the TC yields a positive sorting signal, with higher shifting signal accompanied by more intense wind and larger Z_{DR} , especially for Z_{DR} larger than 0.7 dB. However, result from space borne radar showed different result as shifting magnitude being reduced due to data resolution. Which needs further investigation in the future.



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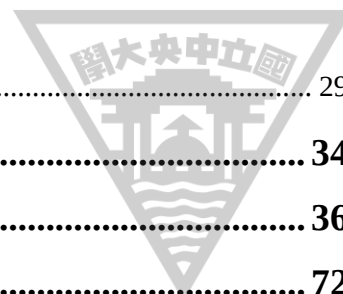
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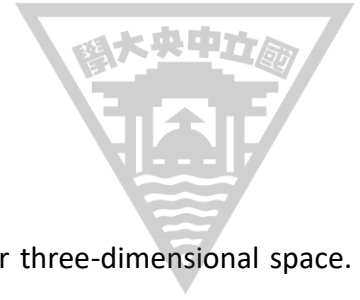
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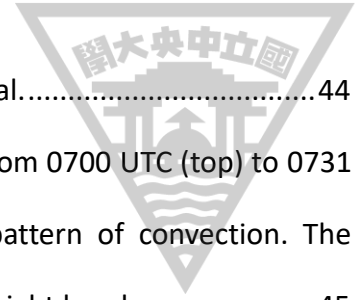
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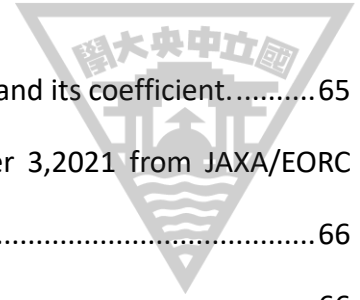
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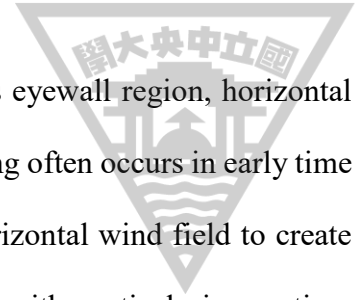


Chapter 1 Introduction

1-1 Research background

Tropical cyclone as one of the most destructive weather phenomenon constantly cause significant threats to human property and life. According to World Meteorological Organization (WMO), over the past 50 years, tropical cyclones had caused over 1.4 trillion U.S. dollar economic lost and over 770 thousand casualties. Therefore, it is crucial to study the behavior and property of tropical cyclone in order to mitigate its impact on human society. Taiwan being an isolated island located east side of China in west pacific, which is frequently threatened by tropical cyclone (Typhoon) every year (Hung et al., 2020; Jian et al., 2022). With approximately 3.7 tropical cyclone impact per year (Le et al. 2024). Especially due to Taiwan's extreme mountainous terrain. The terrain effect may further enhance the already extreme precipitation in Taiwan's mountain region (Agyakwah and Lin 2021; Yu and Chen, 2013).

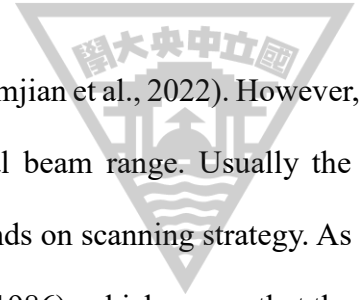
As tropical cyclone being a complex, cross scale structure. Its microphysical process has been a topic for discussion due to its close relationship to the intensity of TC (Fovell et al 2016). Many studies have shown that the microphysical scheme can cause significant differences in TC's intensity based on different parameterization (Mohan et al., 2019; Fovell et al., 2009). The microphysical itself can also cause alteration of tropical cyclone structure. For example, Ge (2018) stated that the existence of evaporation effect can cause the broaden of tropical cyclone as well as SEF (Secondary Eyewall Formation). The eyewall structure of tropical cyclone is also highly sensitive to the environment, especially the deep layer wind shear. Where strong convection often initiates in downshear direction of eyewall (Homeyer et al., 2020; Feng and Bell, 2019; Laurencin et al., 2020; Corbosiero et al., 2002; Frank and Ritchie, 2001; Dehart and Houze, 2014; Zhang and Kieu, 2005).



Among all the microphysical process happening within TC's eyewall region, horizontal size sorting is one of the less discussed one since vertical size sorting often occurs in early time of convective cell but horizontal size sorting requires stronger horizontal wind field to create the differences thus being introduced less frequently compared with vertical size sorting. Different from the vertical hydrometeor size sorting, where difference in terminal velocity within raindrops with different sizes over the convection. Causing larger raindrops to fall faster, reaching lower altitude first. Horizontal size sorting is produced with the presence of strong horizontal wind. As illustrated in figure 1.1, large raindrops with higher terminal velocity advected downstream less than smaller raindrop with lower terminal velocity. Such that small raindrops tend to move further downstream, creating a unique pattern in dual-pol variables (Kumjian and Ryzhkov, 2012; Dawson et al., 2015).

The eyewall region of tropical cyclones is characterized by the radius of maximum wind, where the strongest tangential winds are located, and is also associated with intense deep convection that spans the troposphere (Emanuel, 1991; Willoughby, 1990; Houze, 2010). Such characteristic creates a suitable environment for horizontal hydrometeor size sorting to take place. Previous study has utilized ground-based radar observation to find the size sorting effect and found that in downshear side is the location of convection initiation thus creating large portion of raindrop including both small and large raindrop (Homeyer et al., 2020). As convection propagates further downstream, the larger raindrop denoted by high Z_{DR} decreases drastically, but smaller raindrop denoted by high K_{DP} or Z_H will keep existing further downstream ahead of Z_{DR} (Homeyer et al., 2020; Feng and Bell, 2019; Laurencin et al., 2020). The differences between both variables showcase the horizontal size sorting phenomenon.

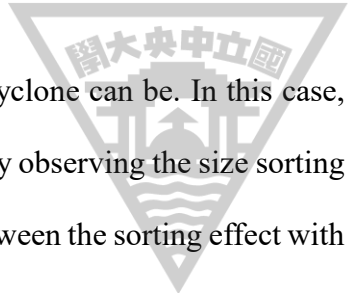
The dual-polarimetric radar observation opened up a brand new opportunity to understand the microphysical structure in three-dimensional perspective. The microphysical process can be analyzed based on the patterns of different dual-pol variables such as differential reflectivity



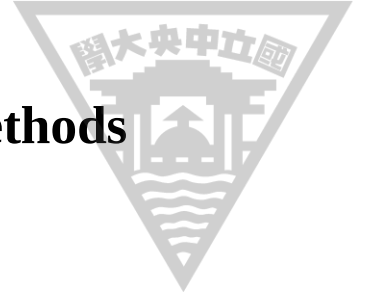
(Z_{DR}) or specific differential phase (K_{DP}) (Homeyer et al., 2021; Kumjian et al., 2022). However, one of the biggest limitation of ground-based radar is the signal beam range. Usually the scanning distance of radar beam is limited to around 460 km depends on scanning strategy. As tropical cyclone being a maritime weather system (Emanuel et al., 1986), which means that the complete observation of tropical cyclone is limited to its near landfalling period. Such limitation restricts the ability to understand the structure of tropical cyclone. In 2014, Global Precipitation Measurement (GPM) program is officially launched. Developed by NASA and Japan Aerospace Exploration Agency (JAXA), which is a successor of previous program TRMM, aims to observe the precipitation over mid-to-low latitude. The Core Observatory carries two advanced sensors, which are Dual-frequency Precipitation Radar (DPR) operating at both Ku and Ka bands and the GPM Microwave Imager (GMI). With its dual-frequency characteristic, GPM is capable of capturing the three-dimensional structure of precipitation as well as their estimation of precipitation microphysical properties such as DSD, mass-weighted mean diameter and normalized intercept parameter (Hou et al., 2014; Skofronick-Jackson et al., 2018). Such capabilities provide a unique opportunity to investigate the three-dimensional microphysical structure of tropical cyclones over the open ocean, where ground-based radar observations are unavailable or severely limited.

1-2 Motivation and purpose

Laurencin (2020) used an idealized simulation to investigate the size sorting effect under pure sedimentation and horizontal forcing. Result shows that the separation between maximum Z_{DR} and K_{DP} is related to sedimentation height and the pre-determined wind speed. Such result indicate that the hydrometeor size sorting effect is actually related to wind speed. Meaning that it is theoretically possible to estimate the wind speed in the eyewall region based on the amount of hydrometeor size sorting observed. As the estimation of the intensity of tropical cyclone has remained a challenge up to this day (Zhang et al., 2023), it is possible to



use such method to be another indicator of how strong a tropical cyclone can be. In this case, we would like to utilize the ground-based dual-polarization radar. By observing the size sorting effect within the eyewall region, we aim to create the connection between the sorting effect with the tropical cyclone intensity using dual-polarization variables (e.g. Z_H and Z_{DR}). Once the size sorting effect is observed, an algorithm can be used to quantify the intensity of sorting effect. Once the connection between eyewall intensity quantification of size sorting is build up. The quantification method can then be further applied onto GPM's satellite-borne radar and see if such method can really assist in intensity estimation.



Chapter 2 Data and methods

2-1 Ground based radar

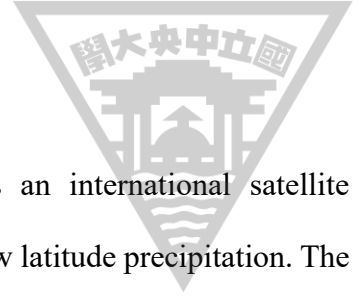
The radar in this research utilized three of Taiwan's ground based radar. Which are RCHL, RCCG and RCWF. Figure 2.1 showcased the terrain and radar location used in this study. All three radars are operational S-band dual-polarimetric radar. The scan strategy for all three radars are from NEXRAD radar system of VCP 215. Including elevation angle ranging from 0.5° to 19.5° , totally 15 scan per 6 minutes. The variables include horizontal reflectivity (Z_H), radial wind (V_R), spectral width (σ_V), differential reflectivity (Z_{DR}), differential phase (ϕ_{DP}) and copolar correlation coefficient (ρ_{HV}). This research will focus on the result from reflectivity and differential reflectivity. Whereas differential phase and copolar correlation coefficient will be used in quality control section. The reflectivity factor can be expressed as equation (2.1) shows:

$$Z = \int_0^{D_{max}} D^6 N(D) dD \quad (mm^6/m^3) \quad (2.1)$$

Where D represent the size of each droplets. Although the intensity of reflectivity is proportional to the six moment of the droplet size, the concentration of the droplet also has significant impact on the magnitude of reflectivity (Hazenberget al. 2011). Different from reflectivity, Z_{DR} , is denoted by equation (2.2) below:

$$Z_{DR} = 10 \log_{10} \left(\frac{Z_H}{Z_V} \right) \quad (dB) \quad (2.2)$$

Where Z_H and Z_V are denoted as horizontal and vertical reflectivity respectively. With larger raindrop particle being more oblate in shape, higher Z_{DR} can be referred as raindrop in the volume being larger. Which can be utilized as an indicator of overall drop size in the area. By combining the property of those variables, the microphysical process amongst the precipitation cloud can thus be revealed.



2-2 GPM satellite radar data

The Global Precipitation Measurement (GPM) mission is an international satellite program developed by both NASA and JAXA to provide mid-to-low latitude precipitation. The DPR onboard the GPM Core Observatory consists of a Ku-band precipitation radar (13.6 GHz) and a Ka-band precipitation radar (35.5 GHz). The dual-frequency observations provide an additional constraint on the drop size distribution (DSD). Which allows the retrieval of precipitation rate, liquid water content, mass-weighted mean diameter and other microphysical variables. This study utilized the Level-2 DPR product (2ADPR), which contains three operational scan modes including Full Scan (FS), Matched Scan (MS) and High-Sensitivity Scan (HS). The FS mode employs only Ku-band radar and provides the widest swath width of approximately 245 km wide. The MS mode represents the overlapping observation area of both Ku and Ka-band with a swath width of approximately 125 km. Whereas HS contains only high sensitivity Ka-band observation over the same 125 km swath. Considering that the FS mode substantially increases the probability of capturing the complete eyewall structure of tropical cyclones, only the FS product is adopted in this study. Which consists of 49 cross-track beams with 176 vertical range bins with horizontal and vertical resolution of approximately 5 km and 125 m, respectively.

Since DPR wavelength is significantly shorter than the standard operational S-band radar. The electromagnetic waves experience severe attenuation caused by absorption and scattering from hydrometeors while propagating, especially under heavy rainfall event such in the tropical cyclone. Therefore, attenuation correction is performed before the microphysical parameters is retrieved. Here the equivalent radar reflectivity factor is expressed as equation (2.3) showed below:

$$Z_e = \frac{\lambda^4}{\pi^5 |K|^2} \int \sigma_b(D) N(D) dD \quad (2.3)$$

Where $N(D)$ denotes the DSD, $\sigma_b(D)$ represents backscattering cross section of a raindrop with diameter of D , λ is the wavelength of radar and K is the dielectric factor of liquid water. Equation (2.3) indicates that the radar reflectivity is obtained by intergrating the backscatter energy contributed by all the drops within the sampling volume. The specific attenuation caused by precipitation is given by equation (2.4) below:

$$k = c_k \int \sigma_e(D)N(D)dD \quad (2.4)$$

Where $\sigma_e(D)$ is the extinction cross section, including both absorption and scattering effects. c_k is a proportionality constant. The attenuation is mainly governed by the total extinction of energy along the propagation path. However, to simply such retrieval problem, the DPR algorithm assumes that the specific attenuation and Z_e satisfy an empirical power-law relationship showed in equation (2.5):

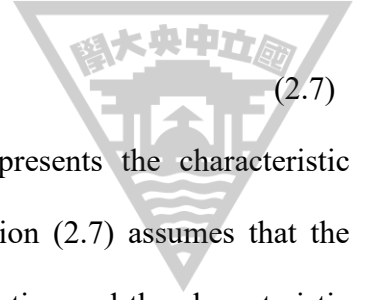
$$k(r) = \alpha(r)Z_e^\beta(r) \quad (2.5)$$

Where α is range-dependent coefficient associated with the DSD, β is assumed to remain constant along the radar profile. This allows the algorithm to process attenuation correction using only the measured radar reflectivity. Equation (2.5) is integrated along the radar beam, which yields the relationship between the measured reflectivity Z_m and the attenuation-corrected reflectivity Z_e showed below:

$$Z_e(r) = \frac{Z_m(r)}{\left[1 - 0.2\ln(10)\beta \int_0^r \alpha(s)Z_m^\beta(s)ds\right]^{\frac{1}{\beta}}} \quad (2.6)$$

Equation (2.6) is the fundamental equation of attenuation correction in single-frequency retrieval algorithm in DPR.

For single-frequency radar, the attenuation correction is an underdetermined problem since both the characteristic of drop size and the drop concentration are unknown. Since there's too many unknown variables, to reduce the complexity of the equation, the DPR algorithm assumes that the DSD can be expressed using normalized distribution as shown in equation (2.7) below:



$$N(D) = N^* n(D; D^*) \quad (2.7)$$

where N^* is the normalized intercept parameter, D^* represents the characteristic diameter and $n(D; D^*)$ is the normalized shape of DSD. Equation (2.7) assumes that the overall shape of DSD remains invariant, where only the concentration and the characteristic diameter vary. By substituting equation (2.7) into equation (2.3) and (2.4), equation (2.8) and (2.9) can be derived:

$$Z_e = N^* I_b(D^*), \quad I_b(D^*) = \frac{\lambda^4}{\pi^5 |K|^2} \int \sigma_b(D) n(D; D^*) dD \quad (2.8)$$

$$k = N^* I_e(D^*), \quad I_e(D^*) = \frac{0.01}{\ln(10)} \int \sigma_e(D) n(D; D^*) dD \quad (2.9)$$

By taking the ratio between equation (2.8) and (2.9), the unknown parameter N^* can be eliminated and equation (2.10) is received:

$$\frac{k}{Z_e} = \frac{I_e(D^*)}{I_b(D^*)} \quad (2.10)$$

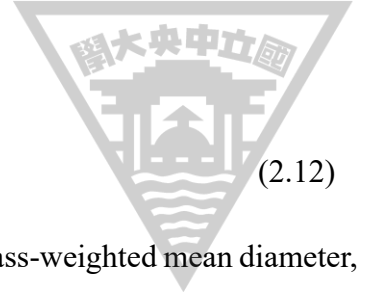
Such relationship further indicates that the attenuation-to-reflectivity ratio can depends only on the characteristic diameter D^* . Which can be retrieved using a pre-computed scattering lookup tables.

Although equation (2.10) reduces the retrieval to a single unknown variable, additional constraints are still required to stabilize the attenuation correction process. The DPR algorithm therefore employs the Surface Reference Technique (SRT). This technique estimates the path-integrated attenuation (PIA) by comparing the normalized surface backscatter beneath precipitation with reference observation acquired under rain-free conditions. The estimated PIA is expressed as equation (2.11) below:

$$PIA_{SRT} = -\frac{10}{\beta} \log_{10} \left[1 - 0.2 \ln(10) \beta_\epsilon \int_0^r \alpha(s) Z_m^\beta(s) ds \right] \quad (2.11)$$

The retrieved PIA provides an independent constraint on the attenuation correction, thereby reducing the uncertainty associated with the single-frequency retrieval.

After the attenuation correction, the DPR algorithm assumes that the DSD follows a



gamma distribution function as shown in equation (2.12):

$$N(D) = N_m D^\mu \exp \left[-\frac{(4 + \mu)D}{D_m} \right] \quad (2.12)$$

where N_m is the corresponding scale factor, D_m represents the mass-weighted mean diameter, μ is the shape factor which is assumed to be a known constant. Here the mass-weighted mean diameter is defined as equation (2.13):

$$D_m = \frac{\int D^4 N(D) dD}{\int D^3 N(D) dD} \quad (2.13)$$

which represents the diameter weighted by the liquid water mass of raindrops rather than by their number concentration. Since the mass of individual raindrop is proportional to three dimension of raindrop, the mass-weighted mean diameter emphasizes larger raindrops which contributed more to the total liquid water content. That way, D_m is more representative of precipitation microphysics than using plain arithmetic mean diameter. After attenuation correction, the DPR forward model computes the reflectivity based on assumed gamma DSD and iteratively adjusts the value of D_m and N_w until the simulated reflectivity matched the observed attenuation-corrected reflectivity. Then the retrieved D_m and N_w are then used to derive further information such as precipitation rate, liquid water content and other microphysical variables in the Level-2 DPR products.

All the aforementioned variables are filtered with `heightStormTop` and `binClutterFreeBottom`. Where all data above storm top or below clutter-free bottom are removed to ensure no contamination is included in low-altitude data since those data are usually unrecognizable and incorrect.



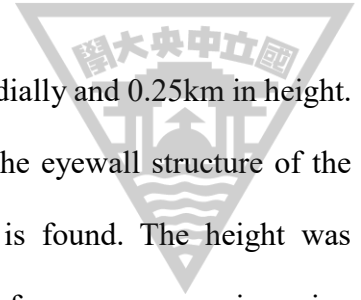
2-3 Data quality control and interpolation

2-2-1 Data quality control

To ensure the consistency of radar data, a series of data quality control process is completed. Which including removing non-meteorological signal with $\rho_{HV} < 0.75$, 5 gates standard deviation of $\phi_{DP} > 15^\circ$, as well as Z_{DR} bias correction, attenuation correction for reflectivity and Z_{DR} . The aforementioned frame work is based on Loh et al, (2022) which established the process based on Taiwan's climatology and radar of S-band radar. The quality control procedure can resolve the issue of system bias and wet-radome effect. Radial wind went through an extra step of unfolding process since radial wind folding is very common in strong rotating system such as tropical cyclone or tornado (He et al, 2019). A python module is utilized which is called Py-Art (Helmus et al, 2016), within contain various package that aids the needs or radar data modification, one of them being wind unfolding. The method selected is unwrapping based on noncontinuous path (Herraez et al, 2002) since this method produced the best result with minimum false unfolding.

2-2-2 Data interpolation

In order to access to the quantification method mentioned in later part, a set of data interpolation is done onto all of the data, including ground-based radar and GPM cases. Figure 2.2 showed the data before and after the interpolation. The data was first obtained in Plain Position Indicator (PPI) format. Which is stored based on each elevation angle, azimuthal angle and range. The data is first interpolated them into Constant Altitude Plain Position Indicator (CAPPI) coordinate. Which is calculated based on each height. The resolution used is 0.5 km in both X and Y direction and 0.25 km in height. After that the data is further interpolated into cylindrical coordinate. That is, the coordinate governed by azimuthal angle, radial range and



height. The resolution used in this study is 1° azimuthally, 1km radially and 0.25km in height. The data is only interpolated up to 50 km in radius to focus on the eyewall structure of the tropical cyclone where the most intense wind and convection is found. The height was interpolated from surface up to 10 km since this research wants to focus on warm rain region microphysical process especially for data below 5 km height where the hydrometeor tends to be in liquid phase. Noted that both reflectivity and differential reflectivity are both first linearized then interpolated. After that, the variables were transfer back into log scale. The interpolated result is shown as figure 2.2. The red arrow in figure 2.2 represent the deep layer wind shear direction and magnitude. The wind shear is obtained using ERA5 hourly reanalysis data. By calculating the difference between 850 hPa and 200 hPa wind speed and wind direction around TC. Only the data with the radius between 350 km and 800 km around TC center is taken into consideration to prevent the effect from TC itself and calculate the impact from the environment itself.

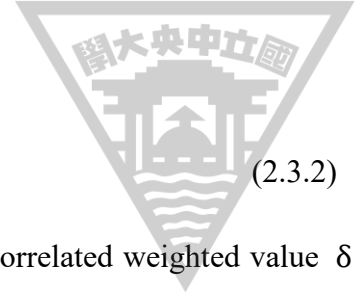
2-3 Shifting Quantification Method

The introduction part mentions that one of our main goal is develop an algorithm to quantify the shifting effect caused by horizontal hydrometeor size sorting in the eyewall region of TC. In this chapter, the method of quantifying the sorting effect in the eyewall will be introduced. While radar reflectivity depends on both raindrop concentration and size through the sixth-power weighting of drop diameter, differential reflectivity is much more directly related to the mean raindrop size and is relatively insensitive to variations in drop concentration (Seliga and Bringi, 1978; Illingworth and Blackman, 2002). In order to trace the variability between those two variables. Z_H is utilized to indicate the location of smaller size droplets and Z_{DR} for larger size droplets. Since smaller raindrops tends to be moved by horizontal wind further away from the location of convection initiation (Laurencin et al.2020). Whereas larger raindrops locate in upstream compared with smaller raindrops. Hence there will be a

discrepancy between observed Z_H location and Z_{DR} location. The reason that Z_H is being chosen instead of K_{DP} which is physically more precisely close to the liquid water content is due to data consistency. As Z_H is direct measurement from radar itself, K_{DP} is a differential result using differential phase (ϕ_{DP}). Such result consists of uncertainty as fluctuation in K_{DP} may cause inconsistency in result. In order to quantify such phenomenon. Correlation coefficient is calculated based on two selected variables (Z_H and Z_{DR}). The equation used to calculate the correlation coefficient ρ between Z_H and Z_{DR} is shown in equation (2.3.1):

$$\rho = \frac{\sum_{r,\theta} (Z_H(r, \theta) - \overline{Z_H})(Z_{DR}(r, \theta) - \overline{Z_{DR}})}{\sqrt{\sum_{r,\theta} (Z_H(r, \theta) - \overline{Z_H})^2 \sum_{r,\theta} (Z_{DR}(r, \theta) - \overline{Z_{DR}})^2}} \quad (2.3.1)$$

The r and θ here represent radial and azimuthal coordinate ranging from 0 to 50 km and 0 to 360°. Such process is done by comparing the data at each point together, with each height yields one ρ . By comparing the original data altogether, a one-dimension data of ρ can be calculated, since the goal is to emphasize the effect on how smaller drops, namely high Z_H can be shifted by wind compared with large drops, which is high Z_{DR} . The field is virtually "rotated" to investigate the outcome if Z_H got modify to upstream and downstream. To emphasize, only Z_H will rotate clockwise or counterclockwise, while keeping the Z_{DR} field fixed. Since the data is all calculated in cylindrical coordinate, the angular rotation of the field will be 1°. With the maximum rotation of -90° to 90°. The correlation coefficient is calculated every time the field rotate, which will create a two-dimension figure showcased in Figure 2.3. In figure 2.3 5 km were chosen as reference height. Which is top layer data utilized in this study, as previous study found that melting layer height is typically between 4-7 km height (Qiao et al.2022). With bottom layer being 1 km height since data coverage under low altitude is often poor leading to bad computation outcome. In the figure, if the value is closer to 1, the color will be in warmer color and vise versa. All value below 0 is removed since negative correlation is not the expected and such value will cause further impact to the result. The weighted line shown in figure 2.3 is



calculated using weighted function showed below:

$$\delta = \frac{\sum \rho_i * i}{\sum \rho_i} \quad (2.3.2)$$

Where i represents shifting angle ranging from -90° to 90° . The correlated weighted value δ is weighted by the correlation at each rotated angle. With larger shifting angle and higher correlation value having more weighting. If the value turns out positive, it means that the Z_H tend to have higher overall correlation when rotated clockwise. Meaning that the strong reflectivity signal will be located in further downstream comparing with the location of strong Z_{DR} . Such result will match the hypothesis of size sorting. Which is smaller droplets being further downstream, here is counter clockwise, comparing with larger droplets. The value further quantifies the magnitude of the separation between both variables, creating an unique opportunity for us to evaluate the magnitude of the size sorting effect based on dual-polarimetric radar variables. The process is also applied on GPM radar variables but using equivalent reflectivity (Z_e) and mass-weighted mean diameter (D_m).



Chapter 3 Ground based result

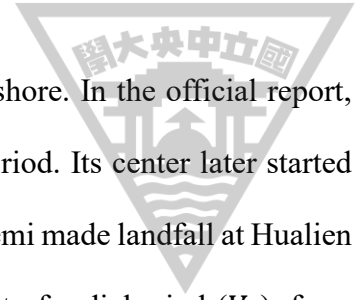
3-1 Ground-based case analysis

3-3-1 Case overview

In ground-based cases this study analyzed total of four cases. Which includes Gaemi (2024), Danas (2025), Chanthu (2021) and Krathon (2024). Figure 3.1 showcased the best track of each case based on CWA's analysis. Figure 3.2 are time series of estimated TC intensity including wind speed in knots and central pressure in mb. The selection of our cases are based on the data quality, especially for the data coverage at low altitude, for the purpose of fully analyze the evolution of TC structure over liquid phase. In addition, dual-polarimetric variables such as Z_{DR} is also necessary so it's possible to analyze the microphysical structure in the eyewall region. Due to the upgrade of dual-polarimetric radar for RCHL, RCCG took place in recent year, and the lack of landfalling TC in the recent year. Only those cases mentioned satisfied the selection. Table 1. showed the case and time of interest as well as radar utilized in each case. In this chapter, three of the ground based cases will be discuss, especially focusing on the size sorting process within.

3-1-2 Gaemi (2024)

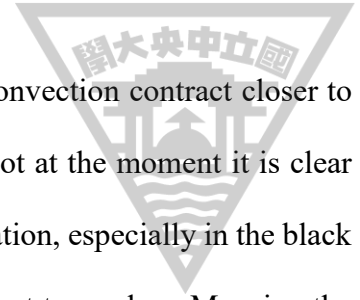
Before discussing the quantification of the size sorting effect, an investigation for size sorting within chosen cases is necessary. Gaemi (2024) is selected as the first cases since TCs with higher wind speed tend to have higher chance to observe clear size sorting effect (Homeyer et al. 2021; Laurencin et al. 2020). Figure 3.1(a) is the best track of Gaemi based on CWA analysis. Figure 3.3 is the surface analysis at 00 UTC 24 July, 2024. Based on those two figure,



Gaemi is approaching Taiwan from east coast, namely Hualien's shore. In the official report, Gaemi experienced an intensification process over the research period. Its center later started to slow down and made a counter clockwise looping. After that, Gaemi made landfall at Hualien coast, sped up and headed west-northly. Figure 3.4 is the box plot of radial wind (V_R) from RCHL with 90 – 99 percentile to represent the average maximum wind speed. Figure 3.4 shows that during 0500 UTC to 0800 UTC, the wind speed is very intense in the eyewall region, with median wind speed exceeding 60 m/s.

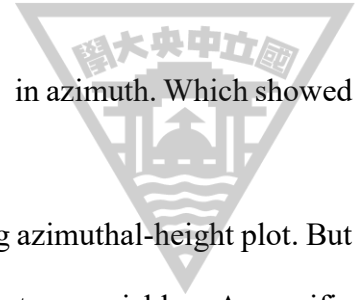
Figure 3.5 and Figure 3.6 are the hovemöller diagram for Z_H and Z_{DR} at 2 km and 5 km height respectively. The acronym (e.g. DL,DR,UL,UR) in the bottom represents the four quadrants relative to the deep layer shear direction. Which are Upshear Left (UL), Upshear Right (UR), Downshear Left (DL) and Downshear Right (DR). Figure 3.5 and 3.6 show that strong Z_H and Z_{DR} both tend to appear in downshear direction. This result is similar to previous study who stated that convection effected by environmental wind shear often occur in downstream direction (Frank and Elizabeth. 2001; DeHart et al. 2014). The intensity of both Z_H and Z_{DR} tends to increase in lower altitude as seen that signal received at 2 km height is generally stronger than ones at 5 km height. The eyewall circulation drives the convection toward counter clockwise direction, which is from right to left in Figure 3.5 and 3.6. Two main waves of strong convection were observed during the time of interests. Which are 0541 – 0618 UTC and 0636 – 0749 UTC. In figure 3.6, it is clear that Z_{DR} also performs similarly to Z_H . However, a difference is also noticed in around 0700 UTC. At the time, a strong Z_H signal extending toward upshear right part of the eyewall. Which in comparison, isn't evident in figure 3.6 (b). Therefore, the structure over the period when Z_H and Z_{DR} show discrepancy will be discuss in next part.

Figure 3.7 is a series of CAPPI plot for Z_H and Z_{DR} at 2 km height. The figure shows from 0700 UTC to 0730 UTC, the convection is intense in donwshear direction (red arrow),



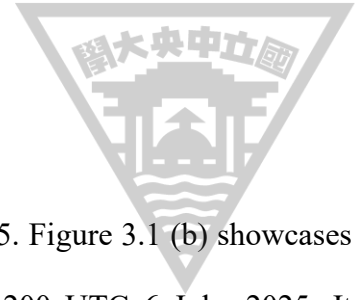
such signal extends counter clockwise to upshear region. As the convection contract closer to the center over the 30 minute period. By comparing the CAPPI plot at the moment it is clear that the location of strong Z_H and Z_{DR} appear to have some deviation, especially in the black circle outlined in Figure 3.7 (g) – (j). Here both variables' signal start to weaken. Meaning the strong convection's front end locate around this region. Previous study has shown that under intense TC, the convection tends to further prolong to upshear direction (Shimada et al. 2018). In Gaemi's case, the convection extends to upshear right. However, the locate of front end Z_H and Z_{DR} are different. With Z_H being slightly further downstream, Z_{DR} in comparison, is in relative upstream side.

Figure 3.8 is a series of azimuthal-height plot from 0700 to 0731 UTC, featuring both Z_H and Z_{DR} ranging from surface to 10 km height. The azimuthal angle represents direction relatively to the eye center. The Z_H in the figure shows an increasing tendency toward the surface. With similar feature appears in Z_{DR} indicating that the eyewall region contain collision-coalescence microphysical process (Kumjian et al. 2022; Wang et al. 2023). From Z_{DR} side as shown in black rectangle in figure 3.8 (b), (d), (h), at around 5 – 6 km there's a slight increment of Z_{DR} signal, which can be referred as the bright band signature (Loh et al., 2025). Where ice phase particle melt into water phase. Such phenomenon is more common in stratiform rain region, which is less prominent in convective-dominant eyewall structure. One of the important feature in the azimuthal-height plot is the black triangle highlighted in figure 3.8 (e), (f), (k), (j), where a strong convection was found. In Z_H part a tilting signal extend from surface to up to 10 km. The strong development of convection is often seen in tropical cyclone eyewall region (Romps and Kuang. 2009). Which shows that the strong convection burst into higher altitude and sediment downstream by eyewall's extreme horizontal wind. Similar feature is also visible for Z_{DR} part. But in comparison, the tilting structure is relatively weaker than Z_H . At 0712 and 0731 UTC, the front end of high Z_H and extend to nearly 330°



in azimuth, but for Z_{DR} , such front end can only went to at most 30° in azimuth. Which showed a large difference between both variables.

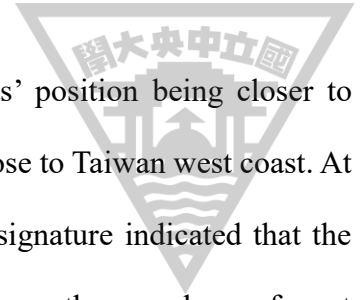
Last part discovers the difference between Z_H and Z_{DR} using azimuthal-height plot. But in order to further analyze the spatial variability between those two variables. A specific threshold is utilized to define the boundary of strong signal. Figure 3.9 is the contour plot of 75th percentile Z_H and Z_{DR} from 0700 UTC to 0731 UTC. The color of the plot represents the height of the data. With warmer the color, higher the altitude and vice versa. The range used in this figure are from 1 km to 5.25 km. As lowest few altitude layer (e.g. 0-1 km) contains too little data due to ground based radar beam travel characteristic, and thus not included. The contour line in figure 3.9 represents the 75th percentile data boundaries. The reason 75th percentile is used is based on a sensitivity test showing that higher threshold will keep too little signal and lower threshold will keep too many signal. Therefore, 75th percentile is selected to represent the location of strong signal in TC's eyewall. To emphasize the convection system in the eyewall region and prevent noisy, small convection data from contaminating the figure. A filter is applied by eliminating the scattered signal that passes the threshold but not connected to the main convective cell. Such process is completed on each height level. The outcome will be like in figure 3.9. From figure 3.9 it is clear to see the evolution of downstream side of front end in both Z_H and Z_{DR} . From Z_{DR} part it's clear that the vertical variability of Z_{DR} is very minimum. Almost all the time the strong Z_{DR} tend to have a very erect structure pointing straight up and down. In contrast, Z_H showed a very dynamic outcome. The front end of high Z_H signal appears to rotate downstream as the height decrease. Such phenomenon indicates that as the convection-induced droplets advected out of where they were generated in downshear side of eyewall, as they advected counter clockwise toward upshear side, meanwhile sediment toward the surface. The differences between Z_H and Z_{DR} signal provide a promising result to the existence of hydrometeor size sorting in the eyewall region of Gaemi.



3-1-3 Danas (2025)

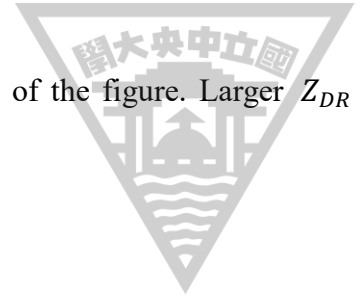
The second case investigated in this study is Danas from 2025. Figure 3.1 (b) showcases the track of Danas and Figure 3.10 is the surface analysis of 1200 UTC 6 July, 2025. It approached Taiwan from Bashi Channel, headed north-east direction and made a landfall in Chia Yi in July 6, 2025. Which is the first TC in record to make landfall in Chia Yi. The intensity slightly increased over the time of interest based on official report from CWA. At 1200 UTC, the estimated center pressure for Danas is 960 hPa, which is weaker than Gaemi (940 hPa). Its track through Taiwan Strait provide an optimal opportunity to observe the evolution of its eyewall structure through dual-polarimetric radar in Chi Gu. Figure 3.11 is hovmöller diagram of Z_H and Z_{DR} at 5 km and 2 km respectively. By comparing 5 km result with 2 km, it shows that both variables exhibit increasing toward surface. This signal indicates that the microphysical process is also likely to be collision-coalescence dominance. The donwshear direction for Danas' case tend to appear at around 120° relative to center. However, the location of convection appeared different in comparison of Gaemi's case. Despite the shear direction pointing toward 120° , the shear magnitude in Danas' case is significantly smaller compare with Gaemi. With 10 m/s of wind shear in Gaemi and only around 3 - 5 m/s of wind shear in Danas. While strong convection will induce asymmetric eyewall structure in downshear direction, weaker wind shear magnitude won't enhance such process as much. Therefore, there should be other factor governing the evolution of the convection.

Figure 3.12 is a series of CAPPI plot showcasing the evolution of structure in center region of Danas. In earlier time like 1000 UTC, in figure 3.12(a), (b). The convection mostly appeared in north side of the eyewall. As time proceeds, the main location of convection started to shift toward north-west gradually in later time at 1500 UTC (e.g. Figure 3.12 (k),(l)). Such result is different from the expected result as seen in Gaemi's case where convection is mainly located



in downshear direction. One potential reason is related to Danas' position being closer to landfall. In figure 3.12 (i), (k) showed that Danas' center is very close to Taiwan west coast. At the moment the convection mainly located over the ocean, such signature indicated that the convection generally initiate at the coastal region and intensify over the nearshore of west Taiwan. As previous study had shown that the convection tends to initiate in offshore side of eyewall as the atmospheric instability increases with the drier air from land advected toward the ocean (Chan et al, 2003 & 2012). The Taiwan's complex terrain may also create recirculation flow which intensify the convection in the offshore side of the eyewall (Chi et al, 2024). From the time evolution of Danas, it's early time convection is governed by the relative weak shear since at the moment it's still further away from Taiwan's terrain. But in later time as eye approach coastal region, the location of convection starts to shift to onshore-offshore related perspective instead of deep layer shear related scheme.

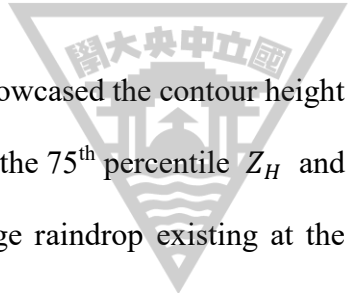
To investigate the size sorting effect in temporal and spatial scheme. The contour plot for 75th percentile plot is also applied onto Danas' case. Figure 3.13 shows that from 1000 UTC – 1300 UTC the tilting in front end side of convection are visible except for earlier time (e.g. 1000 and 1100 UTC), where only data from higher altitude (above 3 km) is available. Lower altitude data (below 3 km) at 1000 UTC are not covered by radar as in figure 3.13 (a), (b) the arc-like pattern shrinking toward top right corner as height decreases, which is the location of radar responsible for the observation (RCCG). This shows the limitation of ground-based radar measurement as data under lower altitude are very limited. However, in later time it's still able to observe the similar sorting effect as discovered in Gaemi's case, but in Danas' case Z_{DR} tends to have downwind propagation as well. By calculating the 75th percentile value of each variable over the selected height. A clear view of the general intensity of the structure is observed. As for Danas' case, the 75th Z_{DR} is ranging from 0.3 – 0.69 dB, as for Gaemi's case, the 75th percentile Z_{DR} can reach up to 0.9 dB. In the production of contour-height plot, the



value of 75th percentile Z_{DR} can greatly influence the formation of the figure. Larger Z_{DR} threshold will restricted the contour upstream and vice versa.

3-1-4 Krathon (2024)

The third ground-based case is Krathon from 2024. Figure 3.14 is the surface analysis before Krathon made landfall in between Koahsiung and Pingtung. At the moment Krathon approach Taiwan after passing through Bashi Channel with relatively slow translation speed. Which is optimal to observe its eyewall structure. The intensity of Krathon gradually weaken based on CWA's official report due to center approaching Taiwan's terrain. Figure 3.15 is the hovemöller diagram for Krathon before landfalling. The direction of deep layer wind shear is close to the translation direction at the time. The strong convection in Krathon are mainly located in left shear side. The reflectivity signal has several period of stronger convection which are 1830, 2100 and after 2300 UTC. The last one showed the strongest and longest. Which may be the result from Krathon approaching to the terrain in Taiwan. By coupling with shear direction and the land-sea difference, the strong convection is produced in the off-shore side of eyewall after 2300 UTC in figure 3.15 (c), (d). Such pattern is similar compare with the pattern we see in Danas' case. The vertical variation between both variable shows that the eyewall is experiencing collision-coalescence process similar to two previous cases as intensity increases toward lower altitude. Figure 3.16 is a series of figure showcasing the convection distribution of Krathon during 2300 to 2330 UTC. The figure shows that the convection mainly located in downshear direction but propagate toward left shear side. It is found that the structure appears to have two convection core that located very closely to each other denoted by black circle in figure 3.16 (j), (l) where higher Z_{DR} is observed. Which provides an information that the convection can be initiated first, by the deep layer shear, and second, by the interaction between the land-sea differences.



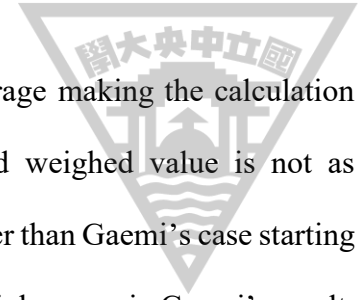
As for the size sorting effect within the eyewall, figure 3.17 showcased the contour height of both reflectivity and Z_{DR} . It shows that over the presented time, the 75th percentile Z_H and Z_{DR} value is relatively high, reaching almost 1 dB, meaning large raindrop existing at the moment. The location of high Z_H and Z_{DR} span through down shear toward left shear. The front end showed a similar pattern as previous cases. All showing a downstream tilting with reflectivity being further downstream highlighted by red circle in figure 3.16. Noted that the result only showed data at higher altitude. Which is caused by the data coverage issue. The data in lower altitude is not covered by radar, which can also be seen in figure with blue line appeared with a concentric circle pattern.

3-2 Statistical analysis

Previous chapter have investigated the hydrometeor size sorting phenomenon and found that the location of high Z_{DR} and high Z_H existed a displacement. Such that high Z_H tends to appears in further downstream than high Z_{DR} . This chapter will use the mathematical method mentioned in chapter 2-3 to evaluate the sorting effect magnitude based on ground-based radar cases and its relationship between TC's intensity.

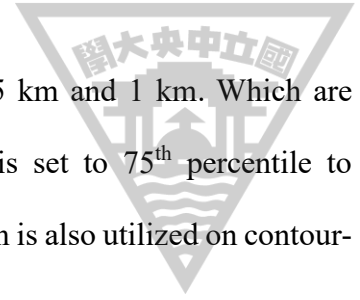
Figure 3.18 is the example of three ground based cases, including Gaemi (a), Danas (b) and Krathon (c), with the time mentioned in case analysis part respectively. From figure 3.18, the calculated correlated weighted value (δ) overall yields a positive value. With positive tilting meaning that the high reflectivity will needs to rotate clockwise to match the high Z_{DR} . In TC's circulation term, high concentration of smaller drops signified by high reflectivity in downstream needs to rotated upstream to match the high Z_{DR} which represents location of larger raindrops.

For Gaemi's case (Figure 3.18 (a)), the correlated weighted value (δ) showed a linear increasing value toward surface. Such result is ideal since the horizontal size sorting is a continuous process that happens throughout the whole rain shaft. The small bump appears in



lowest few altitude might be caused by the decreasing data coverage making the calculation instable. In Danas' case (Figure 3.18 (b)) shows the correlated weighed value is not as significant as Gaemi's result. The value of top layer is slightly higher than Gaemi's case starting with a positive value. But the increment in lower altitude is not as high as one in Gaemi's result. Which may be due to weaker intensity compared with Gaemi's case. As for Krathon's case (Figure 3.18 (c)), the correlated weighted line value showed a similar pattern as one seen in Gaemi's result. A slight difference is that the value of correlation coefficient is higher compared with Gaemi's result. Which may due to the nonlinear relationship between reflectivity and Z_{DR} . When reflectivity and Z_{DR} is larger, the relationship will further deviate from linear relationship, causing linear correlation calculated to decline due to its non-linear property. In Krathon's case, it shows that the correlated weighted value decrease in lowest height similar to Gaemi's case. Which is also caused by decreasing in data coverage.

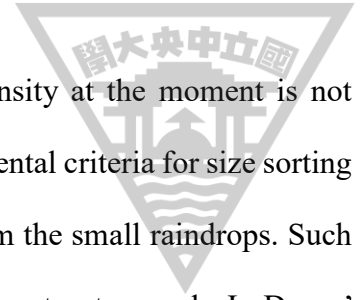
As the correlated weighted value over time of interest within our ground based cases is being collected. Figure 3.19 is presented as our representation of the horizontal size sorting quantification time series. Figure 3.19 showcased four ground based radar cases including Gaemi (a), Danas (b), Krathon (c) and Chanthu (d). Positive shifting value are denoted by yellow and red color while negative shifting is denoted by green and blue. All correlated value shown in Figure 3.19 are standardized processed. Which means all data are subtracted by the top layer value. Therefore, the top layer will always be set to 0° . The thick solid black line represents 50% data coverage. Which are calculated based on quality controlled data between both reflectivity and Z_{DR} . The data coverage calculated here are only accountable for data point with no signal observed or filtered. Which means the data point might either contain no signal or not within the radar observation range. Therefore, those data under 50% data coverage threshold will be filtered out in later study but will still be displayed in the figure. The three colored line with different symbol represent three different dual-polarimetric variables with



their 75th percentile value over the rain shaft, here are between 5 km and 1 km. Which are reflectivity (red), Z_{DR} (blue) and K_{DP} (green). The threshold is set to 75th percentile to represent the overall intensity of such variables at the moment which is also utilized on contour-height plot.

In Gaemi's case, the Z_{DR} 75th percentile value is overall above 0.75. The changes in reflectivity is more significant. Between 0600 UTC and 0700 UTC, the 75th percentile reflectivity value gradually increases overtime, reaching its peak value at around 0654 and 0700 UTC later slightly decline. The normalized correlated value showed a slightly negative value in earlier time. At the moment the eyewall structure is relatively symmetric as shown in figure 3.20. The center is surrounded by uniform strong reflectivity signal. Which didn't show a tilting feature as expected, causing the correlated weighted line to shown a noisy result. In contrast the correlated weighted value in 0700 UTC showed a very high result. The result has been highlighted in chapter 3-1-2. Such result is well corresponded to time with high reflectivity. Which may indicate that the shifting intensity is related to the intensity of the eyewall convection.

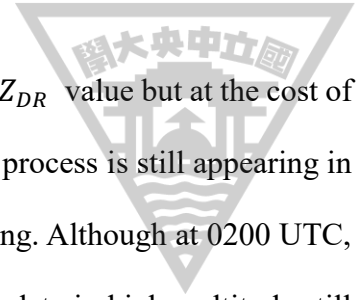
Figure 3.19 (b) is the result from Danas. The biggest difference between Gaemi's and Danas' result is that the correlated value has a large difference. Danas' result overall showed a relatively poor result, especially in earlier time where the 75th percentile of Z_{DR} is only around 0.4 dB. Figure 3.21 showcased the density plot between Z_H and Z_{DR} . In earlier time (e.g. 1300 UTC), the 75th percentile reflectivity and Z_{DR} are both weak, and its relationship between both variables showed a flat relationship where increasing in reflectivity didn't result in a increment of Z_{DR} . Such phenomenon can also be seen in Figure 3.22 where all 4 hours of data are taken into account. As white arrow shows, the increasing in reflectivity has an exponential-like pattern with little increment under low reflectivity and increase exponentially under high reflectivity. Comparing result from 1300 and 1530 UTC where low and high 75th percentile Z_{DR} is



observed. The low Z_{DR} value indicates that the convection intensity at the moment is not strong enough to generate enough large raindrop. Since the fundamental criteria for size sorting to be prevalent is that the large raindrops need to be separated from the small raindrops. Such feature can't be done if there's no large raindrop presented or at least not enough. In Danas' case, the 75th percentile Z_{DR} value increases in later time which also corresponded to the increasing in shifting value. The increase of Z_{DR} showcased the active convection being initiated as Danas approached Taiwan coast.

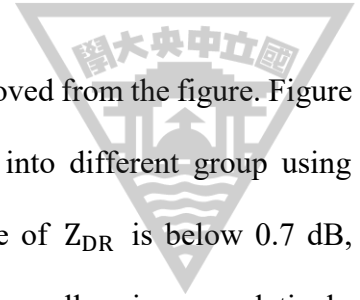
In Krathon's case, the normalized correlated weighted value overall showed a positive result similar to the one discovered in Gaemi's case. The biggest difference is that the 50% data coverage for Krathon tend to be higher in terms of altitude. Such result is due to the distance between RCCG and center of Krathon is relatively further compared with all other cases. Krathon's calculated 75th percentile Z_{DR} exhibited a higher value, reaching up to 1 dB in some period with some fluctuation overtime. Comparing with Danas' result, considering that both cases were observed using RCCG. The significant higher Z_{DR} as well as overall shifting magnitude may indicate that the magnitude of sorting effect might be related to Z_{DR} intensity.

The last case includes in our statistical analysis is case Chanthu. Which is observed using RCWF. The 50% data coverage altitude is even higher compared with all previous cases include Krathon. Two main factor causing such issue is first, the distance between radar site and center of Chanthu is relatively far and second, the altitude of RCWF is considerably higher among all the S-band radar in Taiwan. With the mountainous terrain in northern Taiwan, considering the observation view of radar. The altitude of RCWF is around 740 meters above sea level. This caused the already poor data coverage in lower altitude to even worsen. As for RCWF data, the data in northern section of radar site suffer from significant electromagnetic wave interrupting, causing observed Z_{DR} value to show distinct bias. Other than that, the Z_{DR} data itself suffer from significant bias influence. The Z_{DR} data in Chanthu's case went through an extra bias



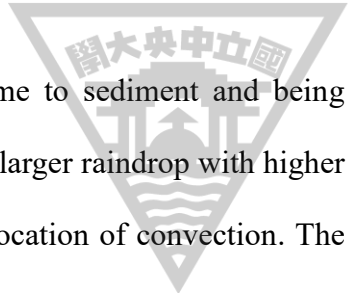
correction based on weak echo region. Such process stabilized the Z_{DR} value but at the cost of overall intensity. Despite the low data coverage rate, some shifting process is still appearing in Chanthu's case. Both 0200 and 0330 UTC showed a positive shifting. Although at 0200 UTC, the result below 50% data coverage showed a strong variation, the data in higher altitude still yields a positive result.

In the introduction part, one of the research purpose mentioned is to find the relationship between the quantification of sorting effect and tropical cyclone intensity. To achieve this, we used 75th percentile Z_{DR} and 90-99th percentile absolute radial wind (V_R) average as our standard of filtering data based on their intensity. The reason we're using 90-99th absolute average instead of 75th percentile is that the radial wind in tropical cyclone contains a dipole structure showing a wave number 1 symmetric pattern. The maximum value can be considered the real tangential wind as its corresponded angle to the radar can yield maximum/minimum value, which is identical to real wind speed magnitude. Therefore, the absolute value of V_R is utilized in consideration of the geometric characteristic of V_R , and we used 90-99th percentile average instead of maximum to prevent the influence of extreme value. Figure 3.23 showcased the density plot of all ground based cases. All the results were normalized by subtracting the top layer value as mentioned previously. The total data time included in this figure is 217, which are collected from all four ground cases. Noted that all the data here went through the filtering of 50 % data coverage, that being said, all data coverage below 50 % are removed to ensure data quality and calculated representativeness. In figure 3.23, the result showed a generally positive tendency with the average weighted value at 2 km height being 8.9°. The pink line illustrated the evolution of weighted value throughout the rain shaft. Which generally follows the 10° line. Meaning that the overall shifting between the 3 km rain shaft will cause the sorting effect to create a 10° discrepancy between Z_{DR} and Z_H . However, in lower altitude, the average value start to decrease. Such phenomenon is also caused by the decrease in data



coverage as those with data with coverage rate below 50 % are removed from the figure. Figure 3.24 and 3.25 further classified those ground based case result into different group using different threshold of both Z_{DR} and V_R . From fig 3.23 the value of Z_{DR} is below 0.7 dB, meaning that at the moment, the overall raindrop size within the eyewall region are relatively small. Fig 3.23 (a) is for both $Z_{DR} < 0.7$ dB and $V_R < 40$ m/s. Despite the result showed a positive shifting value but the magnitude is relatively small, with 4.5° average at 2 km. Noted that the valid profile for this criteria is only 4 profile. Such data number is yet not enough to be significantly enough to be well represent the trend, therefore, more case analysis is required if the data needs more representativeness. Despite that, all the other criteria in figure 3.24 still showed a very small shifting magnitude with mean value not larger than 10° and the result mostly didn't have significant positive shifting as height decrease. In contrast, figure 3.25 is similar figure to figure 3.24 but for Z_{DR} above 0.7 dB. Although data with lower V_R value also received less profile available, the trend of mean correlated value changed drastically. For V_R below 40 m/s, the result still showed a similar pattern of the one discovered in figure 3.24 where Z_{DR} is small. However, for V_R larger than 40 m/s, the ideal pattern of positive correlated value start to prevail. With 2 km height average being around 13° to almost 15° , as well as the positive tendency toward surface. Such result further confirms that the hypothesis of hydrometeor size sorting effect can be observed in tropical cyclone eyewall. The shifting also has a property of continuous forcing throughout the rain shaft, causing the weighted value to gradually increases throughout the rainfall process.

In this chapter the horizontal hydrometeor size sorting effect as well as its quantification using ground-based radar is investigated. By comparing the pattern of Z_H and Z_{DR} . Result shows that the horizontal size sorting effect is captured signified by high Z_H leading Z_{DR} being advected to downstream (counter clockwise) direction. As the droplets descend, the location of high Z_H front end become further downstream than Z_{DR} . Such signature is caused



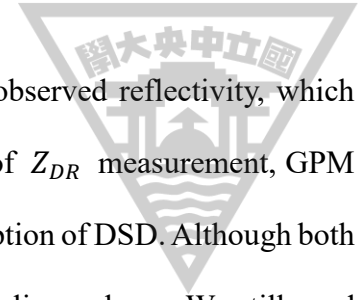
by smaller drops with smaller terminal velocity having more time to sediment and being advected by tropical cyclone's intense horizontal wind field, while larger raindrop with higher terminal velocity falls faster and sediment relatively close to the location of convection. The quantification method is then utilized to quantify such phenomenon. Result shows positive correlated weighted value over most cases with exception related to the intensity of convection signified by value of 75th percentile Z_{DR} . From the statistic view the standardized correlated weighted value yields positive average in all scenario. However, for weighted value to yields high enough value, the combination of both high Z_{DR} (>0.7 dB) and high V_R (>40 m/s) is optimal. Such result shows that the magnitude of sorting effect is proportion to both wind intensity and general raindrop size.



Chapter 4 GPM result

4-1 Data validation

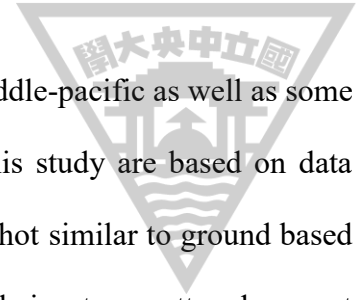
In the last chapter the ground based radar data is utilized to find the hydrometeor size sorting within eyewall region of tropical cyclone, and some preliminary result is received. Result showed that it's possible for us to observed the size sorting effect within eyewall and its magnitude is related to the value of Z_{DR} . Since the goal is to observe the size sorting over the ocean region where ground base radar had difficulty reaching. This chapter will further extend our analytical methodology onto Global Precipitation Measurement (GPM) program. However, in ground based radar, the gate resolution of each beam is around 250 meters, but for GPM radar the resolution decrease to only 5 km in radius. Which is significantly coarser than ground based radar. In concerns of the effect of poor data resolution and its impact on our sorting quantification result. A sensitivity test is conducted which aims to evaluate the effectiveness of our measure method on GPM's resolution. Figure 4.1 is the similar figure from figure 2.2, the only modification is the resolution being downscaled to 5 km in horizontal to simulate the same resolution from GPM's data. Figure 4.2 is the density plot between ground based resolution which represent the original data, and its downscaled version with resolution downscaled to 5 km horizontally. The correlation showed value of 0.82, indicate that the impact on decreasing data resolution still exists, causing some uncertainty and variation. But the Linear regression line showed that despite variation exists, the overall trend of the original and downscaled data can still remain. Keeping the ratio to be almost identical. The bias showed that in lower resolution, the result tends to have a negative bias. And the 0.98 ratio meant that the correlated value will slightly decrease in higher shifting scenario. Nevertheless, the impact of coarser data resolution is small enough for us to keep the original sorting signature.



As mentioned in the data and method, GPM only contains observed reflectivity, which went through a series of attenuation correction. In the deficiency of Z_{DR} measurement, GPM used retrieved mass-weighted mean diameter (D_m) based on assumption of DSD. Although both Z_{DR} and D_m are sensitive to the overall size of raindrops in sampling volume. We still need to establish an equation to build up the relationship between both variables. To achieve it, we utilized T-matrix simulation to estimate the relationship between Z_{DR} and D_m . Figure 4.3 showed the simulated result. We utilized 11 years of Joss-Waldvogel Disdrometer (JWD) data to simulate the Z_{DR} and D_m under S-band wavelength with 6 minutes temporal resolution. To emphasize the DSD characteristic under convection situation, we used an extra filter of 35 dB reflectivity to focus on convective environment. As shown in Figure 4.3, the Z_{DR} and D_m are corresponded to x and y axis. The density here is displayed using logarithm scale as shown in the right. We used power-law fitting to establish the relationship between two variables. The coefficients are shown in bottom right box. By following this equation, we set up a general relationship linking both variables. In previous chapter we've done a couple of sensitivity test, which found that for size sorting effect to be well quantified, according to power law fitting result the equivalent relationship between Z_{DR} and D_m are 0.7 dB and 1.56 mm respectively. In later part such threshold will be used to determine the existence of enough large raindrops.

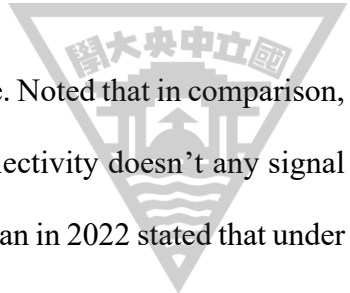
4-2 GPM analysis

In previous part we've confirmed that our methodology can work on both fine and coarse resolution. In this part, we'll investigate into the GPM radar cases and see the performance of the quantification result. To acquire the available tropical cyclone information, we adopted the data from JAXA/EORC tropical cyclone database. Where the time frame and satellite orbital information is collected and displayed when a tropical cyclone's structure is snapshotted. We then further obtain the GPM DPR Level-2A precipitation profile data based on the information collected. The data are manually cropped based on time and domain of interest to keep only the



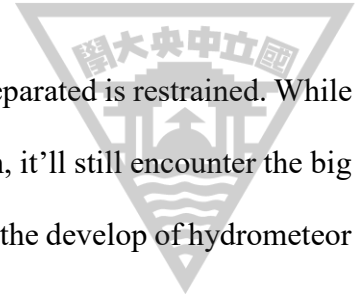
valuable information. All GPM snapshot from west-pacific and middle-pacific as well as some of the east-pacific cases is investigated. The cases selected in this study are based on data integrity as well as overall intensity of TC at the moment of snapshot similar to ground based cases. Cases with chopped eye structure or convection structure being too scattered are not taken into account for this study. Table 2 showcased the intensity information as well as the calculated standardized weighted value, the weighted value here was standardized based on top 5 layers' average. In table 2, we also use 75th percentile to demonstrate the overall size information similar to ground base analysis. Noted that the variable is displayed in mass-weighted mean diameter (D_m). If we use the aforementioned threshold retrieved from T-matrix simulation, in GPM's cases, most of the cases selected exceed the 1.56 mm D_m threshold. As for the standardized weighted value at 2 km height, the variable calculated in GPM's part are equivalent reflectivity (Z_e) and mass-weighted mean diameter (D_m).

Figure 4.4 is the maximum reflectivity snapshot captured by GPM radar. The snapshot captured the vertical profile of TC Nyatoh from 2021. The white parallel line represents the boundary of GPM swath, the structure showed a slightly asymmetric pattern, with stronger convection appearing to the west-to-north part of eyewall. Despite the asymmetric structure, the calculated correlated value at 2 km from table 2 showed negative value. Figure 4.5 is the correlation plot for case Nyatoh. In the original correlated weighted profile, it's found that the correlation starting with positive value, but slightly decreases in lower altitude. Such pattern will result in negative normalized shifting in lower altitude. In the goal of finding the reason such small shifting appeared in lower altitude. We evaluate the original structure of Nyatoh at different height. Figure 4.6 showcased the reflectivity and D_m at three different height, from 4 to 2 km approximately. In the outer ring it's find that the reflectivity gradually rotates downstream toward lower altitude which is close to our expectation. However, when altitude decrease, the D_m showed a different pattern compared with reflectivity. In figure 4.6 (c) to (f)



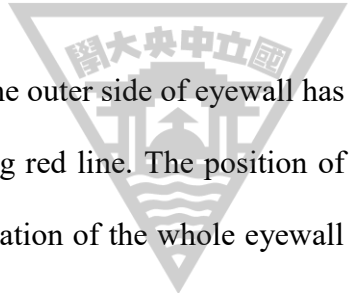
the black circle highlighted the location of abnormal high D_m value. Noted that in comparison, reflectivity didn't perform an expected high value. Instead, the reflectivity doesn't any signal of strong convective, with lower reflectivity in lower altitude. Kumjian in 2022 stated that under vertical rain profile, the increasing in Z_{DR} (here D_m) but decreasing in reflectivity can be referred as vertical size sorting or evaporation where small size raindrops decrease in concentration. But if reflectivity increase then it can be referred as coalescence where small drops collide together to form larger raindrops, increasing Z_{DR} or D_m value. In reality, the aforementioned microphysical process can occur simultaneously, the changes in variable value depends on which process dominates the sampling volume. The high D_m appearance in downstream lower altitude also effect the correlation calculation. With increase D_m appears in downstream direction, the correlation with negative shifting also increases, leading to correlated weighted value to decrease in lower altitude. Yielding negative normalized correlated weighted value in lower altitude.

Figure 4.7 is another case from GPM radar. The eyewall showed a uniform structure, with very strong estimated intensity from table 2. As from table 2, the shifting value at 2 km height is negative despite its intensity. Such result is contrary to result found in ground based cases. Therefore, an inspection into its structure is conducted to find out the potential cause. Figure 4.8 showed that the correlation weighted line displayed little variation in terms of height. The value at top layer is just slightly above zero to yield a negative normalized value at 2 km height. Figure 4.9 and figure 4.10 are the contour-height and CAPPI at 2km of both reflectivity and D_m . From the CAPPI plot shows its inner core of eyewall forms a strong signal around the center. Such pattern is very uniform throughout the eye of Vongfong for both variables. Figure 4.9 shows the similar pattern occurs throughout the rain shaft, meaning that the whole eyewall is surrounded by strong convection. However, such phenomenon is not ideal for us to observe the horizontal hydrometeor size sorting effect. If the circulation of the eyewall is too uniform,



the spatial condition for large raindrops and small raindrops to be separated is restrained. While small raindrops got transport downstream, despite leaving its origin, it'll still encounter the big raindrops in downstream. With the raindrops being mixed together, the develop of hydrometeor size sorting is suppressed, thus causing an unidealized result.

Figure 4.11 is another case from GPM analysis. This case is a tropical cyclone from middle pacific. Despite the east side of eyewall is partially cut off, the main convection which located in north west side relative to center is still well-captured. Figure 4.12 is the azimuthal-average of case Kilo. The strongest convection is mostly located in north side of the eyewall, and propagate downstream as they sediment. In the east side (90°) the result shows that there's no reflectivity signal, which is due to the swath missing issue. By comparing the signal of both reflectivity and D_m in figure 4.12, both variables showed a tilting signature. However, as shown in figure 4.12, the purple line illustrated the general location of front end, and the black rectangle showed the location of main convection denoted by the high D_m column. The tilting signature between reflectivity and D_m showed a little variability where reflectivity tile slightly further downstream compared with D_m . Such signal is not very significant relative to ground based cases such as Gaemi. But in the correlation plot as shown in figure 4.13, a positive shifting signal is captured. If inspects the figure closely, the correlation in negative shifting part actually decays faster than positive side. Such feature indicates that the structure showed a very steep changes in upstream direction, where initiated convection propagates downstream only. The narrower the positive correlation is, the more asymmetric the eyewall may be. Where Vongfong's correlation plot showed a high correlation over all shifting angle since its eyewall structure is too uniform. In this case, the highly asymmetric eyewall structure provide an ideal environment for hydrometeor size sorting effect to take place. However, noted that in figure 4.14, the contour-height plot shows only small portion of convection. Which tells us that the only location of strong convection is in the north. The main convection (shown in black circle)



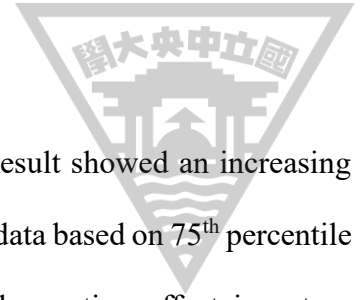
showed little difference between reflectivity and D_m . In contrast, the outer side of eyewall has another slightly shallower signal, the front end is highlighted using red line. The position of reflectivity is further downstream. As the correlation is the computation of the whole eyewall structure, those strong and weak shifting are combined as one coefficient. Thus providing the overall condition of eyewall tilting and sorting magnitude.



Chapter 5 Conclusions and future work

In this study, the horizontal hydrometeor size sorting effect within the eyewall region of tropical cyclone is investigated. Both ground-based and space-borne radar is utilized to observe the structure of eyewall. In ground-based cases, investigation of the time evolution of the structure with a 6 minute interval in conducted. An innovated methodology of quantifying the horizontal hydrometeor size sorting effect in eyewall region is adapted. By comparing the correlation between two radar variables, namely horizontal reflectivity (Z_H) and differential reflectivity (Z_{DR}). The evolution of small raindrop and large raindrop over the rain shaft can be captured. Such methodology is then being applied onto both ground based radar and GPM radar. The following are the findings in our research.

- (1). The convection location tends to be around downshear direction in the eyewall using ground based radar. Such tendency deviates as tropical cyclone approach land and terrain. When approach near land, the convection shifts toward offshore direction side of circulation.
- (2). The horizontal hydrometeor size sorting is discovered using Z_H and Z_{DR} . Strong signal of Z_H located in downstream direction of Z_{DR} , namely counterclockwise side. The front end of strong signal is recorded using 75th percentile signal. It is found that the structure of high Z_{DR} tends to be more erect, in contrast, the structure for high Z_H tends to tilt downstream. As small size raindrops sediment, they get push to downstream direction causing high Z_H appearance.
- (3). The size sorting effect is quantified using correlation coefficient. Ground based cases showed mostly positive shifting signal, exhibiting positive correlated weighted value in lower altitude. The value of correlated weighted value increases as height decreases. Indicating that the separation between large raindrops and small raindrops increases



toward surface.

- (4). Statistical analysis is conducted using ground based cases. Result showed an increasing tendency of weighted value as height decrease. By classifying data based on 75th percentile Z_{DR} value. Result showed that if Z_{DR} is below 0.7 dB, the sorting effect is not as significant as when Z_{DR} is above 0.7 dB. And the value of radial wind also effect the outcome. With V_R below 40 m/s the sorting effect is not significant even if Z_{DR} is high. Showing that both Z_{DR} and V_R play a crucial role in creating hydrometeor size sorting.
- (5). In GPM cases it shows that generally the shifting magnitude is lower than ones found in ground base cases. With exception of negative shifting cases. Such result was due to the various microphysical process appearing within the eyewall region.
- (6). In GPM's cases the cases shows that if the eyewall structure is too symmetric, size sorting effect actually got diminished. As large raindrop and small raindrop don't receive enough space to be separated. Therefore, for size sorting effect to be prominent, asymmetric eyewall structure is more preferable.

Despite all the findings mentioned, there are still many issues that need to be addressed, as further validation is required to provide a more comprehensive understanding of the results. More cases analysis is required as current cases involved too little time profile, such requirement also applies to GPM cases. An idealized simulation is also needed in order to evaluate the performance of the algorithm on ideal condition as well as evaluate the capability for model to simulated the horizontal size sorting effect.



Figures

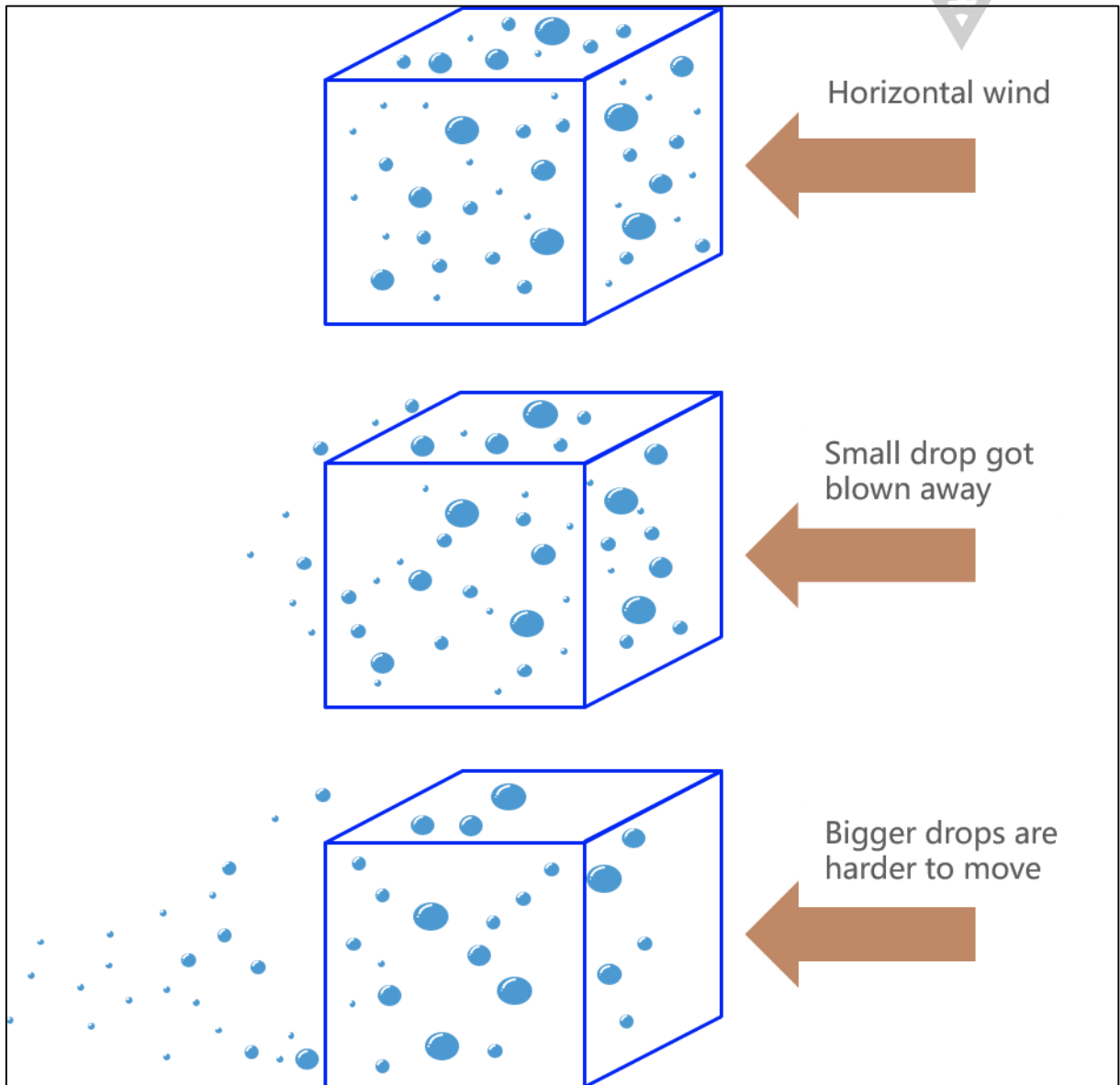


Figure 1.1 Illustration of horizontal hydrometeor size sorting over three-dimensional space.

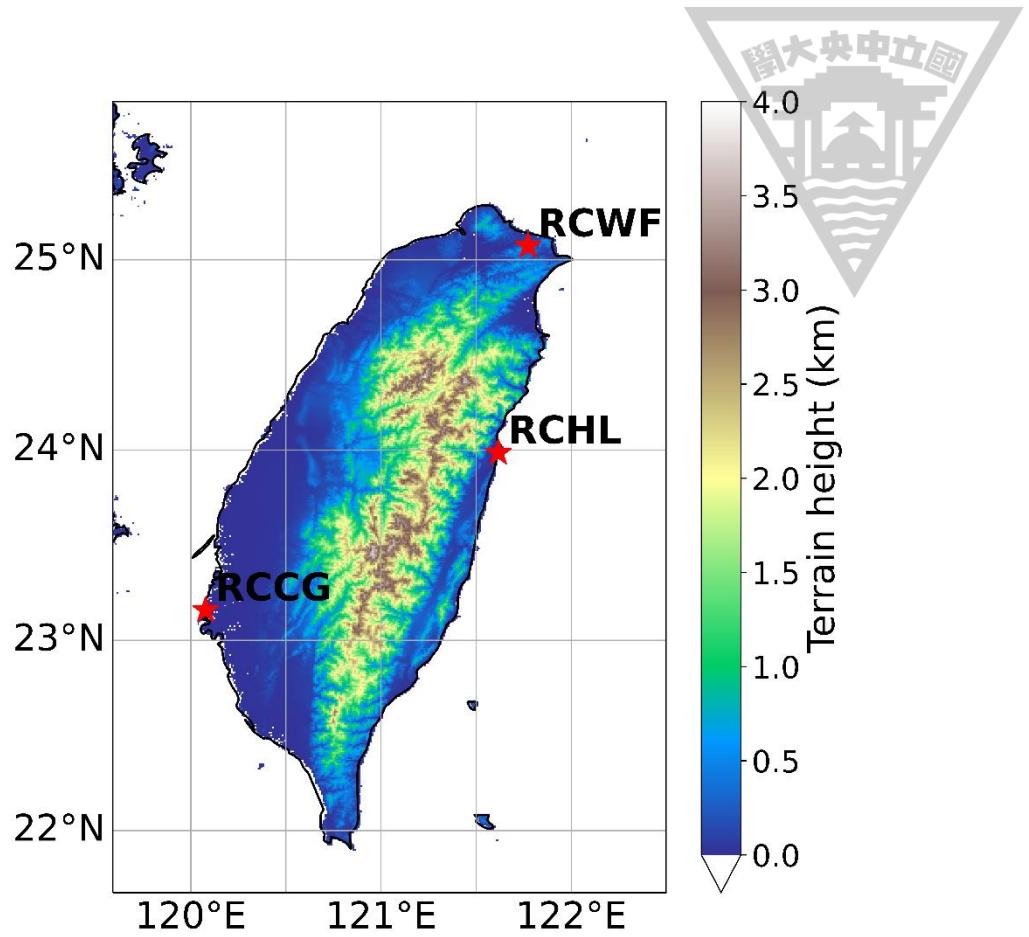


Figure 2.1 Taiwan terrain plot and the radar location of RCHL, RCWF and RCCG.

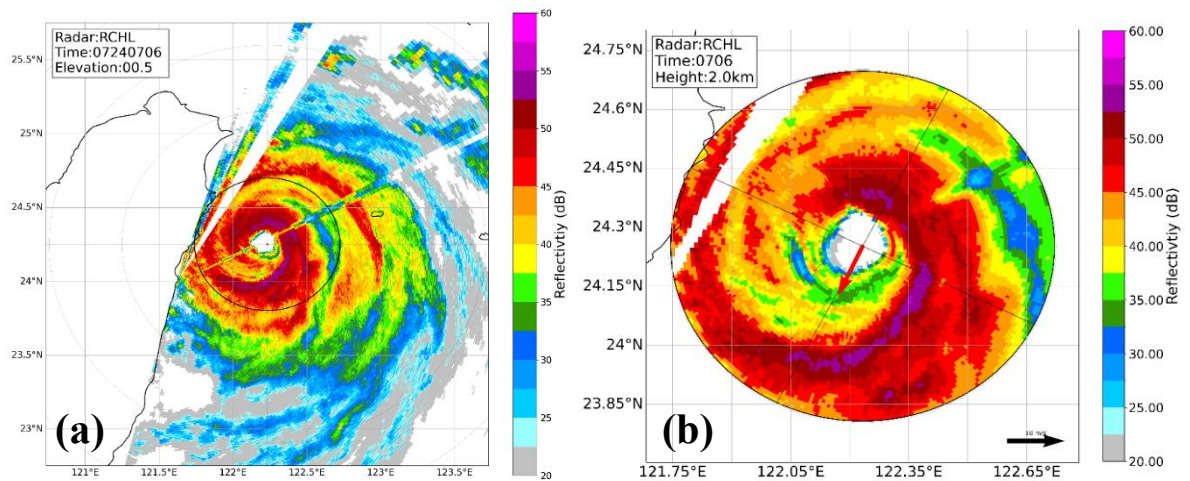


Figure 2.2 (a) 0.5° elevation angle PPI scan of reflectivity from RCHL at 0706 UTC 24 July, 2024. (b) 2 km CAPPI of reflectivity at the same time with (a). The red arrow represents the deep layer wind shear direction and magnitude.

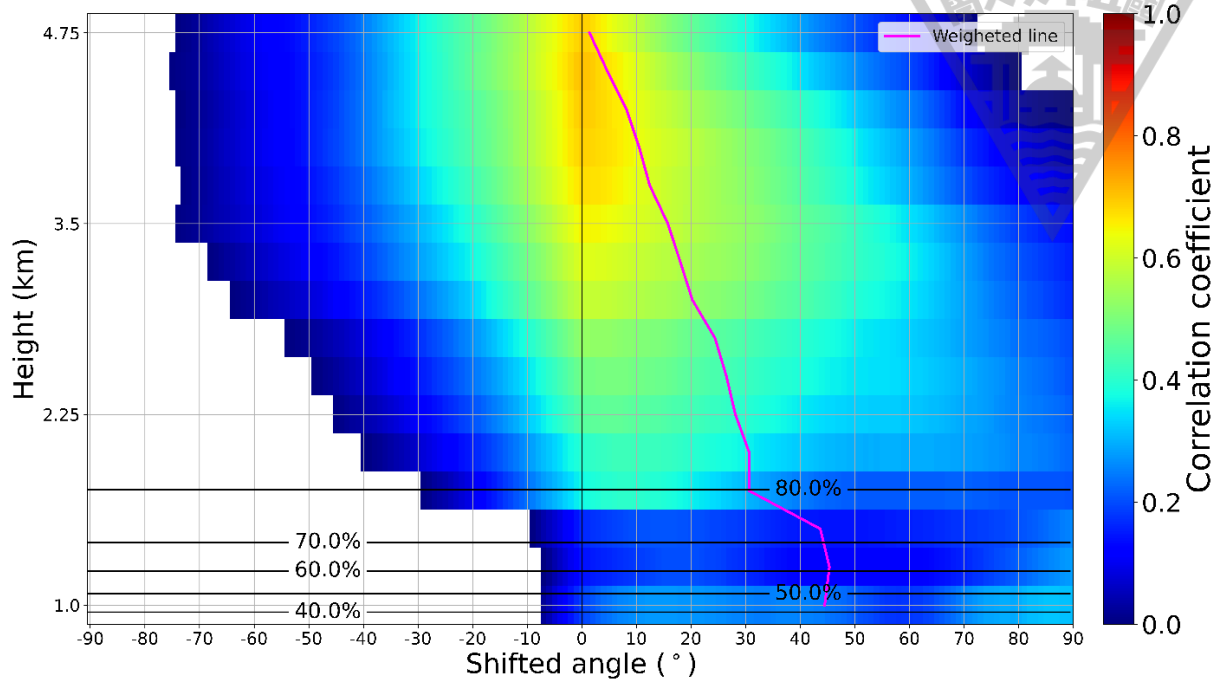


Figure 2.3 Correlation plot between reflectivity and differential reflectivity for case Gaemi using RCHL at 0700 UTC 24 July, 2024. Solid line represents data coverage under no rotation condition. Magenta line represent correlated weighted value at each height.

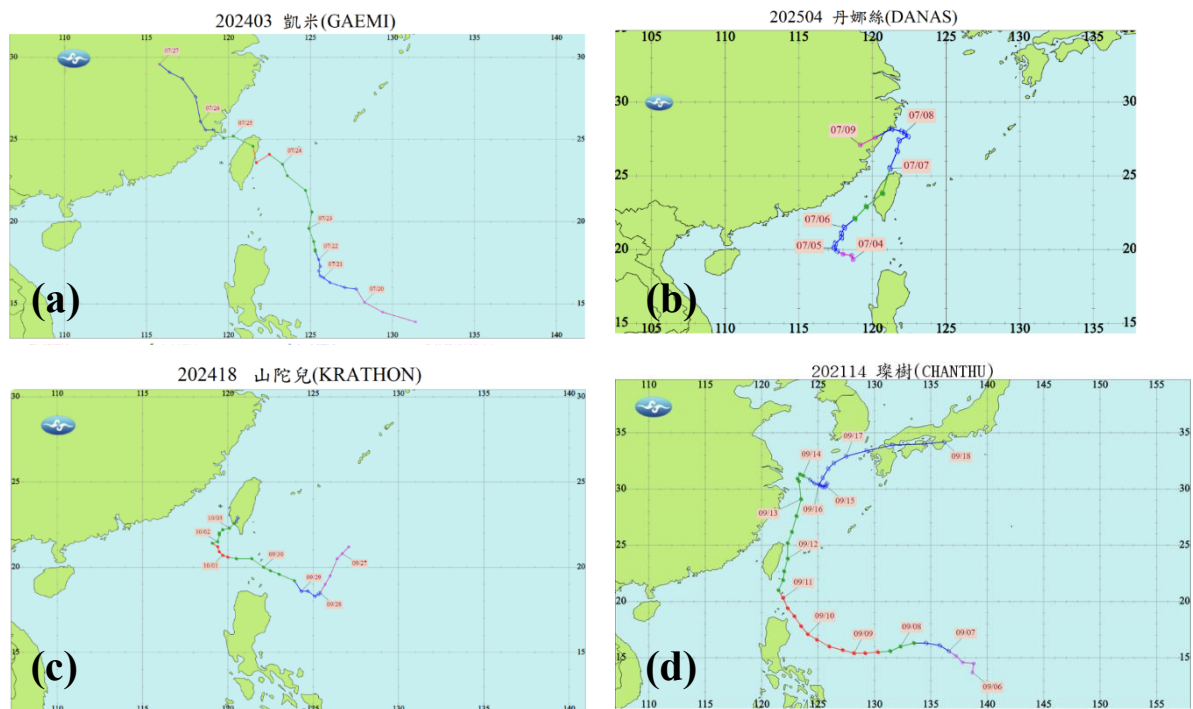
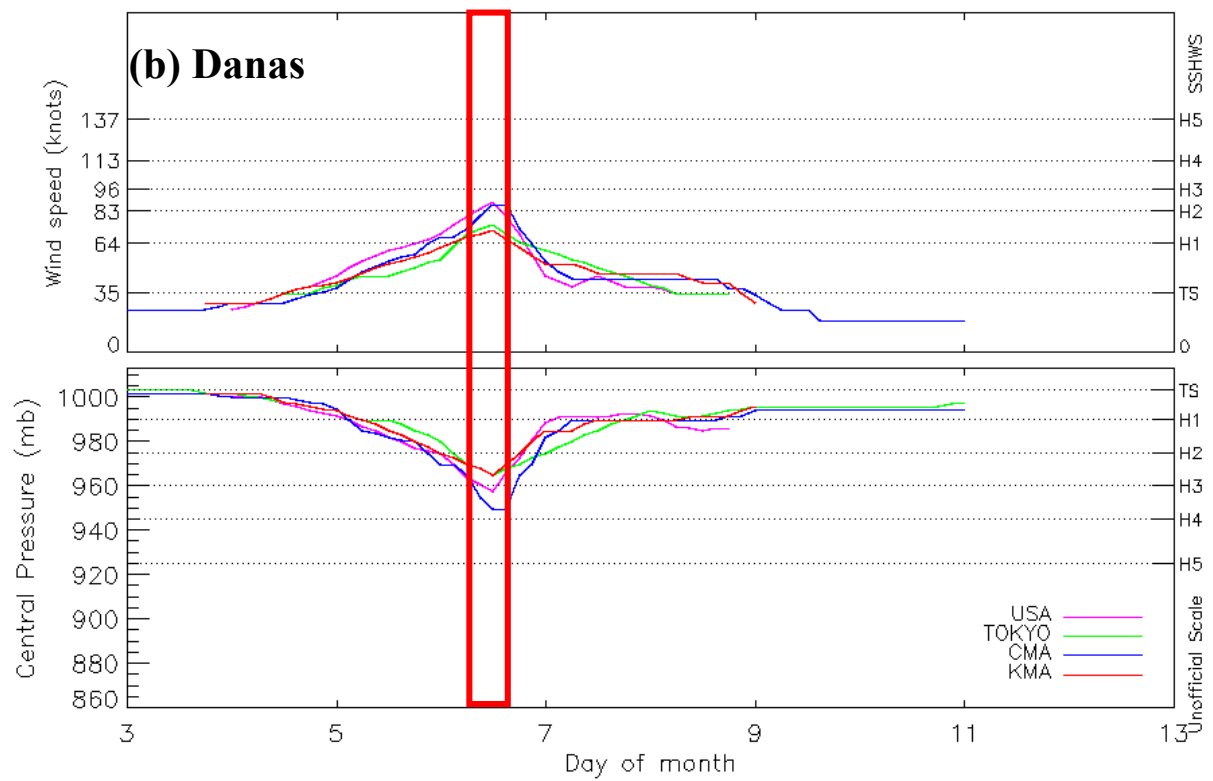
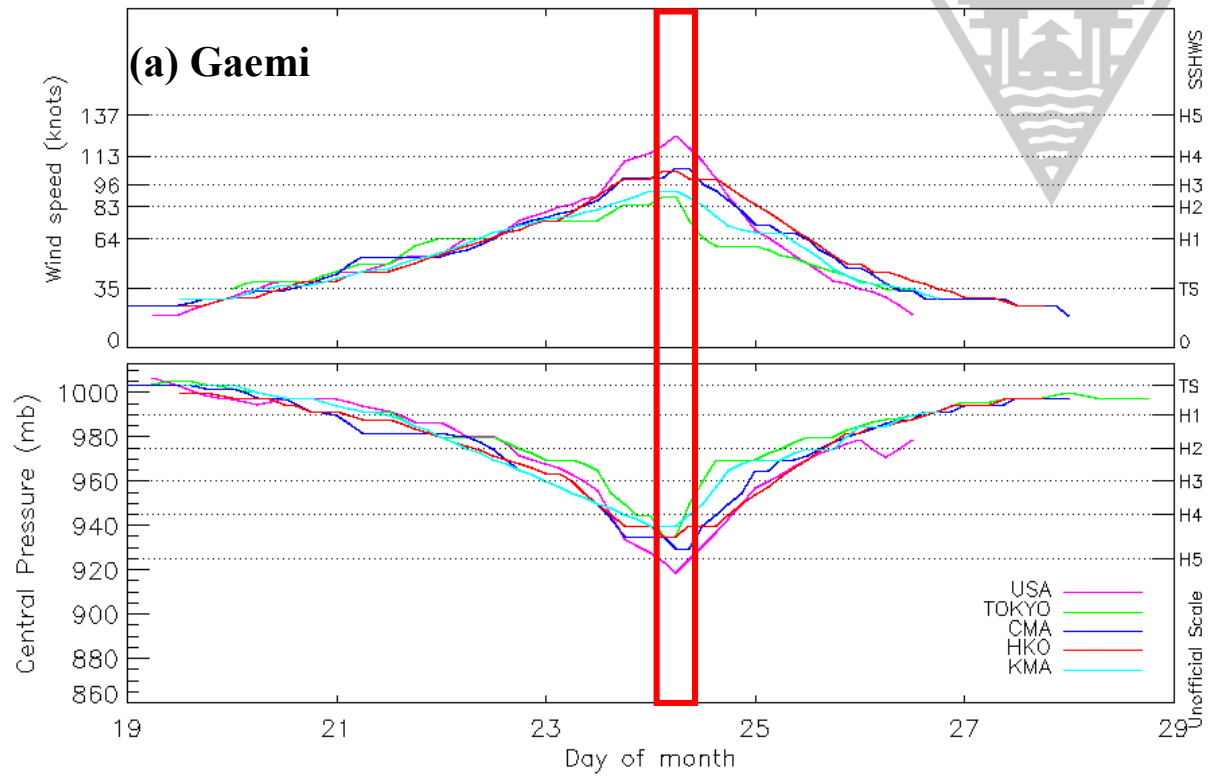
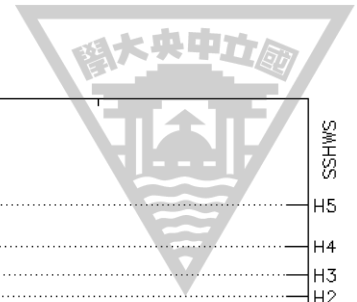


Figure 3.1 6 hours interval best track of TC (a) Gaemi (2024), (b) Danas (2025), (c) Krathon and (d) Chanthu based on CWA.



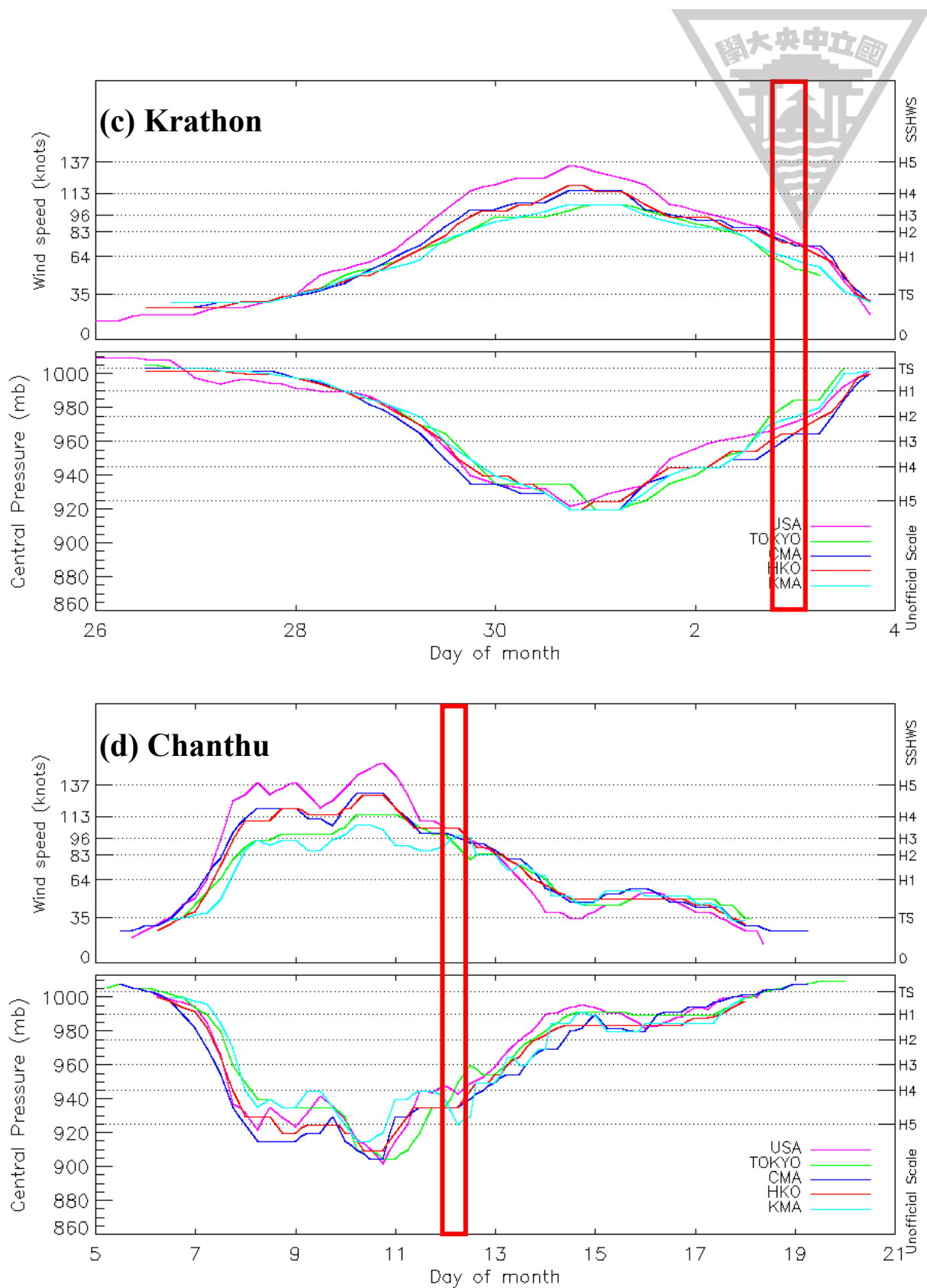


Figure 3.2 IBTrACS intensity estimation of wind speed and central pressure for (a) Gaemi, (b) Danas, (c) Krathon and (d) Chanthu. Red rectangle indicate the time of interest in each cases.

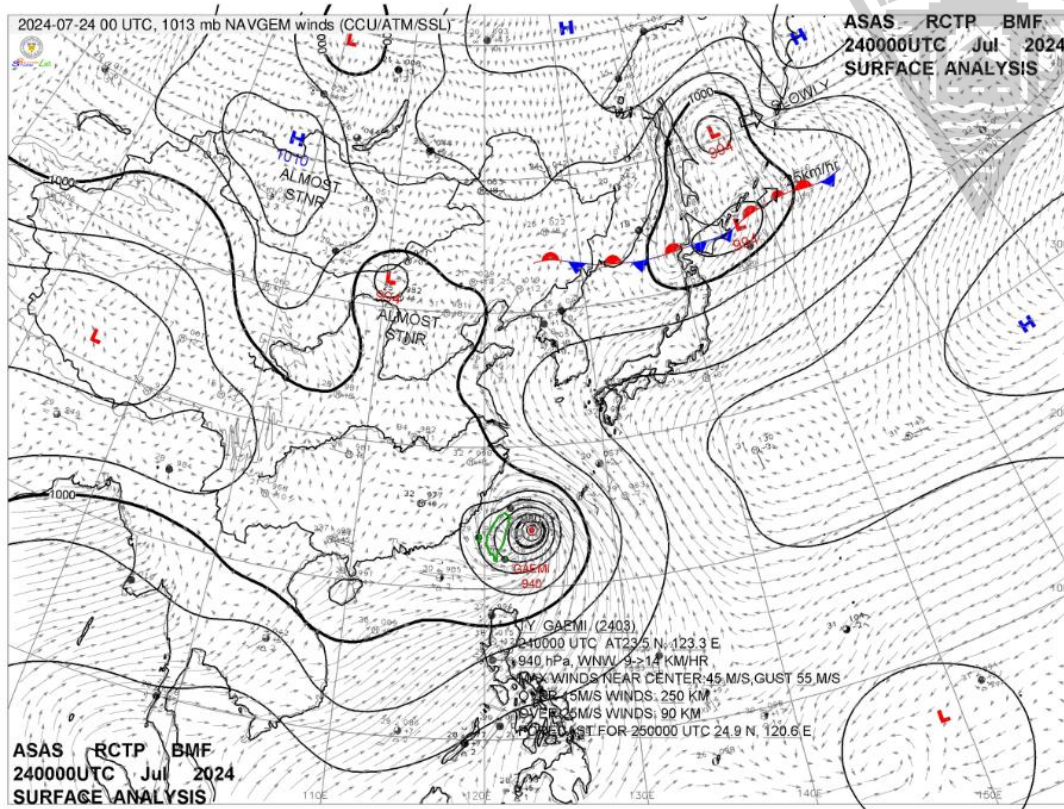


Figure 3.3 Surface weather analysis plot at 00 UTC 24 July, 2024.

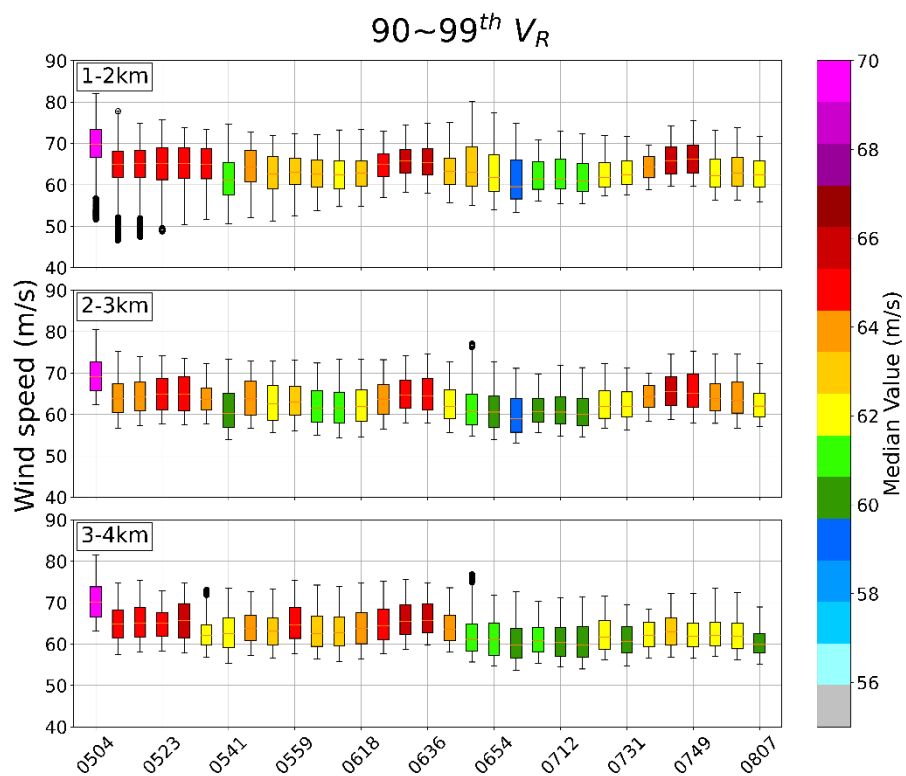


Figure 3.4 90 – 99 percentile radial wind over 1 – 2 km (top), 2 – 3 km (middle) and 3 – 4 km (bottom). Color of the box itself represents median wind speed.

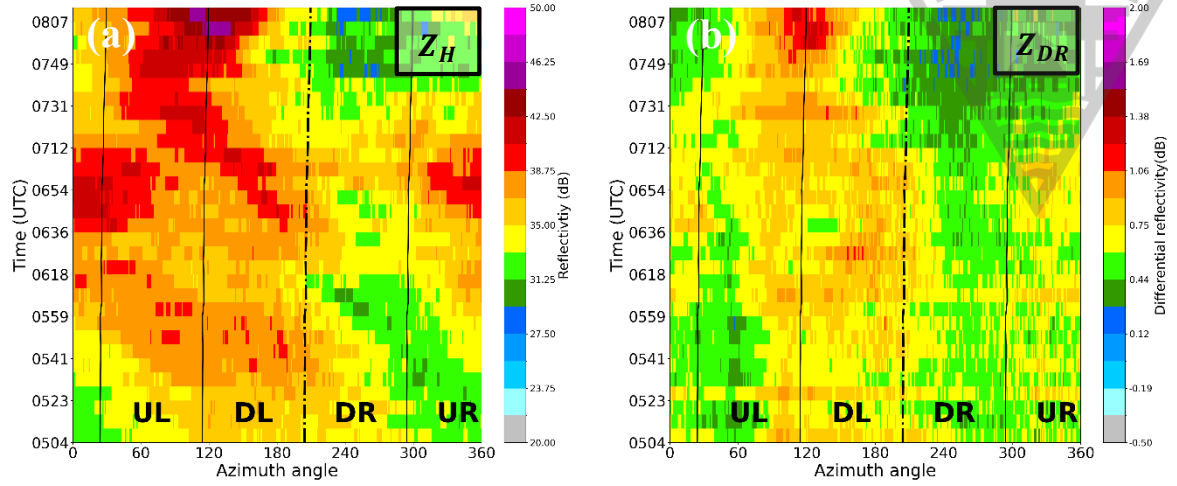


Figure 3.5 Hovmöller diagram of 5 km height Z_H (a) and Z_{DR} (b) for case Gaemi from 0504 – 0807 UTC 24 July, 2024. Dash line represents the direction of deep layer shear; with thin black line represents the boundary of four quadrants.

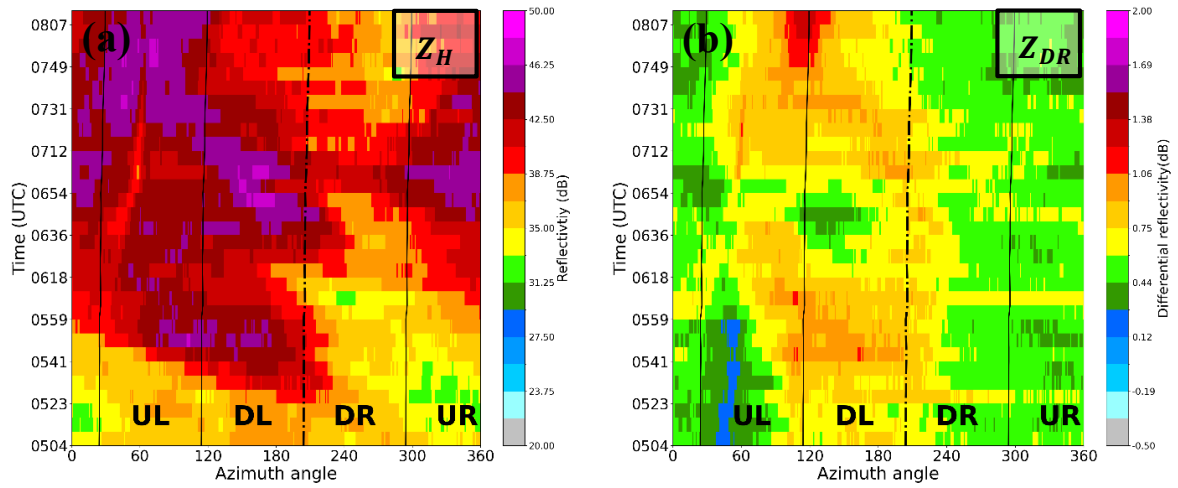
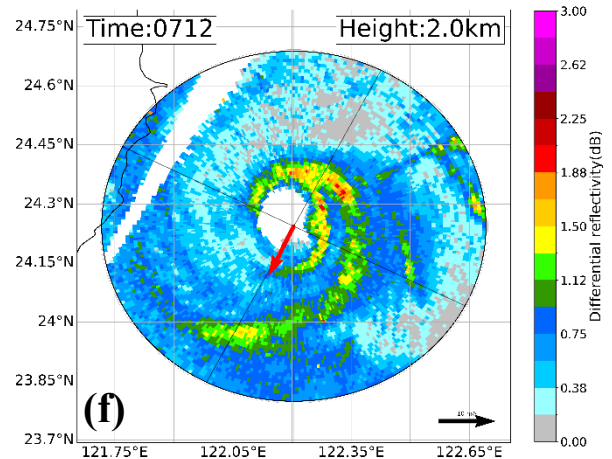
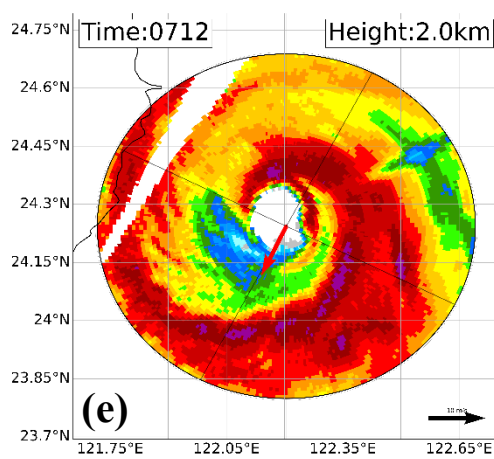
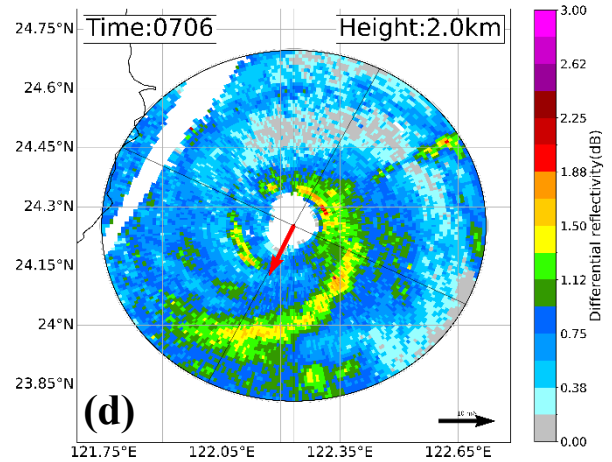
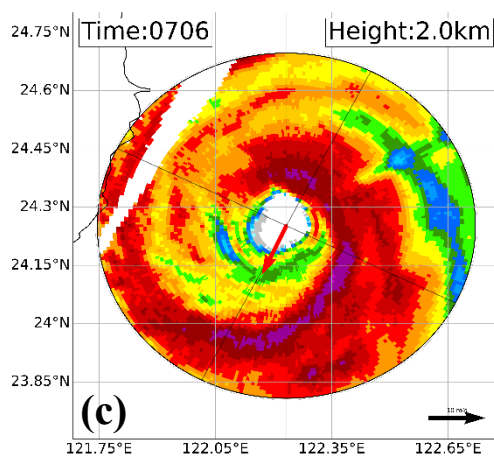
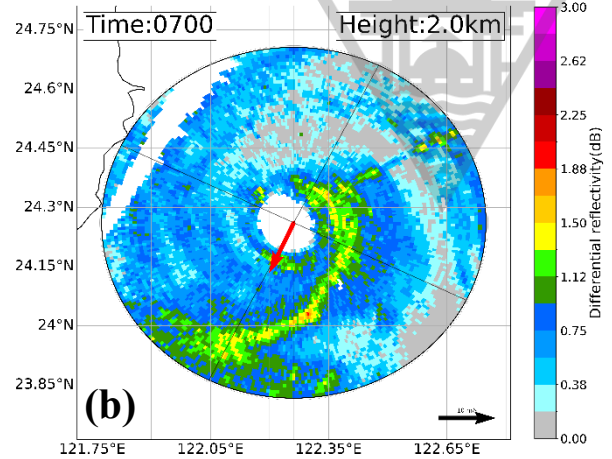
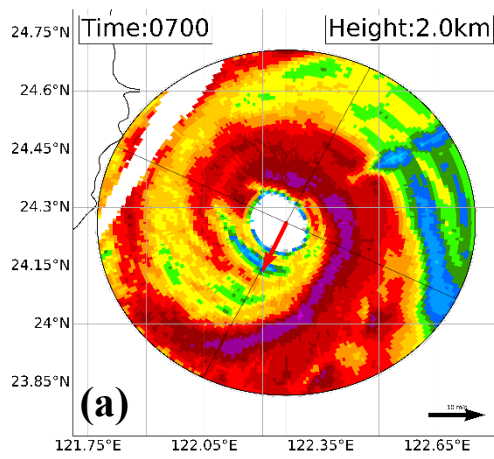


Figure 3.6 Hovmöller diagram of 2 km height Z_H (a) and Z_{DR} (b) for case Gaemi from 0504 – 0807 UTC 24 July, 2024..



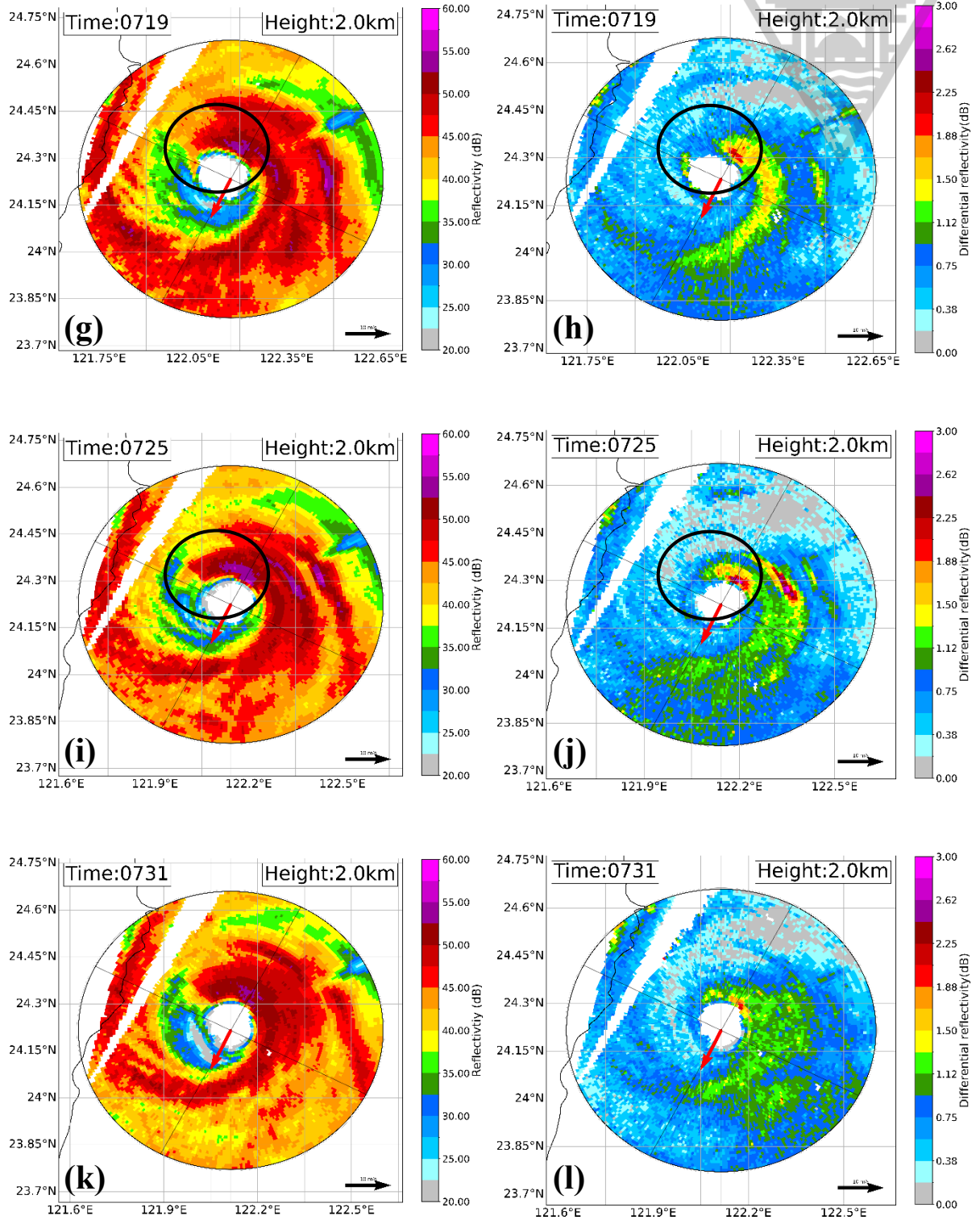
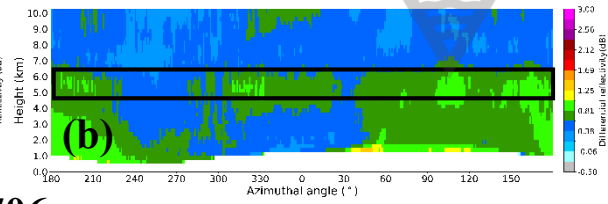
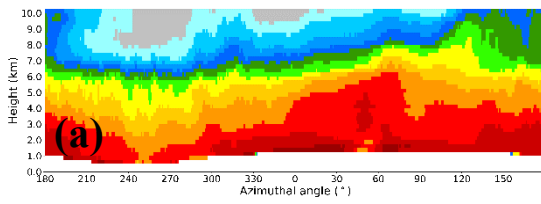


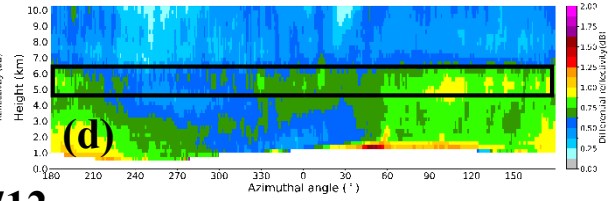
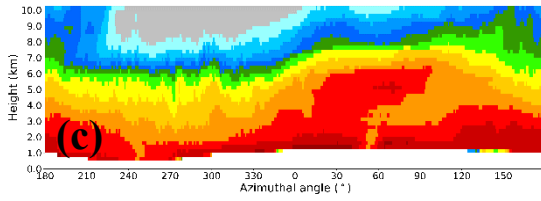
Figure 3.7 2 km height Z_H (left) and Z_{DR} (right) from 0700 UTC (top) to 0731 UTC (bottom). Circles in (g), (h), (i), (j) represent the front end of strong signal.



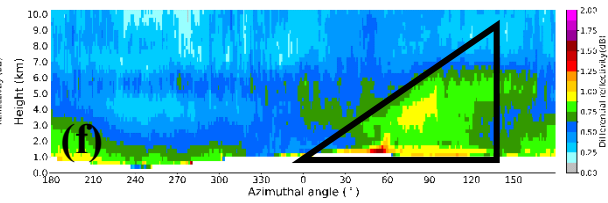
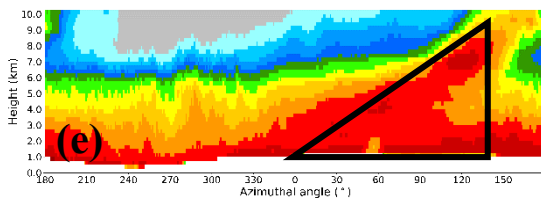
0700



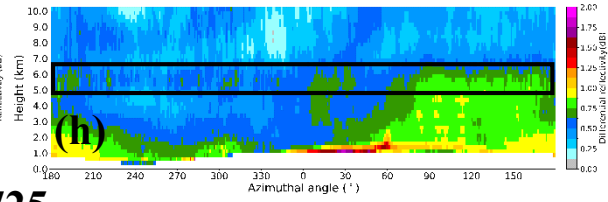
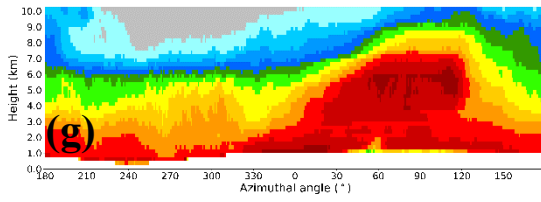
0706



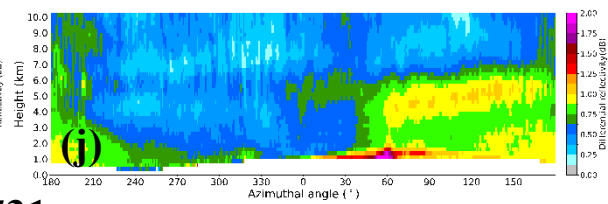
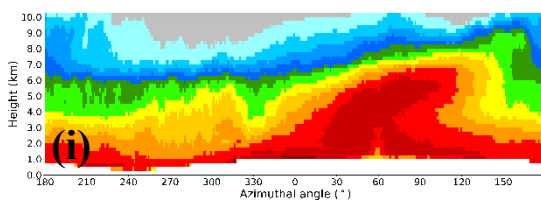
0712



0719



0725



0731

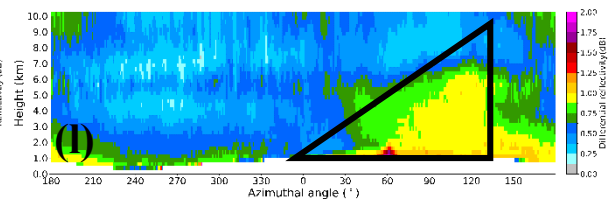
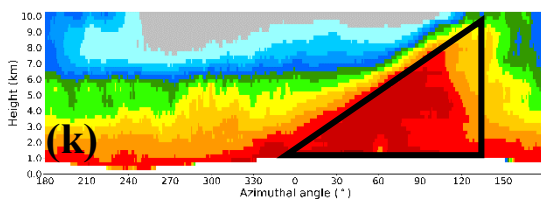
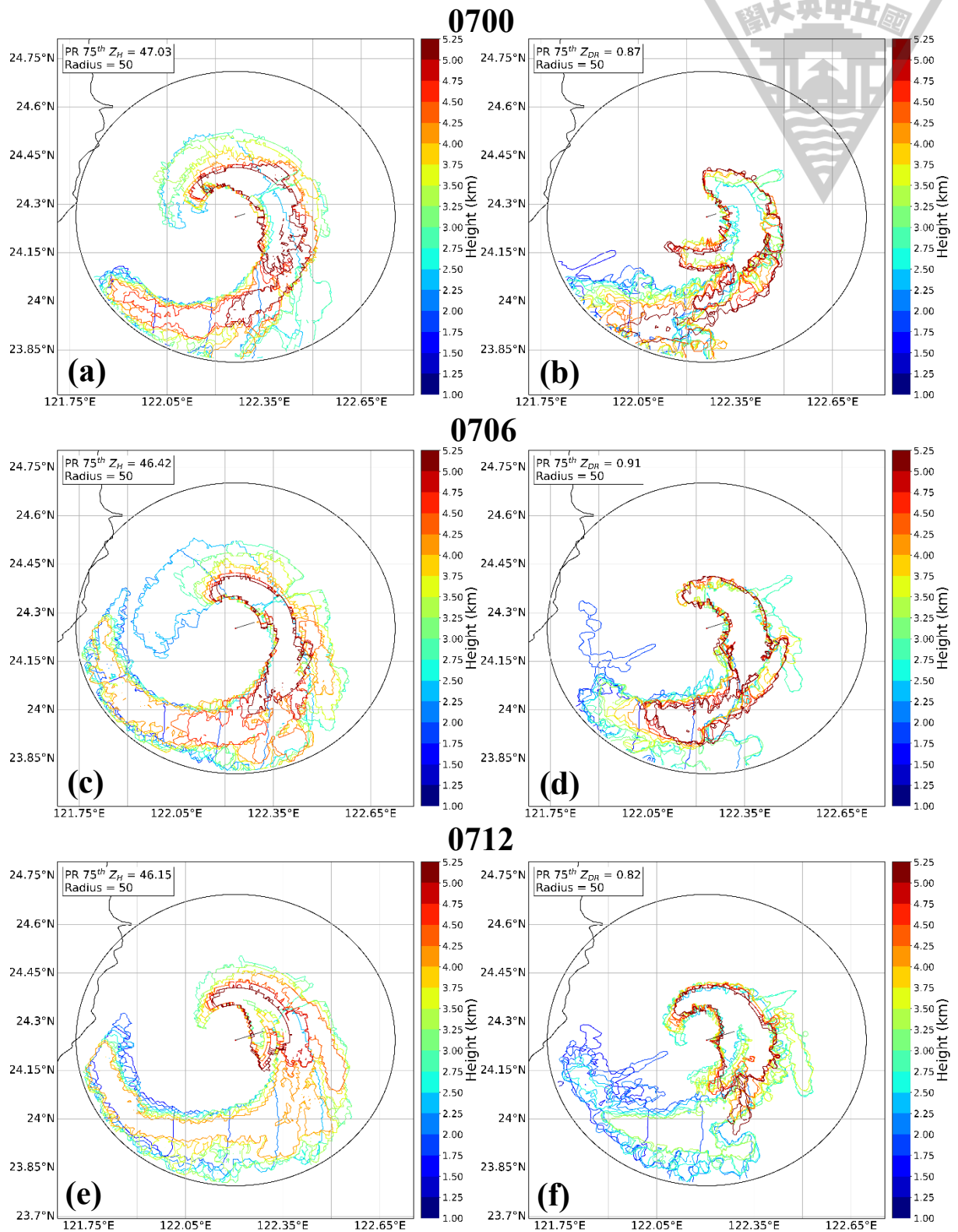


Figure 3.8 Azimuthal-height plot of Z_H (left) and Z_{DR} (right) from 0700 UTC (top) to 0731 UTC (bottom). Triangles in (e), (f), (k), (l) represent the pattern of convection. The rectangles in (b), (d), (h) represent the location of potential bright band.



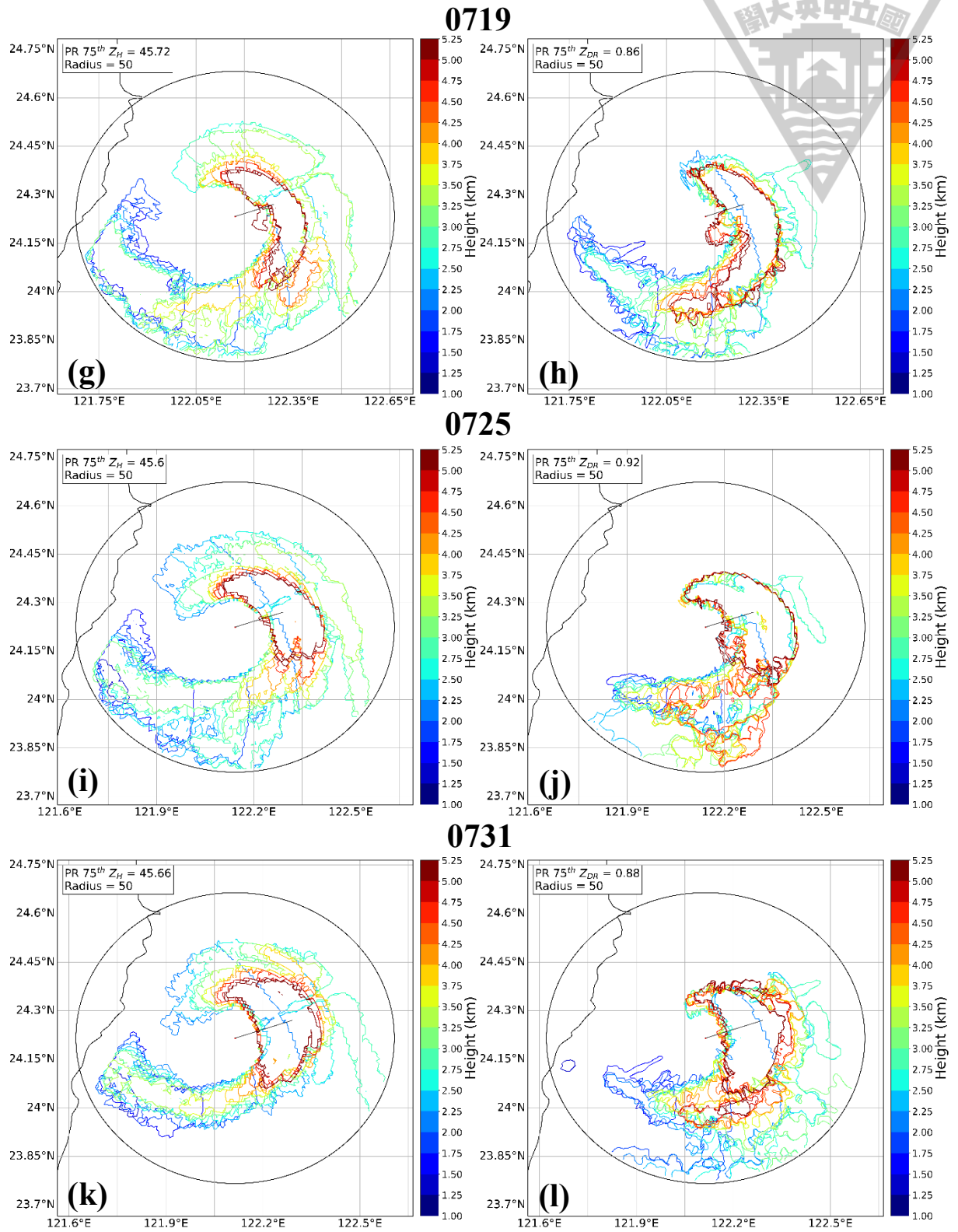


Figure 3.9 Contour-height plot of Z_H (left) and Z_{DR} (right) from 0700 UTC (top) to 0731 UTC (bottom). Contour line color in the figure represents height (km), the contour itself represents the 75th value

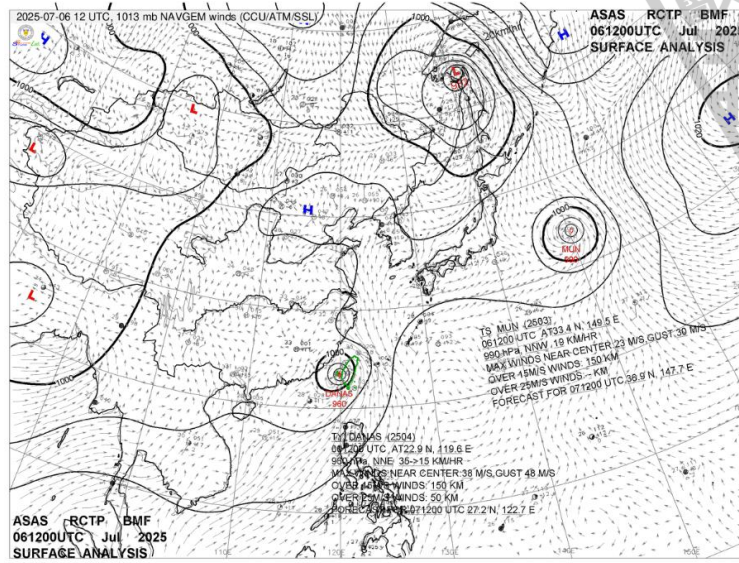


Figure 3.10 Surface weather analysis plot of 1200 UTC 6 July, 2025.

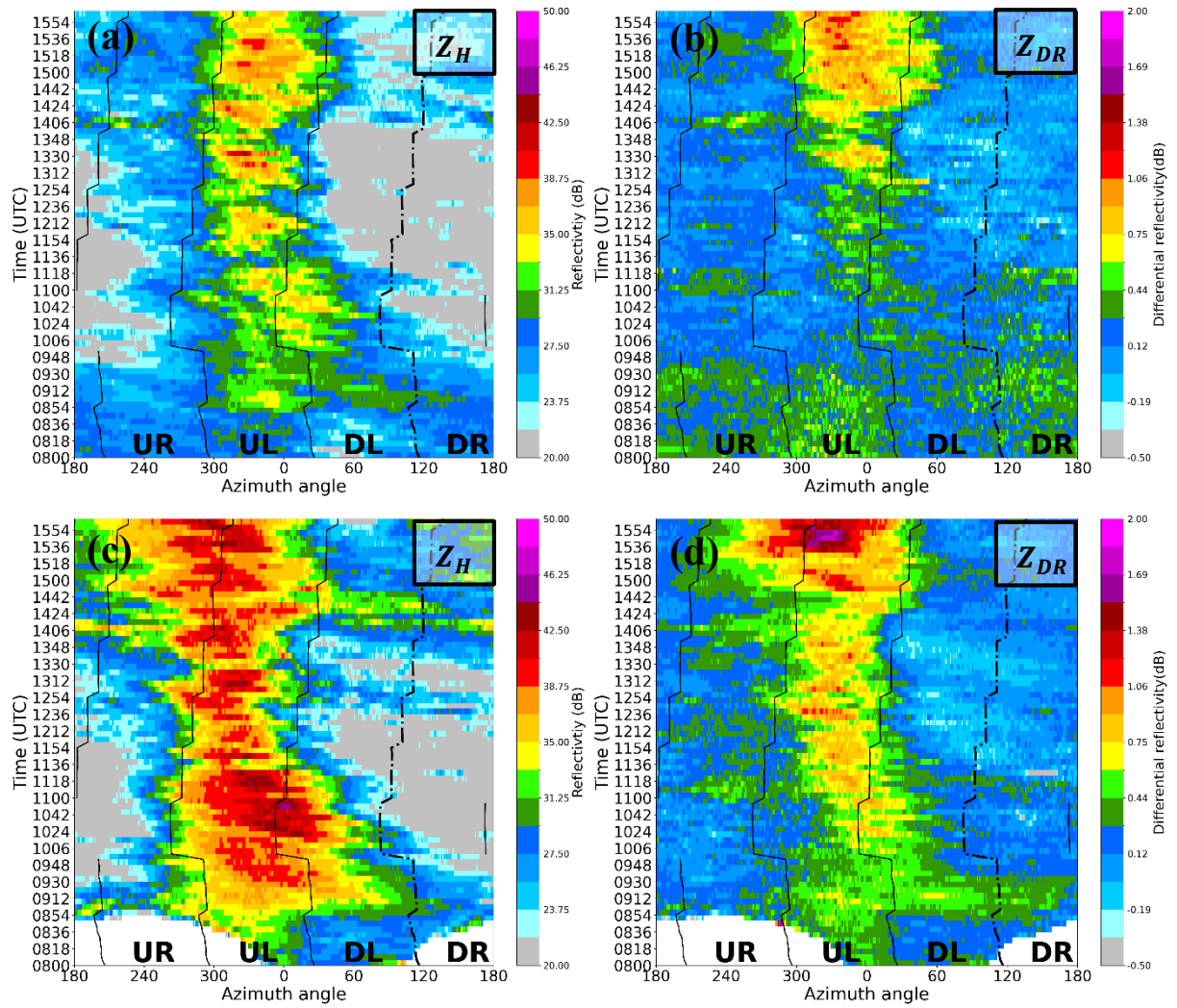
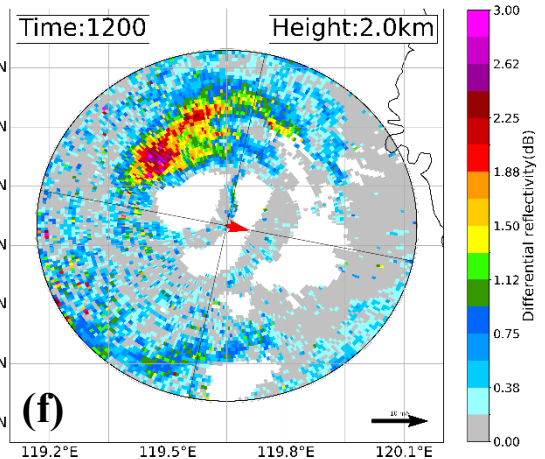
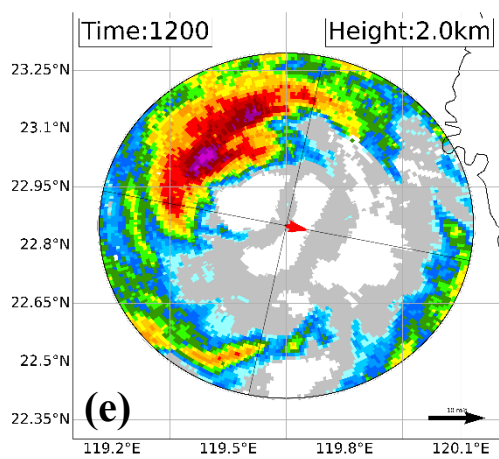
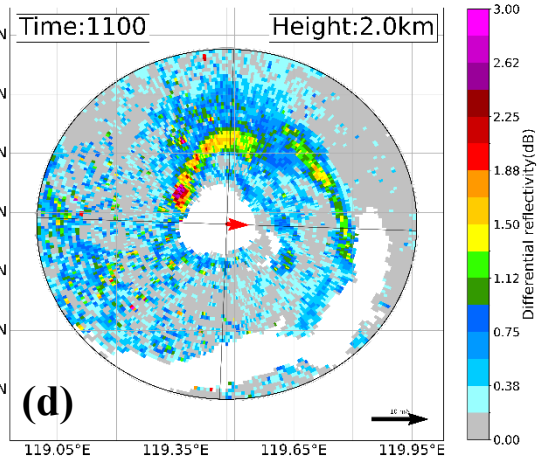
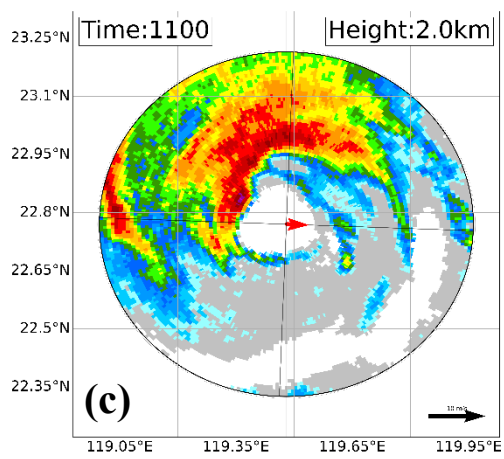
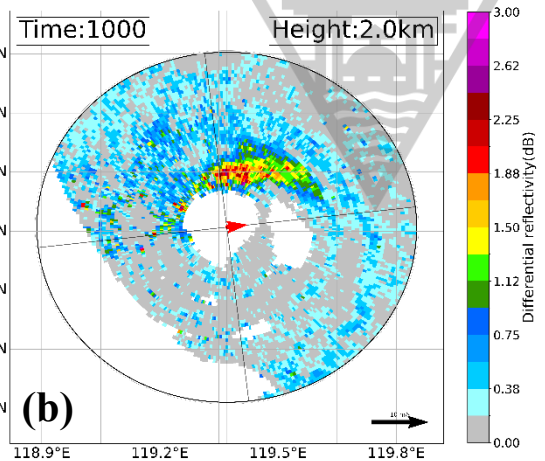
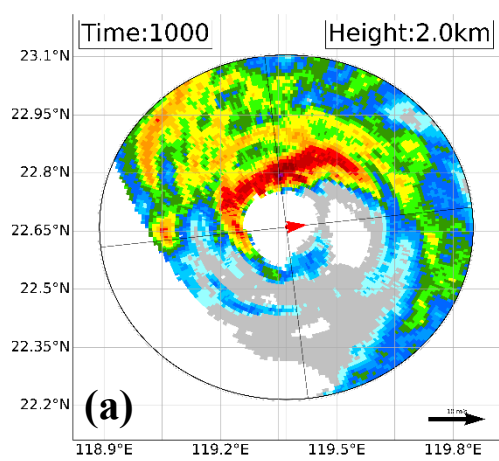


Figure 3.11 5 km height (top) and 2 km height (bottom) Hovmöller diagram for Danas (2025) for Z_H (left) and Z_{DR} (right) from 0800 – 1600 UTC July 6, 2025.



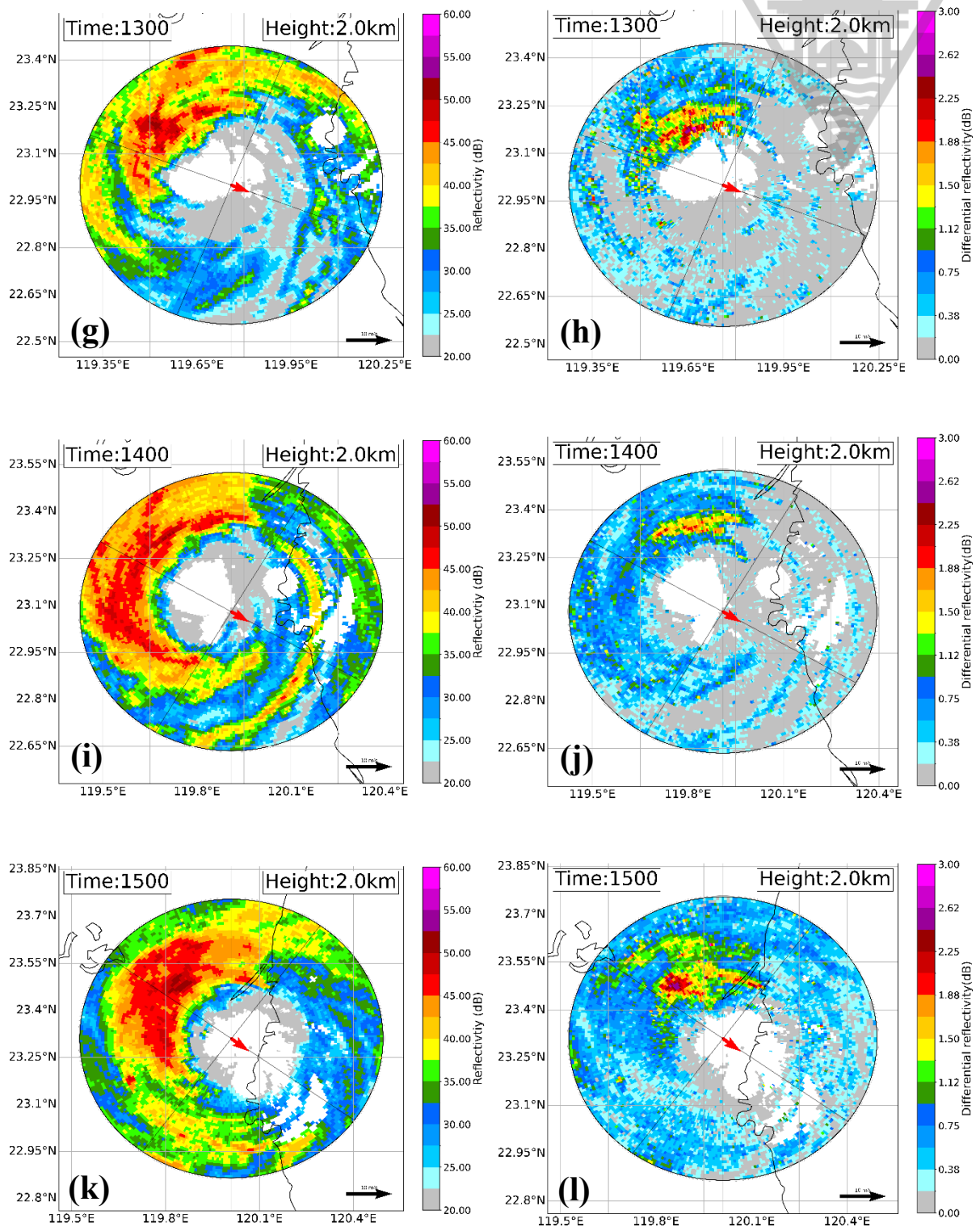
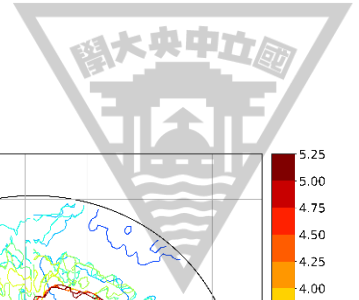
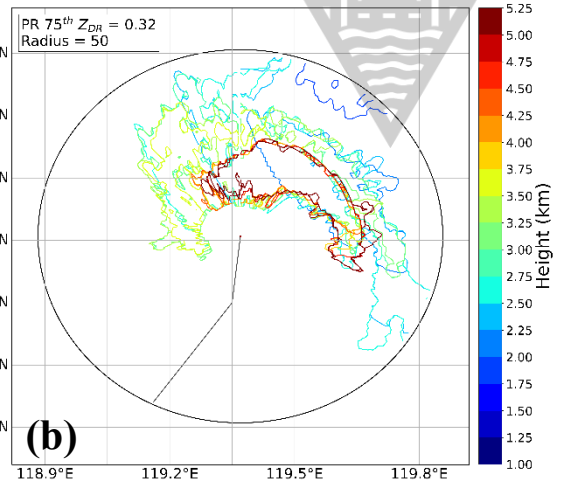
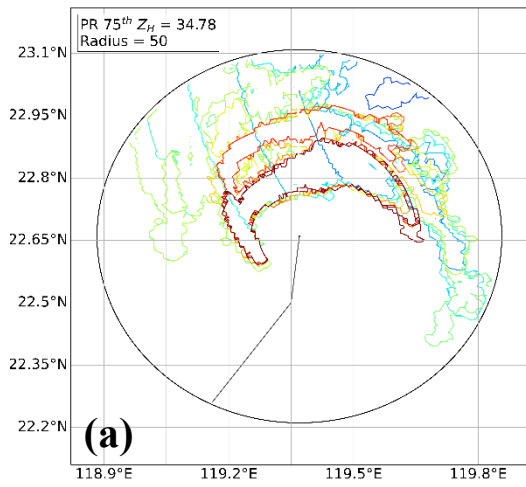


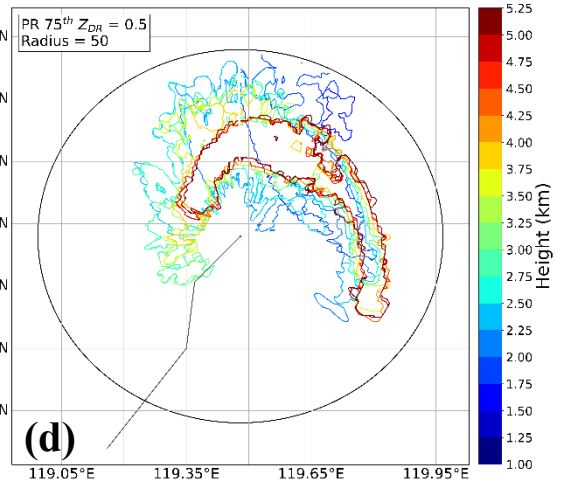
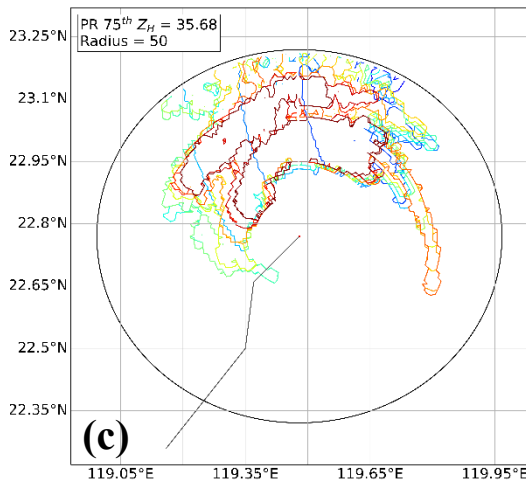
Figure 3.12 2 km height CAPPI Z_H (left) and Z_{DR} (right) from 1000 UTC (top) to 1500 UTC (bottom) with 1 hour interval.



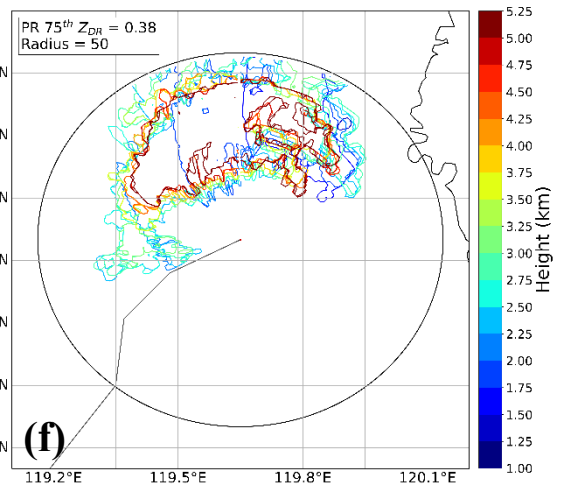
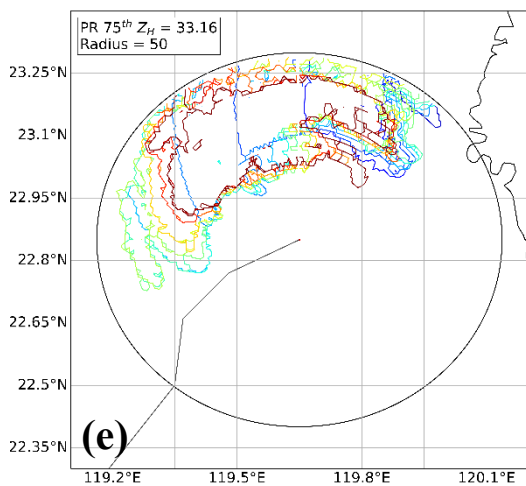
1000



1100



1200



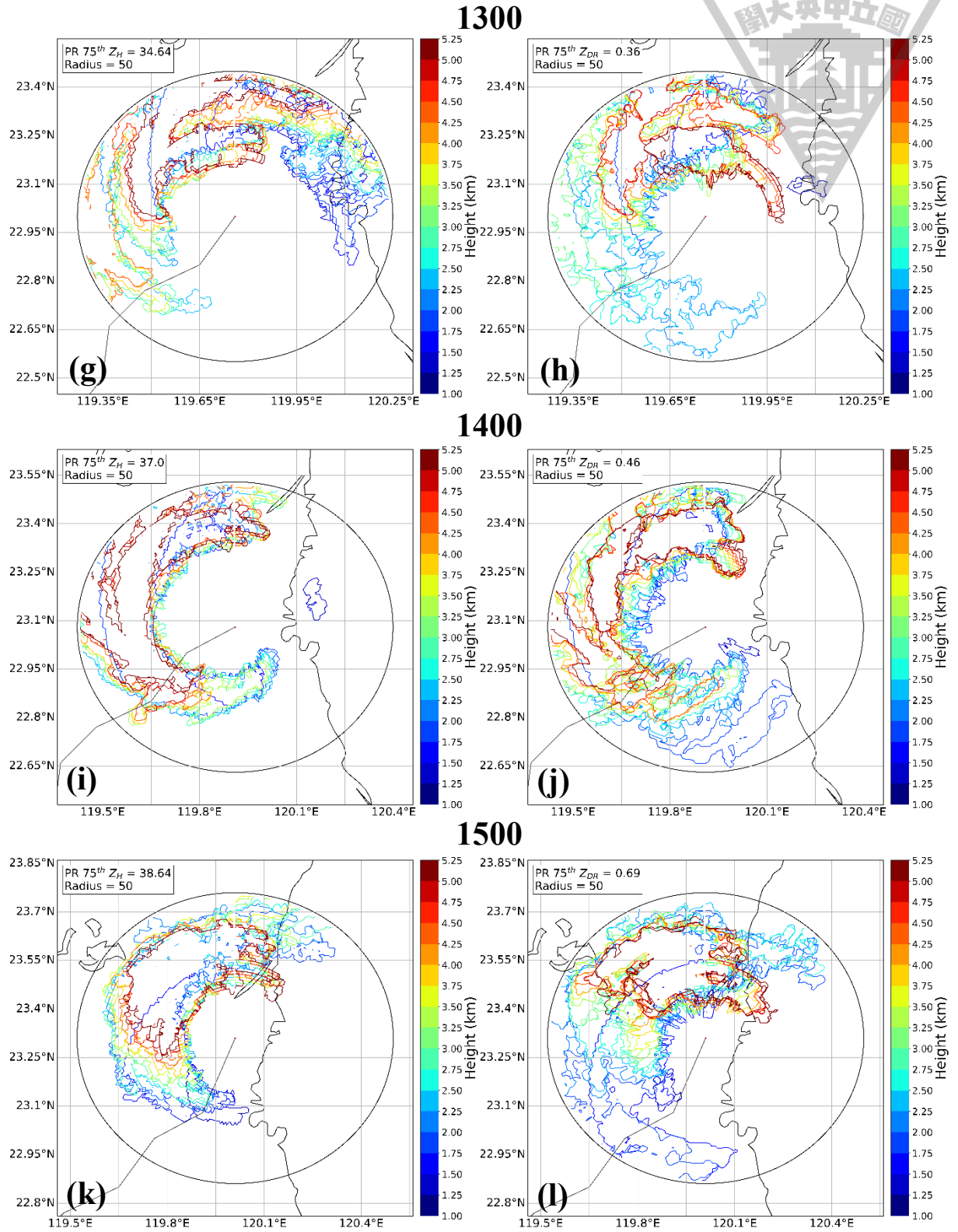


Figure 3.13 Contour-height plot of Z_H (left) and Z_{DR} (right) for case Danas from 1000UTC (top) to 1500 UTC (bottom) July 6, 2025 with 1 hour interval.

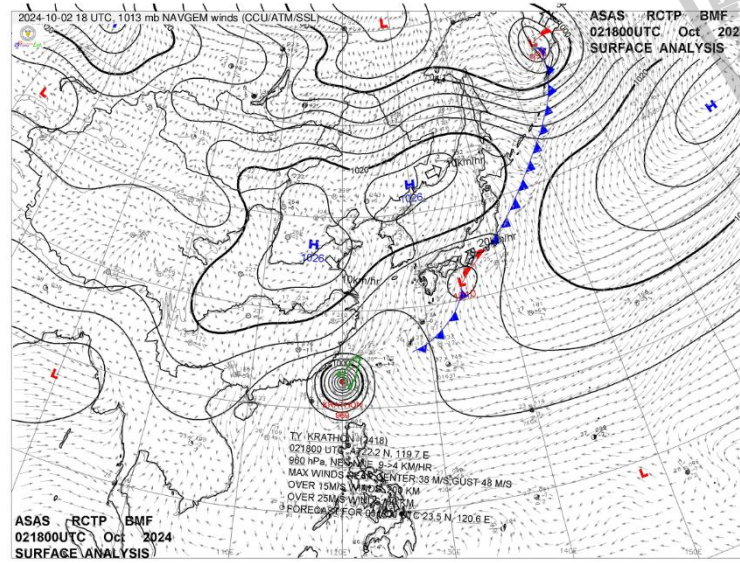


Figure 3.14 Surface weather analysis plot of 1800 UTC 2 October, 2024

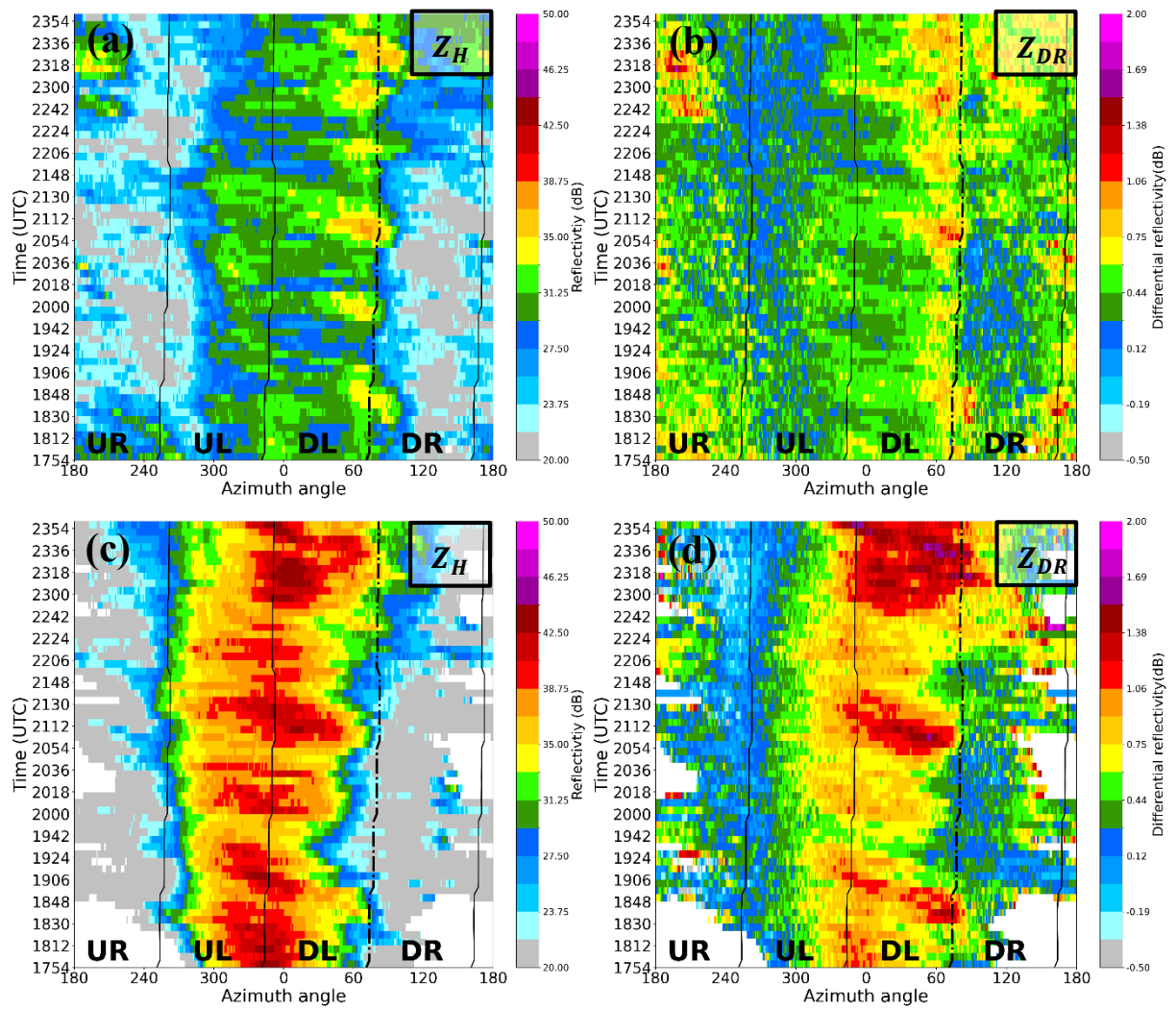
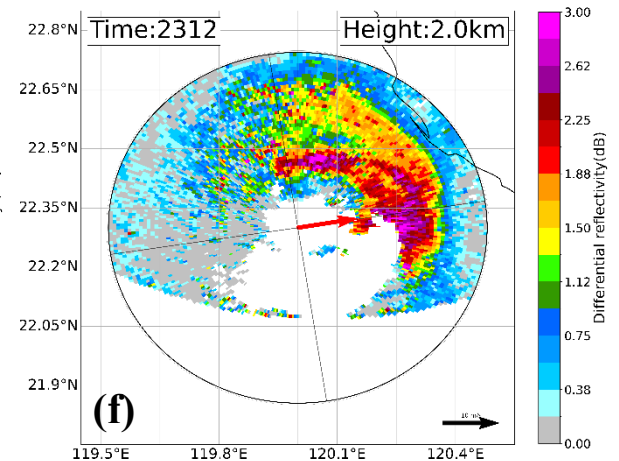
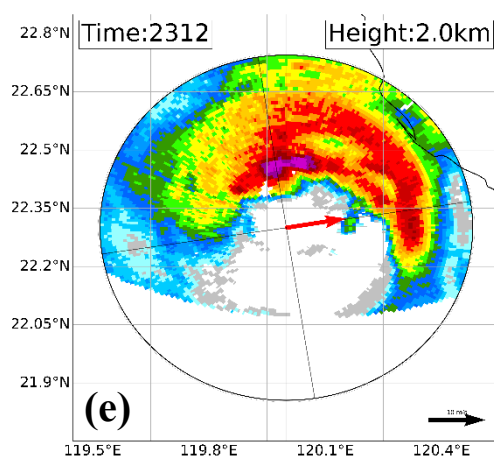
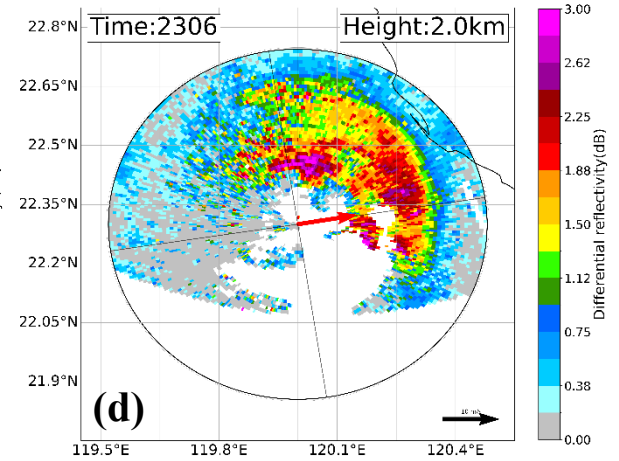
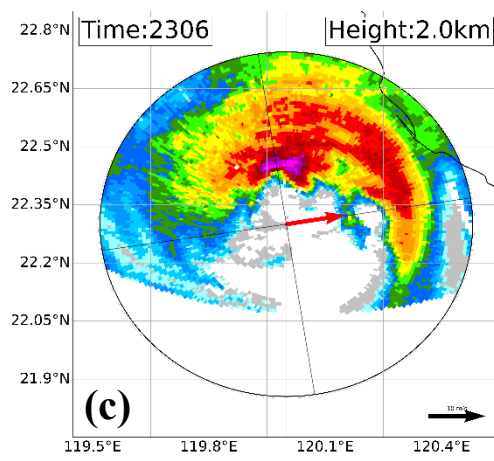
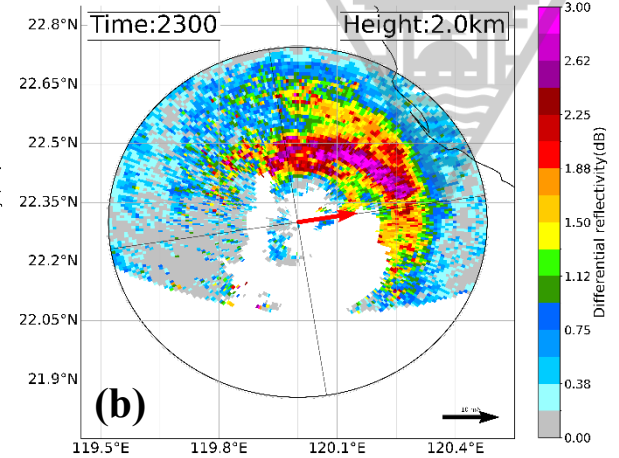
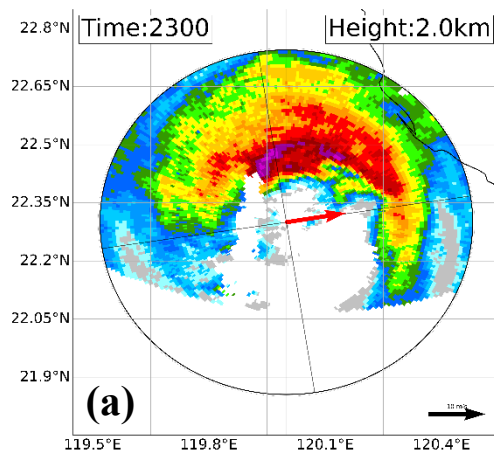


Figure 3.15 5 km height (top) and 2 km height (bottom) Hovmöller diagram for Krathon (2024) for Z_H (left) and Z_{DR} (right) from 1754 – 2354 UTC October 1, 2024.



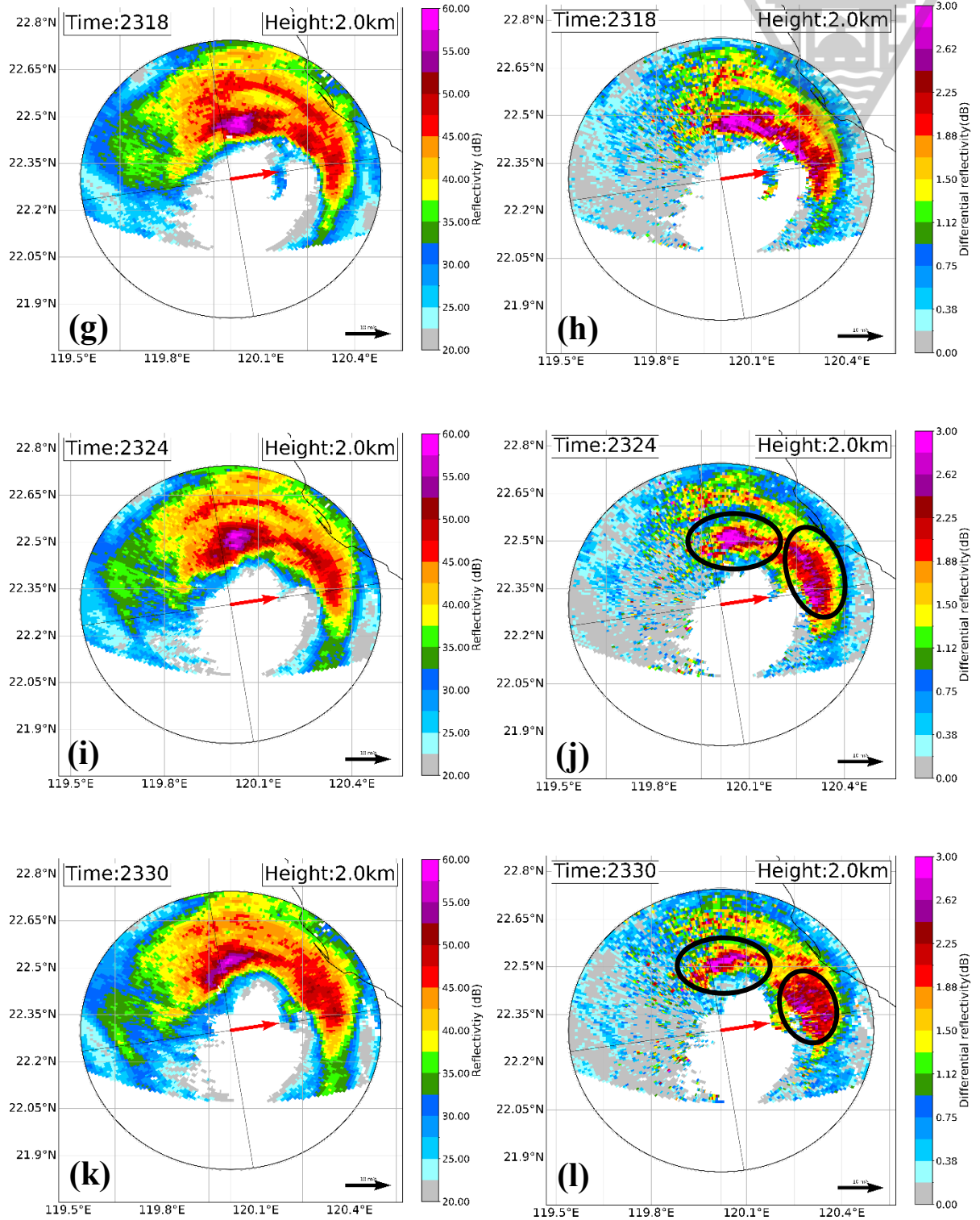
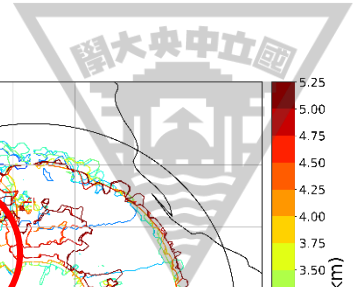
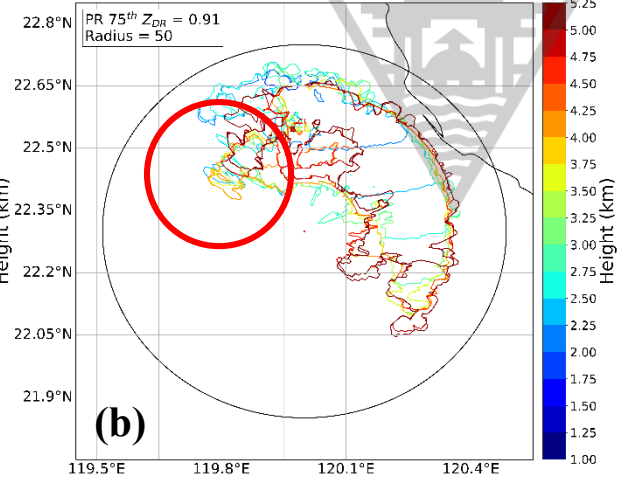
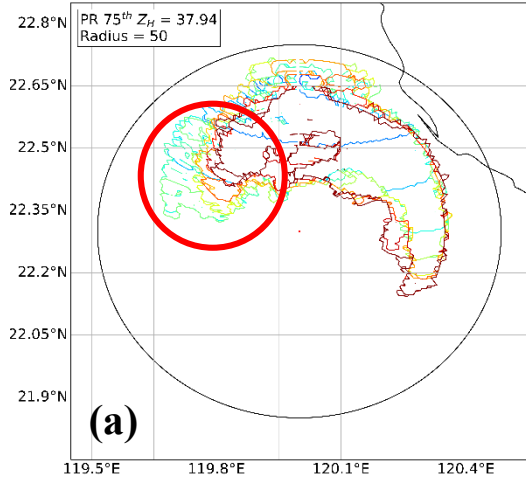


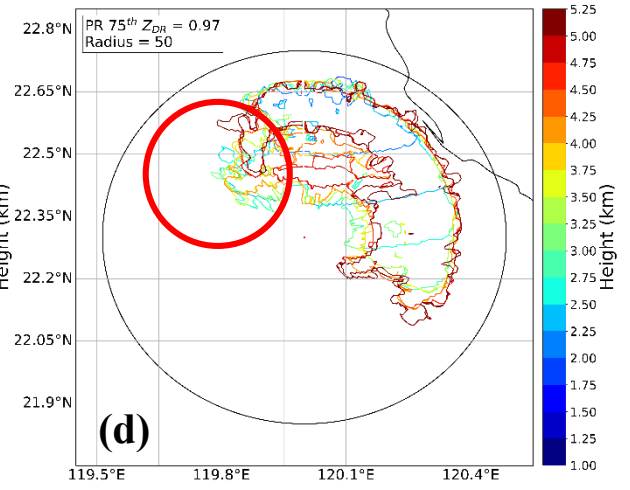
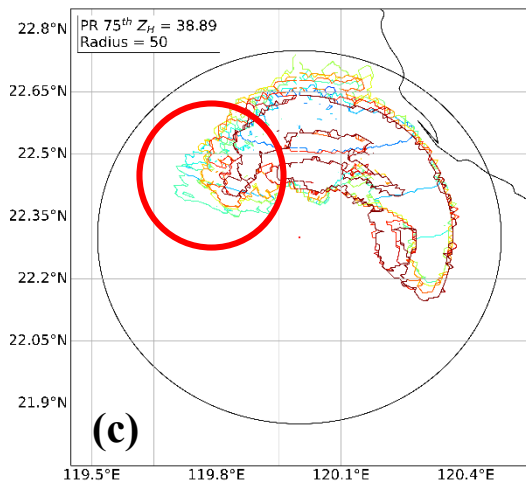
Figure 3.16 2 km height Z_H (left) and Z_{DR} (right) from 2300 UTC (top) to 2330 UTC (bottom). The two circles in (j) and (l) represent the convection caused by two potential interactions.



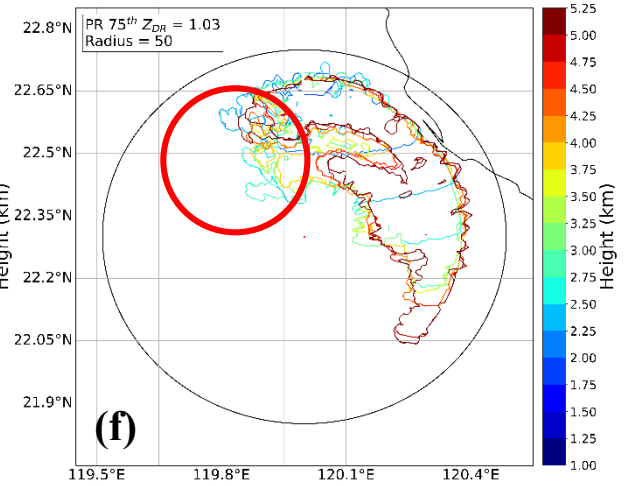
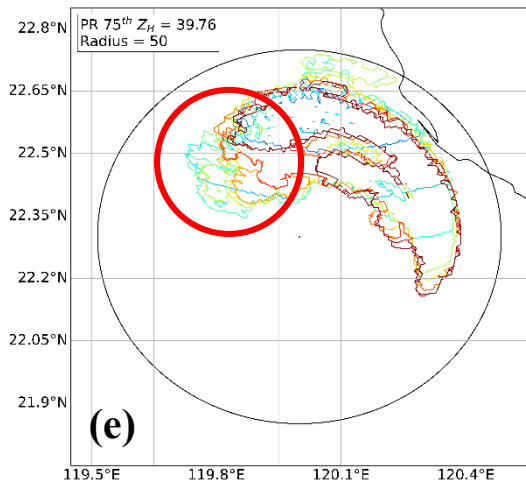
2300



2306



2312



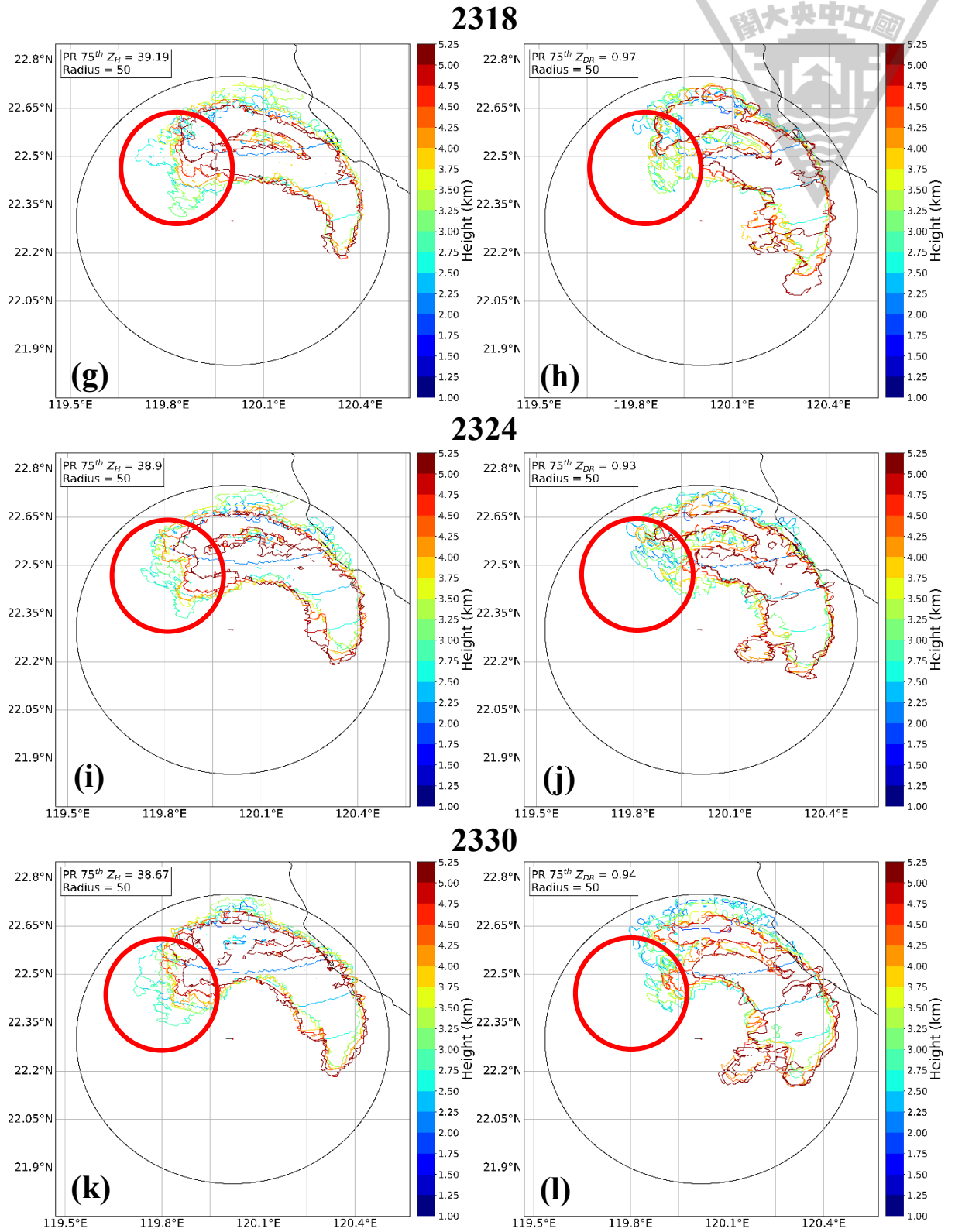


Figure 3.17 Contour-height plot of Z_H (left) and Z_{DR} (right) for case Krathon from 2300 UTC (top) to 2330 UTC (bottom) October 2, 2024. The red circles represent the location of convection front end.

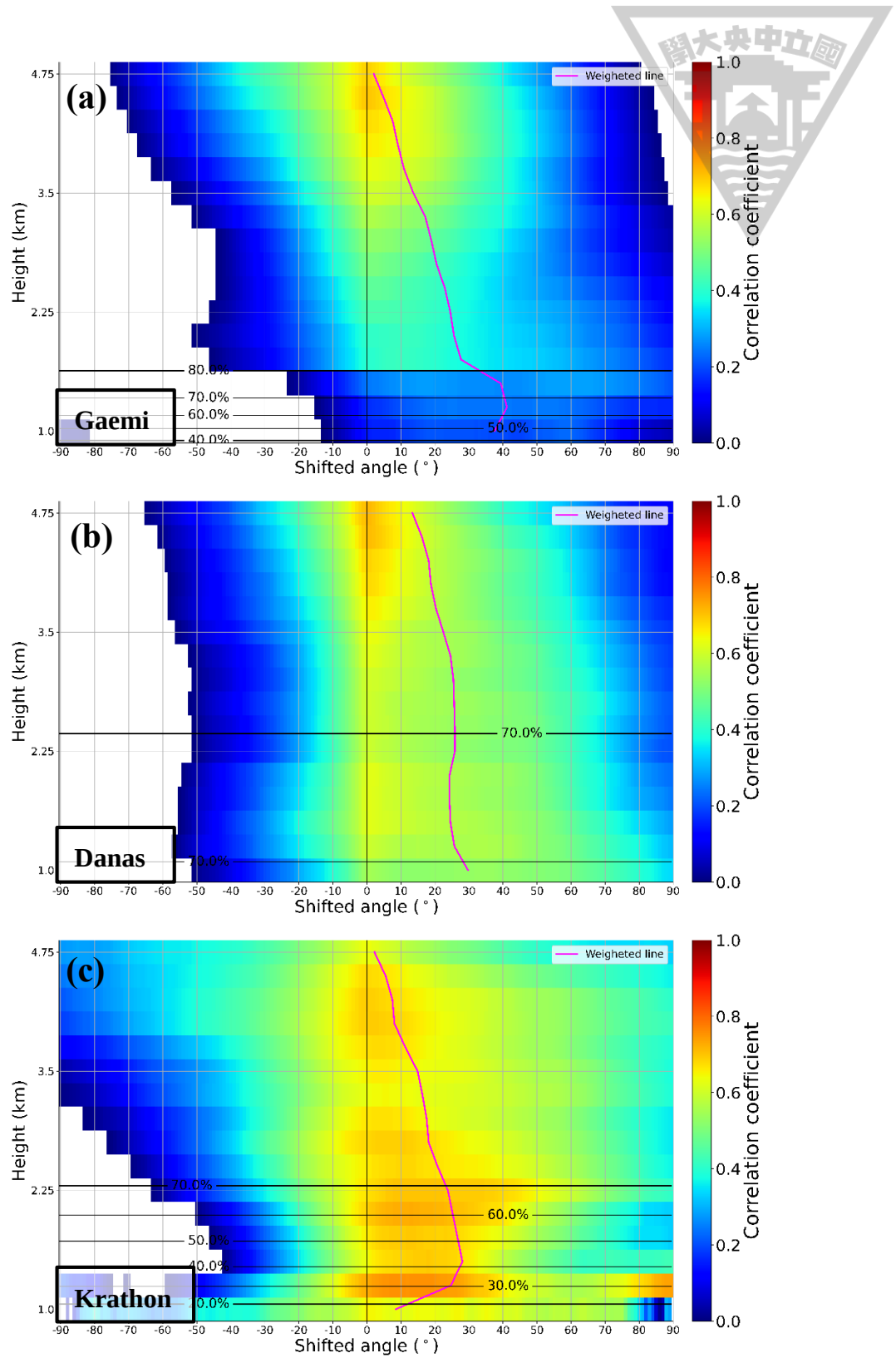
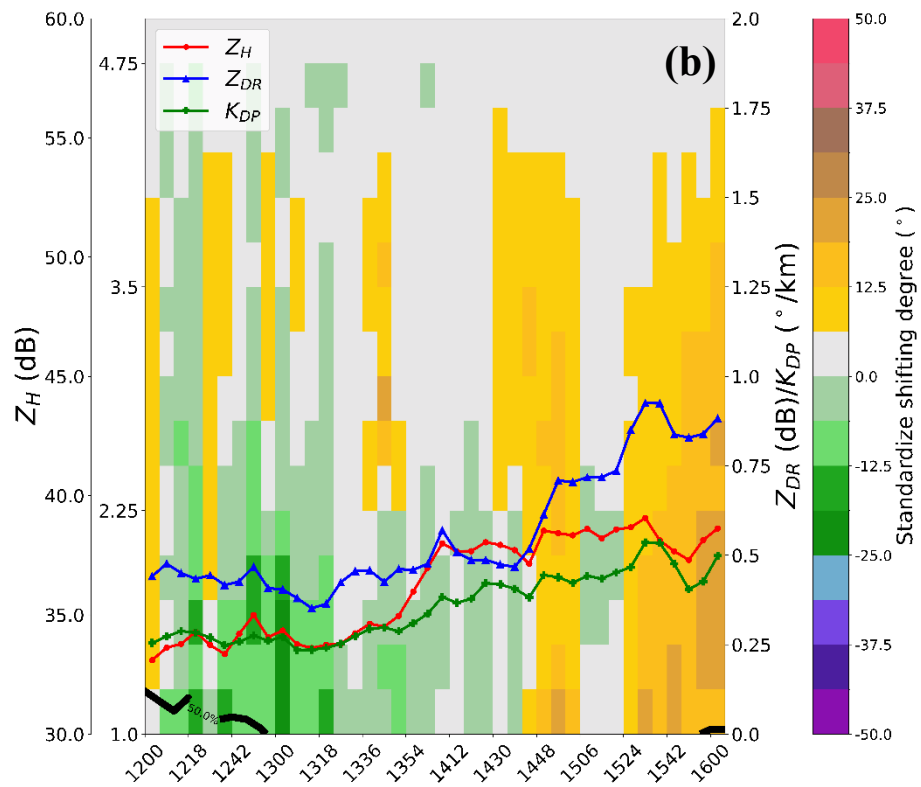
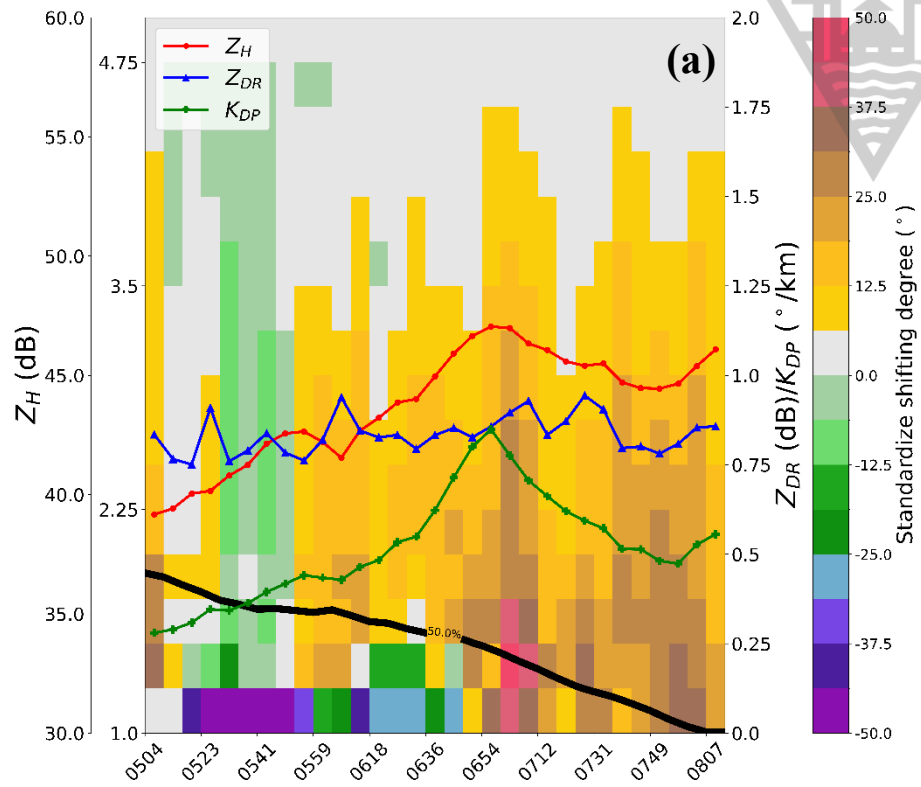
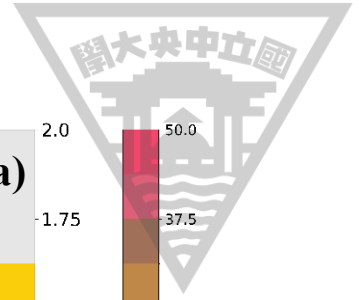


Figure 3.18 Correlation plot between Z_H and Z_{DR} for case Gaemi at 0706 UTC July 24, 2024 (top), Danas at 1500 UTC July 6, 2025 (middle) and Krathon at 2300 UTC October 2, 2024 (bottom).



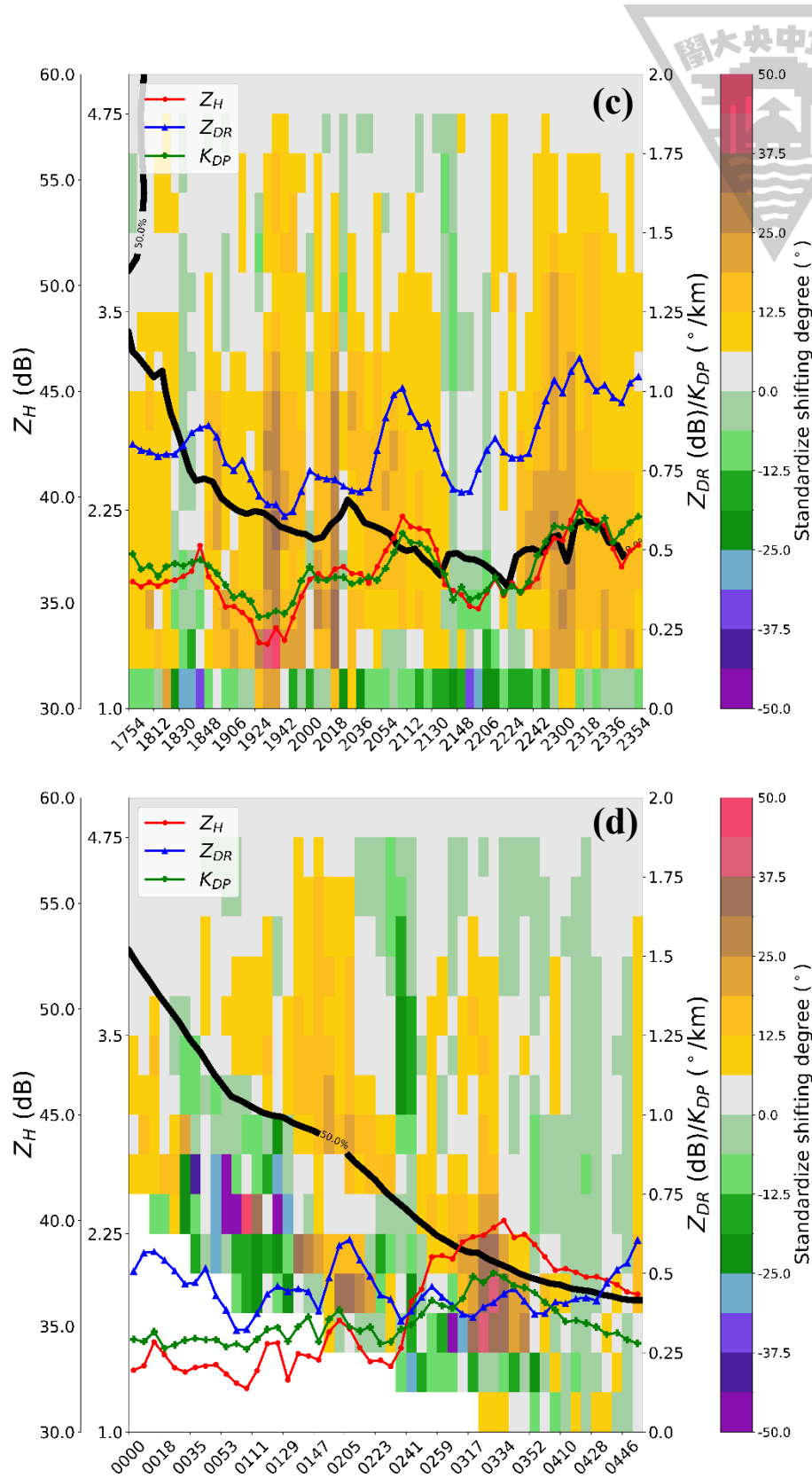


Figure 3.19 Correlation weight value time series of ground based cases (a) Gaemi, (b), Danas, (c) Krathon and (d) Chanthu. Black thick line represents 50% data coverage height. Red, blue and green line represent 75th percentile of reflectivity, Z_{DR} and K_{DP} , respectively.

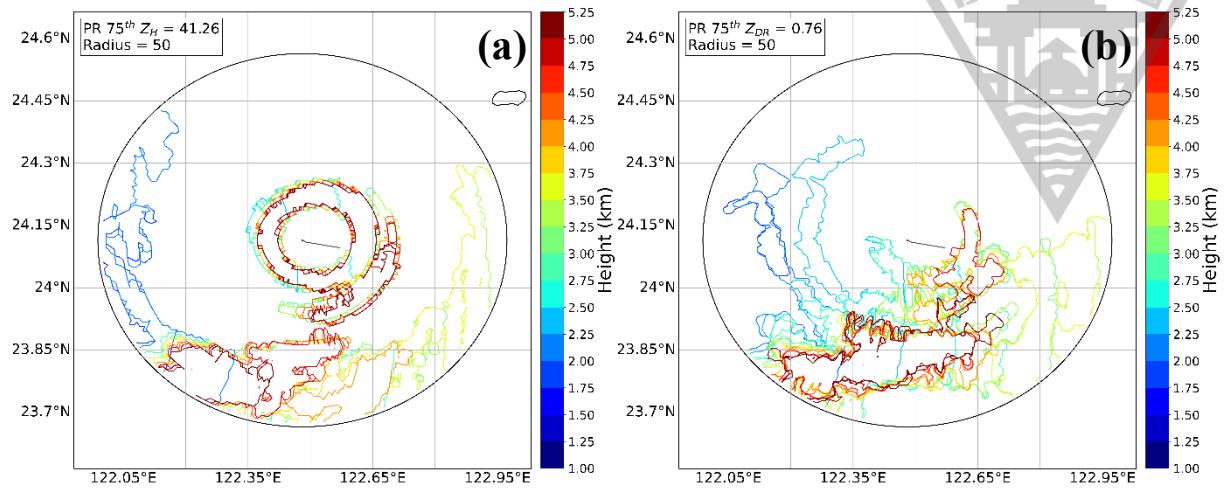


Figure 3.20 Contour-height of Z_H (left) and Z_{DR} (right) at 0535 UTC July 24, 2024.

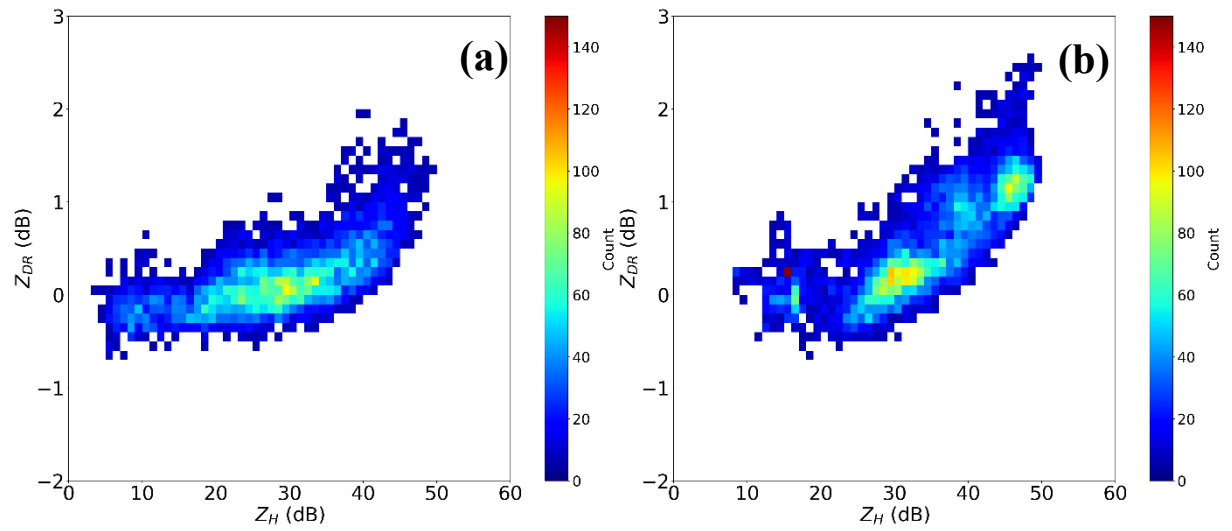


Figure 3.21 2 km height Density plot between reflectivity and Z_{DR} at 1300 UTC (left) and 1530 UTC (right) July 6, 2025.

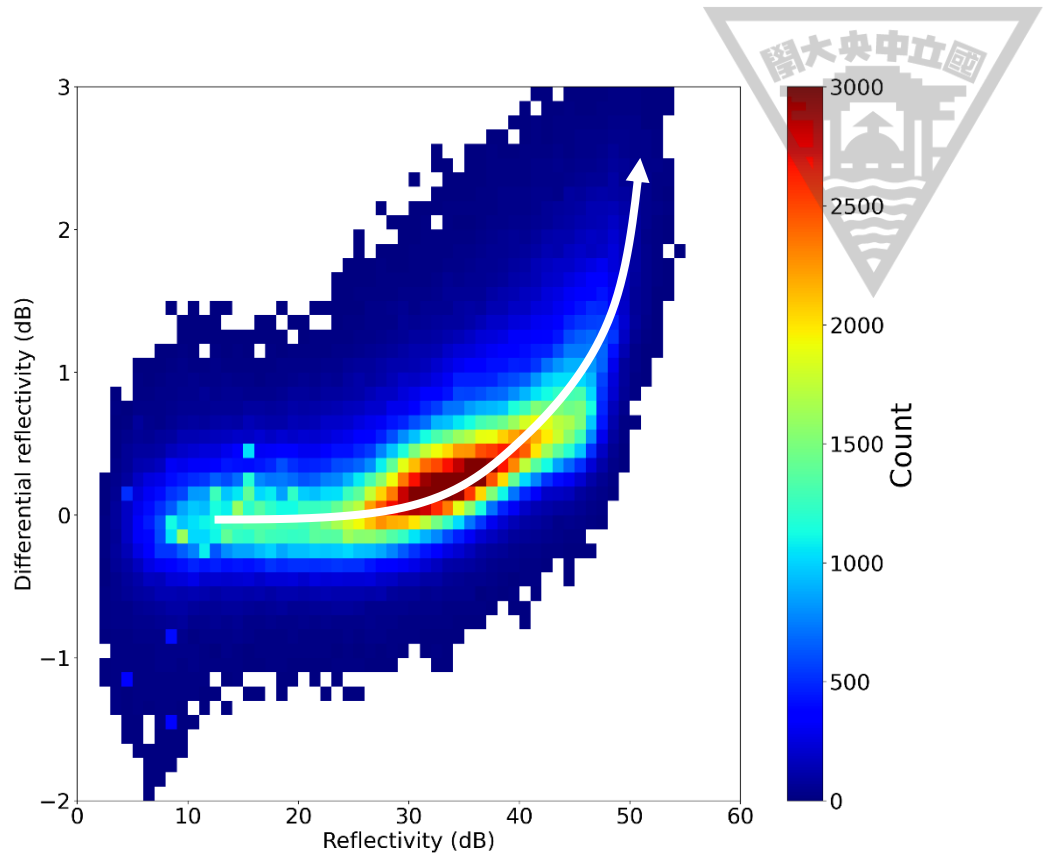


Figure 3.22 Same as Fig 3.20 but for time from 1200 UTC to 1600 UTC July 6, 2025. The arrow indicate the general tendency between Z_{DR} and Z_H .

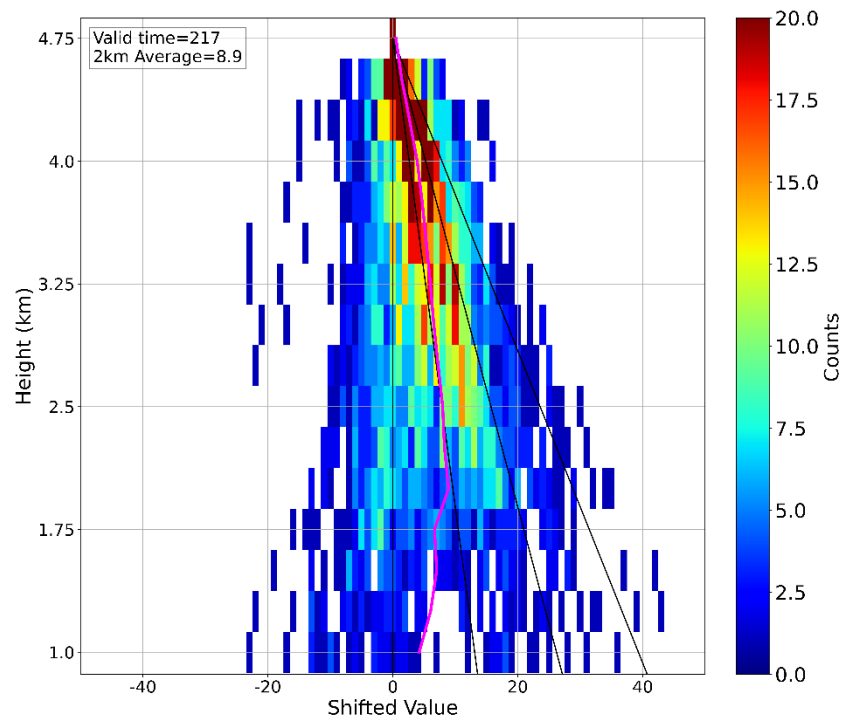


Figure 3.23 Density plot of correlated weighted value over all ground base cases. Pink line represents mean weighted value over each height. 2km average represents mean weighted value at 2km height. Four black line from left to right represents 0° , 10° , 20° and 30° shifting value at 2 km and its extension to top layer.

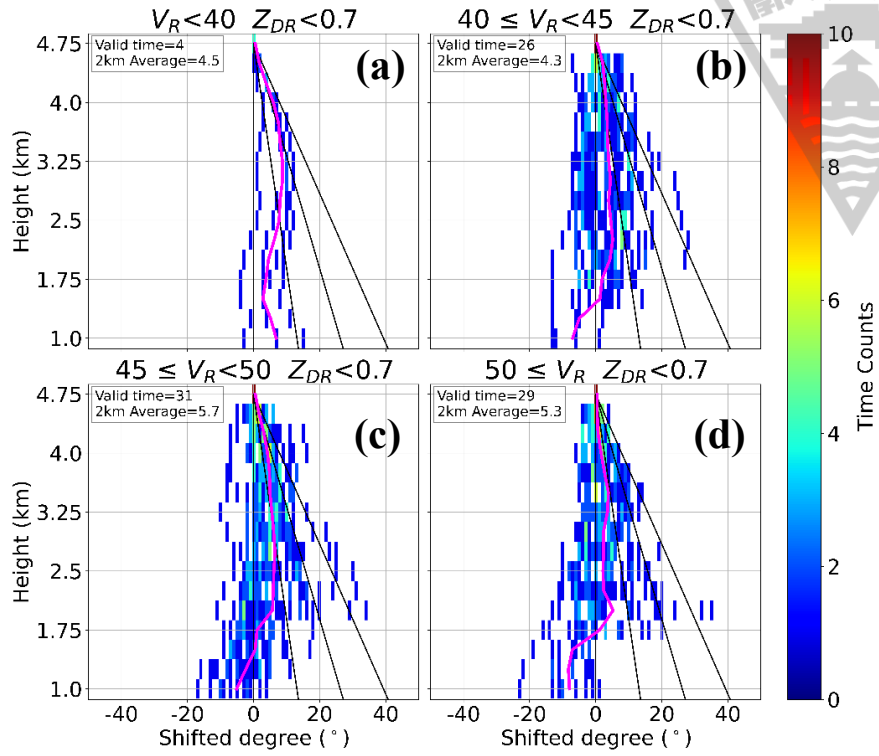


Figure 3.24 Density plot of all ground base cases classified based on 90-99th percentile averaged V_R and 75 percentile Z_{DR} below 0.7 dB. From (a) $V_R < 40$ m/s, (b) $40 \text{ m/s} < V_R < 45$ m/s, (c) $45 \text{ m/s} < V_R < 50$ m/s and (d) $50 \text{ m/s} < V_R$.

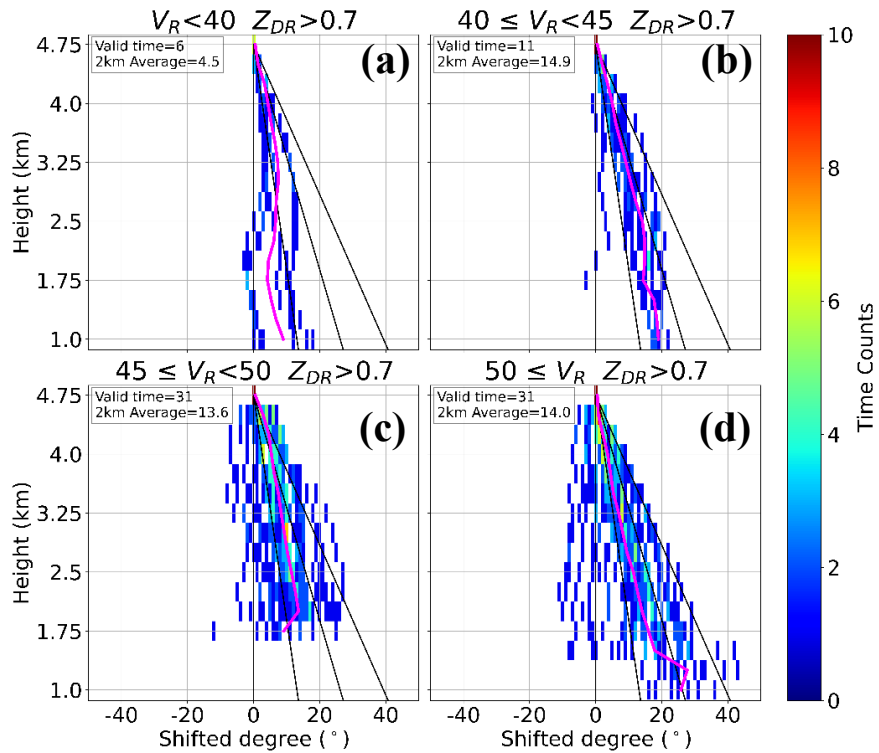


Figure 3.25 Similar to Fig 3.23 but for Z_{DR} above 0.7 dB.

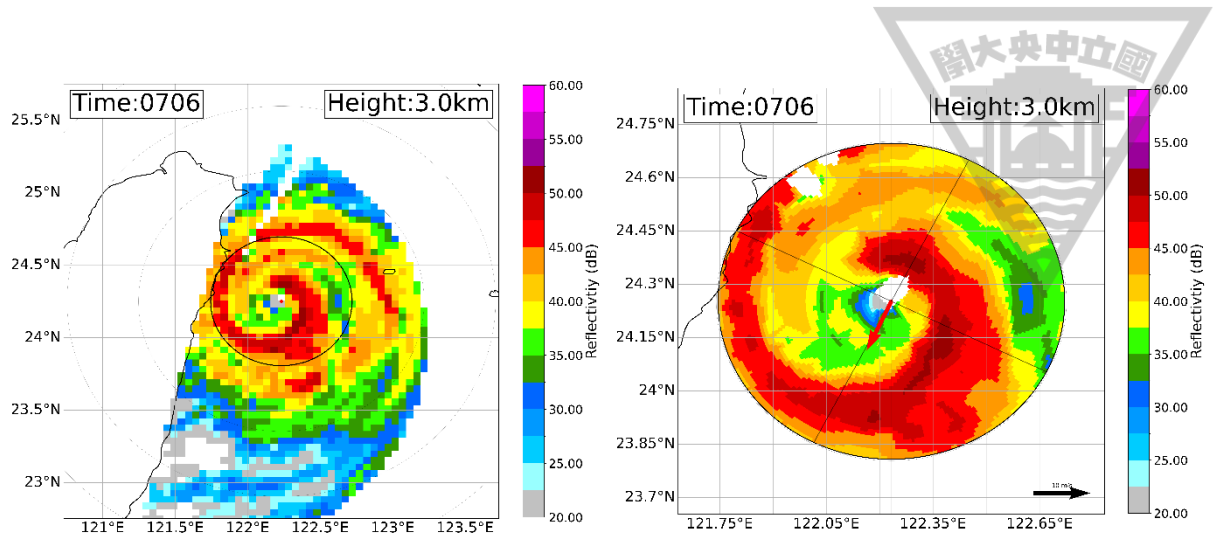


Figure 4.1 Downscaled to 5 km horizontal resolution of (a) 3 km height CAPPI of reflectivity from RCHL at 0706 UTC 24 July, 2024. (b) cylindrical coordinate interpolated at 3 km of reflectivity at the same time with (a).

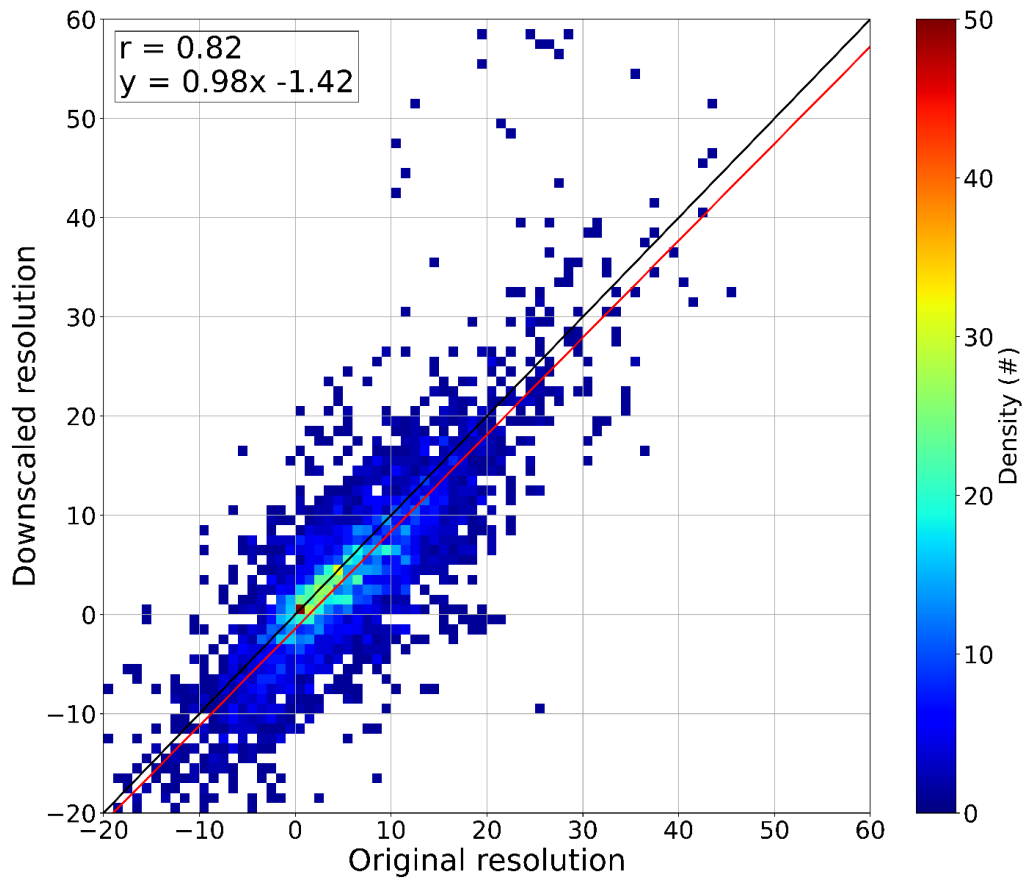


Figure 4.2 Density plot of correlated weighted line between original resolution (x-axis) and downsampled resolution (y-axis). r represents Pearson correlation coefficient and equation on top left represents the linear regression line coefficient.

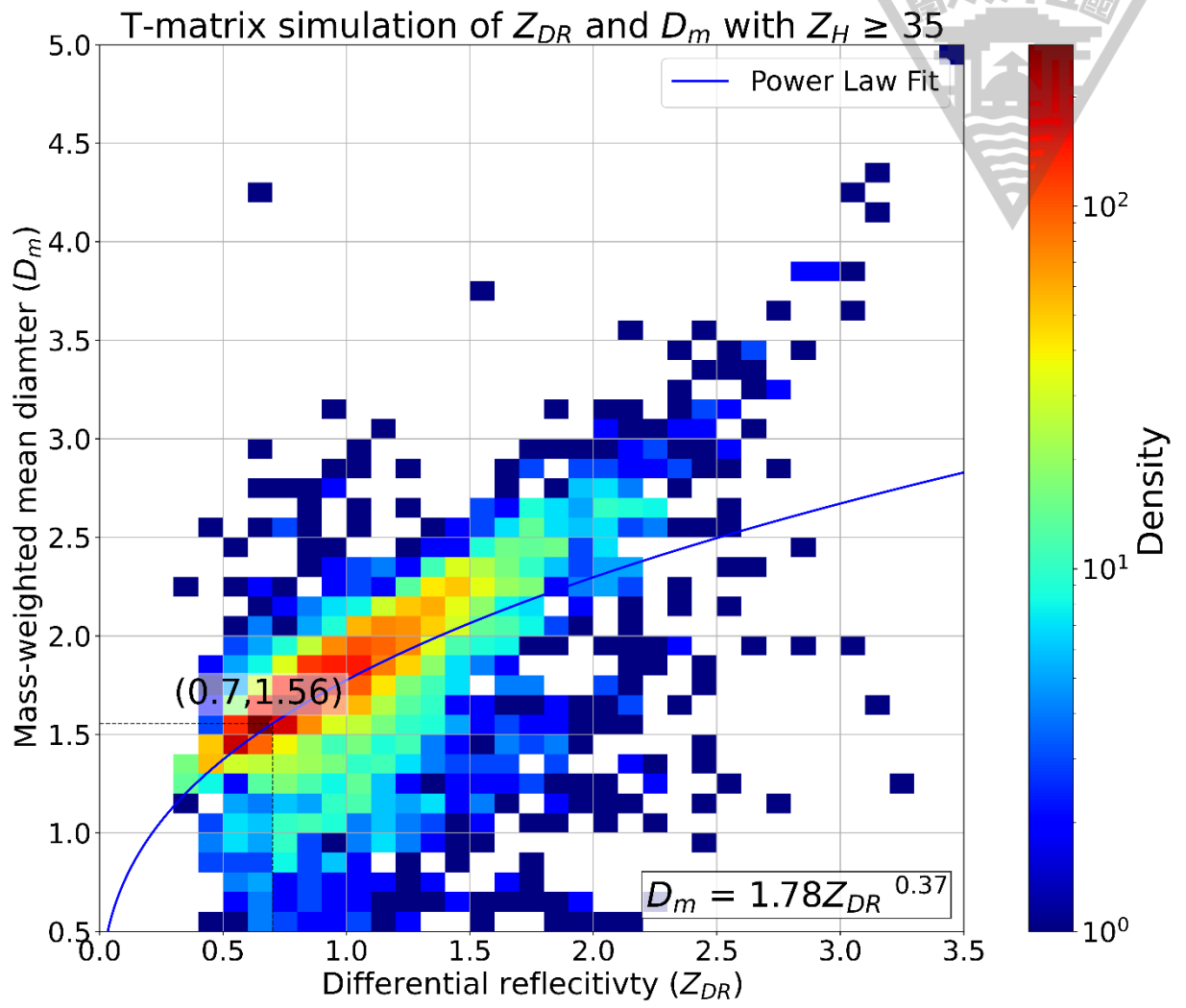


Figure 4.3 T-matrix simulation of Z_{DR} (x-axis) and D_m (y-axis) with reflectivity threshold of 35 dBZ.

Bottom right equation is the power-law fitting result and its coefficient.

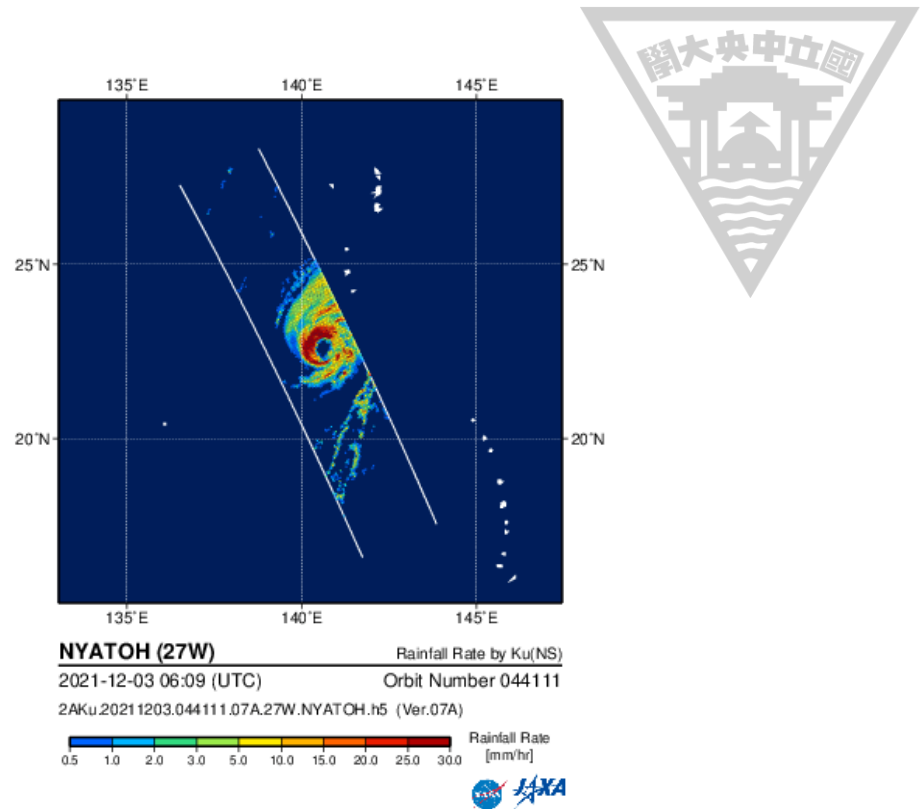


Figure 4.4 Maximum reflectivity of Nyatoh at 06 UTC December 3,2021 from JAXA/EORC database.

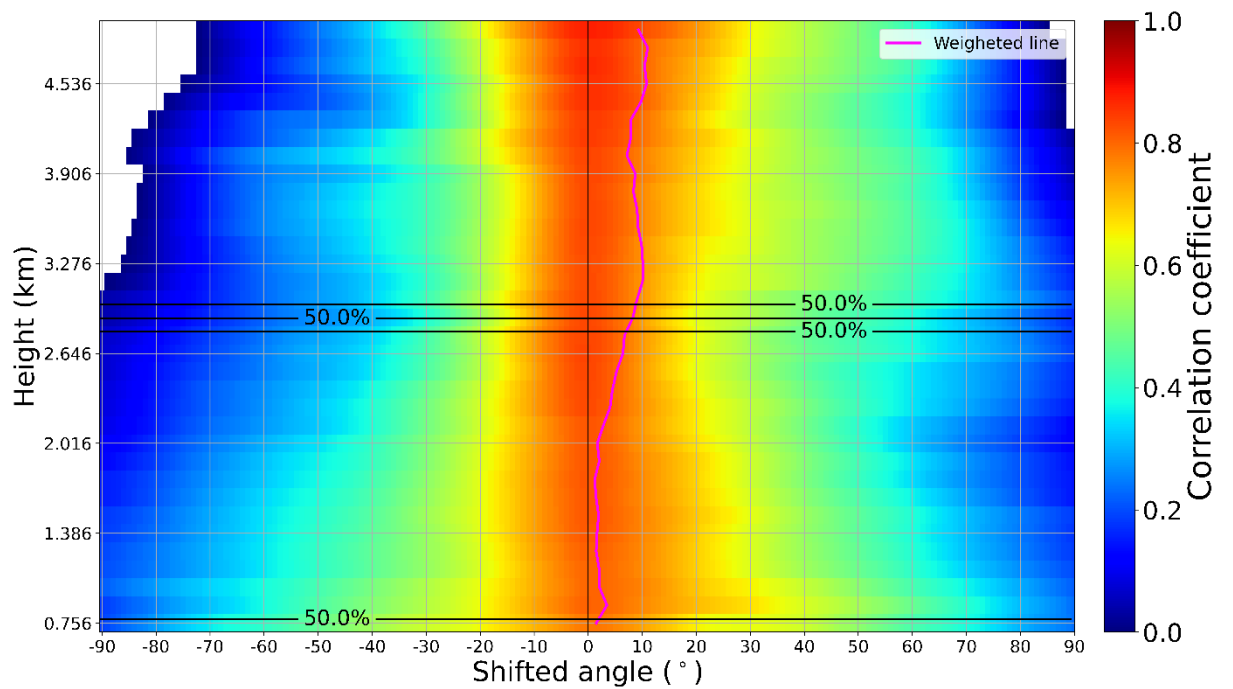


Figure 4.5 Correlation plot between Z_e and D_m for case Nyatoh.

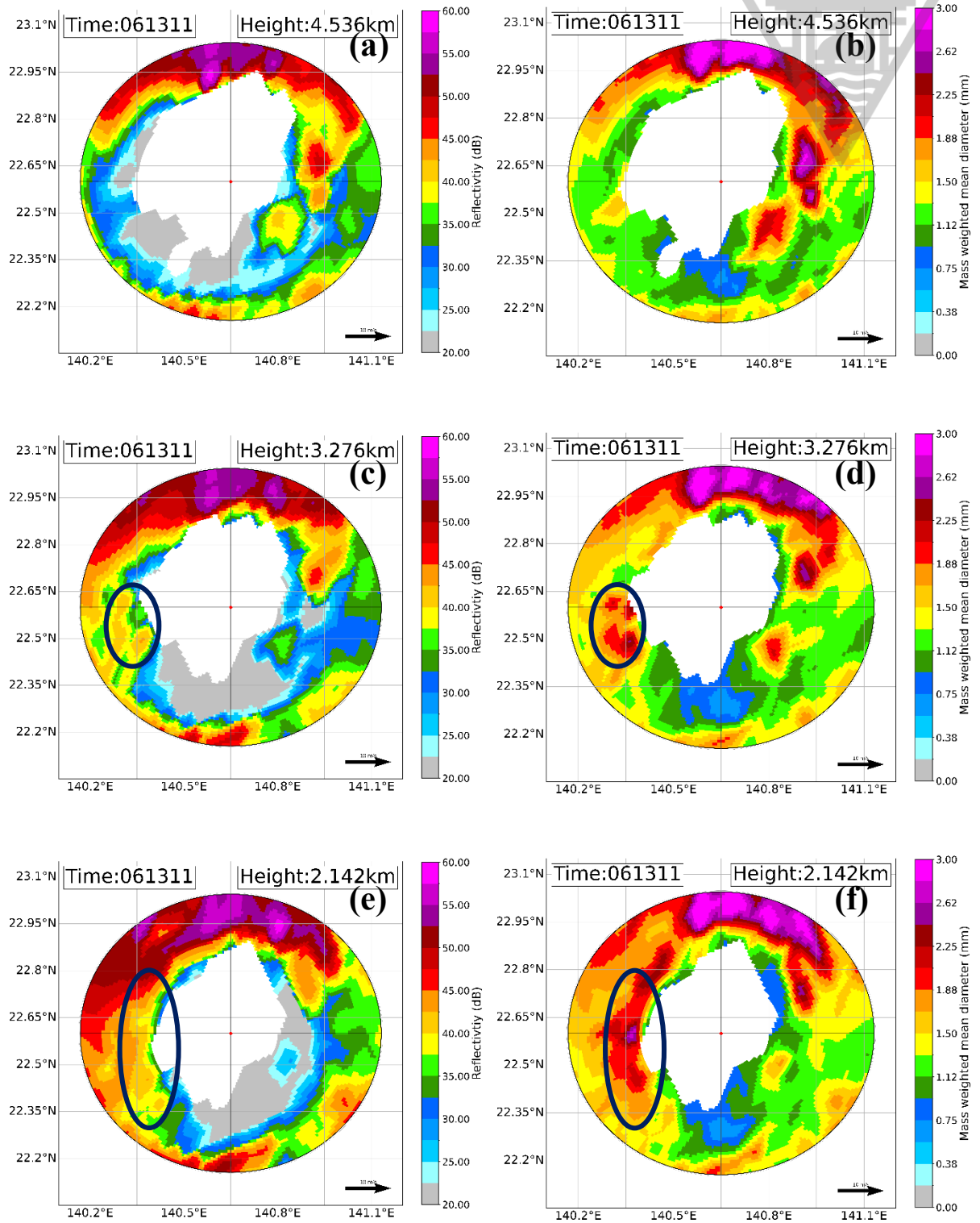


Figure 4.6 CAPPI plot of Z_e (left) and D_m (right) at 4.53 km height (top), 3.28 km (middle) and 2.14 km height (bottom). The circles in (c), (d), (e), (f) are location of high D_m but lower Z_e .

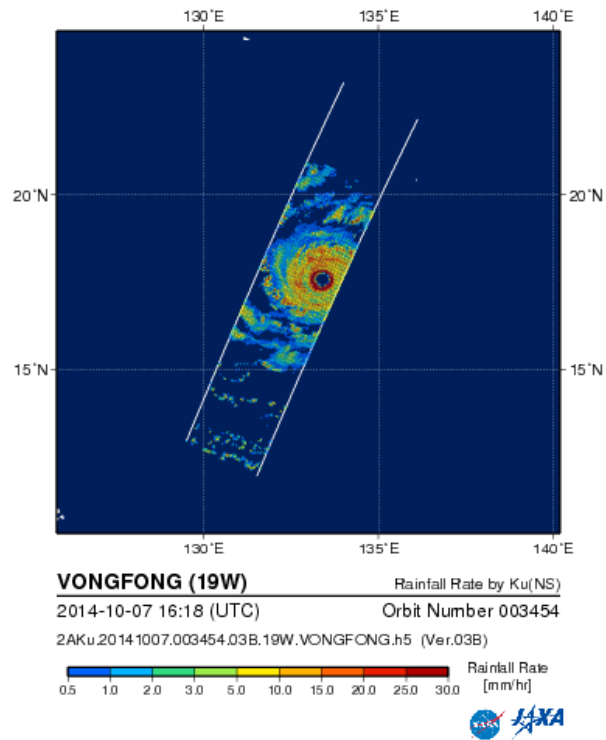


Figure 4.7 Maximum reflectivity of Vongfong at 16 UTC October 7, 2014 from JAXA/EORC database.

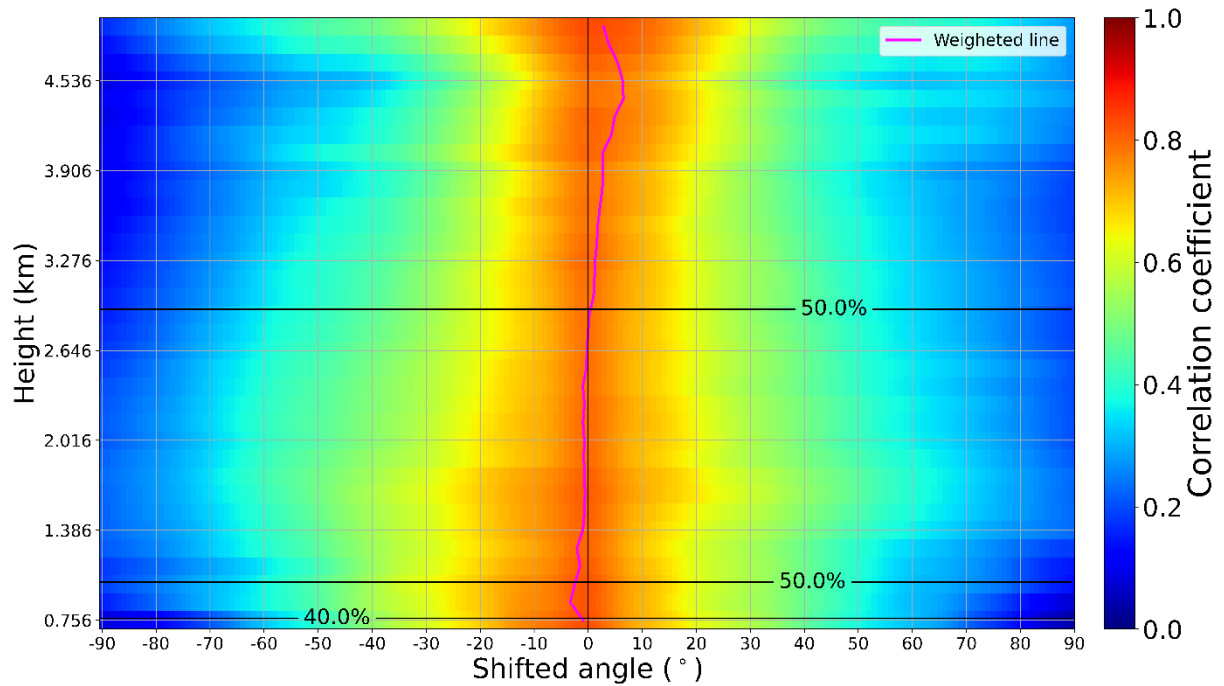


Figure 4.8 Correlation plot plot between Z_e and D_m for case Vongfong.

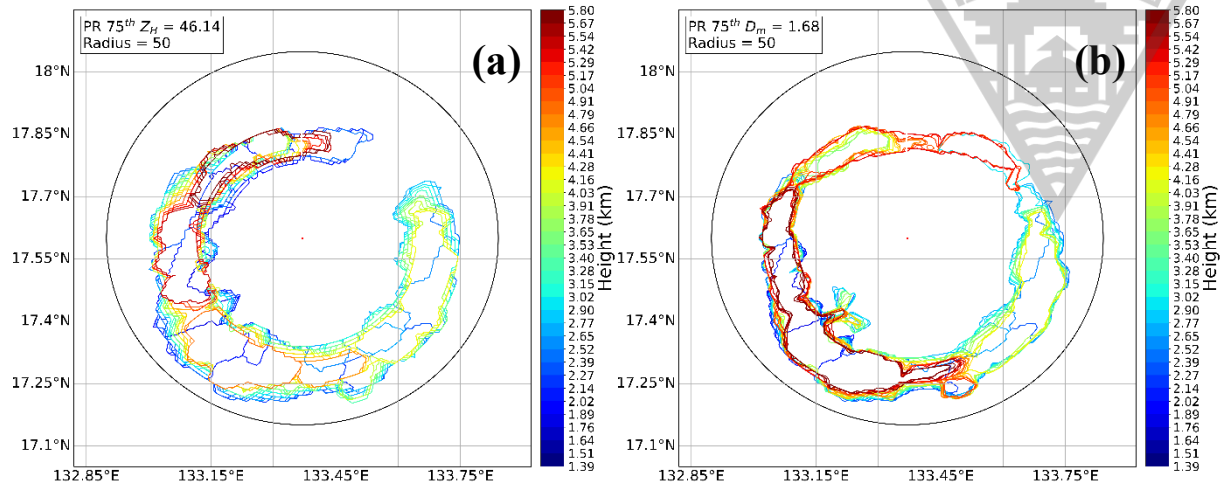


Figure 4.9 Contour-height plot for case Vongfong with equivalent reflectivity (left) and D_m (right).

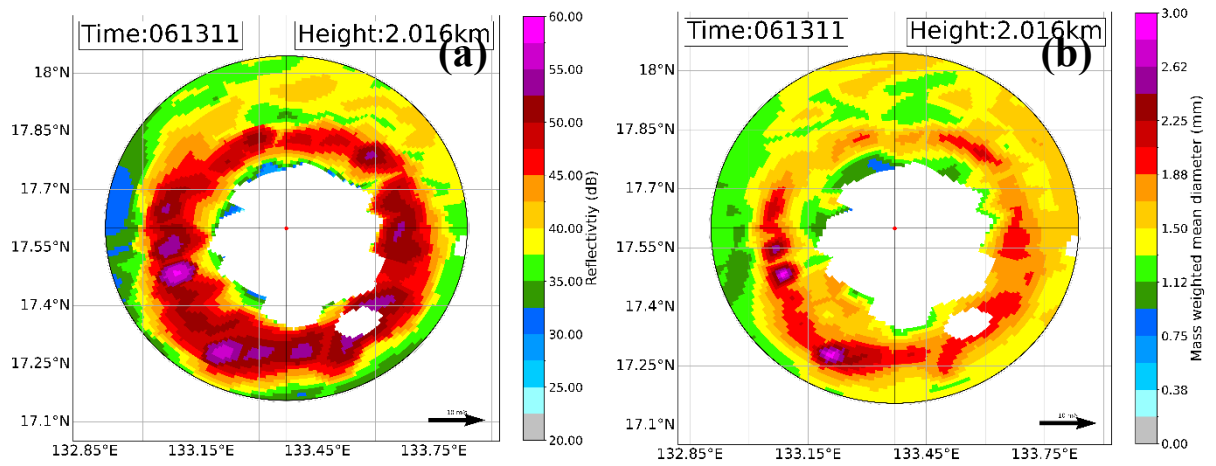


Figure 4.10 2 km height CAPPI for case Vongfong with equivalent reflectivity (left) and D_m (right).

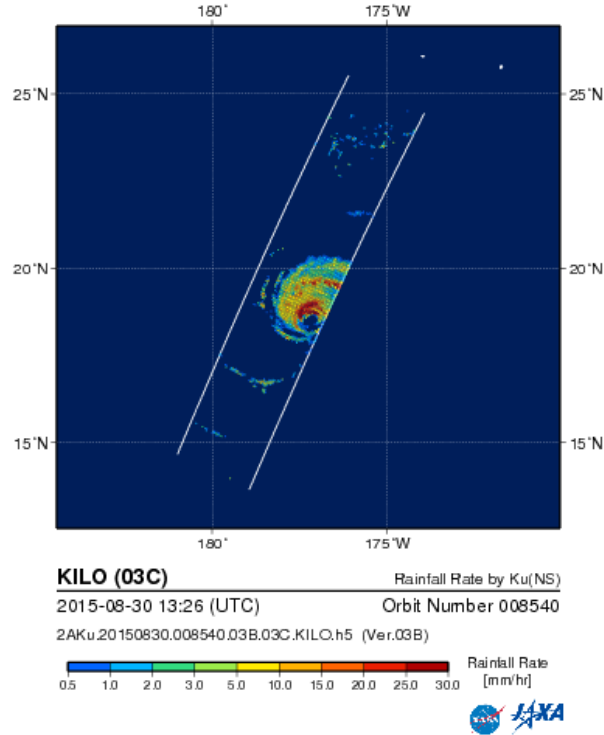


Figure 4.11 Maximum reflectivity *Kilo* at 13 UTC August 30, 2015 from JAXA/EORC database.

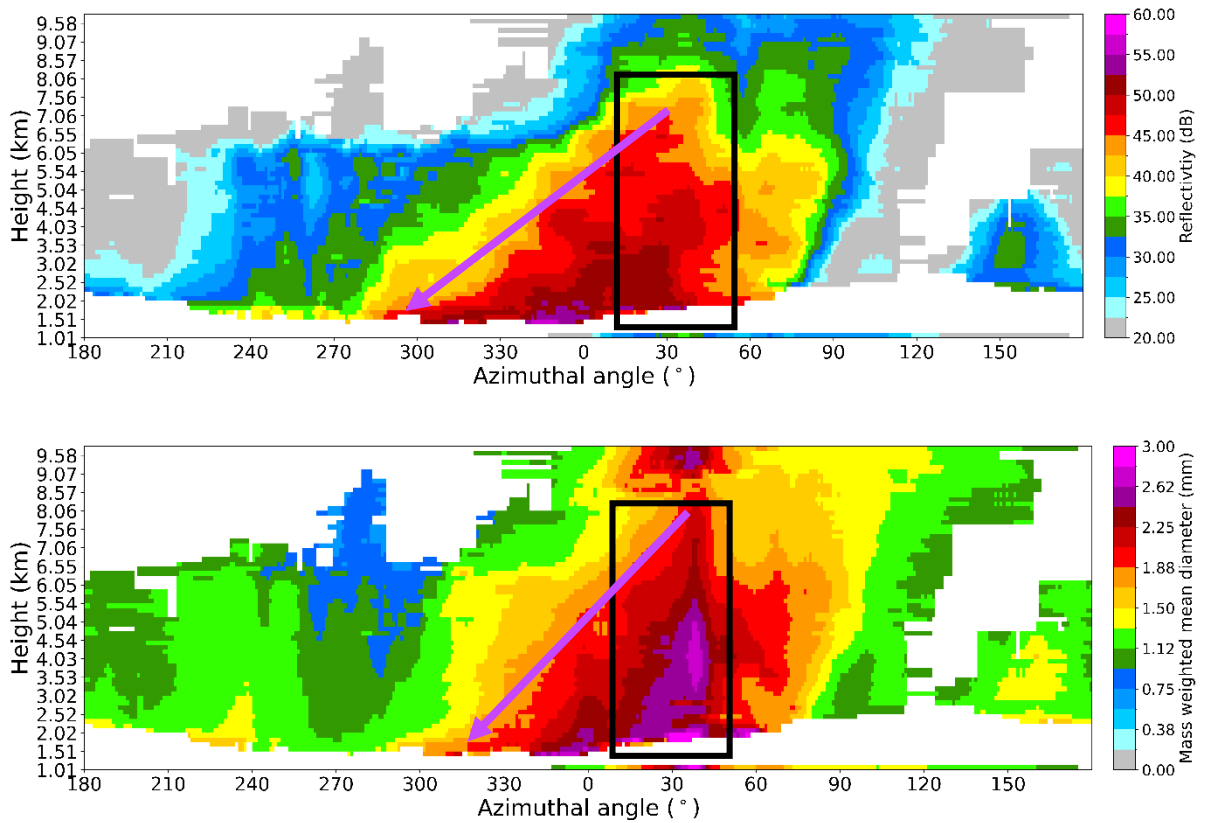


Figure 4.12 Azimuthal-height plot of reflectivity (top) and D_m (bottom) for case *Kilo*. The arrow indicate the tendency of strong signal's front end.

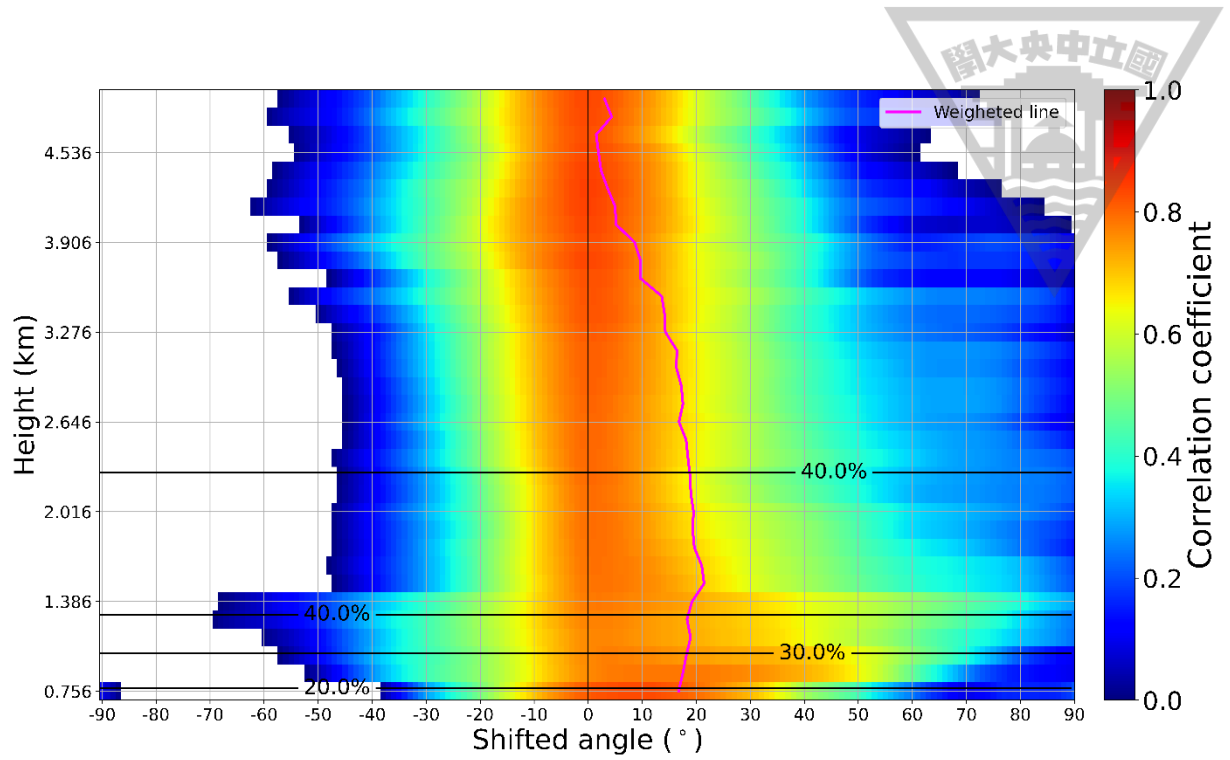


Figure 4.13 Correlation plot between Z_e and D_m for case Kilo.

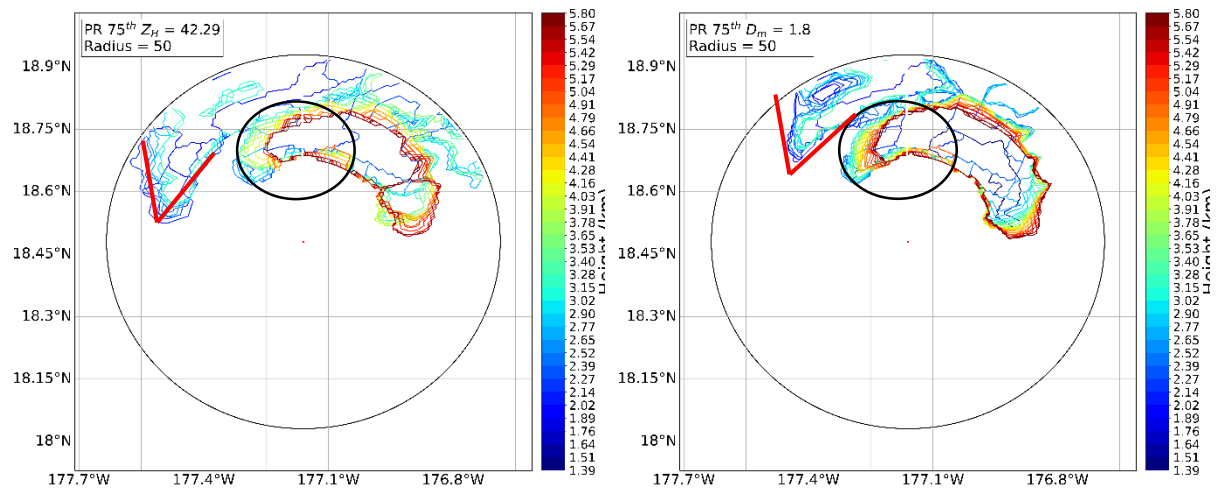


Figure 4.14 Contour-height plot for case Kilo between reflectivity (left) and D_m (right).



Tables

Table 1 Ground-based radar cases name, time of interest (UTC) and radar used.

Case name	Time of interest (UTC)	Radar
<i>Gaemi</i>	0500 – 0800 UTC Jul. 24, 2024	RCHL
<i>Danas</i>	0800 – 1600 UTC Jul. 6, 2025	RCCG
<i>Chanthu</i>	0000 – 0500 UTC Sep. 12, 2021	RCWF
<i>Krathon</i>	1500 – 2400 UTC Oct. 2, 2024	RCCG

Table 2 Case info for GPM radar. Central pressure and wind speed information are estimated from IBTrACS data base.

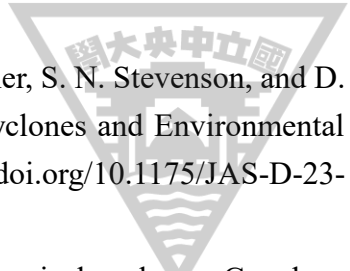
Case name	Time (UTC)	Central pressure (mb)	Wind speed (kts)	PR 75 th D_m	Standardized shifting at 2km
<i>Halong</i>	2019 11 06 11	920	105	1.98	6.74
<i>Kilo</i>	2015 08 30 13	946	115	1.8	16.87
<i>Maysak</i>	2015 04 03 23	967	75	1.59	7.19
<i>Vongfong</i>	2014 10 07 16	913	148	1.68	-5.73
<i>Calvin</i>	2023 07 15 08	970	90	1.33	14.75
<i>Erick</i>	2019 07 31 11	958	105	1.25	5.22
<i>Fernanda</i>	2017 07 18 01	968	94	2.01	0.59
<i>Mangkhut</i>	2018 09 11 04	927	133	1.63	13.97
<i>Wutip</i>	2019 02 27 02	976	80	1.86	5.75
<i>Nyatoh</i>	2021 12 03 06	938	120	1.76	-8.58
<i>Chanthu</i>	2021 09 11 07	930	125	1.59	6.23

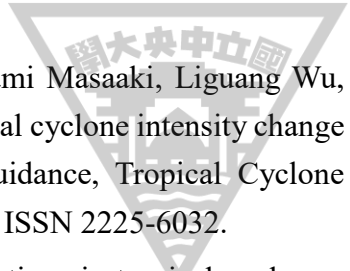


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